NUCLEAR ENERGY – STATUS AND OUTLOOK
ÉNERGIE NUCLÉAIRE – SITUATION ACTUELLE ET PERSPECTIVES

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Abstract

Rising expectations best characterize the current prospects of nuclear power in a world that is confronted with a burgeoning demand for energy, higher energy prices, energy supply security concerns and growing environmental pressures. It appears that the inherent economic and environmental benefits of the technology and its excellent performance record over the last twenty years are beginning to tilt the balance of political opinion and public acceptance in favour of nuclear power. Nuclear power is a cost-effective supply-side technology for mitigating climate change and can make a substantial contribution to climate protection.

This paper reviews the current status of nuclear power and its fuel cycle and provides an outlook on where nuclear power may be headed in the short-to-medium run (20 to 40 years from now).

Résumé

Le mieux que l'on puisse dire à propos des perspectives de l'électronucléaire, c'est que cette technologie correspond à des attentes accrues suscitées par une demande énergétique en plein essor, des prix de l'énergie plus élevés, des préoccupations concernant la sécurité des approvisionnements énergétiques et des pressions croissantes en matière d'environnement. Il semble que ses avantages économiques et environnementaux intrinsèques et son excellent bilan de performance au cours des vingt dernières années commencent à faire pencher la balance en sa faveur – tant en ce qui concerne les opinions politiques que son acceptation par le public. Il s'agit en effet d'une technologie rentable, axée sur l'offre qui, en atténuant les changements climatiques, peut contribuer sensiblement à la protection du climat.

Le présent document fait le point sur la situation actuelle de l'électronucléaire et de son cycle du combustible et présente les perspectives de ce secteur envisageables à court et moyen terme (pour les 20 à 40 prochaines années).

1 Nuclear Power Today

1.1 Nuclear Power Plants in Operation and Under Construction

Worldwide there are 435 nuclear power reactors in operation, totalling 367 GW(e) of generating capacity (see Table 1). In 2005 nuclear power supplied about 16% of the world's electricity. The world's fleet of nuclear power reactors maintained a high average availability factor of 81 percent (see Figure 1) which in 2005 allowed a record production of 2 626 TWh. Data for 2006 are likely to show a decrease in this percentage as retirements during the year exceeded new capacity brought on line while total electrical generating capacity (nuclear power plus all other sources) continued to grow at almost 4% per year. Moreover, the past increase in availability factors that has helped keep the nuclear share relatively stable for the last 15 years despite limited investment in new build appears currently to have plateaued.

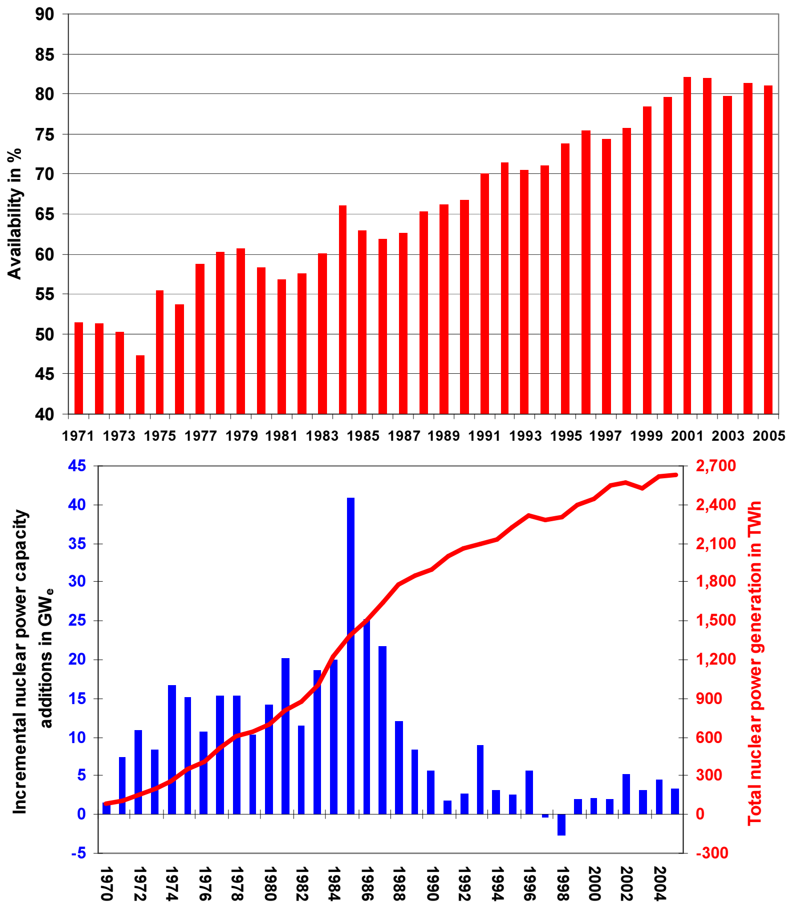

Figure 1: Average availability of the world's fleet of nuclear power plants (top) and incremental nuclear generating capacities and nuclear electricity generation (bottom)

Two new reactors were connected to the grid in 2006, one in China and one in India. This compares with four new connections in 2005 (plus the reconnection of one laid-up reactor) and five new connections in 2004 (plus one reconnection). There were eight nuclear power reactor retirements in 2006: the two Kozloduy Units 3 & 4 in Bulgaria and Bohunice-1 in Slovakia in compliance with the accession arrangements with the European Union, the UK's four oldest reactors at Dungeness A and Sizewell A after more than 40 years of operation, and Jose Cabrera-1 in Spain. This compares to two retirements in 2005 and five in 2004. The resulting net decrease in global nuclear generating capacity during 2006 was 806 MW(e).

Table 1: Nuclear Power Reactors in Operation and Under Construction in the World (as of 1 January 2007)[a]

COUNTRY	Reactors in Operation		Reactors under Construction		Nuclear Electricity Supplied in 2005		Total Operating Experience through 2005	
	No of Units	Total MW(e)	No of Units	Total MW(e)	TW·h	% of Total	Years	Months
ARGENTINA	2	935	1	692	6.4	6.9	54	7
ARMENIA	1	376			2.5	42.7	38	3
BELGIUM	7	5 801			45.3	55.6	205	7
BRAZIL	2	1 901			9.9	2.4	29	3
BULGARIA	2	1 906	2	1 906	17.3	44.1	137	3
CANADA	18	12 584			86.8	14.6	442	8
CHINA	10	7 572	4	3 610	50.3	2.0	56	11
CZECH REPUBLIC	6	3 373			23.3	30.5	86	10
FINLAND	4	2 676	1	1 600	22.3	32.9	107	4
FRANCE	59	63 363			430.9	78.5	1 464	2
GERMANY	17	20 339			154.6	31.0	683	5
HUNGARY	4	1 755			13.0	37.2	82	2
INDIA	16	3 483	7	3 112	15.7	2.8	252	0
IRAN, ISLAMIC REPUBLIC OF			1	915				
JAPAN	55	47 593	1	866	280.7	29.3	1 221	3
KOREA, REPUBLIC OF	20	16 810	1	960	139.3	44.7	259	8
LITHUANIA	1	1 185			10.3	69.6	39	6
MEXICO	2	1 360			10.8	5.0	27	11
NETHERLANDS	1	450			3.8	3.9	61	0
PAKISTAN	2	425	1	300	2.4	2.8	39	10
ROMANIA	1	655	1	655	5.1	8.6	9	6
RUSSIAN FEDERATION	31	21 743	7	4 595	137.3	15.8	870	4
SLOVAKIA	5	2 034			16.3	56.1	112	6
SLOVENIA	1	656			5.6	42.4	24	3
SOUTH AFRICA	2	1 800			12.2	5.5	42	3
SPAIN	8	7 450			54.7	19.6	237	2
SWEDEN	10	8 916			69.5	44.9	332	6
SWITZERLAND	5	3 220			22.1	32.1	153	10
UKRAINE	15	13 107	2	1 900	83.3	48.5	308	6
UNITED KINGDOM	19	10 982			75.2	19.9	1 377	8
UNITED STATES OF AMERICA	103	98 145			780.5	19.3	3 087	6
Total[b]	435	367 479	31	23 711	2 625.9		11 991	8

