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Nuclear Power

HIGHLIGHTS

- **PROCESS AND TECHNOLOGY STATUS –** In nuclear reactors, the energy released by the uranium (U) fission reactions provides heat to a coolant fluid. The fluid may either directly drive a turbine-powered electricity generator or heat a secondary coolant, which drives the turbine. This process produces no greenhouse gas emissions. Some 440 nuclear power plants (about 372 GW) are currently (2009) in operation worldwide, providing 15% of the global electricity (25% in OECD countries). Nuclear capacity grew by 17% per year from 1970 to 1990, (some 218 plants were built in the 1980s) and slowed to 2% from then onward as a consequence of the 1986 Chernobyl accident. Existing plants are equipped with ***Generation II*** (***Gen II***) reactors that first appeared in the 1970s. ***Gen III and Gen III+*** reactors are evolutionary designs that were developed in the 1990s. To various extents, they include passive safety features and have a longer lifetime, reduced costs, and shorter licensing and construction time. Gen III and III+ reactors were built mostly in East Asia. More than 40 GW are presently under construction mostly in China, India, Russia, Ukraine, South Korea, Japan, Taipei, Bulgaria, Finland, France, and the United States. A further 23 GW have been approved for construction and some 40 GW are currently under consideration.

- **COSTS –** Recently, the cost of nuclear electricity has been reassessed by several studies. Volatile prices of materials and technologies, i.e. the 2008 price peak and the economic crisis that followed, make the economic assessments particularly arduous as the final cost of nuclear electricity is dominated by the investment cost. An analysis by the UK Department of Trade and Industry (2007), based on the French EPR reactor, suggested *overnight* investment costs between \$1700 and \$3200/kW (central value of \$2500/kW) and levelized electricity costs between \$62 and \$88/MWh (central estimate of \$76/MWh), assuming a 6-year construction, 80% load-factor, 40-year lifetime; 10% interest rate, and including waste and decommissioning costs. The then current private-sector estimates suggested an average electricity cost between \$58 and \$68/MWh. The most recent study called *Projected Costs of Generating Electricity* (IEA-NEA, March 2010), based on data from more than 25 Countries and international organisations for nuclear, coal and gas-fired power plants to be commissioned by 2015, suggests nuclear overnight investment costs between \$1600 and \$5900/kW (\$4100/kW central value) and electricity costs between \$42 and \$137/MWh, assuming a 10% interest rate, 5-6 years construction, 85% load-factor, 60-year lifetime; and including waste and decommissioning costs. If the interest rate is 5%, the nuclear electricity cost drops to \$29-82/MWh and, in most countries, it turns out to be the most convenient option for electricity generation. With a 10% interest rate, coal- and gas-fired power are slightly more convenient (even assuming a price of \$30/tCO_2 for CO2 capture and storage in coal-fired power plants), but results of the comparison depend much more on local conditions (labour, materials, fuels, technology prices, and energy policies). Quoted nuclear power costs are also available from vendors. The overnight investment cost of the AREVA EPR reactor under construction in Flamanville (France) was €2060/kW in 2007 and rose to €2500/kW in 2008 (1€~1.3US\$); the cost of the Finnish EPR in Olkiluoto was €1875/kW in 2003, but current estimates are more than double because of construction problems and delays; the Westinghouse AP1000 and the GE-Hitachi ABWR reactors are both in the range of \$3000/KW (2008); at the end of 2009, the South Korean (KEPCO) APR reactor won an international bid to build four 1400-MW units in the United Arab Emirates at an estimated price of \$2300/kW against the AREVA EPR at \$2900/kW and the GE-Hitachi at \$3600/kW. In terms of electricity cost, the APR's \$30/MWh was lower than the EPR's \$40/MWh and the GE's \$69/MWh. Increasing prices of fossil fuels and pricing of CO_2 emissions make nuclear power an attractive option for base-load electricity generation. However, it is perceived as *financially* risky if compared to coal or gas power because of the high investment cost and long licensing, construction and return time.

