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Nuclear Energy and Climate Change

Abstract

In this paper, we will discuss the potential for the development of nuclear energy in the world in the medium and long term. We will correlate the prospects with the emissions of CO_2 and the effects on climate change. In particular we will discuss the problems nuclear energy faces if it is to make a large contribution toward mitigating climate change.

Introduction

Concerns about the consequences of climate change have increased significantly in the last years. The United Nations Climate Change Conference in Copenhagen in December 2009 will try to work out a way for the world to act together to preserve the planet in the face of rising temperatures for after 2012, the end of the Kyoto protocol. However, getting all the major governments to agree on one solution seems a very long way off. The essential problem is burden-sharing: which countries are going to cut their CO_2 emissions, and by how much? It has become apparent that global emissions of CO_2 are shooting up at a rate that far exceeds anything the UN's Intergovernmental Panel on Climate Change (IPCC) thought possible in its scenarios of 2000 (ref. 1).

It is now obvious that all countries need to be in the next climate change agreement - developed countries including the United States as well as developing countries including China and India. In the Clean Development Mechanisms, nuclear power should be included. Since the election of President Obama, the energy-environment questions are one of the priorities in the United States.

With the new environmental constraints, governments are re-evaluating nuclear power as a possible solution to global warming.

The use of nuclear power in electricity generation is on the rise, especially in Asia. In the Western hemisphere, only a few countries with nuclear power plants have phase-out policies for nuclear energy (some are changing their mind presently), while most others are extending the licenses of existing reactors and/or are building new reactors. The nuclear renaissance today is driven by considerations of energy supply security, by the climate change threat and by economic advantage comparing to fossil fuels or renewables.

In the longer term, gradual depletion of fossil fuels, especially the easiest to extract and geopolitically most favorable, will favor nuclear, provided fast breeder reactors are deployed, assuring nuclear fuel supply for thousands of years rather than for decades as with present technologies.

Indeed, the imperative need for development of some countries will increase the demand for energy, especially for electricity, in spite of economically justified efforts to increase energy efficiency and conservation. This, combined with the need to replace fossil fuels, will oblige mankind to develop new sources of energy.

One obvious and very popular solution is presented by renewable energies, notably solar and wind. However, fundamental issues of low density and varying availability over time, coupled with the difficulty of electricity storage, will tend to limit their role in baseload energy production, which is needed especially for large cities.

We must therefore look for other, complementary technologies to produce reliable baseload electricity without greenhouse gas emissions.

One solution may be coal-fired power with capture and storage of carbon dioxide, CO_2. But CCS technology is still not developed on an industrial scale, and if and when it becomes available, it will likely add substantial cost to electricity production from coal. In addition, coal resources, even if larger than those of oil and gas, are still finite and therefore do not solve the problem for the long term.

Of course, other technologies may be invented and developed in the future – thermonuclear fusion energy, solar energy from space – but it is not certain if and when they may be developed and especially what will be their economic performance. In the meantime, society must have technologies that are economically and environmentally acceptable and available for the very long term. One such solution, nuclear fission with breeder reactors, exists today and operates satisfactorily, even if improvements in technology, especially fuel cycle technology, remain necessary. The real problem for nuclear energy is not so much technology or economic performance, but the acceptance and active support by societies at large and by decision makers.

The large variations in the projected development of nuclear energy – between low and high scenarios – are linked to the way decision makers and societies will weigh different attributes of different sources of energy:

- security of supply,
- impact on climate change,
- impact on public health,
- cost,
- non-quantified fears.

Two other important issues are:

- how much attention societies will pay to the future and to the distant future,
- how societies find compromises between the general interests of a region, of a country, and of the world, and the local interest of those who live near an industrial facility.

The way societies react as well as economic conditions – cost and availability of capital, of a skilled workforce – vary strongly from country to country. Therefore, after some general considerations, we will address the situation in selected countries.

This paper is divided into three parts. In the first section, we will present our view concerning the potential of nuclear energy in the near and medium term and the more distant future and therefore its maximum role as a mitigator of carbon dioxide emissions. In the second section, we will discuss the important factors influencing the development of nuclear power. In the last section, we will review the situation in three countries that are particularly important for nuclear power: the United States, France and China.

Section I. Energy Scenarios (ref. 2, 3, 4, 5, 6, 7)

Typically three dates are used in energy scenario projections: up to 2030, up to 2050, and up to 2100 for the longer term. Let us begin by discussing the short-term future, up to 2030. For energy, 20 years, we believe, is a short term.

I.1. The period 2010–2030

For this time frame there are many scenarios and calculations of what may happen, published by many diverse institutions including the Nuclear Energy Agency (NEA) of the OECD, the World Nuclear Assocaition (WNA), the International Atomic Energy Agency (IAEA), the OECD International Energy Agency (IEA), as well as BP-Exane (a joint venture of Banque Paribas and the private consulting company Exane). The common characteristic of these projections is that they have at least two scenarios, one high and one low. The IEA does not call them high and low, but rather "reference scenario" and "450 scenario," corresponding to stabilization of greenhouse gases in the atmosphere at 450 parts per million in 2030. The other characteristic of these scenarios is that the low scenarios have practically no growth of nuclear capacity, or very slight growth or even a slight decrease, that is, 10 percent or 20 percent over the 20 years. The high scenarios are more diverse: one can find scenarios that lead to between 600 gigawatts and 890 GWe of nuclear power capacity in operation in 2030, as compared to the 372 GWe of today.

