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Climate change, energy and sustainable development: How to tame King Coal?

Coal Working Group

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Climate change, energy and sustainable development: How to tame King Coal?

Foreword

Shortly before World War I, Winston Churchill, as First Lord of the Admiralty, converted the Royal Navy from coal to oil. In addressing the risks associated with this historic move, Churchill declared "Safety and certainty in oil lie in variety and variety alone". According to Dan Yergin, with that Churchill "was articulating the fundamental principle of energy security: diversification of supply". The principle of energy security is part of all energy policies, be it in Europe or in other parts of the world. Yet, with the end of the Cold War, the short-lived crisis before the Gulf war and overall low-to-moderate energy prices since 1986, the world has experienced a long period of overconfidence.

The time of complacency is now over. To paraphrase the International Energy Agency (IEA), the world is facing a "triple E" challenge, with the need to provide for, and at the same time, Energy security of supply, Economic efficiency and Environment protection. This challenge was the core of the Johannesburg September World Energy Conference. As Jean-Marie Chevalier pointedly observed, the world needs to solve a riddle and "reconcile the world's energy needs and the protection of the environment, while securing the economic development needed to provide for 3 billion people who currently survive with less than US\$2 per day". It is clear to everyone that the world can't do without fossil fuels. All scenarios, including the recent IEA ones, show that fossil fuels will remain a key component of any security of supply policy for the next thirty years. This is the case for oil in the transportation sector, and even more so for gas and coal in the power sector. 2004 statistics show it clearly: coal keeps an overwhelming share in power generation. Coal represents 40% of the worldwide 17 400 TWh production, whereas gas contributes for 20%, and hydro and nuclear, each, for 16%.

Devoting such a big role to coal might seem surprising to French readers. Indeed, France has progressively switched from coal to nuclear for power generation, and the last French coal mine was closed in 2004. While this move was triggered by the 1973 oil shock, some further clarifications might be useful.

Since France didn't enjoy the same plentiful geological resources as the United Kingdom or Germany, our country had to import part of its coal needs as early as in the 19th century. Being dependant on coal imports led the French authorities to start thinking about diversifying

its power generation mix right after the end of World War I. This opened the era of hydro, with the construction of dams. A few dams were built before World War II, but the trend gained momentum when EDF launched its large-scale program between 1946 and 1960. Over that period, the use of coal was devoted to the reconstruction of the country that is to say for industrial needs and heating. For a short period, between 1960 and 1973, cheap oil prices allowed fuel oil to make inroads in power generation. However the first oil shock reversed the trend to the benefit of coal, while the nuclear plants slowly took over. As soon as 1984, France turned into a power exporter. By then, the share of nuclear reached 70% of the country's installed power capacity. As coal had to be mined deeper and deeper, costs escalated at the expense of competitiveness. Eventually, it was decided in 1994 to put a definitive, but phased in, end to coal mining activities. This decision was formally supported by most trade unions.

With this policy, France has succeeded in the power generation sector both to secure its independency and its security of supply, while minimizing the impact on environment as far as greenhouse gases are concerned.

This success is due to a particular set of circumstances: large hydraulic resources, very limited fossil fuel resources, advanced technological capacity and a huge investment in research and development. I would therefore not suggest that it can be set as an example to be exactly reproduced. However, this experience teaches us a lesson for today - nuclear must remain an option-, and it confirms that tomorrow's achievements depends on technological breakthroughs and research.

This is a consensus view, widely shared by all international organizations. It was also the conclusion of the July 2005, G8 Gleneagles Summit, and can be summed up as follows:

- There is no perfect technology course as far as sustainable development is concerned
- Given the huge financial investments needed in the energy sector by 2030, it seems safer to explore all the venues, utilize all kind of fuels and benefit from all available technologies. It means keeping all options open, in particular nuclear and renewables.
- There is not a single desirable energy mix. It differs from country to country, according to each country's natural resources.

To secure security of supply while staying competitive, coal has a major role to play, especially in some developing countries, which have to address a rapidly growing energy demand, and where coal is the only option which is domestically available. Forecasts concerning different countries tell us that:

- In OECD countries most of the growth in generation will be from natural gas, but coal will also expand.
- Both coal- and natural gas-fired power plants will be built at a fast pace in developing countries.
- In all of these countries, the existing resources will largely drive fuel and technology choices on the domestic soil, security and economics.
- In most cases, the most abundant, secure and economical fuel will be coal or natural gas. China and India will account for 32% of the incremental world energy demand and 60% of incremental coal demand till 2030.

Therefore, the main question is how to mitigate greenhouse gas emissions. In that respect, Europe has been both a pioneer and a leader. Even if it is difficult to talk about a common European energy policy, the 25 European Union members share what can be seen as a "common European energy vision" aiming at reducing greenhouse gas emissions, ensuring security of supply and enhancing the competitiveness of the European economy. However, even a full implementation of the Kyoto protocol shows the limits of the exercise, as it would

allow to tackle only a third of the world CO₂ emissions, as the United States are not a party to the treaty and as large countries such as China or India do not have compulsory targets.

When one considers the technical facts and the outlook for building new coal-fired power plants, the magnitude of the stake is clear. Over the period 2003-2030, nearly 1400 GW of new coal-fired power capacity will be built worldwide. About two-third of these plants will be built in developing countries. They will be, in general, less efficient than coal plants in OECD countries. In many developing countries the efficiency of coal use is still at the level reached by OECD countries over 50 years ago. The average efficiency of coal-fired generation in the OECD was 36% in 2002, compared with just 30% in developing countries. This means that one unit of electricity produced in developing countries emits almost 20% more dioxide than does one unit of electricity produced in an OECD coal plant.

The real question is "how to tame king coal?" *The Economist* has summed up the quandary with two titles: "Coal Environment Enemy" in 2002, followed by "The future is clean coal" in 2004. As one can see, in two years time, coal has succeeded in changing its image. Now in international symposiums devoted to coal, the main message is "coal is not the problem but part of the solution". Actually, this reports aims at presenting an excellent synthesis of all the technology breakthroughs that aim at burning clean coal.

While the implementation of existing electricity generation efficiency improvement technologies and mechanisms can provide useful reductions in CO₂ emissions in the short to medium term, in the long run CO₂ emissions reductions will crucially depend on the development and deployment of ultra-low emissions technologies, including carbon capture and storage (CCS) technology developments.

As this document shows, many initiatives are currently under way worldwide. The current state of technological development of CCS system components may be the most crucial for the future of the coal industry. Only a few of them have reached the mature market phase; many are still in the research or the demonstration phase; some are now economically feasible under special conditions. Yet, whereas the goal is to master the technology, it is also important to find economical ways to transfer the much-needed technologies.

How to transfer clean coal technologies into the market place? Today, there is no full answer to this question, but a few paths are worth exploring. For instance, extend beyond 2012 and for a rather long period of time, the carbon trading scheme, in order to have enough time to put in place a financing scheme. Besides, it might seem desirable to carry experiences simultaneously in developed and in developing countries, instead of starting by developed countries.

What is sure is that it is not enough to rely on initiatives taken by states or international organizations. As stated by Lord Browne, "private enterprise has an important role to play. We should be looking at how to transfer know how to poorer nations, which cannot afford the same investment in intellectual property. Without this technology transfer, poorer nations will be doomed to satisfy their increasing energy needs by using the old dirty technologies now superseded in the developed world".

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Climate change, energy and sustainable development: How to tame King Coal?

Executive Summary

A key energy in the debate

In summer 2004, the World Energy Council¹ (WEC) published *Sustainable Global Energy Development: the Case of Coal*. It puts decisively the debate on coal on the policy agenda. This study aims at developing reply to the question "whether and to what extent coal use could be economic and sustainable in meeting global energy demand in 2030 and beyond". It covers markets, trade and demand, mining and combustion technologies, restructuring and international policies, and perspectives. It considers also the need for coal to adapt to the exigencies of security of supply, local environmental protection and mitigation of climate change. Nevertheless, it did not address the question of how to tackle compulsory targets.

Then, the IPCC² (Intergovernmental Panel on Climate Change) Special Report approved September 25th, 2005, by the 8th Session of IPCC Working Group III, focused the debate on Carbon dioxide Capture and Storage (CCS). It addresses the questions of what CO₂ capture and storage is and how it could contribute to mitigating climate change. It emphasizes also on topics such as the costs, the technical and economic potential, the local health, safety and environment risks, the legal and regulatory issues and the gaps in knowledge concerning CCS³. At the United Nations Climate Change Conference held in Montreal, from November the 28th to December the 9th 2005, was decided that the secretariat of UNFCCC⁴ (United Nations Framework Convention on Climate Change) would organize, in May 2006, a workshop on considering carbon dioxide capture and storage as clean development mechanism project activities, taking into account issues relating to project boundary, leakage and permanence. Finally, the President of the French Republic, announced⁵ that the development of clean coal power station was a key element of the French Innovation and Research policy, in particular through a new agency, the Agence de l'innovation industrielle (AII).

¹ www.worldenergy.org

² www.ipcc.ch

³ At the French level, was held, september the 15th & 16th, 2005, an international symposium on reduction of emissions and geological storage of CO₂, organized by IFP (Institut Français du Pétrole), ADEME (Agence de l'Environnement et de la maîtrise de l'Energie) and BRGM (Bureau de Recherche Géologique et Minière), see www.CO2symposium.com, www.ifp.fr, www.ademe.fr & www.brgm.fr.

⁴ unfccc.int

⁵ Allocution de Jacques Chirac, Président de la République, à l'occasion des vœux aux forces vives. Palais de l'Élysée - Jeudi 5 janvier 2006. www.elysee.fr.

A strong demand for coal

In absolute value, the global trend of hard coal demand has been one of increase over the last thirty years. Backed by its vast and well-distributed resource base, at the world level, in 2004, were produced 4 620 Mt⁶ of hard coal and 879 Mt of brown coal. Compared to 2000, when 3 633 Mt of hard coal were produced, it represents a strong increase of 27% driven notably by China's demand. This figure, by itself, shows how much alive is this energy that some judge outdated.

Coal supplied, in 2003, 24.4% of total primary energy supply (i.e. 2 583 Mtoe) and is used to produce 40.1% of world electricity (i.e. 6681 TWh)⁷ and 70% of steel⁸. Two thirds of consumed coal is used for power production. The 10 largest countries are the United States with 2 083 TWh, China with 1 515 TWh, India with 433 TWh, Germany with 314 TWh, Japan with 293 TWh, South with Africa 214 TWh, Australia with 176 TWh, Russia with 172 TWh, Poland with 143 TWh and the United Kingdom with 140 TWh. Countries such as the United States, Germany or Denmark use coal for more than 50% of their power production. In China, coal ensures 77% of the production of electricity and in India, it ensures 70%. The International Energy Agency⁹ (IEA) predicts that the use of coal will increase, from 2003, by 39% in 2030 so as to reach 3 597 Mtoe (i.e. 21.8% Total Primary Energy Supply). The conclusions of the WEC study are similar. It suggests that taking into account the significant coal reserves, an increase in the production of electricity from coal is envisaged in the world, in particular, in the USA and in China where a significant plan of renewal and growth of the park of power stations will be implemented quickly.

The strong link between power and coal reinforce the resistance of coal use. Indeed, according to IEA, a growing share of world energy consumption will be for power generation. In 1971, electricity accounted for 9% of world total final energy consumption. In 2002, it was 16%. By 2030, its share will be 20%. Due to conversion and transmission losses, the shares of primary energy supply devoted to power generation are even larger, 36% in 2002 and 40% in 2030. Thus the coal consumption for the production of electricity that was equal to 1500 Mtoe in 2000 could go up to 2500 Mtoe in 2030. This increased use of coal can even be accelerated by a possible massive switch from hydrocarbon based liquid fuels toward coal to liquid fuels (C2L), produced for example through gasification and Fisher-Tropsch processes. According to WEC, syngas from coal may contribute about an extra 100 Mtoe on 2020 (i.e. 4% of world liquid fuel demand or 1% of total primary energy supply) and up to 660 Mtoe (14% or 3% total primary energy supply) by 2050.

A major issue with greenhouse gas emissions

Nevertheless, the growth of the coal consumption poses problems in the field of the environmental protection, at the local level (reduction of the emissions of SO_x, NO_x, of mercury...) and even more dramatically as at the global level with its effect on climate change. Under these conditions, the development of clean technologies for the use of coal represents a major and critical stake.

⁶ Meaning of acronyms is given in an annex.

⁷ IEA World Energy Outlook 2005, IEA.

⁸ Source: World Coal Institute.

⁹ www.iea.org

In this volume, we focus solely on the coal sector. Our aim is therefore not to draw a global strategy, which would encompass energy efficiency, renewable energy, nuclear energy and fossil energy. Of course, only a relevant mix of those options may address the challenges we face. At the opposite, we build specific projections for power generation prolonged up to 2050, which correspond to different technological scenarios. We want to be illustrative on the case of coal and therefore do not intend to build a general equilibrium model for energy. Different works put the question in a more general setting. This is the case with the new WETO (World energy, technology and climate policy outlook) 2050 report, published by the European Commission. We will focus on the impact of the deployment of more efficient coal combustion processes in power stations, of fuel switch and of CO₂ Capture and Sequestration. We compute the corresponding level of CO₂ emissions. The 2003 global emissions of CO₂ were approximately 25.0 GtCO₂. Power generation accounted for 9.4 GtCO₂ and coal based power production for 6.6 GtCO₂. In our business as usual scenario, by 2030, global emissions will increase by 14.0 GtCO₂ – a 56% increase - and emissions linked to power production will grow by 7.5 GtCO₂ – a 80% increase – out of which 4.8 GtCO₂ are from coal. At the horizon 2050, those figures are even more dramatic. Emissions linked to power production will reach 30.5 GtCO₂ or an increase of 21.1 GtCO₂ – a more than triple increase -. If we deploy the “Best available clean technology” for coal based power generation, we will limit this increase by 6.7 GtCO₂ – 23,8 GtCO₂ instead of 30.5 GtCO₂ i.e. a 22% decrease compared to the baseline, at the horizon 2050 and a 11% decrease compared to the baseline at the horizon 2030 -. If we deploy the “Future best available clean technology”, we will limit the increase by 9.7 GtCO₂ i.e. a 32% decrease compared to the baseline, at the horizon 2050 and an 18% decrease compared to the baseline at the horizon 2030.

We can add the effects of fuel switch from half of new gas fired power plants to nuclear power. The improvement in term of GHG emissions is very substantial i.e. a 47% decrease compared to the baseline, at the horizon 2050. Finally, when we both use the capture and sequestration and switch half gas increase to nuclear scenario, we can drastically decrease CO₂ emissions i.e. a 79% decrease compared to the baseline, at the horizon 2050. It corresponds at a division by between 4 and 5 at the global level. Only this last scenario corresponds to an absolute decrease of CO₂ emissions generated by power generation. At the 2050 horizon, in absolute term compared to the starting point, it corresponds to a decrease by 30%, instead of an increase, which would more than triple the emissions. In any case, even a full deployment of future best available clean coal technologies only limits the increased of CO₂ emissions. A major switch from gas to nuclear, with those future technologies, would limit even more the increase. The full deployment of Ultra Low emission coal and gas technologies is compulsory so as to contribute to an absolute decrease of GHG emissions. In our projection it corresponds more precisely at 30%. The full deployment of Ultra Low emission technologies is therefore required, if one want to keep coal running and limit GHG emissions.

Therefore, our main conclusion is that, in addition to the deployment of more efficient coal technologies, we need to accelerate substantially the deployment of “Ultra Low emission” coal technologies, so as to stabilize CO₂ concentrations at a reasonable level. Those “Ultra Low emission” coal technologies require technologies such as Coal Capture and Sequestration (CCS). They have a cost and they increase the price for power. Therefore, to have this deployment effective, it requires the adequate framework, which will have to be based on the relevant tools such as market mechanisms, fiscal instruments and norms. Together they will fix an implicit or explicit carbon price. The case of technology transfer will also have to be addressed. There are the prerequisites to a real tackling of climate change issues on the coal side.

An industrial battle

IEA estimates the cumulative investment requirements coal-based power stations during 2001-2030 at US\$1 500 billion¹⁰. This is 10% of the investments required by the world energy supply industries as a whole (US\$16 000 billion). It will be higher if "Ultra Low emission" coal technologies are deployed. In the next decades, the right "really clean" investments may be decided. It's a tremendous effort but in the same time a huge opportunity. These new considerations create a new market for technologies. It is an opportunity for Industry to export technologies, patents and equipments. Best operating power companies may also get an edge for the global deployment.

All over the world, significant R&D programs have been started. In Europe, several actions have been undertaken to develop new CO₂ capture processes. As such, the Castor project was built to develop efficient post-combustion separation processes with the goal to divide by two the cost of the CO₂ capture. Within this project a pilot capable to treat up to 2 tons of CO₂ per hour is implemented in the Esbjerg coal-fired plant in Denmark operated by the Danish company Elsam. Operations begins in March 2006, making them the larger ones in the field of capture. Pre-combustion or oxy-combustion CO₂ capture processes are also being investigated in the ENCAP project. During the UK presidency of the European Union, at the EU-China Summit, September the 5th, 2005, was declared that "We will aim to achieve the following co-operation goals by 2020: To develop and demonstrate in China and the EU advanced, near-zero emissions coal technology through carbon capture and storage". Preliminary work is launched so as to build a pilot in China. Other actions are beginning 2005 within the European Hypogen technology platform running in parallel with the US FutureGen program. This project aims at developing, based on several demonstration projects, a clean technology of production of electricity and hydrogen using coal as a feedstock and including CO₂ capture and storage facilities. At this stage we are still at the paperwork stage. In Australia, the program is called COAL21 and also is at the paperwork stage.

In France, ALSTOM is well positioned to market equipments and complete installations on the large international markets and in particular in China. IFP (Institut Français du Pétrole) carries out, to a large extent in collaboration with ALSTOM, a whole set of R&D actions in CO₂ capture applicable to coal. IFP is developing also technologies to eliminate local pollutants such as mercury. Other corporation and institutions are involved such as BRGM, Gaz de France, Total, Air Liquide EDF, Arcelor, CNRS, GEOSTOCK, INERIS, Lafarge, SARP Industries, Schlumberger & ADEME. Several complementary actions are also led to the national level, in particular via the CO₂ Club and the Network of oil and gas technologies (Réseau des technologies pétrolières et gazières - RTPG). Finally, in France, so as to reinforce those programs, two agencies have been created. The first one - Agence Nationale de la Recherche - is devoted more on fundamental research. The second one, AII is devoted for almost deployable technologies. European corporations like Siemens are equally present in the league of major players. In the United States, corporation like GE are very active. **What is at stake is major and central in the energy policies of the world, above all in the developed countries, but also in the developing ones if the question of technology transfer is tackled. There are opportunities for the European industry by taking a technological leadership in the capture and storage of CO₂, developing patents and managing their rights. The decision that will be taken in the coming decades concerning coal will be pivotal to tackle climate change.**

¹⁰ The cumulative investment requirements for coal mining and shipping (including port facilities) during 2001-2030 add an extra US\$398 billion.

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World coal demand on the rise according to business as usual scenarios

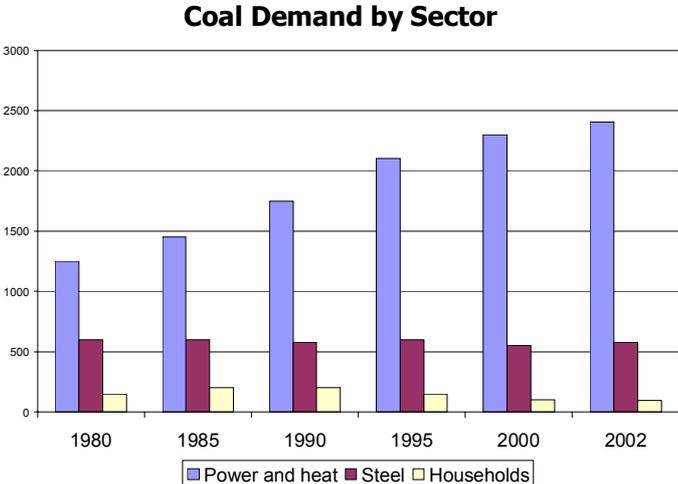
Demand for coal has more than doubled over the past thirty five years¹¹.

Rapid growth ...

The International Energy Agency (IEA) data show an increase in world primary energy supply linked to coal from 1 442 Mtoe in 1971 to 2 583 Mtoe in 2003, an increase of 79%. In term of quantity of coal, the figures are higher. The demand for coal went from 2 208 Mt in 1970 to 4 629 Mt in 2004, an increase of 110%. Over the same time period, oil use increased by 49% and remains the largest energy source. Gas usage increased by 135% over this time. The share of coal remains robust decreasing slightly from 26% in 1971 to 24.4% in 2003.

... driven by power production

Hard coal is used for two main purposes – electricity generation (steam coal) and coke production for use in steel making (coking coal). Approximately 16% (almost 600 Mt) of total hard coal production is used by the steel industry, with almost 70% of the world’s total steel production being dependent on coal. While coal supplies around 24% of the total global primary energy demand, it supplies around 40% of total world electricity production and is an essential input for steel production via the BOF (Basic Oxygen Furnace) process, which accounts for almost 70% of total world steel production.



As the chart demonstrates, the increased demand for coal over recent years has been exclusively a result of increased demand from just one sector – the power and heat sector. Overall consumption within the steel industry has declined slightly, due mainly to increased use of pulverized coal injection (PCI), although increased use of electric arc furnaces and higher rates of steel recycling may also play a part.

¹¹ Source: WEC, *Sustainable Global Energy Development: the Case of Coal*.

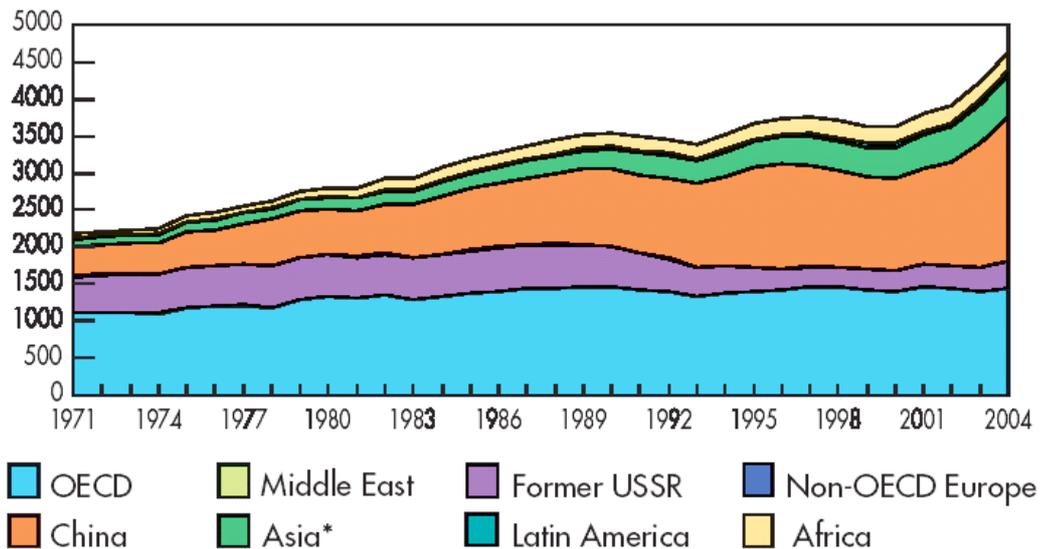
The pressure of China and Asia

Regional consumption patterns have also changed over this period, with the bulk of the increased total demand coming from the Asian region. More precisely, during the last 30 years, production rose steeply in China (with a temporary adjustment recently, already ended), India, United States, South Africa, Australia, Canada, Colombia and Indonesia, but declined in Europe with its high-cost deposits.

Therefore, significant changes in the location of coal demand have taken place over the last twenty years. In 1980, Europe, FSU and North America consumed roughly equal quantities of hard coal, around 600 Mt. North America's demand, as a percentage of total global consumption, has stayed roughly static at around 25% (in real terms, an increase of 300 Mt over the period). However, by 1990, the trends were of decreasing demand in Europe and the FSU. By 2000, European demand had fallen to just 10% of total global hard coal consumption (in physical terms, a decrease from 584 Mt in 1980 to 373 Mt in 2000).

The decline of coal consumption in the EU can be attributed to a number of factors, including more stringent environmental legislation, and the availability of gas from the North Sea, Russia, and North Africa. At long as gas prices were relatively low, as older coal-fired plants faced retirement, the total costs of building combined cycle gas plants were considerably lower than building a new coal-fired plant with the required environmental controls. However, such long-term decisions can be affected by the vagaries of gas prices – as occurred in the UK in 2001, when coal fired plants were brought back on-line due to sudden increases in gas prices. The effects of enlargement within the EU will also have an impact on coal demand in the region, as much of the power generation capacity of accession countries is coal-fired. Poland and the Czech Republic, for example, generate 96% and 71% of their electricity demand from coal.

