International Status and Prospects of Nuclear Power

2010 Edition

IAEA
International Atomic Energy Agency

INTERNATIONAL STATUS AND PROSPECTS OF NUCLEAR POWER

2010 EDITION

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

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A. DEVELOPMENTS SINCE 2008

For nuclear power, the past two years have been paradoxical. In both 2008 and 2009, projections of future growth were revised upwards despite a worldwide financial crisis and a two year decline in installed nuclear capacity. No new reactors were connected to the grid in 2008, making it the first year since 1955 without at least one new reactor coming on-line. In 2009, two new reactors were connected. There were, however, ten construction starts in 2008, the most since 1987, and twelve in 2009, extending a continuous upward trend that started in 2003.

The global economic and financial crisis that began in the autumn of 2008 appeared to have had a limited impact overall on plans for nuclear power development. Expansion plans in China and elsewhere in Asia offset announcements of delays for new build projects in Europe and North America.

Public confidence in nuclear power showed small improvements. While public confidence is dependent on national contexts and difficult to aggregate, polls conducted in some countries indicated increased acceptance of nuclear power.

Continued concerns regarding an ageing workforce of experienced personnel have been addressed over the past two years by a resurgence in the number of commercial companies becoming involved in the nuclear industry and in related education and training programmes in many countries. In addition, a number of bilateral cooperative programmes in education and training for nuclear power have been launched.

The United Arab Emirates (UAE) accepted a bid by a consortium led by the Korea Electric Power Corporation (KEPCO) to supply 1400 MW(e) of nuclear power by 2020. This deal marks the first successful bid by a 'newcomer' country and the emergence of the Republic of Korea as an exporter of nuclear reactor technology. The KEPCO led consortium retains an interest in plant operations for a significant portion of the plant life, which is also a new development, while the UAE has announced plans to increase local participation in its national nuclear power programme.

In April 2009, the Government of China hosted an International Ministerial Conference on Nuclear Energy in the twenty first century in Beijing to review the status and prospects of nuclear power, including progress in the evolution of technology, and to discuss actions necessary for further nuclear power expansion. The concluding statement of the President of the Conference, noted that, "While respecting the right of each State to define its national energy policy in accordance with its international obligations, the vast majority of participants affirmed that nuclear energy, as a proven, clean, safe, competitive technology, will make an increasing contribution to the sustainable development of humankind throughout the 21st century and beyond."

The International Conference on Fast Reactors and Related Fuel Cycles, held in Kyoto, Japan, in 2009, indicated that fast reactor and associated fuel cycle research and technology development are, in many countries, back on the research agenda in academia and industry. China's experimental fast reactor reached first criticality in July 2010, and Japan announced the re-start of the Monju industrial prototype fast reactor in May 2010. It has been 18 years since an international conference was last held on this subject, and it was agreed, based on activities in China, India, Japan, the Russian Federation, and elsewhere, to hold such a conference every three years.

In the area of waste management, the United States of America (USA) announced in 2009 that it was withdrawing the licence application for a geological repository at Yucca Mountain, effectively signalling a policy shift back to interim storage.

Little or no progress was made on recognizing the contribution of nuclear power to mitigating climate change at the Conference of the Parties to the Kyoto Protocol in Copenhagen in December 2009.

Recognizing the importance of international cooperation in the regulatory area, experienced regulators are launching efforts to better coordinate assistance to countries introducing nuclear power. Following discussions, including in 2009 and 2010 in the International Nuclear Safety Group (INSAG) and the Senior Regulators' Meeting, in 2010, a Regulatory Cooperation Forum, including States with established nuclear power programmes and those considering nuclear power, was launched by States with IAEA facilitation and promotion to improve collaboration and coordination for regulatory capacity building.

Efforts to establish mechanisms to ensure that countries can be confident of a secure fuel supply made progress. In March 2010, the IAEA entered into an agreement with the Russian Federation to establish an international reserve of low enriched uranium (LEU) that could be made available to a State in the event of disruption of supply of low enriched uranium for nuclear power plants unrelated to technical or commercial considerations.

In March 2010, the French Government and the Organisation for Economic Co-operation and Development (OECD) hosted the International Conference on Access to Civil Nuclear Energy. Its aim was to promote the peaceful and responsible use of nuclear power and to discuss how to use bilateral and multilateral cooperation to help countries wishing to embark on nuclear power to fulfil their international obligations. At the conference, the French President emphasized seven topics critical for a successful nuclear renaissance: financing, transparency, education and training, safety, non-proliferation, access to nuclear fuel, and spent fuel and waste management. In the area of education and training, he announced the creation of an international nuclear energy institute that will include an international nuclear energy school.

The International Conference on Human Resource Development for Introducing and Expanding Nuclear Power Programmes was convened in Abu Dhabi, UAE, in March 2010. The conference confirmed the importance of a balanced approach to human resource development that emphasizes building capacity and expertise in all, rather than only selected, relevant areas of the nuclear field. An initiative was announced to conduct a number of surveys of human resource needs and supplies, throughout the nuclear power field, and to develop workforce planning tools for countries considering new nuclear power programmes. Other areas discussed were how to retain workers and how to attract young workers and women into the nuclear field.

In June 2010, the Global Nuclear Energy Partnership (GNEP) was renamed the International Framework for Nuclear Energy Cooperation (IFNEC) and adopted a new mission statement. The changes were intended to provide a broader scope, wider international participation and more effective exploration of important issues related to the expansion of nuclear energy.

B. CURRENT STATUS OF NUCLEAR POWER

B.1. USE OF NUCLEAR ENERGY

Currently, nuclear energy produces slightly less than 14% of the world's electricity supplies and 5.7% of total primary energy used worldwide.

The global energy supply and energy use per capita are increasing. The total energy requirements of the world rose by a factor of 2.5 between 1970 and 2008, from 4.64 billion tonnes of oil equivalent (toe) to 11.9 billion toe (195 to 499 exajoules (EJ))[1]. Over the past few decades, the share of electricity in total energy use has steadily increased.

Figure B-1 shows the contribution of different energy sources to the global energy mix over this period. The share of nuclear grew from just below 0.5% in 1970 to above 7% in the 1990s and declined to 5.7% by 2008. Fossil fuels remain the dominant energy source.

[1] 1 EJ = 10^{18} J or 2.78 ×105 GW·h(th) or 31.7 GW·a.

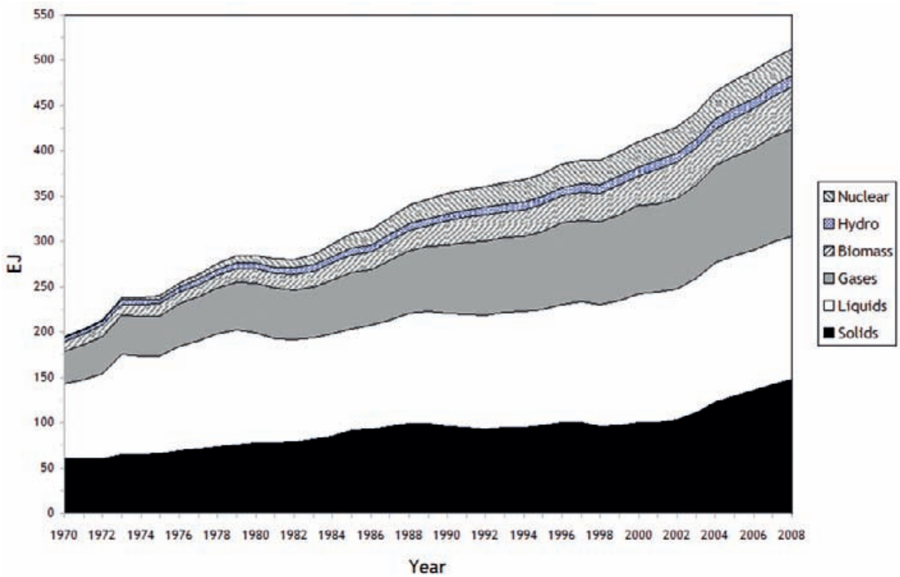

FIG. B-1. Share of energy sources in world total energy production, 1970–2008.

Nuclear power has been used to produce electricity for public distribution since 1954. Since that time, nuclear power plants have been operated in 32 countries[2]. Currently, 29 countries operate 441 plants, with a total capacity of 375 GW(e). A further 60 units, totalling 58.6 GW(e), are under construction[3]. During 2009, nuclear power produced 2558 billion kW·h of electricity. The industry now has more than 14 000 reactor years of experience.

The contribution of nuclear energy to total electricity generation varies considerably by region (Tables B-1 and B-2). In Western Europe, nuclear generated electricity accounts for almost 27% of total electricity. In North America and Eastern Europe, it is approximately 18%, whereas in Africa and Latin America it is 2.1% and 2.4%, respectively. In the Far East, nuclear energy accounts for 10% of electricity generation; in the Middle East and South Asia it accounts for 1%.[4] Nuclear energy use is concentrated in technologically advanced

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[2] Argentina, Armenia, Belgium, Brazil, Bulgaria, Canada, China, Czech Republic, Finland, France, Germany, Hungary, India, Italy, Japan, Kazakhstan, the Republic of Korea, Lithuania, Mexico, Netherlands, Pakistan, Romania, the Russian Federation, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Ukraine, the United Kingdom (UK) and the USA.

[3] Unless indicated otherwise, all such statistics are as of 26 August 2010.

[4] There are no nuclear power plants in the South-east Asia and the Pacific region, so nuclear accounts for no electricity generation there.

TABLE B-1. USE (IN EJ) AND PERCENTAGE CONTRIBUTION (%) OF DIFFERENT TYPES OF FUEL FOR ELECTRICITY GENERATION IN 2008

Region	Thermal (a)		Hydro		Nuclear		Renewables (b)		Total	
	Use (EJ)	%	Use (EJ)	%	Use (EJ)	%	Use (EJ)	%	Use (EJ)	%
North America	25.13	66.15	2.32	13.72	9.76	19.04	0.76	1.09	37.98	100
Latin America	5.14	39.15	2.56	57.54	0.32	2.38	0.39	0.93	8.41	100
Western Europe	16.06	52.45	1.89	17.06	8.97	26.68	0.72	3.81	27.64	100
Eastern Europe	18.18	64.59	1.12	17.04	3.64	18.30	0.03	0.07	22.96	100
Africa	5.73	80.51	0.37	16.95	0.14	2.11	0.05	0.43	6.29	100
Middle East and South Asia	19.09	87.54	0.62	11.47	0.16	0.99	0	0.00	19.87	100
Southeast Asia and the Pacific	6.78	88.92	0.25	9.29			0.39	1.79	7.41	100
Far East	43.46	74.27	2.65	15.23	5.35	10.15	0.49	0.35	51.95	100
World total	139.57	67.15	11.77	17.66	28.34	14.03	2.83	1.16	182.51	100

(a) The column headed 'Thermal' is the total for solids, liquids, gases, biomass and waste.

(b) The column headed 'Renewables' includes geothermal, wind, solar and tide energy.

countries. Over the past two years the contribution of nuclear generation to world electricity production has declined from 15% to less than 14%, largely due to a rise in total electricity generation worldwide without an increase of nuclear generation.

The number of reactors under construction increased from 33 with a total capacity of 27 193 MW(e) at the end of 2007 to 60 with a total capacity of 58 584 MW(e) on 26 August 2010. In many countries with existing nuclear power programmes there are significant increases in investment in future nuclear power plants. Of these 60 plants, 11 have been under construction since before 1990, and of the 11 possibly only three are predicted to be commissioned in the next three years. There are a few reactors which have been under construction for over 20 years and which currently have little progress and activity. In 2008, there were 10 construction starts and in 2009 there were 12 (see Fig. B-2), extending a continuous upward trend that started in 2003. All 22 of the construction starts in 2008 and 2009 were pressurized water reactors (PWRs) in three countries: China, Republic of Korea and Russian Federation.

Since the accident at Chernobyl in 1986, industry safety records have improved significantly.[5] Unplanned automatic scrams continue at the low level of 0.5 per 7000 hours critical.[6] The improved availability and safety records are, in part, attributable to increased information sharing of best practices and lessons

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[5] *Nuclear Safety Review for the Year 2009*, GOV/2010/4, IAEA, Vienna (2010).

[6] WORLD ASSOCIATION OF NUCLEAR OPERATORS, *2008 Performance Indicators*, WANO, London (2009).

TABLE B-2. NUCLEAR POWER REACTORS IN THE WORLD (26 AUGUST 2010)[7]

Region	In operation		Under construction		Electricity supplied in 2009 (TW·h)
	Number	Net Capacity (MW(e))	Number	Net Capacity (MW(e))	
North America	122	113316	1	1165	882
Latin America	6	4119	2	1937	30
Western Europe	129	122956	2	3200	781
Central and Eastern Europe	67	47376	17	13741	326
Africa	2	1800	0		12
Middle East and South Asia	21	4614	6	3721	17
Far East	94	80516	32	34820	510
World	441	374697	60	58584	2558

learned in the industry, through implementation of risk based regulation, and through industry consolidation.

B.2. AVAILABLE REACTOR TECHNOLOGY

Although a wide range of different technologies remain in operation today, most of the reactors currently in operation are light water reactors (LWRs). Of the commercial reactors in operation, approximately 82% are light water moderated and cooled reactors; 10% are heavy water moderated heavy water cooled reactors; 4% are gas cooled reactors; 3% are water cooled and graphite moderated reactors. One reactor is liquid metal moderated and cooled. Table B-3 indicates the numbers, types and net electrical power of currently operating nuclear power plants. In addition to the countries on this list, other countries have also operated fast reactors, which have now been shut down.

About three quarters of all the reactors in operation today are over 20 years old, and one quarter are over 30 years old, as can be seen in Fig. B-3. Through plant

[7] Source: IAEA Power Reactor Information System (PRIS).