IEA's World Energy Outlook (WEO) – a very serious review and prognosis of energy situations in 2030, was published in 2007 and 2008. In 2007 the WEO projected 833 GWe of nuclear capacity in 2030; for the same scenario in 2008, the prognosis for nuclear is 640 GWe in 2030. This is quite a large variation and shows the volatility of expected values because things are complicated and change quickly. The complications stems from the fact that we have to deal not only with economic and technical problems but also with political and social issues, especially if one is talking about nuclear energy. The predictions are therefore quite difficult: how governments and societies will behave over this length of time is not an easy thing to predict.

Considering the situation as of August 2009 based on available recent studies, it seems that a value of around 800 GWe installed nuclear capacity in 2030 is a reasonable upper limit. This corresponds to some 6 gigatonnes of CO_2 saved if we assume that nuclear electricity generation from these 800 GWe replaces coal-fired generation with present technology and without Carbon Capture and Storage, or CCS, systems. When and if CCS is available on an industrial scale, its cost may make coal less attractive than nuclear as a source of electricity.

We believe that the most likely competition for more nuclear capacity will come in the near future from coal. Indeed, renewable energy sources will be installed at a maximum rate compatible with some specific limit, like adequate siting for new hydro and windpower plants, and with the amount of subsidies that different nations will be willing to pay for these kinds of electricity. At least for baseload electricity produced in large plants and for large grids, which still will represent the great majority of future electricity production, renewables are now, and are likely to remain, more expensive than coal or nuclear. For example, the recent tender in France for a large amount of electricity to be produced by biomass gave a result of some 125 euros per MWh, as compared with 54 euros per MWh projected for power from the new Flamanville reactor, or some 60 euros per MWh for power from future nuclear plants in France, and around 46 euros per MWh for power from the existing French nuclear plants, which were cheaper to build.

To give an idea of economic performance of two other important renewables, wind and solar, we may note that in France presently the rates paid by utilities for electricity produced by wind and solar are very largely subsidized to permit the energy to develop : solar – 580 €/MWh; land-based wind power – 66 €/MWh; and offshore wind – 130 €/MWh. These rates are guaranteed for 15 to 20 years. The value of the electricity replaced is estimated at around 30 €/MWh for the French grid (ref. 8). Hopefully, renewables will make major economic progress, but the magnitude and timing of that progress cannot be predicted today.

In the UK, about half the regional governments solicited refused permission to install wind farms on their territory, which led one of the main producers of wind power equipment in the UK to lower its output substantially below its capacity.

The IEA WEO 2008 gives values for MWh from wind, gas, coal and nuclear for selected regions of the world. The values for windpower seem close to those from coal and nuclear and much cheaper than that for gas. However, there is an element that is not often included in these projections: the fact that windpower has to be taken when it is available. That means that during peak demand, for example during very hot or very cold weather, the probability of having windpower may be 25% or even less. This characteristic is certainly a problem for windpower and should normally decrease the calculated value of electricity produced by wind by a factor that may depend on local conditions, and on the type of grids (energy mix) to which the electricity is sold, but it is certainly not negligible. Therefore, even if the cost of windpower seems to be not too far from the cost of electricity generated by other fuels, electricity consumers pay a substantial subsidy by accepting windpower at prices which do not take into account the intermittent nature of windpower.

As for gas, as we mentioned earlier, the WEO 2008 indicated that the cost of baseload electricity produced by gas presently is substantially higher than that from coal, nuclear or wind. In addition, a negative evolution is to be expected for electricity produced from gas because resources of gas are being slowly but inevitably exhausted. A recent British Petroleum survey projected some 60 years for the available natural gas resource base if it is used at today's pace. This number may decrease if gas is used more extensively. In addition, the easiest and cheapest resources are the first to be exhausted and also probably those that are less sensitive from the geopolitical viewpoint. The geopolitics of gas resources are not very favorable, and this may add to the tension around prices in the future and increase concern about security of supply to which every consumer and producer of electricity is sensitive.

I.2. The periods 2010–2050 and 2100 (ref. 9, 10)

There are fewer detailed projections for the time period 2030-2050. The best-known are the IEA Energy Technology Outlook 2008 and the NEA Nuclear Energy Outlook 2008. There exist also general scenarios, notably in the book published by the Institute for Sustainable Energy Development under the auspices of UNESCO in 2009, and an older study with the participation of NEA, IAEA, Los Alamos National Laboratory, the University of Tokyo, the Russian Academy of Sciences and University Paris Dauphine, published by CGEMP in 2002, which covers the period up to 2100.