Evolution from 1971 to 2004 of Hard Coal Production by Region (Mt)

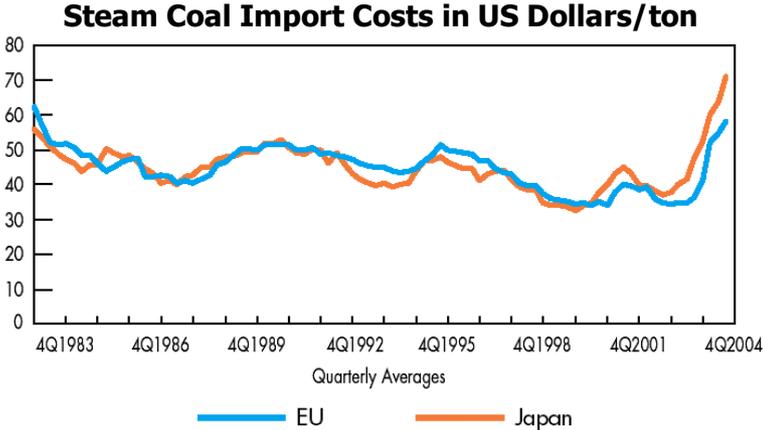


Source: IEA, 2005

Demand in the Asia-Pacific region for hard coal, in contrast, has increased dramatically from 34% (of global demand) to 52% over the same period – an increase equivalent to almost one billion tons. One reason for this is the huge increase in demand for electricity in Asian countries. China's electrification program, for example, has connected 700 million people over the last fifteen years. As a result of the program, electricity production in China has increased

by nearly 1000 TWh. 84% of this is coal-fired. Forecasts indicate that this regional trend will continue, with the bulk of the projected increase in global coal demand coming from the region. Japan continues to be the largest importer of hard coal – both steam coal and coking coals – and is projected to account for 24% of total world imports by 2020. Other Asia-pacific countries, such as Malaysia, Philippines, Thailand, are looking to coal to diversify their energy mix and provide a secure supply of affordable energy to meet their growing electricity needs.

In 2004, were produced 4 620 Mt of hard coal and 879 tons of brown coal. Compared to 2000, when 3 633 Mt of hard coal were produced, it represents a strong increase of 27% driven notably by China’s demand. The increases of prices reflect this increase in demand.



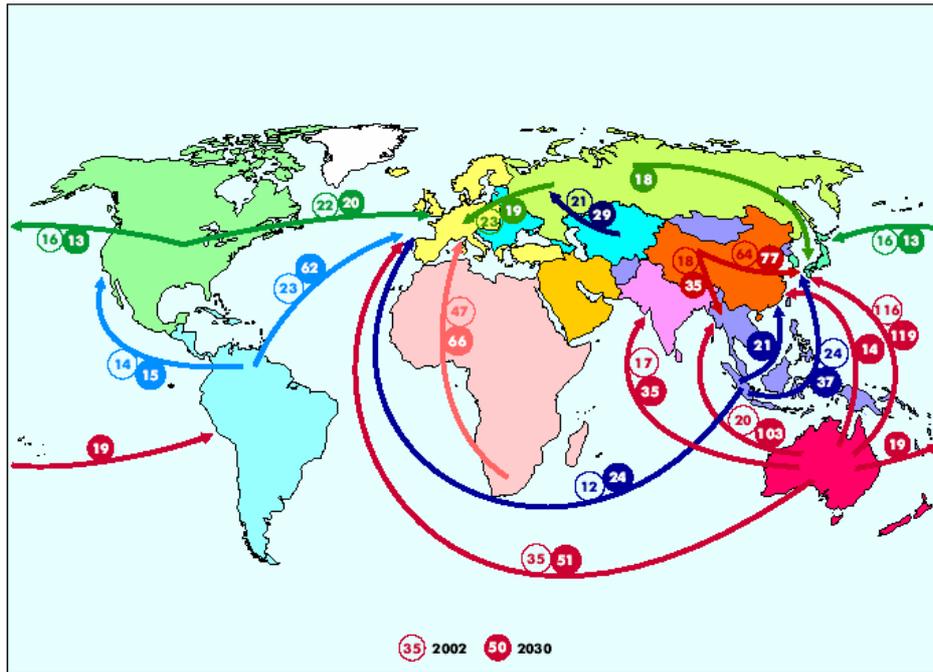
Source: IEA 2005

Only a relatively small fraction of this consumption is internationally traded – about 17% - but this has increased much faster than overall demand.

Because of the expense of transportation, most traded coal is hard coal, which has higher value and energy content. Seaborne trade in hard coal, has on average risen by around 4% a year since 1970, with the growth dominated by the trade in steaming coal (used mainly for electricity generation). The initial growth in coal trade during the 1970s was due to strong growth in steam coal demand as coal widely replaced oil in electricity generation as a result of oil price rises. More recently, the growth in steam coal trade has been driven by greater imports from Japan, developing Asia and Latin America where there are inadequate domestic reserves to meet growing demand. The largest coal exporters are Australia, South Africa, Indonesia, United States, China and Colombia. In 2004, hard coal trade reached 755 Mt. The share of hard coal trade in the global hard coal output was 16%. Worldwide hard coal trade is divided into 94% of maritime trade and 6% of internal trade.

In 2004, international hard coal trade in maritime traffic totaled about 16% of worldwide hard coal output. Thus almost 85% of hard coal output is consumed in the mining country itself – in particular for power generation and, in addition, by some key industries, such as iron and steel, cement and chemicals. This is especially true for the three largest hard coal producers China, US and India. Of total hard coal overseas seaborne trade in 2001, approximately 398 Mt were accounted for by steam coal and 174 Mt by coking coal. The most important exporting countries in 2001 were Australia, China, South Africa and Indonesia, whose exports totaled 73% of seaborne hard coal trade. The major importing continents are Asia (mostly Japan) and, despite a general decline in overall consumption, Europe.

Major Inter-regional Coal Trade Flows, 2002-2030 (Mt)

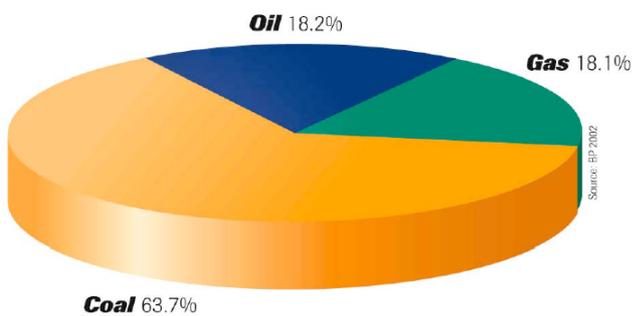


Source: IEA – World Energy Outlook 2004

There is a large availability of coal into the future.

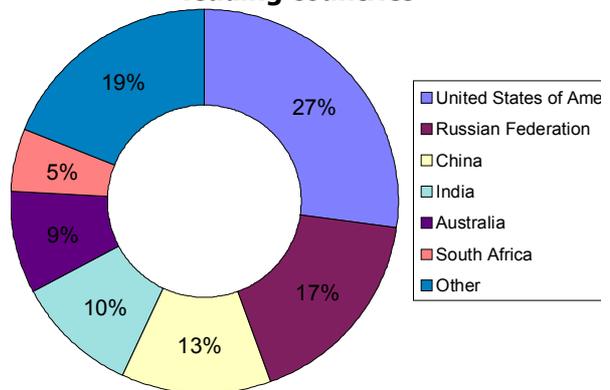
Coal is in a unique position compared to oil and gas. Economically recoverable coal reserves are huge. Reserves have increased by over 50% in the last 22 years. Despite increased production during the next thirty years, only 25% of presently known coal reserves would be depleted compared with 84% of oil reserves and 64% of gas reserves. Moreover, depletion ratios would slow due to the anticipated increase in power plant efficiency and related fuel savings of as much as 35%. Nevertheless, the industry should remain active in exploration, if only to enhance coal’s contribution to energy security.

Fossil reserves in 2002



Source: BP

Proved coal reserves at end 2004 leading countries



Source: WEC

Moreover on the energy security aspect, coal also has a strong performance as proven reserves are present almost everywhere worldwide. According to the 2004 WEC Report on *Sustainable Global Energy Development: The Case of Coal*, the top ten countries accounted

for just over 90% of the total reported coal reserves at the end of 2004. The seven leading countries are the United States, Russia, China, India, Australia, Germany and South Africa. The quality of their reserves is somewhat diverse especially in term of cost of recovery.

On a geographic basis, both North America and Asia have over 25% each of total reserves. While the reserves in North America are almost equally split between bituminous coal and sub-bituminous/lignite, Asia has a significantly higher proportion of reserves in the bituminous classification, accounting for around 35% of total bituminous reserves worldwide. Total coal reserves held by Europe were slightly over 30% of the world total, while the individual categories show a higher share of world sub-bituminous and lignite reserves and a lower proportion of bituminous (22%). European reserves are dominated by two countries: Germany (21%) and the Russian Federation (50%). In respect of bituminous reserves, Germany, Poland, Russian Federation and the Ukraine account for over 95% of the European total. The cost of recovery for German coal is amongst the highest of large producer countries.

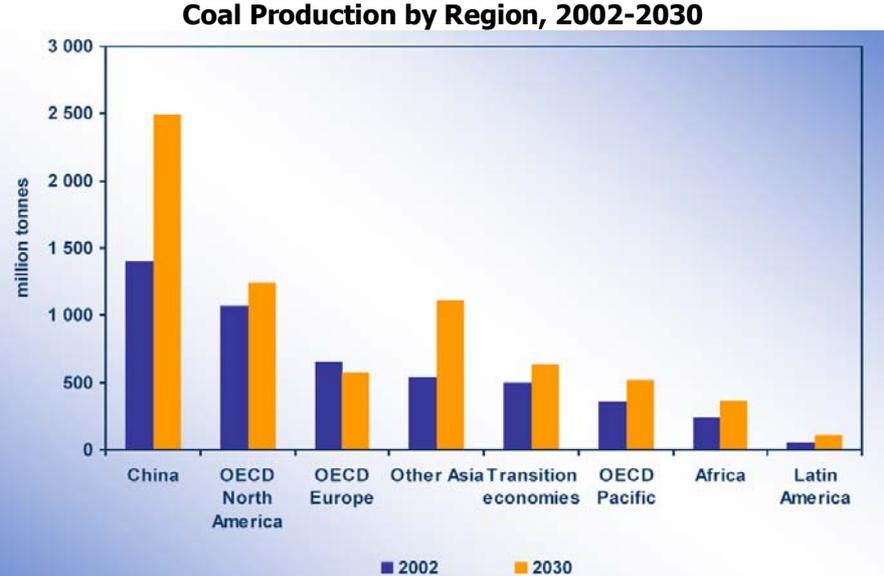
Africa has less than 6% of total reserves with these reserves concentrated in the bituminous category and dominated by South Africa with about 90% of the total. Botswana and Zimbabwe have the only significant reserves outside South Africa. South America is the one continent with little in the way of coal reserves – only 2.2% of total reserves and only 1.5% of the bituminous reserves.

In a business as usual scenario, coal demand would be expected to increase during the next three decades everywhere in the world, except in Western Europe.

There are many projections regarding future coal demand. They provide rather diverse pictures. However, all concur to say that without a major limitation due to environmental concerns, global coal demand will increase over the next 30 to 50 years.

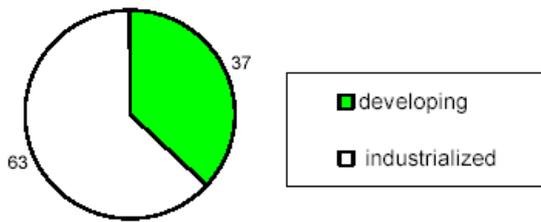
Increase in demand driven by Asia

According to WEC, the increase would be strongest in the developing countries: China, India, South-East Asia, sub-Saharan Africa and Latin America. Coal demand by developing nations would actually double from 1.5 Gt in 2000 to 3.1 Gt in 2030. By that year, 60% of world coal demand would be generated in developing countries, against 45% in 2000. We give IEA data, in the next figure.

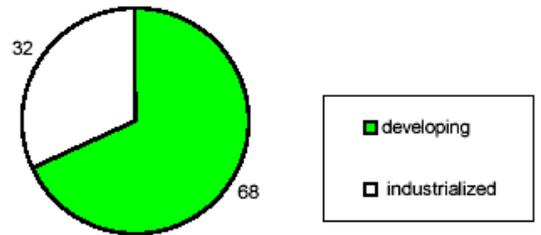


Source: IEA

Regional breakdown of world coal demand, 1990



Regional breakdown of world coal demand, 2020



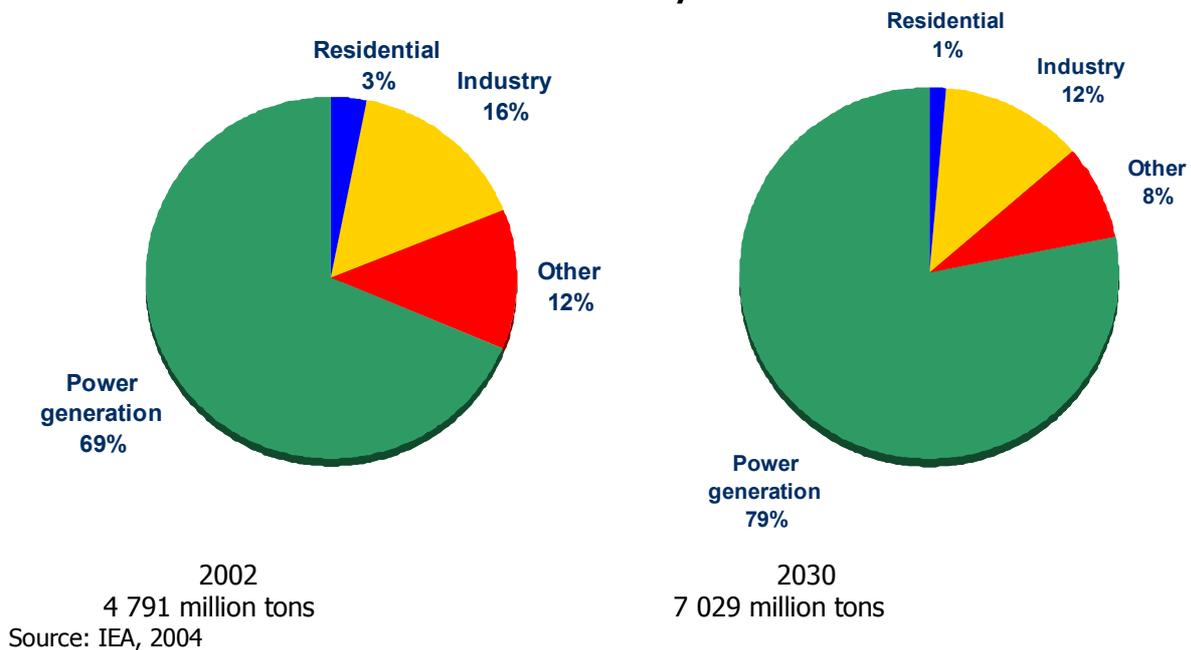
Source: WEC

The developing countries are the growth engine behind global coal demand and for them coal remains critical. Despite competition from natural gas, in the developing world, coal would account for 33% of total primary energy supplies in 2030 (against 39% in 2000). More importantly, in developing countries coal would secure 53% of electricity generation in 2030, against 56% in 2000. Coal-based power generation would more than triple.

Increase in demand driven by power plants

Most of the increase of coal demand will be from power plants, which will absorb in 2030 some 79% of coal supplies, against 69% in 2002. Three decades from now, coal would cover 45% of world power needs, compared with 40.1% in 2002.

Coal Demand by Sector



Increase in demand driven by syngas

New use would even be added such as the production of liquid fuel and hydrogen from coal. While world primary energy supply linked to coal correspond to 2 355 Mtoe in 2000, according to WEC, syngas from coal may contribute about 100 Mtoe on 2020 (or 4% of world liquid fuel demand) and up to 660 Mtoe (14%) by 2050.

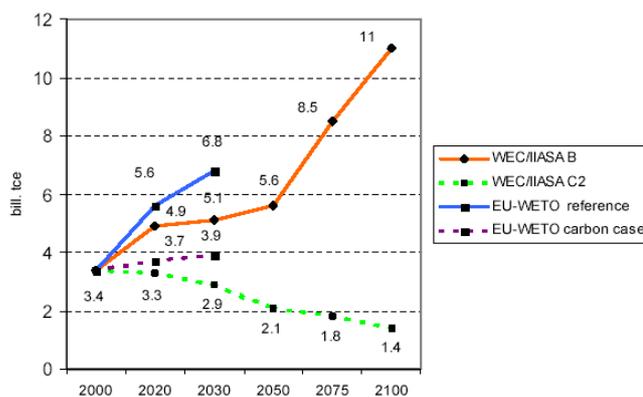
Business as usual versus constrained scenarios¹²

IEA, in its reference scenario, expects coal demand to grow by 39%, from 2003 to 2030 (from 2 581 to 3 597 Mtoe). For EU-WETO - *World energy, technology and climate policy outlook* -, in the business as usual scenario, coal will continue to play a key role in the world energy mix, meeting 22% of all energy needs in 2030, a small decrease from the current level of 24.4%. Coal demand is projected to increase by 1.4% per year between 2002 and 2030. By 2030, according to EU-WETO¹³, coal demand – at 6.8 billion ton coal equivalent – will be almost 50% higher than at present. Power stations will absorb most of the increase, with coal remaining the dominant fuel for power generation. Asian countries will see the highest increase in demand for coal, with China and India alone accounting for 68% of the increase in demand to 2030. World electricity generation is projected to rise from 16 074 TWh in 2002 to 31 657 TWh in 2030. The largest increase will be in China, who will account for a quarter of the world's projected growth. Coal-fired power plants provided 40% of global electricity needs in 2002. This will fall only slightly over the period, to 38% in 2030.

The *International Energy Outlook 2005 (IEO2005)* projections, published in July 2005 and provided by the Energy Information Agency¹⁴ of the DoE, indicate continued growth in world energy use, including large increases for the emerging economies of Asia. The demand for coal increase by 59% between 2002 and 2025¹⁵. This projection sees a bigger expansion for coal than the one of AIE¹⁶. The largest increases in coal use worldwide are projected for China and India, where coal supplies are plentiful. Together, China and India account for 87% of the projected rise in coal use in the emerging economies region and 72% of the total world increase in coal demand over the forecast period.

In the business as usual scenario, for EU-WETO the increase is seen at 100%. In the abatement, scenario, the increase is only of 15%. WEC/IIASA¹⁷ proposes also very contrasting scenarios. They are used for the IPCC Special Report on Emissions Scenarios (SRES).

World coal demand projections



tce for ton coal equivalent

Source: WEC and EU-WETO

Projections of the global primary energy supply linked to coal to 2050 for the six Scenarios (Gtoe)

1990	2050					
	A1	A2	A3	B	C1	C2
2.2	3.8	7.8	2.2	4.1	1.5	1.5

Source: WEC/IIASA

At the horizon 2050, in market-driven scenarios, the increase of coal demand goes from 0 to 230%. In the climate friendly setting, the demand decreases by 36%.

¹² As seen in Annex 1.

¹³ http://europa.eu.int/comm/research/energy/gp/gp_pu/article_1257_en.htm

¹⁴ www.eia.doe.gov

¹⁵ It corresponds to the data of the reference case. A high growth case gives 76% and the low growth 47%.

¹⁶ The *IEO2005* 2025 forecast for coal use in the emerging economies is nearly 13% higher than in the 2004 version.

¹⁷ www.iiasa.ac.at

In the WEC/IIASA scenario B, coal demand would increase by 72%, i.e. from 3.4 Gtce to 5.6 Gtce. However, demand would decrease in the CO₂-constrained scenario C2 by 37%. Even in this scenario, coal demand would stand in 2050 at two-thirds of coal demand in 2000 or 2.2 Gtce.

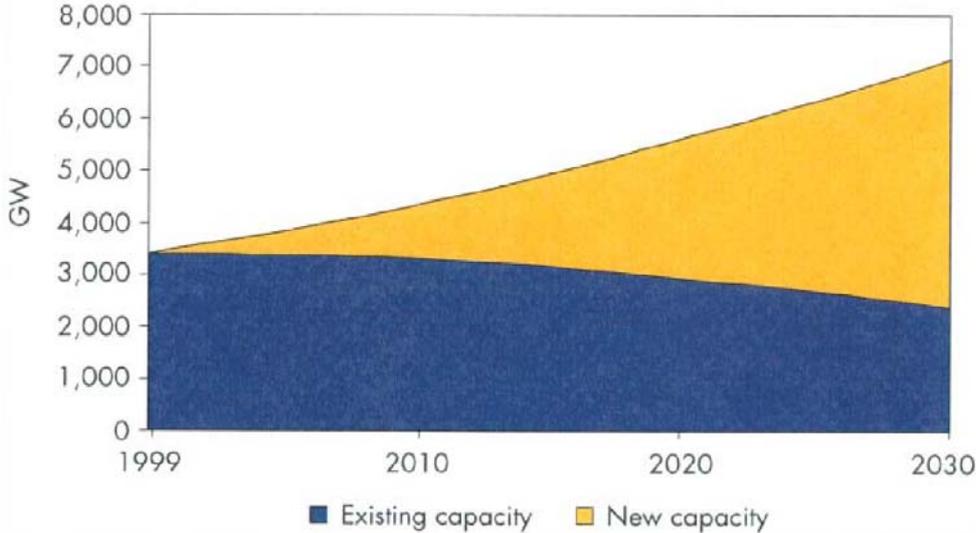
Investments in coal mining and combustion

Coal mining is less capital-intensive than the extraction of oil and gas. Before the strong increase of energy prices these last years, the mining of a ton of coal (in toe equivalent) required less than US\$5, compared with US\$22 for the extraction of oil and almost US\$25 for gas, according to WEC. Today all those cost have increased due to the fact that less competitive extraction possibilities have been exploited.

IEA estimates the cumulative investment requirements for coal mining and shipping (including port facilities) during 2001-2030 at US\$398 billion. Cumulative global coal investments needs are shared equally by developed and developing nations, with China requiring 34%, the United States and Canada 19%, Australia and New Zealand, 9%, the transition economies, 8%, OECD Europe, 7% and India, 6%.

If investments for coal-based power stations were added, the total cumulative investment needs would amount to US\$1 900 billion. This is 12% of the investments required by the world energy supply industries as a whole (US\$16 000 billion). It will be higher if "Ultra Low emission" coal technologies are deployed. In the next decades, the right "really clean" investments may be decided. It's a tremendous effort but in the same time a huge opportunity. These new considerations create a new market for technologies. It is an opportunity for Industry to export both technologies and equipments. Best operating power companies may also get an edge for the global deployment.

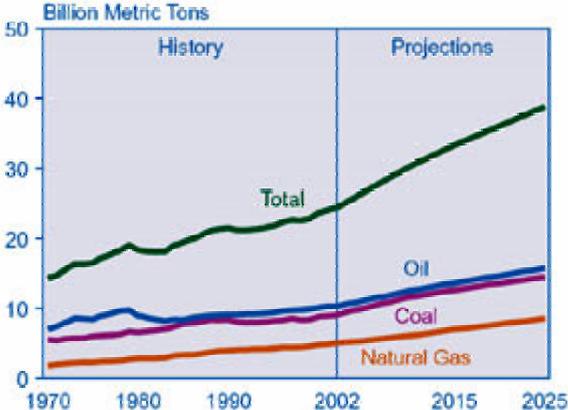
World Installed Electricity



Source: IEA

Coal will need to reduce its environmental footprint.

World CO₂ emissions by fuel type, 1970-2025

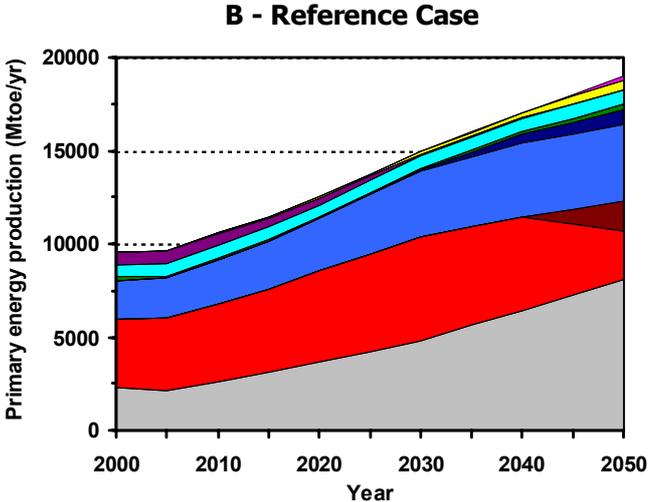


Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2002*, DOE/EIA-0219(2002) (Washington, DC, March 2004), web site www.eia.doe.gov/iea/. **Projections:** EIA, *System for the Analysis of Global Energy Markets* (2005).

