French Republic

PARLIAMENTARY OFFICE FOR SCIENCE AND TECHNOLOGY ASSESSMENT

New energy technologies and CO2 sequestration

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Reducing CO_2 emissions is an enormous technical and economic challenge. Fossil fuels indeed play a predominant role in supplying the world with energy, with 88% of the primary energy consumed. The volumes of CO_2 emitted are huge, approximately 25 billion tonnes per year. Emission sources are innumerable and often of low unit volume.

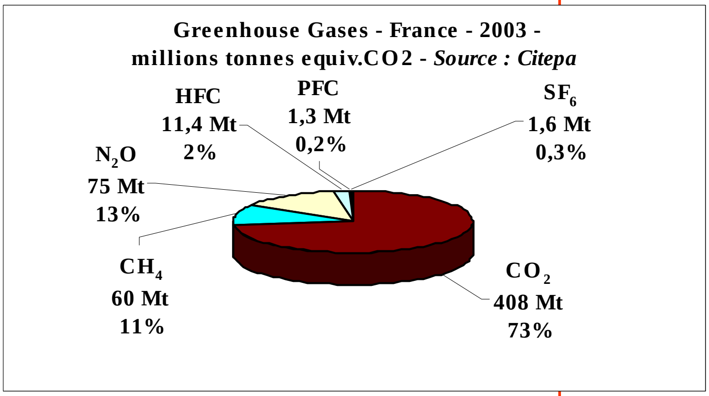
Control over CO_2 emissions will not result from a single technology but from a set of means being rolled out simultaneously: not only the development of carbon-free energies, but also control over emissions from fossil energies of which the reserves are too high for them to be forsaken.

Present research and development has led to a proliferation of technologies which have become interwoven. Many opportunities therefore exist for progress which – provided geological resources and the laws of physics are not ignored - are compatible with economic growth in that they have an acceptable cost.

Summary Analysis

• *Various greenhouse gases*

CO_2 emissions mainly result from the burning of fossil energies – coal, oil, natural gas – in the transport, residential, service industries (building trade) and industrial sectors.



In terms of emission volumes, CO_2 is the major greenhouse gas (GHG), with nearly 80% of world emissions and 70 to 75% of the emissions of industrialised countries. CO_2, carbon dioxide or carbonic gas, has seen its atmospheric concentration increase by 30% between 1745 and 1998.

Other gases absorbing infrared radiation emitted by Earth are released by human activities, especially in industrialised countries: methane, nitrous oxide or fluoride compounds.

Methane is emitted by agricultural (stock-farming, crops) or industrial (energy industries) activities and also by landfills of household garbage or industrial waste. In France, an industrialised country with a strong agriculture, methane (CH_4) represents more than 10% of total emissions. The volumes of CH_4 emitted are low but its global warming power is 21 times greater than that of CO_2. The atmospheric methane concentration has increased 2.5 times since the beginning of the industrial revolution.

Nitrous oxide (N_2O), whose global warming power is 310 times greater than that of CO_2, results from the use of nitrogenous fertilisers, transport energy consumption and some industrial processes. N_2O accounts for 13% of global emissions. Lastly, fluoride compounds correspond to emissions with a low volume but whose impact is very high owing to their far greater noxiousness than that of CO_2.

• *Enormous volumes of carbon dioxide emissions and variable performances of various countries*

Energy-induced CO_2 emissions stood at 25 billion (bn) tonnes in 2003. The United States, responsible for 27% of world emissions, is the foremost emitter, with 6.6bn tCO_2, i.e. 72% more than the European Union of 25. Russia, after a 24% fall in its emissions between 1990 and 2003 owing to declining economic growth, could encounter difficulties in stabilising its emissions at the 1990 level, the commitment it gave by ratifying the Kyoto Protocol in 2004.