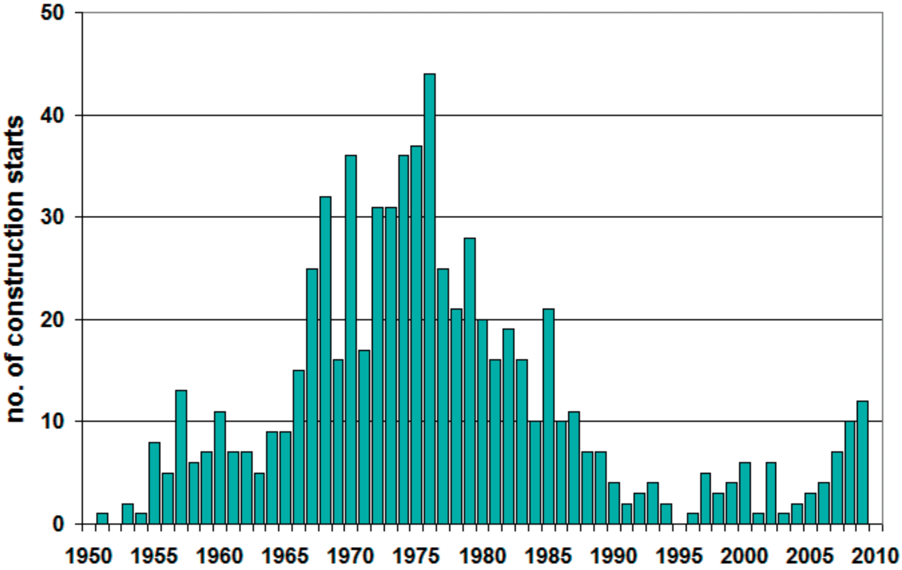

FIG. B-2. Construction starts of nuclear power plants by year. Source: IAEA (PRIS), 2010.

life management programmes, many plants have had their original operational period extended to allow continuing operation for up to 20 additional years. Ageing reactors face issues of materials degradation and technology obsolescence such as in instrumentation and control. Plant life management is implemented to cope with these issues in order to increase the return on investment and, since experience has shown strong operating performance, to also extend plant licensed life.

The majority of nuclear power plants operating around the world were designed in the late 1960s and 1970s and are not offered commercially today. Reactor designs increased gradually in size, taking advantage of economies of scale to be competitive. Many of the earliest reactors, which started commercial operation in the 1950s, were 50 MW(e) or smaller. The current fleet in operation ranges in size from less than 100 MW(e) to up to 1500 MW(e). The average reactor size in operation in 2010 was 850 MW(e).

All of the new construction starts in 2008 and 2009 were PWR type reactors.

Reactor technology available for use today is fundamentally based upon previous designs and takes into account the following design characteristics:

- Sixty year life;
- Simplified maintenance — on-line or during outages;
- Easier and shorter construction;
- Inclusion of safety and reliability considerations at the earliest stages of design;

TABLE B-3. CURRENT DISTRIBUTION OF REACTOR TYPES[8]

Country	PWR		BWR		GCR		PHWR		LWGR		FBR		Totals	
	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)
ARGENTINA							2	935					2	935
ARMENIA	1	375											1	375
BELGIUM	7	5934											7	5934
BRAZIL	2	1884											2	1884
BULGARIA	2	1906											2	1906
CANADA							18	12569					18	12569
CHINA	11	8748					2	1300					13	10048
CZECH REP.	6	3678											6	3678
FINLAND	2	976	2	1745									4	2721
FRANCE	58	63130											58	63130
GERMANY	11	14033	6	6457									17	20490
HUNGARY	4	1889											4	1889
INDIA			2	300			17	3889					19	4189

For footnote see p. 10.

TABLE B-3. CURRENT DISTRIBUTION OF REACTOR TYPES[8] (cont.)

Country	PWR		BWR		GCR		PHWR		LWGR		FBR		Totals	
	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)
JAPAN	24	19286	30	27537									54	46823
KOREA, REP. OF	17	15943					4	2722					21	18665
MEXICO			2	1300									2	1300
NETHERLANDS	1	487											1	487
PAKISTAN	1	300					1	125					2	425
ROMANIA							2	1300					2	1300
RUSSIAN FEDERATION	16	11914							15	10219	1	560	32	22693
SLOVAKIA	4	1762											4	1762
SLOVENIA	1	666											1	666
SOUTH AFRICA	2	1800											2	1800
SPAIN	6	6006	2	1510									8	7516
SWEDEN	3	2799	7	6504									10	9303

For footnote see p. 10.

TABLE B-3. CURRENT DISTRIBUTION OF REACTOR TYPES[8] (cont.)

Country	PWR		BWR		GCR		PHWR		LWGR		FBR		Totals	
	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)	No.	MW(e)
SWITZERLAND	3	1700	2	1538									5	3238
UK	1	1188			18	8949							19	10137
UKRAINE	15	13107											15	13107
USA	69	66945	35	33802									104	100747
WORLDWIDE	269	248295	92	83834	18	8949	46	22840	15	10219	1	560	441	374697

The totals include six units, 4980 MW(e), in Taiwan, China.
PWR: pressurized water reactor; BWR: boiling water reactor; GCR: gas cooled reactor; PHWR: pressurized heavy water reactor; LWGR: light water cooled, graphite moderated reactor; FBR: fast breeder reactor.

[8] As of 26 August 2010. Source: IAEA (PRIS).

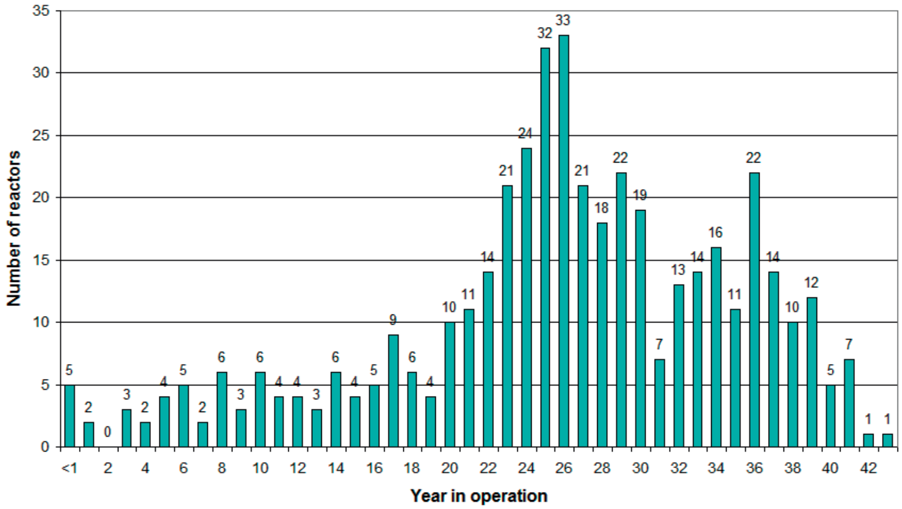

FIG. B-3. Number of operating nuclear power plants by age in the world as of 26 August 2010 (note that a reactor's age is determined by the date when it was first connected to the grid). Source: IAEA (PRIS).

- Modern technologies in digital control and the human–machine interface;
- Safety system design guided by risk assessment;
- Simplicity, by reducing the number of rotating components;
- Increased reliance on passive systems (gravity, natural circulation, accumulated pressure, etc.);
- Addition of severe accident mitigating equipment;
- Complete and standardized designs with pre-licensing.

Although the industry has historically and overwhelmingly pursued greater economies of scale, deployment of small (less than 300 MW(e)) and medium sized (between 300 MW(e) and 700 MW(e)) reactors continues. Such small and medium size reactors (SMRs) are being developed for: (a) use in a small grid with limited interconnections, such as those that exist in some developing countries; (b) as a power or multipurpose energy source in an isolated area; and (c) for incremental investment to avoid financial risks. Transportable reactors of small capacity are being proposed which would allow the power plant to be delivered as a pre-constructed package.

B.3. HUMAN RESOURCES

While neither the IAEA nor other international organizations collect comprehensive statistics, it is estimated that in 2009 all nuclear power plants in operation worldwide continued to employ more than 250 000 people. Many more are employed in the construction of new plants, engineering and technical support, training and education, regulatory bodies, government ministries, research and development, radioactive waste management, radiation protection, design and manufacturing, outage support, fuel supply, and other services, and through supply contractors. As shown in Fig. B-3, about three quarters of all reactors in operation today are over 20 years old, and one quarter are over 30 years old. The generation that constructed and operated these plants has either already retired or will do so soon. Many of the organizations that are licensed to operate these plants also have projects under way or under consideration to build new units, and are facing shortages of experienced personnel and loss of knowledge as they look to replace retiring staff for their existing fleet while at the same time staffing new projects. There is a general impression that the current nuclear workforce is ageing, and many of these sectors are facing shortages of experienced personnel and loss of knowledge and experience due to retirement even in countries with established nuclear programmes.

In light of the above, knowledge preservation, recruitment and retention for the industry and regulators are important issues. The complexity of nuclear technology requires a highly educated and specifically trained workforce. There has been a trend in recent years towards promoting education and training in the nuclear industry although there are limited sources of such specialized education and training, and up to ten years are needed to obtain the appropriate training for some industry positions. In some countries, the government has provided incentives to develop academic programmes and recruit students to nuclear fields. Regional networks for information sharing have also been established, and networking among operators has improved. These efforts are geared, among other things, towards bridging the experience gap as the workforce renews and expands.

The concerns about possible shortages of qualified people are different in different countries. For countries with expanding nuclear power programmes, the challenge is to scale up their existing education and training in order to have the required qualified workforce as soon as it is needed. Countries planning to supply nuclear technology to others not only have to meet their national human resource needs but must also be able to transfer education and training capacity together with the technology they transfer. Experience shows that countries embarking on nuclear power will need to rely significantly on their technology supplier to help train qualified people for construction, licensing and startup. In addition, the technology supplier countries will be expected to offer opportunities to develop the required national capabilities and domestic training programmes. Cooperation between experienced and embarking countries is also helping to bridge the experience gap. In the past two years, for example, France has established cooperation ties in the area of education and training with Jordan and Poland.

The *International Conference on Human Resource Development for Introducing and Expanding Nuclear Power Programmes* held in Abu Dhabi in March 2010 identified the steps that governments, industry, utilities and universities can undertake to recruit, retain and improve the workforce needed for the global nuclear industry. Benchmarking and sharing of lessons learned were identified as important means towards accomplishing the steps. A special emphasis was placed on recruiting the next generation of workers as well as increasing participation of women in the nuclear workforce. Making the nuclear workplace more attractive to these groups can be achieved by offering, for example, more flexibility in working hours, opportunities for collaboration, mentoring and recognition.

To gain better data on the global workforce demographics, it was announced at the Abu Dhabi conference that the IAEA and other organizations would launch an initiative to undertake the following activities on a global scale: a survey of human resources at existing nuclear power plants, including contractors and suppliers; a survey of the demand and supply of human resources for nuclear regulatory bodies; a survey of educational organizations and programmes that support nuclear power; the development of workforce planning tools for countries considering or launching new nuclear power programmes; and integration of the above into an accessible database that can be used to model global or national supply and demand of human resources.

B.4. FUEL CYCLE ACTIVITIES

The manufacturing of fuel for reactors and the management of the fuel after use (the fuel cycle) require several steps, as shown in Fig. B-4. They are normally divided into front end activities (mining, conversion, enrichment and fuel fabrication) to produce fuel assemblies[9] to be inserted in the reactor, and back end activities to manage the spent nuclear fuel (including storage, reprocessing and waste disposal).

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[9] Most reactors use low enriched uranium (LEU) with an enrichment between 2% and 5%. A few (PHWRs) do not use enriched uranium.

B.4.1. Front end

An established and effective market for the different front end services exists. Most of the activities are performed under long term contracts, but spot markets also exist.

In the two years since this report was last issued, the most notable expansion of activities in the front end of the fuel cycle was in the area of uranium exploration and mining. Uranium mining now takes place in 19 countries, with eight countries[10] accounting for 93% of world capacity. Currently, 35% of uranium needs are covered by secondary supplies — stored uranium or ex-military material — and recycled materials. Following about 20 years of low uranium prices, the spot market price increased substantially after 2004, by as much as a factor of ten, in anticipation of increasing demand and declining secondary supplies. After a peak value in 2007, the spot price is now about five times the price before 2004. The price increase has also stimulated increases in mine capacities and uranium exploration. The identified resources of uranium in the ground are adequate to supply the present demand for almost 100 years.

The mined material is turned into chemical feedstock for the rest of the industry, generally into uranium hexafluoride (UF_6), through a process called conversion. More than 90% of the world's capacity is in six countries[11], and the world conversion capacity is currently about twice what is needed. Low enriched UF_6, which is suitable for fuel fabrication, is treated as a commodity in the market.

Current enrichment capacity is sufficient to cover demand for the next decade. Older plants based on gaseous diffusion technology are being replaced by plants based on centrifuge technology that require less input energy. In preparation for expected increased demand, plants are being built in France and the USA.

The fuel assembly, which is the main energy producing component of the reactor, is a technologically specific product involving significant intellectual property. In addition, the fuel in the assembly provides the first barrier against release of radioactive material and requires regulatory authorizations. Fuel assemblies from different suppliers are not generally interchangeable, although many utilities do periodically change suppliers to maintain competition. The

[10] Australia, Canada, Kazakhstan, Namibia, Niger, the Russian Federation, Uzbekistan and the USA.

[11] Canada, China, France, the Russian Federation, the UK and the USA.

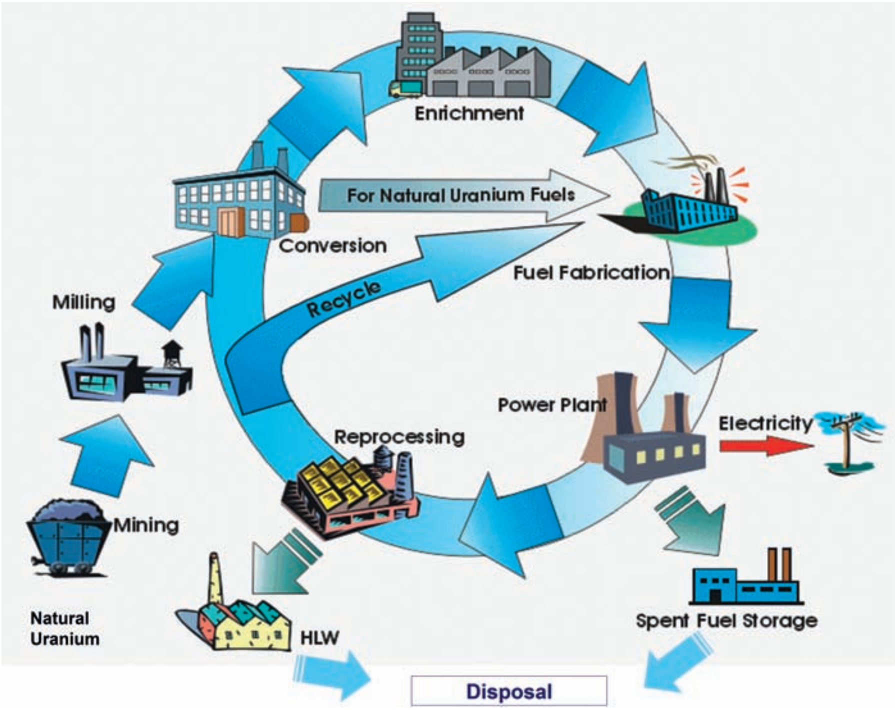

FIG. B-4. The nuclear fuel cycle.

main fuel manufacturers are also the main suppliers of nuclear power plants or closely connected to them. The largest fuel manufacturing capacity can be found in France, Japan, the Russian Federation and the USA, but fuel manufacturing is carried out in at least seven other countries, often under licence from one of the main suppliers.

