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Talking about energy differently

ALL ABOUT NUCLEAR FUEL p.04

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EDITORIAL

BY NOBUO TANAKA,
Executive Director, International Energy Agency (IEA)

WE NEED AN ENERGY REVOLUTION

In the new edition of *Energy Technology Perspectives, 2008*, the IEA focuses on ways to cut CO_2 emissions in half by 2050. Improving energy efficiency is the first step and results in immediate cost savings. The second step is to reduce emissions from power generation. In fact, this is a sector that would need to be completely "decarbonized". Given the growing demand for electricity, this would mean that 38 coal-fired plants and 20 gas-fired plants would have to be equipped with a carbon capture and storage system (CSS) each year from 2010 to 2050. Beyond that, we would have to build 26 nuclear power plants per year as well as 17,000 wind turbines. And in addition to all this, we would need to reduce the carbon intensity of the transportation sector eightfold. This last objective is most certainly the costliest and most complex, due to very strong growth and limited potential for improvement, based mostly on existing technologies.
The investment required to bring about such change is gigantic. Based on current energy use, our preliminary assessment puts it at 50 billion dollars. The costs for "decarbonization", which would be 50 dollars per metric ton of CO_2 in the energy sector, would rise to 200 or even 500 dollars per ton to achieve real improvement in the transportation sector. On top of that, it would require aggressive political action and technological breakthroughs on an unprecedented scale. This would trigger a new energy revolution that would radically transform the way we produce and use energy. ■

Cover
Nuclear fuel pellets, Romans (France)

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Energy is our future, don't waste it!

AT A GLANCE

60%
This is how much Italy depends on natural gas for its electric power generation.
In May, Italian Minister of Economic Development Claudio Scajola announced that his country will build new-generation nuclear power plants to increase its energy independence and "produce energy on a large scale safely, economically and in an environmentally-friendly manner." Back in 1987, the country had renounced nuclear power in a referendum.

2012
By this date, the energy efficiency of real estate offered for sale in classified advertisements must be disclosed in France. Buildings are the biggest consumers of energy in France. They represent 42.5% of total energy consumption and generate 23% of the country's CO_2 emissions.

2.3 MW
This is the generating capacity of the first floating wind turbine, to be built next year off the coast of Norway by the Norwegian oil company StatoilHydro. Offshore wind turbines already exist in many places around the globe, but they are all anchored to the ocean floor. Floating wind turbines can be moved easily to deeper waters, where the wind is often stronger.

ALL ABOUT NUCLEAR FUEL

Yellow cake: the first product from uranium ore processing
After crushing and grinding, uranium ore undergoes a series of chemical processes to increase the uranium content to 80%. The resulting product is called "yellow cake".

The demand for energy continues to rise while natural resources are depleted day after day and the planet chokes on greenhouse gas emissions. It's not easy to strike a balance, yet these issues must be resolved. The nuclear revival in a number of countries may be the beginning of a solution. This is a good time to take a closer look at this industry and learn about the different "lives" of nuclear fuel.

World demand for energy is set to increase under the combined pressures of population growth, economic development and more widespread access to energy. Nuclear power is one of the solutions that can help meet our needs without greenhouse gas emissions. More often than not, nuclear energy is discussed only in terms of nuclear reactors or waste, but these are just two links in a long chain. Nuclear power is organized around the two main phases of the fuel cycle, the front end and the back end, which occur before and after power is generated in the reactor.

1. Uranium mining and conversion

Uranium can be extracted from open pit or underground mines. In most instances, the rock contains very little ore. The concentration of natural uranium in the ore is in the range of 0.2% to 2%. It can be as high as 14% in a few exceptionally high-grade mines in Canada. A number of concentration operations are performed to convert the natural uranium into uranium oxide (U_3O_8). The ore is crushed and dissolved in sulfuric acid, producing a yellow powder called yellow cake or uranium concentrate, which is about 80% uranium.

Yellow cake still contains a variety of impurities and cannot be used in that form. It is therefore purified during processing to convert the uranium into uranium hexafluoride (UF_6).

New deposits to be mined

According to the Nuclear Energy Agency (NEA), annual world demand for uranium came to 67,320 metric tons as of January 1, 2005. World supply, at a little less than two thirds of consumption, is inadequate. New deposits will have to be brought into production to replace depleted inventories and meet growing demand.

Resources are classified based on the likelihood of recovery. Already identified resources are classified as "reasonably assured" or "inferred". These are deposits that have been discovered, characterized and properly evaluated. They were estimated at around 15 million metric tons as of January 1, 2005, or more than 200 years of supply at the current rate of consumption. In addition, the OECD and the IAEA distinguish conventional resources that have not yet been discovered ("prognosticated" and/or "speculative" resources), estimated at 10 million tons.

The level of reserves depends on the price one is willing to pay to recover them. More deposits can be economically mined now that the price of uranium has risen significantly, going from 19 dollars per kilogram at the end of 2001 to almost 300 dollars per kilogram at the end of 2007, a fifteen-fold increase.

Evenly distributed reserves

Unlike oil and gas, which are unevenly distributed, with 70% of all oil reserves and 40% of all natural gas reserves located in the Middle East, uranium reserves ▸▸

Three countries control 60% of the world's uranium production

MAIN URANIUM PRODUCING COUNTRIES (production in metric tons)

Ranking	Country	Production	%
1	Canada	9,481	23%
2	Australia	8,611	21%
3	Kazakhstan	6,637	16%
4	Russia	3,413	8%
5	Niger	3,155	8%
6	Namibia	2,881	7%
7	Uzbekistan	2,300	5%
8	United States	1,800	4%
9	China	950	2%
10	Ukraine	900	2%
Total Top 10		40,128	95%
Other		1,572	4%
Word production		41,700	100%

Source: AREVA 2007.

91 new reactors planned or under construction

As of the end of 2006, 438 reactors were connected to the grid in 31 countries, representing 371 GW in installed capacity. Another 29 reactors were under construction as of that same date, and 62 reactors had been ordered or were planned. The world market is dominated by light water reactors (LWR). There are two major types of light water reactors: boiling water reactors (BWR) and pressurized water reactors (PWR). The water in the primary cooling system, which comes into contact with the fuel cladding, is kept under pressure to prevent boiling. The recovered heat is transferred to a secondary cooling system, which produces steam. The steam powers a turbine, which drives the turbo-generator that generates electricity. The water from the secondary cooling system is condensed, cooled and recycled.

⏭ are relatively evenly distributed throughout the world, significantly reducing the geopolitical risk for operators of nuclear power plants. The industrialized countries of the OECD, the main users of nuclear power, possess about 40% of the world's uranium reserves. The bulk of the reserves are located in Australia (23% of total world reserves), Kazakhstan (18.5%), Canada (9.5%), South Africa (8.6%), the United States (7.5%), Russia (5.8%), Namibia (5.6%) and Niger (5%).

2. Uranium enrichment and fuel fabrication

Natural uranium is a mixture of two isotopes, or atoms: U_{238} and U_{235}, in the proportion of 99.3% and 0.7% respectively. Only uranium 235 is easily susceptible to the fission reaction that generates energy in the core of a nuclear reactor. Light water reactors, representing 85% of all reactors worldwide, require uranium enriched in U_{235} to operate. Enrichment is the process used to raise the proportion of U_{235} from 3 to 5%.