Already, China is emitting practically as much CO_2 as the European Union of 25, with 15% of world emissions. India emits three times less CO_2 than China. Within the European Union, France's remarkable performance must be emphasised. In 2003, it emitted 2.2 times fewer tonnes of CO_2 than Germany and 1.4 times less than the United Kingdom. As a ratio of GDP, France's emis-

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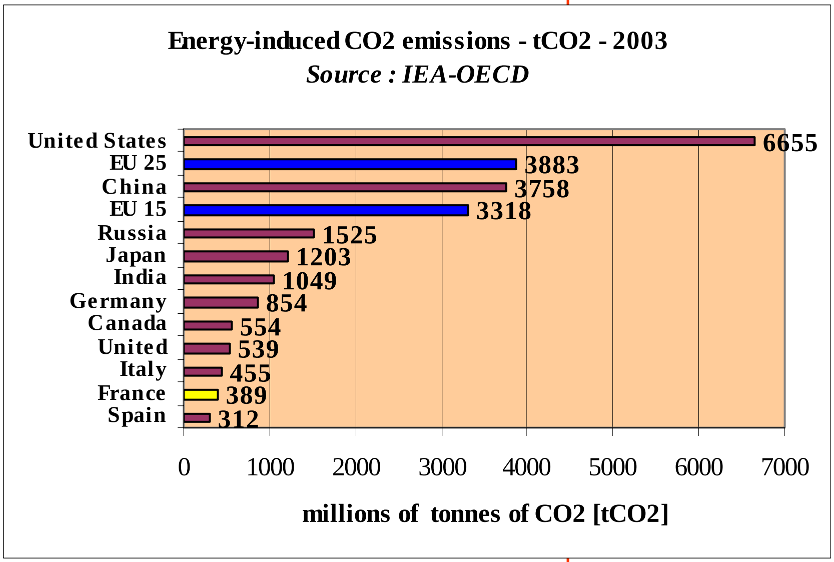
sions are half those of Germany.

Does implementation of the Kyoto Protocol within the ‘European bubble’ take this disparity sufficiently into account ? Germany’s goal is indeed to reduce its GHG emissions by only 21% with respect to its 1990 levels. After this change, German emissions will remain very much higher than those in France, even if France has merely committed to stabilising its emissions at the 1990 level.


Energy-induced CO2 emissions - tCO2 - 2003
Source : IEA-OECD

• *Two major action sectors: production of electricity and heat, and transport*

Electricity production and the entire energy branch – heat production, refineries – accounted for 40% of world CO_2 emissions in 2004. Transport causes a quarter of world emissions, with a high growth rate, owing to the rapid increase in the number of cars on the roads.

Industry causes a fifth of world CO_2 emissions and the residential and service industries sector from 15 to 20% depending on the estimations.

Thanks to its electronuclear industry, France has a highly singular performance as regards its sectoral emissions. The energy branch represents in total only 14% of total emissions. Consequently, transport emissions stand at 38% of the total, and the residential and service industries sector at 27%.

Actually the performance of the French transport sector is not worse than in other countries. The environmental excellence of French electricity production merely has the paradoxical consequence of turning the spotlight on this sector, more than elsewhere.

• *Reducing CO_2 emissions and energy security*

In the world distribution of fossil fuels, after the Middle East which possesses 60% of oil reserves and 40% of natural gas reserves, Europe and the countries of the former USSR have greater reserves than the other continents, if coal, oil and gas are taken into account.

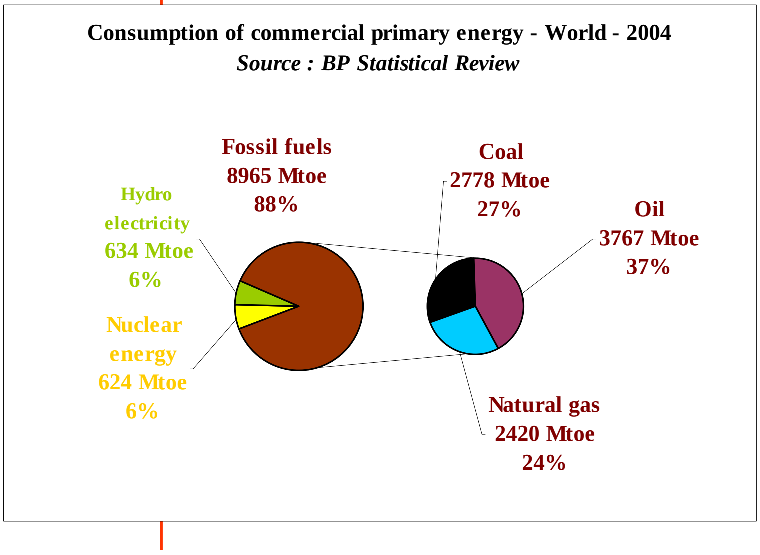
Understandably, the temptation may therefore be high to hook Europe to Russia to ensure its supplies of oil and above all of natural gas. This is a major political choice already made by the European Commission. The recent natural gas crisis between the Ukraine and Russia shows the dangers of such a policy.