B.4.2. Back end

Some countries see spent fuel as a waste product to be disposed of as high level waste (HLW). Others see it as a resource for reprocessing and potential reuse. Currently, a market for reprocessing and manufacturing of mixed uranium and plutonium oxide (MOX) fuel exists, but not for storage or disposal.

For both strategies, the spent fuel is stored first in the reactor pool and then in separate stores at the reactor site or in a central facility. While most fuel is stored in water pools, increasingly the current approach is to use modular dry storage facilities, such as casks or vaults. The length of the expected storage time depends on when the fuel can be transported to reprocessing or to disposal. Storage times of several decades are foreseen in most countries.

Currently, around 15% of all spent fuel is reprocessed to recover and recycle uranium and plutonium. Reprocessing is carried out in France, Japan, the Russian Federation and the UK, with some PHWR fuel reprocessed in India. Existing reprocessing capacity is only utilized to about 50% due to uncertainties of the future use of the reprocessed material. The reuse of uranium and plutonium (as MOX) is currently carried out mainly in LWRs, but to obtain maximum use of uranium resources through a closed fuel cycle, the implementation of fast reactors or other advanced systems is being actively considered in a number of countries. Closing the fuel cycle can also lead to a decrease in the radiotoxicity of the waste. For the present, much reprocessed material is kept in storage.

Irrespective of whether the fuel is reprocessed or not, there will remain some high level and long lived waste that will need safe and secure disposal. In many cases after reprocessing, the waste products are sent back to the country where the fuel was used. Currently, as with the spent fuel, this material is stored.

B.5. MANAGEMENT OF RADIOACTIVE WASTE AND DECOMMISSIONING

Radioactive waste is generated at different stages of the fuel cycle, and can arise in the form of radioactive liquids, gases or solids and with a large spectrum of activity levels. Depending on its activity level and its future management and disposal, it is classified as low, intermediate or high level waste. Treatment, conditioning and long term storage of all kinds of waste are mature technologies and are normally performed at the nuclear facilities where the waste is generated. Storage periods of 50 years or more are not unusual. This allows decay of most radioactive nuclides and flexibility for decisions on disposal.

Disposal of low level waste (LLW) and intermediate level waste (ILW) is carried out on an industrial scale in several Member States according to established safety standards. Nevertheless, there are several countries with operating nuclear power plants that have not yet been able to site and construct an LLW disposal facility, primarily due to lack of political and public acceptance.

It is the widely held view of technical experts that the method of final disposal for HLW and spent nuclear fuel is likely to be in deep geological repositories. While no deep geological repository for high level waste is currently in use, Finland, France and Sweden are well advanced in their development of such repositories. Experience indicates that the time needed to site and develop geological repositories is several decades. Finland is constructing an exploratory tunnel to disposal depth with a plan to apply for a repository construction licence in 2012 so that final disposal can begin in 2020. The USA recently announced the withdrawal of the licence application to build and operate the waste storage facility at Yucca Mountain, and appointed the Blue Ribbon Commission on America's Nuclear Future to provide recommendations for developing a safe, long term solution to managing the USA's used nuclear fuel and nuclear waste including all alternatives.

As power reactors reach the end of their life cycles they need to be decommissioned. As some parts of the reactors are radioactively contaminated, they will need to be dismantled in a controlled way and the radioactive waste taken care of. The timing of the dismantling is dependent on several factors, for example, radiation protection considerations, availability of funding and availability of disposal facilities. As of the end of 2009, 123 power reactors had been shut down. Of these, 15 reactors had been fully dismantled, 51 were in the process of being dismantled, 48 were being kept in a safe enclosure mode, 3 were entombed, and, for 6 more, decommissioning strategies had not yet been specified. The radioactive waste from decommissioning is mostly low and intermediate level and can be handled and disposed of accordingly. For some of the components that are very large, special approaches, such as intact disposal, have been successfully used.

B.6. INDUSTRIAL CAPABILITY

The number of nuclear power plants under construction peaked in 1979 at 233, compared with between 30 and 55 for the past 15 years (see Fig. B-5). The number of reactors under construction as of 21 July 2010 reached 61. The nuclear supply industry has adjusted to the past 25 or so years through consolidation. However, the nuclear supply industry is now also adjusting to meet the growth in future demand, particularly in heavy industrial capacity.

During the period of peak construction there were major nuclear system supply companies in Canada, France, Germany, Japan, the Russian Federation, Sweden, Switzerland, the UK and the USA. Today, nuclear system suppliers exist in Canada, China, France, India, Japan, the Republic of Korea, the Russian Federation and the USA. There are other potential suppliers who are developing designs such as in Argentina and South Africa. The designers of currently available nuclear systems have been reduced to a small group who increasingly work very closely together, for example, through collaboration between Areva and Mitsubishi, GE and Hitachi, and Toshiba and Westinghouse.

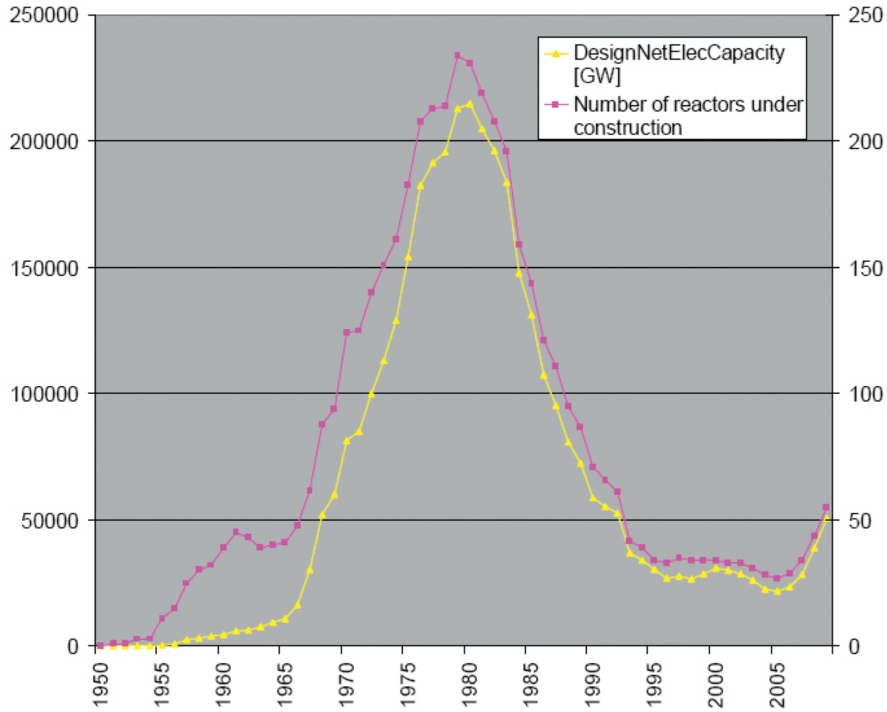

FIG. B-5. Number of reactors (and total reactor capacity) under construction from 1951 to 2010. Source: IAEA (PRIS).

A similar change has taken place among the architect–engineers[12]. The number of companies with recent experience in managing the construction of a complete nuclear power plant has decreased due to the lack of orders, particularly in North America and Europe. Many of the companies that were leading organizations in the nuclear industry in 1980 have moved away completely from the nuclear business, amalgamated with others in the nuclear field or redirected their business approach to activities related to decommissioning and waste management where there has been an increase in activity in the past few years. This has resulted in a smaller group of companies, in fewer countries, with the

[12] An architect–engineer is usually responsible for project management, procurement, project engineering, installation, commissioning, quality control, and schedule and cost control during construction and startup.

capability of managing the construction of a complete nuclear power plant. Conversely, in China, India and the Republic of Korea the growth of nuclear capability through localization of many of the skills and capabilities provides the possibility that these countries may contribute further to meeting the world's need for nuclear construction expertise. This is already happening, as a Korean consortium led by KEPCO won a bid to build plants in the UAE.

There is some evidence that past concern about the industry's ability to meet demand for key components (such as pressure vessels and key forgings) is being addressed through investments in facilities. The suppliers of heavy industrial equipment are in China, the Czech Republic, France, Japan, the Republic of Korea and the Russian Federation. New capacity is being built by Japan Steel Works (JSW) and Japan Casting & Forging Corporation (JCFC) in Japan, Shanghai Electric Group and subsidiaries in China, and in the Republic of Korea (Doosan), France (Le Creusot), the Czech Republic (Plzeň) and the Russian Federation (OMZ Izhora and ZiO-Podolsk). JSW, for example, has plans to triple its capacity by 2012. China has announced that it has the capability to produce heavy equipment for six large reactors per year, and the Shanghai Electric Group has stated that it will have the ability to produce large forgings for the AP1000 by the end of 2010.

B.7. NON-ELECTRIC APPLICATIONS

Most of the world's energy consumption is for heat and transportation. Nuclear energy is currently used only to a very limited extent for non-electric applications. The desalination of sea water using nuclear energy has been demonstrated, and nearly 200 reactor-years of operating experience have been accumulated worldwide. District heat involves the supply of heating and hot water through a distribution system which is usually provided in a cogeneration mode in which waste heat from power production is used as the source of district heat. Several countries (Bulgaria, Hungary, Romania, the Russian Federation, Slovakia, Sweden, Switzerland and Ukraine) have or have had district heating using heat from nuclear plants. Regarding nuclear hydrogen production, Japan, the USA and other countries have research and development programmes, but no commercial operation exists.

C. PROSPECTS FOR THE FUTURE APPLICATION OF NUCLEAR ENERGY

Recently, expectations for the future application of nuclear energy have been on the rise in many countries, both in countries that have operating nuclear power plants and in countries that are considering their introduction. This section discusses the potential drivers that influence national positions on the application of nuclear energy, international predictions of the future use of nuclear energy and the potential for applications of nuclear energy for non-electric uses.

C.1. PROSPECTS IN COUNTRIES ALREADY USING NUCLEAR POWER

The number of countries with operating nuclear power plants has decreased since 2008 due to the closure of the Ignalina plant in Lithuania. Lithuania is, however, planning a new plant — possibly jointly with its Baltic neighbours — to replace the closed plant in the next decade.

In the 29 countries with operating nuclear power plants, the share of national electricity they provide ranges from 76% of French electricity generation to 2% of Indian and Chinese electricity. It is expected that future expansion of nuclear power worldwide will depend principally on those countries that already have nuclear power. As discussed below, the difference between the IAEA's low and high nuclear power projections is in both the total installed capacities in the 29 countries already with nuclear power and the increase in the number of countries with nuclear power. In terms of installed capacity, the global increase in the high projection occurs mainly through increases in the countries already with nuclear power, particularly India, China and other countries of the Far East, plus the Russian Federation and countries in Europe and North America.

Table C-1 presents a review of available information on the expansion plans of countries currently operating nuclear power plants. This includes Member State presentations to the 2009 General Conference and other public expressions of their positions. According to this review, expansion of existing nuclear programmes is currently largely centred in Asia, where the greatest expansion in energy needs is also expected. Many countries in Europe and North America also expect to expand their nuclear programmes, though few new construction starts have been seen.

Each of the 29 countries has been classified into one of the groups in Table C-1, which thus provides an indication of the expected future intentions of the 29 countries already with nuclear power.

TABLE C-1. POSITION OF COUNTRIES WITH OPERATING NUCLEAR POWER PLANTS

Description of group	Number of countries
Intending to phase out nuclear plants when the current plants come to the end of their life or reach an agreed cumulative power output	2
Reviewing energy needs and including nuclear as a potential option	5
Permitting new plants to be proposed but with no incentives	4
Supporting the construction of new plant/plants	5
New plant/plants under construction	13

C.2. PROSPECTS IN COUNTRIES CONSIDERING THE INTRODUCTION OF NUCLEAR POWER

In recent years, in every region of the globe, many countries have expressed a new or renewed interest in nuclear power. In the context of growing energy demands to fuel economic growth and development, climate change concerns, and volatile fossil fuel prices, as well as improved safety and performance records, some 65 countries are expressing interest in, considering, or actively planning for nuclear power. This comes after a gap of nearly 15 years, during which international markets, energy systems and strategic concerns have evolved. Countries introducing nuclear power now face different conditions than in the past, and are responding to them in new and creative ways. Countries planning the expansion of existing nuclear power programmes, some of which have not built new reactors for more than a decade, may also share some of these issues.

Another indicator of growing interest is the threefold increase in the number of IAEA technical cooperation (TC) projects related to nuclear power. There were 13 in the 2007–2008 cycle, and there are 35 in the current cycle, 2009–2011. As of 2009, 58 countries were participating in national and/or

TABLE C-2. POSITIONS OF COUNTRIES WITHOUT OPERATING NUCLEAR POWER PLANTS

Description of group	Number of countries
Not planning to introduce nuclear power plants, but interested in considering the issues associated with a nuclear power programme[13]	31
Considering a nuclear programme to meet identified energy needs with a strong indication of intention to proceed	14
Active preparation for a possible nuclear power programme with no final decision	7
Decided to introduce nuclear power and started preparing the appropriate infrastructure	10
Invitation to bid to supply a nuclear power plant prepared	–
New nuclear power plant ordered	2
New nuclear power plant under construction	1

regional projects related to the introduction of nuclear power through the IAEA's TC programme.

Table C-2 shows the numbers of countries at different stages of nuclear power consideration or development. Sometimes referred to as 'nuclear newcomers', some countries, such as Bangladesh, Egypt and Vietnam have in fact been planning for nuclear power for some time. Others, such as Poland, are reviving the nuclear power option after plans had been curtailed when governments and public opinion changed. Countries such as Jordan, Mongolia and Uruguay are considering nuclear power for the first time. What they have in common is that they are all considering, planning or starting nuclear power programmes, and have not connected a first nuclear power plant to the grid.

The Islamic Republic of Iran has announced plans to complete commissioning of its first nuclear power plant at Bushehr soon.

[13] Based upon participation in the current TC Programme through regional/national TC projects.

