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Nuclear Power

IN SUMMARY

- **PROCESS AND TECHNOLOGY STATUS -** In the nuclear reactors, 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. Nuclear power is a nearly carbon-free source of energy. If it is used to replace super-critical coal-fired power plants, a 1-GW reactor can avoid the emission of more than 6 million tonnes of CO_2 per year and related airborne pollutants. Some 443 nuclear power plants (about 370 GW) are currently in operation worldwide. They provide 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% onward because of the Chernobyl accident, market liberalisation and low-cost fossil fuels. Existing plants are ***Generation II*** (***Gen II***) reactors that appeared in the 1970s. ***Gen III and Gen III+*** reactors are evolutionary designs developed in the 1990s. They include passive safety features, long lifetime, and reduced costs, licensing and construction time. Gen III and III+ reactors have been built mostly in East Asia. At present, 31 new units (24 GW) are under construction mostly in China, India, Russia, Ukraine, South Korea. ***Gen IV*** reactors are expected to enter the market beyond 2030. They aim to further improve safety and reduce costs, radioactive waste and proliferation issues.
- **COSTS -** Increasing price of fossil fuels and CO_2 pricing to reduce emissions make nuclear power cost-competitive against coal and gas power. However, nuclear power is perceived as *financially* more risky than conventional power because of the high investment cost, the long construction and return time. In the past four years, the cost of nuclear electricity has been reassessed by several studies. A recent analysis by the UK Department of Trade and Industry (2007), based on new French EPR reactors, suggests *overnight* investment costs between $1700 and $3200/kW (central value of $2500/kW) and levelised electricity costs between $62 and $88/MWh (central estimate of $76/MWh, with 6-years construction, 80% load factor, 40-year lifetime; 10% interest rate, including waste and decommissioning costs). Current private-sector estimates suggest an average electricity cost between $58 and $68/MWh. Other quoted cost information include vendor overnight investment costs for the French EPR in Flamanville (€2060/kWe in 2007 and €2500/kWe in 2008, 1€~1.3US$), for the US EPR version ($2400/KWe, 2007), and cost estimates for the Westinghouse IRIS and AP1000 reactors and for the GE-Hitachi ABWR reactor, all ranging around $3000/KW (2008). The growing cost of materials and engineering has a significant impact on the cost of nuclear power, which is dominated by the investment cost.
- **POTENTIAL & BARRIERS -** 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. Policy incentives and simplified licensing procedures are being implemented to encourage private investments. An additional 116 GW are planned by 2020 worldwide. Assuming a carbon price of $50/t$CO_2$ and the construction of 30-GW nuclear capacity per year between now and 2050, the IEA (2008) projects the nuclear share of global electricity to increase from the current 15% to 19-23% by 2050 and nuclear energy to contribute some 6% to 2050 CO_2 savings vs. the business-as-usual scenario. Today's technical and economic capacity could in theory enable the construction of 35 to 55 GW per year, but estimates do not take into account the reorganisation of the nuclear industry and the ongoing lack of industrial facilities and human skills. Major international initiatives such as the Gen IV International Forum and the Global Nuclear Energy Partnership (GNEP) aim to foster the renaissance of the nuclear industry and the development of a new generation of cost-competitive nuclear power plants. At the current demand level, uranium proven reserves are sufficient for some 85-100 years. Geologically estimated resources could extend reserves by a factor of 3. The use of *fast breeder reactors* could in principle extend reserves by a factor of 60 and make nuclear fuel unlimited. Waste management, proliferation risks and public perception about nuclear safety remain major issues for nuclear power.

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. Nuclear power is a nearly 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 more than 6 million tonnes of CO_2 per year and related airborne pollutants. Depending on the reactor type, the U fuel may be either natural (U^{238} with 0.7% of U^{235} isotope) or enriched (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 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. High interest also exists in high-temperature gas-cooled reactors (HTGR), which offer high efficiency, small-size and modularity, and some inherently safety characteristics. Fast-breeder reactors (FBR) have been built for demonstration purposes. They are receiving renewed attention because their fast neutrons can convert U^{238} into Pu^{239}, a usable fuel, and produce fuel in excess of their own consumption. In principle, FBR could increase some *sixty-fold* the energy extracted from natural U and make U resources unlimited.