The highest values of these different projections and scenarios correspond to 1,400 GWe to 2,000 GWe of nuclear power in operation by the year 2050. The average value of the high projections for 2050 is 1,700 GWe of nuclear capacity in operation, corresponding to an annual saving of some 13 gigatonnes of CO_2 assuming that nuclear replaces coal-fired power plants without CCS. To appreciate the impact of this quantity of avoided emissions on climate change, we may mention that the difference between the unsustainable "business as usual" scenario and the sustainable "450 stabilization" of the IEA WEO corresponds to the emission of 19 Gt of CO_2 per annum in 2030. The UNESCO and CGEMP scenarios indicate values of 5,000 to 7,500 GWe of nuclear capacity in the year 2100. If realized, this would have a decisive beneficial impact on CO_2 emissions at that date.

We will not try to make a new prognosis. Rather, we will concentrate on the major factors which influence the future development of nuclear energy. We will also discuss the situation in a few selected countries that are important for the development of nuclear power, since the interplay between those factors is quite different from one country to the other.

Section II. Important factors for the development of nuclear power

II.1. General

- The will and the determination of national governments, especially of large CO_2-emitting nations, to limit their contribution to climate change, and agreement on this issue between developed and emerging countries;
- The sensitivity of nations and societies, especially certain important ones, to the health effects of local and regional pollution by fossil fuel combustion. We are thinking about SO_2, NO_x and particulate emissions, among others; recently some people in the US brought up the issue of mercury emissions;
- The ability of industry to build and operate a large fleet of nuclear plants in a safe, reliable, timely and cost-effective way.
- Support by public and national and international authorities for different fuels based on comparative evaluation of their merits and

drawbacks, including environmental and health effects, safety, economy and security of supply - and not an emotional approach for choosing solutions.
- The sensitivity of national governments and societies to the selection of the cheapest solution, considering that money or resources spent on energy or on electricity supply will restrict the available resources for other important social issues, like provision of food, health care, education and others.
- The technical and economic success of commercial-scale CCS and, in the near term, the perception of the potential for this technology.

II. 2. Weak points of nuclear power

There are also four characteristics of nuclear energy that are often considered as its weak points.

- The first is the issue of the risk associated with <u>large accidents</u>. The excellent operation of Generation 2 reactors and the improved safety characteristics of Generation 3 reactors which, even in the event of a very large, and very unlikely, accident, will not impose large damage to the environment, make the safety performance of nuclear energy very favorable compared to coal, gas and even hydro power plants. However, the public perception of nuclear plant safety may still pose a problem.
- There seems to be a consensus among scientists and decision makers that at least <u>final nuclear waste</u> should be placed in deep geologic repositories. However, the major issue here is the “NIMBY” effect - Not In My Back Yard - which makes it extremely difficult to select a site because of opposition from local people. Today in western countries, only Finland and Sweden have resolved this NIMBY issue. This issue is likely to remain difficult, but may be resolved more easily in large countries like Russia, China and India. We believe it is strongly connected with the perception by the public and politicians of the need for, and environmental and economic benefits of, nuclear energy. Technically, the risk associated with deep-geologic disposal seems much lower than that associated with waste from other types of energy production (fossil fuels) or even from other industries. It may also be minimized by introduction of fast reactors. It is, however, a delicate issue, but should not be insoluble.
- The issue of nuclear weapons proliferation is connected with sensitive technology used in the nuclear fuel cycle – uranium enrichment, spent fuel reprocessing – and not really with the construction and operation of nuclear power plants. Worldwide expansion of nuclear energy will therefore require the implementation of internationally safeguarded programs aimed to assure customers of secure fuel supply – such as nuclear fuel banks or other mechanisms envisaged under the US-inspired Global Nuclear Energy Partnership, or Russia’s Putin Initiative. In any case, for a very large fraction of the nuclear plants to be built in the next 20 to 40 years, the issue of weapons proliferation is practically resolved. Indeed, the vast majority of countries that can be expected to build nuclear plants over this period either have nuclear weapons and the technology needed to build them, or already have sensitive technology but are considered as members in good standing of the Non-Proliferation Treaty, or agree to

renounce sensitive technology in exchange for assured nuclear fuel supply.

This is even more true now that India has concluded an agreement with the Nuclear Suppliers Group, even if some details about transfer of sensitive technology (reprocessing) remain to be worked out.

- The transitional character of short-term present nuclear plant technology. If dynamic development of nuclear power is to occur, the issue of uranium resources may appear as a constraint for present nuclear power technology in the years 2050-2060, or even before. Indeed, all reasonable and speculative uranium resources (see IAEA/NEA "Red Book" 2007) (ref. 11) may be required to provide the necessary fuel for reactors built up to that time. Therefore, the key condition is the development of fast breeder reactors capable of using uranium at least 60 times more efficiently than today's reactors, which use only about 1% of natural uranium. This would extend nuclear fuel reserves, with already mined uranium, for a few thousand years of operation of thousands of GWe. In addition, breeders may justify utilization of very expensive uranium resources such as those contained in granite and seawater, extending available resources by a factor of more than 100. They can also use the world's large reserves of thorium. This would make nuclear energy a quasi-renewable energy source.