Continually evolving technologies

Two enrichment technologies are used today: gaseous diffusion and ultracentrifugation (*see "word for word", page 9*). France has used the gaseous diffusion process since 1978. This process consumes large amounts of electricity and is being replaced by ultracentrifugation technology, which consumes 50 times less. Production is slated to begin in the first half of 2009 at AREVA's Georges Besse II enrichment plant. Enriched uranium is produced in gaseous form (UF_6). It is then converted into a solid material (UO_2) and shaped into pellets, which are inserted into long metal tubes or "fuel rods". The fuel rods are bundled together and held in place with spacer grids to form a fuel assembly. The assemblies are arranged side by side inside the reactor vessel according to a predetermined, usually cylindrical configuration. Together, these assemblies form the reactor core.

3. Recycling

The fuel assemblies release energy in the reactor through the fission of atomic nuclei. The proportion of fissile atoms decreases over time, whereas the quantity of fission products increases. The fuel becomes less and less reactive until it finally stops producing energy. The used fuel must then be replaced with fresh fuel.

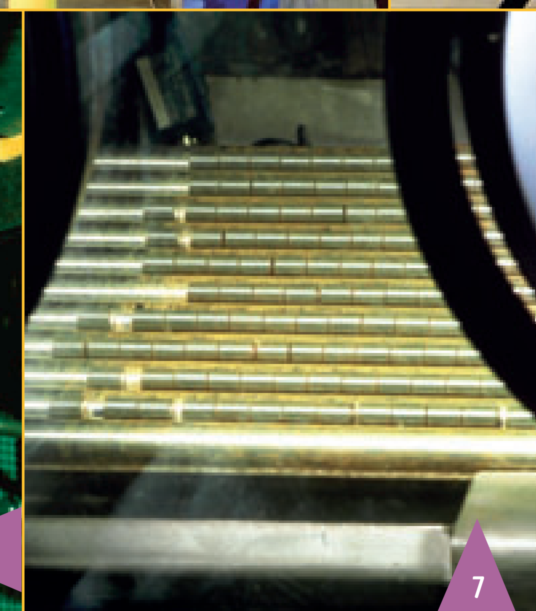
Used fuel treatment consists in separating recyclable uranium and plutonium from final waste, which is packaged for disposal. For every 100 kilograms of used fuel, 95 kilograms of uranium and 1 kilogram of plutonium are recovered through treatment. The rest consists of fission products and minor actinides, both of which are final waste and will be vitrified. Some of the uranium recovered from used fuel treatment is recycled into fresh fuel; the rest is stored. Plutonium is used to fabricate another type of fuel called MOX, a mixture of uranium and plutonium oxides (*see "Zoom", page 7*). For countries that use this approach, treatment and recycling increase energy independence by using the energy potential of the recycled uranium and plutonium and conserving fresh uranium resources. These stages of the fuel cycle also reduce the volume and radioactivity of the used fuel. With demand rising faster than supply, the pressures on the uranium market are growing. Although uranium prices have dropped in recent months, this was preceded by four years of continuous price increases. The price outlook is still on an upward trend. In light of this situation, a number of major countries have begun to commit to fuel treatment and recycling, or are at least considering it. ⏭

The unique cost structure of nuclear power

Fossil fuel plants are very susceptible to changes in the cost of fuel. Conversely, changes in uranium prices have little impact on the cost of nuclear generated electricity. In fact, the price of fuel has little effect on the economic model for nuclear power. According to the Lappeenranta University of Technology in Finland, fuel represents about 7% of the cost of nuclear power, versus 70% for natural gas and 55% for coal. Even at 40 dollars per pound of uranium, fuel costs would remain well below 10% of the total kilowatt-hour cost. Capital expenditures, including dismantling expenses, represent approximately 60% of the kilowatt-hour cost for nuclear power generation in light water reactors. Operating and maintenance expenses average about 20% of the total and fuel cycle expenses account for the remaining 20%. Of the latter, 90% of the expenses relate to the front end of the fuel cycle and 10% to the back end.

Nuclear fuel's eight lives

- **1. Uranium mining**
  Somair open pit mine (Niger)
- **2. Uranium conversion**
  UF_4 to UF_6 conversion plant, Tricastin (France)
- **3. Uranium enrichment by gaseous diffusion**
  Georges Besse plant, Tricastin (France)
- **4. Fuel fabrication**
  Visual inspection of a fuel assembly, Romans (France)
- **5. Reactor loading**
  Civeaux nuclear power plant (France)
- **6. Used fuel treatment**
  Used fuel storage pool, La Hague plant (France)
- **7. MOX fuel fabrication**
  Sorting pellets at the Melox plant (France)
- **8. Vitrification of final waste**
  Glass pouring in a radioactive waste vitrification facility



ZOOM
From plutonium to MOX

Plutonium is an inevitable by-product of nuclear reactions in a reactor fed with low-enriched uranium. While it is responsible for most of the toxicity of used fuel, plutonium also contains a great deal of potential energy. Mixed oxide fuel, or MOX, is a mixture of about 93% depleted uranium powder and 7% plutonium oxide powder. In France, twenty of the twenty-eight 900 MW reactors connected to the grid operate with a fuel core that is 30% MOX. There are only two MOX fuel fabrication plants in the world: AREVA's Melox plant at the Marcoule site, and the Sellafield plant operated by BNFL/BNG in Great Britain. A plant is also scheduled to be built at the Rokkasho-Mura site in Japan.

EXPERT OPINION

DR DOROTHY R. DAVIDSON

Dr Dorothy R. Davidson[1], the nuclear fuel specialist, is in charge of relations with the US Department of Energy (DOE) as project manager of the International Nuclear Recycling Alliance (INRA), which is conducting studies on the closing of the fuel cycle in the United States.

WHAT IS THE FUTURE of the fuel cycle in the United States?

Alternatives: What characterizes the nuclear fuel cycle in the United States?

Dorothy R. Davidson: Nuclear power currently generates 20% of the electricity in the United States and the vast majority of the power plants should continue to operate for several decades more. We expect another 30 or so reactors to be built. The nuclear industry is searching for the best way to manage used fuel in the future, both in terms of economics and in terms of safety. This is why the Department of Energy asked industry to define the conditions for an integrated fuel management strategy that would satisfy growing worldwide demand for energy safely and reliably while protecting the environment. Today, the fuel cycle in the United States is characterized by on-site storage of used fuel and geologic disposal of final waste. This is why the President initiated the Global Nuclear Energy Partnership (GNEP), whose goal is to meet the growing demand for energy, reduce future volumes of used fuel and limit the risk of proliferation. Another goal of GNEP is to expand international cooperation for the safe and peaceful use of nuclear power around the world, with a view to sustainable development.

What is INRA's contribution to the GNEP program?

D. R. Davidson: INRA is a group of companies[2] that joined together to propose the best nuclear technologies from the United States, France and Japan to the US government. We have almost 50 years of experience in managing the commercial fuel cycle in accordance with IAEA[3] and Euratom regulations. We also benefit from 40 years of expertise in the design and construction of light water reactors and sodium cooled reactors. This expertise forms the basis of studies for the design, funding and construction scheduling of two major facilities: the Consolidated Fuel Treatment Center (CFTC) and the Advanced Recycling Reactor (ARR), a next-generation reactor to convert long-lived waste into short-lived waste while generating power.