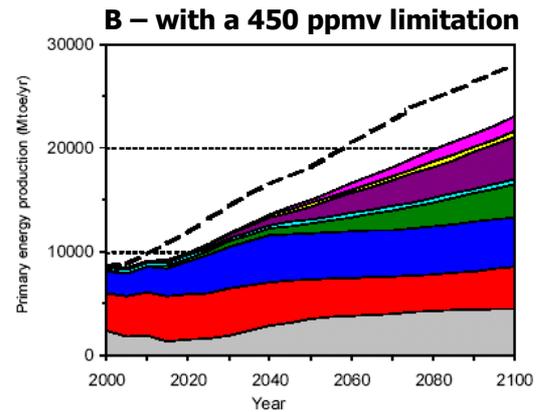
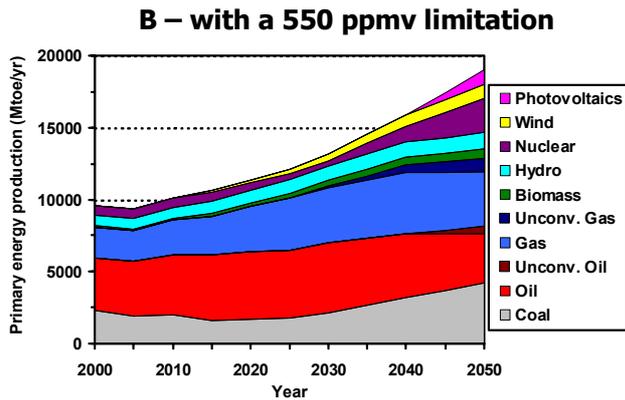
The growth of the coal consumption poses problems in the field of the environmental protection, at the local level (reduction of the emissions of SO_x, NO_x, of mercury..., actions considered to be priority by the emergent countries) like at the total level with its effect on the global climate change; in particular, GHG (greenhouse gases) emissions linked with the objectives of the United Nations Framework Convention on Climate Change (UNFCCC) (and the Kyoto Protocol). Coal is a major emitter as shown in the corresponding diagram and is the most carbon-intensive of the fossil fuels at the point of combustion.

More precisely, in 2002, coal usage is responsible for 2.5 GtC (9.1 GtCO₂) of emissions out of a total of 6.7 GtC (24.4 GtCO₂). In the *IEO2005* reference case, world carbon dioxide emissions from the consumption of fossil fuels are expected to grow by 59% from 2002 to 2025. These emissions in 2025 are projected to total 10.6 GtC (38.8 GtCO₂), exceeding 1990 levels by 81%. Emissions linked to coal will increase by 58.8%, by natural gas by 70.7% and by oil by 52.9%.

The objective of reducing the level of CO₂ emission will have a dramatic impact on the use of energy and in particular coal. For example, we can see that through results given by the world energy model, DNE21+, proposed by the Japanese Research Institute of Innovative Technology for the Earth (RITE). They build scenarios based on B base scenarios (medium growth) constrained by CO₂ concentration caps respectively at 550 and 450 ppmv. The lower the concentration cap is, the lower the increase of temperature is.



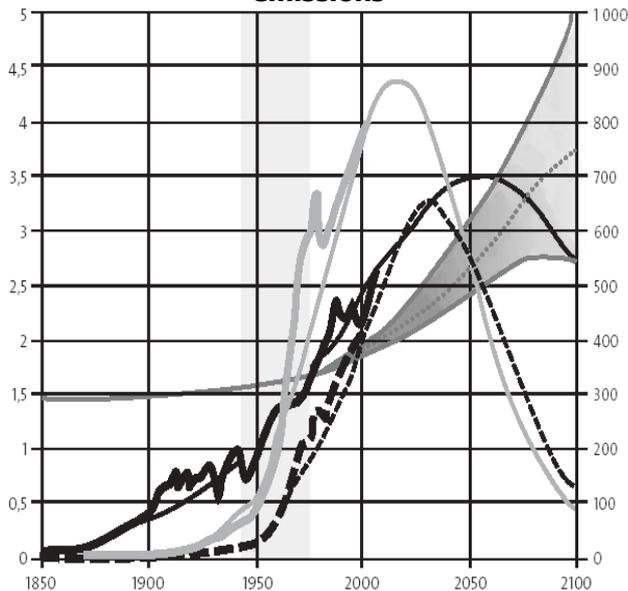
In the reference case, in 2050, primary energy production linked to coal reaches 7.5 Gtoe in 2050 instead of reaching 2.6 to 2.8 Gtoe for a CO₂ cap at a concentration of 450 or 550 ppmv.



Source: DNE21+ from (RITE).

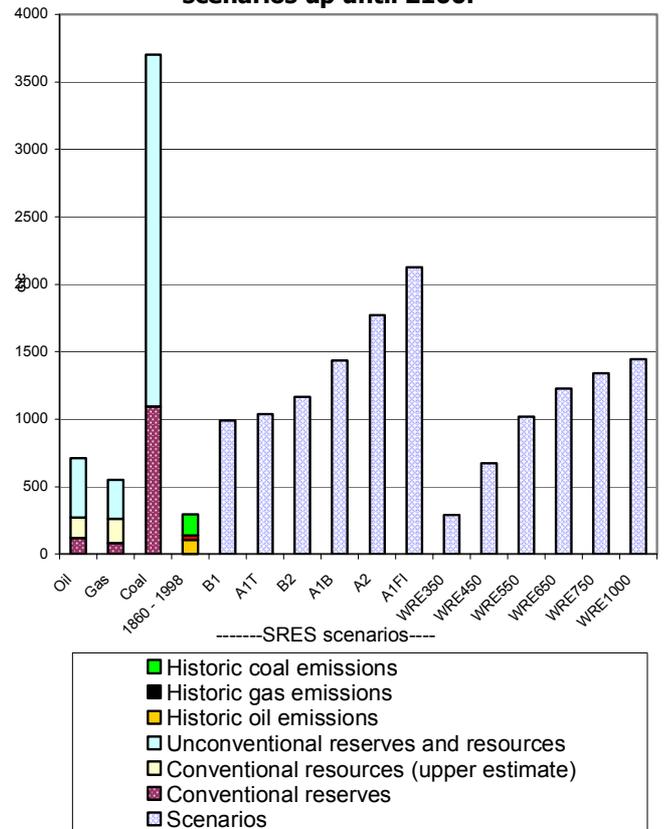
If one takes into account the reserve factor as Jacques Varet from BRGM¹⁸, we can see that limitation due to the rarity of resources is less stringent on coal than on natural gas and oil. It makes the case of coal even trickier as it induces that the future price of coal will be more moderate than the one of its competing fossil energies. In any case the limitation of fossil resources will not be sufficient to tackle the climate change issue.

Oil, natural gas & coal peak oil versus CO₂ emissions



Source: Jacques Varet, La Géothermie. Orléans: BRGM (coll. Enjeu des géosciences), 2004.

Carbon in oil, gas and coal reserves and resources compared with historic fossil fuel carbon emissions 1860-1998, and with cumulative carbon emissions from a range of SRES scenarios and TAR stabilization scenarios up until 2100.



Source: IPCC

¹⁸ www.brgm.fr

German coal-fired power stations are Europe's dirtiest

A new study by the global conservation organization the WWF, published on 4 October 2005, has revealed that Germany is host to some of the most polluting power stations in Europe. It looks at the efficiency of EU power stations in terms of the amount of CO₂ emitted for each kilowatt hour produced. Most of the WWF's 'Dirty Thirty' are located in Germany (9 plants), followed by Poland (5 plants), Italy, Spain, and the UK (4 plants each). Germany's RWE runs four of the ten dirtiest plans, thereby topping the list of the biggest CO₂ emitters, followed by Vattenfall, E.ON, Endesa, EDF and Electrabel. Twenty seven out of the 30 most polluting power stations are coal-fired. "Coal-fired power stations rank dirtiest, because they use the most CO₂-intense fuel. To switch off global warming we have to replace them with cleaner alternatives, such as gas and renewables," said WWF's Imogen Zethoven.

Source: <http://assets.panda.org/downloads/dirty30rankingfinal260905.pdf>

Coal's technological agenda

Efficient coal use is currently the primary means of reducing coal's GHG impacts as carbon dioxide capture and storage is not yet commercially viable.

In the short term, a reduction of CO₂ emissions is sought through increased efficiency of steam-cycle power plants as existing technologies. Due to the size of those existing investment, further improvements in the efficiency of these technologies will continue, even in the medium term. In this medium term, combined cycles on a coal basis that are currently being tested or developed may be applied. Such technologies are the integrated gasification combined cycle (IGCC), pressurized pulverized combustion (PPC), pressurized fluidized-bed combustion with partial gasification (second generation) and externally fired combined cycle (EFCC). In addition, another possibility is to use coal plants biomass added to coal through co-firing. It can be done also in steel production. In the longer term, numerous concepts are under consideration. These include gas turbine combined cycle (GTCC or GCC) with a high-temperature fuel cell and combinations of coal gasification, high-temperature fuel cell and gas combined cycle (IGCC with fuel cell, integrated gasification fuel cell power plant). But beyond the improvement of power plant efficiency, so as to have a real clean coal technology, i.e. an ultra low emitting technology, capture and sequestration are absolutely compulsory.

CO₂ induced reduction by increased efficiency of existing steam cycle power plants

Except for some pilots, up to date, only steam cycle power plant process has managed to penetrate the market. All steam power plants are based on the same principle. The fuel is burnt with air, and hot combustion gas, also called flue gas, is produced. The flue gas heats the water in the steam generator, thereby producing hot steam at high pressure. Downstream the steam generator, the flue gas is conducted to the flue gas treatment plant and, along with the vapor of the cooling tower, is discharged into the atmosphere via a stack. The energy of the steam is converted into rotational movement in the turbines to produce electricity in generators. Downstream the turbine, the low-energy steam condenses by heat release and is then fed back into the cycle by condensation and feedwater pumps. The highest energy losses during the conversion of coal's chemical energy into electric energy occur in the steam cycle

upon condensation by heat loss. This combination of firing and subsequent steam generation can be used for different fuels. The choice of the market to rely on steam power plant is the result of many decades of gradual further development of these processes. The progress was achieved in this field especially in the last ten years so that these processes are currently clearly superior to the others from the aspects of cost efficiency, availability and reliability, and also represent a benchmark for all other power plant processes in the long term. The main technology is linked to pulverized fuel (PF) combustion. A second one is fluidized bed combustion (FBC).

Pulverized fuel (PF) combustion technology

The majority of the world's coal-fired power stations use pulverized fuel combustion technology, which has been the main generation technology for over 50 years. In this system, powdered coal is burnt with air in a boiler. The high-pressure steam generated drives a turbine to make electricity. The efficiency of energy conversion depends on factors such as the quality of the coal and the design and maintenance of the boiler. At present, conventional coal-fired technology tends to be favored by utilities and lending institutions over other more advanced options because of perceived operational risks. For this reason, advances in clean coal technology are primarily being targeted, by industry, at improving efficiency, increasing the longevity of parts and enhancing emissions mitigation.

They have reached a high technical level. Today maximum efficiency values of 46% are obtained for hard coal and more than 43% for lignite. Rigorous further development in the fields of fluid mechanics, thermodynamics, materials technology and new coal drying technologies will enable the efficiency of steam cycle power plants to be increased to about 51% by 2010. Even higher efficiencies will probably be achieved by 2020 by further increasing the live steam parameters, reducing the off-gas losses of the steam generator and by sophisticated high-temperature blading of the steam turbines.

For hard coal, supercritical pulverized coal combustion presently operates at efficiencies of 45% and offers prospects for an increase to 48%; this technology remains the preferred option for large units and for up to 2020. For lignite, supercritical pulverized firing attains more than 43% (in the so-called BoA unit of the German plant of Niederaussem), with a target of 50% and more if pre-drying and new materials were used (timeframe 2020). Supercritical PF-fired power plants will remain the preferred technology in the near future. In particular, recent examples in Germany have shown a tremendous improvement in efficiency. Further potential for cost reductions is being investigated for future applications.

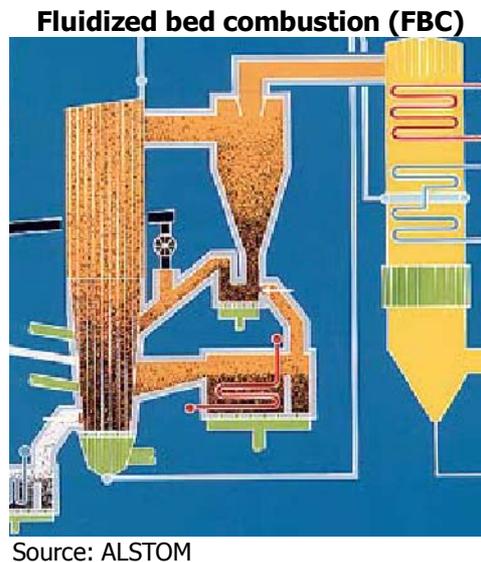
Fluidized bed combustion (FBC)

As an alternative to pressurized fluidized (PF) combustion, the fluidized bed combustion (FBC) technology could be used for hard coal as well as lignite. The "fluidized bed" process was first used for the gasification of coal and for industrial chemical process reactions between solid materials and gases. From 1970, the first plants burning solid fuels were used. Today the most common principle is circulating fluidized bed combustion (CFBC).

Fluidized beds offer several advantages over pulverized fuel combustion, notably low NO_x emission, in-process capture of SO₂¹⁹ and the ability to burn a wide range of low-grade and potentially difficult fuels (including ash-rich fuels, waste and biomass), as well as mixed fuels.

¹⁹ With these systems, sulphur and nitrogen are removed during combustion (rather than by post-combustion flue-gas scrubbing) using an SO₂ absorbent (limestone).

Combustion temperature is lower, at approximately 850°C. The "conversion" (combustion or gasification) of solid fuels for production of heat and/or electricity can be made by various fluidized bed techniques working at atmospheric pressure or under pressure, usually: "bubbling" and "circulating" fluidized beds.



Supercritical steam conditions can be used for fluidized bed boilers (atmospheric and pressurized) and efficiencies in the range of 45 per cent may be attained in the near future. In addition, large scale Circulating Fluidized Bed Conversion units are now being offered in sizes up to 650 MWe range, so that FBC are now available at full utility scale.

In addition, the technology can be employed for incineration and existing units have been successfully used for the disposal of high level PCB contaminated wastes, oil remediation and the elimination of low calorific wastes. The technology is also widely used in the metallurgical industry among others.

Not largely deployed technologies at this stage

Today, particularly high levels of efficiency can normally be achieved with natural gas in combined cycle processes. Gas turbines can only be operated with ashfree fuels. In order to make coal usable as a fuel for the combined gas and steam turbine process, various variants of the combined cycle process have been developed. These include the combined unit with integrated coal gasification (IGCC), the combined process with pressurized fluidized bed combustion (PFBC); and the pressurized pulverized coal combustion system (PPCC). Those processes based on coal profit especially from technological progress in natural-gas-based combined cycle power plants, but also from new materials and technologies in conventional processes.

Individual projects have already reached a high technical level. Particularly beneficial is their considerable development potential with respect to efficiency, emission standards (ultra-clean coal), fuel flexibility, efficient CO₂ capture and product flexibility (electricity, synthesis gas). At the moment, the high specific costs and the risks of a new technology hinder a broader market penetration.

Integrated gasification combined cycle (IGCC)

In Integrated gasification combined (IGCC) technology, solid or liquid fossil fuels are converted into a gaseous fuel known as synthesis gas (syngas), a mixture of carbon monoxide and hydrogen. Pollutants are then removed and the syngas is used as fuel in a combined cycle power system.

The IGCC process has been realized worldwide in a number of demonstration and commercial plants. As yet, a lack of competitiveness, reliability and availability has prevented the commercial breakthrough of this most extensively developed new power plant process with a wide range of potential. With respect to CO₂ capture, the IGCC process has advantages in comparison to the other processes due to the possible separation of CO₂ from the pressurized coal gas or fuel gas before combustion. The next development step in this process is a coal-fired IGCC demonstration power plant with high efficiency, reduced costs and high availability that can be constructed from 2010 to 2015. IGCC, at demonstration stage, achieves 43%, but may attain 51 to 53%²⁰. It represents the necessary intermediate stage for a later IGCC power plant with maximum efficiencies (> 55%) and optional CO₂ capture.

An important intermediate objective is the development of a gas turbine for the use of synthesis gas. A necessary boundary condition for the implementation of the IGCC process is regarded as the demonstration of the high availability of the existing plants and the reliability of this technology. To this end, R&D activities in parallel to further developments should be particularly concerned with evaluating the existing extensive operating experience with IGCC and gasification plants and in realizing technically and economically optimized concepts with the aim of demonstrating the commercial breakthrough.

Beginning in 1972, STEAG gained experience with this technology at the Lünen power station, including the world's first prototype plant with an electric rating of 170 MW. Intensive work is currently being done on further development at other demonstration plants. Proof of successful operation still has to be furnished for raw power plant operation with high availability under changing conditions of use. Reliably controlled coal gasification, on the one hand, and the combined cycle process, on the other, has to be developed first to achieve a highly available unit.

Interesting efficiency prospects emerge, particularly if higher gas turbine inlet temperatures can be used with purified coal gas. In the case of the combined process with integrated coal gasification, efficiencies of around 45% are currently feasible. In Europe, demonstration plants are operating on an industrial scale in Buggenum/The Netherlands and at Puertollano/Spain. In the US, some demonstration plants are also being operated. The aim of more recent investigations has been to demonstrate the possibilities of improving IGCC, which will lead to higher efficiency levels, higher plant capacity and, hence, to reductions in costs compared with the plants built until now. Plant availability, has to also be improved.

Pressurized pulverized combustion (PPCC)

Pressurized pulverized coal combustion (PPCC) can achieve power plant efficiencies of over 50% when designed as a combined cycle power plant process. For this, coal must be combusted at high temperatures under a pressure of about 16 bar. The present target is to achieve a gas turbine temperature of 1 250°C, which completely exhausts the efficiency of current turbines. This temperature should increase with further developments in gas turbines.

²⁰ Source: WEC.

The PPCC flue gas contains a large number of minerals and other substances, which would very rapidly destroy the gas turbine blades by erosion and corrosion. Realization of the GCC process with PPCC therefore requires that the ash and alkali components in the flue gas present during the combustion of solid fuels like coal should be separated so that the gases can be tolerated by the gas turbines. This task defines an essential part of future research priorities.

The necessary boundary condition for implementation of the PPCC process is cleaning the flue gases of particles and alkalis at very high temperatures of up to about 1 600 °C. To this end, it may possibly be necessary to conceive of completely new paths within the framework of basic research.

Pressurized fluidized bed combustion (PFBC)

Combined gas and steam turbine power plants with pressurized fluidized bed combustion are considered in the discussions on advanced fossil-fired power plants. They promise an alternative concept for efficient and low-emission generation of electricity from hard coal and lignite. The suggested concept of pressurized fluidized bed combustion offers the exciting possibility of using the primary fossil fuel coal directly in the gas turbine without the intermediate gasification step. It is fundamentally different from the oil and gas-fired combined cycle plants in the pressurized fluidized bed concepts. Heat is transferred to the water steam cycle in the fluidized bed to reduce the combustion temperature to some 850-900°C.

In spite of a large number of demonstration projects worldwide, pressurized fluidized bed combustion (first generation) did not succeed in achieving a commercial breakthrough. Fluidized bed combustion, suitable for smaller capacities and high ash coals, presently operates at 40% efficiency with prospects for up to 44%. Due to its limited efficiency potential, work has begun on developing a PFBC concept (second generation) with which efficiencies of 53 to 55% will be achieved, comparable to those of other coal combined cycles.

However, acceptance of this further developed PFBC process can only be achieved if the availability and reliability of the existing stationary PFBC plants is appreciably improved and a combination with gasification technology reliably tested. Only then will it be meaningful to press ahead with this process. A necessary boundary condition for the further development of the PFBC process (second generation) is the existence of an operational product gas cleaning system in the high-temperature range (approx. 400 to 900 °C), from which the IGCC technology would also benefit.

Externally fired combined cycle (EFCC)

The necessary boundary condition for the implementation of the EFCC process is the development of a ceramic high-temperature heat exchanger that can be exposed to the unpurified flue gases of up to 1600 °C. This also primarily requires basic research.

Even More futuristic processes

With Integrated gasification combined (IGCC) technology, the use of a fuel cell and/or capture of CO₂ should be contemplated, more precisely with solid-oxide fuel cells (SOFC). Those

technologies are often called hybrid processes. In this case, the CO/H₂ ratio of the syngas can be adjusted towards more hydrogen by means of the water gas shift reaction: $\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$. Very high efficiencies are envisaged with those plants. They are calculated to reach about 70%, and coal-fired integrated gasification combined cycle with fuel cells about 60%.

The basic principle of hybrid-cycle power plants has been demonstrated in small gas-fired pilot plants. The efficiency could also be increased by combining coal gasification with SOFC (IGFC, using SOFC waste heat for endothermic coal gasification). An improvement in all processes with oxygen blown coal gasification can be expected through the development of ion-conducting membranes. The energy required for the production of oxygen can probably be significantly reduced by such membranes.

The necessary precondition for operating SOFCs or other high-temperature fuel cells in large-scale power plants is further development towards higher operating pressures, an increase in unit capacity (combination of stacks to form power units > 50 MW) and a dramatic reduction in costs. It is expected to take about 20 years before suitable fuel cells are commercially available for this type of power plant design.

Other designs described in the literature such as the power plant magneto hydrodynamic generator (MHD) combined with a thermal power plant, the Kalina process, Graz cycle, multi-media cycles and thermal direct energy conversion processes do not, from the present perspective, permit higher efficiencies than can be achieved with hybrid power plants.

Efficiency of different technologies

Coal-fired generating capacity of about 1 000 GW is installed worldwide. Driven by the progress made in advanced clean coal technologies, the efficiency of conventional process equipment with pulverized fuel (PF)-fired boilers, which account for the majority of the world's coal-fired power plants, has gradually improved, while maintaining high availability as well as competitiveness, in terms of generating costs and low emission levels.

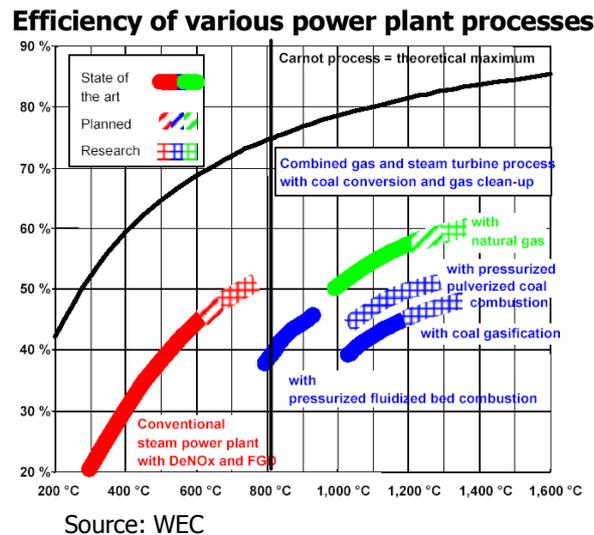
Improved conventional clean coal processes, employing supercritical PF-boilers on a hard coal basis can reach an efficiency level of around 45% to 47%, depending on plant location (e.g. sea water cooling). Similar developments are under way for lignite-fired power plants. The lignite unit with optimized plant technology ('BoA' = "Braunkohlenkraftwerk mit optimierter Anlagentechnik") has an operating efficiency of over 43%. It went on stream in August 2002 after an approximately four-year construction period. The next development phase will integrate optional lignite predrying. A plant based on this concept is expected to reach an efficiency of around 47%.

Efficiency depends primarily on the characteristics of the thermodynamic steam cycle, which has undergone considerable changes. Steam pressure and temperature have steadily increased with improved characteristics in the available materials. Further progress is still achievable, by taking advantage of new materials to accommodate even higher steam conditions and to further improve cycle characteristics.

A wide range of other clean coal power plant technologies is currently being discussed. These include coal gasification and liquefaction as components. Due to intensive and continuous research and development efforts in past decades, gas and steam turbine power plants now achieve maximum efficiency values of about 58%. The rigorous further development of fluid

mechanics and materials technology will continue to improve the thermal efficiency of the open gas turbine and the internal efficiency of the steam turbine.

By 2010, combined gas and steam turbine power plants could thus be realized with an electrical efficiency of about 60%. On the way to this goal, in addition to the topics already mentioned, transonic turbo components optimized with respect to fluid mechanics and materials technology are to be developed for the steam generators and steam turbines, the cooling air consumption in gas turbines will be optimized by multifunctional cooling air management, combustion chambers with high fuel flexibility and stability will be further developed, and internal and peripheral flow and heat losses minimized.



Production of synthetic liquid fuels from coal

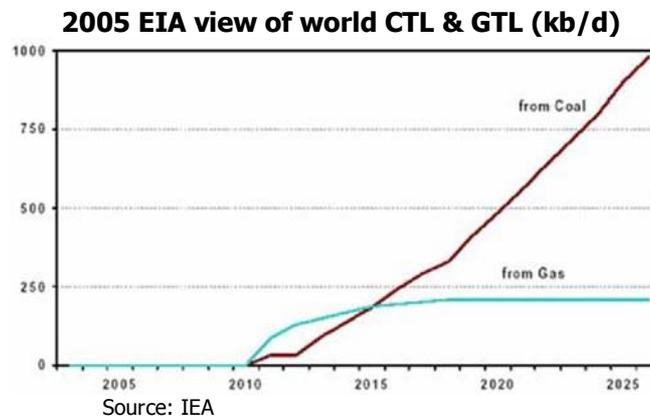
After gasification of coal, it is possible to produce synthetic liquid fuels. Fischer-Tropsch fuels are the most promising compared to other possibilities such as methanol or DME (dimethyl ether). It is thus possible to produce fuels easy to transport and use. For the production of fuel, technologies Coal To liquid (CTL) can be classified in two categories.