a. Data are from the Agency's Power Reactor Information System (http://www.iaea.org/programmes/a2/index.html)
b. Note: The total includes the following data in Taiwan, China:
— 6 units, 4884 MW(e) in operation; 2 units, 2600 MW(e) under construction;
— 38.4 TW·h of nuclear electricity generation, representing 20.3% of the total electricity generated in 2005;
— 146 years, 1 month of total operating experience.

Using the International Atomic Energy Agency (IAEA) definition that construction begins with the first pouring of concrete, there were five construction starts in 2006: Lingao-4 (1 000 MW(e)) and Qinshan II-3 (610 MW(e)) in China, Shin Kori-1 (960 MW(e)) in the Republic of Korea, and two

35 MW(e)/200 MW(th) reactors in the Russian Federation for a barge-mounted cogeneration plant to produce both electricity and district heat. In addition, active construction resumed at Beloyarsk-4 in Russia.

The five construction starts in 2006 and the resumption of construction at Beloyarsk-4 compare to three construction starts in 2005 plus resumed construction at two reactors. In 2004 there were two construction starts plus resumed construction at two other reactors.

1.2 Nuclear Capacity Expansion

Current expansion, as well as near-term and long-term growth prospects, remain centred in Asia. As shown in Table 1, of the 31 reactors under construction by the end of 2006, 17 are in Asia. Twenty-six of the last 36 reactors to have been connected to the grid were in Asia. Increased nuclear capacity in some countries (e.g., USA, Belgium, Finland, Spain, Sweden, Switzerland and Germany) is the result of uprating existing plants, which can add up to 20% of additional capacity. This is a highly cost-effective way of bringing new capacity on-line.

In 2006, the US Nuclear Regulatory Commission (NRC) approved eight more licence renewals of 20 years each (for a total licensed life of 60 years for each nuclear power plant), bringing the total number of approved licence renewals to 47 at the end of the year. In the USA there are proposals for over twenty new reactors and the first combined construction and operating licenses for these are likely to be applied for in 2007. In the Netherlands, the government granted a 20-year extension to the Borssele nuclear power plant for a total licensed lifetime of 60 years. The government also set conditions for new nuclear plants, a shift from the country's earlier nuclear power phase-out policy. The French Nuclear Safety Authority (ASN) conditionally cleared Electricité de France's twenty 1 300 MW(e) pressurized water reactors for an additional ten years of operation, for a total currently licensed period of 30 years. As well, in May 2006 Electricité de France (EDF) gave the go-ahead for the construction of a 1 600 MW(e) European pressurised water reactor (EPR) unit at Flamanville at an estimated cost of €3.3 billion. The Flamanville site already hosts two 1 330 MW(e) pressurised water reactors (PWRs). In Canada, Point Lepreau received a three-year licence renewal through 2011.

The completion date of Teosulliden Voimy Oy's (TVO's) project to build a European Pressurized Water Reactor (EPR) — the first nuclear power plant ordered in Western Europe in 15 years at the Olkiluoto site in Finland — has been pushed back by over a year. Delays have been caused by non-conformity with specifications of the concrete used in the new unit's foundations as well as delivery problems with subcontractors. Observers suggest that the problems faced in building Olkiluoto-3 are common for a first-of-a-kind plant, especially when most of the subcontractors involved have not worked to nuclear standards for many years, if at all. It is of the utmost importance to build on the lessons learned for future construction projects.

1.3 Rising Expectations

1.3.1 Fossil Fuel Prices

Higher world market prices for fossil fuels have put nuclear power on the agenda of many countries currently without nuclear power and have revived interest in countries with stagnating nuclear power programmes. Because they are driven largely by demand, current high prices for fossil fuels are likely to be more permanent than were those of the 1970s. Energy demand growth driven by continuing economic development is expected to persist — hence the pressure on prices is likely to last. High world market prices for fossil fuels have the greatest impact on countries that are highly dependent on energy imports, particularly developing countries with relatively scarce financial resources. A doubling of international prices translates into generation cost increases of about 35–45% for coal-fired electricity and 70–80% for natural gas. In contrast, a doubling of uranium prices (which have also increased recently — see below) increases nuclear generating costs by about 5%.

Rising fossil fuel and uranium prices not only affect the relative competitiveness of electricity generating options but can also affect supply security. Concerns about energy supply security were important in the nuclear expansion programmes of France and Japan at the time of the 1970s oil shocks, they are one of the arguments advanced in Europe today for expanding nuclear power, and they may prove an important motivation for some countries currently without nuclear power to strongly consider the possibility.

Developing countries with sizable domestic fuel resources have recently begun looking at the possibility of introducing nuclear power in the 2015–2020 time frame. These include OPEC members Indonesia and Nigeria as well as six member countries of the Gulf Cooperation Council. For them the immediate impact of increased oil prices is not the same as that for oil importers, but the logic may lead in the same direction. Nuclear power can be a vehicle to increase export revenues by substituting domestic demand for natural gas (and to a lesser extent oil) with nuclear power. The additional export earnings may well finance the construction of part or all of a country's first nuclear power plants. Also some oil and gas exporters, for example Indonesia, may be interested in nuclear power as a way to reduce currently high rates of oil and gas resource depletion.

1.3.2 Economics

Nuclear power plants have a 'front-loaded' cost structure, i.e. they are relatively expensive to build but relatively inexpensive to operate. The low share of uranium costs in total generating costs protects plant operators against resource price volatility. Thus existing well-run operating nuclear power plants continue to be a generally competitive profitable source of electricity, but for new construction, the economic competitiveness of nuclear power depends on several factors. First it depends on the alternatives available. Some countries are rich in alternative energy resources, others less so. Second, it depends on the overall electricity demand in a country and how fast it is growing. Third, it depends on the market structure and investment environment. Other things being equal, nuclear power's front-loaded cost structure is less attractive to a private investor in a liberalized market that values rapid returns, than to a government that can look longer-term, particularly in a regulated market that assures attractive returns. Private investments in liberalized markets will also depend on the extent to which energy-related external costs and benefits (e.g. pollution, greenhouse gas (GHG) emissions, waste and energy supply security) have been internalized. In contrast, government investors can incorporate such externalities directly into their decisions. Also important are regulatory risks. Political support for nuclear power varies across countries, and, within a given country, it can change over time. An investor must weigh the risk of political shifts that might require cancellation of the project midstream or introduce delays and costs that would vitiate an originally attractive investment. Different countries also have different approval processes. Some are less predictable than others and create greater risks, from the investor's perspective, of expensive interventions or delays.