The reduction of CO_2 emissions contributes to France’s commitment to stabilise its GHG emissions at the 1990 level and also has many secondary benefits. First, it makes it mandatory to reduce unit consumptions and increase energy efficiency, which can contribute to a fall in production costs. Second, it promotes the development of carbon-free energies and therefore a possible reduction in external energy dependency.

I.- REDUCING FOSSIL ENERGY-INDUCED CO2 EMISSIONS

88% of the primary energy consumed in the world comes from fossil fuels. 80% of world fossil fuel reserves are made up of coal. Food for thought!

‘Consuming less fossil energies by better consumption’ is therefore a priority.


Consumption of commercial primary energy - World - 2004
Source : BP Statistical Review

Various means can contribute to this goal. The replacement of obsolete coal thermal power plants by high energy performance facilities greatly decreases CO_2 emissions with a constant production level. Increasing the role of natural gas to replace coal leads to the same result. CO_2 sequestration, in other words its capture and geological storage, reduces the emissions of concentrated and massive industrial sources. Reducing transport emissions is also essential.

• *High performance clean coal technologies*

The replacement of a thermal power plant with a performance lower than 30% by a new generation power plant with a performance higher than 40% reduces CO_2 emissions by 25%, with a constant electricity production level.

After reducing the emissions of dust, SO2 and nitrogen oxides, the new challenge of electricity production from coal is to generalise supercritical or ultrasupercritical steam power plants. Operating at pressures of 200 to 300 bars and at temperatures above 500°C, these have performances reaching 50%.

IGCC (Integrated Gasification Combined Cycle) thermal power plants represent another possibility. The performances reached are lower than those of ultrasupercritical power plants but various types of fuels can be used.

The ultimate goal is to develop the future thermal power plant, emitting neither pollutants nor carbon dioxide. This inevitably requires sequestering the CO_2 produced at the same time as electricity.

In any case, thermal power plant CO_2 emissions can be greatly decreased, by a factor of 6 to 8, but will probably not be reduced to zero, owing to the energy cost of the processes and their decreasing performances.

• *Combined gas cycles*

Among the industrial applications of natural gas, the production of electricity is expanding rapidly and should continue to do so over the years ahead.

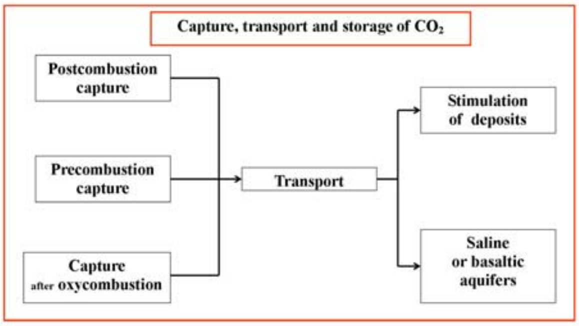
Carbon dioxide emissions per kWh produced can be halved by replacing coal thermal power plants by combined gas cycles. An 800 MW combined gas cycle emits only 365 grams of CO_2 per kWh produced, as against 777 g CO_2/kWh for a pulverised coal thermal power plant.

The production of electricity using natural gas combined cycles however presents disadvantages. First, a 900 MW combined cycle producing in base load emits 2.6 million tonnes of CO_2 per year. Second, as the cost of fuel represents 63% of the total cost before tax, the cost of the MWh is highly sensitive to changes in the price of natural gas. This price, it should be noted, appears to be rising on a long-lasting basis. It rose from 6 \$/MBtu in February 2005 to 15 \$/MBtu in August 2005 and stood at 9 \$/MBtu in January 2006.

• *Carbon capture and storage (CCS)*

CCS, also called CO_2 sequestration, comprises two main operations: first the capture of carbon dioxide in the gaseous state and, second, its storage so as to avoid any emission into the atmosphere. Transport, a third operation, may be necessary whenever storage takes place at a different site than capture.

The capture of CO_2 resulting from the use of fossil fuels is performed, in practice, using three major types of technology.



Postcombustion capture corresponds to the collection of CO_2 from the smoke resulting from combustion.

Precombustion capture corresponds to the decarbonisation of the fuel prior to combustion. Carbon dioxide is then collected upstream of combustion which burns only hydrogen and which emits only water vapour.