- **POTENTIAL & BARRIERS –** Nuclear power is practically a carbon-free source of energy. If it is used to replace super-critical coal-fired power plants, a 1-GW_e nuclear reactor can save some 6 million tonnes of CO_2 emissions per year and related airborne pollutants. Several countries are currently reconsidering the role of nuclear energy to reduce CO_2 emissions and the use of fossil fuels. To encourage private investments in nuclear power and to lower the *financial* risk compared to coal or gas power, policy measures and streamlined licensing procedures are being implemented in several countries. Globally, some 115 GW are under construction, approved and/or planned by 2020. In the long term, assuming the construction of an average 30-GW nuclear capacity per year between now and 2050 and a carbon price of \$50/t$CO_{2,}$ the International Energy Agency (IEA-ETP, 2008) predicts that the nuclear share of global electricity will increase from the current 15% to 19-23% by 2050 and nuclear energy will contribute some 6% to the global 2050 CO_2 reduction versus the business-as-usual scenario. Today's technical and economic capacity could enable the construction of 35 to 55 GW per year, but estimates do not take into account the need for nuclear industry reorganisation and the ongoing lack of industrial facilities and human skills. Major international initiatives such as the ***Gen IV*** International Forum (GIF) and the Global Nuclear Energy Partnership (GNEP) aim to promote the renaissance of the nuclear industry and the development of new-generation reactors with improved safety and economic performance, reduced waste and nuclear proliferation issues. A new generation of nuclear reactors with improved performance (***Gen IV***) is under development and could be commercialised beyond 2030. As for uranium availability, at the current demand level, proven reserves are sufficient for about 85-100 years. Geologically estimated resources could extend reserves by a factor of 3 and the use of *fast breeder reactors* could in principle extend reserves by a factor of 60, thus making nuclear energy unlimited. In some countries, nuclear fuel enrichment and handling are still considered to be military operations submitted to strict domestic and international rules, and monitored by the International Atomic Energy Agency (IAEA). Waste management, health and proliferation risks raise public concern about the civil use of nuclear energy.

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PROCESS AND TECHNOLOGY STATUS

In a nuclear reactor, the energy released by uranium (U) fission reactions provides heat to a coolant fluid. The fluid may either directly drive a turbine-powered electricity generator or heat a secondary coolant, which drives the turbine. The process produces neither greenhouse gas emissions nor airborne gaseous pollutants. Depending on the reactor type, the U fuel may be either natural (U^{238} with 0.7% of U^{235} isotope) or enriched uranium (3% to 5% of U^{235}). Nuclear reactors can be classified by the energy level of their neutrons (thermal or fast), by the coolant (water, gas, liquid metal), or by the neutron moderator (water, heavy water, graphite). Existing plants are mostly (80%) thermal reactors using water as a coolant and as a moderator (light water reactors, LWR), either in the form of pressurised or boiling water (PWR or BWR). Pressurised heavy water (D_2O) is mostly used in the Canadian reactors (PHWR). Gas-cooled reactors (GCR) using CO_2 as the coolant are used in the United Kingdom. A lot of interest is also shown in high-temperature gas-cooled reactors (HTGR), which offer high efficiency, small-size and modularity, and some inherent safety characteristics. Fast-breeder reactors (FBR) have been built for demonstration purposes only. They are receiving renewed attention because fast neutrons can convert U^{238} into Pu^{239}, a usable fuel, and produce fuel in excess of the input. In principle, FBR could increase by some *sixty-fold,* the energy extracted from natural U and make U resources unlimited. Furthermore, if operated as fast burners, FBR can convert undesirable actinides, thus reducing the stewardship period for radioactive waste as well as the number and size of high-level waste repositories.

■ **Status of Nuclear Power** - Some 440 nuclear power plants (about 372 GW) are currently in operation worldwide. They provide 15% of the global electricity (25% in OECD countries). Almost 60% of this capacity is installed in the United States (104 plants), France (59 plants producing 78% of the French electricity) and Japan (55 plants). The global operating experience of nuclear reactors exceeds 12,000 reactor-years. Nuclear capacity grew by 17% per year from 1970 to 1990, and some 218 plants were built in the 1980s (58 French reactors came into operation between 1977 and 1993). Nuclear power growth slowed to 2% from 1990 to 2004, as a consequence of the Chernobyl accident. Market liberalisation and cheap fossil fuels also lead to nuclear power being less attractive in the 1990s. Since then, nuclear electricity generation has been growing and keeping pace with global electricity as a result of improved plant availability and load-factor (from 76% to 83%; in some countries 88%, with a peak value of 94% in Finland), and power up-rating in existing plants. In the United States, power up-rating led to an additional 5-GW power output over the past 10 years and many plants have also been granted a life extension of up to 60 years.