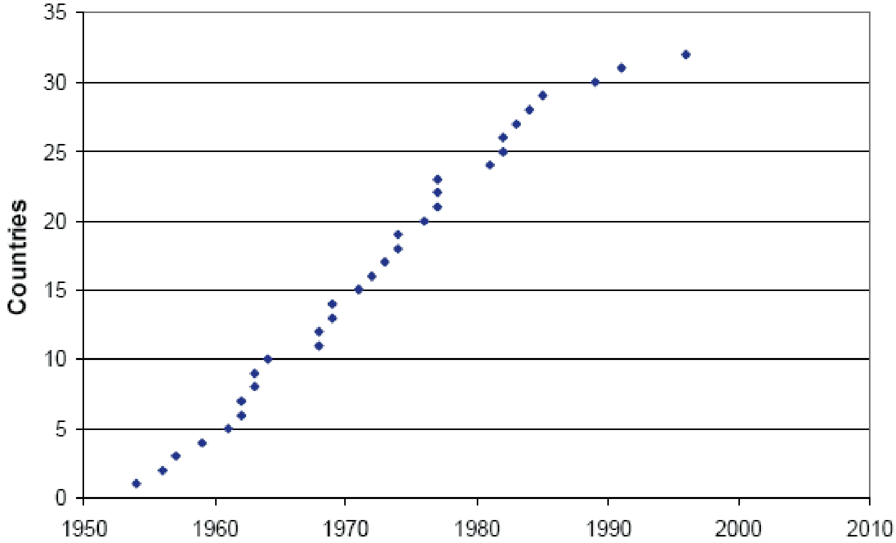

FIG. C-1. Year of new country operating its first nuclear plant. Source: IAEA (PRIS).

Of the 65 countries expressing an interest in the introduction of nuclear power, 21 are in Asia and the Pacific region, 21 are from the Africa region, 12 are in Europe (mostly Eastern Europe) and 11 are in Latin America.

The rate at which new countries joined the list of countries operating nuclear power plants was fairly steady through the early 1980s (Fig. C-1). Only three countries connected their first nuclear power plants to the grid in the post-Chernobyl era — China, Mexico and Romania. The countries now planning for their first nuclear power plants are doing so after an experience gap of fifteen years. Of the countries expressing an interest in their first nuclear plant, 25 have expressed target dates for the first operation before 2030, including 14 between 2015 and 2020 which, if achieved, would result in the greatest number of new countries entering nuclear energy production that has ever occurred within such a short period.

Overall, Tables C-1 and C-2 are consistent with trends reflected in the IAEA's low and high projections described below, i.e. there remains substantial uncertainty in projections about nuclear power, the expected increase in the use of nuclear power would be driven more by expansion in established nuclear power countries than by countries starting nuclear power programmes, and approximately 25 new countries might have their first nuclear power plants in operation by 2030 in the high projection compared with about ten new countries in the low projection.

C.3. REGIONAL COLLABORATION

In some regions, cooperative activities for the introduction of new nuclear power plants are planned. A regional project has been considered by the Baltic States at the Ignalina site in Lithuania. The member countries of the Cooperation Council for the Arab States of the Gulf are considering the possibility of a regional approach to the introduction of a nuclear programme. Argentina and Brazil, both with nuclear power programmes, plan to increase cooperation in the nuclear field, including preparation of a model nuclear power plant concept for both countries and potentially for other countries in the region.

C.4. POTENTIAL DRIVERS FOR THE INTRODUCTION OF NUCLEAR POWER

The phrase 'rising expectations' best characterizes 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. There are several drivers for these rising expectations for nuclear power growth, some of which are:

- Growing energy needs;
- Security of energy supply;
- Environmental concerns and constraints;
- Rising and volatile prices of fossil fuels;
- Improved relative economic competitiveness of nuclear power;
- Increasing experience of nuclear power and its good performance;
- Interest in advanced applications of nuclear energy.

This section examines these potential drivers of nuclear power growth in general while recognizing that nuclear power's relative attractiveness compared with alternatives will be different in different situations. In general, nuclear power is more attractive where energy demand is growing rapidly, where alternatives are scarce or expensive, where energy supply security is a priority, where reducing air pollution and greenhouse gas (GHG) emissions is a priority, or where financing can extend over the longer term.

C.4.1. Fossil fuel prices

Coal and natural gas fired power generation will be the principal alternatives to nuclear power in the near and medium term. Prices for both have been volatile in recent years. Coal prices more than doubled from 2003 to mid-2008 across most regions of the world, but then fell by 70% between July and December of 2008. Recently they have shown some signs of recovery. Similarly, gas prices, which more than doubled in parallel with coal prices, declined in 2009 but then began to increase slightly in the second quarter of 2010. The rising coal and gas prices between 2003 and 2008 were a contributor to rising expectations for nuclear power. Uranium prices also showed some volatility, rising to peak in 2007 before declining in 2009. Uranium costs, however, contribute a smaller share of overall generating costs than do coal and gas costs, so potentially volatile and increasing fuel costs have a more significant impact on investment decisions for fossil fuelled plants than for nuclear plants.

C.4.2. Energy security

Concerns about energy supply security were important in the nuclear expansion programmes of France and Japan at the time of the oil shocks of the 1970s. They are one of the arguments advanced today in countries considering nuclear power. In the UK, for example, energy supply security was a major issue in reassessing the national energy situation and was a major factor in the change in approach to nuclear power.

Moreover, nuclear power has two features that generally further increase resiliency. The basic fuel, uranium, is available from diverse producer countries, and small volumes are required, making it easier to establish strategic reserves. 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. However, the option of establishing relatively low cost strategic reserves enabling the storage of sufficient fuel for several years of nuclear power plant operation remains available for countries that find this important.

C.4.3. Environment

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. The complete nuclear power chain, from resource extraction to waste disposal including reactor and facility construction, emits the same carbon equivalent per kilowatt-hour as wind and hydropower. It is increasingly cited as a positive technology alternative to GHG emitting power sources. Nuclear power's low GHG emissions were given concrete economic value when the Kyoto Protocol entered into force in February 2005. Among the nine electricity generation mitigation technologies assessed by the Intergovernmental Panel on Climate Change (IPCC), nuclear power has the largest mitigation potential by a large margin and (after hydropower) the second lowest range of mitigation costs. However, it should be noted that even with the most ambitious global nuclear expansion programmes the growth in nuclear power would not alone stabilize worldwide GHG emissions.

The Conference of the Parties to the Kyoto Protocol (COP-15) in Copenhagen in December 2009 marked the culmination of a two year negotiating process to enhance international climate change cooperation. The key deliverable was a new international environmental agreement with ambitious mid-term GHG emission reductions to come into force in 2012. The negotiations were difficult, focusing on setting targets for GHG emissions especially from those countries which were not signatories to the Kyoto Protocol. In contrast to the current stigmatization of nuclear power in the clean development mechanism and joint implementation, there is no longer any reference, in the text prepared by the Ad Hoc Working Group on Long-term Cooperative Action under the Convention (AWG-LCA), excluding nuclear power from 'nationally appropriate mitigation actions' (NAMAs). This is considered to be a move towards recognizing the role of nuclear energy as a potent mitigation option. Further details are provided in the Annex.

C.4.4. Performance and safety records

In the 1990s, performance and safety records improved significantly, and they have remained high.[14] Well run nuclear power plants have proven quite profitable. The improvement in the global average energy availability factor and reduction in the number of unplanned reactor trips reflect this improvement.[15] However, in both areas, there is still room for improvement for many operators, which should lead to further overall improvement. The good safety and performance records over the past two decades, the resulting increased profitability, and the expectation of further improvements all contribute to rising expectations for nuclear power.

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[14] *Nuclear Safety Review for the Year 2009*, GOV/2010/4, IAEA, Vienna (2010).

[15] WORLD ASSOCIATION OF NUCLEAR OPERATORS, *2008 Performance Indicators*, WANO, London (2009).

TABLE C-3. ESTIMATES OF NUCLEAR ELECTRICITY GENERATING CAPACITY (GW(e))

Region	2008	2010		2020		2030	
		Low	High	Low	High	Low	High
North America	113.3	114	115	126	130	127	168
Latin America	4.0	4.0	4.0	6.9	8.0	10.8	23
Western Europe	122.5	119	122	90	131	82	158
Eastern Europe	47.5	47	47	68	81	83	121
Africa	1.8	1.8	1.8	2.8	4.1	6.1	17
Middle East and South Asia	4.2	7	10	13	24	20	56
South East Asia and the Pacific						0	5.2
Far East	78.3	79	80	138	165	183	259
World total	371.6	372	380	445	543	511	807

C.5. PROJECTIONS OF THE GROWTH IN NUCLEAR POWER

For the reasons listed above, recent years have seen a general rise in the projections of nuclear power that are published regularly by several organizations.

The IAEA has published annually, since 1981, projections of global energy, electricity and nuclear power use.[16] The estimates are prepared in close collaboration and consultation with several international, regional and national organizations and international experts dealing with energy related statistics and projections. Table C-3 presents the IAEA's projections made in 2009 for nuclear generating capacity, disaggregated according to regions of the world. In the low projection, nuclear capacity grows from 372 GW(e) in 2008 to 511 GW(e) in 2030. In the high projection it grows to 807 GW(e).

Table C-3 shows that the greatest expansion of nuclear capacity is projected for the Far East. Significant expansion is also projected for the Middle East and South Asia, the region that includes India. The region with the greatest uncertainty, i.e. the greatest difference between the low and high projections, is Western Europe. Although approximately 25 new countries are included in 2030, the global increase in the high projection comes mainly from increases in the 29 countries already with nuclear power. The low projection also includes

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, *Energy, Electricity and Nuclear Power Estimates for the Period up to 2030*, Reference Data Series No. 1, IAEA, Vienna (2009).

approximately ten new countries that might have their first nuclear power plants in operation by 2030.

The projections by the IAEA have changed over the past few years. In particular, the high projection for the rate of increase in installed nuclear power plant capacity between 2020 and 2030 has more than doubled from the projections done in 2001, reflecting an increase in optimism about nuclear power in some regions. The low projection in 2001 showed declining installed capacity as plants were taken out of service without replacement. Today, even the low projection predicts a continuing small growth in the installed capacity. Other studies also project growth in installed nuclear plant capacity.

The World Energy Outlook (WEO) published by the International Energy Agency (IEA) also includes regularly updated projections of nuclear power. The WEO includes a reference scenario and alternatives, rather than low and high projections as issued by the IAEA. The IEA reference scenario has edged up slightly in recent years, and the IEA's latest alternative scenario, which assumes additional measures to limit the atmosphere's concentration of GHGs to 450 parts per million (ppm) CO_2 equivalent, projects that nuclear power in 2030 would be 50% higher than it would be in the reference scenario.[17]

Other projections indicate a wide spread in the possible range of future nuclear energy use. The World Nuclear Association (WNA) publishes high, low and reference scenarios of nuclear capacity every two years. The range in its 2009 updated projections for 2030, from 248 GW(e) to 815 GW(e), shows slightly more uncertainty than it did two years earlier. The high projections of the WNA and IAEA are quite similar and about 10% higher than the WEO's scenario limiting the GHG concentration to 450 ppm.

C.5.1. Uncertainties in the projections

As can be seen above, the spread in the predictions of the future use of nuclear power remains wide. There are several issues that affect the future implementation of nuclear power programmes, and hence the accuracy of the predictions of nuclear power use:

- Nuclear power has generated stronger political passions than have alternatives. The alternatives to nuclear power — natural gas, coal, hydropower, oil, renewables — face nothing comparable to the prohibitions and phase-out policies that several countries have adopted for nuclear power.

[17] INTERNATIONAL ENERGY AGENCY, *World Energy Outlook 2009*, OECD/IEA, Paris (2009).

- Because of the front loaded cost structure of a nuclear power plant, high interest rates, or uncertainty about interest rates, will weaken the business case for nuclear power more than for alternatives.
- Nuclear power's front loaded cost structure also means that the cost of regulatory delays during construction is higher for nuclear power than for alternatives. In countries where licensing processes were relatively untested in recent years or have yet to be established, investors face potentially more costly regulatory risks with nuclear power than with alternatives.
- The strength, breadth and durability of commitments to reducing GHG emissions will also influence nuclear power's growth.
- The nuclear industry is a global industry with good international cooperation, and hence the implications of an accident anywhere will be felt in the industry worldwide.
- Similarly, nuclear terrorism *may* have a more far reaching impact than terrorism directed at other fuels.
- While a nuclear power plant in itself is not a principal contributor to proliferation risks, proliferation worries can affect public and political acceptance of nuclear power.

C.6. EXPECTATIONS FOR NON-ELECTRIC APPLICATIONS

Nuclear power has been proposed as a source of heat (or a combination of heat and electricity) for a variety of industrial processes (such as paper, chemical and fertilizer manufacturing and refineries), for the production of an energy carrier (hydrogen), or to improve access to fossil fuels (through coal liquefaction or extraction of oil from tar sands). However, the majority of current reactors (LWRs) do not provide steam or available heat at temperatures that would enable some of these additional applications to be introduced.

Experience with nuclear in the heat and steam market in the lower temperature range does exist. A further extension of that experience appears possible in the short term in the areas of desalination, district heating and tertiary oil recovery. In the higher temperature heat/steam range, significant potential exists for using nuclear energy for hydrogen production and for the petrochemical industries, including the production of liquid fuels for the transportation sector. There are many industrial sectors (such as chemical and petrochemical industries, paper and pulp, food industry, automobile industry and textile manufacturing) which have a high demand for electricity and heat/steam at various levels of temperature and pressure. The development of dual use power plants, with electricity production and the use of steam for industrial processes, may provide significant economic benefits, which could be further improved by the deployment of high temperature steam and heat sources, potentially through high temperature reactors.

C.6.1. Desalination

Currently, nuclear desalination is used in a very limited number of countries. Predictions by the UN World Water Development Report indicate that the number of people experiencing water stress or scarcity may increase to 3.5 billion by 2025. Consequently the need for desalination systems may act as a contributing factor for the expansion of nuclear power into Middle Eastern or African countries with potable water scarcity. Currently, Japan operates desalination plants for make-up water at ten nuclear power plants. India has several demonstration projects in operation, and Pakistan, the Republic of Korea and the Russian Federation are working on design and demonstration projects. Other countries are studying the technical and economic viability of different processes.

C.6.2. Transportation

Transportation is a significant contributor to GHG emissions. If nuclear energy could contribute further to the transport sector, it could have a significant impact. Nuclear power can make an increasing contribution to electricity production for hybrid or electric driven vehicles or mass transportation, and through the production of hydrogen (see Section E.3.2).

D. CHALLENGES FOR NUCLEAR EXPANSION

D.1. KEY ISSUES AND TRENDS FOR NEAR TERM NUCLEAR EXPANSION

D.1.1. Safety and reliability

Safety and reliability are fundamental to an effective nuclear power programme. There is a need to maintain diligence and vigilance in regard to the operation of, and also preparation for, the introduction of nuclear power plants. Any plant damage, significant project delay or reduction of standards, either in the countries operating nuclear power plants, or in those countries introducing nuclear power in the future, may have a very significant effect on the expansion of nuclear energy worldwide. Efforts to reduce construction costs and times, as described in Section E.1.1, will thus be important.

D.1.2. Economic competitiveness and financing

Nuclear power plants are more capital intensive than other large scale power generation plants. In the overall cost of nuclear electricity generation, the cost of capital is offset by lower and more stable fuel costs during operation. Investment typically represents some 60% of the total generation cost of nuclear electricity. Since interest must be paid on the capital during construction, the competitiveness of nuclear power is sensitive to construction delays prior to operation owing to licensing or legal issues, technical problems, or the availability of expertise, equipment and components.