Capture by ***oxycombustion*** corresponds to the replacement of the usual combustive-fuel – oxygen in air – by pure oxygen, whereby a very concentrated or pure carbon dioxide flow is obtained downstream.

None of the capture technical solutions will reduce to zero the emissions from the same source, owing to the decreasing performances of the processes and the resultant high incompressible costs.

As for the transport of CO_2, the most plausible solutions are transport by gas pipeline, already used, or by boat.

Turning to CO_2 storage, the mineralisation method is eliminated because of its cost and ocean storage on account of its environmental consequences. The two preferred solutions are storage in hydrocarbon deposits which can be stimulated by the injection of CO_2 and storage in deep saline or basaltic aquifers.

Many capture and storage experiments are currently taking place. The cost of sequestration is still very high, according to Gaz de France, the operator with experience of the entire chain. Capture is the most costly operation, amounting to between 40 and 60 €/tCO_2. The cost of transport ranges from 2 to 20 €/tCO_2. As for the cost of storage, it ranges from 0.5 to 10 €/tCO_2.

All in all, in the present state of techniques, sequestration costs between 43 and 90 €/tCO_2.

The capture and storage of CO_2 emissions apply only to static sources of massive emissions, and they use processes that are not totally efficient. Furthermore, they are limited to emitting facilities located sufficiently close to favourable geological formations.

According to estimations made by the hydrocarbons industry, a reduction of nearly 20% of the CO_2 emissions of the United States, the European Union and China could be obtained using sequestration, which represents approximately 10% of world emissions.

CO_2 sequestration therefore represents an interesting but partial solution. Moreover its roll-out is subject to a considerable fall in its costs.

• *Reducing consumptions in transport*

Several reasons explain the predominance of oil fuels in transportation. The first is, no doubt, the low relative price, for a very period, of petrol and gasoil with respect to all other sources of fuels. The second is the inertia of energy systems – production, distribution, engines –, whose roll-out requires heavy investments.

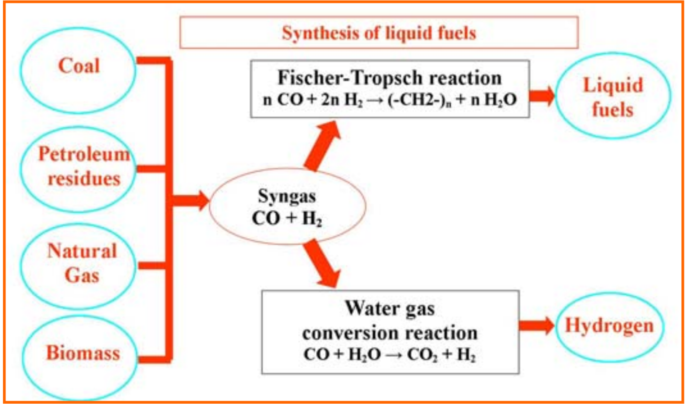
Another reason is of a technical nature, namely the decisive advantage of liquid fuels, owing to their high energy content, ease of storage and distribution, and rapidity of tanking up at the pump.

In comparison, LPG (liquefied petroleum gas) must be placed under a pressure of 5 bars. NGV (natural gas vehicle) must be compressed to 200 bars in a car tank, and it takes a night to fill it with an individual compressor. Turning to hydrogen, 4.6 litres of the gas compressed to 700 bars are needed to obtain the equivalent energy of a litre of petrol. For its part, electricity is stored in long to recharge batteries and which presently permit a maximum driving range of only 100 to 200 km for private motor vehicles.

Another important factor for the continued use of car fuels, liquid fuels can be produced from the enormous reserves of coal and natural gas.

If liquid fuels continue to prove irreplaceable for car and air transport, the well known synthesis gas and Fischer-Tropsch processes could develop, by allowing their production to be diversified from coal and natural gas. The CO2 produced owing to the energy consumed during the conversion of coal and natural gas would then have to be sequestered.

Producing synthetic fuels from coal received priority attention in Nazi Germany's war effort. At the maximum of its production capacity, at the beginning of 1944, Germany was producing 124,000 barrels a day of synthetic fuels from coal, in 25 plants, based equally on the two processes - Bergius or Fischer-Tropsch. The Bergius hydrogenation process supplied high quality petroleum for aircraft engines. Fischer-Tropsch synthesis supplied high quality gasoil, lubricants and petroleum of lesser quality.