■ **Current Reactors** - Most existing nuclear plants are Generation II (**Gen II**) reactors that first appeared in the 1970s. **Gen III** reactors were developed in the 1990s as evolutionary designs which included *passive safety features*[1];long lifetime; modular design to reduce costs, licensing and construction time; and higher fuel burn-up to optimise fuel use and minimise waste. **Gen III+** reactors are an advanced version of these design features. Gen III and III+ reactors have been built mostly in East Asia or are now currently under construction, approval or consideration in several countries. Four General Electric advanced BWR reactors have been built in Japan. Two Westinghouse advanced PWRs (AP1000) are under construction in China (Zhejiang province) and two more units are planned for the Shandong province, and three Combined Construction and Operating Licenses (COLs) for AP1000 reactors have been filed in the United States (one under construction). The French AREVA is marketing a 1.6-GW PWR (EPR) with 36% efficiency, 92% availability and a 60-year lifetime. The first EPR is under construction in Finland (Olkiluoto) and the second one in France (Flamanville). The Canadian AECL offers an advanced HWR concept while the Japanese Mitsubishi offers an advanced PWR. The South Korean KEPCO is becoming a strong international competitor offering a 1.4-GW PWR (APR) reactor based on the experience gained in the construction of several domestic units. At present, more than 40 GW are currently under construction mostly in China, India, Russia, Ukraine, South Korea, Japan, Taipei, Bulgaria. A further 23 GW have been approved for construction and some 40 GW are under consideration. An additional capacity of 116 GW is planned by 2020.

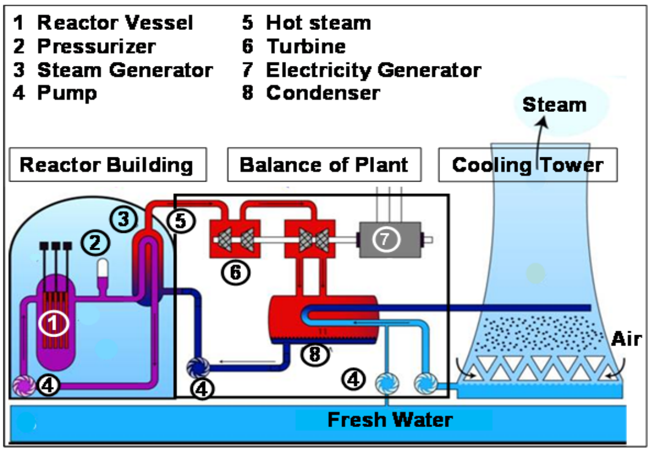

Fig. 1 – Schematic of a PWR Nuclear Power Plant

■ **Small and Medium-sized Reactors** - SMR with a capacity of up to 500-600 MW are being developed to meet the needs of small countries or off-grid remote communities (cogeneration, water desalination). Their commercial availability is expected between 2015 and 2030. Reduced size and complexity, as well as inherent and passive safety approaches, (e.g., small reactivity margins) result in lower investment cost, shorter construction time and more flexibility. SMR concepts are often based on *integral designs*[2] and/or *factory-refuelling*[3]

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[1] e.g. shut-down during major accident with no active intervention.

[2] Primary cooling loop, steam generators, pumps and control rods inside the pressure vessel to minimise piping, accidents, and avoid rod ejection events.

[3] To avoid on-site waste management and to centralise fuel recycling in a few sites worldwide under international control (proliferation safeguard).

concepts. Other design concepts offer long refuelling intervals or continuous refuelling through fuel pebbles gradually moving into the core. Near-term SMR designs include integral PWR designs (e.g. SMART - Korea; IRIS - Westinghouse International Consortium), factory-built PWR (Russian KLT-40) and the South African 900°C, helium-cooled, pebble-bed modular reactor (PBMR).

■ **Future Gen IV reactors** could enter the market beyond 2030. They aim to further improve safety and proliferation resistance, to reduce costs and minimise the production of long-life radioactive waste. Gen IV include **fast reactors** cooled by liquid **lead** (LFR), **sodium** (SFR) or **gas** (GFR), and **thermal reactors** cooled by **very high-temperature helium** (VHTR), **molten-salt** (MSR), and **supercritical water** (SCWR). Fast reactor concepts run on closed fuel cycles to burn U^{238} and actinides, and to produce and recycle Pu. Thermal reactors use high fuel *burn-up* to extract more energy from U. All concepts have high coolant temperatures (500°C to 1000°C) to achieve high efficiency (40% to 50%). In-factory manufacturing and modularity (plant size from 200MW onward) help minimise costs and adapt to different markets and grids. The GFR concept (850°C helium-cooling, 48% efficiency) includes the on-site spent-fuel treatment and re-fabrication plant. LFR variants include the nuclear battery concept, a small-size reactor with very long (several years) refuelling time, which builds on nuclear submarine technology. The SFR is based on the vast experience with the French sodium-cooled fast reactors (e.g. Superphenix). The SCWR (510°C water-cooling, 44% efficiency) uses super-critical water coolant to offer higher efficiency than the existing LWR. The VHTR (950°C helium-cooling, 50% efficiency) is designed for a combined generation of electricity and hydrogen via thermo-chemical processes. The MSR uses molten salt (Na, Zr fluorides) with dissolved U or Pu as a coolant and fuel. All the Gen IV concepts require significant further R&D to reach commercialisation.