Where does this program stand today?

D. R. Davidson: With INRA, we have reached the following conclusions:

- The recycling technology allowing us to avoid separating pure plutonium is mature and available.
- The size of the recycling facilities will depend on the demand for treatment of used light water reactor fuel and sodium cooled reactor fuel.
- The industry has the capacity to build sodium cooled reactors, but further R&D must demonstrate their profitability compared with light water reactors.
- International R&D programs can be instrumental in accelerating the development of sodium cooled reactors.
- It is desirable for the United States to establish a regulatory agency to oversee the strategy for used fuel management.
- A proven model for privately funded fuel recycling already exists and offers appropriate guarantees.

As a follow-up to this first phase, INRA will continue to assess the recycling business model, improvements to be made to the ARR, and the operating license process for the ARR and for a recycling center. ■

1. Dr. Davidson is also Vice President, Nuclear Energy, AREVA, Inc.
2. AREVA, Mitsubishi Heavy Industries Ltd. (MHI), Japan Nuclear Fuel Limited (JNFL), URS Washington Division, Babcock & Wilcox Technical Services and Battelle Energy Technology.
3. International Atomic Energy Agency.

The French example, which has already been transposed to Japan, where a plant almost identical to AREVA's La Hague plant was inaugurated in 2005, will be reproduced in the coming years. In 2007, the United States and China each decided to build and operate a recycling plant.

4. Waste management

The future of used fuel is a subject of ongoing debate, with two opposing strategies. In one, used fuel is considered final waste. This "once-through" or "open" fuel cycle option has been chosen by countries such as Sweden, Finland, Spain and Canada. In the other, used fuel is treated to recover recyclable materials, which make up 96% of the fuel. This is the "closed" fuel cycle. France and other countries, including Japan, the United Kingdom, Russia and China, treat their used fuel. The United States had abandoned treatment 25 years ago, but is showing renewed interest now.

The classification of waste is fairly complex (*see table*). There are five categories of waste, based on radioactivity and half life. Very low level waste (VLLW) and short-lived low or medium level waste represent more than 90% of the waste produced in France since the beginning of its nuclear program. These categories include waste from ore processing (metal scrap, rubble, etc.) and waste from the maintenance and operation of nuclear power plants. When the radioactivity of the short-lived low and medium level waste is low, the waste is compacted and packaged in steel drums. When the radioactivity is higher, the waste is encapsulated in concrete or resins and isolated in concrete containers.

Andra's low and medium level waste disposal center in Aube (France)
The site receives all short-lived low and medium level waste. It will stop accepting waste in around 2050.

A wealth of options

Definitive solutions have already been implemented in France for very low level waste and short-lived low or medium level waste. These types of waste are stored above ground at two sites, one in the Aube Department (Champagne-Ardenne region) and one in the Manche Department (Normandy). The debate mainly concerns the long term management of long-lived, highly radioactive, non-recyclable waste. This waste includes the fuel cladding, untreated used fuel and fission products (*see "Zoom", opposite*). The French Law of June 28, 2006 indicates that the three avenues for research stipulated in the Waste Act of 1991 (the "Bataille Law") are complementary, but designates retrievable disposal in deep geologic formations as the baseline solution. A new law should be adopted by 2015 at the latest to define the conditions for retrievability. While identifying deep geological disposal as the preferred solution, the law of 2006 calls for an in-depth examination of the other two possible solutions. One involves the storage of the waste above or below ground, while in the other the waste's radioactivity is reduced through separation and transmutation (*see "word for word" below*). From uranium ore mining to used fuel management and recycling, each step of the fuel cycle is a complete and complex industry unto itself. The entire cycle takes several decades from beginning to end. While other aspects of the nuclear industry are better known, time is also one of the distinctive features of this sustainable, reliable and CO_2-free source of energy. ■

More than 90% of waste is very low level or short-lived

WASTE VOLUMES PRODUCED IN FRANCE SINCE THE BEGINNING OF THE NUCLEAR POWER PROGRAM IN 1974

Waste category	Volume	% of total volume	% of radioactivity
Very low level	108,219 m^3	11.1%	≃0
Low and medium level – short-lived	778,322 m^3	79.6%	0.07%
Low level – long-lived	44,559 m^3	4.5%	0.01%
Medium level – long-lived	45,359 m^3	4.6%	3.87%
High level – long-lived	1,639 m^3	0.2%	96.05%

Source: Andra 2004.

Websites for more information on nuclear power:

- International Atomic Energy Agency (IAEA): **www.iaea.org**
- National radioactive waste management agency of France (Andra): **www.andra.fr**
- French Atomic Energy Commission (CEA): **www.cea.fr**
- **www.laradioactivité.com**: this site explains radioactivity very simply, from its discovery to its numerous applications (Andra).
- French Nuclear Energy Society (SFEN): **www.sfen.org**
- World Nuclear Association: **www.world-nuclear.org**

A site opposed to the development of nuclear power:

- Greenpeace: **www.greenpeace.org**

Used fuel shipping cask.

ZOOM

Measuring radiotoxicity

In France, approximately 1 kilogram of radioactive waste is produced per person per year. Of this, 990 grams will return to natural radioactivity levels in less than 300 years, but 10 grams will remain highly radiotoxic for a very long time. A French family of four people that uses nuclear-generated electricity for 25 years would have generated 12 cm^3 of high level, long-lived waste.

word for word

ISOTOPE: An element whose atoms have the same number of electrons and protons, but a different number of neutrons.

OPEN CYCLE/CLOSED CYCLE: The fuel cycle is said to be "closed" when it includes used fuel treatment and recycling of fissile materials. It is said to be "open" or "once-through" when the used fuel is sent directly to disposal as waste.

SEPARATION-TRANSMUTATION: The purpose of separation is to recover fission products and minor actinides. The latter are radioactive elements named after actinium, a heavy metal with relatively similar chemical properties. Transmutation occurs when the heavy nuclei of minor actinides are bombarded with neutrons and split, or fission, into lighter nuclei.

ULTRACENTRIFUGATION: In this process, a series of cylinders or "bowls" are lined up. They separate the uranium hexafluoride molecules by spinning at very high speed. The heavier particles containing the U_{238} isotope are projected to the walls of the cylinder. The lighter molecules containing the U_{235} isotope remain near the center. The proportion of light, radioactive molecules increases from one cylinder to the next, thus enriching the gas.

EUROPE: ROADMAP FOR A SINGLE ENERGY MARKET

Europe's energy market is not unified… yet. Many standards and procedures differ from one country to the next, there still are not enough grid interconnections and some markets operate as if national monopolies were not a thing of the past, particularly the gas market. We need a real Schengen area for energy. Here are some ideas on creating one.

THE OPINION OF
JEAN-MARIE CHEVALIER

Jean-Marie Chevalier is a professor at the University of Paris-Dauphine, where he heads up the Center of Geopolitics of Energy and Raw Materials (CGEMP). He is also director of the Paris branch of Cambridge Energy Research Associates (CERA) and the author of numerous articles and books. In October 2007, as part of the independent economic advisory body CAE, he and co-author Jacques Percebois submitted a report to the French Prime Minister entitled *Gaz et électricité, un défi pour l'Europe et la France* [Gas and electricity, a challenge for Europe and France].