In Japan and the Republic of Korea, the relatively high cost of alternatives benefits nuclear power's competitiveness. In India and China rapidly growing energy needs encourage the development of all energy options. In Europe, high electricity prices, high natural gas prices and GHG emission limits under the European Union Emission Trading Scheme (EU ETS) have improved the business case for new nuclear power plants. In the USA the 2005 US Energy Act significantly strengthened the business case for new construction. Previously new nuclear power plants had not been an attractive investment given plentiful low-cost coal and natural gas, no GHG emission limits, and investment risks associated from the lack of recent experience in licensing new nuclear power construction. The provisions of the Energy Act, including loan guarantees, government coverage of costs associated with certain potential licensing delays and a production tax credit for up to 6 000 MW(e) of advanced nuclear power capacity, have improved the business case enough to prompt announcements by nuclear firms and consortia of possible Combined License (COL) applications covering approximately 25 possible new reactors in the USA.

Figure 2 summarizes estimates from seven recent studies of electricity costs for new power plants with different fuels. Except for oil-fired electricity generation (estimated in only one study) the high end of each cost range is at least 100% higher than the low end. This is due partly to different techno-economic assumptions across the studies, but also to the factors listed above. Moreover, the ranges in Figure 2 incorporate only internalized costs. If high enough priority is given to improving national energy self-sufficiency, for example, the preferred choice in a specific situation might not be the least expensive.

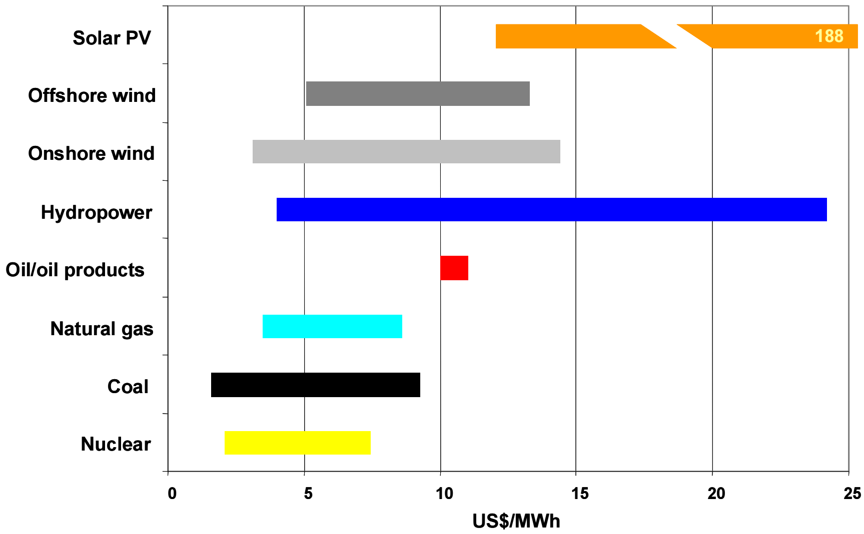

Figure 2: The ranges of levelized costs associated with new construction as estimated in seven recent studies for electricity generating technologies in different countries (PV: photovoltaic).

1.3.3 Energy Security

The best way to strengthen a country's energy supply security is by increasing the number and resiliency of energy supply options, and for many developing countries, expanding nuclear power would increase the diversity of energy and electricity supplies. Moreover, nuclear power has two features that generally further increase resiliency. The first was noted above: that nuclear electricity generating costs are much less sensitive to changes in resource prices than are fossil-fired electricity generating costs. Second, the basic fuel, uranium, is available from diverse producer countries, and small volumes are required, making it easier to establish strategic inventories. In practice, the trend over the years has been away from strategic stocks toward supply security based on a diverse well-functioning market for uranium and fuel supply services. But the option of relatively low-cost strategic inventories remains available for countries that find it important.

1.3.4 Environment

Environmental considerations may weigh increasingly in favour of nuclear power. Nuclear power at the point of electricity generation does not produce any emissions that damage local air quality, cause regional acidification or contribute to climate change. There are some emissions associated with plant construction and the nuclear fuel cycle (i.e. mining, enrichment, transportation, etc.). But on a per kWh basis over the lifetime of the plant these are far below emissions from fossil fired power plants and at least comparable to those of wind power and biomass conversion (see Figure 3).

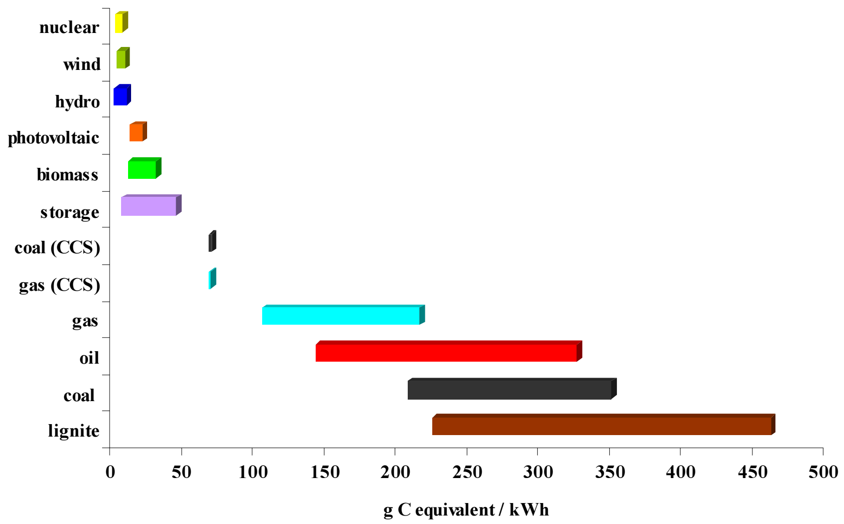

Figure 3: Life-cycle GHG emissions from different electricity generating chains [1]

The Kyoto Protocol, which entered into force in February 2005, requires most developed countries to limit their greenhouse gas (GHG) emissions in the 'first commitment period', 2008–2012. Before the Protocol's entry into force, nuclear power's advantage of very low GHG emissions was largely invisible to investors, as the lack of restrictions or taxes on such emissions meant there was no economic value to their avoidance. Different countries have adopted different policies to meet their Kyoto Protocol limits. Not all benefit nuclear power despite its low GHG emissions, but in the longer run, the limits on GHG emissions should make nuclear power increasingly attractive. For example, a charge on carbon dioxide emissions of € 20 per tonne of carbon dioxide (tCO_2), would improve a nuclear plant's generating costs relative to a modern coal-fired plant by 10%-20%. During 2006, CO_2 traded in Europe between € 6 and € 29 per tCO_2.

With respect to emission reductions after the first commitment period, the 11th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP11) in 2005 decided to start discussions in an ad hoc working group, which has now met twice, in May and November 2006. Discussions are still in an early phase, and have not yet begun to address specifics such as the current exclusion of nuclear power projects from the clean development mechanism and joint implementation.