This quasi-renewable quality of nuclear energy would make its development much more attractive for society compared to the limited role of the present-day technology. Unlike nuclear fusion technology, fast breeder technology exists. But of course it must be improved, especially as regards the fuel cycle. Many fast breeder reactors have been operated successfully in the world and some are still in operation, notably the BN-600 (600 MWe) in Russia which has been operated for more than 25 years with a very high capacity factor. The Russians are building an improved version of BN-600 called BN-800 (800 MWe), now expected to operate in 2014, and have tentative plans for a 1,600-MWe fast breeder of a similar design. Meanwhile, the Indians are building a 500-MWe prototype fast breeder that is tentatively scheduled to operate in 2011, and have plans to build four more of the same type by 2020. There are indications that the Chinese, who are finishing construction of a 65-MW (thermal) fast reactor, are also interested in purchasing the Russian BN-800 technology (this was mentioned in a declaration in 2008, during a meeting between the presidents of Russia and China).

France successfully operated the fast breeder reactors Rapsodie (40 MWth), Phenix (250 MWe), and Superphenix (1200 MWe). The first two reactors were shut down at the end of their useful life, but operation of Superphenix was interrupted unfortunately by a political decision that was not justified on technical and economic grounds. France now has plans to build a prototype of a new generation of fast breeder reactors which is scheduled to operate in 2020 (under provisions of the 2006 nuclear waste program act, confirmed by a recent (2009) interview of the chairman of the Commissariat à l'Energie Atomique). Japan also plans to build a similar new-generation fast breeder reactor prototype for operation around 2025. However, some important countries, notably the US, do not consider breeder reactors as attractive, at least on the political level. That may limit the enthusiasm of these countries for nuclear power.

Section III. Country overview

Let us now review the situation in a few selected countries: the United States, France, and China (see also ref. 12)

III.1 United States

The US is the world's largest producer of nuclear energy and has more than 100 GWe installed. The present technology most used in the world – light water reactors – was developed in the US. However, the experience of construction of nuclear plants in the US in the 1970s and 1980s was quite disastrous. The initial construction schedules and budgets were exceeded by a factor of two to three, making nuclear generation not competitive with alternatives. This was not connected with the technology itself, but rather with a sharp evolution in nuclear safety requirements following the accident at Three Mile Island in 1978, requiring modifications to the design during construction, the lack of standardization of the designs, strong societal opposition, and unfavorable regulatory and legal systems (ref. 13).

In contrast, the operation of the large fleet of constructed reactors was strongly improved in the 1990s and achieved very high standards both economically and safety-wise, with average availability exceeding 90%. At the same time, a very large part of the existing reactor fleet has been or is expected to be authorized to operate for up to 60 years. So we have a contrast between poor construction experience and good operating experience. As a result, the financial community considers nuclear construction as a more risky business than construction of coal-fired power plants (the real competition to nuclear today in the US), and has penalized new nuclear construction by increasing the cost of capital for new nuclear plants to 11%/year instead of 7.8% for coal plants (see MIT 2003 report, updated in 2008 – ref. 14).

Under these conditions, the MIT report calculates that new nuclear power plants will not be competitive with coal plants without a strong penalty for CO_2 emissions. However, the same report indicates that if the capital cost of nuclear plants were the same as costs for coal or gas-fired plants, nuclear power would be competitive in the US with coal and gas-fired power on a levelized lifetime cost basis, even without a CO_2 penalty.

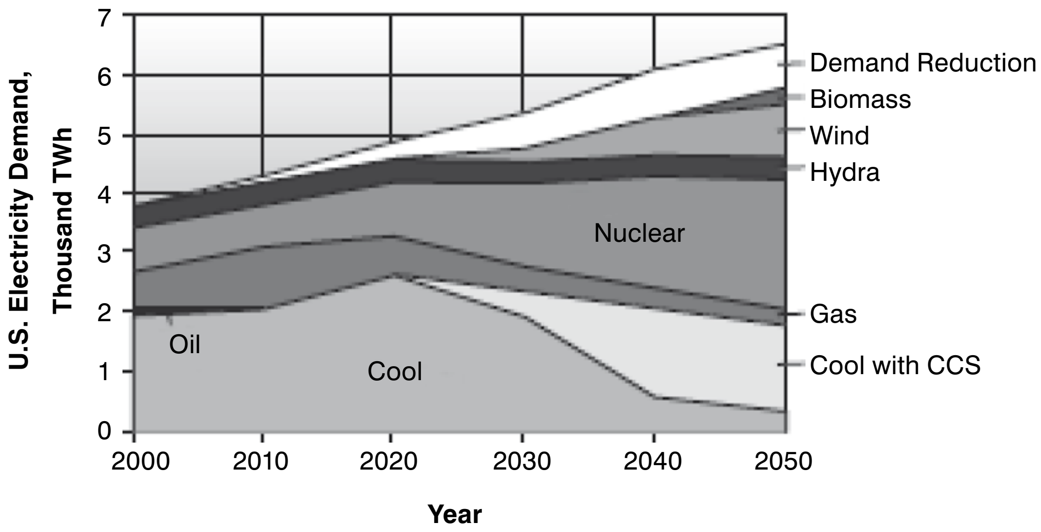
In addition, the US federal system, which devolves much authority to the states, sometimes makes it more difficult to go ahead with a large national program even if the program is strongly supported by the federal government and the Congress, which was the case for nuclear energy under Republican presidents. The administration of President Obama and the Democratic Congress are perhaps less enthusiastic about nuclear, although we don't know exactly what will be their attitude after they experience the real cost of CCS or renewable energies in limiting CO_2 emissions. Limiting CO_2 emissions is certainly now a major goal, and maybe even more important for the Obama administration than for the previous Republican administration.