The first one which is the indirect liquefaction implements a succession of technologies. It is based on obtaining synthetic gas ($\text{CO} + \text{H}_2$) by gasification of coal in the presence of water followed by a unit of Fischer-Tropsch synthesis. The energetic efficiency is in this case of about 50%. The products obtained are of very high quality and in particular the diesel which is deprived of sulphur and aromatic. Its combustion in a current car allows a significant reduction of the particulate emissions and pollutants (CO , NO_x). A unit exists in South Africa since 1955. The current production amounts to approximately 7 Mt/y of fuel and chemicals. There is also a project in China in the province of Shanxi for the construction of 3 then 6 fuel Mt/an using the technology of indirect liquefaction (gasification and Fischer-Tropsch unit). Technology used could be one developed by African South Sasol or an other one by Shell (similar technology based on Gas - Gas to Liquid in Malaysia in 1993 for a capacity from approximately 0.7 Mt/y). The capacities could be carried in 15 Mt/y in 2015 and increased by 10 Mt/y additional in 2020.

The second one is the direct liquefaction which consists in using specific processes of hydrogenation returning liquid coal without passing by a preliminary stage of obtaining gas of synthesis. The effluents obtained require downstream treatments pushed to obtain fuels with

the necessary specifications. The energetic efficiency is higher than 60%. In this field, IFP is implied in a whole of acquisitions and work of development of competitive technologies H-coal, for liquefaction, and T-star, for the hydro-treating. The construction of the first unit began in China in Inner Mongolia in 2004 and the unit must start in 2007 (production of 1 liquid products Mt/an starting from 6 000 coal t/d). Technologies used are process HTI (HTI Direct Coal Liquefaction) for liquefaction, the process of hydro-treating T-Star of Axens, subsidiary of IFP, and two Shell gazifiers of 2 200 coal t/d to produce 300 000 hydrogen Nm³/h necessary to the various treatments. An extension to 5 Mt/y is planned right now for 2010. For the Chinese unit of Shenhua, Axens laid not only off the process T-star but also conceived the unit HTI.

IFP develops in collaboration with Group ENI, a powerful process of Fischer-Tropsch synthesis. A 20 barrels of GTL per day unit was brought into service in 2003 at Sannazzaro (Italy). The objective of IFP is to reduce the today production costs by at least 20%. Today, the investment is of US\$50 000 per barrel of capacity. It can be compared with the amount already very high of US\$30 000 per barrel for the current projects in Qatar of Gas To Liquid (GTL).



Cofiring biomass with coal²¹

There is considerable current interest in the use of biomass for power generation. Many countries have initiated incentives in recent years to encourage the utilization of biomass for electricity production. According to IEA, cofiring does not involve the high capital costs of building a new biomass plant but the significantly lower retrofitting costs at an existing plant. Retrofitted boilers can fire biomass when biomass supplies are plentiful but switch back to coal when biomass supplies are low. Cofiring increases the efficiency of the energy conversion by firing the fuel in a larger plant compared to a smaller plant firing biomass alone. Biomass conversion efficiencies when cofired range from 30% to 38% which is very much higher than in a dedicated biomass plant. The other advantages of the use of biomass include the fact that it diversifies the power plant's fuel portfolio. In addition to reducing net CO₂ emissions, cofiring enables the coal-fired plant to reduce SO₂ emissions as biofuels generally contain less sulphur than coal. Biofuels also tend to contain less nitrogen, which leads to lower NO_x emissions. The operating costs of cofiring could be higher due to the higher costs of biomass compared with coal. In spite of this, cofiring is often the cheapest form of renewable energy production.

²¹ Source : IEA Clean Coal Centre (CCC), *Fuels for biomass cofiring*, by Rohan Fernando, June, 29th, 2005.

Biomass fuel properties differ significantly from those of coal and there is a greater variation in these compared with typical coals. The issues regarding the delivery, storage and preparation of biomass are different from those for coal. Biomass has a much lower bulk density, is generally moist, strongly hydrophilic and is non-friable. The heating values and particle densities of biomass are generally about half that of coal and bulk densities about one fifth of coal. Hence the overall fuel density of biomass is about one-tenth that of coal. The long-term storage of wood in chip form, for example, can cause difficulties if the moisture content exceeds 20% as biological activity can lead to heating of the storage pile. Problems may also arise as most mills utilizing pulverizing coal depend on the brittle fracture of the coal particles whereas biomass does not mill by this mechanism. If the biomass does not mill satisfactorily, the biomass/coal cofiring ratio may be limited.

The extent of slagging and fouling can be affected by cofiring as biomass can contain a higher proportion of alkaline species compared with coal though the total ash content must also be considered. The major proportion of inorganic materials in biomass is in the form of salts or bound in organic matter, whereas in coal they are bound in silicates, which are more stable. The effects on deposition when cofiring biomass with coal are that the rate and extent of slag formation increases. Most types of biomass are high fouling fuels and cofiring biomass with coal in almost all cases increases the likelihood of fouling. In many cases the appropriate response to problems of slagging and fouling during cofiring, is to reduce the cofiring ratio. Experience in Europe suggests that slagging and fouling are unlikely to be a problem for cofiring ratios less than 10%.

SO₂ emissions invariably decrease during biomass cofiring, often in proportion to amount of biomass used, as most types of biomass contain far less sulphur than coal. NO_x emissions when cofiring biomass are more difficult to predict and may increase, decrease or remain the same as when firing coal depending on the particular type of biomass, firing conditions and operating conditions. The emissions of CO₂ arising from biomass can be regarded as being carbon neutral if the biomass is grown in a managed forest.

Biomass cofiring has been successfully demonstrated in over 150 installations worldwide for most combinations of fuels and boiler types. About a hundred of these have been in Europe. In the United States there have been over 40 commercial demonstrations and the remainder have been mainly in Australia. A broad combination of fuels, such as residues, energy crops, herbaceous and woody biomasses have been cofired where the proportion of biomass has ranged from 1% to 20%.

With ULCOS, Europe moves towards a new era in steelmaking

A consortium of 48 European companies and organizations has entered into an agreement to launch a cooperative Research and Development initiative searching for new steel production processes that would drastically reduce CO₂ and other greenhouse gas emissions of the sector. The consortium is called ULCOS, an acronym for "Ultra Low CO₂ Steelmaking".

ULCOS will examine a set of new concepts for making steel on the process route based on iron ore that have the potential of reducing the specific CO₂ emissions of the steel industry by more than 30%. To reach this degree of reduction, the steel industry needs to develop new process paradigms using breakthrough technologies. One technology is based on the recycling of blast furnace top gas after decarbonization. CO₂ capture and storage technologies can be added. Other breakthrough technologies are also being examined. They include electrolysis,

use of hydrogen, use of carbon and natural gas with CO₂ capture and sequestration in reactors different from the blast furnace, or utilization of biomass.

The consortium is led by a core-group of steel producers comprising ThyssenKrupp Stahl, Arcelor, Corus, Riva, Voestalpine, Saarstahl and Dillinger Hüttenwerke and the ore and pellet producer LKAB. Arcelor is the consortium's coordinator. The ULCOS program is part of a multidisciplinary steel research platform co-financed by the innovation programs of the European Commission officially launched on March 12, 2004. The total funding of €45 million is being provided in roughly equal amounts by the European Commission and the companies involved in the program.

The reduction aimed at by ULCOS is an ambitious requirement, as the integrated steel production route generates about two tons of CO₂ per ton of steel at present. In the past, intense efforts by the industry have allowed reduction of the energy requirements as well as the CO₂ emissions of steel mills: specific energy consumption has thus gone down by 60% in the last 40 years, while the total CO₂ emissions of the steel industry were reduced by 50% over the same period.

ULCOS is to deliver a concept process route, based on iron ore, with a verification of its feasibility in terms of technology, economic projections and social acceptability within five years. First commercial implementation can be considered after a pilot phase lasting another five years. The advancements of the program will be followed by the Industrial Technologies Research Directorate units of the European Commission.

Carbon Capture and Storage (CCS)

So as to limit the emission of CO₂, Carbon Capture and Storage (CCS) has to be considered. The basic idea behind CCS is that CO₂ is captured before it is emitted into the atmosphere and then injected deep underground where it would remain for thousands of years or longer. The idea of CCS was first developed in the late 1970's in the hydrocarbon world. With the GHG debates, it has now emerged as one of the most promising options for deep reductions in CO₂ emissions.

CCS is a four-step process where: first, a pure or nearly pure stream of CO₂ is captured from flue gas or other process stream; next it is compressed to about 100 atmospheres; it is then transported to the injection site; and finally, it is injected deep underground into a geological formation such as an oil and gas reservoir where it can be safely stored for thousands of years or longer.

Over the past 10 years, IEA member countries have begun to investigate carbon capture and storage (CCS) technologies²² with attention now shifting from feasibility studies and laboratory tests to pilot projects in order to better understand the various engineering, environmental and cost factors involved.

The more the price of CO₂ is high, the more those technologies have a chance to be applied. Many experts believe that CCS technologies could become competitive in the future with a CO₂ price ranging from 20 to 40 €/tCO₂. It does not mean that all the emissions will be avoided at this price. But a certain quantity will be managed by the corresponding processes.

²² McKee, B (2002), *Solutions for the 21st Century. Zero Emissions Technologies for Fossil Fuels*, International Energy Agency, Working Party on Fossil Fuels.

Capture of CO₂ can be applied to large point sources. The CO₂ would then be compressed and transported for storage in geological formations, in the ocean, in mineral carbonates, or for use in industrial processes. Large point sources of CO₂ include large fossil fuel or biomass energy facilities, major CO₂-emitting industries, natural gas production, synthetic fuel plants and fossil fuel-based hydrogen production plants.

Profile by process or industrial activity of worldwide large stationary CO₂ sources with emissions of more than 0.1 million tons of CO₂ (MtCO₂) per year.

Process	No. of sources	Emissions (MtCO ₂ /yr)
Fossil Fuels		
Power (coal, gas, oil and others)	4 942	10 539
Cement production	1 175	932
Refineries	638	798
Iron and steel industry	269	646
Petrochemical industry	470	379
Oil and gas processing	Not available	50
Other sources	90	33
Biomass		
Bioethanol and bioenergy	303	91
Total	7 887	13 466

Source: IPCC Special Report approved September 25th, 2005, on Carbon dioxide Capture and Storage

CO₂ Capture Technology

Carbon dioxide is emitted from electrical generation plants and other combustion sources as a flue gas that contains mostly nitrogen and only from 5 to 15% carbon dioxide. Before it can be injected underground, the CO₂ must be separated from the remainder of the gas. Because of the low concentration of CO₂ in the gas, separating it is expensive, requires large surface facilities, and a lot of energy. For CO₂ capture from power generation or industrial boilers, capture technologies are grouped according to whether the CO₂ is captured after the fossil fuel is combusted, so-called post combustion capture ("end-of-pipe"), or prior to combustion (pre-combustion) in which chemical processes are used to gasify the fossil fuel to extract H₂ before it is combusted. Alternatively, from power stations, capture can be accomplished by using oxygen instead of air to combust the fossil fuels, thereby producing emissions of only CO₂ and water, from which the CO₂ is easily separated.

Post-combustion

Of these separation technologies, only post-combustion capture is considered to be a well-developed technology. In short, post-combustion capture using amine solutions²³ is a demonstrated technology that could be applied broadly today, but costs and energy demands

²³ Pollution capture technologies in use today tend to use separation techniques in the post- rather than pre-combustion stage. CO₂ is normally only a small part of the flue gas stream emitted to the atmosphere by a power station so some method of separation is required to capture it. This can be done using a range of techniques developed and proven in other applications. The main one in use today is to separate CO₂ from flue gases by 'scrubbing' the gas stream using an amine solution, a technique established over 60 years ago in the oil and chemical industries for removing hydrogen sulphide and CO₂ from gas streams. After leaving the scrubber, the amine is heated to release high purity CO₂ and the CO₂-free amine is then re-used. A disadvantage of this technique is that the low concentration of CO₂ in the flue gas means a significant volume of gas has to be handled, requiring large and expensive equipment. Powerful solvents must be used to capture CO₂ meaning that a large amount of energy is then needed to release the carbon dioxide.

are high. The alternatives to post-combustion capture have significant advantages but more research, development and demonstration projects are needed before they are likely to be adopted by the power generation industry.

In the short term, amine scrubbing is likely to continue being used for post-combustion CO₂ capture. Commercially, it is the best established of the techniques available for capture although practical experience is mainly with gas streams that are chemically reducing, the opposite of the oxidizing environment of a flue gas stream. Monoethanolamine (MEA) is a widely-used type of amine for CO₂ capture. Improved solvents could reduce the amount of degradation due to the oxidizing environment and cut energy requirements by as much as 40% compared with conventional MEA solvents.

Pre-combustion

In pre-combustion separation of CO₂, physical solvents are used for capture, with the advantage that it can be released mainly by depressurization, thus avoiding the high heat consumption of amine scrubbing processes. Physical solvent scrubbing of CO₂ is well established in the chemical industries for activities such as ammonia production but less so in power generation. When CO₂ is extracted under pressure in IGCC processes, the energy needed to capture and compress it for transport to a sequestration site is less than would be required for CO₂ scrubbed directly from the more dilute atmospheric pressure flue gases of PF systems. However, depressurization of the solvent still results in a significant energy penalty.

Oxy-combustion

CO₂ concentrations can be increased significantly by using concentrated oxygen instead of air for combustion either in a boiler or gas turbine. The advantage of oxygen-blown combustion is that the flue gas has a CO₂ concentration of typically greater than 80 to 90%, so only simple CO₂ purification is required.

The downside is that current methods of producing large quantities of high purity oxygen are expensive, both in terms of capital cost and energy consumption. An alternative method is to increase CO₂ concentrations using pre-combustion capture in an integrated gasification combined cycle system. The process is, in principle, the same for coal, oil or natural gas.

CO₂ transport and storage

Assuming capture were applied on a large scale as a means of reducing atmospheric pollution, the captured CO₂ would then need to be transported and stored in vast, leak-free repositories²⁴. The concept of storage itself faces a number of technological and environmental hurdles to its implementation and is by no means a given in a low-emissions future. CO₂ is largely inert and easily handled. It is already transported in long distance, high-pressure pipelines more than 2 000 km of which are in use today. If CO₂ capture and storage (CCS) was to be widely applied, an infrastructure network would need to be put in place to transport CO₂ to selected storage sites. In some regions, this would require construction of pipeline grids, such as those used for gas distribution, an upfront cost which would need to be proven economically before it could be applied on a large scale. Ships could also be used for long distance transport, an activity already in use on a small scale today and one similar in concept to the transport of LPG.

²⁴ *Transport and Environmental Aspects of CO₂ Sequestration*, IEA Greenhouse Gas R&D Program, 1995

Options for CO₂ storage

Disused Oil and Gas Reserves (estimated global capacity: 900 – 1 200 GtCO₂)

An attractive option because of their well-known geology, low exploration costs and potential for re-using production equipment to inject CO₂. Underground storage has also been an integral part of the natural gas industry for decades. Injecting CO₂ can also enhance oil recovery by 10-15%.

The combined estimate of total ultimate storage capacity in discovered oil and gas fields is therefore very likely 675–900 GtCO₂. If undiscovered oil and gas fields are included, this figure would increase to 900–1200 GtCO₂, but the confidence level would decrease.

Deep Saline Reservoirs (estimated global capacity: at least 1000 GtCO₂)

Underground aquifers unsuitable for potable water supply could store CO₂, which would partially dissolve in the salt water, react with minerals to form carbonates and lock up CO₂. The Sleipner Vest pilot project is testing this by injecting 1 mt CO₂ a year into a saline reservoir in the Norwegian sector of the North Sea as part of gas production activities, a project led by Norway's Statoil and the IEA Greenhouse Gas R&D Program.

More than 14 global assessments of capacity have been made by using these types of approaches (IEA-GHG, 2004). The range of estimates from these studies is large (200–56 000 GtCO₂), reflecting both the different assumptions used to make these estimates and the uncertainty in the parameters. Most of the estimates are in the range of several hundred GtCO₂. The assessment of SRCCS is that it is very likely that global storage capacity in deep saline formations is at least 1000 GtCO₂. Confidence in this assessment comes from the fact that oil and gas fields 'discovered' have a global storage capacity of approximately 675–900 GtCO₂, and that they occupy only a small fraction of the pore volume in sedimentary basins, the rest being occupied by brackish water and brine. Moreover, oil and gas reservoirs occur only in about half of the world's sedimentary basins.

Unminable Coal Measures (estimated global capacity: >15 GtCO₂)

CO₂ injected into coal seams is adsorbed onto the coal, locking it up permanently. Injected CO₂ can be used to displace methane in the coal, which can then be extracted using depressurization techniques. Injecting CO₂ enables both more methane to be extracted (over 50%), while at the same time sequestering CO₂.

Assuming that bituminous coals can adsorb twice as much CO₂ as methane, a preliminary analysis of the theoretical CO₂ storage potential for ECBM recovery projects suggests that approximately 60–200 GtCO₂ could be stored worldwide in bituminous coal seams (IEA-GHG, 1998). More recent estimates for North America range from 60 to 90 GtCO₂ (Reeves, 2003b; Dooley *et al.*, 2005), by including sub-bituminous coals and lignites. Technical and economic considerations suggest a practical storage potential of approximately 7 GtCO₂ for bituminous coals (Gale and Freund, 2001; Gale, 2004). Assuming that CO₂ would not be stored in coal seams without recovering the CBM, a storage capacity of 3–15 GtCO₂ is calculated, for a US annual production of CBM in 2003 of approximately 0.04 trillion m³ and projected global production levels of 0.20 trillion m³ in the future.

Deep Ocean Storage (estimated global capacity: >5 000 GtCO₂)

A highly speculative option because of the complexity of the natural processes involved and potential environmental risks to marine life. At present, CO₂ in the atmosphere is naturally deposited in the ocean and circulated at a slow rate. Deliberate injection at depths of at least 3 000 meters could speed up the accumulation. Studies suggest retention times of several hundred years compared to 1 000 years at present.

Other options

Though less economically competitive, underground caverns such as mined salt domes could be created to store CO₂ as a solid (dry ice) in repositories surrounded by thermal insulation to minimize leakage. Alternatively, CO₂ could be reacted with minerals, such as magnesium silicate, to produce carbonates.

Note: Capacity estimates relate to the IPCC's IS92a projection for total CO₂ emissions for 2000-2050 under a 'business as usual' scenario

Source: IPCC Special Report on Carbon dioxide Capture and Storage & IEA Greenhouse Gas R&D Program

Once captured, CO₂ could be stored in the ocean or underground (in depleted oil and gas fields, coal seams or aquifers), possibly in tandem with the enhanced production of oil, gas and methane. IPCC estimates put total underground storage capacity at least at 2 000GtCO₂ without considering deep ocean storage. The net cost of underground storage is put at between US\$7-17 per ton of CO₂ stored (not including the cost of capture and transmission)²⁵. Local conditions will dictate how far the CO₂ has to be transported from where it is produced to where it is stored. The cost of pipeline transport is estimated to be in the range of US\$1-3/t

²⁵ IEA Greenhouse Gas R&D Program

CO₂ per 100 km of distance. In cases where injection leads to enhanced hydrocarbon production, the income generated could partially offset overall costs.

To achieve stabilization at 550 ppmv, the Third Assessment Report of IPCC in 2001 showed that, by 2100, the reduction in emissions might have to be about 38 GtCO₂ per year compared to scenarios with no mitigation action. Therefore storage capacity is in an amount which makes it a real element of a strategy.

For example, Gaz de France carries out an experiment in the North Sea, on the offshore oil rig gas layer K12B, off Dutch coasts. This layer has the advantage of being close to other gas layers with strong content CO₂. A feasibility study carried out in 2003 showed that with the proviso of adapting the existing installations, it was interesting to separate CO₂ from the fields neighborhood to reinject it in this layer. The pilot is operational since semi-2004, the initial flow of injection will be 20 000 tons per annum and could then be increased into 2005/2006 with an annual throughput of approximately 480 000 tons.

The IEA's ETP model²⁶ is assessing the impact of using CO₂ capture compared to other emissions mitigation options over the period 2020-2040, and thence the consequences of capture and sequestration for energy and environment policies. Preliminary results suggest CCS can play an important role in reducing emissions in the first part of the 21st century - with up to 3 Gt of CO₂ per year able to be captured by 2020 and up to 6 GtCO₂/yr by 2040. This relates to CO₂ from electricity production, the production of diesel and gasoline, and to a limited extent hydrogen production. ETP model results suggest that fossil fuel-fired power plants with capture technology could represent up to 22% of total global electricity production capacity by 2030 and 40% by 2050.

According to the IPCC Special Report approved September 25th, 2005, on Carbon dioxide Capture and Storage, large point sources of CO₂ are concentrated in proximity to major industrial and urban areas. Many such sources are within 300 km of areas that potentially hold formations suitable for geological storage. Preliminary research suggests that, globally, a small proportion of large point sources is close to potential ocean storage locations. Currently available literature regarding the matches between large CO₂ point sources with suitable geological storage formations is limited. Detailed regional assessments may be necessary to improve information. Scenario studies indicate that the number of large point sources is projected to increase in the future, and that, by 2050, given expected technical limitations, around 20 - 40% of global fossil fuel CO₂ emissions could be technically suitable for capture, including 30 - 60% of electricity generation and 30 - 40% of industrial CO₂ emissions. Emissions from large-scale biomass conversion facilities could also be technically suitable for capture. The proximity of future large point sources to potential storage sites has not been studied.

Performance

The two major hurdles facing the uptake of capture technologies in power production are loss of generating efficiency and increased capital cost. In general, while capture reduces emissions of CO₂ per unit of electricity by some 80 to 90%, it also decreases overall generating efficiency by 8-13 percentage points. Adding capture technology approximately doubles the capital cost of a

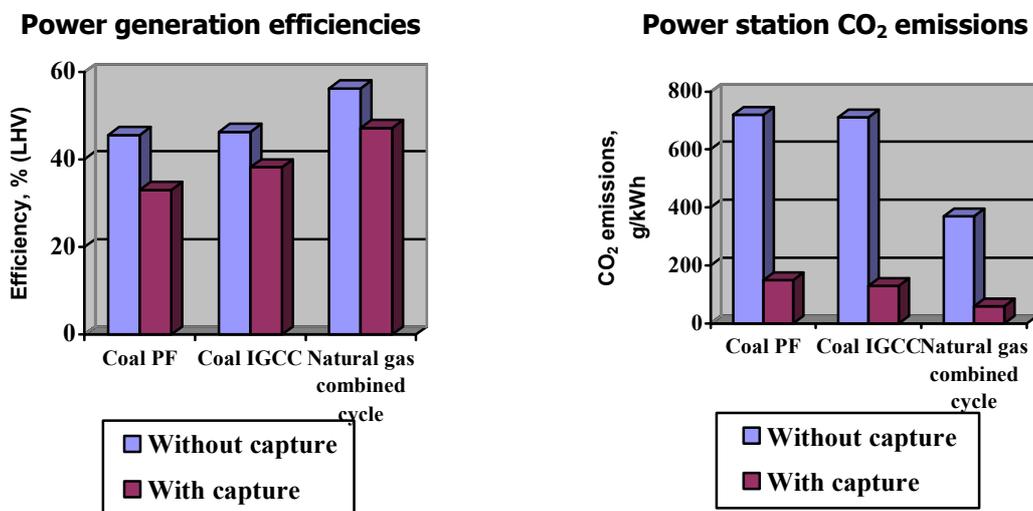
²⁶ Gielen, D, *The Future Role of CO₂ Capture and Storage. Results from the IEA-ETP Model*, International Energy Agency, November 2003

natural gas combined cycle plant while increasing the capital cost of a pulverized coal plant by 80% and that of an IGCC plant by 50%, according to IEA Greenhouse Gas R&D Program.

In the following examples, which illustrate the performance and cost of gas, oil and coal-fired power plants with and without CO₂ capture, results are presented for power stations with post-combustion capture using amine scrubbing, and pre-combustion capture using physical solvent scrubbing.

The coal IGCC plant uses pre-combustion capture and the pulverized coal and natural gas combined cycle plants post-combustion capture (the efficiency and emissions would be similar for a natural gas combined cycle with pre-combustion capture). Compression of the CO₂ to a pressure of 110 bars for transportation to storage is included. Capital and operating costs of power stations with and without capture have been estimated to an accuracy of ±25%.

An assessment of the cost and efficiency characteristics of likely and speculative gas and coal-fired generation technologies with and without CO₂ capture has been made by the IEA Secretariat using its Energy Technology Perspectives (ETP) model²⁷. The efficiency loss due to capture ranges from 12% for existing coal-fired power plants to 4% for future designs with fuel cells. In general, capture increases the cost of gas-fired generation by about 0.015 US\$/kWh. Post-combustion capture increases the cost of generation in a pulverized coal plant by about 0.03 US\$/kWh. With regard to electricity cost, the gas-based systems with capture seem cheapest, although this depends on local fuel prices and discount rates. It is rather uncertain that it remains valid with the gas price hike that we see today. In percentage terms, the increase in cost of electricity to the final consumer would be less because of the added costs of distribution and sales.



Source: IEA Greenhouse Gas R&D Program

Finally, the IPCC Special Report approved September 25th, 2005, on Carbon dioxide Capture and Storage gives cost indications. Application of CCS to electricity production, under 2002 conditions, is estimated to increase electricity generation costs by about 0.02 - 0.05 US dollars per kilowatt hour (US\$/kWh), depending on the fuel, the specific technology, the location, and the national circumstances.