• *Synthesis of liquid fuels other than petroleum fuels*

Liquid fuels are today synthesised from coal in South Africa. 200,000 barrels a day of coal-to-liquid (CTL) fuels are produced, representing nearly 40% of the national consumption.

Using a related process, Qatar has begun to exploit its enormous natural gas reserves (15% of world reserves) by producing gas-to-liquid (GTL) fuels.

Reducing the liquid fuel consumption of internal combustion engines therefore appears vitally important. The number of cars on the roads worldwide is estimated at nearly 700 million in 2004 and is expected to increase by 84% by 2030, according to the International Energy Agency.

Private vehicle consumption in France is decreasing on average by a litre per hundred kilometres every four years.

Thanks to technical progress, the downsizing of engine cubic capacity without sacrificing performance presents the double advantage of reducing consumption while increasing power and especially acceleration, with the generalisation of turbo engines. The dieselisation of cars is also reducing average consumption.

French carmakers are at the forefront in Europe, as seen by the indirect measurement of consumption by the average CO_2


Sasol plant-South Africa

emissions of the cars sold by Renault and PSA: 148 g/km, as against 160 g/km for the European average. Small vehicles with emissions lower than 120 g/km form the most buoyant market segment in France.

Apart from technical progress as regards engines, other developments would improve the energy efficiency of car transport such as relieving traffic congestion, which is a considerable source of energy inefficiency. In addition, the generalisation of good driving practices, especially compliance with speed limits, would be an important source of energy savings.

The development of carbon-free energies forms the second strand of action helping to reduce CO_2 emissions and external dependence.

II.- DEVELOPMENT OF CARBON-FREE ENERGIES

Research and investment on carbon-free energies must focus on two sectors – electricity production and transport – given their share in CO_2 emissions.

Rising electricity consumption goes hand in hand with economic development.

There are two possible and complementary emission reduction strategies. The first is a change in the electricity production model, with a multiplication of decentralised electricity production means. This is a costly strategy investment-wise and limited in production volume terms since the aim is mass electricity production with techniques geared to decentralised production.

Without changing the electricity production model, nuclear energy, on the other hand, is perfectly adapted to mass production, competitive and based on considerable uranium reserves.

As for transport, there are two promising paths: first- and above all second-generation biofuels and then, in a more distant future, fuel cells.

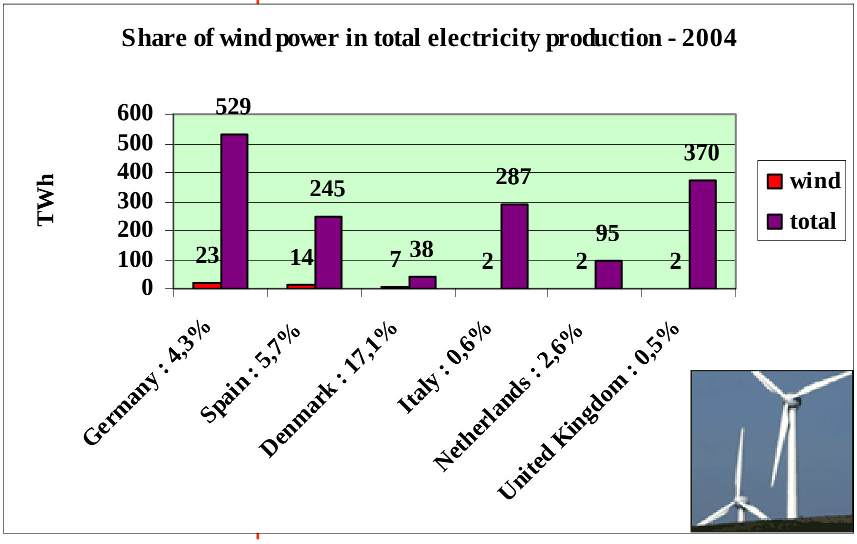
• *Wind power: low national but considerable local contribution*

The operation of wind turbines depends on the weather and not on the demand for electricity. Below a given wind speed, generally 5 m/s, i.e. 18 km/h, a wind turbine cannot supply power, is disconnected from the grid and turns for nothing, or else is purely and simply stopped. Also, with winds over 25 m/s, i.e. 90 km/h, wind turbines must be stopped because they cannot withstand the corresponding mechanical efforts. The average wind speed, another important variable conditioning effective electricity production, can, by varying by a factor of 1,7, triple the quantity of energy supplied, hence the interest of locating these machines in areas with regular and moderate wind regimes.