Four years ago, in view to promote nuclear as a way to limit CO_2 emissions and enhance security of supply, the US Congress enacted a law that provides for substantial subsidies and loan guarantees for the first six new nuclear power plants. One might have expected that this would lead quickly to construction of these first six Generation 3 plants, especially since regulation was also streamlined – one-stop licensing, early site permitting, generic design approval. In fact there is great interest – some 17 to 20 projects are under consideration for construction – but construction has not yet started. Part of the explanation is the long time taken by the Department of Energy to implement the subsidies. It seems today that new plant orders may start in 2010.

In our opinion there exists another major issue for nuclear energy in the US. It is the disposal of spent fuel and/or final waste, which is the responsibility of the federal government. The fight between the US federal government and the state of Nevada, which opposes the construction of a spent fuel repository in Yucca Mountain, makes the success of the project very doubtful, illustrating the power of the "NIMBY syndrome" ("not in my back yard"). After years of development and expenditures of billions of dollars, it is still many years from operation, and recently the Obama administration seems to have given up on this project, bowing to Senator Reid, who is the majority leader of the Senate and Senator of Nevada. The new position is that spent fuel can be kept in storage at reactor sites or at temporary storage sites above ground or in shallow storage vaults, for 100 years. During this time, a policy can be developed for spent fuel disposal or perhaps reprocessing and reusing some "precious" elements – plutonium and the remaining uranium – and burning some of the more radiotoxic products so as to diminish sharply the radiotoxicity of the final waste and facilitate its disposal. This seems very reasonable on paper, but it requires clear development to ensure that within the necessary time – 100 years minus the 40 years or so for already operating reactors – there will be a solution. This is a fundamental issue that, as long as it is not resolved, poses problems for nuclear energy. At the same time, as we noted earlier, as long as only about 1% of natural uranium is used to produce energy – because breeders are rejected – uranium resources may become a problem in the next 30 or 40 years depending on the pace of nuclear power development. The rejection of breeders also creates a major difference between nuclear power and renewables, the first becoming only a short-time transitional solution. The 2008 MIT report observed that there is an inconsistency because some US state governments - and perhaps future federal governments – mandate a minimum use of renewables to produce electricity independent of cost in view to diminish CO_2 emissions, but the same regulations do not include nuclear energy or coal with CCS, which also minimize CO_2 emissions. Therefore, they may play against the cheapest way to reduce CO_2 emissions. This inconsistency may be explained, at least in part, by the short-term character of present nuclear technology.

On the contrary, if the breeder concept, which was initiated in the US, is accepted and developed, the use of more than 60% of natural uranium is possible and one can use very expensive uranium – perhaps even the abundant resources in seawater or granite – making

Figure 1. EPRI's PRISM analysis projects a possible electricity generation mix for achieving substantial carbon dioxide emission reductions



Source: EPRI (2009).

nuclear energy a quasi-renewable energy, as we mentioned earlier. That should make a big difference in how nuclear energy is perceived. The Global Nuclear Energy Partnership – proposed by former President Bush, began to address this issue by considering construction of a fast neutron reactor which would burn plutonium and other toxic elements. It was designed specifically to decrease the radiotoxicity of final waste and to facilitate its disposal, but could easily be converted to a breeder if desired.

It seems to us therefore that there are three major issues that will influence nuclear energy development in the US:

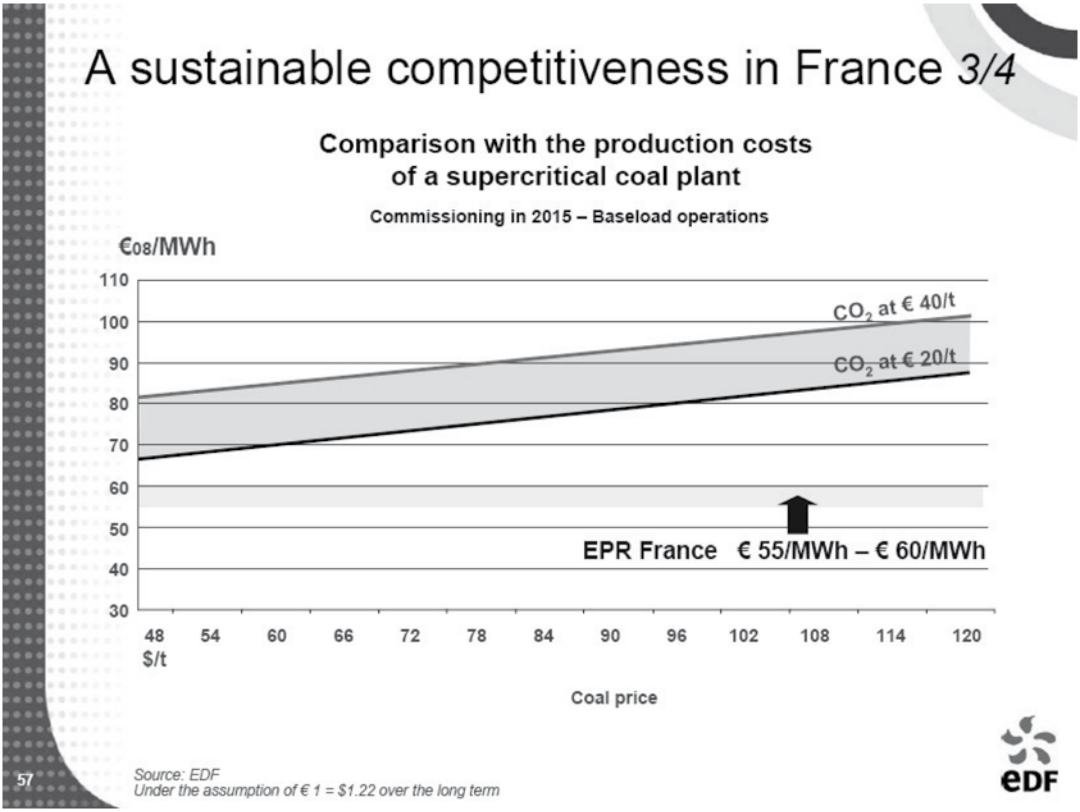
– whether or not the construction of six Generation 3 nuclear power units is realized on time and within budget;
– how the issues of reprocessing, waste disposal and ultimately the breeder reactor are addressed.
– to what extent US society will accept more expensive electricity resulting from subsidies paid for renewables

The answers to these questions may make a huge difference in the development of nuclear energy in the US, which needs many power plants and has the financial and technical ability to build such a fleet. The MIT 2008 study projects some 300 Gwe of nuclear generating capacity in the US in 2050; the recent EPRI study shows similar numbers (see Figure 1) (ref. 15).

III. 2. France

Let's look at the country which is the second largest nuclear power producer in the world today: France, with more than 60 GWe of nuclear power capacity operating successfully. Most of these nuclear power plants were built under Westinghouse license, but due to the different ways the industry operated in

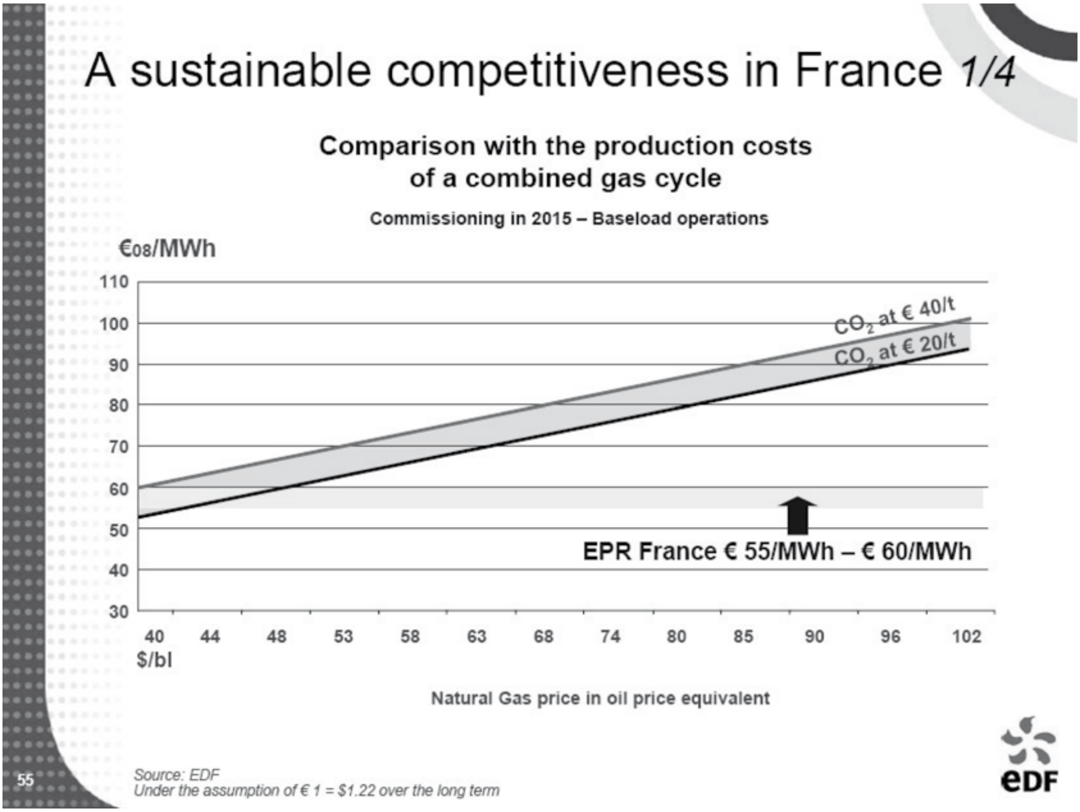
Figure 2.