²⁷ The ETP is a bottom-up systems engineering model, based on the MARKEL modeling paradigm developed by the Energy Technology Systems Analysis Program (ETSAP), an IEA collaborative R&D program. The ETP covers the period 2000-2050 in five-year periods. The world is divided into 15 regions (US, Canada, Mexico, Latin America, IEA Europe, Eastern Europe, Former Soviet Union, Africa, Middle East, India, China, South Korea, Japan, Rest of Asia, Australia/NZ). In each region, several hundred technologies are considered

Costs of CCS: production costs of electricity for different types of generation, without capture and for the CCS system as a whole.

Power plant system	Natural Gas Combined Cycle (US\$/kWh)	Pulverized Coal (US\$/kWh)	Integrated Gasification Combined Cycle (US\$/kWh)
Without capture (reference plant)	0.03 - 0.05	0.04 - 0.05	0.04 - 0.06
With capture and geological storage	0.04 - 0.08	0.06 - 0.10	0.05 - 0.09
With capture and Enhanced Oil Recovery (EOR)	0.04 - 0.07	0.05 - 0.08	0.04 - 0.07

The cost of a full CCS system for electricity generation from a newly built, large-scale fossil fuel-based power plant depends on a number of factors, including the characteristics of the power plant and the capture system, the specifics of the storage site, the amount of CO₂, and the required transport distance. The numbers assume experience with a large-scale plant. Gas prices are assumed to be 2.8 - 4.4 US\$ per gigajoule (GJ), coal prices 1 - 1.5 US\$/GJ (what is different of the nowadays spot prices)
Source: IPCC Special Report approved September 25th, 2005, on Carbon dioxide Capture and Storage

Including the benefits of Enhanced Oil Recovery (EOR) would reduce additional electricity production costs due to CCS by around 0.01 to 0.02 US\$/kWh. Increases in market prices of fuels used for power generation would generally tend to increase the cost of CCS. The quantitative impact of oil price on CCS is uncertain. However, revenue from Enhanced Oil Recovery (EOR) would generally be higher for higher oil prices. Whilst applying CCS to biomass-based power production at current small scale would add substantially to the electricity costs, co-firing of biomass in a larger coal-fired power plant with CCS would be more cost-effective.

CO₂ avoidance costs for the complete CCS system for electricity generation, for different combinations of reference power plants without CCS and power plants with CCS (geological and Enhanced Oil Recovery (EOR)).

Type of power plant with CCS	Natural Gas Combined Cycle reference plant (US\$/tCO ₂ avoided)	Pulverized Coal reference plant (US\$/tCO ₂ avoided)
Power plant with capture and geological storage		
Natural Gas Combined Cycle	40 - 90	20 - 60
Pulverized Coal	70 - 270	40 - 220
Integrated Gasification Combined Cycle	30 - 70	20 - 70
Power plant with capture and Enhanced Oil Recovery (EOR)		
Natural Gas Combined Cycle	20 - 70	0 - 30
Pulverized Coal	50 - 240	10 - 40
Integrated Gasification Combined Cycle	20 - 190	0 - 40

The amount of CO₂ avoided is the difference between emissions of the reference plant and the emissions of the power plant with CCS. Gas prices are assumed to be 2.8 - 4.4 US\$/GJ, coal prices 1 - 1.5 US\$/GJ (what is different of the nowadays spot prices)
Integrated Gasification Combined Cycle is not included as a reference power plant that would be built today since this technology is not yet widely deployed in the electricity sector and is usually slightly more costly than a Pulverized Coal plant. The incremental cost in US\$/tCO₂ avoided for an Integrated Gasification Combined Cycle plant when CCS is applied would range from 15 to 55 US\$/tCO₂ avoided with geological storage, and -5 to 30 US\$/tCO₂ avoided with EOR.
Source: IPCC Special Report approved September 25th, 2005, on Carbon dioxide Capture and Storage

Costs of retrofitting CCS to existing installations vary. Industrial sources of CO₂ can more easily be retrofitted with CO₂ separation, but integrated power plant systems would need more profound adjustment. In order to reduce future retrofit costs, new plant designs could take future CCS application into account. Costs for the various components of a CCS system vary widely, depending on the reference plant and the wide range in CO₂ source, transport and storage situations. Over the next decade the cost of capture could be reduced by 20- and more should be achievable by new technologies that are still in the research or demonstration phase. The costs of transport and storage of CO₂ could decrease slowly as the technology matures further and the scale increases. Obviously, CCS induces a price increase. In the same time, the cost of alternative none emitting technologies such as nuclear power and renewable energy may be more competitive. Therefore, this cost increase, moderated by the improvement of the efficiency of the combustion phase, may limit the expansion of coal base power production.

Cost ranges (2002) for the components of a CCS system, applied to a given type of power plant or industrial source.

CCS system components	Cost range	Remarks
Capture from a coal-or gas-fired power plant	15 - 75 US\$/tCO ₂ net captured	Net costs of captured CO ₂ , compared to the same plant without capture
Capture from hydrogen and ammonia production or gas processing	5 - 55 US\$/tCO ₂ net captured	Applies to high-purity sources requiring simple drying and compression
Capture from other industrial sources	25 - 115 US\$/tCO ₂ net captured	Range reflects use of a number of different technologies and fuels
Transportation	1 - 8 US\$/tCO ₂ transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO ₂ /yr.
Geological storage	0.5 - 8 US\$/tCO ₂ injected	Excluding potential revenues from EOR or ECBM. Over the long term, there may be additional costs for remediation and liabilities
Geological storage: monitoring and verification	0.1 - 0.3 US\$/tCO ₂ injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements
Ocean storage	5 - 30 US\$/tCO ₂ injected	Including offshore transportation of 100 - 500 km, excluding monitoring and verification
Mineral carbonation	50 - 100 US\$/tCO ₂ net mineralized	Range for the best case studied. Includes additional energy use for carbonation

The costs of the separate components cannot simply be summed to calculate the costs of the whole CCS system in US\$/CO₂ avoided. All numbers are representative of costs for large-scale, new installations with natural gas prices assumed to be 2.8 - 4.4 US\$/GJ and coal prices 1 - 1.5 US\$/GJ. Source: IPCC Special Report on Carbon dioxide Capture and Storage

Legal and regulatory issues for implementing CO₂ storage

According to the IPCC Special Report approved September 25th, 2005, on Carbon dioxide Capture and Storage, Some regulations for operations in the subsurface exist that may be relevant or in some cases directly applicable to geological storage, but few countries have specifically developed legal or regulatory frameworks for long-term CO₂ storage. Existing laws and regulations regarding inter alia mining, oil and gas operations, pollution control, waste disposal, drinking water, treatment of high-pressure gases, and subsurface property rights may be relevant to geological CO₂ storage. Long-term liability issues associated with the leakage of CO₂ to the atmosphere and local environmental impacts are generally unresolved. Some States take on long-term responsibility in situations comparable to CO₂ storage, such as underground mining operations. No formal interpretations so far have been agreed regarding whether or under what conditions CO₂ injection into the geological sub-seabed or the ocean is compatible with certain provisions of international law. Currently, there are several treaties (notably the London²⁸ and OSPAR Conventions²⁹) that potentially apply to the injection of CO₂ into the geological subseabed or the ocean. All these treaties have been drafted without specific consideration of CO₂ storage.

Environmental impact of geological storage likely small, but not well characterized

For the IPCC, Special Report on Carbon dioxide Capture and Storage (SRCCS), the Environmental impact of geological storage is likely small, but not well characterized. More precisely, according to the IPCC SRCCS, the monitoring, risk and legal implications of CO₂

²⁸ Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972), and its London Protocol (1996), which has not yet entered into force.

²⁹ Convention for the Protection of the Marine Environment of the North-East Atlantic, which was adopted in Paris (1992). OSPAR is an abbreviation of Oslo-Paris.

capture systems do not appear to present fundamentally new challenges, as they are all elements of regular health, safety and environmental control practices in industry. However, CO₂ capture systems require significant amounts of energy for their operation. This reduces net plant efficiency, so power plants require more fuel to generate each kilowatt-hour of electricity produced. The increased fuel requirement results in an increase in most other environmental emissions per kWh generated relative to new state-of-the-art plants without CO₂ capture and, in the case of coal, proportionally larger amounts of solid wastes. In addition, there is an increase in the consumption of chemicals such as ammonia and limestone used by PC plants for nitrogen oxide and sulphur dioxide emissions control. Advanced plant designs that further reduce CCS energy requirements will also reduce overall environmental impacts as well as cost. Compared to many older existing plants, more efficient new or rebuilt plants with CCS may actually yield net reductions in plant level environmental emissions.

According to the IPCC SRCCS, current standards, developed largely in the context of EOR applications, are not necessarily identical to what would be required for CCS. Pipeline transport of CO₂ through populated areas also requires detailed route selection, over-pressure protection, leak detection and other design factors. However, no major obstacles to pipeline design for CCS are foreseen. CO₂ could leak to the atmosphere during transport, although leakage losses from pipelines are very small. For ships, the total loss to the atmosphere is between 3 and 4% per 1000 km, counting both boil-off and the exhaust from ship engines. Boil-off could be reduced by capture and liquefaction, and recapture would reduce the loss to 1 to 2% per 1000 km. Accidents can also occur. In the case of existing CO₂ pipelines, which are mostly in areas of low population density, there have been fewer than one reported incident per year (0.0003 per km-year) and no injuries or fatalities. This is consistent with experience with hydrocarbon pipelines, and the impact would probably not be more severe than for natural gas accidents. In marine transportation, hydrocarbon gas tankers are potentially dangerous, but the recognized hazard has led to standards for design, construction and operation, and serious incidents are rare.

According to the IPCC SRCCS, the risks due to leakage from storage of CO₂ in geological reservoirs fall into two broad categories: global risks and local risks. Global risks involve the release of CO₂ that may contribute significantly to climate change if some fraction leaks from the storage formation to the atmosphere. In addition, if CO₂ leaks out of a storage formation, local hazards may exist for humans, ecosystems and groundwater. These are the local risks. With regard to global risks, based on observations and analysis of current CO₂ storage sites, natural systems, engineering systems and models, the fraction retained in appropriately selected and managed reservoirs is very likely to exceed 99% over 100 years, and is likely to exceed 99% over 1000 years. Similar fractions retained are likely for even longer periods of time, as the risk of leakage is expected to decrease over time as other mechanisms provide additional trapping. With regard to local risks, there are two types of scenarios in which leakage may occur. In the first case, injection well failures or leakage up abandoned wells could create a sudden and rapid release of CO₂. This type of release is likely to be detected quickly and stopped using techniques that are available today for containing well blow-outs. Hazards associated with this type of release primarily affect workers in the vicinity of the release at the time it occurs, or those called in to control the blow-out. A concentration of CO₂ greater than 7–10% in air would cause immediate dangers to human life and health. Containing these kinds of releases may take hours to days and the overall amount of CO₂ released is likely to be very small compared to the total amount injected. These types of hazards are managed effectively on a regular basis in the oil and gas industry using engineering and administrative controls. In the second scenario, leakage could occur through undetected faults, fractures or through leaking wells where the release to the surface is more gradual and diffuse. In this case, hazards primarily affect drinking-water aquifers and

ecosystems where CO₂ accumulates in the zone between the surface and the top of the water table. Groundwater can be affected both by CO₂ leaking directly into an aquifer and by brines that enter the aquifer as a result of being displaced by CO₂ during the injection process. There may also be acidification of soils and displacement of oxygen in soils in this scenario. Additionally, if leakage to the atmosphere were to occur in low-lying areas with little wind, or in sumps and basements overlying these diffuse leaks, humans and animals would be harmed if a leak were to go undetected. Humans would be less affected by leakage from offshore storage locations than from onshore storage locations.

Projects and Current R&D

R&D concerning Coal Capture & Sequestration

Europe

The fifth Framework Program funded projects GESTCO and CO₂STORE. These projects are looking at CO₂ storage opportunities in Europe, specially at storage reservoirs in UK, Germany, Netherlands, Belgium, France, Denmark and Norway. For underground storage, issues yet to be resolved include the current incomplete understanding of reservoir processes, storage methods, seepage and the environmental safety of CO₂ storage. Technologies for measuring injection must also be improved for the purposes of monitoring and verifying storage to determine dispersion through the field, injection strategies and to build confidence in the idea of storage and its large-scale application. Research is underway in several countries including the Norwegian Statoil Sleipner scheme, where 1 Mt of CO₂ per year have been sequestered in a deep saline aquifer since 1998. Other projects are in the planning stage, such as the In-Salah project in Algeria where CO₂ will be stored in an empty gas field, the Snohvit project in the Norwegian part of the Barents Sea where CO₂ will be stored in an aquifer.

The Sixth Framework Program (FP6) differs significantly from previous ones. A key difference is its role in contributing to the creation of the European Research Area (ERA) in sustainable energy systems. This means that the aim is to assemble a critical mass of resources, to integrate research efforts by pulling them together, and to make this research more coherent on the European scale. To ensure concentration of effort and maximize the impact of the program, the intention is to focus research on a limited number of priority topics. In the field of CO₂ capture and storage, the priorities are:

- post-combustion CO₂ capture
- pre-combustion CO₂ capture
- geological storage of CO₂
- chemical/mineral sequestration of CO₂

Sixth Framework Program of the European Union: On-going projects

Project Acronym	Title	EU funding (M€)	Coordinator	Duration (months)	No of Partners	No of countries
CO2SINK	In-situ laboratory for capture and sequestration of CO ₂	8.7	Potsdam Research C	60	14	8
ENCAP	Enhanced capture of CO ₂	9.8	Vattenfall	60	33	9
CASTOR	CO ₂ from capture to storage	8.5	IFP	48	30	12
CO2GEONET	Network of excellence on geological sequestration of CO ₂	6	BGS	60	13	7
ISCC	Innovative in-situ CO ₂ capture technology for solid fuel gasification	1.9	Univ. of Stuttgart	36	14	7

Source: CEC

CO₂ from capture to storage (CASTOR) led by IFP (Institut français du Pétrole)
(more details are given in a specific annex)

CASTOR is a project funded after the first call in FP6, led by IFP (Institut Français du Pétrole). The project's objective is to make possible the capture and geological storage of 10% of European CO₂ emissions, or 30% of the emissions of large industrial facilities (mainly conventional power stations). To accomplish this, two types of approach must be validated and developed: new technologies for the capture and separation of CO₂ from flue gases and its geological storage, and tools and methods to quantify and minimize the uncertainties and risks linked to the storage of CO₂. In this context, the CASTOR project is aimed more specifically at reducing the costs of capture and separation of CO₂ (from €0-60/tCO₂ to €20-30/ tCO₂), improving the performance, safety, and environmental impact of geological storage concepts and, finally, validating the concept at actual sites.

The R&D work is divided into three sub-projects: Post-combustion capture (65% of the budget) ; Geological storage (25% of the budget) ; Strategy for CO₂ reduction (10% of the budget).

Work on capture is aimed at developing new CO₂ post-combustion separation processes suited to the problems of capture of CO₂ at low concentrations in large volumes of gases at low pressure. The processes will be tested in a pilot unit capable of treating from 1 to 2 tons of CO₂ per hour, from real fumes. This pilot will be implemented in the Esbjerg power station, operated by Elsam in Denmark. The objectives of work on post-combustion capture are:

- Development of absorption liquids, with a thermal energy consumption of 2.0 GJ/ton CO₂ at 90% recovery rates
- Resulting costs per tCO₂ avoided, not higher than 20 to 30 €/tCO₂, depending on the type of fuel
- Pilot plant tests showing the reliability and efficiency of the post-combustion capture process.

Following the first FP6 call for proposals in December 2003, five projects were selected for EC funding in this area, with a total EC contribution of up to €35 million. The emphasis on the new instruments of FP6 – Integrated Projects and Networks of Excellence – highlights the scale of the effort required and the need for critical mass in order to achieve significant progress. A further project (INCA-CO₂, a Specific Support Action on the international collaboration in the field of CO₂ capture and storage) is currently under negotiation following the second call for proposals in September 2003.

In addition there is a third and last call ongoing. New proposals are under negotiation in 5 fields:

- CACHET: CO₂ capture and hydrogen production from gaseous fuels (IP)
- CO2REMOVE: the monitoring and verification of CO₂ geological storage (IP)
- DYNAMIS: Preparing for large scale H₂ production from decarbonized fossil fuels including CO₂ geological storage (IP) (HYPOGEN PHASE1)
- CLC GAS POWER, C3-Capture, DeSANNs, HY2SEPS: Advanced separation techniques (STREP)
- EU GeoCapacity: Mapping geological CO₂ storage potential matching sources and sinks (STREP)

CO2GeoNet

The Network of Excellence "CO2GeoNet" (13 institutes) contains a critical mass of research activity in the area of underground carbon dioxide (CO₂) storage. Through the Joule 2, FP4 & 5 projects Europe has led the world on R&D in this area, with rapid growth this decade. National programs are also emerging. This success has a downside, by creating fragmentation through diversification. The main aim of CO2GeoNet will be to integrate, strengthen, and build upon the momentum of previous and existing European R&D, as well as project European excellence internationally, so as to ensure that Europe remains at the forefront of CO₂ underground storage research'. The Network focus is on the geological storage of CO₂ as a green house gas mitigation option. It has several objectives over the 5 year period of EC funding for integration:

- To maintain and build upon the momentum and world lead that Europe has on geological CO₂ sequestration and project that lead into the international arena.
 - To improve efficiency through re-alignment of national research programs, prevention of duplication of research effort, sharing of existing and newly acquired infrastructure and IPR.
 - To identify knowledge gaps and formulate new research projects and tools to fill these gaps. Seek external funding from national and industrial programs in order to diversify, build and strengthen the portfolio of shared research activities.
 - To provide the authoritative body for technical, impartial, high quality information on geological storage of CO₂, and in so doing enable public confidence in the technology, participate in policy, regulatory formulation and common standards.
- Provide training to strengthen the partners, bring in new network members and sustain a replacement supply of researchers for the future.
- To exploit network IPR, both as a revenue earner to sustain the network and to equip European industry to be competitive in the emerging global low carbon energy markets.

The 7th Framework Program is still in finalization mode³⁰. In the Energy priorities, two concern directly our subject: CO₂ capture and storage technologies for Ultra Low emission power generation & Clean coal technologies and one indirectly: Hydrogen and fuel cells. The goal of the first is to drastically reduce the environmental impact of fossil fuel use aiming at highly efficient power generation plants with near Ultra Low emissions based on CO₂ capture and storage technologies. The goal of the second is to substantially improve plant efficiency, reliability and cost through development and demonstration of clean coal conversion technologies. The Key EU considerations are that:

- Fossil fuels projected to be an important part of power generation mix in the decades to come
- Environmental compatibility is a « sine qua non conditio »: need to drastically reduce CO₂ emissions for transition to sustainability
- Huge projected demand for new generation capacity: European industry should be highly competitive

Tentative Timetable for the Seventh Framework Program of the European Union

06/04/2005	Commission – Adoption of FP7 proposals
09-mai	Commission – Proposals on SPs and Rules for participation and dissemination
Late 2005	Commission – Proposals under Articles 169 and 171
01-juin	Council – Common position
06-juin	Council and EP – Adoption of FP and Rules
07-juin	Council – Adoption of the SPs

Source: CEC

³⁰ See Angel Pérez Sainz (2005).

The Joint Statement of the Eighth China-EU Summit in Beijing on 5th September 2005 underlined the determination of both parties to tackle the serious challenge of climate change through practical and results-oriented co-operation. A Joint Declaration on Climate Change between China and the EU was issued on the same occasion which established a China-EU partnership on Climate Change designed to strengthen practical cooperation on the development, deployment and transfer of clean fossil fuels technologies, to improve energy efficiency and to achieve a low carbon economy, including cooperation in carbon dioxide capture and storage.

This partnership includes co-operation on the development, deployment and transfer of low carbon technologies, including the aim to develop and demonstrate, in the EU and in China, advanced near-zero emission power generation technology, through carbon dioxide capture and storage, by 2020. The UK, the current EU Presidency, has offered to provide concrete and practical support to assist the first phase of this co-operation.

It was agreed, based on the Joint Declaration on Climate Change, to co-operate to reduce the impact on the global Climate Change of the use of fossil fuels, particularly coal. Agree that Cooperation shall focus on the opportunity for near-zero emissions use of fossil fuels, particularly coal, in power production and industry, through the application of carbon dioxide capture and geological storage. Such Cooperation will have the following objectives:

- (a) The assessment of the potential for near-zero emissions coal use through carbon dioxide capture and storage in China
- (b) The developing of knowledge and expertise; and
- (c) To develop and demonstrate in the EU and China, by 2020, advanced, near-zero emissions coal technology through carbon dioxide capture and storage.

It foresees three phases of the Cooperation, namely:

- (a) Phase 1: Exploring the feasibility of, and options for, near-zero emissions coal technology in China through carbon dioxide capture and storage;
- (b) Phase 2: Defining and designing a demonstration project; and
- (c) Phase 3: Construction and operation of a demonstration project.

France is closely associated to these initiatives. Many French corporations and institutions are involved such as IFP, Alstom, Gaz de France, Total, EDF, Air Liquide, Arcelor, BRGM, CNRS, GEOSTOCK, INERIS, Lafarge, SARP Industries, Schlumberger & ADEME.

Several complementary actions are also led to the national level, in particular via the CO₂ Club and the Network of oil and gas technologies (Réseau des technologies pétrolières et gazières - RTPG). The CO₂ club, under the presidency of ADEME (Agence de l'environnement et de la maîtrise de l'énergie) and thanks to the support of IFP and BRGM, gathers the major actors concerned and supports several research projects mainly in the field of collecting.

RTPG which associates companies, research centers and universities aims to promote research in the oil field by granting refundable advances intended to finance research projects. Since 2001, it intervenes on the topic of collecting and of the storage of CO₂ and concentrates on the optimization of storage in various geological formations and on its long-term effects. Finally, in France, so as to reinforce those programs, two agencies have been created. The first one - Agence Nationale de la Recherche - is devoted more on fundamental research. The second one - Agency for Innovation and Industry (AII) - is devoted for almost deployable technologies.

The CO₂ Club

The CO₂ Club was formed in 2002 on the initiative of Ademe and with the support of IFP and BRGM, the latter acting as secretary. It represents a key element in the organization of French research in the field of CO₂ capture and storage. It is in fact a response to the need to more effectively federate national efforts, whilst giving them better public visibility. Under the presidency of Ademe, the Club gathers together the major concerned players in the industrial sector and in research. A clearinghouse for exchanges, information and initiatives amongst its members in the area of studies and technological developments concerning CO₂ capture, transport and storage, the Club encourages cooperation at a national level between the public and private sectors, and to its initiatives can be credited a number of research projects.

Theme-based groups have been formed to collect all information on this technological option. The data serve to identify directions where progress should be made and make recommendations to decision-makers and funding bodies to initiate multidisciplinary work. Lastly, it plays the role of showcase for promoting the French technological know-how within the European and international arena.

As of 1 November 2005, the CO₂ Club will count the following as members: ADEME, Air Liquide, Alstom, Arcelor, BRGM, CNRS, EDF, Gaz de France, GEOSTOCK, IFP, INERIS, Lafarge, SARP Industries, Schlumberger, Total.

Source: www.clubco2.net

GHG Capture and Geological Sequestration at Gaz de France

Gaz de France takes a keen interest in all methods of reducing greenhouse gas emissions, in particular carbon sinks and geological CO₂ storage (as well as energy efficiency and lower-carbon and renewable energy sources). Over the last five years, Gaz de France has leveraged its existing know-how in the area of stripping CO₂ from natural gas during natural gas production, transport and underground storage to develop new expertise in CO₂ storage. The Group is involved in French and European research projects involving a range of scientific and industrial partners, and Gaz de France is also a member of several knowledge-sharing networks (including the CO₂NET network in Europe and "Club CO₂" in France) that make information about current and planned operations available for use in future projects.

The main aims of these R&D projects are to validate technical solutions capable of capturing CO₂ at an economically acceptable cost and to prove the feasibility of large-scale storage facilities.

Although CO₂ capturing technologies exist, they are still expensive. Research efforts relating to such technologies tend to focus either on reducing the cost of capturing CO₂ present in smoke and fumes, or on oxygen combustion technologies. These emission reduction goals are the major objectives of R&D projects in this field, and in particular CASTOR (*CO₂ from CAPture to STORage*), an EU project involving Gaz de France.

In the area of CO₂ storage, Gaz de France has been involved in the RECOPOL project to inject CO₂ into coal seams in Poland. The Group also took part in GESTCO, a project to identify and document CO₂ storage sites across Europe. In France, Gaz de France is conducting a series of studies into depleted hydrocarbon deposits and saline aquifers as part of the PICOREF (*PIégeage du CO₂ dans les REservoirs géologiques en France*) project, in partnership with an industry organization called Réseau Technologies Pétrolières et Gazières (RTPG).

Since 2004, Gaz de France Production Nederland (Proned) has been reinjecting CO₂ into K12B, a near-depleted natural gas deposit in the North sea, off the Dutch coast. This deposit, which has been worked since 1987, naturally contains 13% of CO₂. To make the gas saleable, it is processed on the production platform in order to reduce the CO₂ content to 2%. Until early 2004, the CO₂ stripped from the gas was discharged into the atmosphere.