Consequently, the electricity supply for users, whether private individuals or manufacturers, cannot rely exclusively on wind turbines. These must necessarily be combined with complementary production means.

In short, wind power does not appear capable of ensuring a large share of national electricity production. This can be seen in Germany, where the 16,600 MW of installed wind power capacity supplied only 4% of the total production of electricity. At the other end of the spectrum there is indeed Denmark with 17.1% of the national production of electricity but the amount produced does not exceed 7 TWh. On the other hand, wind power can form one of the production elements of a locally important grid.

Last, offshore wind power does not appear to represent a qualitative leap for wind power. Construction costs entailed by offshore wind power are indeed twice those of land wind power.



Share of wind power in total electricity production - 2004

• *Photovoltaic solar power: exclusively geared to decentralised production*

Photovoltaic solar provides increasingly efficient and competitive solutions for decentralised electrification. Yet the large-scale operations carried out in various countries to equip housing must not lead to believe that photovoltaic solar is adapted to mass electricity production.

The cost of photovoltaic electricity is approximately 500 €/MWh for a facility connected to the grid and approximately 1000 €/MWh for an isolated facility.

While interesting for isolated sites, photovoltaic solar could not in any case ensure mass electricity production, for technical and economic reasons.

Production by a photovoltaic solar panel is intermittent. In any case, the electricity produced from a programme like the German 100,000 roofs programme is negligible in comparison with conventional production means.

100,000 roofs with a power of 3 kWc each provide the annual equivalent of 0.4 TWh, i.e. 150 times less than French hydroelectric production, with an annual additional cost of 200 million €.

Industrialised countries are in fact seeking to develop photovoltaic solar to stimulate their national industry, with the prospect of the development of decentralised electrification markets in developing countries.

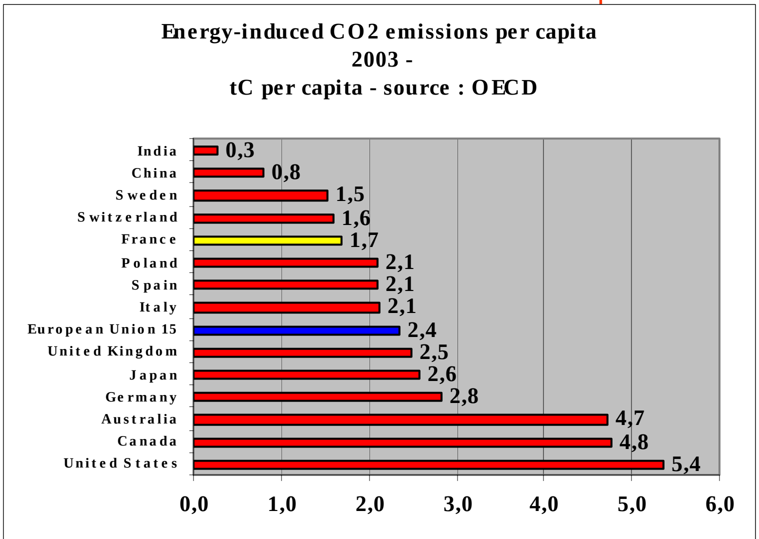
• Nuclear power: reducing CO_2 emissions and producing competitive electricity

6,5%: that was, in 2003, the share of civil nuclear energy in world primary energy production, in other words a total close to that of world hydroelectric energy.

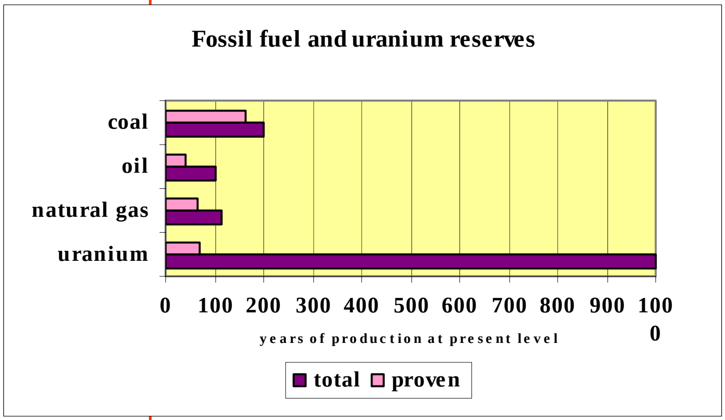
If we focus on electricity, nuclear power provided, in 2003, 16% of world production, hydropower 16%, coal 40%, and oil and gas 26 %.