We need a single European energy market, a Schengen area for electricity and gas that would allow competition to really play its role, stimulating innovation and forcing suppliers to compete on prices. But we are far from it; the markets are still pretty much national. Electricity is well ahead of gas on all of the key issues, including regulations, power systems and complex exchanges, but there is still a critical lack of interconnections between national power grids. Grid interconnection is an essential condition for establishing a truly continental market. The grids become interdependent, allowing electricity to flow freely from one country to another. Prices can be arbitrated and competition flourishes, as is the case between France and the Benelux countries.

More interconnections and even excess capacity are urgently needed for truly seamless interchange on the European scale. The European authorities have clearly identified this as a goal, and it is one of the priority measures published in January 2007. From measure to decision, however, it takes time for interconnections to come into being.

Still very little competition between national energy markets

The markets themselves are dysfunctional. European electricity markets are extraordinarily complex, almost impenetrable, and a powerful electric utility can still influence the market considerably. Like the stock markets, there is a need for greater oversight.

The issues are different for the changing gas industry. For the past fifty years, the European natural gas network has been designed to deliver gas directly from one fixed point – the deposit – to another fixed point – the consumer. But today's gas grid is changing, becoming tighter and denser as it matures. Liquefied natural gas (LNG) is coming in from Norway, Qatar and Egypt, and pipelines are being built from new gas-producing countries, increasing the number of entry points. Slowly but surely, this trend will stimulate competition between natural gas suppliers.

Pooled storage gaining ground

Gas storage is still a problem. The grid was designed by and for national operators, and the storage areas they control give them a sizeable competitive advantage that is beyond the reach of small companies. Pooled storage is catching on, though. I think that, like the electric power industry, we will wind up with completely independent transmission system operators capable of investing Europe-wide.

These independent operators are already emerging. Little by little, utilities like the German companies EON and RWE are thinking of selling their transmission systems. But we have to go further and faster. Ideally, we should create a single European transmission system. A single transmission company would necessarily mean a single regulatory authority and a single European market.

In every instance, the proliferation of national rules and regulations is an impediment to the creation of a single market. It is becoming urgent to harmonize the standards, procedures and regulations of European countries and to increase the independence of grid operators. They should have the same responsibilities and the same scope of operations in every country. European associations such as the European Regulators' Group for Electricity and Gas (ERGEG), which brings together European regulators with European Transmission System Operators (ETSO), will be very instrumental in achieving this. The process is admittedly slower than initially planned, but we should have a single electricity market in ten years or so. For gas, it will undoubtedly take a bit longer. ■

Gaz et électricité, un défi pour l'Europe et la France [Gas and electricity, a challenge for Europe and France], *Jean-Marie Chevalier and Jacques Percebois, La Documentation française.*
Les grandes batailles de l'énergie
[The great energy battles],
Jean-Marie Chevalier, Folio Gallimard.

@
- Une politique de l'énergie pour l'Europe *[An energy policy for Europe]*
Measures recommended by the European Commission, published on January 10, 2007:
http://europa.eu/scadplus/leg/fr/lvb/l27067.htm
- The third European legislative package for the electricity and gas markets, published on September 19, 2007:
English version: **http://europa.eu/scadplus/leg/fr/lvb/l27067.htm**

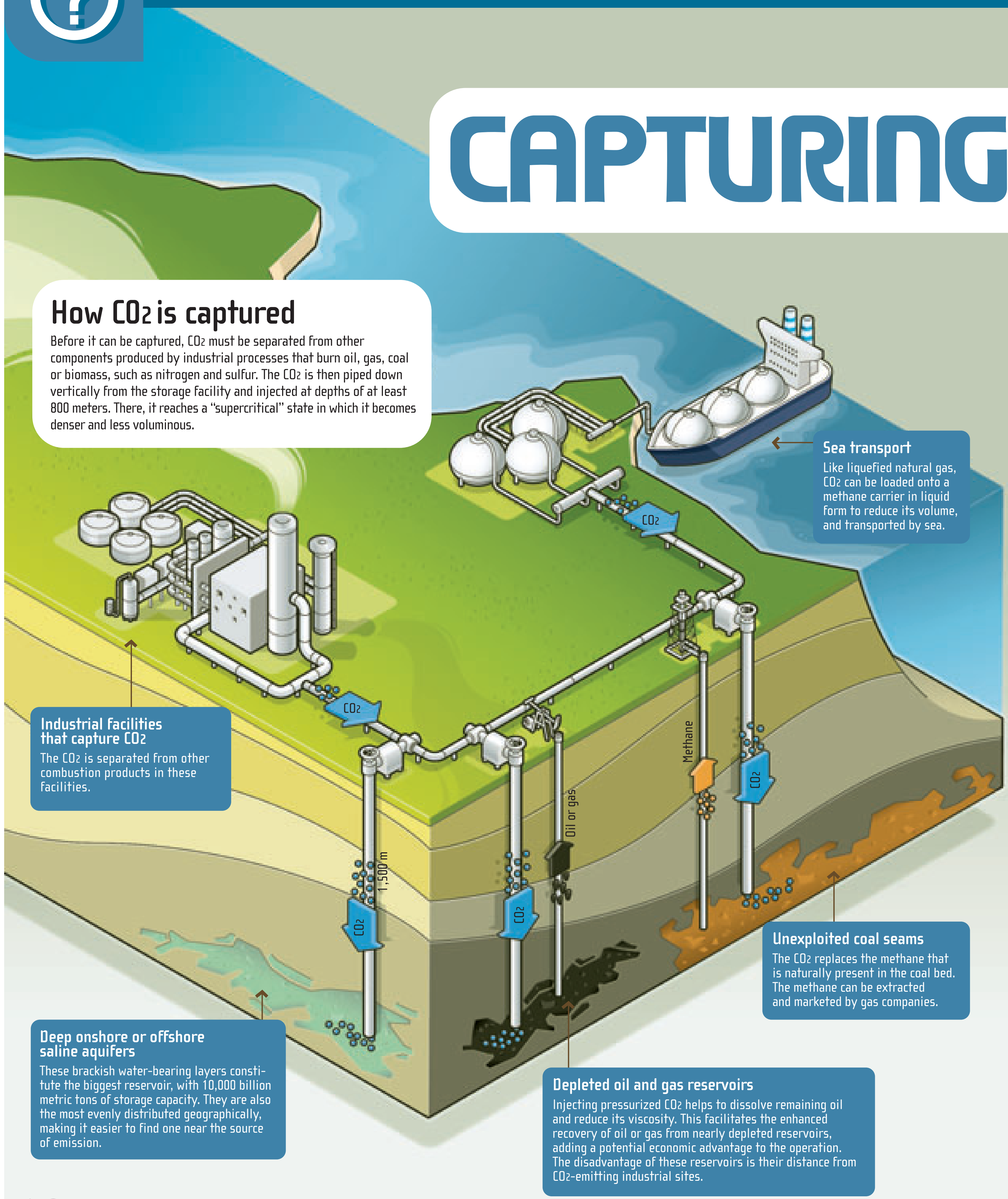
> “ Ideally, we should create a single European transmission system. A single transmission company would necessarily mean a single regulatory authority and a single European market. ”

ZOOM
Electrical interconnections

These are grid connection points at the borders of two countries, which determine their capacity to trade electricity. The physical capacity is provided by extra high voltage lines (EHV) and dedicated equipment. European auction systems in place since 2004 regulate the commercial side of operations. France is linked to the United Kingdom, Germany, the Benelux countries, Switzerland, Italy and Spain. At some of the borders, for example between France and Spain, there is not enough physical capacity. Reinforcing these grid interconnections is a project of European interest. Some progress in that direction should finally be made: French and Spanish grid operators will be proposing a new route linking Perpignan and Figueras before the end of June.