COSTS

Over the past years, the cost of nuclear electricity (levelised electricity cost, LEC[4]) has been assessed in several studies. Increasing prices of fossil fuels and carbon emissions make nuclear power a competitor for coal- and gas-fired power. In principle, the cost of nuclear electricity is more stable and predictable than the cost of coal- or gas-based electricity as the fuel (uranium) cost is only a small part of the generation cost. However, licensing, public acceptance and other issues may prolong the construction time of nuclear power plants. As the cost of nuclear electricity is dominated by the investment cost, this may cause the final generation cost to increase significantly. Streamlining licensing procedures and keeping construction time on schedule may reduce the investment risk. Today's cost assessments are also made arduous by volatile prices of materials and technologies following the 2008 price peak, the subsequent drop due to the economic crisis and market speculative dynamics.

■ **In 2004, a University of Chicago study** supported by the US Dept. of Energy, suggested that a projected cost of electricity from new nuclear power plants was between $47 and $71/MWh, including a first-of-a-kind (foak) extra-cost of 35%, an incremental 3% financing risk premium, and then current tax level in the United States. It was estimated that after the construction of a few plants, a technology learning rate between 3% and 10% could reduce the cost to $31-$46/MWh. The study assumed overnight investment costs of $1200/kW for mature designs and $1500-1800/kW for advanced designs including a *first-of-a-kind* (*foak*) penalty; lifetime of 40-60 years; construction in 5-7 years; capacity factor 85%; investment return rate of 10% (debt) and 15% (equity); fuel cost of $4.3/MWh; O&M cost of 10$/MWh; decommissioning $350/kW; waste disposal fee of $1/MWh. The electricity from *foak* nuclear power plants emerged as more expensive than fossil-based electricity (i.e. then current $33-$45/MWh, excl. CO_2 capture & storage). However, technology learning and CO_2 pricing, could make nuclear power attractive as opposed to fossil fuel plants.

■ **In 2006 the IEA World Energy Outlook** (IEA, 2006) compared projected (2015) costs of nuclear, coal, gas and wind electricity assuming nuclear investment costs were between $2000/kW and $2500/kW and two different return scenarios - a *slow* one based on 8% (debt) and 12% (equity), interest rate, with a capital return in 40 years - and a *fast* one based on 10% debt 15% equity interest rates and a capital return in 25 years. Other key figures were the investment costs for coal, gas and wind power (1400, 650, and 900 $/kW, respectively); costs of nuclear, coal and natural gas fuels (0.5, 2.2 and 6.0 $/GJ, respectively); a nuclear capacity factor of 85% and a construction time of 5 years. Assuming *slow return* and low investment costs, nuclear electricity emerged as the cheapest option at $49/MWh). With *slow return* and high investment cost, the nuclear option ($57/MWh) was