France and in the US – and more importantly to continuous strong support from all political parties as well as from society at large, and to better-adapted legal and regulatory systems – the program was a success. Except for the last four units – whose design was derived from Westinghouse technology but free of the Westinghouse license, and which therefore were first-of-a-kind and experienced some delays and extra cost – the French nuclear fleet was built practically on schedule and at no more than a few percent above the initial budget. It was therefore a commercial success. The operation of this fleet is also good. Its availability is not as good as that of US reactors, about 80% compared to 90% in the US, but there are reasons for this which would be too long to explain here.

Today in France, with a reasonable assumption for the cost of oil (about $60/barrel) and of gas, and probably of coal – which is more or less linked to oil and in spite of a sharp increase in capital cost compared to existing units – nuclear power is competitive even without a CO_2 penalty for fossil fuel. We are referring here to the new 1,650-MW EPR nuclear plant under construction at Flamanville, which is expected to produce electricity at a cost of 54 € per MWh. For economic projections we refer to Figures 2, 3, 4, presented by Electricite de France in London, December 2008 (ref. 16).

Figure 3.



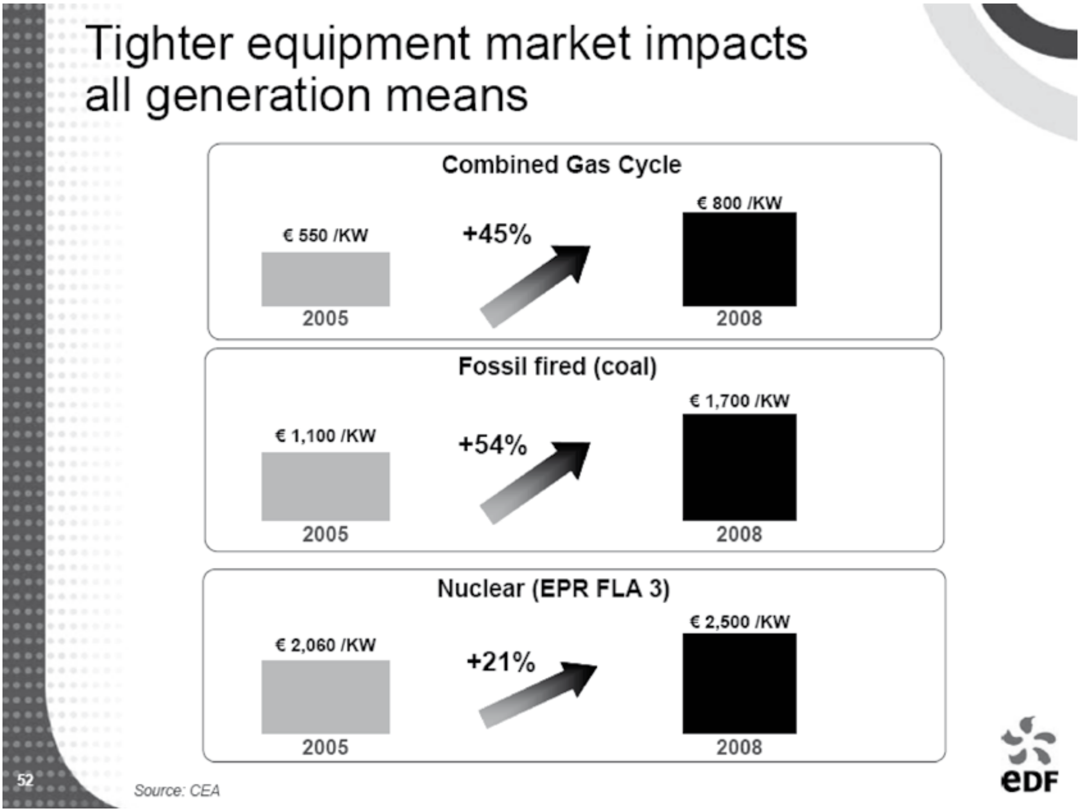
Considering this situation, France's major utilities, Electricite de France and the Franco-Belgian GDF-Suez, are very eager to build more nuclear plants. However, the need in France for baseload electricity over the next 20 years is limited; therefore, today France is building only one EPR in Flamanville and has decided to build a second one in Penly beginning in 2012. On the other hand, the two utilities mentioned above have many plans to participate in building nuclear plants outside France – EDF is participating in two units in China and proposes to build at least four in the UK, four in the US, and four in Italy. GDF-Suez wants to participate in nuclear construction in the UK. Both GDF-Suez and EDF are participating in a French consortium proposing two nuclear units in the United Arab Emirates.