CAPTURING AND STORING CO_2

A promising way to combat global warming is to capture CO_2 produced by industry and bury it in deep geologic formations. The processes are technically complex… and still expensive. A closer look.



To combat the accumulation of CO_2 in the atmosphere, capturing it and storing it underground offers a promising alternative until non-emitting energies become widespread. Large stationary sources (*see chart below*) are targeted first. Full-scale experiments are under way to capture CO_2 from these sources at an acceptable cost using available technologies.

Recovery technology still very expensive

Capturing CO_2 at the source requires separating it from the other components produced by industrial processes that burn oil, gas coal or biomass, such as water vapor, nitrogen and sulfur. For the moment, there appear to be three suitable technologies for doing that. They are used primarily in areas that are also conducting geologic disposal experiments, including the United States, Japan and Europe.

• **Post-combustion capture** consists in scrubbing flue gases, usually with amine solvents. It is easy to retrofit facilities with the technology, although it is really applicable only for large gas volumes at low pressure and low CO_2 concentrations. It is the most mature solution, but results in an electric kilowatt-hour that costs 50 to 70% more.

• **Oxyfuel capture** consists of replacing the use of air for combustion with pure oxygen. In this case, the concentration of CO_2 in the flue gases can be as high as 90%, facilitating capture by a cryogenic system at the outlet. This solution is also expensive and consumes a lot of energy. It is best suited to new facilities.

• **"Pre-combustion" capture** involves converting the fossil fuel before use into syngas, a mixture of carbon monoxide (CO) and hydrogen. The CO reacts with water in a step called "shift conversion", forming CO_2 and hydrogen, which are then separated. The hydrogen can be used as a clean, non CO_2-emitting fuel to generate electricity or heat.

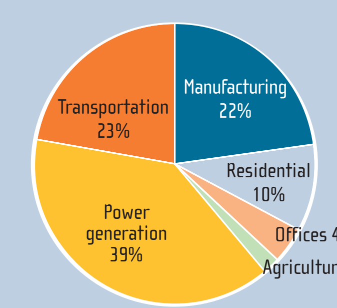
Once the CO_2 has been captured, it can be transported to storage sites either overland in high-pressure gas pipelines, or by sea in methane carriers, just like liquefied natural gas (LNG), i.e. in moderately pressurized liquid form, which reduces its volume. The United States has the largest land-based pipeline network, with some 50 million metric tons of CO_2 carried per year from enhanced oil recovery operations or from industrial plant emissions. Fewer than 3,000 kilometers of pipeline network are allocated to CO_2 transport worldwide, a sign of how inadequate the infrastructure is.

Three types of underground reservoirs tested so far

There are three main alternatives for deep geological storage of CO_2. In all three cases, the CO_2 is injected at depths of at least 800 meters. There, at temperatures of more than 31° C and pressures greater than 74 bar, it reaches a supercritical state in which it becomes denser and less voluminous.

• **Deep saline aquifers** – These brackish water-bearing layers represent the greatest volume potential for CO_2 storage, with up to 10,000 billion metric tons available. That is equivalent to several centuries' worth of global CO_2 emissions. The aquifers are also very well distributed geographically. These two advantages make it easier to find an aquifer near an emission source. At the Sleipner natural gas production site in the North Sea, the 4 to 10% CO_2 contained in methane is extracted and re-injected more than 1,000 meters beneath the ocean floor. Each year, a million metric tons are buried under the ocean floor in Norwegian waters rather than being released to the atmosphere. More study is needed to characterize the long-term behavior of these aquifers. ⏭

CO_2 is produced in every sector



Worldwide CO_2 emission sources by type of activity

61% of the CO_2 emissions from fossil fuel use come from large stationary sources, such as power generation and manufacturing, where it is much easier to capture the CO_2.
Source: AIE, 2003.

• **Depleted or nearly depleted oil and gas reservoirs –** We already know a lot about these onshore and offshore geological environments. As natural reservoirs, they have been proven to be leak-tight, as long as all the wells leading to them are sealed off. They are not ideally located, being far from CO_2-emitting industrial sites. Using them requires investing heavily in expensive infrastructure or other means to bring in the CO_2, such as pipelines or methane carriers. Demand also outstrips available volumes, estimated at about 930 billion metric tons.
Injecting pressurized CO_2 for the enhanced recovery of oil or gas does provide some interesting possibilities, though. The Canadians are experimenting with it at the Weyburn oil field in Saskatchewan. CO_2 from a nearby U.S. coal gasification plant is injected under pressure into the oil layer, where it dissolves in the oil, lowering its viscosity and making it easier to recover. After treatment, the dissolved CO_2 is separated and reinjected into the underground reservoir.
• **Unexploited coal seams –** These can be used to take advantage of coal's "affinity" for CO_2 which, when injected, replaces the methane naturally present in the coal bed. Gas companies can then extract the methane (the major component in natural gas), inject it into their pipeline networks, and market it for industrial and domestic use. Since 2001, the European RECOPOL research project in Poland has been testing the feasibility of injecting CO_2 into coal seams in the Upper Silesian Basin. The possibility of injecting large quantities of CO_2 into these low-permeability seams without boring a lot of injection wells, which would increase the risk of leaks, must be verified. At an estimated 40 billion metric tons, the global storage capacity of these seams is sorely inadequate.
There are two additional solutions. The first involves storing the CO_2 in carbon "lakes" in the ocean at a minimum depth of 1,500 meters, but this has been rejected due to concerns about the impacts on the marine ecosystem and how long the CO_2 would be contained. The second solution, carbon sequestration by mineral carbonation, is of more interest. Here, CO_2 reacts with naturally occurring subsurface calcium and magnesium to become a carbonated rock similar to limestone, which is insoluble and therefore perfectly stable over the long term.

Capture is 70% of the overall cost

The entire CO_2 capture, compression, transport and sequestration process can cost up to 42 euros (about 65 dollars) per metric ton of CO_2. This exceeds the floor price of 30 euros (about 47 dollars) per MT of CO_2 currently negotiated on the cap and trade market. Capture technologies represent 70% of the total in terms of cost, so they constitute a considerable economic challenge. They are the most in need of optimization from this viewpoint and are being tested in national and European projects (*see "Zoom"*).
The long-term safety of geological storage is a major criterion in deciding how much and how densely CO_2 can be stored underground. Using information from the many naturally occurring CO_2 deposits and lessons learned from pioneering storage sites, it is possible to establish rules for safe storage over more than 1,000 years. The European Commission published a draft directive in January 2008 that will be debated over the next few months in the European Council and Parliament. The directive sets the conditions for CO_2 storage licensing based on thorough site characterization and assessment and on an adequate monitoring program drawing on geophysical, geochemical and biological techniques.
Questions are already being raised about these underground storage reservoirs, destined to become permanent, so the final test will no doubt be whether or not the public accepts them. ■

The Sleipner precursor site in the North Sea
The Sleipner project is the first commercial example of CO_2 sequestration in a deep saline aquifer. The Sleipner field is located in the North Sea off the coast of Norway and is operated by StatoilHydro, the country's largest oil company.