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[4] **LEC** is the ratio of total lifetime costs (**investment**, **O&M**, **fuel**, **waste management**, **decommissioning**) to the total electricity output, expressed in present value equivalent. LEC is the price that repays the investor for all costs incurred, with a return rate equal to the interest rate. The **Investment costs** depend on the **pre-construction and construction time**, on the **overnight construction cost** (costs with no interest) and on the **interest rate**. Pre-construction costs may reach 8-10% of the construction cost and may be reduced through design standardisation, simplified licensing and regulations. **Construction time** may often be longer than 5 years, but recent nuclear plants in Asia have been built in less than 60 months, with best performance achieved in Japan (40 months). **Overnight construction costs** are usually based on vendor estimates, which tend to minimise the apparent cost of the plant. The **interest rate** depends on the discount rate, on the financial share between debt and equity to finance the investment, and on the return rate required by the stakeholders. The IEA-NEA study (2005) shows that LEC may increase by some 50% if the discount rate increases from 5% to 10%. The financial cost may increase from 30% to 40% of the overall expenditure if the construction time is delayed from 5 to 7 years (University of Chicago, 2004). The interest rate for nuclear plants may be higher than for fossil power plants because of the higher investment risk. **O&M costs** include operation, maintenance, inspection, safeguard, labour, insurance, security, and spare generation capacity. They reflect local conditions, e.g. O&M costs in Japan are usually double the O&M costs in Europe. **Fuel cost** is a small part of the nuclear electricity cost. In spite of the recent increase of the U spot price, current fuel-cycle cost is about 12% of the LEC (UK, 2006). It includes basic uranium (25%), conversion into oxide (5%), enrichment (30% for LWR), and fuel manufacturing and disposal (15% to 25%, depending on waste treatment, direct disposal or reprocessing). In the United States, the average nuclear production cost (O&M and fuel costs) in 2002 was $17/MWh. In Europe, production costs are €10/MWh in Finland and Sweden and €14/MWh in France (Stricker & Leclerq, 2004). **Waste management and decommissioning costs** usually occur decades after the reactor start-up and have a limited impact on LEC. In some countries, the cost of direct waste disposal (no recycling) is conventionally estimated at $1/MWh. Based on direct experience, decommissioning costs range from $500 to $800/kW ($2-3/MWh). The cost of nuclear electricity is also sensitive to the **load factor**. A reduction from 90% to 80% may result in an additional $10/MWh. **External costs** of nuclear power are mostly internalised. The process produces virtually no emission, and health and environmental costs are internalised through safety and radiation protection standards. Fuel supply is not sensitive to disruptions.

cheaper than the gas option, but more expensive than coal as long as coal prices did not exceed $2.8/GJ ($70/t). In these conditions, a 50% increase of uranium, gas and coal prices resulted in an incremental 3% for the nuclear option, 20% for coal and 38% for gas, thus making nuclear the cheapest one. In the *fast return* scenario, nuclear energy ($68-$81/MWh) was the most expensive option. However, it was again competitive assuming CO$_2$ emissions prices were between $10 and $25/tCO$_2$. It should be noted that the current CO$_2$ price in the EU emissions trading market is around €14/tCO$_2$ and that the typical cost of CO$_2$ capture & storage (CCS) in coal power plants is currently quoted at some €50/tCO$_2$ (predicted to decrease to €30/tCO$_2$ by 2020), resulting in an incremental electricity cost of $20-40/MWh.

■ **A study by the UK Department of Trade and Industry** (DTI, 2007) was based on the French EPR reactor and the following assumptions: overnight investment cost between $1700 and $3200/kW (central value of $2500/kW); construction time of 6-10 years (6 yr); load factor of 60-90% (80%); lifetime of 30-60 years (40 yr); O&M cost of $9-15.5/MWh (15.5); fuel cost of $4000-6000/kg ($4800/kg, $9/MWh); waste disposal cost of $550-640 million ($550 million, after 40 yr); decommissioning cost of $800-1900 million/GW ($1270 million/GW, after 40 yr); interest rate of 7-12% (10%). These assumptions led to a LEC between $62 and $88 per MWh, with a central estimate of $76/MWh. The DTI did consider its central estimate as conservative and the higher one as unlikely. The DTI also reported then-current vendor estimates to be between $58 and $68/MWh.

■ **The most recent study *Projected Costs of Generating Electricity* (IEA-NEA, March 2010)** is based on data from more than 25 countries and international organisations for nuclear, coal and gas-fired power plants to be commissioned by 2015. It reports that nuclear overnight investment costs are between $1600 and $5900/kW ($4100/kW central value). Assuming a 10% interest rate, 5-6 years construction, 85% load-factor, 60-year lifetime; and including waste and decommissioning costs, the electricity cost is between $42 and $137/MWh. If the interest rate drops to 5%, the nuclear electricity cost is between $29 and $82/MWh and, in most countries, nuclear power turns out to be the most convenient option for electricity generation. With a 10% interest rate, coal- and gas-fired power plants are slightly more convenient (even assuming a price of $30/tCO$_2$ for CO2 capture and storage in coal-fired power plants). However, the advantage is small and does very much depend on local conditions (i.e. labour, materials, fuels and technology prices, and energy policies).