The fact that they are willing to commit money for new projects shows clearly their belief that nuclear power is a sound investment in France and in other selected countries.

The two main lessons to be learned from the French experience are:

- A very dynamic expansion of nuclear power worldwide, as foreseen by the highest projections, should not be impossible from the industrial point of view. France, a medium-size country, was able to expand its nuclear capacity by more than 50 GWe in 20 years and increase nuclear's share in its electricity

Figure 4.



supply from a few percent to 80% over this period.

- Strong and constant support for the nuclear program from politicians and to a large extent from society, combined with a rational industrial organization and a good base of technically skilled workforce led to a technically and economically successful program. Today, French nuclear power plants and, more generally, the French nuclear industry are important assets for the French economy upon which many other countries look with envy.

III. 3. China

Let's now have a look at the situation in China. This country, according to the WEO 2008, will have the largest increase of electricity demand in the world over the next 20 years – more than one-third of the world increase, or some 500 GWe. China has the financial and technical resources to achieve it. For a very large majority of these new plants – more than 80% – the choice will be between coal and nuclear. According to a Chinese official cited in the specialized publication Nucleonics Week, rising prices of imported coal, followed by higher prices for domestic coal, make nuclear plants economically more attractive than coal-fired plants (see Platts Nucleonics Week, 30 April 2009).

We assume that this statement concerns modern coal plants which strictly limit emissions of SO_2, NO_x, and particulates according to international standards.

The older, much cheaper but more polluting technology is still used for some construction of new coal-fired plants in China, but the disastrous health effects of these plants on a local level (hundreds of thousands of premature deaths each year) but also on a regional level (South Korea, Japan or even California) tend to favor the more expensive clean coal plants.

The above facts, combined with the saturation of domestic rail traffic with coal transports and with the will of the Chinese government to limit the increase in CO_2 emissions, make nuclear very attractive. The Chinese government is now giving nuclear development high priority. Recently, the goal for nuclear electricity production by 2020 was increased from 3.5% to 5% or more of total electricity production, versus today's level of less than 2%. There are also indications of plans for some 60 GWe or more of nuclear generating capacity in operation in 2020 and 100 GWe to 160 GWe by 2030. Today there are less than 9 GWe of nuclear capacity in operation in China.

From the industrial point of view, the situation is quite favorable. Generation 2 reactors built recently by Russian, Canadian and French industry were, with some exceptions, on schedule and within budget, as were Generation 2 reactors built by domestic industry. China ordered in 2008 Generation 3 reactors of foreign technology from Toshiba/Westinghouse (four AP1000 units of 1,100 MWe) and from Areva (two 1,650-MWe EPR units), and in the near future may order two to four 1,200-MWe VVERs of Russian design. Chinese industry is also building "Generation 2+" reactors of 1,000 MWe class, designed domestically based on French technology.

The Chinese industry is also developing, in cooperation with Toshiba/Westinghouse, a larger version of the AP1000, designed to produce up to 1,400 MWe, planned for operation in 2017–2019, and may later design a 1,700-MWe PWR based on Toshiba/Westinghouse technology (see Platts Nucleonics Week, 23 April 2009 and 28 May 2009 – ref. 17). These large Chinese-Japanese-American designs are expected to lower substantially the cost per kilowatt-hour (see NW 18 October 2007). Other sources (Alain Tournyol du Clos, the nuclear attaché of the French embassy in China, 2009), give indications of tentative plans for 70 GWe of nuclear capacity in 2020 and 250 GWe in 2050, producing some 20% of China's total electricity production.

We may conclude that strong development of nuclear energy is under way in China, maybe even stronger than assumed in most scenarios mentioned in this paper.

In addition, the Chinese nuclear industry is expanding quickly and it will be not a surprise if in 15–20 years from now, it has become a major player (exporter) on the world market. Development similar to that undergone by the South Korean nuclear industry may indeed be expected.

Conclusion

There are strong signs that nuclear energy development over the next 20 to 40 years will be very dynamic, at least in Asia - China, India, Japan, and South Korea. On the other hand, there are large uncertainties regarding the pace of development in other parts of the world, notably in the US and some European countries. We can see that Asian industry – currently based in Japan and South Korea – already plays a major role in nuclear development worldwide and will likely play an even more important role in the future when the Chinese and Indian nuclear industries mature and strike out to foreign markets.

The development of nuclear energy in the world, an essential element of sustainable development, could be strongly accelerated if nuclear energy – as would appear rational – were accepted in the future post-Kyoto climate change agreement as a clean technology eligible for credits under the Clean Development Mechanism.

Our societies face two major challenges: now, climate changes linked to human activities; and soon, depletion of fossil fuel resources.

To avoid major catastrophes connected with these challenges, we have to use all available tools, in particular efficient and parsimonious use of energy. But we need also new energy sources, and in particular nuclear energy. It is to be hoped that our societies will be able to develop these new sources in a safe and timely manner so as to prevent, or at least to mitigate, the disruption and the suffering linked to energy crises.

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