ZOOM
Europe hosting international projects

Quite a few research projects on CO_2 capture and storage (CCS) have entered an active phase.
One of these is CASTOR (CO_2 from Capture to Storage), a European project that covers the entire CO_2 capture-transport-storage chain and, by extension, looks into hydrogen storage. Another is CO2GeoNet, a Network of Excellence on Geological Storage of CO_2 that brings together the main European geological institutes (www.co2geonet.com).

FURTHER READING

- **La capture et le stockage géologique du CO_2 [CO_2 capture and geologic storage].** Reducing greenhouse gas emissions – Geoscience series (2005) – BRGM Publications (in French).
- **Capter et stocker le CO_2 dans le sous-sol [Capturing and storing CO_2 underground].** A technological solution for combating climate change. Geoscience series (2007) – BRGM Publications (in French).
- **Limiter les émissions de CO_2 pour lutter contre le réchauffement climatique [Reducing CO_2 emissions to combat global warming].** Series on prevention at the source and sequestration – BRGM Publications – public document (in French)

Brussels, January 23, 2008
Neelie Kroes, EU Competition commissioner, Andris Piebalgs, Energy commissioner, José Manuel Barroso, European Commission president, and Stavros Dimas, Environment commissioner, unveil Europe's energy and climate plan.

ENERGY AND CLIMATE: Brussels plan put to the test

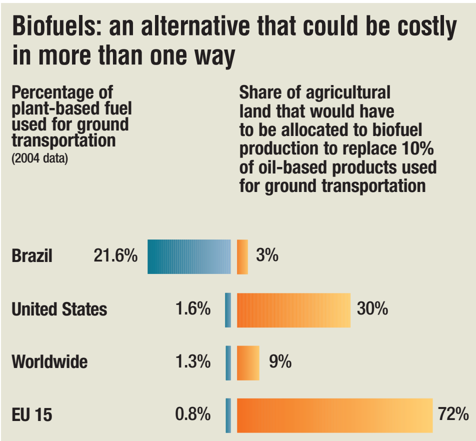
In early 2008, the European Commission presented its highly ambitious plan to reduce greenhouse gas emissions. Two stumbling blocks stand in the way: industry's obvious reluctance, and the unanswered but crucial question of how to fund the proposed measures.

The European Commission presented an important series of measures on energy and the climate in late January. It even described the plan as "historic". Included are measures to reduce energy consumption, increase the share of renewable energies and boost energy efficiency. But controversy surrounds the proposed plan.

> "France must more than double its share of renewable energy in total production."

Nuclear power ignored in the EU document

The main goal is to cut greenhouse gas emissions by at least 20% by 2020, compared with 1990 levels. Brussels even promised a 30% cut if an international agreement is reached. Member states would have to ensure that renewable energies represent at least 20% of their energy consumption by 2020 (average for the 27 countries), compared with 8.5% in 2005 (*see table page 17*).
So that the EU's poorest countries are not penalized, the directives propose to distribute the effort among the 27 member states based on per-capita gross domestic product (GDP). Thus, France must raise its share of renewable energies from 10.3% to 23% of the total. Nathalie Kosciusko-Morizet, the French minister for the Environment, said at the end of January that *"France is a special case because of its reliance on nuclear power."* She added: *"France has requested greater recognition of the specific nature of its energy production and consumption system."* Nuclear power is ignored in the EU document and is not considered a renewable source of energy. Hoping to include nuclear power, France had previously argued in vain in favor of quotas on energy with "low carbon emissions".
In transportation, 10% of all fuel used in European vehicles must be biofuels such as ⏭



Source: OCDE, quoted by Le Monde, March 13, 2008.

ethanol and biodiesel by 2020. Many consider this an unrealistic target, with potentially harmful consequences for the planet (*see* Alternatives *no. 16*). *"For the first time in history, we propose to promote sustainable biofuels,"* said Energy commissioner Andris Piebalgs. To be consistent with the EU's environmental goals, plant-based biofuels will still have to reduce greenhouse gas emissions by 35% compared with gasoline or diesel fuel. They may not be manufactured with raw materials obtained from virgin forests or natural preserves.

Plan price tag: 90 billion euros in 2020

For EU Commission President José Manuel Barroso, "this is the most comprehensive package in the world". It tackles the issue of climate change at an estimated cost of "3 euros per person per week." Oil and gas imports would drop by 50 billion euros, or 0.3% of GDP. Brandishing the report by Nicolas Stern, who attempted to calculate the cost of global warming (5-20% of the world's GDP), Commission President Barroso considered that the "cost of doing nothing" would in any event be higher than the cost of the recommended measures. The tab for Europe is estimated at 0.6% of GDP, or 90 billion euros in 2020. CO_2 emission credits received under Kyoto Protocol mechanisms would reduce it to 0.45% of GDP.

Businesses required to buy CO_2 emission quotas

One of the landmark measures of the Commission's plan is to require the European Union's most pollution-intensive industries to pay for previously free "rights to pollute" starting in 2013. The power generation sector, particularly coal-, gas- and oil-fired plants, which generate a large share of the CO_2 emissions, will have to pay in full for these rights to pollute, to be sold at auction as of that date. The Commission stressed that this pay-to-pollute system will "gradually" include other economic sectors, such as the aluminum industry, ammonia production and air transportation. Commission president Barroso nonetheless indicated that Europe would "take action" if an international agreement on the climate is not reached, particularly with the United States and emerging countries, to reduce CO_2 emissions. What this means in practice is that the most "energy-greedy" industries would be able to obtain permits to pollute "free of charge", while importers of competing non-European products would have to pay for them.

Seven member states ask for clarification

"No member state considers its target to be unattainable," affirms José Manuel Barroso. Energy commissioner Andris Piebalgs tempers that, without naming the dissidents, with *"I would say that at least 20 of the 27 member states have accepted their national targets so far."* In fact, reactions from the leaders of the 27 member states are mixed. At the end of February, seven EU countries asked for clarification on future rights to pollute for Europe's heavy industry, concerned that the proposed measures might weaken their companies. The ministers in charge of Industry in Austria, the Czech Republic, Finland, France, Germany, Hungary and Luxembourg argued that *"Our industries need clarification concerning their contribution to the fight against climate change."* In a joint letter sent to the Slovenian presidency of the EU council and to EU Industry commissioner Günter Verheugen, these countries wrote that *"medium and long term investment planning requires certainty on the future system as soon as possible."* They also requested, "before 2011", a review of specific risks to certain industries that must reduce pollution while competing with imports from less responsible countries.

Chemical industry in the Netherlands
For José Manuel Barroso, the "cost of doing nothing" would be higher than the cost of the recommended measures.

Waiting for takeoff at the Paris airport
Airlines will also be required to purchase "rights to pollute".