■ **Vendors** do also provide quoted information on nuclear power costs. The overnight investment cost of the AREVA EPR reactor under construction in Flamanville (France) was €2060/kW in 2007 and rose to €2500/kW in 2008 (1€~1.3US$); the cost of the Finnish EPR in Olkiluoto was €1875/kW in 2003, but current estimates have more than doubled because of construction problems and delays; in 2007, the US EPR version (four units) as certified by the US NRC was $2400/KW; in June 2008, the Westinghouse AP1000 and the GE-Hitachi ABWR and ESBWR reactors were all in the range of $3000/KW). At the end of 2009, the South Korean KEPCO won an international bid to build four 1400-MW Korean APR units in the United Arab Emirates at an estimated price of $2300/kW against the Areva EPR at $2900/kW and the GE-Hitachi at $3600/kW. With some $30/MWh the APR was also the best option in terms of generation cost over the EPR's $40/MWh and the GE's $69/MWh. In general, the utilities tend to quote even higher costs including interest and other costs.

POTENTIAL & BARRIERS

■ **Nuclear Power Expansion** - Nuclear power is practically a carbon-free source of energy. If it is used to replace super-critical coal-fired power plants, a 1-GW nuclear reactor can avoid the emission of some 6 million tonnes of CO$_2$ per year and related airborne pollutants. Several countries are currently reconsidering the role of nuclear power to reduce CO$_2$ emissions and the use of fossil fuels in their energy mix. In the OECD countries, Japan and South Korea have approved plans to build new nuclear capacity (9 GW in Japan by 2015 and 12 GW in Korea by 2017). The United States, the United Kingdom and France have recently announced plans for new nuclear plants. In the US, incentives to encourage private investment include simplified licensing (Early Site Permit, Construction & Operating Licence), electricity production tax credits, support for construction delay and loan guarantees. Other countries are streamlining the regulatory framework. In Sweden and Germany, former decisions to phase out nuclear power are being reconsidered. Italy is also reconsidering the nuclear option. Outside the OECD regions, Russia aims to increase nuclear electricity's share from 16% to 25% by 2030 and plans to build about 22 GW by 2020. China plans to build 40 GW by 2020. India is planning on 16 GW by 2020 and has announced a new target of 40 GW by 2030. A further 16 GW of nuclear capacity has been approved by the government of the Ukraine. In total, an additional 116 GW are planned by 2020. Global energy policies including carbon trading schemes and new regulatory frameworks would help rebuild investors' confidence in nuclear power.

■ **Nuclear Power Outlook** - Assuming a carbon price of $50/tCO$_2$ and the construction of 30-GW nuclear capacity per year between now and 2050, the IEA (*Energy Technology Perspectives,* IEA 2008) suggests that the nuclear share of global electricity could increase from the current 15% to 19-23% by 2050 (up to 30% in most favourable scenarios) and that nuclear energy could contribute some 6% to the global 2050 CO$_2$ reduction versus the business-as-usual scenarios. These projections imply that global nuclear capacity would have more than doubled by 2050 and that key nuclear issues associated to waste disposal, proliferation and social acceptance would have been definitely addressed. The United Nations IPCC (2007) also suggests that nuclear power could supply 18% of the total electricity in 2030. The extrapolation of historical data suggests that today's technical and economic capacity could enable the construction of 35 to 55 GW per year (including the replacement of obsolete plants). The extrapolation does not take into consideration the ongoing reorganisation of the nuclear industry in several countries, and the unavailability of appropriate human skills, materials and components. For example, few companies worldwide are able to produce the high-quality, ultra-large forgings that are needed for reactor pressure vessels, and these companies have a multi-year order backlog. On the other hand, major international initiatives such as the Gen IV International Forum (GIF), the IAEA International Project for Innovative Nuclear Reactors and Fuel Cycles (INPRO) and the Global Nuclear Energy Partnership (GNEP) aim to promote the renaissance of the nuclear industry and to develop a new generation of cost-effective nuclear power plants.

■ **Uranium Resources** - Uranium is produced by a number of countries and major suppliers that are politically stable such as Canada and Australia. Uranium resources are plentiful and increasing. With the current demand level of some 67,000 tonnes per year (2006), identified uranium reserves (5.5 million tonnes) are sufficient for around 100 years. Recycled and secondary U and Pu^{239} (from fuel reprocessing and military use) could extend conventional reserves to beyond 100 years. Resources are more uncertain, but geological evidence shows availability is likely to be at least an additional 10 million tonnes, which could extend supply to more than 300 years. A pure fast reactor fuel cycle could in principle extract some sixty-fold more energy from uranium and make reserves practically unlimited. The price of uranium ore rose from $13/kg to $95/kg in the period 2001-2006 and has recently continued to grow. While it slightly affects the cost of nuclear electricity, the high price is expected to trigger new discoveries and production. One more option for extending nuclear fuel reserves is the use of thorium (Th) to produce U^{233}. Once started with U^{235} or Pu^{239}, neutron-efficient reactors such as advanced HWR and HTGR could convert Th^{232} into U^{233}. India holds 25% of global Th reserves, which are roughly comparable to U reserves. However, the Th fuel cycle requires further R&D and considerable investment.