The economics of nuclear power depend upon national conditions. Economic competitiveness depends on the cost of capital, regulatory environment, availability and cost of alternative sources and costs of energy, and the business case for a specific power project. Predicted nuclear generating costs for new plants (including plant management and operation, and fuel) vary widely in different countries from approximately US $30/MW·h to US $80/MW·h, if a discount rate of 5% is used. In comparison, gas-fired generating costs range from approximately US $35/MW·h to US $120/MW·h, also at a discount rate of 5%. In most countries currently using nuclear power, the projected future generation costs for nuclear power are lower than those of either gas or coal generation. The OECD Nuclear Energy Agency projections of electricity generating costs show that in eleven countries reporting cost estimates for both nuclear and fossil fuelled electricity generation, nuclear power is projected to be consistently cheaper than gas-fired power in all eleven if a 5% discount rate is used, and in five of the eleven if a 10% discount rate is used. Nuclear power is consistently cheaper than coal fired power in nine of eleven countries at a 5% discount rate, and in eight of eleven countries at a 10% discount rate.[18]

One characteristic of nuclear power is that substantial expenditure is required after power production and revenue generation have ceased in order to pay for the decommissioning of the reactors and the management of spent fuel and radioactive waste. It is estimated that decommissioning costs represent 10–15% of the capital costs of nuclear plants. The total costs for waste management until final disposal in an operating repository are of the same order

[18] OECD NUCLEAR ENERGY AGENCY, *Projected Costs of Generating Electricity: 2010 Edition*, OECD, Paris (2010).

of magnitude. The nuclear industry uses a variety of arrangements for ensuring that these costs are estimated and that necessary funds are available when needed. In many countries, these costs are regarded as operational costs and funds are collected by the operators while the plant produces electricity, though not all plants in operation have sufficient arrangements in place. Assured funding of waste management and spent fuel programmes is an important aspect of the economy of nuclear power production and of the overall safety and security of the nuclear programme.

The economic value to investors of nuclear power's very low GHG emissions varies across countries. In countries with no limits on GHG emissions, there is no tangible economic value attached to emitting only very low levels of GHGs. In countries that place restrictions or taxes on such emissions, low emissions do have an economic value. The economic competitiveness of nuclear power would be improved in the near term if nuclear were eligible for worldwide carbon trading schemes associated with the reduction of GHG emissions.

The financial and economic crisis that began in the autumn of 2008 has had only a modest impact on nuclear power projects, and projections made in 2009 even increased as discussed in Section C.4. First, the crisis has not affected the longer term drivers of nuclear energy, most importantly growing energy demands due to population growth and economic development, an interest in stable and predictable generating costs, and concerns about energy security and environmental protection, especially climate change. Second, the crisis has had a more pronounced impact on projects with short lead times. The prospect of lower demand growth in the near term reduces the pressure for near term investment decisions, and the long lead times associated with nuclear projects allow for additional analysis and less rushed preparation. Thus, the crisis affected most nuclear projects in the early planning stages, years before key financing decisions would have to be made. Hence, only a few nuclear expansion plans have been postponed or cancelled, and the order pipelines remain filled. Third, while the investment costs of nuclear power appear to have doubled since 2004, the investment costs for non-nuclear generation options have also increased, and the relative economics of electricity generation options have been realigned only marginally, if at all.

This does not mean that the global financial and economic crisis left the nuclear power business unscathed. It was cited as a contributing factor in near term delays or postponements affecting nuclear projects in some regions of the world, especially Europe and North America. For example, Vattenfall put its decisions on nuclear new build in the UK on hold for 12–18 months, citing the economic recession and market situation. The Russian Federation announced that for the next few years, because of the financial crisis and lower projected electricity use, it would slow planned expansion from two reactors per year to one. By the end of 2009, reviews of 5 of the 28 reactors in 18 combined licence applications in the USA had been suspended at the request of the applicants. In South Africa, Eskom extended the schedule for its planned next reactor by two years to 2018.

D.1.3. Public perception

The public perception of nuclear power has focused on concerns over safety, proliferation and waste management. After the Three Mile Island and Chernobyl nuclear accidents, the public was concerned not only about the dangers of radiation to people and the environment, but also about the speed and accuracy of available information. Concerns about proliferation and nuclear terrorism continue to play a role in the public perception of nuclear power.

Public perception is also dependent on many factors specific to a given society such as the local energy supply position, national experience with nuclear power and national perceptions of environmental considerations. In many countries, the public attitude towards nuclear power has changed in recent years. Public support for nuclear power has grown with the recognition of concerns over climate change and the lack of practicable and affordable alternatives. The changing public perception of nuclear power is partly due to the successful generation of nuclear energy over the past 20 years, and also to the perception that nuclear energy can make a valuable contribution to reducing global warming. Continuing successful experience with decommissioning and spent fuel management may also have contributed to increased public confidence. In other States, however, public concerns about nuclear power remain a major obstacle to extending or initiating nuclear power programmes. In some countries, public perception may be heavily influenced by observations that nuclear power has made valuable contributions to raising living standards in other countries.

For any country considering or operating nuclear power, open communication with all stakeholders (decision makers, public, media and neighbouring countries) on all of the issues surrounding nuclear power (benefits, risks, commitments and obligations) is essential in order to build and maintain trust and confidence in a nuclear power programme.

D.1.4. Human resources

The availability of human resources is a critical challenge to the expansion and growth of nuclear power. It is a challenge for the nuclear industry to recruit and train a large number of qualified individuals just to replace those very experienced individuals who are retiring. Additional human resources will be needed to support the planned expansion or implementation of new nuclear power programmes. Taken together, the challenges are substantial.

For those countries initiating a nuclear programme, one proven way for those who will operate and maintain the first plants to obtain the competence needed is through gaining experience in existing facilities using similar technology. It is through this practical training and experience that both the competencies and safety culture needed in the nuclear power industry are transferred. With the large number of retirements in countries operating nuclear power plants coming at the same time as planned expansions, having sufficient human resources with suitable experience to carry out these tasks can be a significant challenge. The development of competent national human resources in the future operating company and in the nuclear regulator remains a high priority for countries initiating a nuclear power programme.

Most industry managers agree that the buildup of a nuclear workforce should be thoroughly planned. However, it is not essential to have the whole workforce established before construction has started, since the years that it takes to build a plant provide time to train most of the non-nuclear specialist portions of this workforce.

D.1.5. Spent fuel and waste management and disposal

The management of new or additional spent nuclear fuel and radioactive waste needs to be considered when planning for the expansion or introduction of nuclear power, and a policy and strategy for its implementation and funding need to be developed.

Most of the world’s spent fuel continues to be stored in reactor pools or dry storage. However, storage represents an interim stage in all spent fuel management strategies, and the final disposal of spent fuel or HLW from spent fuel reprocessing can take decades. Spent fuel continues to accumulate in larger quantities and needs to be stored for longer time periods than initially envisaged (over 100 years). Furthermore, fuel designs are developing to allow much higher burnups than initially considered in the design basis of many types of storage. Therefore, many different physical, chemical and thermal processes, for example, need to be researched and tested for continued operability, reliability, safety and security of the storage and the spent fuel, and to ensure that the spent fuel can ultimately be safely and securely transported from storage to reprocessing or disposal.

Some countries such as France, India, Japan and the Russian Federation have ongoing programmes to recycle spent fuel. However, because final disposal is necessary in all options for the back end of the fuel cycle, every country needs access to disposal. There is a need to support final disposal options, initiatives and projects. Special support to newcomer countries to develop strategies for spent fuel management is needed.

The disposal of LLW is a mature technology; nevertheless, experience shows that difficulties with public acceptance can be encountered in the construction of an LLW or ILW disposal facility. The disposal of HLW and spent fuel generated by nuclear power plants has not yet been implemented.

Spent nuclear fuel is either reprocessed for reuse or regarded as waste depending on economic conditions. Reprocessing separates plutonium and uranium from the waste for recycling as mixed oxide (MOX) fuel. The remaining ILW and HLW need safe disposal. At present, only a few countries reprocess and recycle their fuel (the closed fuel cycle). Other countries have decided against reprocessing because of economic as well as proliferation or environmental concerns relating to the separation of plutonium. In these countries, the fuel is planned to be disposed of in a geological disposal facility following approximately 30–40 years of interim storage (the once-through fuel cycle). However, as mentioned above, storage times are expected to grow considerably. Most countries with nuclear power plants have, however, adopted a wait and see position. Recently, interest in the closed fuel cycle over the long term has increased worldwide for sustainability reasons (better utilization of resources). Advanced reprocessing may also simplify the final disposal of the remaining HLW.

International or multinational approaches to the back end of the fuel cycle are also being studied to increase efficiency and to reduce proliferation concerns. These include multinational repositories, fuel leasing and take-back, and reprocessing services.

In addition, the future decommissioning of nuclear reactors and the management of the radioactive waste from decommissioning should also be considered at the initial stages of the design and operation of the plant. The technology for decommissioning is available and mature, and radiation hazards, doses, the amount and type of wastes, schedules and costs can all be substantially optimized if decommissioning is taken into account at an early stage.

D.1.6. Transport

An increase in the number of countries with reactors operating worldwide would lead to an increase in the overall volume of transport of uranium, fresh and spent fuel, and waste. In terms of fresh fuel, the increase would be proportional to the growth in electrical production, about 45% more by 2030 using the IAEA's low projection and 130% more at the high projection. The increase in the volume of spent fuel and waste transport is harder to predict, as it would be tied to national policies regarding reprocessing and other factors. In the short term, the number of cross-border spent fuel transports is likely to remain lower than in the 1990s, with the opening of the Rokkasho reprocessing plant in Japan and the end of contracts for reprocessing foreign fuel in the UK and France. In a longer term perspective, with increased reprocessing and recycling such transports are likely to increase.

Over the past few years, the IAEA has taken note of increased denials of shipment of radioactive material, primarily radioactive sources for medical or industrial purposes, but also uranium and fresh nuclear fuel, regardless of the transport method. The IAEA is collecting additional information on this trend and has formed a steering committee to further investigate its impact. The transport of spent fuel and waste, which is normally performed in dedicated consignments, has not been affected by denials, but has been subject to public protests connected to opposition to the use of nuclear energy.

D.1.7. Proliferation risks and nuclear security

Although civil nuclear power plants in themselves pose a limited proliferation risk, an increase in the amount of nuclear material in use, storage and transport may intensify this risk. The dissemination of nuclear technology and the existence of international terrorism can also raise perception of an increased risk.

As a consequence, the international community may need to consider the challenges associated with improving control over sensitive parts of the nuclear fuel cycle (such as implementing multinational approaches to the nuclear fuel cycle), enhancing international commitment to support the IAEA's strengthened safeguards system, and enhancing the sharing of international security measures.

Growth and globalization in nuclear power would require additional safeguards activities, but the IAEA's verification workload is not likely to increase proportionally if States accept greater transparency measures. Verification activities will increasingly become information driven. The increasing number of facilities approaching the end of their life cycle presents a growing verification challenge during shutdown and decommissioning. The verification burden from new reactor technology and types of fuel cycle facilities may be lessened by the development and integration of 'safeguards friendly' technology that allows efficient and effective verification.

Vulnerability of material in transit is one aspect that may require additional measures if the volume of reactor fuel shipments increases. In this regard, INFCIRC/225, *The Physical Protection of Nuclear Material and Facilities*, would need to be revised to include additional provisions on transport.

D.1.8. Infrastructure building in new nuclear countries

The implementation of an appropriate infrastructure to address all relevant issues for the introduction of nuclear power is of key importance, especially for countries planning a first nuclear power plant. Infrastructure comprises the governmental, legal, regulatory, managerial, technological, human and other resource support for the nuclear programme throughout its life cycle. It covers a wide range of issues — from physical delivery of electricity, the transport of the material and supplies to the site, the site itself, and special facilities for handling the radioactive waste material, to the legislative and regulatory framework and the necessary human and financial resources. In brief, infrastructure, as used in this context, includes all activities and arrangements needed to set up and operate a nuclear programme.[19] This is relevant regardless of whether the nuclear power programme is planned for the production of electricity, seawater desalination or any other peaceful purpose.

Governmental organizations, utilities, industrial organizations and regulatory bodies in a country adopting or expanding a nuclear power programme all play a role in the establishment of a national nuclear infrastructure. Exporting governments and suppliers may also contribute as stakeholders in understanding the adequacy of a national infrastructure before supplying nuclear equipment and material. The development of the competence of these organizations is a key aspect that needs to be established at the beginning of preparations for a nuclear power programme.

The buildup of all elements of a national nuclear infrastructure should be thoroughly planned. However, it is not essential to have the whole infrastructure established before preparation for a nuclear power programme starts since the infrastructure should be developed in a phased manner consistent with the development of the programme.

D.1.9. Relationship between electricity grids and reactor technology

Grid size, quality, stability and interconnectedness are issues for consideration by countries that currently use nuclear power, but especially by nuclear newcomers. The value of 10% of grid capacity is widely believed to be the maximum capacity of an additional unit of any type in order to prevent grid interface problems. Interconnected grids increase overall capacity. Protection

[19] The IAEA publication *Milestones in the Development of a National Infrastructure for Nuclear Power* (IAEA Nuclear Energy Series No. NG-G-3.1) lists 19 issues to be addressed in national infrastructure.

systems that isolate parts of the grid in the event of transients can reduce the risk of instability.

Many countries interested in introducing nuclear power plants have small and isolated grid networks. Seventeen of the 31 countries considering or planning for nuclear power have grids of less than 5 GW(e), which would make them too small, according to the 10% guideline, to accommodate most of the reactor designs on offer without improved international grid interconnections. Grid issues may also place limitations on technology options for additional countries with grids smaller than 10 GW(e). Commercial availability of designs below 600 MW(e) is limited, though many designs are in development. Technology advancements in small reactors to improve commercial viability, as well as to decrease dependence on grid stability and reliability, would widen the choices for countries with small grids. Very small reactors with characteristics that would enable them to be fully independent of a grid network may also be of interest for applications in isolated circumstances.

D.2. KEY ISSUES FOR LONG TERM DEPLOYMENT

Design developments in both reactor and fuel cycles are necessary to achieve an increase in nuclear energy's long term contribution to sustainable development. The aim of sustainable development is to achieve equity within and across countries as well as across generations, by integrating growth, environmental protection and social welfare. Sustainability can be considered from four related, but different, viewpoints or dimensions: social, economic, environment related and institutional infrastructure. To achieve these in a nuclear energy system, improvements in sustainability are considered in the context of developments in the areas of safety, economics, proliferation resistance, waste, environment, resource utilization, security and infrastructure. The principal update in this section is in the estimate of uranium resources.