The seven countries recalled the "fundamental" importance of the "European Union's resolve" to establish rules on unfair competition, if necessary by way of a carbon tax on imports from outside Europe. *"We must be careful not to weaken the competiveness of our companies and the employment of our workers unilaterally with these measures,"* stated the seven governments. *"We cannot accept a relocation of jobs and production centers because of increased costs incurred to reduce CO_2 emissions,"* they added.

Commission hoping for approval of its plan before the end of 2008

The EU Parliament and the Commission must approve the draft directives as soon as possible if Europe is to influence international negotiations at the next climate conference in Poznan, Poland in late 2008 or, at the very latest, at the next conference in Copenhagen at the end of 2009. The president of the Commission hopes to receive a green light from Parliament and the member states by the end of the year. He gave assurances that Slovenia, currently presiding the EU, and France, which takes over in July, are both "determined to act expeditiously." ■

For more information on the European Commission's plan
http://ec.europa.eu/france/pdf/climate-change-memo_fr. pdf.

How to use pollution permits

Italy, Ilva chemical production plant
The EU's energy action plan requires the most pollution-intensive industries in the European Union to purchase "rights to pollute".

"Pollution permits" or "rights to pollute" refer to tradable CO_2 emission permits. The tradable pollution permit market is like a financial market: it operates based on the supply and demand of capital that companies allocate to CO_2 emission reduction. Demand is generated by companies that are not able to reduce their emissions below the allocated quota. To ensure compliance, these companies must buy quotas on the market. Supply comes from companies that were able to reduce their emissions below their quotas. They can then sell their excess quotas on the market to fund their CO_2 emission reduction efforts.

Renewable energies: country targets for 2020

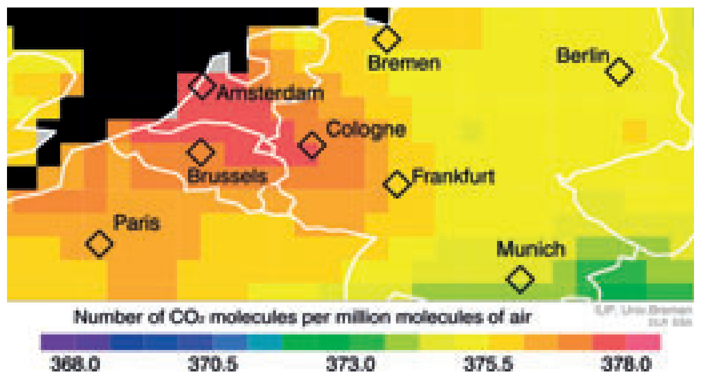
Country	Share of renewable energies in 2005 consumption	2020 objective
Sweden	39.8%	49%
Latvia	34.9%	42%
Finland	28.5%	38%
Austria	23.3%	34%
Portugal	20.5%	31%
Denmark	17.0%	30%
Estonia	18.0%	25%
Slovenia	16.0%	25%
Romania	17.8%	24%
Lithuania	15.0%	23%
France	10.3%	23%
Spain	8.7%	20%
Greece	6.9%	18%
Germany	5.8%	18%
Italy	5.2%	17%
Bulgaria	9.4%	16%
Ireland	3.1%	16%
Poland	7.2%	15%
United Kingdom	1.3%	15%
Slovakia	6.7%	14%
The Netherlands	2.4%	14%
Czech Republic	6.1%	13%
Belgium	2.2%	13%
Cyprus	2.9%	13%
Hungary	4.3%	13%
Luxembourg	0.9%	11%
Malta	0.0%	10%
EU	**8.5%**	**20%**

Source: European Union, 2008.

MAPPING

Satellite monitoring of European carbon dioxide **emissions**

The European observation satellite ENVISAT has finished mapping human-origin carbon dioxide in the atmosphere for the region of Europe. This is a first! To distinguish CO_2 produced by human activity from CO_2 normally present in the atmosphere, German researchers at the University of Bremen processed and analyzed data collected from 2003 to 2005 by the SCHIAMACHY onboard sensor. Results confirm that the concentration of anthropogenic CO_2 (from human activities) is highest over the major industrial cities of Northern Europe. It is estimated that fossil fuel combustion, industrial operations and transportation release a total of 30 billion metric tons of CO_2 each year. These emissions increase the amount of carbon dioxide normally found in the atmosphere and exacerbate the greenhouse effect and global warming. ■



Source: Insitute of Environmental Physics (IUP) of the University of Bremen, German Aerospace Center (DLR), European Space Agency.

ENVIRONMENT

British citizens soon to be held accountable for their CO_2 emissions?

The British government could be a pioneer in CO_2 credits for individuals. The idea is to give each individual an annual quota of carbon credits instead of charging a carbon tax on the most fossil energy-intensive products. Project proponents, including David Miliband, former Environment minister in the Blair government and currently Minister of Foreign Affairs in the Brown government, describe it as a more egalitarian approach that makes each person responsible for managing his or her own carbon consumption, transportation, energy expenses, etc. Unused credits could be sold on a carbon market similar to the one operating today for industry. The Carbon Limited project, under the aegis of the Royal Society for the Encouragement of Arts, Manufactures and Commerce (RSA), was given three years to develop an individual carbon card concept. Others outside the UK are watching the experiment with interest, including the Irish government and experts in the United States. ■

NATURAL GAS

Gazprom looking to triple production from gigantic Shtokman field

Although production has not yet started at the huge Shtokman gas field, Russian gas company Gazprom already plans to triple its output. The Shtokman field lies beyond the polar circle in the middle of the Barents Sea, 500 kilometers from the Russian coast. It is estimated to have 3.7 trillion cubic meters of natural gas, i.e. 2% of the planet's natural gas reserves or one year of global demand. Gazprom heads up a consortium including Total and StatoilHydro that will exploit Shtokman starting in 2013. Consortium president Iouri Komarov believes that Gazprom should increase the field's annual output from 23.7 billion m^3 initially to 71 billion m^3 by 2020. The gas is intended for Gazprom's western clients. Part of it will be liquefied. ■

RESEARCH

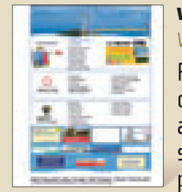
CERN: large-scale proton collisions to begin this summer

At last, the European Organization for Nuclear Research, known as CERN, has completed the assembly of the Large Hadron Collider (LHC), the world's largest particle accelerator with it 27-kilometer ring of magnets. This scientific instrument spanning the border between France and Switzerland near Geneva, more than 100 meters underground, will begin operating in June 2008. The 9,300 superconducting magnets in the tunnel are chilled to a temperature of close to absolute zero (minus 271°C). Researchers will analyze collision results under the magnifying lens in a vacuum equivalent to that of interstellar space. They hope to discover the secret of physical phenomena that occurred just after the Big Bang, including the origin of particle mass and their interactions. ■

Lowering the end-plug of the CMS detector
This last component will be assembled underground with other slices of the Compact Muon Solenoid detector. CMS is one of the four large detectors of the LHC particle accelerator, where proton-proton collisions will soon begin.