■ **Reactor Safety** - While the Chernobyl accident (1986) dramatically made the serious concerns of the old Soviet Union power plants evident, new- generation western reactors meet high international safety standards, based on multiple safety systems and containment structures that complement inherent and passive safety features (in-depth-defence). The efficacy of this approach has been tested in severe accidents (e.g. Three Mile Island, 1979) which resulted in no fatalities and health threats for the population. Nevertheless, the social acceptance of nuclear energy in the OECD countries remains a concern and the nuclear industry continues to enhance safety strategies.

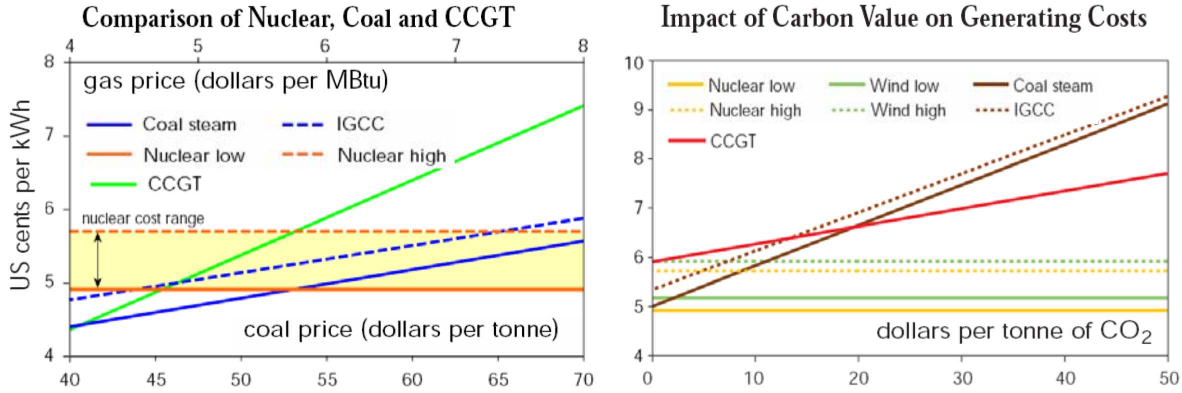
■ **Nuclear Waste** – Nuclear wastes represent less than 1% of total toxic waste from industry and are classified by their radioactivity level. Low-level wastes (LLW) represent about 90% of nuclear waste in volume, have short-life radioactivity and require no shielding or geological disposal. Intermediate-level wastes (ILW) represent from 5 to 7% of nuclear waste volume and require shielding and disposal in shallow repositories. High-level wastes (HLW) are fission products and actinides from spent fuel. They have long-life radioactivity, represent some 3 to 5% in volume and 95% of the total radioactivity. They require shielding, deep geological disposal and cooling as the decay of radioactive elements generates heat even outside the reactor. Typically, a 1-GW power plant produces annually 200-350 m^3 of LLW and ILW, and 10-20m^3 of HLW (some 1000 tonnes over 40-year lifetime). After recycling, HLW from a 1-GW power plant amount to less than 3 m^3/yr of vitrified waste to be stored for thousands of years.