D.2.1. Effective use of available resources

The latest estimate of global uranium resources published by the OECD/NEA and the IAEA in 2010 shows identified conventional uranium resources of 6.3 million tonnes (Mt U). This corresponds to almost 100 years of consumption at the present level. Although this figure is high compared with other mineral resources, the important challenge is to improve the utilization of the uranium resource, i.e. to increase energy output per tonne of uranium mined. In parallel, it can be expected that increased exploration and utilization of unconventional resources (such as uranium from phosphates and sea water) will increase uranium resources.

Certain improvements in the use of natural resources (up to a doubling of the energy output) in the present generation of reactors can be achieved by reducing the fraction of uranium-235 in enrichment plant tails, reusing uranium and plutonium extracted from spent fuel, increasing fuel burnup and modernizing plant systems (e.g. installing more efficient turbines).

One of the future measures to improve the effective use of available resources would be the introduction of fast reactors and associated fuel cycles. With multiple recycling, the energy output per tonne of uranium can be increased by as much as 60 times compared with the present generation of LWRs. Innovative reactors that use thorium fuel may also be commercially developed, thus increasing the world's usable sources of nuclear fuel.

In addition to using uranium and thorium resources efficiently, an effective use of structural materials such as steel is also an important aim. Several design concepts of evolutionary reactors provide technical solutions that directly or indirectly ensure material savings for economic competitiveness. Among the solutions are: longer design life; increasing thermal efficiency of the power conversion cycle; reduction of steel consumption; and compacting plant layout. In a longer term perspective, the recycling of radioactive structural materials arising from decommissioned nuclear reactors may also contribute to the effective use of resources.

D.2.2. Reactor design innovation

The second key issue for long term deployment is reactor design innovation. Innovations for large power reactors are discussed in Sections E.1.2 and F. Innovations to extend the possible application of nuclear power plants include increases in operating, and hence outlet, temperatures. These innovations are being approached through both the development of high temperature gas cooled reactors and developments to increase the output temperature from water cooled reactors, including the development of supercritical water cooled reactors. Innovations responding to increasing interest in nuclear power for small reactor applications are focused on the development of reactors that can be operated either on small grids or off-grid, although it is not clear what the market for reactors in this size range will be. In addition, reactors that are mobile or that can be transported are also being developed for remote or isolated applications.

D.2.3. Fuel cycle innovation

In parallel with the development of innovative reactors, corresponding fuel cycle facilities need to be developed in the long term. These include advanced reprocessing facilities which can handle the fuel of innovative reactors and separate plutonium and minor actinides for recycling, and the fuel manufacturing technologies for these fuels.

Increasing amounts and longer storage times of spent fuel and the introduction of innovative reactors with fuel recycling will lead to increased handling of proliferation sensitive material, and may thus increase safeguards requirements. A number of innovative approaches to address this issue have been proposed, including multilateralization of sensitive fuel cycle facilities, i.e. enrichment and reprocessing facilities. Other possible solutions may include a system where some countries both provide fresh fuel to reactors and take back spent fuel as a service. The fuel taken back will thus be a resource for recycling in fast reactors and may, in the longer term, have a positive value. The use of recycled material may, however, also lead to increased safety and security concerns during transportation.

An increased use of closed fuel cycles may also have an effect on the final disposal of HLW. With the removal of plutonium and minor actinides, the radiotoxicity and heat load of HLW will be reduced and waste packages can be stored more closely together, thus making it possible to increase repository capacity. The potential benefits of international or regional repositories are also being discussed, although arrangements for such facilities continue to face political and public acceptance challenges.

E. DEVELOPMENT OF REACTOR AND FUEL CYCLE TECHNOLOGY[20]

E.1. NUCLEAR REACTORS AND SUPPORTING TECHNOLOGY DEVELOPMENTS

Most of the advanced nuclear power plant designs available today are evolutionary improvements on previous designs. This has the benefit of maintaining proven design features and thus minimizing technological risks. These evolutionary designs generally require little further research and development or confirmatory testing.

Innovative designs, on the other hand, incorporate radical conceptual changes in design approaches or system configuration in comparison with existing practice. Innovative designs will probably require greater investment in research and development as well as construction of a prototype or demonstration plant.

E.1.1. Evolutionary development

Near term growth in nuclear power use will be based mostly on evolutionary designs. Such designs incorporate feedback from operational experiences in the human–machine interface, component reliability, improved economics and safety. As part of the system is already proven, evolutionary designs require at most engineering and confirmatory testing. Examples of commonly utilized elements of evolutionary design for improved economics are:

- Simplified designs;
- Increased reactor power;
- Shortening the construction schedule, reducing the financial charges that accrue without countervailing revenue;
- Standardization and construction in series spreading fixed costs over several units;
- Productivity gains in equipment manufacturing, field engineering and construction;

[20] Assessments in this section are based on information available to the Secretariat at the time of writing, including information from publicly available sources, and may therefore not be exhaustive or fully accurate.

- Multiple unit construction at a single site;
- Self-reliance and local participation.

In addition to improved economics, several means are commonly used to improve safety and reliability in evolutionary designs through increased attention to external hazards and advances in testing and inspection, and the application of probabilistic safety assessment (PSA). Evolutionary designs also place increased emphasis on the human–machine interface, including improved control room and plant design for ease of maintenance. Instrumentation and control systems are also updated to make use of digital systems.

Light water reactors

Advanced LWR designs are being developed in several countries. China, in addition to its extensive nuclear power programme with PWRs, water cooled water moderated power reactors (WWERs) and heavy water reactors (HWRs) supplied by foreign vendors, has already developed and operates its own domestic medium size PWR designs. Furthermore, the China National Nuclear Corporation (CNNC) has developed the evolutionary China Nuclear Plant (CNP-1000) incorporating the experience from the design, construction and operation of the existing plants in China. Two CNP-1000 units are in operation (Lingao-1 and -2) and several more units are under construction and planned. The State Nuclear Power Technology Corporation (SNPTC), which was created in May 2007, is responsible for the assimilation of the Westinghouse AP-1000 technology to develop the Chinese large scale passive design CAP1400, as well as some other advanced reactor concepts, including small and medium sized reactors (SMRs) and a supercritical water cooled reactor (SCWR).

In France and Germany, AREVA has designed the European Pressurized Water Reactor (EPR), which meets European utility requirements. Its power level of 1600+ MW(e) has been selected to capture economies of scale relative to the latest series of PWRs operating in France (the N4 series) and Germany (the Konvoi series). The first EPR is at present under construction for TVO of Finland at the Olkiluoto site. Commercial operation is planned for 2012. Also, Électricité de France is constructing an EPR at Flamanville (Unit 3), with commissioning scheduled for 2012, and is planning to start construction of an EPR at Penly beginning in 2012. Two EPR units are also under construction in China at Taishan, Units 1 and 2. AREVA's US EPR design is currently being reviewed by the US Nuclear Regulatory Commission (NRC) for design certification in the USA and by the UK Health and Safety Executive for generic design assessment in the UK.

AREVA is also working with Mitsubishi Heavy Industries (MHI) in a joint venture to develop the 1100+ MW(e) ATMEA-1 PWR, and with several European utilities to develop the 1250+ MW(e) KERENA BWR.

In Japan, the benefits of standardization and series construction are being realized with the large advanced boiling water reactor (ABWR) units designed by General Electric, Hitachi and Toshiba.[21] Several ABWRs have been proposed for construction in the USA.

Also in Japan, MHI has developed the advanced pressurized water reactor (APWR+), which is an even larger version of the large advanced PWR designed by MHI and Westinghouse for the Tsuruga-3 and -4 units. MHI has submitted a US version of the APWR, the US-APWR, to the NRC for design certification. A European version of the APWR, the EU-APWR, is currently under evaluation against the European Utility Requirements (EURs).

With the goals of sustainable energy through high conversion (a conversion ratio equal to or beyond 1.0) of fertile isotopes to fissile isotopes, Hitachi is developing in Japan the large, reduced moderation resource-renewable BWR (RBWR) and the Japan Atomic Energy Agency (JAEA) is developing the large reduced-moderation water reactor (RMWR).

In the Republic of Korea, the benefits of standardization and series construction are being realized with the 1000 MW(e) Korean Standard Nuclear Plants (KSNPs). Ten KSNPs are in commercial operation. The accumulated experience has been used by Korea Hydro & Nuclear Power Company (KHNP) to develop an improved version, the 1000 MW(e) Optimized Power Reactor (OPR), of which four units are under construction in Shin-Kori-1 and -2 and Wolsong-1 and -2, with grid connection scheduled between 2010 and 2012. A 1000 MW(e) Advanced Power Reactor (APR) is under development, with enhanced safety and economics, and is scheduled to be completed by 2012.

KHNP's APR-1400 builds on the KSNP experience with a higher power level to capture economies of scale. The first two APR-1400 units are under construction at Shin-Kori-3 and -4, and a contract has been awarded to KHNP for the construction of four APR-1400 in the UAE. Activities are under way in the Republic of Korea to design an APR+ of approximately 1500 MW(e), with the goal to complete the standard design by 2012.

In the Russian Federation, evolutionary WWER plants have been designed building on the experience of operating WWER-1000 plants. WWER-1000 units are currently under construction at the Kalinin and Volgodonsk sites and WWER-1200 units at the Novovoronezh-2 and Leningrad-2 sites. Additional WWER-1200 units are planned by 2020 at the Novovoronezh, Leningrad,

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[21] Two ABWRs are also under construction in Taiwan, China.

Volgodon, Kursk, Smolensk and Kola power plants. A WWER-1000 evolutionary unit will be constructed in Belene, Bulgaria, using some features of AES-2006 design basis. Two evolutionary WWER-1000 units were connected to the grid at Tianwan, China, and the construction of more WWER-1000 units is under way in India.

In the USA, designs for a large APWR (Combustion Engineering System 80+) and a large ABWR (General Electric's ABWR) were certified by the NRC in 1997. Westinghouse's mid-size AP-600 design with passive safety systems was certified in 1999. Westinghouse has developed the AP-1000 applying the passive safety technology developed for the AP-600 with the goal of reducing capital costs through economies of scale. An amendment to the NRC 2006 design certification of the AP-1000 is currently under review.

General Electric is designing the large Economic Simplified Boiling Water Reactor (ESBWR), applying economies of scale and modular passive system technology. The ESBWR is currently in the design certification review phase with the NRC.

A prototype or a demonstration plant will most likely be required for the supercritical water cooled systems, which have been selected for development by the Generation IV International Forum (GIF). In a supercritical system, the reactor operates above the critical point of water (22.4 MPa and 374ºC) resulting in higher thermal efficiency than current LWRs and HWRs. Thermal efficiencies of 40–45% are projected with simplified plant designs. The large thermodynamically supercritical water cooled reactor concept being developed by Toshiba, Hitachi and the University of Tokyo is an example. The European Commission is supporting the High Performance Light Water Reactor (HPLWR) project for a thermodynamically supercritical LWR. Activities on thermodynamically supercritical concepts are also ongoing at universities, research centres and design organizations in Canada, China, Germany, India, Japan, the Republic of Korea, the Russian Federation, Ukraine and the USA.

Heavy water reactors

Advanced HWR designs are also being developed in a number of countries. In Canada, Atomic Energy of Canada Limited (AECL) is working on the Enhanced CANDU 6 (EC6) concept based on the latest CANDU 6 plant built in Qinshan, China, that has been updated to meet the latest codes and standards and incorporates the latest regulatory requirements. AECL is also developing the large, evolutionary advanced CANDU reactor, the ACR-1000, using slightly enriched uranium and light water coolant and incorporating improvements derived from research and development conducted in recent decades. Also, as a part of the GIF initiative, AECL is developing an innovative pressure tube reactor design with heavy water moderator and supercritical light water coolant.

In India, a process of evolution of HWR design has been carried out since the Rajasthan-1 and -2 projects. India's 540 MW(e) HWR design incorporates feedback from the indigenously designed 220 MW(e) units, and in September 2005 and August 2006 the two 540 MW(e) units at Tarapur began commercial operation. India is also designing an evolutionary 700 MW(e) HWR, and a 300 MW(e) Advanced Heavy Water Reactor using heavy water moderation with boiling light water coolant in vertical pressure tubes, optimized for utilization of thorium, and with passive safety systems. Research is also under way on heavy water moderated, pressure tube designs with thermodynamically supercritical water coolant.

Gas cooled reactors

In several countries, prototype and demonstration GCR plants with helium coolant using the Rankine steam cycle for electric power generation have been built and are being operated. In France, Japan, the Russian Federation, South Africa and the USA, considerable efforts are being devoted to the direct cycle gas turbine high temperature reactor, which promises high thermal efficiency and low power generation cost. China plans construction of a 250 MW(th) high temperature gas cooled reactor–pebble bed module (HTR–PM) with an indirect (steam turbine) cycle at Shidaowan. In South Africa, the design of the demonstration 165 MW(e) pebble bed modular reactor (PBMR) has been changed to a steam turbine concept that can generate electricity or be used for process purposes. This change has led to a delay in the PBMR project, and its future is under intense discussion in South Africa.

Fast reactors

Resource utilization is an important factor for the long term sustainability of the nuclear industry. Fast spectrum reactors with fuel recycling significantly enhance the sustainability indices. Hence, fast reactor and associated fuel cycle research and technology development is, in many countries, back on the agenda of research and industrial organizations, as well as academia.

Important immediate and forthcoming milestones in fast reactor development include the planned commissioning of the Chinese Experimental Fast Reactor (CEFR), which achieved first criticality in July 2010, the restart of the industrial prototype Monju in Japan in May 2010, the planned commissioning between 2011 and 2013 of power fast reactors in India and the Russian Federation (Prototype Fast Breeder Reactor (PFBR) and BN-800, respectively), the planned construction around 2020 of the French prototype fast reactor ASTRID, and further advanced demonstration and commercial reactor construction projects planned for 2020–2050 in India, Japan, the Republic of Korea and the Russian Federation.

China is about to reach the first essential stage in its fast reactor technology development with the forthcoming commissioning of the 65 MW(th) CEFR, which achieved first criticality in July 2010. The conceptual design of the 600–900 MW(e) China Demonstration Fast Reactor (CDFR) is ongoing. The next concept, currently under consideration, leading to the commercial utilization of fast reactor technology around 2030 is the 1000–1500 MW(e) China Demonstration Fast Breeder Reactor (CDFBR). By 2050, China foresees increasing its nuclear capacity up to the level of 240–250 GW(e), to be provided mainly by FBRs.