1.3.5 Political and Public Acceptance

Rising expectations for nuclear power are also founded in positive government statements about, and newly expressed interest in, the technology. In March of 2005 high level representatives of 74 governments, including 25 representatives at the ministerial level, gathered in Paris at a conference organized by the IAEA to consider the future role of nuclear power. The vast majority of participants affirmed that nuclear power can make a major contribution to meeting energy needs and sustaining the world's development in the 21st century, for a large number of both developed and developing countries.

A meeting organized by the IAEA in December 2006 to examine *Issues for the Introduction of Nuclear Power* was attended by 28 countries that currently do not operate nuclear power plants.

Contributors to the rise in expectations are nuclear power's good and lengthening track record, the persistent growth in global energy needs, new environmental constraints, concerns in some countries

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[1] Energy storage technologies include: compressed air, pumped hydro, battery systems

about energy supply security, and specific nuclear power expansion plans in countries such as India, China, Japan, the Republic of Korea and the Russian Federation. Nuclear power's good and lengthening track record is reflected in the more than 12 400 reactor-years of experience to date, improved capacity factors, lower generating costs and an excellent safety record.

There has been one accident with major off-site consequences — at Chernobyl in 1986. That accident cost lives and caused widespread misery. But it also brought about major changes including the founding of a 'safety culture' of constant improvement, thorough analysis of experience and sharing of best practices. This safety culture has been demonstrating its effectiveness for nearly two decades, and this safety record provides the basis for countries considering constructing nuclear power plants.

Public policies and public opinion towards nuclear power development remain divided — especially in Europe. While some countries vigorously support nuclear development others have either placed a total ban on atomic energy (Austria, Denmark, Ireland) or have legislated nuclear phase-out policies (Sweden, Belgium, Germany). A recent global public opinion survey commissioned by the IAEA shows a continuing diversity of views. The survey polled 18 000 people in 18 countries. There was substantial diversity across countries. Aggregated results are shown in Figure 4. A majority of 62% wished to keep current plants running at the same time that a majority of 59% did not want new plants built. A follow-up question was also asked that included brief information about nuclear power's very low greenhouse gas emissions, following which the percentage in favour of expanding nuclear power rose from 28% to 38%, and the percentage opposing expansion dropped from 59% to 47%.

Figure 4: Aggregate results of a global public opinion poll. Source: (IAEA, 2006a)

Public policies with regard to nuclear power plants often reflect the views of the public, but this is not always the case. Recently the mood has been changing, and more positive attitudes towards nuclear power are emerging in some countries. For example, in the United Kingdom positive public attitudes toward nuclear power are evidently becoming more favourable, and the UK government has given the clearest indication yet that it will change policy to encourage new nuclear power with its new energy policy review commissioned to supersede the 2003 government white paper. The majority of the public also supports this policy change. According to a Mori survey of 1 500 people conducted in early 2006, 54% said they would accept new nuclear power stations if they would help fight climate change. And 48% agreed that the nation needs nuclear power because renewables alone are not able to meet its electricity needs. Polls also found that pitting nuclear power against renewables hurt support for nuclear power while a combination of both appears often quite acceptable.

In Poland, where nuclear development was halted by a Parliamentary decision in 1990, the Council of Ministers approved a draft energy policy in early 2005 that explicitly includes nuclear power.

In the United States, public support for the continued use of nuclear energy now stands at a record high of 70% and shows a continued upwards trend, according to a new opinion poll conducted for the US Nuclear Energy Institute (NEI).

On the back of these recent positive political developments in Europe a cross-party group of 25 EU members of parliament endorsed the vital contribution of nuclear energy in countering climate change and called for more investment in all low- or zero-carbon power generation technologies. They said nuclear power should remain central in the EU's energy and environmental policy planning, and called for a global strategy to address climate change.

1.4 Uranium Availability

1.4.1 Short-term Outlook

Driven partly by the renewal of interest in nuclear power and partly by several technical mishaps at key mines, uranium spot prices continued to rise throughout 2006, reaching \$72/lbU_3O_8 in January 2007, more than ten times higher than their historic low in December 2000 (see Figure 5).[2] The price increase triggered the beginning of a correction of an almost twenty-year old market anomaly. Exploration and mine development have begun to follow uranium prices with the number of exploration and mining companies mushrooming ten-fold and exploration expenditures increasing four-fold between 2001 and 2006.

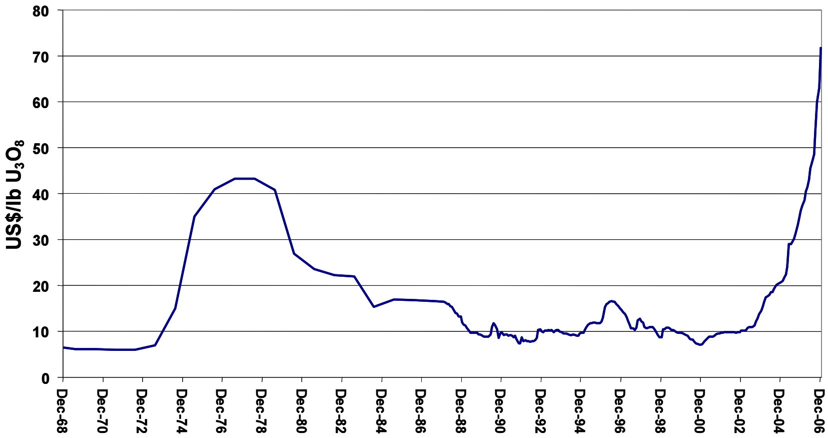

Figure 5: Development of uranium prices, 1968 - 2006. Source: Adapted from NEA/IAEA, 2006.

The market anomaly is shown in Figure 6. Until the early 1990s global uranium production exceeded reactor requirements by unnaturally wide margins (even when accounting for the fact that a fair share of the excess production served military purposes) compared with what a 'balanced market' would suggest. After the mid-1980s when growth prospects for nuclear power slowed down, uranium production began to adjust to long-term demand expectations. Then after 1990 the appearance of secondary supplies, i.e. uranium derived from warheads, military and commercial inventories, re-enrichment of depleted uranium tails as well as enriching at lower tail assays, reprocessed uranium and mixed oxide fuel drastically reduced demand for fresh uranium. In addition, new entrants to the world uranium market, e.g., the Russian Federation, Kazakhstan and Uzbekistan, further exerted competitive pressures.

1.4.2 Uranium Resources

With long-term demand on the rise and a growing perception that secondary sources, which have covered the difference, are becoming exhausted[3], it has become obvious that soon primary production of fresh uranium will have to meet reactor requirements. The latest estimate of global uranium

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[2] Most uranium, however, is bought on long-term contracts, and between 2000 and 2006 medium- and long-term uranium prices only increased by 20–50%.

[3] Precise information on secondary sources is not readily available, and possible future political decisions on releasing military material for commercial purposes add an additional element of uncertainty.