The reservoir has an estimated capacity of 8 MtCO₂. At an injection rate in the region of 400 000 metric tons per year, over a 20-year operating life, this represents the equivalent of approximately 0.5% of the Netherlands' industrial emissions. A similar project to inject CO₂ into an aquifer is being planned as part of the development of the Snøhvit deposit in the Barents Sea, in conjunction with Statoil.

This CO₂ injection project, one of only two currently operating in Europe (the other being Statoil's Sleipner facility), places Gaz de France firmly among the leading industrial players, alongside Statoil and BP, allowing it to develop its CO₂ sequestration experience.

CO₂ Capture and Geological Sequestration at Total

Total Exploration & Production's R&D teams are participating in a variety of studies on CO₂ capture and geological sequestration.

In the area of capture, Exploration & Production has deployed a research and investigation program on managing CO₂ from steam generation during production of heavy oil on projects such as Sincor and Surmont (see section on The Future of Energy). One of the capture methods being assessed by Exploration & Production, in cooperation with France's Air Liquide, is a promising technology known as oxycombustion (asphalt combustion with oxygen) that should be accessible in the near medium term.

In the area of sequestration, Exploration & Production is involved in:

- Various subcontracting or cooperation partnerships with universities, laboratories and France's National Scientific Research Center (CNRS) to examine issues related to the sustainability and integrity of storage reservoirs and injection structures such as wells. These issues include the geomechanical behavior of caps during CO₂ injection, fault activation, carbonate rock damage, and aging of cements.
- The French Oil and Gas Technological Network's (RTPG) PICOR project on CO₂ sequestration in reservoirs, specifically the geochemical interactions and thermodynamic parameters affecting injection and storage potential. The *Institut Français du Pétrole* (IFP) is managing the project, in partnership with the French Geological and Mining Research Bureau (BRGM), Géostock, the Saint-Etienne Mining School and the universities of Bordeaux, Montpellier, Grenoble and Toulouse.
- A Statoil-led project on pilot CO₂ stores, divided into two main parts. The first is an extension of the Saline Aquifer CO₂ Storage (SACS) project, storing one million metric tons of CO₂ a year from the West Sleipner field, in which Total has an interest, in the Utsira formation. The second entails feasibility studies for four pilot capture and sequestration facilities in Germany, the United Kingdom, Norway and the Netherlands.
- A pilot enhanced oil recovery (EOR) project to sequester near-pure CO₂ in the EnCana-operated mature Weyburn field in Saskatchewan, Canada. The CO₂ comes from an American coal gasification plant located 300 kilometers south of the reservoir.

September the 16th, 2005, Total announced that it will spend an extra 50 million euros to build a pilot CO₂ capture and sequestration unit at Lacq and to develop other technologies to reduce

greenhouse gas emissions related to the use of fossil fuels. The general manager of Total Exploration Production France, Pierre Nergararian, has announced that a unit of capture and CO₂ injection will be created on the basin of Lacq at 2008 horizon. Initially, only the capture will be tested. The second phase will see the test of CO₂ injection. This unit could trap some 75 000 tons of CO₂ per annum, for a production on the basin, all activities accounted for, of 500 000 tons. The technology of capture will be probably based on the oxycombustion. This realization is estimated around 40 million euros.

As well, Total participates in Club CO₂ with French public research institutes, the European Carbon Dioxide Thematic Network (CO₂NET), and the International Energy Agency Greenhouse Gas (IEAGHG) R&D Program.

Source: www.total.com & Sud Ouest - 20/09/2005 from www.centre-cired.fr

Germany

Without being exhaustive, we can note the most important projects. The Swedish Vattenfall, which owns mines and power stations in Germany, is projecting a pilot there. The technology being developed by is designed primarily for use with lignite, or brown coal, which is one of eastern Germany's primary mineral resources. Vattenfall is to build its new plant at Schwarze Pumpe, south-east of Berlin in the state of Brandenburg, where it already operates a conventional coal-fired power station. It will use the Oxyfuel process. Vattenfall plans to have the 40m€ 30 MW plant in operation by 2008.

The question of the storage of the CO₂ is not yet solved. A studied solution consists in the transport of the CO₂ toward a pilot site managed by Shell. Shell is indeed conducting, with the support of the European Commission and in association with Geo-Research Center, Potsdam and other partners, a CO₂ sequestration field test near Berlin that aims to provide detailed insight into the subsurface behavior and movement of CO₂. For the longer term, other locations, such as Schweinrich, are investigated such as to provide very large storage sites

United States & Australia

FutureGen³¹ is an initiative to build the world's first integrated sequestration and hydrogen production research power plant. The US\$1 billion dollar project is intended to create the world's first zero-emissions fossil fuel plant. When operational, the prototype will be the cleanest fossil fuel fired power plant in the world. Additionally, other countries will be invited to participate in the demonstration project through the Carbon Sequestration Leadership Forum and other mechanisms. The prototype plant will establish the technical and economic feasibility of producing electricity and hydrogen from coal (the lowest cost and most abundant domestic energy resource), while capturing and sequestering the carbon dioxide generated in the process. The initiative will be a government/industry partnership to pursue an innovative 'showcase' project focused on the design, construction and operation of a technically cutting-edge power plant that is intended to eliminate environmental concerns associated with coal utilization. This will be a 'living prototype' with future technology innovations incorporated into the design as needed. The project will employ coal gasification technology integrated with combined cycle electricity generation and the sequestration of carbon dioxide emissions. The project will be supported by the ongoing coal research program, which will also be the

³¹ www.fossil.energy.gov/programs/powersystems/futuregen/

principal source of technology for the prototype. The project will require 10 years to complete and will be led by an industrial consortium representing the coal and power industries, with the project results being shared among all participants, and industry as a whole. In the operational phase, the project will generate revenue streams from the sales of electricity, hydrogen and carbon dioxide. The revenue will be shared among the project participants (including the U.S. Government) in proportion to their respective cost-sharing percentage.

US backed FutureGen Project Launched

Secretary of Energy Samuel Bodman announced December the 7th 2005, that the Department of Energy has signed an agreement with the FutureGen Industrial Alliance to build FutureGen, a prototype of the fossil-fueled power plant of the future. The nearly US\$1 billion government-industry project will produce electricity and hydrogen with zero emissions, including carbon dioxide, a greenhouse gas. The FutureGen Initiative was initially announced by President Bush in February 2003. The project is being funded through the Department's Office of Fossil Energy and will be managed by the National Energy Technology Laboratory. The initiative is a response to President Bush's directive to develop a hydrogen economy by drawing upon the best scientific research to address the issue of global climate change. Today's announcement marks the official "kick-off" for the FutureGen Project. Over the next year, site selection, design activities, and environmental analyses will lay the groundwork for final project design, construction, and operation.

The FutureGen Industrial Alliance will contribute US\$250 million to the project. Current Alliance members are: American Electric Power (Columbus, Ohio); BHP Billiton (Melbourne, Australia); CONSOL Energy Inc. (Pittsburgh, Pa.); Foundation Coal (Linthicum Heights, Md.); China Huaneng Group (Beijing, China); Kennecott Energy (Gillette, Wyo.); Peabody Energy (St. Louis, Mo.); and Southern Company (Atlanta, Ga.). The Industrial Alliance plans to issue a site selection solicitation in early 2006, to develop a short list of the most qualified candidate sites by mid-2006, and to make a final site selection in mid to late 2007.

FutureGen will initiate operations around 2012 and virtually every aspect of the prototype plant will be based on cutting-edge technology. The project will integrate testing of emerging energy supply and utilization technologies as well as advanced carbon capture and sequestration systems. Technologies planned for testing at the prototype plant could provide future electric power generation with zero-emissions that is only 10% higher in cost than today's electricity.

At the heart of the project will be coal gasification technologies. These technologies will turn coal into a highly enriched hydrogen gas, which can be burned much more cleanly than directly burning the coal itself. Alternatively, the hydrogen can be used in a fuel cell to produce ultra-clean electricity, or fed to a refinery to help upgrade petroleum products. In the future, the plant could also become a model hydrogen-production facility for President Bush's initiative to develop a new fleet of hydrogen-powered cars and trucks. Carbon sequestration will be one of several key features that will set the prototype plant apart from other electric power plant projects. FutureGen will be designed to capture carbon dioxide and sequester it in deep underground geologic formations. No other power plant in the world has been built with this capability. The initial goal will be to capture 90% of the plant's carbon dioxide, but capture of nearly 100% may be possible with advanced technologies.

Once captured, the carbon dioxide will be injected as a compressed liquid-like fluid deep underground, perhaps into saline reservoirs thousands of feet below the surface of much of the United States. It could even be injected into oil or gas reservoirs, or into unmineable coal

seams, to enhance petroleum or coal bed methane recovery. Once trapped in these formations, the greenhouse gas would be permanently isolated from the atmosphere.

The project will include an intensive measurement and monitoring effort to verify the efficacy of carbon sequestration. The FutureGen plant will be sized to generate approximately 275 MW of electricity, which is roughly equivalent to a medium-size coal-fired power plant and sufficient to supply electricity to approximately 275 000 average U.S. households.

The ultimate goal for the FutureGen plant is to show how new technology can dramatically reduce concerns over atmospheric emissions of pollutants from the future use of coal. Coal is the most abundant fossil fuel in the United States with supplies projected to last 250 years at the current utilization rate and is the workhorse of the United States' electric power sector, supplying more than half of the electricity the nation consumes.

Research is also being done on the commercial, technological and environmental viability of the large-scale injection of CO₂ to enhance the recovery of oil, gas and potentially methane from geological deposits. At present, CO₂-enhanced recovery represents only a fraction of total enhanced oil recovery (EOR). Preliminary analysis of the CO₂ storage potential for enhanced coal-bed methane (ECBM) projects worldwide indicate that 148 GtCO₂ could be sequestered in coal at total cost of under US\$110/tCO₂ (excluding capture and transmission costs). The most favorable coal basins have capacity estimated at up to 15 GtCO₂ with potential for cost saving between US\$0 and US\$20/t CO₂.

CO₂-ECBM is being tested in various research projects – since the mid 1990s, Burlington Resources has been operating a 13-well CO₂-ECBM pilot operation in the San Juan Basin in New Mexico; a similar project is underway in Poland; and Alberta Research Council has also been conducting research into this technology option. Laboratory testing is being undertaken in several countries to examine the physical and chemical processes involved. The factors likely to be important for CO₂-ECBM include coal rank, maceral composition and ash content, water saturation and gas composition.

The Weyburn project in Canada where CO₂ is being used to enhance oil recovery. Other projects are in the planning stage, such as the recently-announced Teapot Dome oilfield sequestration project in the US.

Initiated by the Australian Coal Industry, COAL21³² is a program aimed at fully realizing the potential of advanced technologies to reduce or eliminate greenhouse gas emissions associated with the use of coal. The program will also explore coal's role as a primary source of hydrogen to power the hydrogen-based economy of the future. The program is a collaborative partnership between Federal and State governments, the coal and electricity generation industries and the research community.

COAL21 is not an organization. It is a partnership between the coal and electricity industries, unions, federal and state governments and the research community. It commenced in March 2003 when the Australian Coal Association issued invitations to participate in a process aimed at first identifying and then realizing the potential for reducing or eliminating greenhouse gas emissions from coal-based electricity generation in Australia.

It is well recognized that fossil fuels will continue to play a strong role in meeting global energy demand, energy security, and, in Australia's case, generating export income,

³² www.coal21.com.au

employment and investment. As an energy intensive economy with a strong dependence on coal, reducing emissions that arise from its use is one of a broad suite of responses that will be needed if Australia is to make significant cuts in stationary energy sector emissions in the foreseeable future. Other measures will need to include greater emphasis on end use efficiency, greater use of lower carbon fuels and alternative technologies where they are most practical, greater use of renewables and a strong commitment to RD&D in all areas. COAL21 is intended to complement these measures, not replace them.

The objectives of COAL21 recognize the important role that coal plays in sustaining Australia's energy security and economic competitiveness. They also recognize the need to reduce greenhouse gas emissions over time in ways that maintain the advantages of a secure and competitive energy supply. The first stage of COAL21 was the development of the COAL21 National Action Plan. The process ran from March 2003 to March 2004 and involved input from a wide range of participants and consultation with other key stakeholders. The National Action Plan was officially launched in March 2004. The second stage of COAL21 commenced in 2004 and is focused on implementing the measures identified in the National Action Plan, including fostering greater community awareness and understanding of the key issues.

International Partnerships

The Carbon Sequestration Leadership Forum³³ (CSLF) is an international climate change initiative of the US Government focusing on development of improved cost-effective technologies for the separation and capture of carbon dioxide. The purpose of the CSLF is to make these technologies broadly available internationally; and to identify and address wider issues relating to carbon capture and storage. This could include promoting the appropriate technical, political, and regulatory environments for the development of such technology.

The CSLF charter was signed on June 25, 2003 in Washington, DC by representatives of 13 countries and the European Commission. Since then, Germany, South Africa, and France have joined, bringing the total number of members to 17. The charter will stay in effect for 10 years. While there are several large scale international CO₂ sequestration projects underway, this first-ever ministerial-level sequestration forum underscores the new importance given to international cooperation.

The activities of the CSLF are conducted by a Policy Group, which governs the overall framework and policies of the CSLF, and a Technical Group, which reviews the progress of collaborative projects and makes recommendations to the Policy Group on any required action. Collaborative projects may be undertaken by the CSLF as authorized by the Policy Group at the recommendation of the Technical Group. This specifically includes projects involving the following: information exchange and networking; planning and road-mapping; facilitation of collaboration; research and development; demonstrations; public perception and outreach; economic and market studies; institutional, regulatory, and legal constraints and issues; support to policy formulation; and others as authorized by the Policy Group.

For the option of ocean storage, both the International Geosphere-Biosphere Program³⁴ (IGBP) and the World Climate Research Program³⁵ (WCRP) are assessing the role oceans play in regulating atmospheric CO₂ levels, finding which would be relevant to understanding the concept of sequestering more CO₂ in the oceans. Links must also be established with research

³³ www.cslforum.org

³⁴ www.igbp.kva.se

³⁵ www.wmo.ch

to understand the impact of CO₂ on the marine ecology. If large-scale ocean sequestration of CO₂ is to be considered, new initiatives are required in this area.

Research into the practicalities and potential for combining methane extraction from natural gas hydrates with CO₂ storage in permafrost regions estimated the cost to be comparable with extracting free gas from an as-yet-unexploited Arctic gas field, providing transmission facilities were available. Recent research by the Mallik 2002 Gas Hydrate Partnership (which include teams from Asia, the US and Europe), found that depressurizing coupled with heating could effectively free methane particles from their frozen hydrate state. At this state, however, hydrates are not considered a useful fossil fuel resource so large-scale exploitation is not expected to begin before 2010 at the earliest.

The IEA Greenhouse Gas R&D Program has established international research networks on CO₂ capture testing, biofixation of CO₂, and non-CO₂ greenhouse gases (jointly with the US Environmental Protection Agency and the European Commission Environment Directorate General). It is also a partner in several international collaborative storage projects: GESTCO (responsible for mapping capacity in European geological reservoirs), ICBM (studying the basic science of storage in coal seams), RECOPOL (trialing injection into a coal seam in Poland from 2003), NGCAS (researching the safety, monitoring and verification issues of storage in an offshore depleted offshore oil field in Europe), NASCENT (a European project studying natural long-term accumulations of CO₂ in geological formations for use as reference sites for future projects), and GEO-SEQ (reducing the cost, risk and implementation time of sequestration).

R&D in power generation

Much R&D for fossil fuel combustion and gasification technologies is focused on improving gas-fired turbine efficiencies and lowering costs while advancing plant lifecycles through advances in parts and materials. Similarly, clean coal technology programs aimed at reducing emissions by improving boiler efficiency to increase the amount of energy gained from each ton of coal.

The European Commission-backed CAME-GT (Cleaner and more Efficient Gas Turbines³⁶) project is seeking to co-ordinate R&D for industrial gas turbines, including fossil fuels and biomass and gas turbines in CHP applications and combined cycles. The CAME-GT group includes international input from gas turbine manufacturers and research groups in the EU and Eastern Europe. Similarly, the US Department of Energy is running a program which aims by 2008 to have developed advanced power systems capable of achieving 50% thermal efficiency at a capital cost of US\$1 000 per kilowatt or less for a coal-based plant.

Research to advance turbine technology is being undertaken by Germany's Siemens, Siemens Westinghouse of the US, France's ALSTOM, GE Energy Products and Turbomeca, Italy's Nuovone Pignone, Rolls-Royce and Demag Delaval Industrial Turbomachinery of the UK, and Germany's MAN Turbomaschinen among others. Research organisations such as EPRI and Oak Ridge National Laboratory in the US, and the UK's Imperial College and Cranfield University are also studying aspects of advanced turbine materials design and performance.

In Japan, for example, the Centre for Coal Utilization (CCUJ) is working with the New Energy and Industrial Technology Development Organization (NEDO) to develop FBC and gasification technologies backed by government funding. In line with Japan's plans to continue using fossil

³⁶ www.came-gt.com

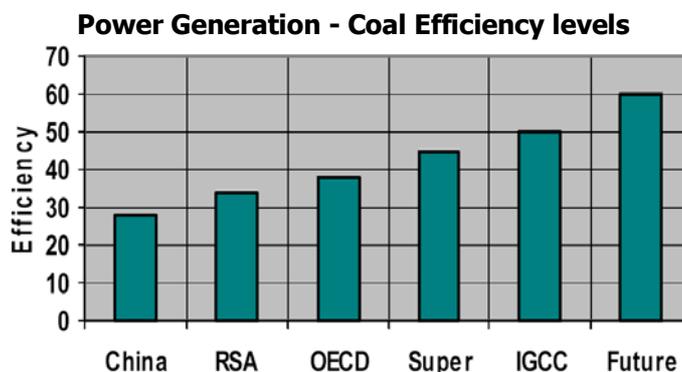
fuels for the majority of its energy supply up to 2050, technologies which cut CO₂ emissions by over 30% will be developed by 2030 backed by separation and sequestration. As part of this, Japan is aiming to commercialize IGCC and IGCC fuel cells with efficiencies of 43-48% and 55% respectively within the next decade. Continuing development of ultra-supercritical PCC technology is proposed over the next 30 years to continue achieving higher steam conditions. In Germany, IGCC is also a key part of R&D for coal-fired CC processes because of its potential advantages for CO₂ separation. Similar activities are being prioritized in the UK and Australia.

On a multi-national level, international cooperation among IEA member countries in areas relating to the combustion of fossil fuels and clean technology options for the future exists through six IEA collaborative R&D programs which operate under the auspices of the Working Party on Fossil Fuels: Fluidized Bed Combustion, the IEA Greenhouse Gas R&D Program, Multiphase Flow Sciences, Clean Coal Sciences, the IEA Clean Coal Centre, and the International Centre for Gas Technology Information. These provide for and facilitate the exchange of information on ongoing research between international participants.

Energy – GHG emission scenarios: Full deployment of Ultra Low Emission Technologies is required to limit emissions.

The economics of long term emissions

Coal-fired generating capacity of about 1 000 GW is installed worldwide. The present world average of the efficiency level is 32%. The average efficiency of coal-fired generation in the OECD is higher, at 36% in 2002 (and around 37-38% for EU15) compared with 30% in developing countries. As a result, one kilowatt-hour produced from coal in developing countries emits 20% more carbon dioxide than in industrialized countries. Moreover, almost two-thirds of the international coal-fired power plants over 20 years old have an average efficiency of 29%.



Source: World coal institute

New installations can differ markedly with respect to CO₂ intensity. According to WEC, the latest full-size state of the art plants in industrialized countries have efficiency around 42 to

45%. Further deployment and development indicate that this could exceed 50%³⁷. According to WEC, in 2030, 72% of world coal-based electricity generation is expected to be with clean coal technologies.

Illustrative simulation bases

In this section, we compute with IEA and EU-WETO data, specific projections for power generation prolonged up to 2050, which correspond to different technological scenarios³⁸. We compute the corresponding level of CO₂ emissions³⁹. We will focus on the impact of the deployment of more efficient coal combustion processes in power stations, of fuel switch and of CO₂ Capture and Sequestration.

The 2003 global emissions of CO₂ were approximately 25.0 GtCO₂. Power generation accounted for 9.4 GtCO₂. In our business as usual scenario, which is the 2004 IEA reference case, by 2030, global emissions will increase by 14.0 GtCO₂ – 56% increase - and emissions linked to power production will grow by 7.5 GtCO₂ – 80% increase -. At the horizon 2050, those figures are even more dramatic. Emissions linked to power production will reach 30.5 GtCO₂ or an increase of 21.1 GtCO₂ – a more than triple increase -.

World Electricity generation	Power generated TWh			GHG emissions GtCO ₂						
				Business as usual (32%)			Best available clean technology (45%)		Future best available clean technology (55%)	
	2003	2030	2050	2003	2030	2050	2030	2050	2030	2050
Coal	6 681	10 374	21082	6 585	11 357	23 080	9 440	16 412	8 355	13 428
Oil	1 150	1 064	1 002	1 042	1 000	942	1 000	942	1 000	942
Gas	3 232	7 714	10 874	1 773	4 571	6 444	4 571	6 444	4 571	6 444
Nuclear	2 632	2 394	12 879							
Hydro	2 649	3 458	4 722							
Other renewable	317	1 596	10 936							
Total	16 661	26 600	61 495	9 400	16 929	30 466	15 011	23 798	13 926	20 814

DIDD simulations⁴⁰

If we deploy the “Best available clean technology” for coal based power generation, we will limit this increase by 6.7 GtCO₂ – 23.8 GtCO₂ instead of 30.5 GtCO₂ i.e. a 22% decrease compared to the baseline, at the horizon 2050 and a 11% decrease compared to the baseline at the horizon 2030 -.

If we deploy the “Future best available clean technology”, we will limit the increase by 9.7 GtCO₂ i.e. a 32% decrease compared to the baseline, at the horizon 2050 and an 18% decrease compared to the baseline at the horizon 2030.

³⁷ More precisely, for hard coal, supercritical pulverized coal combustion presently operates at efficiencies of 45% and offers prospects for an increase to 48%; this technology remains the preferred option for large units and for up to 2020.

³⁸ We took advantage of the work of Bouttes, Trochet & Benard (2005).

³⁹ We do not take into account the energy used to transport fossil fuels, in particular coal. This could account for about 10% of the CO₂ emissions due to the use of coal (and gas).

⁴⁰ For 2003 and for 2030 in the business as usual scenario, we take IEA data, in particular the reference case. For 2050, concerning the power generated we take the data from WETO Reference case of May 2005. For the emissions, the business as usual scenario uses the same emissions coefficient than the IEA reference case for 2030. For the two scenarios, Best available clean technology and Future best available clean technology, we recomputed the emissions with 45 and 55% efficiency rates. At the 2030 horizon, half of the capacity is supposed to be implemented.

Future best available clean technology + "gas increase switch to 50% nuclear" scenario

World Electricity Generation	Power generated TWh			GHG emissions GtCO ₂		
	2003	2030	2050	2003	2030	2050
Coal	6 681	10 374	21 082	6 585	8 355	13 428
Oil	1 150	1 064	1 002	1 042	1 000	942
Gas	3 232	5 473	7 053	1 773	3 172	4 109
Nuclear	2 632	4 635	16 700			
Hydro	2 649	3 458	4 722			
Other renewable	317	1 596	10 936			
Total	16 661	26 600	61 495	9 400	12 527	18 479

DIDD simulations⁴¹

We can add the effects of fuel switch from half of new gas fired power plants to nuclear power. The improvement in term of GHG emissions is very substantial i.e. a 47% decrease compared to the baseline, at the horizon 2050. **Nuclear energy is therefore another clear critical element of solution to the limitation of GHG emissions.**

We can then compute the impact of capture and sequestration on GHG emissions.

Future best available clean technology + capture and sequestration (90% rate of success) + "gas increase switch to 50% nuclear" scenario

World Electricity Generation	Power generated TWh			GHG emissions GtCO ₂		
	2003	2030	2050	2003	2030	2050
Coal	6 681	10 374	21 082	6 585	4 637	1 477
Oil	1 150	1 064	1 002	1 042	1 000	942
Gas	3 232	5 473	7 053	1 773	3 172	4 109
Nuclear	2 632	4 635	16 700			
Hydro	2 649	3 458	4 722			
Other renewable	317	1 596	10 936			
Total	16 661	26 600	61 495	9 400	8 809	6 527

DIDD simulations⁴²

Finally, when we both use the capture and sequestration and switch half gas increase to nuclear scenario, we can drastically decrease CO₂ emissions i.e. a 79% decrease compared to the baseline, at the horizon 2050. It corresponds at a division by between 4 and 5 at the global level. Only this last scenario corresponds to an absolute decrease of CO₂ emissions generated by power generation. At the 2050 horizon, in absolute term compared to the starting point, it correspond to a decrease by 30%, instead of an increase which would more than triple the emissions.

In any case, even a full deployment of future best available clean coal technologies can only limit the increased of CO₂ emissions. A major switch from gas to nuclear, with those future technologies, would limit even more the increase. The full deployment of Ultra Low emission coal and gas technologies would contribute to an absolute decrease of GHG emissions, more precisely of 30%⁴³. **The full deployment of Ultra Low emission technologies is therefore required, if one want to keep coal running and limit GHG emissions.**

⁴¹ In this scenario, we split the incremental power produced from gas between gas and nuclear.