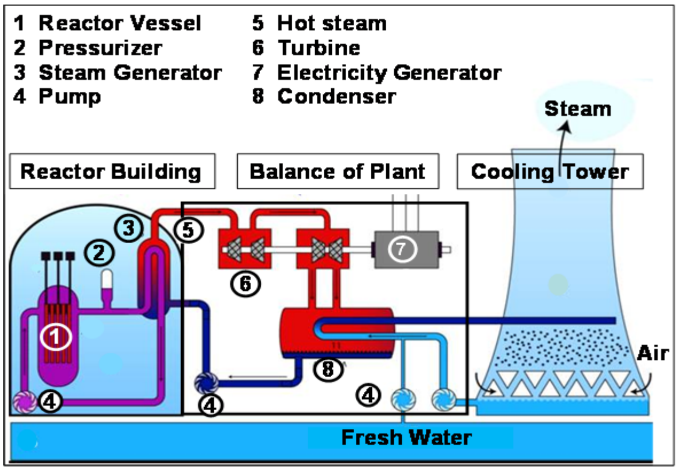

Fig. 1 – Schematic of a PWR Nuclear Power Plant

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Furthermore, if operated as fast burners they can eliminate undesirable actinides, thus reducing the stewardship period for radioactive waste, and the number and size of high-level waste repositories. ■ **Status of Nuclear Power** - Some 443 nuclear power plants (about 370 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. The global operating experience of nuclear reactors exceeds 12,000 reactor-years. Nuclear capacity grew by 17% per year from 1970 to 1990, with some 218 plants built in the 1980s (in France, 58 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 led to reduced nuclear power's attractiveness in the 1990s. Since then, nuclear electricity generation has been growing in pace with global electricity as a result of improved average plant availability and load factor (from 76% to 83%; 88% in some countries; 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 ten years and many plants have also been granted life extension 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 including *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 offer further evolutions of these design features. Gen III and III+ reactors have been built in East Asia or are now under construction. Four General Electric advanced BWR reactors have been built in Japan. Two Westinghouse advanced PWRs (AP1000) are under construction at Zhejiang province in China, other two units are planned in Shandong province in China and three Combined Construction and Operating Licenses (COLs) have been filed for AP1000 reactors in the United States. 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. A second unit is under construction in France. Canadian AECL offers an advanced HWR concept while the Japanese Mitsubishi offers an advanced PWR. At present, 31 new units (24 GW) are under construction in China, India, Russia, Bulgaria, Ukraine, South Korea, Japan and Finland. An additional 116 GW are planned by 2020. ■ **Small and Medium-sized Reactors -** SMR with capacity 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 2010 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] *concepts*. Other 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 900°C, helium-cooled, pebble-bed modular reactor (PBMR) developed by South Africa.

■ **Future Gen IV reactors** could enter the market beyond 2030. They aim to improve safety and proliferation resistance, to reduce costs and minimise the production of long-life radioactive waste. Gen IV include **fast reactor concepts** cooled by liquid lead (LFR), sodium (SFR) or gas (GFR), and **thermal reactor concepts** 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 temperature (500°C to 1000°C) to achieve high efficiency (40% to 50%). In-factory manufacturing and modularity (plant size from 200MW) help minimise costs and adapt to different markets and grids. The GFR concept (850°C helium-cooling, 48% efficiency) includes an 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 sodium-cooled fast reactors (e.g., Superphenix, France). The SCWR (510°C water-cooling, 44% efficiency) uses super-critical water coolant, which offers high efficiency compared to the existing LWR. The VHTR (950°C helium-cooling, 50% efficiency) is designed for 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 further R&D.

COSTS – Increasing prices of fossil fuels and carbon pricing to reduce CO_2 emissions make nuclear energy cost-competitive against coal and gas. Unlike coal and gas power, nuclear power is not sensitive to fuel price variation as the fuel is a small part of the generating cost. In the past, some power plants have required long construction time because of licensing and public acceptance issues. Along with high investment costs, this circumstance resulted in high electricity costs compared to initial estimates and in the perception of investment risk. The risk may be reduced by streamlining the licensing procedures and keeping the construction time within schedules. In recent years, the costs of nuclear power (levelised cost of electricity, LEC[4]) have been reassessed by

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[1] 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)

[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) show 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 twice 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.