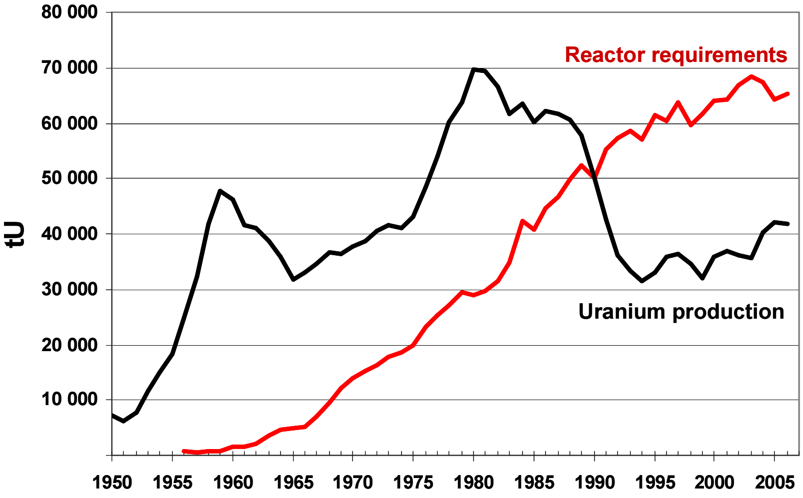

Figure 6: Global annual uranium production and reactor requirements, 1950-2006[4]. Source: Adapted from NEA/IAEA, 2006.

resources published by the OECD Nuclear Energy Agency (NEA) and the IAEA in 2006, *Uranium 2005: Resources, Production and Demand*, shows substantial uranium resources are available, but cautions that it will require significant mine development to turn "uranium in the ground into yellowcake in the can". As so often in the area of resource economics, it is not the physical occurrence in the Earth's crust that is the limiting factor but timely investment in exploration and mining capacity. The time lag between successful exploration and the availability of uranium from new mines can be on the order of 5 to 10 years and more. Hence a quick market turn-around regarding new supplies is next to impossible as both exploration and mining investment picked up momentum only a few years ago. Hence, secondary sources will remain a necessary supplement for another 5 to 10 years.

Because of these lead times, the ability of the uranium and nuclear fuel cycle industry to respond to a nuclear renaissance has been questioned. Especially the issue of long-term uranium supply has been at the centre of debates about nuclear power's role in sustainable energy development. Statements like "the reserve-to-production ratio of uranium is only some 60 years" (essentially implying to the uninitiated that new build NPPs with an anticipated economic life time of 60 years will run out of nuclear fuel before their date of decommissioning) are not only misleading but irrelevant.

Uranium supply is usually framed within a short-term market perspective that focuses on prices, on who is producing with what resources, where might capacity exist to meet short term demand peaks, and how does this balance with demand? In essence, it is the skill of understanding supply/demand/price interdependencies and dynamics for known uranium resources. In contrast, long-term supply is a question of the replenishment of known resources with new ones presently unknown or from known deposits presently not producible for techno-economic reasons. Here the development of advanced exploration and production technologies are essential prerequisites for the long-term availability of uranium. Demand prospects and competitive markets are the essential drivers for technology change and investment to ensure sufficient long-term supply both through the discovery of new resources and the exploitation of known resources previously not accessible.

Identified conventional uranium resources are currently estimated at 3.8 million tonnes (Mt U) for resources recoverable at costs below $80/kg U and at 4.7 Mt U for costs below $130/kg. For reference, the spot market price of uranium at the end of 2006 was $186/kg U. For both categories these estimates have increased in the last two years due both to new discoveries and to the reallocation of

[4] Data for 2006 estimated

some resources from higher cost categories to lower cost categories. *Undiscovered conventional resources* add another estimated 7.1 Mt U at costs less than $130/kg U. This includes both resources that are expected to occur either in or near known deposits, and more speculative resources that are thought to exist in geologically favourable, yet unexplored areas. There are also an estimated further 3.0 Mt U of speculative resources for which production costs have not been specified.

Unconventional uranium resources and thorium further expand the resource base. Unconventional uranium resources include about 22 Mt U that occur in phosphate deposits and up to 4 000 Mt U contained in sea water. The technology to recover uranium from phosphates is mature, with estimated costs of $60–100/kg U. The technology to extract uranium from sea water has only been demonstrated at the laboratory scale, and extraction costs are currently estimated at $300/kg U. Thorium is three times as abundant in the Earth's crust as uranium. Although existing estimates of thorium reserves plus additional resources total more than 4.5 Mt, such estimates are considered still conservative. They do not cover all regions of the world, and the historically weak market demand has limited thorium exploration.

Table 2 summarizes the potential longevity of the world's conventional uranium resources. For both the current LWR once-through fuel cycle and a pure fast reactor fuel cycle[6], the table estimates how long conventional uranium resources would last, assuming electricity generation from nuclear power stays at its 2004 level.

Table 2: Years of Uranium Availability for Nuclear Power[5]

Reactor/fuel cycle	Years of 2004 world nuclear electricity generation with identified conventional resources	Years of 2004 world nuclear electricity generation with total conventional resources	Years of 2004 world nuclear electricity generation with total conventional and unconventional resources
Current once-through fuel cycle with light water reactors	85	270	675
Pure fast reactor fuel cycle with recycling	5 000–6 000	16 000–19 000	40 000–47 000

Exploitation of undiscovered resources would increase this to several hundreds of years, though significant exploration and development would be required to move these resources to more definitive categories. However, given the limited maturity and geographical coverage of uranium exploration worldwide there is considerable potential for discovery of new resources of economic interest.

1.5 Spent Fuel and Reprocessing

Annual discharges of spent fuel from the world's reactors total about 10 500 metric tonnes of heavy metal (t HM) per year. Two different management strategies are being implemented for spent nuclear fuel. In the first strategy, spent fuel is reprocessed (or stored for future reprocessing) to extract usable material (uranium and plutonium) for new mixed oxide (MOX) fuel. Approximately one third of the world's discharged spent fuel has been reprocessed. In the second strategy, spent fuel is considered as waste and is stored pending disposal. Based on now more than 50 years of experience with storing spent fuel safely and effectively, there is a high level of confidence in both wet and dry storage

[5] The values in the last row of Table 2 assume that fast reactors allow essentially all uranium-238 to be bred to plutonium-239 for fuel, except for minor losses of fissile material during reprocessing and fuel fabrication. The resulting values are higher than estimates published in a similar table in *Uranium 2005: Resources, Production and Demand.* The latter estimates assume that not all uranium-238 is bred to plutonium-239 for fuel.

technologies and their ability to cope with rising volumes pending implementation of final repositories for all high level waste.

As of today, China, France, India, Japan, the Russian Federation and the UK either reprocess, or store for future reprocessing, most of their spent fuel. Canada, Finland, Sweden and the USA have currently opted for direct disposal, although in February 2006, the USA announced a Global Nuclear Energy Partnership (GNEP) initiative, which includes the development of advanced recycling technologies for use in the USA.

Most countries have not yet decided which strategy to adopt. They are currently storing spent fuel and keeping abreast of developments associated with both alternatives.

In 2006, final testing for commissioning Japan's new Rokkasho reprocessing plant began in March and is expected to take 17 months. The Rokkasho plant's final product is a MOX powder, which was produced for the first time in November. Commercial-scale production of MOX powder is expected in the second half of 2007. The plant's maximum reprocessing capacity will be 800 tonnes of uranium per year, enough to reprocess 80% of Japan's annual spent fuel production. In China non-radioactive commissioning was completed for the country's first experimental reprocessing plant. Development of new recycling processes is also taking place, e.g. the UREX+ process in the USA to recycle spent nuclear fuel, without separating out pure plutonium, and fabricate the separated transuranic elements into fuel for fast advanced burner reactors.