In France, fast reactor technology development activities are determined by two French Parliament Acts: the 13 July 2005 Act specifying energy policy guidelines and the 28 July 2006 Act outlining policies for sustainable management of radioactive waste and requesting R&D on innovative nuclear reactors to ensure that, first, by 2012 an assessment of the industrial prospects of these reactor types can be made, and, second, a prototype reactor is commissioned by 31 December 2020 (with an industrial introduction of this technology in 2040–2050). To meet the stipulations of these laws, the Atomic Energy Commission (CEA) and its industrial partners (EdF and AREVA) are implementing an ambitious research and technology development programme aiming at the design and deployment of the 300–600 MW(e) sodium cooled fast reactor prototype ASTRID.

Within the framework of Euratom projects, the CEA is also pursuing conceptual design studies for a 50–80 MW(th) experimental prototype reactor called ALLEGRO.

In India, first criticality of the 500 MW(e) PFBR in Kalpakkam, indigenously designed by the Indira Gandhi Centre for Atomic Research (IGCAR) and constructed by BHAVINI is planned by 2011. The next step foresees the construction and commercial operation by 2023 of six additional mixed uranium–plutonium oxide fuelled PFBR type reactors (a twin unit at Kalpakkam and four 500 MW(e) reactors at a new site to be determined). The design of these six fast breeder reactors will follow an approach of phased improvements of the first Kalpakkam PFBR design. Beyond 2020, the Indian national strategy is centred on high breeding gain ~1000 MW(e) capacity reactors, and on the collocation of multi-unit energy parks with fuel cycle facilities based on pyro-chemical reprocessing technology.

In Japan, the Ministry of Education, Culture, Sports, Science and Technology (MEXT) defined the “Research and Development Policy on Fast

Breeder Reactor (FBR) Cycle Technology”, based on the 2006–2011 “Science and Technology Basic Plan”, in which the Council for Science and Technology Policy (CSTP) of the Japanese Cabinet Office identified FBR cycle technology as one of the key technologies of national importance.

Japan announced the restart of the Monju fast reactor prototype in May 2010, and work has begun at the site at which operations were suspended for fifteen years following a fire in 1995. It is expected to reach full operational levels by 2013. The Japanese fast reactor design and deployment activities are expected to lead to the introduction of a demonstration fast reactor around 2025 and to the commercial operation of fast breeder technology around 2050. These goals will be achieved on the basis of operational experience to be gained with the prototype fast reactor Monju and of the results of the Fast Reactor Cycle Technology Development Project (FaCT), started in 2006, which will develop innovative technologies aiming at economic competitiveness, high reliability and safety of the next generation of FBRs.

The fast reactor development activities of the Republic of Korea are being performed within the framework of GIF. Currently, R&D activities are focused on core design, heat transport systems and mechanical structure systems. Specifically, R&D work covers a passive decay heat removal circuit (PDRC) experiment, S-CO_2 Brayton cycle systems, a Na-CO_2 interaction test and sodium technology. Design work on innovative sodium cooled fast reactor and fuel cycle concepts is being carried out. The Republic of Korea is planning to develop and deploy a demonstration fast reactor by 2025–2028.

The Russian ‘Federal Target Programme (FTP) for nuclear power technology of a new generation for the period 2010–2020’ aims at enhancing the safety of nuclear energy and resolving the spent fuel issues. The Russian Federation established a mid-term plan to concentrate on fast reactor technology without constructing new LWRs. The existing LWRs will continue to operate and their spent fuel will be used to fuel the next generation fast reactors. The Russian fast reactor programme is based on extensive operational experience with experimental and industrial size sodium cooled fast reactors. The Russian Federation has also developed and gained experience with the technology of heavy liquid metal cooled (lead and lead–bismuth eutectic alloy) fast reactors. The Russian Federation is currently constructing the sodium cooled, mixed uranium–plutonium oxide fuelled BN-800 with planned commissioning by 2013. The fast reactor development programme includes life extension of both the experimental reactor BOR-60 and the industrial reactor BN-600, and the design of the new experimental reactor MBIR, a 100 MW(th)/50 MW(e), sodium cooled, uranium–plutonium oxide (alternatively uranium–plutonium nitride) fuelled reactor, planned as a replacement for BOR-60. Within the framework of the programme, fast reactor technologies based on sodium, lead and lead bismuth eutectic alloy coolants (i.e. SFR, BREST-OD-300 and SVBR-100, respectively) will be developed simultaneously, along with the respective fuel cycles. The design of the advanced large sodium cooled commercial fast reactor BN-K is also ongoing.

The former programmatic approach in the USA was centred on incremental improvement of existing technologies to allow for short term (≈20 years) deployment of fast reactors. This was driven by the need to better utilize Yucca Mountain. The challenges related to this approach, and the corresponding choices of technologies and integrated systems were determined by the Yucca Mountain characteristics and project timescale (in other words by the coordination with the national geological disposal strategy and plans). A notable consequence of this 'industrial' approach was that very limited investment was made in research and technology development, and in real innovation in the tools needed to develop a better understanding of the fundamentals.

The current US programmatic approach is centred on a long term deployment of fuel cycle technologies, the initial analysis of a broad set of options, and on the use of modern science tools and approaches designed to solve challenges and develop better performing technologies.

One major goal of the US programme is to develop an integrated waste management strategy. The focus of this work is on predictive capabilities for understanding repository performance. Another major research focus is in the area of used fuel separation technologies. Through the use of small scale experiments, theory development, as well as modelling and simulation to develop fundamental understanding, innovative long term options are being explored. The goal of this work is waste reduction. Enhanced materials protection and control is another key goal in the US fast reactor programme. In this area, the work focuses on the development of advanced techniques providing real time nuclear materials management with a continuous inventory (including for large throughput industrial facilities).

The specific research and technology activities include the development of the 'advanced recycle reactor' for closing the fuel cycle, and of the fast reactor needed for final transmutation/transuranics utilization systems. The near term focus is on sodium coolant technology. For future fast reactor technology deployment, the US programme focuses on two major research areas: capital cost reduction and assurance of safety (including high system reliability).

E.1.2. Future innovations

The main factors influencing the development of new generation nuclear energy systems in the twenty first century will be economy, safety, proliferation resistance and environmental protection, including improved resource utilization and reduced waste generation. Many future innovations will focus on fast neutron systems that can produce more fissile material in the form of ^{239}Pu than they consume. Fast neutrons in fast reactors also make it possible to use or transmute certain long lived radioisotopes, reducing the environmental burden of high level waste management. The complexity of these features gives some indication as to why these systems have been in various stages of development for more than 50 years and why they continue to evolve and introduce innovative concepts.

In addition to innovations designed to achieve improved fuel efficiency, there are other issues which require innovative approaches including high temperature applications and designs for isolated or remote locations.

Specific innovative development approaches that could lead to improvements in efficiency, safety and proliferation resistance include, among other benefits:

- Long life fuel with very high burnup;
- Improved fuel cladding and component materials;
- Alternative coolant for improved safety and efficiency;
- Robust and fault tolerant systems;
- High temperature Brayton cycle power conversion;
- Thorium fuel design.

Innovations such as these require extensive research and development as well as testing. Because it is resource intensive, much of the innovative work is currently being conducted under international or bilateral cooperation.

E.2. NUCLEAR FUEL CYCLE AND SUPPORTING TECHNOLOGY DEVELOPMENTS

E.2.1. Fuel cycle technology developments

The present nuclear fuel cycle technology is able to fully support current nuclear power generation. Nevertheless, as in all technical areas, new developments in all stages of the fuel cycle are under way that would further improve economic attractiveness and reduce safety, security and proliferation risks and environmental concerns and ensure, for example, more efficient and less energy consuming enrichment technology.

The fuel used in current reactors is continually evolving to allow greater in-reactor performance and higher burnup, i.e. better utilization of the uranium. Recycling of reprocessed uranium and, particularly, plutonium as MOX fuel, requires fuel fabrication involving remote handling and entails increased doses and thus the need for greater radiological protection of the current workforce.

In the area of reprocessing technology, which was originally developed in the 1960s, research on technology and equipment aims to increase the purity of products, decrease waste generation and increase proliferation control. Processes are being studied that do not separate pure plutonium for recycling, but which, instead, mix the plutonium with other material, uranium or fission products to increase its proliferation resistance. New aqueous and non-aqueous spent fuel reprocessing technologies for LWRs are being investigated, which would make it possible to significantly decrease waste generation. To test and optimize the technologies under development, work is being conducted to establish pilot industrial demonstration facilities.

The principles for disposal of HLW and spent fuel, including disposal at depth in a geological repository and surrounded by multiple barriers, are well accepted internationally. For HLW disposal, development work is under way to investigate suitable sites and specific engineered barriers and to perform safety assessments and implement the technology for encapsulation and disposal.

E.2.2. Future innovation

Different trends in the development of innovative reactors are described in Section E.1.2. Each innovative reactor system will require a specific fuel cycle approach with a dedicated nuclear fuel, using, for example, higher concentrations of plutonium, and requiring a corresponding development in fuel technology and manufacturing.

Fast reactor systems require reprocessing and recycling. Improved reprocessing technologies are being developed that can cope with the higher radiation levels of fast reactor fuel and shorter cooling times. These include current advanced wet processes and new dry processes, such as pyrochemical processing.

To reduce the long term radiotoxicity and heat load of the remaining HLW from reprocessing, new processes are being developed that separate some of the long lived radionuclides, for example, minor actinides such as americium and curium. The separated material can be destroyed by burning (transmutation) in fast reactor fuel. In addition, the separation of caesium and strontium to reduce the heat load of the waste is being studied.

The introduction of advanced recycling systems will also have an important impact on the final disposal of HLW. Although deep geological disposal will still be required, the heat load can be reduced, which increases the capacity of a repository, as the packing density in most cases is determined by the heat load. Also, long term radiotoxicity will be reduced, which could simplify the repository design and increase public acceptance.

E.3. NON-ELECTRIC APPLICATIONS

E.3.1. Seawater desalination and district heating

The demand for potable water is increasing. Electricity or steam from nuclear power plants is already being used for desalination and district heating and does not require substantial development for more widespread application. Possible dual use (electricity and desalination) may increase the flexibility and economics of the nuclear power plant.

E.3.2. Hydrogen production and process heat

Japan, the USA and other States are exploring ways of producing hydrogen from water by means of electrolytic, thermochemical and hybrid processes. Most of the work is concentrated on high temperature processes (>750°C), well above those achieved by water cooled reactors. Advanced reactors, such as the very high temperature GCR, can generate heat at these temperatures. The first demonstration of hydrogen production with GCRs is not expected until around 2015 in Japan and 2020 in the USA. This high temperature steam could also be applied to industrial processes in industries that consume considerable amounts of heat. The appropriateness of hydrogen and process heat applications will depend upon reactor development to achieve high steam temperatures as well as on the economics of alternatives. The long term position currently remains uncertain.

F. COOPERATION RELATING TO THE EXPANSION OF NUCLEAR ENERGY AND TECHNOLOGY DEVELOPMENT

The Generation IV International Forum (GIF) has grown to 13 members[22]. It aims to develop a new generation of nuclear energy systems that offer advantages in the areas of economics, safety, reliability and sustainability, and could be deployed commercially by 2030. Six systems have been selected, and a

[22] Members are Argentina, Brazil, Canada, China, France, Japan, the Republic of Korea, the Russian Federation, South Africa, Switzerland, the UK, the USA and Euratom.

technology road map has been prepared to guide the research and development. The systems are:

- Gas cooled fast reactors;
- Lead alloy liquid metal cooled reactors;
- Sodium liquid metal cooled reactors;
- Supercritical water cooled reactors;
- Very high temperature gas cooled reactors;
- Molten salt reactors.

At the end of 2009 the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) had 31 Members.[23] INPRO's work programme reflects the interests of its members, who contribute in-kind and extrabudgetary resources. INPRO's results are available to all IAEA Member States. INPRO has activities in the following areas, mostly in the form of INPRO Collaborative Projects, in which INPRO members cooperate on specific topical issues:

- Long range nuclear energy system strategies using the INPRO methodology, for example, for Nuclear Energy System Assessments (NESAs);
- Analysing and building global visions, scenarios and pathways to sustainable nuclear development in the twenty first century through modelling of the global nuclear energy system;
- Innovations in nuclear technology and institutional arrangements that may be needed to introduce technological innovations;
- A dialogue forum on nuclear energy innovations, connecting nuclear technology holders and users.

INPRO and GIF coordinate activities through a joint action plan developed initially in February 2008 and most recently updated at the fourth INPRO/GIF coordination meeting in March 2010. It now includes agreements on coordination in the following areas: general information exchange, synergies in evaluation methods (with a focus on proliferation resistance), cooperation in topical studies

[23] INPRO Members are Algeria, Argentina, Armenia, Belarus, Belgium, Brazil, Bulgaria, Canada, Chile, China, the Czech Republic, France, Germany, India, Indonesia, Italy, Japan, Kazakhstan, the Republic of Korea, Morocco, the Netherlands, Pakistan, the Russian Federation, Slovakia, South Africa, Spain, Switzerland, Turkey, Ukraine, the USA and the European Commission. Ten other countries have observer status as they are considering membership or are participating on a working level.

and global dialogue between nuclear technology holders and users. A jointly organized workshop was held in June 2010 in Vienna entitled “Operational and Safety Aspects of Sodium Cooled Fast Reactors”.

The International Framework for Nuclear Energy Cooperation (IFNEC) was originally launched by the USA in 2006 as the Global Nuclear Energy Partnership (GNEP). It was renamed in June 2010 and now has 26 participating and 30 observer countries[24] and three observing international organizations, including the IAEA. The IFNEC currently has two working groups, one on infrastructure development and another on reliable fuel services. The Infrastructure Development Working Group holds biennial workshops on topics of interest to newcomers, such as human resources development, waste management and financing. The Reliable Fuel Services Working Group promotes the development of technical and institutional arrangements that nuclear power plant operators could rely on to provide nuclear fuel for the lifetime of the reactor. The working groups are overseen by a steering committee and an executive committee at the ministerial level.

In May 2008, Kazakhstan and the Russian Federation established the International Uranium Enrichment Centre (IUEC) in East Siberia. Ukraine and Armenia have also joined the IUEC. The IUEC is one step in President Vladimir Putin’s 2006 proposal to create “a system of international centres providing nuclear fuel cycle services, including enrichment, on a non-discriminatory basis and under the control of the IAEA”. Discussions are also in progress for a joint venture between Kazakhstan and the Russian Federation to build another enrichment plant at Angarsk.

In November 2009, the Board of Governors authorized the IAEA’s Director General to sign an agreement with the Russian Federation to establish an international reserve of 120 tonnes of LEU in the event of disruption of supply of LEU for nuclear power plants unrelated to technical or commercial considerations. The Director General would have the sole authority to release LEU from the reserve, in accordance with criteria in the agreement with the Russian Federation. The Russian Federation would be obligated to issue all authorizations and licences needed to export the LEU, and the country receiving the LEU would pay in advance to the IAEA the prevailing market price.