⁴² In this scenario, we consider Coal Capture and sequestration. We estimate that the efficient of coal power plant is decreased by 10%. We consider also that the capture rate is of 90%. At the 2030 horizon, half of the capacity is supposed to be implemented.

⁴³ Taking into account the CO₂ emissions during the transportation of coal and gas would reduce significantly the benefit of CO₂ capture during power generation, but would not change the overall conclusion

Climate change, energy and sustainable development: How to tame King Coal?

Postface

The increasing importance of the stakes related to sustainable development in public policies, makes desirable a reinforcement of the actions of the State in and their coordination. This is why it was decided to institute, near the French Prime Minister, a Délégué interministériel au développement durable (Interministerial delegate for sustainable development), which has the role to animate and coordinate the action of the administrations of the State and publicly owned establishments, in favor of the sustainable development.

This *Climate change, energy and sustainable development Vision paper on How to tame King Coal* has been prepared under the auspices of Coal Working Group of the Délégué Interministériel au Développement Durable. This vision paper has been developed in response to the observation that the coal issue is becoming critical in the energy and climate debate. The International Energy Agency (IEA) shows in its forward projections that global electricity demand could grow by 2.4% each year and that coal-based power generation could account for 90% of this energy growth. Of course, it remarks that this path is not sustainable.

Indeed, on one side, coal is a cheap and relatively accessible fossil energy source. The recent surge in natural gas price reinforces strongly the demand for coal in the power sector. Therefore its very large reserves make it possible to consume fossil energy still for many decades, even in the transport sector thought Coal to Liquid. On the other side, its high carbon content also makes it the biggest CO₂-emitter per unit of electricity produced. Then its impact on climate change is worrisome. In any case, in the future the environmental footprint of coal will have to be reduced. For that purpose, a brand new option appears on the scope: CO₂ Capture and Sequestration (CCS).

This study made it possible to establish the state of the art of technology on a topic in fast change. More precisely, the mandate of the report therefore included the assessment of the demand for coal, the technological maturity of the different options of production and of CCS, the description of the different R & D initiatives as well as the French public and private industrial actions. We have produced internally some illustrative specific simulations for power generation, which correspond to different technological scenarios.

As we focus on the coal sector, our aim is not to draw a global strategy, which would encompass energy efficiency, renewable energy, nuclear energy and fossil energy. Our main conclusion is that, in addition to the deployment of more efficient coal technologies, we need to accelerate substantially the deployment of "Ultra Low emission" coal technologies, so as to stabilize CO₂ concentrations at a reasonable level. Those "Ultra Low emission" coal technologies require technologies such as CCS. They have a cost and they increase the price for power. Therefore, to have this deployment effective, it requires the adequate framework, which will have to be based on the relevant tools such as market mechanisms, fiscal instruments, and norms. Together they will fix an implicit or explicit carbon price. It is the prerequisite to a real tackling of climate change issues on the coal side. Finally, we have to note, that at the present day, a strong research effort has to be deployed so have to have a better and more practical knowledge concerning the environmental impact of CCS.

CCS is not a miracle solution which will allow an unlimited exploitation of coal based power stations and a kind of technological pillow of idleness which would exempt to progress in the demand management, the energy efficiency and the development of the right mix of energy. Of course, only a relevant mix of those options may address the challenges we face. It is then necessary to put in perspective this technology in a new energy system with low percentage of carbon, in the combination of sources of energy including the biomass. It is not the single solution but it will contribute a significant share.

During the second half of 2005, we have built a process of work with French based corporations, consultants, administrations, research organization and with international entities and NGO's. Therefore it constitutes a French view of a global issue. In accordance with our procedures, the responsibility of the paper remains solely one of the Coal Working Group. We wish to express our gratitude to all the participants that provided critical information that were essential to complete this report.

Christian Brodhag
Délégué Interministériel au Développement Durable

Annex

Annex 1: Energy scenarios from WEC and the Commission of the European Union

Annex 2: The example of China

Annex 3: CASTOR, CO₂, from Capture to Storage, Objectives and situation after 18 months of work (September 2005)

Annex 4: BRGM involvement in CO₂ projects

Annex 5: Glossary and Acronym

Annex 6: Bibliography

Annex 1: Energy scenarios from WEC and the Commission of the European Union⁴⁴

The WEC – IIASA scenarios were used for the IPCC Special Report on Emissions Scenarios (SRES)

The World Energy Council (WEC) has developed multiple energy scenarios, which permit to scan the future up to 2100. IIASA (International Institute of Applied Systems Analysis) was commissioned to build a model. The corresponding 1998 publication became the basis of the IPCC SRES report (published ahead of COP6 as the new scenarios for the third assessment)⁴⁵.

The IPCC SRES scenarios explain the world economy and emissions vis-à-vis relative orientation toward economic or environmental concerns and global and regional development patterns. The key driving forces are economic growth, population, emphasis on heterogeneity and self-reliance in regions, speed of introduction of new and efficient technologies, extent of cultural and social interactions.

Six variants were proposed. Three variants were scenarios within the A family: A1 with a strong emphasis on oil and natural gas use; A2 which is coal-intensive (with implications for severe local and regional pollution, and high carbon emissions, unless major and costly efforts are taken to tackle these); and A3 which emphasizes the roles of natural gas, new renewables and nuclear in averting serious problems from emissions. Case B became the single Scenario B - a Middle Course. And Case C was divided into C1 with its emphasis on energy efficiency improvements, new renewables (especially solar in the longer run), but with nuclear power phased out by 2100 because unable to satisfy its critics; and C2 where nuclear power plays an expanding role. In Scenarios A3, C1 and C2 there is relatively rapid progress along technology learning curves.

The main features of the scenarios are summarized in the following tables.

	(Gtoe)			
	1990	2050		
		A	B	C
OECD	4.2	6.7	5.6	3.0
Economies in Transition	1.7	3.7	2.4	1.7
Developing Countries	3.1	14.4	11.8	9.5
Total	9.0	24.8	19.8	14.2

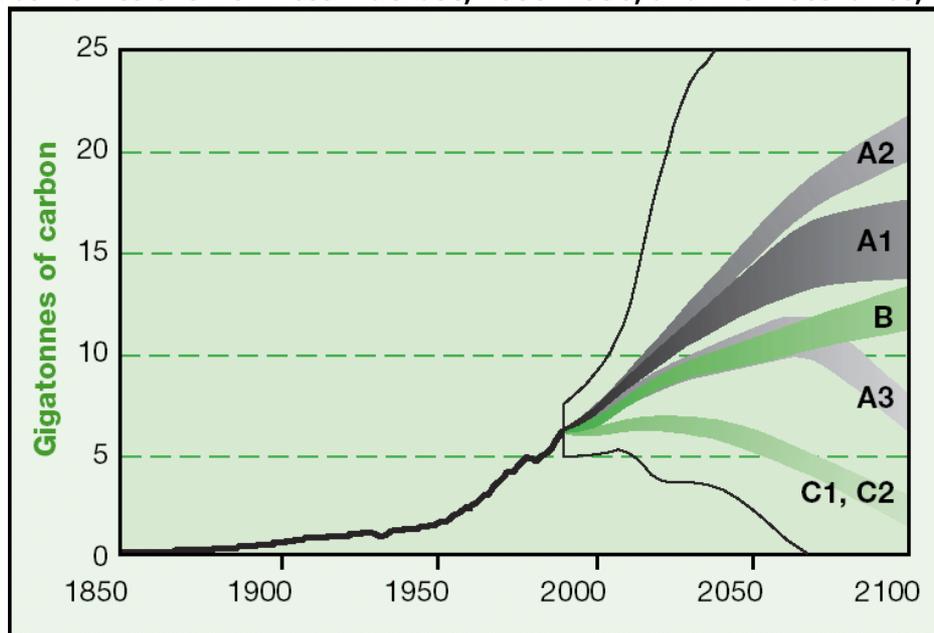
⁴⁴ From WEC.

⁴⁵ IIASA is now coordinating a revision of these scenarios on behalf of the IPCC, to be published as part of the 2007 Fourth Assessment Report.

Summary of Cases for Global Energy Scenarios			
	Case A Hic Growth	Case B Middle Course	Case C Ecologically Driven
World Population 2050 (10 ⁹)	10.1	10.1	10.1
World economic growth 1990-2050	2.7%p.a.	2.2%p.a.	2.2%p.a.
World energy intensity improvement 1990-2050	medium -1.0%p.a.	low -0.7%p.a.	high -1.4%p.a.
Primary energy demand (Gtoe) 2050	25	20	14
Resource availability			
Fossil	high	medium	low
Non-fossil	high	medium	high
Technology Costs			
Fossil	low	medium	high
Non-fossil	low	medium	low
Technology Dynamics			
Fossil	high	medium	medium
Non-fossil	high	medium	low
CO ₂ emission constraint	no	no	yes
Carbon emissions (GtC) in 2050	9-15	10	5
Environmental taxes	no	no	yes

Projections of the Composition of Global Primary Energy Supply and Carbon Emissions to 2050 for the Six Scenarios	(Gtoe)						
	1990	2050					
		A1	A2	A3	B	C1	C2
Coal	2.2	3.8	7.8	2.2	4.1	1.5	1.5
Oil	3.1	7.9	4.8	4.3	4.0	2.7	2.6
Gas	1.7	4.7	5.5	7.9	4.5	3.9	3.3
Nuclear	0.5	2.9	1.1	2.8	2.7	0.5	1.8
Hydro	0.4	1.0	1.1	1.1	0.9	1.0	1.0
New Renewables	0.2	3.7	3.8	5.7	2.8	3.8	3.2
Traditional Biomass	0.9	0.8	0.7	0.8	0.8	0.8	0.8
Total	9.0	24.8	24.8	24.8	19.8	14.2	14.2

Global carbon emissions from fossil fuel use, 1850–1990, and in six scenarios, 1990–2100



Source: WEC -IIASA

The WETO of the Commission of the European Union

The Commission published its *World energy, technology and climate policy outlook* (WETO) in 2003. It compares two different scenarios: a Reference Scenario ('business as usual') and a Carbon Abatement Scenario, looking at the impact that climate change policies can have. This assessment aims to help define priorities for the policies that can be put in place to improve the performance towards reducing CO₂ emissions.

Reference Scenario

The assumptions are the following

- current trends in business, technological and structural change in the world economy continue in the usual way, without major interference from policy-makers;
- no account is taken of specific energy or environment policy objectives and measures that were implemented after 2000, such as the CO₂ reduction objectives of the Kyoto Protocol, the planned phasing-out of nuclear energy in some countries and the target share of renewables in the energy mix;
- The situation of the world energy system in 2030 resulting from the Reference Scenario is used as a benchmark for the assessment of alternatives, particularly with respect to resources, technologies and environmental policy.

The results of the Reference Scenario are:

- world energy demand is projected to increase by about 1.9 per cent per year between 2000 and 2030; this figure is based on assumptions about economic and population growth, as well as developments in energy intensity;
- industrial countries will experience a slowdown in their energy demand, but demand in developing countries will grow rapidly; by 2030, more than half of the world energy demand is expected to come from developing countries (compared to 40 per cent today);

- fossil fuels are expected to continue dominating the world energy system, representing almost 90 per cent of total energy supply in 2030; oil is predicted to remain the main source of energy (34 per cent), followed by coal (28 per cent) and natural gas (25 per cent);
- In the EU, gas will be the second largest energy source after oil, while nuclear and renewable energies will account for less than 20 per cent of EU energy supply.

Carbon Abatement Scenario

The assumptions are the following:

- taking into account different regions' consent to commit themselves to medium-term reductions (so it does not assume a carbon value for the Commonwealth of Independent States (CIS)) and the expected reinforcement of climate change policies beyond the year 2010 (which is the deadline for the Kyoto targets);
- sustainable development policies are implemented in a large number of economic sectors;
- The enlarged EU is ahead of the other countries in terms of climate change policy: in the EU, the carbon value that would be applied to the use of fossil fuels by taking into account greenhouse gas emissions is double that of other regions.
- Aim: to assess the impact of policies aimed at the global reduction of greenhouse gas emissions on the energy sector.

The results of the Carbon Abatement Scenario are:

- 11 per cent decrease in the expected world energy consumption compared to the Reference Scenario; the average growth in demand would thus be 1.3 per cent per year, as opposed to 1.9 per cent.
- impact on carbon intensity, i.e. the global energy mix: a carbon value would primarily affect fuels with the greatest carbon content, namely coal (-42 per cent) and oil (-8 per cent), while gas would remain virtually unchanged;
- worldwide, this market share would be taken up by nuclear energy (+36 per cent) and renewable energies (+35 per cent);
- within the renewables sector, wind, solar and small hydro are expected to increase twentyfold;
- global CO₂ emissions would be reduced by 21 per cent compared to the Reference Scenario; however, they would still be higher in 2030 than they were in 1990;
- Europe's emissions level would be nearly 15 per cent lower than the 1990 level, and 26 per cent lower than in the Reference Scenario by 2030;
- the EU's changes in the energy mix reflect the world pattern, but both coal (-61 per cent) and oil consumption (-13 per cent) are considerably lower;
- In the EU, this decrease is compensated by nuclear (+35 per cent) and renewable energy (+56 per cent).

	Reference Scenario	Carbon Abatement Case	Difference
Energy demand World (Gtoe)	17.1 (+1.8% per year)	15.2	-11%
Energy demand EU (Gtoe)	2.0 (+0.4% per year)	1.7	-12%
Fossil fuels Total World (Gtoe)	14.9	12.4	-17%
- Oil (Gtoe)	5.9	5.4	-8%
- Coal (Gtoe)	4.7	2.7	-42%
- Gas (Gtoe)	4.3	4.3	0%
Nuclear (Gtoe)	0.9	1.2	+36%
Renewables (Gtoe)	1.4	1.8	+35%

Fossil fuels Total EU (Gtoe)	1.66	1.31	-24%
- Oil (Gtoe)	0.73	0.64	-13%
- Coal (Gtoe)	0.39	0.15	-61%
- Gas (Gtoe)	0.55	0.53	-3%
Nuclear (Gtoe)	0.24	0.32	+35%
Renewables (Gtoe)	0.12	0.19	+56%
CO ₂ Emissions World (GtCO ₂)	44.5	35.3	-21%
CO ₂ Emissions EU (GtCO ₂)	4.7	3.5	-26%

Gtoe: Giga ton oil equivalent (= 42.7 Gigajoule)

GtCO₂: Giga ton of CO₂

Source: European Commission, WETO report

IEA's World Energy Outlook

The OECD's International Energy Agency sets out the latest energy projections to 2030 in its report entitled 'World Energy Outlook', published in 2002. Again, a Reference Scenario is compared to an Alternative Policy Scenario. There is a strong focus on concerns about the security of energy supplies, investment in infrastructure, the environmental damage caused by energy production and use and the unequal access of the world's population to modern energy.

Reference Scenario

- takes into account policy measures that were adopted in mid-2002 including recent efforts relating to the Kyoto Protocol and targets for renewables;
- results: energy use continues to grow rapidly, fossil fuels dominate the energy mix, and the energy consumption of developing countries approaches that of the OECD;
- CO₂ emissions are set to grow slightly faster than energy consumption despite the measures taken to date;

The projected emissions differ significantly from the Commission's outlook: while the Commission expects emissions to more than double between 1990 and 2030 (113 per cent increase from 20.8 to 44.5 billion tons of CO₂), the IEA report foresees a growth of 'only' 70 per cent to reach 38 billion tons in 2030; this difference might be attributed to the different methodologies in which the Commission does not take into account any policy measures after 2000, while the IEA does.

Alternative Policy Scenario

- assesses the impact of a range of new energy and environmental policies that OECD countries are considering and faster deployment of new technologies;
- Demonstrates a strong impact of new policies to curb energy demand growth and the energy mix; the latter would also have positive consequences for import dependence of the OECD.

The IEA report predicts that this would eventually stabilize greenhouse gas emissions in the OECD countries by 2030.

The Industry Perspective

The Shell study on 'Energy Needs, Choices and Possibilities - Scenarios to 2050', published in 2001, also devised two different scenarios, which are dependent on societal preferences rather than policy choices. The first scenario, entitled 'Dynamics as Usual', is based on a world where social priorities for clean, secure and ultimately sustainable energy shape the system. In the second scenario 'The Spirit of the Coming Age', superior ways of meeting energy needs are developed to meet consumer preferences regarding mobility, flexibility and convenience. In both scenarios, Shell predicts an important role for natural gas as a 'bridge fuel' over at least the next two decades. The study also projects a rapid growth for renewable energy, and a potential for renewables to be the eventual primary source of energy. The Shell scenarios explore "possible paths towards an affordable, sustainable energy system which has found solutions to environmental concerns", but they do not assess the concrete impact of policy measures on the way to this goal. However, the study suggests that for both scenarios, a stabilizing atmospheric carbon dioxide concentrations below 550 ppmv would be clearly visible. There is no reference to CO₂ emissions.

- ExxonMobil also published a study entitled "The Outlook for Energy - a 2030 view". The key findings of this analysis of the world energy situation up to 2030 are:
- By 2030 world energy demand will increase by 50 per cent (at 1.7 per cent per year), primarily in less-developed countries;
- Oil and gas will continue to be the primary energy sources, accounting for about 60 per cent of total demand;
- Oil will grow fastest in the developing Asia Pacific region due to increasing sales of personal vehicles; however, in North America and Europe, demand growth is expected to be offset by increasing vehicle efficiency;
- Gas will continue to grow faster than the other energy forms, meeting about 25 per cent of the world's energy demand by 2030;
- Carbon emissions will increase as a result of raising use of fossil fuels; this is most pronounced in the Asia Pacific region.
- Renewables will grow quickly, supported by government subsidies, but will contribute only a small fraction of energy supply;
- Nuclear will continue to grow, but only at 0.8 per cent per year; however, some new plants will be constructed in developed countries after 2020 due to mounting environmental and supply security concerns.

To meet higher demand, ExxonMobil maintains that the application of new technology is the best way to meet the energy challenge. This means growing and developing the resource base as well as improving energy efficiency and reducing emissions. Moreover, the company sees increasing opportunities for new coal, nuclear and bio-fuels.

Annex 2: The example of China⁴⁶

Primarily for domestic environmental motives, the interest of the China in clean coal technologies is beyond any doubt. As in other countries, advanced clean coal technologies have substantial potential to improve the efficiency of coal-based power generation and to reduce the harmful impacts of power generation. The average cost of power generation from clean coal technologies is declining and might make them eventually competitive with conventional pulverized fuel (PF) steam plants. The dominant installed technology is pulverized coal combustion with a subcritical steam cycle. Units range widely in sizes from less than 25 to 660 MW. There are still a large number of these subcritical units under construction. Ten supercritical units were in operation in 2003 and twenty more units were approved for construction. There will likely be a surge towards 1000 MW power plants with ultra-supercritical steam conditions (Minchener 2004). The National Development and Reform Commission (NRDC) has recommended advanced supercritical plants for large scale power generation and most recent orders have been for supercritical units. IEA experts indicate that supercritical plants totaling more than 60 GW of capacity were recently ordered. Since the 1960s, Chinese engineers have developed their own designs of small fluidized bed combustion equipment independently of early efforts in other countries (Watson & Oldham 1999).

Over 1000 commercial circulating fluidized bed (CFB) boilers have been put into operation since 1989 and fifteen 300 MWe CFB boilers are in the planning or construction stage (Minchener 2004). More than 30 GW of cogeneration plants are currently in operation, notably in the coldest parts of China. IGCC is not yet a fully mature technology, even in developed countries, where it delivers electricity at a higher cost of about 20%. The main risk factors include capital cost over-run, construction delay, and shortfalls in plant availability and performance. The cost and the risk disadvantages are substantially higher in China, where the average cost of power generation from an IGCC plant would be 32% higher than power from a PC plant; the overall risk factor would be 23% greater, according to the Nautilus Institute (1999). Consequently, there is only 1 IGCC prospect currently in China, for a demonstration plant at Yantai. There is however, considerable knowledge of coal gasification with many examples in the chemical industry for production of fertiliser chemicals. This explains why polygeneration has been suggested as a more realistic alternative for China (Zheng et alii 2003; TFEST 2003). Based on coal gasification ("syngas"), polygeneration systems can produce a variety of energy products: clean synthesis gas and electricity, high-value-added chemicals, high-value-added fuels for vehicles, residential and industrial uses, and other possible energy products. Gasification enables conversion of coal – including high-sulphur coal resources - with very low levels of air pollution compared to most existing coal combustion technologies in China. A recommendation of the China Council for International Cooperation on Environment and Developed made in 2003 to the Chinese Government essentially equates coal modernisation with polygeneration through gasification. An extensive review of the norms and standards for existing and new plants of different types in various parts of China, and other instruments such as effluent charges, are beyond the scope of this paper. They are usually less stringent than equivalent norms and standards in OECD countries, but are frequently revised and tightened. However, they might have little impact given the widespread absence of monitoring equipment, which leads to poor enforcement (Watson & Oldham 1999).

The Chinese government wishes to see large power stations equipped with FGD burn high sulphur coal and leave low sulphur coal for smaller boilers without FGD. Current practice,

⁴⁶ Extensive information in Philibert and Podkanski (2005).

however, is exactly the opposite: to fulfill the more severe standards on large boilers low sulphur coal is burnt in large power plants while smaller boilers only have access to high sulphur coals. Despite the government policy emphasizing the construction of larger, more efficient units of 300 to 600 MW power plants, the main increase in generating capacities consisted of hundreds of smaller units just a few years ago. In 2000, units smaller than 200 MW still represented 65% of a total capacity 237 GW, emitting 60% more CO₂ per kWh than larger units (Novem, 2003). In 1999 the Nautilus Institute (1999) expressed concern that “many of the new plants being built by the local governments are in unit sizes of 50 MW or less. The main reason is that these small units are easier to finance.”

Recently, however, some small units have been shut down and replaced with larger and more efficient units. Moreover, 25~30 GW generation units with unit size equal to or smaller than 50 MW were to be shut down before 2005, and all remaining units were to be shut down before 2010, while retirement of units of a size equal to 100 MW will start before 2010. (Guo & Zhou 2004). China’s main concern is a power shortage according to IEA experts. By the end of 2003, 21 provinces were reported to have a shortage of electricity (Cheng 2004), with a growth in production of 15% per year. Emphasis may be put on shortening siting, permitting and construction delays in such a context. This emergency situation may turn out to be a primary obstacle to technical improvements. Minchener (2004) suggests a similar reason for the failure to introduce emissions trading schemes in China – in about 10 cities: “It has not proved possible to implement a meaningful scheme because of the overall shortage of power and the need to operate each power plant at maximum availability. (...) In the near term the overwhelming need to generate power, with demand exceeding supply, will mean that such schemes cannot be effective.” More efficient designs can be fully competitive, as lower fuel costs compensate for higher initial capital costs; however, the lack of up-front capital can still be a barrier. End-of-pipe techniques, such as FGD, always entail positive costs, and can only be disseminated thanks to environmental regulations. Other techniques, however, such as CFB or polygeneration, can use a great variety of coal quality and help use other fuels (such as biomass), as well as reduce emissions. This might explain why these technique are easier to implement in China.

**Scientific and technical co-operation between France and China
of French companies with capture and sequestration know-how**

L'Institut Français du Pétrole

IFP (French Petroleum Institute) has long experience of co-operation with China in the field of the Exploration-Production. The most illustrative example is the co-operation which took place at the beginning of the years 1980 and which related to the Re-development of the giant field of Daqing by polymer injection in a pilot zone starting from processes developed by the IFP, field whose production continues still today. Beyond the technical success of this process of recovery an effective transfer of technology could be set up, to ensure the control of this process and its extension to the whole of the field. RIPED, research center of company CNPC sponsorises one of the multiclents projects operated by the IFP devoted to oil exploration in the very deep horizons. Lastly, it was decided to organize technical seminars soon making it possible to identify concrete subjects of co-operation, in particular with company CNOOC. 1.2

BRGM

BRGM has several projects co-operation engaged with China carried out within various frameworks which are listed hereafter:

CEFCEET - Participation of the BRGM in the Franco-Chinese Center of the Energy and the Environment of the University of Tsinghua under the coordination of INSA Lyon and in partnership with the ENSMP, the INPL.

European Project ASEM WATERNET: Asset - being negotiated financial with the European Union: (Platform of scientific and technical assistance euro-Asian (Asia of the SE) for the durable management of water).

Network of research P2R/WARM: Project WARM (Toilets Risks Management) was initiated by the CNES and the NRSCC (National Remote Sensing Center of China). For reasons of eligibility, it was proposed with the invitation to tender by the BRGM with the support of the CNES (International Direction) and was selected on September 25, 2003 by the French MAE/MR and the Chinese MOST (Ministry of Science and Technology) within the framework of the research program in networks (P2R) Franco-Chinese.

Beyond these various actions in particular centered on water, another action is more specifically dedicated to the storage of CO₂. The BRGM will collaborate indeed with the MOST and the university of Tsinghua for a first evaluation of the geological storage capacities of CO₂ in China within the framework of the European project GeoCapacity in the Sixth Framework Program for European Research & Technological Development (2002-2006), where IFP is also a partner.