■ **Waste Recycling and Disposal** - If the spent fuel is reprocessed, residual U and Pu are recycled, while fission products and transuranic elements are separated and treated as HLW. Final HLW treatment includes vitrification, sealing in corrosion-resistant containers and disposal in deep, stable rock structures, with impermeable backfill such as bentonite clay. France, the United Kingdom and Russia have large reprocessing plants with a total capacity of 5000 tonnes per year (30% of world annual output). Recycled U and Pu are used to produce mixed oxide fuel (MOX). If the spent fuel is not reprocessed, it is entirely considered as HLW. However, there is reluctance to irretrievably dispose of non-recycled spent fuel as it contains significant amounts of U^{238}, 1% of U^{235}, 1% of Pu^{239}, and about half of the original energy content (excluding U^{238}). In addition, its radioactivity decreases significantly in a few decades. Thus, storing the spent fuel in cooling pools for several years enables easy reprocessing later. Roughly, 270,000 tonnes of spent fuel are in storage today and some 10,000-12,000 tonnes are added each year, of which about 3000 tonnes are reprocessed. While a broad international consensus exists on final geologic disposal of HLW, the selection of repository sites is a long process involving public acceptance issues. It is under consideration in many countries and under way in a few. Finland, Sweden and the United States have identified suitable sites. France, Japan and the United Kingdom plan to identify sites in the near future and to have disposal facilities in the coming decades. Finland and Sweden plan to dispose of the spent fuel with no reprocessing. Public acceptance of nuclear power plants depends to a large extent on satisfactory solutions for waste management. Partitioning and transmutation (P&T) processes in fast reactors or accelerator-driven systems could convert long-lived fission products and transuranic elements into short-lived elements, thus reducing HLW volume. Based on today's knowledge it is suggested that P&T of minor actinides and fission products is technically possible, commercially questionable, but it will certainly not eliminate the need for geological disposal.

■ **Proliferation** - The Treaty on Non-Proliferation of Nuclear Weapons involves 187 countries. Compliance with the Treaty is verified by the safeguard activity of the UN International Atomic Energy Agency, backed up by diplomatic, political and economic measures, and complemented by controls on the import/export of sensitive technologies and nuclear materials. The past decades have shown the need for an additional protocol to enable the IAEA to ensure the absence of undeclared nuclear materials and the non-diversion of declared materials. Some 121 States have signed or approved the Additional Protocol. In spite of the Treaty, proliferation is one of the risks of nuclear energy. Recent studies (Keystone Center, 2007) showed that the time required to convert sensitive quantities of highly enriched U and Pu into components for nuclear weapons is short compared to the IAEA inspection frequency. International fuel-cycle facilities could guarantee nuclear fuel supply to developing countries while creating additional non-proliferation assurances.

Table 1 – Summary Table: Key Data and Figures for Nuclear Power Plants

Technical Performance	**Typical current international values and ranges**			
Energy input	Nuclear fuel: nat. or enriched UO_2, mixed U/Pu oxide (MOX), metallic uranium			
Output	Electricity, Heat			
Nuclear Technologies	LWR (PWR,BWR); HWR; HTGR; FBR;			
Efficiency, %	LWR, HWR: 30-32; LWR/EPR: 36; HTGR: up to 50; FBR 40			
Construction time, months	Minimum 40; Typical 60; Conservative 72			
Technical lifetime, yr	Minimum 30 with possible extension up to 60; LWR/EPR 60			
Load (capacity) factor, %	Typical 83-85, Maximum 94			
Max. (plant) availability, %	95			
Typical (capacity) size, MW	800-1200; Typical 1000; LWR/EPR 1600; SMR 200-600			
Installed (existing) capacity, GW	370			
Average capacity aging	80% of current nuclear plants have been built between 1970 and 1990			
Environmental Impact	**Typical current international values and ranges**			
CO_2 and other GHG emissions, kg/MWh	No emission during operation			
Spent fuel and nuclear waste	25 t. of spent fuel/GW-yr, of which: 200-350 m^3 LLW/ILW; 10-20 m^3 HLW (equal to 95% of total radioactivity). After recycling: 3 m^3 HLW/GW-yr			
Land use, m^2/MW	400			
Special materials and water use	Nuclear grade steel , cooling water (50 m^3/s *GW)			
Costs	**Typical current international values and ranges, US$ 2007**			
Capital cost, overnight, $/kW	1700-3200 (Typical value $2500/kW in 2007 and $3000/kW in 2008)			
O&M cost (fixed and variable), $/MWh	10-16			
Energy/fuel cost, $/MWh	9-10			
Economic lifetime, yr	30-40			
Decommissioning cost, $/kW	800-1300; Typical 800 (equivalent to $2-3/MWh, undiscounted)			
Waste treatment cost, $/MWh	1-2			
Interest rate, %	10			
Total production cost, $/MWh	62-88; Typical 76			
Market share	15% of global electricity output, 25% in OECD countries			
Data Projections	**2020**	**2030**	**2050**	
Capital cost, $/kW	2500		2000	Figures suggested for projection studies
Total production cost, $/MWh	75		60	
Market share, % of global electricity output	15		19-23 (30)	



Competitiveness of Nuclear Power - Source IEA WEO 2006

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