With regard to safety, improvement in the efficiency of the regulatory process has begun through a project to achieve increased cooperation and

[24] IFNEC participating countries are Armenia, Australia, Bulgaria, Canada, China, Estonia, France, Ghana, Hungary, Italy, Japan, Jordan, Kazakhstan, the Republic of Korea, Kuwait, Lithuania, Morocco, Oman, Poland, Romania, the Russian Federation, Senegal, Slovenia, Ukraine, the UK and the USA.

enhanced convergence of requirements and practices under the Multinational Design Evaluation Programme (MDEP)[25]. The MDEP has developed a process for identifying common positions on specific issues relating to new reactor designs between regulatory bodies who are undertaking reviews of new reactor power plant designs. In many aspects there is already a significant degree of harmonization at a general level in the form of the IAEA's safety standards: further harmonization will be assisted by building on these internationally agreed documents. An MDEP expert group noted that throughout the national considerations there is a general level of design requirements that is in line with the IAEA's Safety Requirements in applying a deterministic approach, for example defence in depth, single failure criteria and safety margins. Likewise, there are similarities in the application of probabilistic methods in complementing the deterministic approach. The goal of the MDEP is to build upon the existing similarities between the IAEA's and others' codes and standards, for example, ASME (American Society of Mechanical Engineers), RCC-M (Design and Conception Rules for Mechanical Components of PWR Nuclear Islands, France) and KEPIC (Korea Electric Power Industry Code). The progress that has already been achieved in specific areas demonstrates that a broader level of cooperation and convergence is both possible and desirable while national regulators retain sovereign authority for licensing and regulatory decisions.

[25] Current MDEP Members are Canada, China, Finland, France, Japan, the Republic of Korea, the Russian Federation, South Africa, the UK and the USA.

Annex

CLIMATE CHANGE AND ENVIRONMENT (COPENHAGEN)

1. In December 2009, the Conference of the Parties to the Kyoto Protocol (COP-15) in Copenhagen marked the culmination of a two year negotiating process to enhance international climate change cooperation under the Bali Roadmap (BAP), launched by COP-13 in December 2007. The key deliverable of COP-15 was a new international environmental agreement with ambitious mid-term GHG emission reductions to come into force when the Kyoto Protocol's first commitment period comes to an end in 2012. Under the Kyoto Protocol, 37 States, essentially highly industrialized countries except the USA, plus countries that were undergoing the transition to a market economy at the time of the Kyoto Protocol, have legally binding GHG emission limitations over the period 2008–2012. However, several of the world's largest GHG emitters, such as the USA and key developing countries including Brazil, China and India, did not sign up and have not yet officially committed themselves to any GHG emission reduction targets.

2. Since at least the Fourth Assessment Report on the IPCC in 2007, it has been obvious that emission reduction obligations have to extend beyond these 37 States if the ultimate objective of the "avoidance of dangerous anthropogenic interference with the climate system" is to be met. The challenge at COP-15, therefore, was threefold:

(1) Agreement by all 194 Parties on a global target for the reduction of GHG emissions by 2020 and 2050 respectively;
(2) Agreement by the industrialized countries to take the lead and reduce their GHG emissions significantly (20–45% by 2020 and 80% by 2050) below 1990 levels while the world's newly industrialized and developing countries also contribute to a collective solution;
(3) Agreement on a global climate regime that does not restrain economic growth in the developing countries and does not distort competition in world markets — in essence financial compensation for developing countries for adaptation to the impacts of climate change as well as for the extra costs of mitigation, technology transfer and capacity building.

3. For nuclear energy, the stakes were to recognize nuclear power as a potent mitigation option.

4. Altogether 119 world leaders attended the meetings which, according to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, represented the largest gathering of heads of state and government outside New York in the history of the UN. Overall registration exceeded 40 000 people which prompted access limitations to the conference site (maximum capacity of 15 000 persons), a fact that displeased many non-governmental organizations as government delegations and the UN were given priority access.

OUTCOME

5. After nearly two weeks of barely productive wrangling among thousands of negotiators and the threat of a complete breakdown in negotiations, all important world leaders came to Copenhagen to save a compromise on GHG reduction targets. The Conference ultimately came down to differences between two main players, the USA and China. Late at night, close to 30 leaders negotiated the contours of a final text. The result was an important, but also limited, Copenhagen Accord — a political agreement well short of a new legally binding international environmental agreement. In the end, parties agreed to adopt a COP decision whereby the COP "takes note" of the Copenhagen Accord, which was attached to the decision as an unofficial document.

6. Essential elements of the Accord include the following.

(1) "Dangerous interference with the climate system" is defined, i.e. the IPCC recommendation of a maximum global temperature increase of 2ºC is accepted: "To achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2ºC, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change."

(2) In order to achieve this goal, the accord specifies that industrialized countries will commit to implement quantified economy-wide emissions targets from 2020, to be listed in the accord before 31 January 2010, while a number of developing countries, including major emerging economies, agree to communicate their efforts to limit greenhouse gas emissions every two years, also listing their voluntary pledges before 31 January 2010. As of May 2010, 42 Annex I countries and 42 non-Annex I countries had

provided the agreed information. Voluntary nationally appropriate mitigation actions (NAMAs) seeking international support will be subject to international measurement, reporting and verification (MRV).

(3) Funding is provided for developing countries for adaptation, mitigation and technology transfer: "The collective commitment by developed countries is to provide new and additional resources, to enable and support enhanced action on mitigation, including substantial finance to reduce emissions from deforestation and forest degradation (REDD-plus), adaptation, technology development and transfer and capacity-building through international institutions, approaching $30 billion for the period 2010–2012 with balanced allocation between adaptation and mitigation." This amount is to be increased to $100 billion per year by 2020. These funds should be channelled through the newly created Copenhagen Green Climate Fund.

NUCLEAR ENERGY

7. Not surprisingly, given the lack of agreement on the numbers throughout the negotiations, the role of nuclear energy as a potent mitigation option was barely discussed. At stake has been a reversal of the current exclusion of nuclear power from two of the three flexible mechanisms under the Kyoto Protocol, the Clean Development Mechanism (CDM) and Joint Implementation (JI). The Ad Hoc Working Group on Further Commitments (AWG-KP) considered text prepared by the group throughout the year that included three options, listed below. In subsequent negotiations in the AWG-KP, most recently in June 2010, the three options have all remained under consideration and unchanged.

(1) Nuclear is excluded from the CDM and JI for the second commitment period.

(2) Parties 'refrain' from using nuclear credits for as long as the CDM and JI operate (which is an extension of the current situation beyond the 2008–2012 commitment period).

(3) Nuclear is included in the CDM and JI in principle and further rules are developed to define the specifics of how nuclear is included.

8. There are also options for carbon capture and storage (CCS) projects. CCS was not considered by the Kyoto Protocol and CCS projects also will either be allowed or banned. At Copenhagen nuclear and CCS mitigation options were not further negotiated.

9. In the course of 2010 negotiations continued. The possibilities are that, first, both CCS and nuclear will be excluded. This is unlikely but not impossible. Second, there may be a trade-off where CCS is included but nuclear is excluded. Many of those opposed to nuclear are also opposed to CCS. The supporting countries for nuclear are also often supporters of CCS, but there are supporters of CCS who oppose, or are neutral, about nuclear. Third, both CCS and nuclear might be included, a more likely outcome than that they are both excluded.

10. In contrast to the AWG-KP text, there is no longer any text in the Ad Hoc Working Group on Long Term Cooperative Action (AWG-LCA) text excluding nuclear, or hydropower, from the NAMAs. If this remains the case, this can be taken as a symbolically good result, contrasting with the stigmatization of nuclear in the CDM and JI.

11. The Copenhagen Accord of December 2009 defined dangerous anthropogenic interference with the climate system as an increase in global temperature of more than 2ºC. According to the Fourth Assessment Report (AR4) of the IPCC, avoiding such dangerous interference requires that GHG emissions peak within 15 years and then, by 2050, fall by 50%–85% compared with 2000 levels. While efficiency improvements throughout the energy system, especially at the level of energy end use, offer substantial GHG reduction potentials often at 'negative' costs, nuclear power, together with hydropower, wind power and CCS technologies, is one of the lowest supply side emitters of GHGs in terms of grams of CO_2-equivalent per kW·h generated on a life cycle basis.

12. The low GHG emissions per kW·h of renewables and nuclear power are reflected in the overall GHG intensities of electricity generation in countries with a high share of any of these technologies in their generating mixes. Figure I of this Annex contrasts the relative contributions of nuclear power, hydropower and other renewable technologies in 2006 with the average amount of CO_2 emitted per kW·h. Countries with the lowest CO_2 intensity (less than 100 g CO_2/kW·h, below 20% of the world average) generate around 80% or more of their electricity from hydropower (Norway and Brazil), nuclear power (France) or a combination of these two (Switzerland and Sweden). At the other extreme, countries with high CO_2 intensity (800 g CO_2/kW·h and more) have none (Australia) or only limited (China and India) shares of these sources in their power generation mixes.

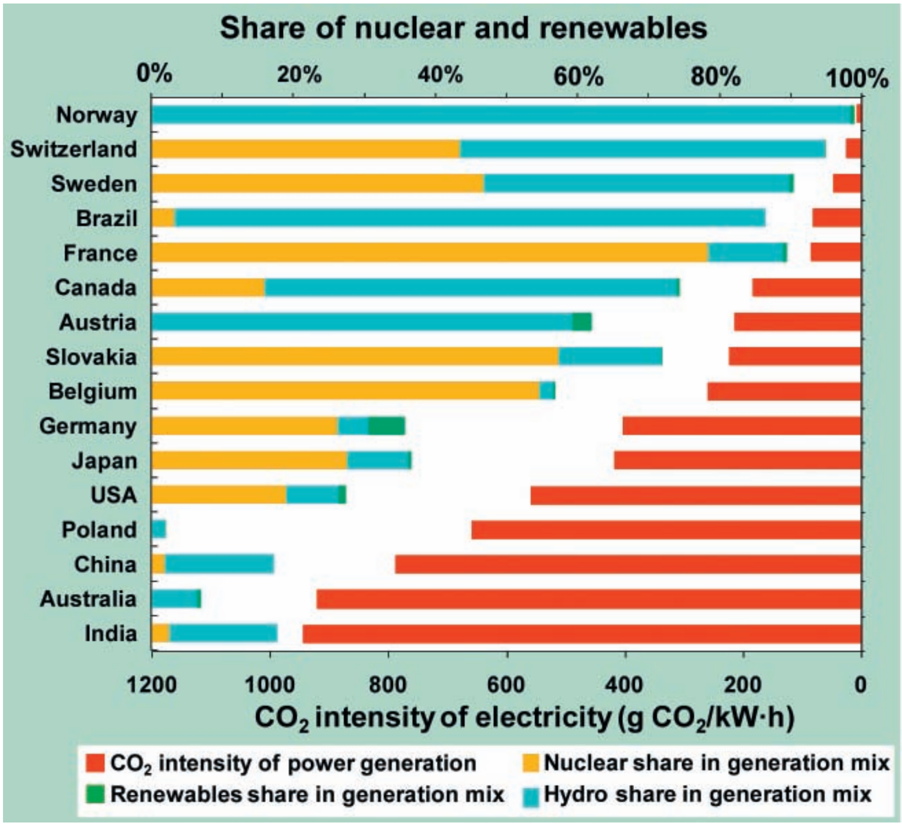

FIG. I. CO_2 intensity and the shares of non-fossil sources in the electricity sector of selected countries. Source: IAEA calculations based on OECD International Energy Agency, CO_2 Emissions from Fuel Combustion, Vol. 2008 release 01 (http://masetto.sourceoecd.org/vl=2367203/cl=14/nw=1/rpsv/ij/oecdstats/16834291/v335n1/s4/p1).

13. Figure II takes a closer look at the GHG mitigation potentials of the principal low carbon power generation technologies assessed by the IPCC. The mitigation potentials of nuclear power and renewables are based on the assumption that they displace fossil based electricity generation. The figure shows the potential GHG emissions that can be avoided by 2030 by adopting the selected generation technologies. The width of each rectangle is the mitigation potential of that technology for the carbon cost range shown on the vertical axis. Each rectangle's width is shown in the small box directly above it. Thus, nuclear power (the yellow rectangles) has a mitigation potential of 0.94 Gt CO_2-eq at negative carbon costs plus another 0.94 Gt CO_2-eq for carbon costs up to

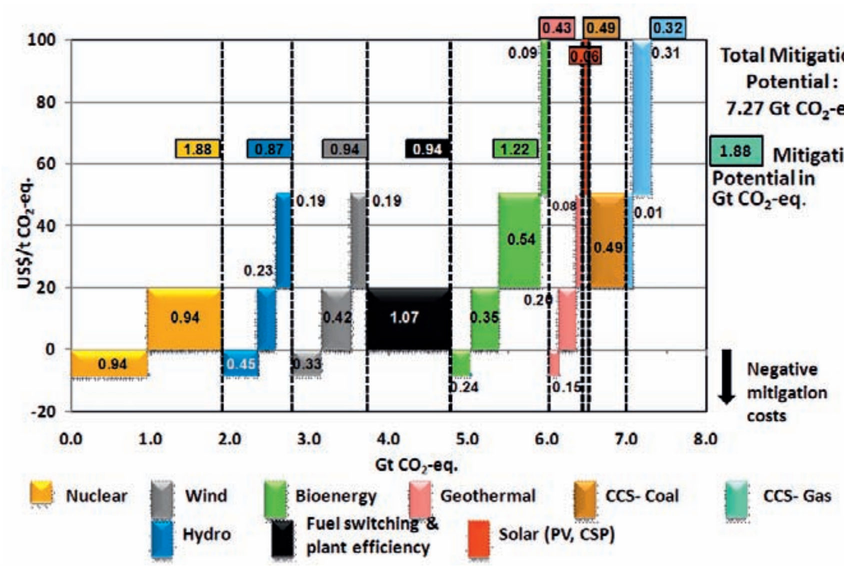

FIG. II. Mitigation potential in 2030 of selected electricity generation technologies in different cost ranges. Source: Based on data in Table 4.19, p. 300, of Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., Eds), Cambridge University Press, Cambridge (2007).

US \$20/t CO_2. The total for nuclear power is 1.88 Gt CO_2 equivalent, as shown on the horizontal axis. The figure indicates that nuclear power represents the largest mitigation potential at the lowest average cost in the energy supply sector, essentially electricity generation. Hydropower offers the second cheapest mitigation potential but its size is the lowest among the five options considered here. The mitigation potential offered by wind energy is spread across three cost ranges, yet more than one third of this can be utilized at negative cost. Bioenergy also has a significant total mitigation potential, but less than half of it could be harvested at costs below \$20/t CO_2-eq by 2030.

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