Countries that have set up a major electronuclear industry are those with the best performances in terms of limiting their GHG emissions, with comparable development levels.

Among the reactors currently operating, 81% are second generation light water reactors using enriched uranium. Their fuel supply does not pose any difficulty, and the same applies to Generation III reactors, such as EPRs (European Pressurized water Reactors), which could replace them from the 2020s on. The proven reserves indeed represent 70 years of consumption at the present level and the probable additional reserves, an additional 100 years; therefore the world electronuclear industry could grow with the same type of reactors.



Uranium supplies will in fact last far longer. Uranium reserves will last several thousand years with fourth generation reactors, which are expected to take over from light water reactors around 2040. These reactors will use a far greater proportion of the energy potential of uranium than light water reactors.



As regards production costs, nuclear power is more competitive than the other sectors, and over a long period of time.

According to the General directorate for energy and raw materials (DGEMP), compared with the 28.4 € cost of the nuclear MWh, the combined gas cycle is more expensive by 20% and pulverised coal by 23%.

Also, the rise in the price of uranium has only a very low impact on the price of the nuclear MWh, uranium accounting for only 5% of the cost of the MWh.


Tricastin Nuclear Power Plant - EDF

Consequently, if the price of uranium increased ten-fold, the production cost of nuclear electricity would increase by only 40%. On the other hand, if the price of gas increased ten-fold, the cost of the gas MWh would increase six-fold.

If the cost of emitted CO_2 is factored in, nuclear power has an even more decisive advantage. Compared with the 28.4 €/MWh of nuclear power, the gas MWh indeed works out at 42.1 € (+48%) and that of coal at 48.3 € (+70%).

Last, all the present and future costs of nuclear power are covered by the price of electricity, and especially radioactive wastes management costs and power plant dismantling costs.

On the basis of a 30 €/MWh production cost, the reserves constituted for reprocessing and disposal of wastes represent 4 €/MWh, i.e. 14.2% of the total and the dismantling reserves represent

2 €/MWh (5.3%).

The Act of 30 December 1991 on research on radioactive waste management has led to the roll-out of solutions for very-low or low short-lived wastes representing 90% of waste volumes, and has allowed methods to be specified for intermediate and high-level long-lived wastes which can be implemented over the next 15 years.

• Second generation biofuels and fuel cells

First generation biofuels are produced from wheat, soja or sunflower seeds or the root of beets, which form the energy reserves of these plants. The next frontier for biofuels will consist in their production from the whole plant. Considerably higher volumes are expected, without competing with food crops. Lignocellulose, a combination of lignin and cellulose which strengthens plant cells, can be envisaged to supply the necessary carbon for the Fischer-Tropsch synthesis gas process - instead of coal and natural gas.

The first stage of the transformation of biomass is represented by synthesis gas. To obtain liquid fuels, the Fischer-Tropsch reaction then merely has to be implemented. Second generation biofuels would therefore present the advantage of exploiting abundant resources and having an almost perfect CO_2 emission footprint if their processes are also fuelled by biomass. In addition, biomass can be a source of hydrogen for fuel cells.

Since 2001, research efforts appear to be leading to the emergence of three main fuel cell technologies: SOFC cells (Solid Oxide Fuel Cells) for the co-generation of heat and electricity, DMFC cells (Direct Methanol Fuel Cells) for mobile applications, and PEMFC cells (Proton Exchange Membrane Fuel Cells) for transport.

According to the IEA, the cost of a fuel cell in relation to its power is between 6000 to 8000 €/kW. However the kW cost of a bus diesel engine is approximately 150 €/kW. For this type of application, a decrease in cost of a factor of 50 is necessary. For individual cars, the challenge appears even more difficult. As the cost of the unit of power of the internal combustion engine is from 30 to 50 €/kW, the cost of the fuel cell would therefore have to be divided by at least a factor of 200 to make it competitive with a conventional engine.

According to the French Petroleum Institute (IFP), the marketing of fuel cells does not appear possible before 2020. Renault envisages them for 2015-2020.

CONCLUSION: ESSENTIAL SHORT-TERM PRIORITIES

• Colossal investments to refurbish and increase capacities

Industrialised countries invested massively in energy between 1960 and 1980 to meet the rising consumption of electricity and car fuels.