In 2006, approximately 180 tonnes of civil origin MOX fuel were loaded on a commercial basis in more than 30 pressurized water reactors (PWRs) and two boiling water reactors (BWRs) in Belgium, France, Germany and Switzerland. The share of MOX fuel assemblies in the core varied from 25% to 50%. No substantial increase in MOX fuel requirements is expected until 2010, when Japan plans to start its 'pluthermal' programme to load MOX fuel in 16 to 18 power reactors. In India, some 50 MOX fuel bundles have recently been irradiated in a pressurized heavy water reactor (PHWR 220) on an experimental basis.

Belgonucleaire's MOX fuel plant in Dessel ceased production in August 2006 with decommissioning scheduled for completion by 2013. As a result of this, there remain two significant MOX fuel fabricators in France and the UK.

1.6 Waste and Decommissioning

The Finnish, Swedish and US repository programmes continue to be the most developed, but none is likely to have a repository in operation much before 2020. The world's one operating geological repository is the Waste Isolation Pilot Plant (WIPP) in the USA. Since 1999, it has accepted long lived transuranic waste generated by research and the production of nuclear weapons, but no waste from civilian nuclear power plants. In 2006 the US Environmental Protection Agency approved WIPP's first recertification application, submitted in 2004. Recertification is required every five years. France's new legislation on spent fuel management and waste disposal, which established spent fuel reprocessing and recycling of usable materials as French policy, also established deep-geologic disposal as the reference solution for high level long lived radioactive waste. The legislation sets goals to apply for a licence for a reversible deep geological repository by 2015 and to open the facility by 2025. It also calls for operation of a fourth-generation prototype fast reactor by 2020 to, among other tasks, test transmutation of long lived radioisotopes. Also in 2006, the UK's Committee on Radioactive Waste Management concluded that the best disposal option for the UK is deep geological disposal, with 'robust interim storage' until a repository site is selected.

In November the Swedish nuclear fuel and waste management company SKB applied to the Swedish nuclear power inspectorate for a permit for an encapsulation plant in Oskarshamn. The encapsulation plant is the first step towards final disposal using the KBS-3 method, in which fuel is encapsulated in copper canisters and deposited in bedrock at a depth of approximately 500 metres. A final ruling on the application is not expected until after 2009, when the application for a final deep geological repository is scheduled to be submitted. Site investigations for a final repository are being carried out near Forsmark in Osthammar and in the Laxemar area of Oskarshamn.

Following a three-year nation-wide consultative process, Canada's Nuclear Waste Management Organization recommended an 'adaptive phased' approach to managing Canadian spent fuel. During the next 30 years spent fuel would continue to be stored at reactor sites, a suitable site for a deep geological repository would be selected, and a decision would be made whether to also construct a centralized interim shallow underground storage facility to start receiving spent fuel in about 30 years. With or without a centralized interim facility, the deep repository would begin accepting spent fuel in about 60 years.

Decommissioning was completed in 2006 at the Big Rock Point nuclear power plant site in the USA, and the site returned to greenfield status. Thus, as of 2006, nine power plants around the world had been completely decommissioned, with their sites released for unconditional use. Seventeen plants have been partially dismantled and safely enclosed, 30 are being dismantled prior to eventual site release, and 30 are undergoing minimum dismantling prior to long term enclosure.

1.7 *Safety*

The international exchange of nuclear power plant operating experiences and, in particular, the broad dissemination of 'lessons learned' are essential parts of maintaining and strengthening the safe operation of nuclear power plants. Collecting, sharing and analysing operating experience are all vital safety management elements, and there is clear empirical evidence that learning from nuclear power plant operating experience has led, and continues to lead, to improvements in plant safety. International mechanisms to facilitate exchange include the World Association of Nuclear Operators (WANO) and the IAEA. Regular meetings of the IAEA–OECD/NEA Joint Incident Reporting System are an additional part of this global exchange process, where recent incidents can be discussed and analysed in detail. Safety indicators, such as those published by WANO and reproduced in Figures 7 and 8, improved dramatically in the 1990s. However, in some areas improvement has stalled in recent years. Also the gap between the best and worst performers is still large, providing substantial room for continuing improvement. Since the 1986 accident at Chernobyl, enormous efforts have been made in upgrading reactor safety features, but facilities still exist at which nuclear safety assistance should be made a priority.

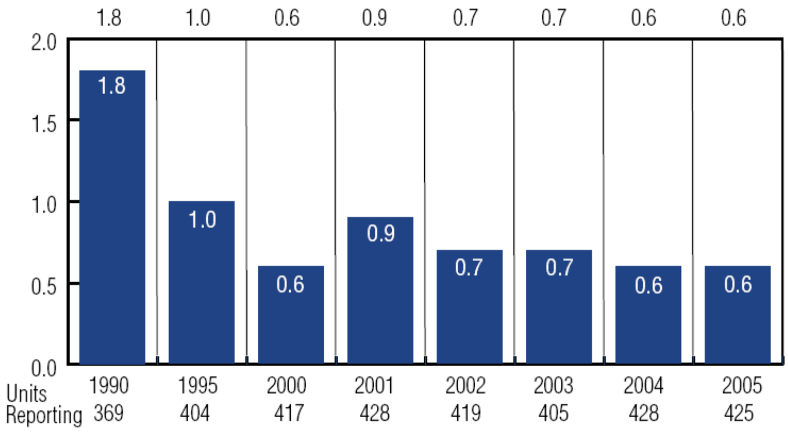

Figure 7: Unplanned scrams per 7000 hours critical. Source: WANO 2005 Performance Indicators.

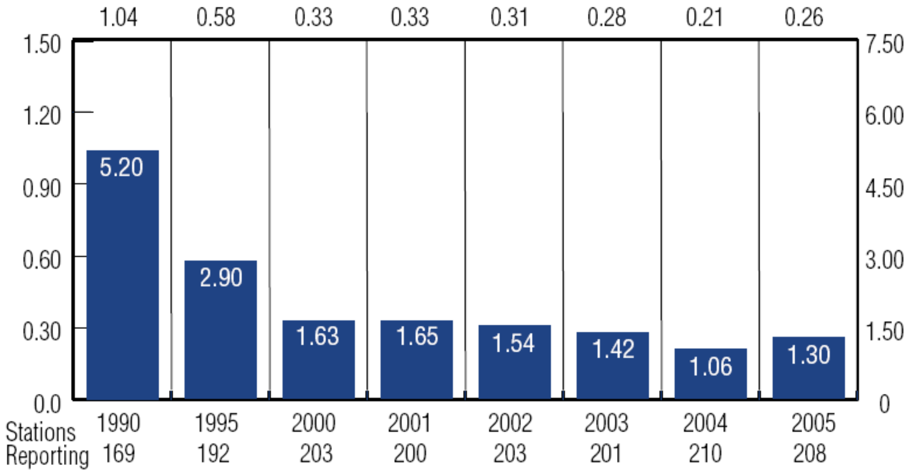

Figure 8: Industrial accidents at nuclear power plants per 1 000 000 person-hours worked. Source: WANO 2005 Performance Indicators.