Annex 3: CASTOR, CO₂, from Capture to Storage, Objectives and situation after 18 months of work (September 2005)

Introduction - Project outline

The overall goal of this project is to develop and validate, in public/private partnerships, a substantial part innovative technologies needed to capture CO₂ at the post-combustion stage and to store CO₂. The CASTOR R&D target is to enable the capture and geological storage of 10% of the CO₂ emissions of Europe, which corresponds to about 30% of CO₂ emitted by European power and industrial plants. To reach this goal, CASTOR will improve current techniques and develop, validate and generalize previously non existent methodologies and technologies for the capture of CO₂ and its subsequent secure underground storage.

Key targets of CASTOR are the following:

- A major reduction in post-combustion capture costs, from 50-60 € down to 20-30 € per ton of CO₂ (large volumes of flue gases need to be treated with low CO₂ content and low pressure)
- To advance general acceptance of the overall concept in terms of storage performance (capacity, CO₂ residence time), storage security and environmental acceptability.
- To start the development of an integrated strategy connecting capture, transport and storage options for Europe.

The project consortium is the following:

R&D organisations	Oil & companies	Gas Power companies	Manufacturers
IFP (FR)	Statoil (NO)	Vattenfall (SE)	ALSTOM Power (FR)
TNO (NL)	Gaz de France (FR)	Elsam (DK)	Mitsui Babcock (UK)
SINTEF (NO)	RIPSA (SP)	Energi E2 (DK)	Siemens (DE)
SINTEF Ener. Res. (NO)	Rohoel (AT)	RWE (DE)	BASF (DE)
SINTEF Pet. Res. (NO)	ENITecnologie (IT)	PPC (GR)	GVS (IT)
NTNU (NO)		E.ON UK (UK)	
BGS (UK)			
BGR (DE)			
BRGM (FR)			
GEUS (DK)			
IMPERIAL (UK)			
OGS (IT)			
Univ. Twente (NL)			
Univ. Stuttgart (DE)			

CASTOR will last 4 years (Feb. 2004- Feb. 2008) and has been accepted for funding by the European Commission within the 6th European Framework Program. Total budget is 16 M€ (8,5 M€ funded by EU). 30 partners will carry out the work - R&D organisations, oil & gas companies, power companies and manufacturers - representing 11 European countries.

For **capture**, a pilot plant will be built in an existing coal-fired power plant operated by ELSAM in Denmark and will be operated during 2 years in order to validate the gas processes developed (new solvents, new membrane contactors, new process flow sheets, integration methods) in the project.

Work on **storage** aims at studying European injection sites and performing risks assessment studies. New methodologies will be developed by improving the knowledge with 4 new storage cases.

CASTOR web site: <http://www.co2castor.com>

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Work performed and main results obtained

Strategy for CO₂ reduction (10% of the budget)

This activity aims to define the overall strategies required to effect a 10% reduction of EU CO₂ emissions and to regularly monitor the effectiveness of the strategies (from capture to storage) from a techno-economical point of view. Research work is also focused on obtaining data on CO₂ sources and potential geological storage capacities from Eastern Europe (extension of GESTCO European project). At the same time solutions will be identified for legal and public acceptance of the concept of CO₂ sequestration as a viable option for CO₂ mitigation, by developing and applying a template for exploring the public perceptions toward carbon storage. The overall impact of the project on EU countries, including Candidate Countries, is therefore taken into account.

The first roadmap for implementation of large scale implementation of the concept has been outlined. The relative importance of the major controlling economic incentives has been estimated and the non-technical incentives and obstacles have been identified.

The data base on storage capacity in Europe have been improved by that eight more countries have been included, Czech Republic, Bulgaria, Croatia, Hungary, Poland, Romania, Slovakia and Slovenia.

Post-combustion capture (65% of the budget)

The objectives of work on post-combustion capture are:

- Development of absorption liquids, with a thermal energy consumption of 2.0 GJ/ton CO₂ at 90% recovery rates
- Resulting costs per ton CO₂ avoided not higher than 20 to 30 €/ton CO₂, depending on the type of fuel
- Pilot plant tests showing the reliability and efficiency of the post-combustion capture process.

For post-combustion capture, absorption technology is a leading option but its implementation in a power station will decrease the efficiency of generation by 15-25% and increase the power cost up to 50%. Some breakthrough in absorption technology is needed and CASTOR will address the following key issues: energy consumption, reaction rates, contactor

improvements, liquids capacities, chemical stability and corrosion, desorption process improvements.



The pilot plant for process integration and validation will be installed in a modern coal-fired plant: Esbjerg Power Station operated by Elsam in Denmark. This test facility with a capacity of 1 t CO₂/hour will be operated during more than 2 years with real flue gas, allowing hands-on experience with absorption technology. This will be the greatest pilot in the world for post-combustion capture of CO₂ on a coal combustion.

This baseline descriptions for the power plants (4 coal fired and 1 gas) and the solvent process (30% MEA) have been defined. Some parametric studies aiming a process optimization have been carried out. Requirements for flue gas desulphurization as imposed by the CO₂ capture process have been defined; These can be met using existing techniques.

The solvent development has resulted in a long list of 30 absorbents which has been reduced to a shortlist of about 10 amines. Amongst these are di-amines, tri-amines, which allow a doubling or a tripling of the CO₂ loading of the solvent compared to MEA. Design data on these amines will be gathered to narrow down the list to max. 3 solvents which could proceed to the pilot plant validation.

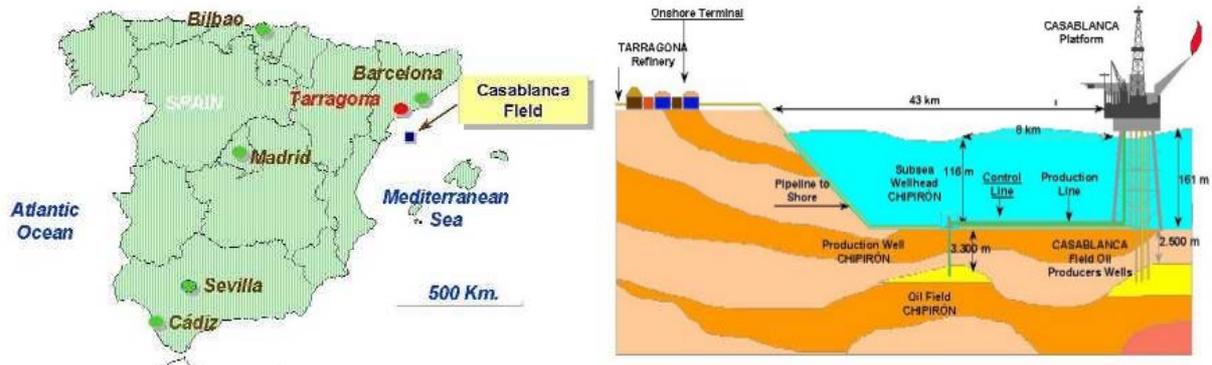
A ranking of membranes suitable for membrane gas absorption applications has been made, which will guide the further work on membrane contactors.

The pilot is under construction and will be ready for operations end of 2005. The official launching of the pilot will be held 15th of March, in Denmark in the presence of high representatives from involved companies, European Commission and national authorities (France, Denmark, Norway, ...)

Storage performance and risk assessment studies (25% of the budget)

The objective is to develop and apply a methodology for the selection and the secure management of storage sites by improving assessment methods, defining acceptance criteria, and developing a strategy for safety-focused, cost-effective site monitoring. The "Best Practice Manuel" will be improved by adding four European cases.

Casablanca oilfield (Spain, operated by Repsol ypf).



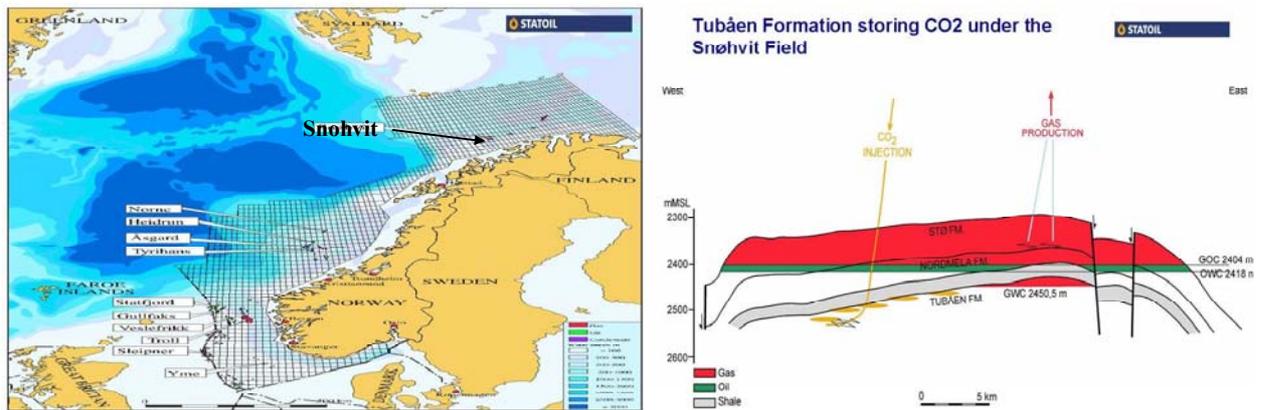
The Casablanca oil field is situated offshore northeastern Spain. This carbonate oil field at a depth of approximately 2500 m below the sea floor has reached its production tail, and production will soon cease. Repsol considers to use this field for storage of approximately 500 000 tons CO₂ per year, which is to be captured at the Tarragona refinery at 43 km distance from the field.

Atzbach-Schwanenstadt gas field (Austria, operated by Rohoel)



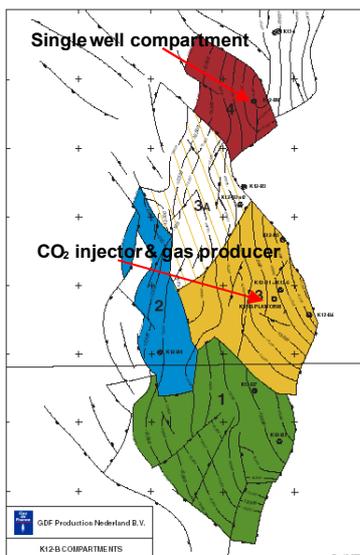
The Atzbach-Schwanenstadt gas field is situated in central northern Austria, between Salzburg and Linz. This onshore sandstone gas field at approximately 1600 m below the surface is almost empty. Rohoel AG considers its transformation into a CO₂ storage site and possibly test the suitability of CO₂ injection for Enhanced Gas Recovery. Potential CO₂ sources are a paper mill (emitting about 200 000 tons CO₂ per year) and a fertiliser plant (emitting about 100 000 tons CO₂ per year). Transport of CO₂ may be by trucks. Injection into the field may start towards the end of the project period, given positive results of the study and financing by industrial partners.

Snøhvit Aquifer (Norway, operated by Statoil)



The Snøhvit field is located offshore in the northern Norwegian Sea. Statoil has got official approval to inject CO₂ separated from produced gas from the Snøhvit field into an aquifer below the reservoir (depth: 2500 m). Injection of 0.75 Mt/year is planned to start in late 2006 and will last for more than 20 years.

K12B gas field (The Netherlands, operated by Gaz de France)



The K12B gas field is situated offshore the Netherlands. Gaz de France has carried out a feasibility study for Enhanced Gas Recovery. Small scale CO₂ injection of about 30 000 tons/year has started in mid 2004 and large scale injection of approximately 400 000 tons/year is intended to start in 2006 with a duration of up to 20 years. The reservoir is at 3500 - 4000 m in Rotliegend clastics. A seismic baseline survey exists.

During the first year of the project, the studies on 3 sites (Casablanca, Atzbach-Schwanenstadt, K12B) have started, consisting in collecting data available data and core samples, starting the experiments (fluid flow, geochemistry and geomechanics) and the reservoir simulations of CO₂ injection.

Dissemination and training activities

During the first year, the CASTOR website has been opened to both public and partners of the project (internal part). CASTOR has been presented in European and international conferences. A first course for PhD students on CO₂ capture/absorption processes has been delivered.

Annex 4: BRGM involvement in CO₂ projects⁴⁷

BRGM stands for Bureau de recherches géologiques et minières

JOULE II project (1993-1995) "The underground disposal of carbon dioxide": pioneer European research project (3rd FWP) that proved the feasibility of the concept of underground disposal of CO₂.

Main BRGM activities: geochemical and coupled reactive-transport modelling, inventory of CO₂ storage capacity in southern Europe, pre-feasibility of micro-seismic monitoring. BRGM was leader of Work Package "Geochemistry".

SACS (Phase 1) (1998-1999) and **SACS2** (Phase 2) (2000-2002) "Saline Aquifer CO₂ Storage project": European research and demonstration project (4th and 5th FWP) which is monitoring and forward modelling the underground CO₂ sequestration operation taking place since 1996 in a deep saline aquifer at the Sleipner gas field offshore Norway.

Main BRGM activities: geochemical and coupled reactive-transport modelling, feasibility of micro-seismic monitoring, contribution to Best Practice Manual. BRGM was leader of Work Package "Geochemistry".

GESTCO (2000-2003) "European potential for the Geological Storage of CO₂ from fossil fuel combustion"

The primary goal of the project was to determine whether the geological storage of carbon dioxide captured at large industrial plants is a viable method of reducing greenhouse gas emissions capable of widespread application in Europe. This was established by a series of case studies that evaluated the CO₂ storage potential of saline aquifers, geothermal reservoirs, coal seams and oil gas reservoirs. The case study approach was used so that currently available, largely theoretical generic information could be applied to real geological situations. This resulted in more rigorous identification of the important issues, which will enable any necessary further research or development to be better focused. In addition, the economic aspects and aspects of safety and environment, conflicts of using underground space and public and stakeholder perception were evaluated. Secondary goals of the GESTCO project were to establish a CO₂ storage GIS for Europe and a Decision Support System (DSS) to serve as an economic analysis tool for CO₂ storage in Europe.

Main BRGM activities: focus on the Paris basin area, investigations on the possible benefits of coupling CO₂ storage with geothermal operations. BRGM is leader of the Theme "CO₂ storage in geothermal reservoirs".

NASCENT (2001-2003) « Natural Analogues for the Storage of CO₂ in the Geological Environment »: European research project (5th FWP) which studied several natural CO₂ accumulations in Europe to predict likely long-term responses of reservoirs to geological storage.

Main BRGM activities: focus on France's carbo-gaseous province, detailed characterization of the Montmiral natural CO₂ field, fluid sampling and analyses (wells, springs), mineralogical analyses, soil gas survey, geochemical and coupled reactive-transport modelling. BRGM was leader of Work Package "Modelling of CO₂/fluid/rock interactions".

WEYBURN (2001-2004) « The Weyburn CO₂ monitoring and storage project »: European research project (5th FWP) carried out in close collaboration with the *IEA Weyburn CO₂ monitoring and storage project*, which are monitoring and forward modelling the underground

⁴⁷ From Jacques Varet of BRGM

CO₂ sequestration operation combined with enhanced oil recovery taking place since 2000 in the Weyburn oil field, Saskatchewan, Canada.

Main BRGM activities: detailed geological characterization of the Weyburn site (baseline geology, hydrogeology and geochemistry), geochemical modelling, hydrodynamic modelling, coupled reactive-transport-flow modelling, soil gas monitoring, micro-seismic monitoring. BRGM was leader of Work Package "Definition of baseline hydrogeological and geochemical conditions" and leader of Task "Predictive computer modelling of the chemical impact of CO₂ injection".

CO2STORE (2003-2006) « On-land and Long Term Saline Aquifer CO₂ Storage »: European research project (5th FWP) that is investigating the long term fate of CO₂ at Sleipner as a follow-up of the SACS project, as well as four new potential sites for CO₂ geological storage in European aquifers, two onshore et two offshore.

Main BRGM activities: long-term reservoir scale modelling at Sleipner (geochemistry & flow), geochemical modelling on the four other sites.

CO2NET (2001-2002) and **CO2NET2** (2003-2005): European Carbon Dioxide Thematic Network (5th FWP) of researchers, developers and users of CO₂ technology, facilitating co-operation between these organisations and the European projects on CO₂ geological storage, CO₂ capture and zero emissions technologies.

Main BRGM activities: Contribution to several WPs: Collaboration of RTD projects, RTD Strategy, Education-Dialogues-Training, Best Practice Assessment. BRGM is member of the Steering Committee and R&D Strategy Committee.

SAMCARDS (2002-2003): "Safety Assessment Technology for Carbon Dioxide Sequestration". Research carried out in the framework of the CO₂ Capture Project (CCP), joint international industrial project that aims to develop technologies for CO₂ capture and geological storage.

Main BRGM activities: reactive-transport modeling, sensitivity calculations. BRGM was subcontractor of TNO.

PICOR (RTPG Subproject A) (2002-2004): « Piégeage de CO₂ dans les réservoirs » (CO₂ storage in reservoirs). French project supported by "Réseau des Technologies Pétrolières et Gazières".

Main BRGM activities: thermodynamics and kinetics of water-rock-gas systems, geochemical modeling, coupled reactive-transport modeling, database on natural CO₂ accumulations. Applications to experimental and field-test cases. BRGM was leader of Work Package "Database on natural CO₂ accumulations " and leader of Task" Application to a carbonated reservoir field test case".

RTPG Subproject B (2004): « Etude de la faisabilité d'un pilote de stockage de CO₂ dans un gisement d'hydrocarbures » (Feasibility study of a pilot test of CO₂ storage into an hydrocarbon reservoir). French project supported by "Réseau des Technologies Pétrolières et Gazières".

Main BRGM activities: Database of reservoir data and useful criteria for site selection, multicriteria analysis for selection of several sites, detailed studies on 3 sites, proposal for one pilot site.

RTPG Subproject C (2004): « La filière du charbon propre en France: un pilote de séquestration du CO₂ pour les centrales thermiques à charbon » (Clean coal in France: feasibility of geological storage of CO₂ emitted by a coal-fired power plant). French project supported by "Réseau des Technologies Pétrolières et Gazières".

Main BRGM activities: Investigation of two case studies: the Gardanne power plant in Southern France and the Carling power plant in Eastern France, with CO₂ storage in nearby aquifers or deep coal seams. BRGM was Leader of this RTPG Subproject C.

PICOREF (2005-2006): "PIégeage du CO₂ dans des Réservoirs géologiques en France" (CO₂ trapping in geological reservoirs in France). The project has the assigned objective of preparing industrial demonstrations of CO₂ injection into the French subsurface (notably into hydrocarbon reservoirs and saline aquifers). It was initiated by the Ministry for Industry in the framework of the Network of Oil and Gas Technologies (RTPG) and by a consortium of French firms and universities. Its objective is to provide descriptive information about CO₂ storage at specific geological sites and to identify pilot demonstration sites in France. In 2005, the project is to examine two types of site in the Paris area: a producing hydrocarbon reservoir and a deep saline aquifer.

Main BRGM activities: Site identification in deep saline aquifers of the Paris Basin, predictive modelling, natural risks analysis, surface deformation monitoring, geochemical and gas monitoring, information dissemination. BRGM is coordinating the aquifer storage theme.

CASTOR (2004-2008): « CO₂, from capture to storage ». European Integrated Project (6th FWP) which seeks to lower the cost of post-combustion CO₂ capture and to validate the CO₂ geological storage concept on four European sites.

Main BRGM activities: Geochemical modelling and long-term flow and chemical simulations on two field cases: the Casablanca oil field in Spain, the K12B gas field in the Netherlands.

CO2GEONET (2004-2009): « European Network of Excellence on Geological Storage of CO₂ » (6th FWP). The focus of CO₂GeoNet is on the geological storage of CO₂ as a greenhouse gas abatement option. The principal aim of the network is to form a durable and complimentary partnership of a critical mass of key European research centers whose expertise and capability becomes increasingly mutually interdependent. This will maintain and build upon the momentum and world lead that Europe has on geological CO₂ storage and project that lead into the international arena. The initial partnership is between 13 European research institutions with worldwide expertise. It is intended to further strengthen European excellence by growing the Network beyond its core, impacting on national research programs, training young researchers, collaborating with major non-EU R&D programs and research centres, while seeking external national and industrial funding.

Main BRGM activities: BRGM is member of the Management Board (Deputy Network manager) and is Leader of Joint Research Activities. BRGM is actively involved in the following five research areas of the network: predictive numerical tools, rock/fluid experiments, monitoring technologies, enhanced risk/uncertainty, geological models.

InCA-CO₂ "International Co-ordination Action on CO₂ Capture and Storage" (2004-2007). This European Specific Support Action project (6th FWP) aims at establishing European know-how in the field of CO₂ capture and storage on the international scene. The project group constitutes a structure for cooperation, dialogue and exchange, on which the European Commission will rely in its international negotiations. A number of orientations are to be developed simultaneously: identify the opportunities for future cooperation between Europe and its international partners (Australia, Canada, the United States and Japan), provide all useful information to the European representatives with seats in international organizations, such as CSFL (Carbon Sequestration Leadership Forum) and derive a coherent point of view on international activity regarding CO₂ capture and storage so as to promote future European policies.

ULCOS (Ultra Low CO₂ Steelmaking project) (2004-2009): This European integrated project (6th FWP) involves all European steelmakers but also research institutes and universities as well as industrial players. The project is intended to come up with a production stream that reduces emissions by between 30 and 70%, starting from iron ore, with verification of its technical feasibility and predictions concerning its economics and social acceptability.

Main BRGM activities: BRGM is Leader of the "Emerging CO₂ Capture and Sequestration Technologies" module. BRGM investigates the potential for mineral carbonation of steel slag and for the geological storage of CO₂ in the vicinity of steel mills.

ICSFFEM (CO₂ emission reduction in phosphate production) (2002-2003): At ICS' request (Industries Chimiques du Sénégal), with funding from FFEM (Fonds Français pour l'Environnement Mondial), BRGM developed an innovative phosphate beneficiation process. Such a process lowers CO₂ emissions by over 80% compared to the standard phosphate calcining process used in phosphate production.

SEQMIN (CO₂ sequestration by mineral carbonation) (2004): This internally funded project demonstrated the viability of mineral carbonation as an alternative for permanent storage of CO₂ through a comprehensive mass and energy balance analysis of indirect and direct carbonation routes.

ProCO₂ (Processes for management of industrial CO₂ emissions) (2005): This internally funded project covers the RTD work undertaken by BRGM on process development for industrial CO₂ emissions. At present, BRGM teams are focusing their efforts on development of a novel CO₂ capture technology from mixed gas streams and investigation of concrete matrices recycling.

BRGM participation in French national committees

MIES (Mission Interministérielle sur l'Effet de Serre, Governmental Committee on Greenhouse Effect). Jacques Varet (BRGM, Directeur de la Prospective) is President of the Scientific Committee.

Club CO₂: The Club gathers together the major concerned players in the industrial sector and in research. A clearinghouse for exchanges, information and initiatives amongst its members in the area of studies and technological developments concerning CO₂ capture, transport and storage, the Club encourages cooperation at a national level between the public and private sectors. The CO₂ Club was formed in 2002 on the initiative of Ademe (Government Agency for the Environment and Energy Resources) and with the support of BRGM and IFP, the latter acting as secretary.

Annex 5: Glossary and Acronym

BOF: Basic Oxygen Furnace

CCS: Carbon Capture & Storage (or Sequestration)

CFBC: circulating fluidized bed combustion :.

COE: Cost-of-Electricity.

CTL: Coal To liquid

DoE: Department of Energy

DME: dimethyl ether

ECBM: Enhanced coal bed methane recovery

EFCC: Externally fired combined cycle

EOR: Enhanced oil recovery

FBC: Fluidized bed combustion :

Gtce: billion metric-ton of coal equivalent (1 Gtce=29.31 exajoules or EJ).

GtC: billion metric ton of carbon.

GtCO₂: billion metric ton of carbon dioxide.

GTL: Gas To liquid

GW: Gigawatt [=1 million kilowatt (kW)=1000 megawatt (MW)]

IEA: International Energy Agency

IIASA: International Institute of Applied Systems Analysis

IGCC: Integrated Gasification Combined Cycle that is designed primarily to generate electricity.

IGPG: Integrated Gasification Poly-Generation first converts coal into synthesis gas (mainly H₂ and CO), which is then used to generate electricity and heat in a combined cycle plus one or more other energy carriers (liquid fuels, hydrogen, etc.) or chemicals through further conversion.

IPCC: Intergovernmental Panel on Climate Change

IPP: Independent Power Producer

MHD: magneto hydrodynamic generator

Mtce: Million tons coal equivalent

Mtoe: Million tons oil equivalent

MWh: Megawatt-hour. 1 MWh is the amount of electricity generated by an 1 MW-unit in 1 hour.

OECD Organization for Economic Co-operation and Development

PC: Pulverized coal

PF: Pulverized fuel combustion technology

PFBC: Pressurized fluidized bed combustion

PPCC: Pressurized pulverized combustion

PPMV: Parts per million by volume

SOFC: solid-oxide fuel cells

SRCCS: Special Report on Carbon dioxide Capture and Storage (from the IPCC)

SRES: Special Report on Emissions Scenarios

ULCOS: "Ultra Low CO₂ Steelmaking".

UNFCCC: United Nations Framework Convention on Climate Change

USC: ultra-supercritical (a coal-combustion-based power generation technology).

WEC: World Energy Council

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