Given the 20-to-50-year lifespan of energy facilities, many thermal power plants, nuclear power plants, and oil refineries, will have to be refurbished in the very near future.

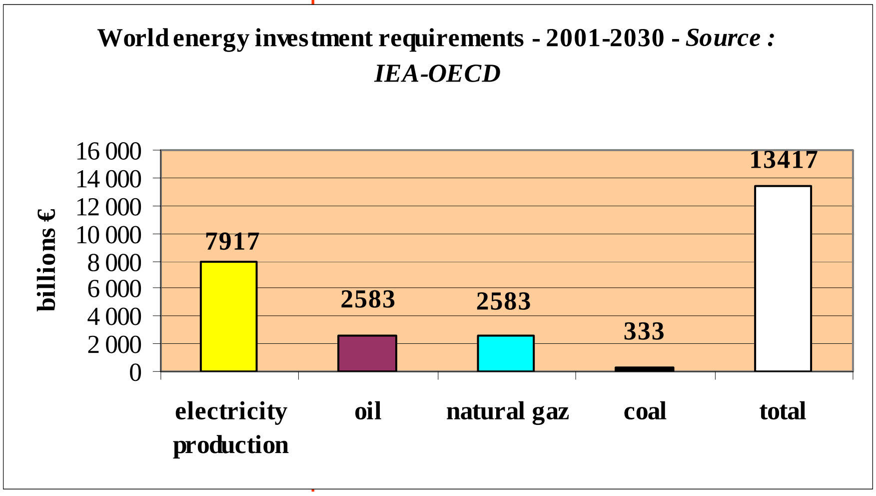
In addition to these refurbishment investments, capacity investments will have to be made in industrialised countries but above all in emerging and developing countries: new electric power plants; oil and natural gas exploration and production; natural gas liquefaction plants; and gas pipelines.

The International Energy Agency estimates at 13,500bn€ the investments to be made world-wide.

The highest investments will be required by the production and distribution of electricity: 60% of the total energy investments. Investments in transport and distribution will be even higher than in production.

• Emission reduction mechanisms must be visible and moderate

The European Union has committed to reducing its GHG emissions by 8% by 2008-2012, with respect to its 1990 level. According to the European Commission, the cost of this reduction should amount to 6.8bn€ per year,



World energy investment requirements - 2001-2030 - *Source : IEA-OECD*

i.e. 0.2% of Community GDP each year. The roll-out of a quota trading system is deemed to half the reduction cost.

In any case, the slackness of European economic growth with respect to its main competitors requires the greatest prudence in the costs which the European Union imposes on itself unilaterally.

During the 2005-2007 period, 11428 European industrial facilities, including 1172 in France, must comply with emission quotas. They would be obliged to buy them on the market should their energy efficiency decrease and their production increase. The quotas market is already active and, it should be noted, the price of emission quotas appears to be positioned on a lasting basis at above 20 €/CO_2.

According to EDF, the capture of CO_2 emitted by a coal thermal power plant would double, with present technologies, the cost of the MWh produced. Transport and storage costs would also have to be factored in. The price of the gas MWh would be increased by 50%.

Thanks to its electronuclear industry, France is not directly concerned. However, the European Union's very economic growth, already slower than in other economic zones, would be threatened.

According to the Commission, the present measures are experimental and can be revised in 2007. This determination to experiment is praiseworthy in itself but creates long term insecurity forming a brake on investment which requires long term visibility, especially in the energy sector. Also, it would have been reasonable to cap the price of the tonne of CO_2, as has been done by the United States with the Clean Air Act and SO_2 emission quotas.

Quite possibly, after the delocalisation of labour-intensive industries, Europe will see the delocalisation of its energy-devouring industries.

• *Main energy dates*

From a technological viewpoint, 2020 will be a watershed for energy. Electric power plant refurbishment investments will have to be rolled out then in most industrialised countries.

Also, many technological breakthroughs will lead to operational achievements then.

In the run-up to 2020 and beyond, energy efficiency must be prioritised: first by reducing the energy consumptions of each of the economic sectors, and, second, by selecting energy systems whose cost benefit ratio is the most advantageous, in terms of CO_2 emissions, investments, and cost price.

Given the scale of the challenges to be met, priorities absolutely must be set. In the run-up to 2020, R&D must be specially active in the energy field so that clear priorities are set as early as possible and significant resources are provided for this purpose.

March 2006