1.8 Proliferation Resistance

At the 2005 NPT Review Conference, the IAEA Director General proposed seven steps to strengthen the non-proliferation regime: reaffirm the goal of eliminating nuclear weapons; strengthen the Agency's verification authority; establish better control over proliferation sensitive parts of the fuel cycle; secure and control nuclear material (e.g. strengthen the Convention on the Physical Protection of Nuclear Material and minimize high enriched uranium in civilian use); demonstrate a commitment to nuclear disarmament; strengthen the NPT non-compliance mechanism; and address the real security concerns of States. Six of the seven do not directly address nuclear power – it is not a principal source of proliferation risk. The one that does address nuclear power proposes tighter control over proliferation sensitive elements of the nuclear fuel cycle, specifically enrichment and reprocessing, while assuring supply of nuclear fuel for peaceful uses.

2 Projected Growth for Nuclear Power

In 2006, updated projections of nuclear power expansion through 2030 were published by the International Atomic Energy Agency (IAEA, 2006b), and by the International Energy Agency (IEA) in its *World Energy Outlook (WEO) 2006* (IEA, 2006). The IAEA provides a high and a low projection for nuclear power. The *World Energy Outlook 2006* includes a reference scenario plus an alternative scenario that assumes additional measures to enhance energy security and mitigate carbon dioxide (CO_2) emissions.

In 2005, the IEA published an additional study with seven scenarios extending to 2050 (IEA, 2005). These include a baseline scenario and six 'accelerated technology scenarios (ACTs)'. The accelerated technology scenarios examine technological options to limit or reverse global growth in CO_2 emissions and oil consumption.

In early 2007, the European Commission (EC) published the World Energy Technology Outlook 2050 – WETO H_2 (EC, 2006). Built on a business-as-usual or reference case, WETO H_2 analyzes two specific scenarios that reflect political objectives of mitigating climate change and promoting new clean energy technologies. A 'carbon constraint case' explores the consequences of more ambitious carbon emissions policies that aim at the long-term stabilization of atmospheric CO_2 concentrations. The 'hydrogen case' builds on the 'carbon constraint case' and explores a series of technology breakthroughs that significantly increase the cost effectiveness of hydrogen technologies.

The four publications thus include, altogether, fourteen scenarios. Their projections for nuclear power are summarized in Figure 9. The bars in Figure 9 show the spread between the 'low' (IAEA), reference scenario (IEA) and reference case (WETO) nuclear electricity projections – the bottom of the respective bars – and the 'high' (IAEA), 'accelerated policy' (IEA) and 'carbon constraint/hydrogen scenarios' (WETO).

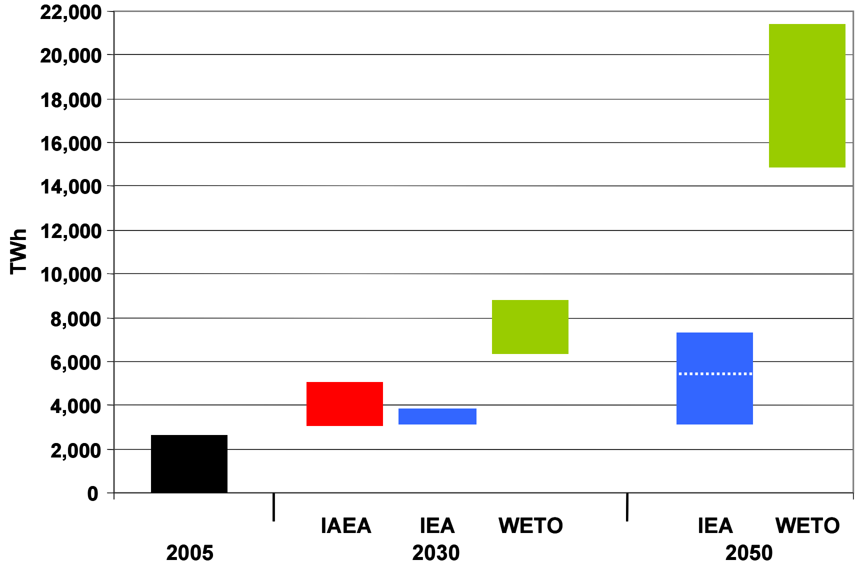

Figure 9: ***Global nuclear electricity generation in 2005 and the ranges of projections for 2030 and 2050 from four studies. Except for 2005, the bottom part of each bar corresponds to the respective 'low' or 'reference projections'; the top of each bar to the 'high', 'accelerated policy' or 'carbon constraint/hydrogen scenarios'.***

In Figure 9 the IAEA low projection assumes that no new nuclear power plants are built beyond what is under construction or firmly planned today, and old nuclear power plants are retired on schedule. Nuclear electricity generation in this projection grows to just 3 100 TWh in 2020 (1.1% growth per year) and remains essentially unchanged through 2030. The IAEA high projection incorporates additional reasonable planned and proposed nuclear projects beyond those already firmly in the pipeline. It shows steady growth to 5 040 TWh in 2030 (2.6% growth per year). Figure 10 shows the nuclear capacity developments by major region for the IAEA high and low projections.

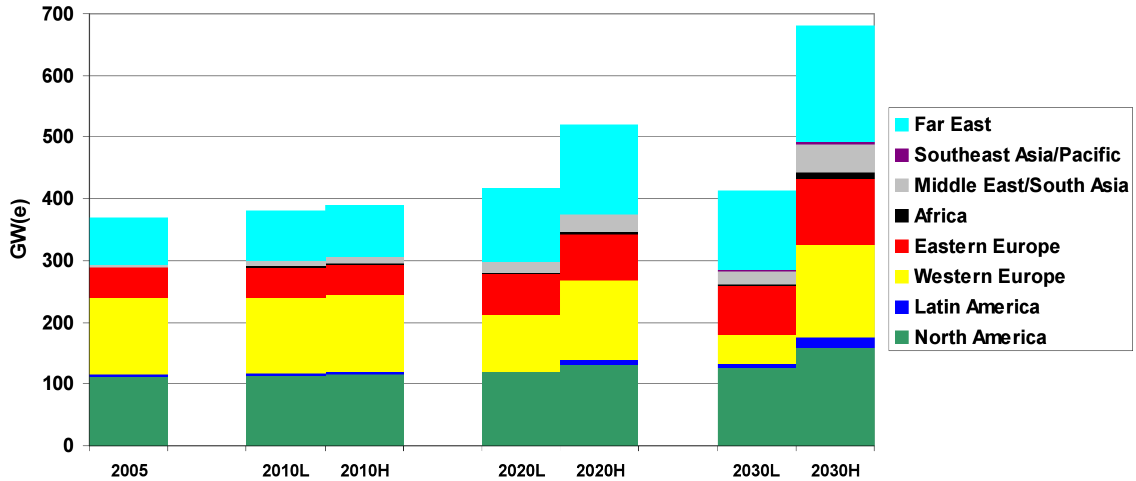

Figure 10: Nuclear capacity projections of the IAEA low (L) and high (H) scenarios.

Figure 10 shows that the global aggregates in Figure 9 mask regional differences, particularly in the low projection. Nuclear electricity generation in Western Europe in the low projection drops by almost 60% between 2005 and 2030, as projected retirements consistently outpace new construction. But nuclear power generation in the Far East grows by 80% and in Eastern Europe by almost 50%. In the high projection, nuclear generation grows in all regions. In both projections, new construction is greatest in the Far East, Eastern Europe, North America and the Middle East/Southeast Asia, in that order.