INTERNET FOR MORE INFORMATION ON TOPICS DISCUSSED IN THIS ISSUE

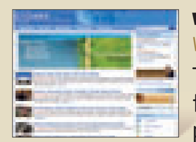
Renewable energies from A to Z



www.energies-renouvelables.org
Website in French //

Free and easy registration gives visitors access to a wealth of information, including "*Systèmes solaires*" (Solar systems), a magazine dedicated to all forms of renewable energy. The site also features articles from Observ'ER. This bi-monthly publication of the *Observatoire des énergies renouvelables* (the Renewable Energy Observatory) presents the most recent data on various forms of energy (wind power, photovoltaic, solar energy, geothermal, etc.). Another major area covered by the website concerns the activities of the *Fondation énergies pour le monde* (Energy for the World Foundation), which supplies energy to populations in need.

The world's nuclear police



www.iaea.org
Website in English //

The International Atomic Energy Agency (IAEA) reports to the United Nations Security Council. It promotes the peaceful uses of nuclear energy and seeks to limit the development of its military applications. The site explains the ongoing missions and programs in which the agency is participating. It reports on inspections performed in all countries, including countries where the agency is in a position to provide credible assurance regarding the absence of undeclared activities, and other countries, including Iran. In addition to the many activities of the IAEA, the site provides nuclear news from around the globe as well as scientific and technical publications.

All the news from the world of energy

www.enerzine.com
Website in French //

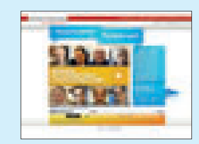
"Daily energy" is the creed of this fascinating site, which lives up to its promises. It covers all of the economic, technical, commercial and environmental news regarding the energy industry. Register for free to receive a daily portal update.

A model for waste management

www.andra.fr
Website in French and English //

The French national radioactive waste management agency, Andra, is a state-funded industrial and commercial agency created by the Waste Act of December 30, 1991. Andra operates independently of the waste producers. It comes under the supervision of the French ministries for Industry, Research and the Environment and is responsible for the long-term management of radioactive waste produced in France. The site tells you all you always wanted to know about radioactivity and nuclear waste, including what, where and how much.

"Let's talk about recyclable energy!"



www.alternatives.areva.com
Website in French //

Recyclable energy is a fascinating subject with momentous consequences for society. How can we use nuclear energy to satisfy our needs? Why is it a "recyclable" energy? How is it produced? These questions are both captivating and controversial.

On July 3, we launched our debate on nuclear waste: the risks, the drawbacks and the solutions. We encourage you to take part! The forum will be open until August 18.

BOOKS

A treatise on energy issues around the globe

Le Monde et l'Énergie - Enjeux géopolitiques (Volume II, Les Cartes en mains) (The World and Energy: the Geopolitical Challenges, Volume II, The Cards Are in Our Hands) **by Samuele Furfari, published by Éditions Technip – 2007, 424 pages, 45 euros**

This two-volume set explains the geopolitics of energy and outlines prospects for the planet's future. The second volume describes the main energy markets. A major section of the book focuses on Europe's energy supply and East-West relations, particularly as concerns the gigantic natural gas reserves of Russia. Another section is dedicated to countries that are "energy gluttons", both in the developed world (the United States) and in the emerging world (China and India). They are cultivating North-South relations, with the United States turning to the Middle East and South America while China and India turn to Africa, but also with areas traditionally coveted by Europe.

The CEA opens the book on nuclear fuel

Les Combustibles nucléaires - **Monographie du Commissariat à l'énergie atomique (Nuclear Fuel - A Monograph by the French Atomic Energy Commission). Co-published by Le Moniteur and the CEA – 2008, 148 pages, 18 euros**

This work recounts the history of the CEA's fuel research and development programs just as nuclear power begins a new cycle of growth. Fuel design and properties have a major impact on the performance and safety of nuclear reactors. Nuclear fuel optimization has significant economic benefits, even though fuel represents a very small portion of the cost of electricity produced in nuclear reactors. This technical monograph summarizes the state-of-the-art on fuel behavior, its design limits and areas for further research and development.

Answers … to your questions

Biofuels: it's a matter of generation…

As a retired engineer interested in energy, I was a little bit disappointed with your article on biofuels (Alternatives, no. 16), although the title of the article rightly points out that the future is fraught with uncertainty. I would make the following comments:
- First, these fuels are now increasingly referred to as "agrofuels" to reflect the fact that production rarely meets "organic" criteria. Chemical fertilizers and pesticides are used systematically in grain production and deforestation continues in Brazil!
- Your article does not mention second-generation agrofuels, which have the advantage of using the entire plant. This technology may still be in its infancy, but it could be a promising area for research and development in Europe, rather than mimicking Brazil or the United States in the case of ethanol.
- Another possibility for replacing fossil fuels is often overlooked: biogas!

Mr. André Guéry (comment received by e-mail)

First, thank you for your acute analysis. The debate has evolved considerably since we published our article on biofuels two months ago. Second-generation biofuels that use more diversified resources are now on the top of the agenda. Several research areas have been identified. The first would be to produce synthetic biodiesel from vegetable oil or animal fat. A second, parallel path would be to produce biodiesel from ligno-cellulose biomass from plants, i.e. from stalks and trunks. Biogas is produced by fermentation of organic waste in anaerobic conditions. It is possible to use household waste, green plant waste, sludge from sewage treatment stations, animal waste such as pig slurry, and agribusiness waste. Biogas is approximately 65% methane and 35% carbon dioxide. It can be used as fuel to produce heat or electricity or as motor fuel. We will discuss these new technologies in an upcoming issue.

The real benefits of daylight savings time

How does daylight savings time save energy, and how much? Please enlighten me!

Mr. Paul Sacla, Perpignan, France

Daylight savings time refers to the practice of adjusting the official time, usually by one hour, in the spring or summer and early fall. The goal is to save energy by making our hours of activity coincide with natural sunlight to limit the use of artificial lighting. Many countries take this approach, particularly in temperate regions where seasonal variations in daylight make it useful. In France, daylight savings time was established in 1975 after the first oil shock of 1974. Estimates produced in 1996 and 2006 indicate that the annual energy savings vary from 0.7 to 1.2 billion KWh. The latter figure represents 4% of all electricity used for lighting in France, or the entire electricity consumption of a city of 200,000 inhabitants for an entire year.

Follow-up on our previous website selection…

Belgium's Nuclear Research Center, SCK*CEN, is contributing to sustainable development with R&D, training, communication and services related to nuclear safety and radiation protection, medical and industrial applications, and the closed nuclear fuel cycle.

Mrs. Anne Verledens, SCK*CEB Press Relations, Mol, Belgium

Our apologies for the erroneous presentation in Alternatives no. 17. Contrary to what we implied, the CEN is not involved in any defense nuclear applications.

WRITE TO US:

This is your space, send us your questions!
We will respond in future issues.

Magazine Alternatives // T.M.S. //
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@ alternatives@publicorp.fr

e next issue… In the next issue… In the next issue… In the next issue… In the

Extreme oil: where are the limits?

Supplies of fossil fuels, mainly oil and gas, are dwindling. But with technology advancing, mining costs falling and oil prices soaring, so-called "unconventional" oils are becoming profitable.
These heavy crude oils, located mainly in Canada and Venezuela, represent additional resources practically equivalent to the existing reserves of Saudi Arabia. With long experience in offshore drilling, oil companies are now exploiting "ultra-deep" deposits at depths of more than 1,500 meters.
The technological envelope is continually being pushed back. How far can it go?