The WEO reference scenario is a 'business-as-usual' scenario that assumes the continuation of current policies and trends. Projected nuclear electricity generation in this scenario is almost identical to that in the IAEA low projection. The measures in the alternative scenario to enhance energy security and mitigate CO_2 emissions are expected to boost nuclear electricity generation but, as shown in Figure 9, not enough to match the IAEA high projection.

The EC WETO reference case foresees a much faster expansion of nuclear generated electricity — the 6 300 TWh by 2030 are approximately twice the amount projected by both IEA and IAEA. While in the IAEA and IEA scenarios the nuclear share declines to 12-13% (IAEA) and 10% (IEA), the WETO cases project, after some decline by 2020, a return to the 16-17% market share observed between the early 1990s and 2005. Although the reference case is essentially a continuation of existing economic and technological trends, the short-term constraints on the development of oil and gas production, a receding public reservation against nuclear power and the implementation of moderate climate policies lead after 2020 to a strong expansion of nuclear power for its climate friendly characteristics and for reasons of energy security (see Figure 11).

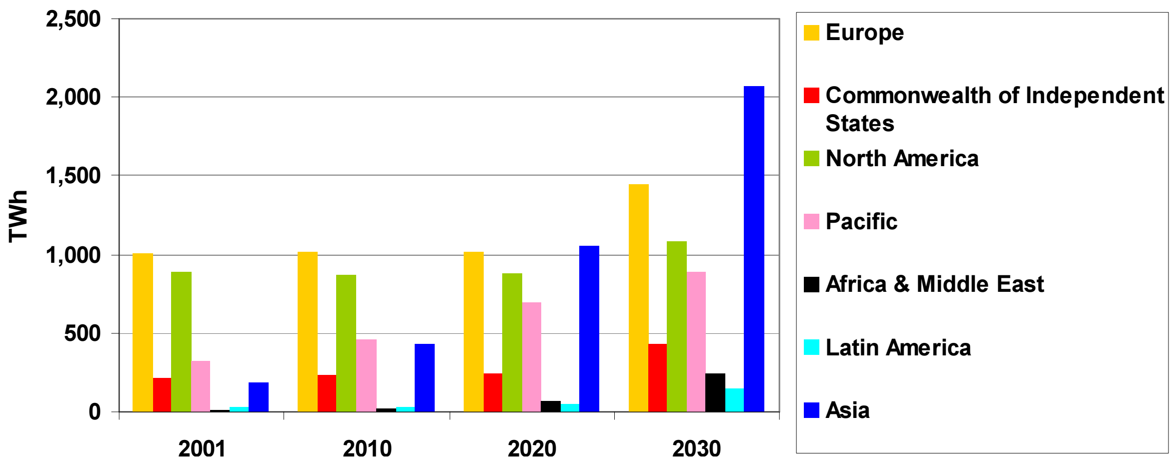

Figure 11: Electricity generation from nuclear power in the WETO-H_2 reference case.

The 'carbon constraint' case involves only marginally higher nuclear electricity generation than the reference case, but the nuclear share approaches 19% due to the lower global demand for electricity in an inherently more energy efficient world economy. A world that develops, commercializes and adopts hydrogen end-use technologies as well as supply infrastructures would boost demand for nuclear electricity to more than 8 800 TWh (top of the WETO bar for 2030 in Figure 9) or 1 200 GWe installed capacity by 2030.

For the IEA scenarios in 2050, near the right side of Figure 9, the low end of the range is defined by the baseline scenario and a 'low nuclear scenario'. These are essentially extensions of the WEO 2006 reference scenario. The high end of the range is set by the TECH Plus scenario, which assumes accelerated cost reductions for fuel cells, renewables, biofuels and nuclear power. In this scenario, nuclear electricity generation continues to grow to 2050 at essentially the same rate as in the IAEA high projection, and its share of global electricity generation reaches 22%. The other four IEA scenarios cluster around the level of the dotted white line, at about 5 650 TWh, or an average growth rate of 1.7% from 2005.

The WETO cases in 2050 use between 14 800 TWh (reference case — 25% share) and 21 400 TWh (hydrogen case — 37% share) of nuclear electricity — certainly an outlook that breaks with short-term trends and the cautious projections of IEA and IAEA. The WETO cases assume the implementation of drastic climate change policies (carbon taxes, etc.) consistent with a definition of a 2^{o}C increase in mean global temperature (or a maximum CO_2 concentration of 450 ppmv) as the normative limit for the avoidance of dangerous anthropogenic interference with the climate system. Other critical assumptions are accelerated innovation and technology learning, technology diffusion and adoption of Generation IV nuclear technologies and fuel cycles. Nuclear power would become a major supplier of both electricity and hydrogen.

The nuclear shares of the WETO cases are consistent, however, with many long-term business-as-usual scenarios that were developed for assessing greenhouse gas emission profiles in the absence of designated climate policies. Scenarios that extend to 2050 and beyond account for a changed overall energy resource situation including depletion of low cost fossil occurrences or the likely fact that the most convenient sites for renewables will have already been utilized. Fossil fuels extracted in 2050 therefore come from higher cost categories than the cheaper fossil fuels against which nuclear energy is competing in the shorter run. For example, the non-climate intervention scenarios of the Intergovernmental Panel on Climate change (IPPC) project between 15% and 26% nuclear electricity for the year 2050 (IPCC, 2000).

3 Concluding Remarks

Taken together, these new projections and scenarios present a picture with opportunities for significant nuclear expansion, but still with substantial uncertainty. A number of developments in 2006 suggest that the renewal of interest in nuclear power may reasonably soon lead to increases in construction. These include expansion plans announced in 2006 by Japan and the Russian Federation, as well as previously announced expansion plans of China, India, the Republic of Korea and Pakistan. They include the large number of intended Combined License applications that companies and consortia have announced in the USA, which together cited approximately 25 new reactors. They include two site preparation applications in Canada and the UK energy review's conclusion that new nuclear power stations would make a significant contribution to meeting the UK's energy policy goals. They include a joint feasibility study launched by utilities from Estonia, Lithuania and Latvia of a new nuclear power plant to serve all three countries, and the Belarus government's approval of a working plan for construction of the country's first nuclear power plant to follow the expiration of a 10-year moratorium on nuclear construction. They include announcements made by Egypt, Indonesia, Nigeria, Poland, Turkey and Vietnam on steps they are taking toward their first nuclear power plants. Finally, they include the explicit interest in nuclear power expressed by more than two dozen countries that currently do not operate nuclear power plants.

Whether and how quickly this interest ripens into a broader commitment to nuclear power will in large part depend on economics: on the affordability of nuclear power relative to alternatives, on the ability of next generation nuclear technologies to cut capital costs, on the ability of nuclear power to deliver its services and benefits at reasonable costs, and on creative fuel cycle arrangements that allow countries to enjoy the benefits of nuclear power plants without the need to incur the costs of a nuclear infrastructure (take-back and leasing of nuclear fuel or nuclear batteries). It will also depend on government policies: environmental considerations driving or driven by the Kyoto Protocol, and supply security considerations driving or driven by the need to strengthen the NPT. But most importantly, it will depend on the continued safe and economic operation of the current fleet of nuclear power plants around the world.

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