several studies. ■ **The University of Chicago study (2004)**, supported by the US Department of Energy, suggested a projected cost of electricity from new nuclear power plants between $47 and $71/MWh, including a first-of-a-kind (foak) extra-cost of 35%, an incremental 3% financing risk premium, and tax level applicable in the United States. After the construction of the first few plants, technology learning (3%-10% learning rates) was estimated to reduce the cost to $31-$46/MWh, with no policy incentive. The study assumed an overnight investment cost of $1200/kW for mature designs, $1500/kW for new designs including *foak* penalty, and $1800/kW for advanced designs also bearing *foak* penalty. Other basic assumptions were: lifetime of 40-60 years; construction in 5-7 years; capacity factor 85%; investment financed by debt (50%) and equity (50%), with return rate of 10% and 15%, respectively; fuel cost of $4.3/MWh; O&M cost of 10$/MWh; decommissioning $350/kW; waste disposal fee of $1/MWh. In the study, the electricity from *foak* nuclear plants emerged as more expensive than fossil-based electricity (then-current $33 to $45/MWh). Technology learning, however, could bring the cost of nuclear power closer to the level of fossil fuel plants, and CO_2 emission pricing could make nuclear power economically competitive. ■ **The joint IEA-NEA study (2005)** placed the cost of nuclear electricity from new plants - to be commissioned in the IEA countries in the period 2010-2015 - between $30 and $50/MWh[5], with 70% investment cost, 20% O&M cost, 10% fuel cost, and assuming a 10% interest rate and no corporate tax. The overnight investment cost ranged from $1000 to $2000/kW and the construction time from 5 to 7 years. The study estimated then-current coal-based electricity cost between $35 and $60/MWh (assuming investment costs of $1000-$1500/kW and 4-years construction time) and gas-based electricity cost between $40 and $63/MWh (with investment cost of $400-$800/kW, 2-3 years construction time and gas price of $4.5/GJ). The recent increases of fossil fuel price make nuclear power even more competitive. ■ **The IEA World Energy Outlook (IEA, 2006)** compared projected (2015) costs of nuclear, coal, gas and wind electricity assuming nuclear investment costs between $2000/kW and $2500/kW and two different discount rates: low (debt and equity return rate of 8% and 12%, respectively, with capital recovery in 40 years); and high (debt and equity return rate of 10% and 15%, with capital recovery in 25 years). Other key figures included projected investment costs for coal, gas and wind power plants (1400, 650, and 900 $/kW, respectively); costs of nuclear fuel, coal and natural gas (0.5, 2.2 and 6.0 $/GJ, respectively); nuclear capacity factor of 85% and construction time of 5 years. Using low discount rates and investment costs, nuclear emerged as the cheapest option ($49/MWh). Using high investment costs, the nuclear electricity ($57/MWh) was cheaper than gas-based electricity, but more expensive than coal electricity so long as coal prices did not exceed $2.8/GJ ($70/t). A 50% price increase of uranium, gas and coal resulted in an incremental 3% for nuclear cost, 20% for coal and 38% for gas, and made nuclear electricity the cheapest option, even with capital costs of $2500/kW. Using high discount rates, nuclear energy was more expensive ($68-$81/MWh) than the other options. Of course, nuclear competitiveness increases considering CO_2 emission pricing. With high discount rate and CO_2 price between $10 and $25/t$CO_2$, nuclear emerged to be competitive with coal at both low and high capital costs. It should be noted that the typical CO_2 price in the EU emissions trading market is around $25/t$CO_2$ and that the typical cost of CO_2 capture & storage (CCS) in coal power plants is currently quoted at above $50/t$CO_2$ and projected to decrease to $30 by 2020. This results in an additional coal electricity cost of $20-40/MWh. ■ **The study of the United Kingdom Department of Trade and Industry (DTI, 2007)** includes a sensitivity analysis. Based on the French EPR under construction in Finland and on French construction plans, the DTI assumes: overnight construction cost between $1700 and $3200/kW, with a central value of $2500/kW; pre-construction time of 7-9 years (8 yr); 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 lead to a LEC estimate between $62 and $88/MWh, with central estimate of $76/MWh. Key cost factors are the overnight cost and the interest rate. The DTI considers its central estimate as conservative, and its higher estimates as unlike. Low-cost assumptions are similar to 2004 French estimates for the construction of ten new reactors. The DTI also mentions private sector 2006 estimates with an average value of $60/MWh. ■ **Other quoted studies** and information on nuclear energy cost include the 2007 Keystone Centre study (new nuclear power plants LEC between $80 and $110/MWh); the vendor overnight investment costs for the Finnish EPR (€1875/kWe, 2003); the overnight cost of the French EPR in Flamanville (€2063/kWe in 2007, increased to €2500/kWe in 2008); the overnight cost of the US EPR version (four units) certified by NRC ($2400/KWe, 2007); and the costs of IRIS and AP1000 by Westinghouse, and of ABWR and ESBWR by GE-Hitachi (all around $3000KW, June 2008). The US utilities quote higher costs including interest and construction time of 5 years.

POTENTIAL & BARRIERS – ■ **Nuclear Power Expansion** - 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, the decision to phase out nuclear power is matter of debate. 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 some 22 GW by 2020. China plans to build 40 GW by 2020. India plans 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 Ukraine. In total, an additional 116 GW are planned by 2020. Worldwide energy policies including carbon trading schemes along with new regulatory frameworks would help rebuild investor's confidence with nuclear power ■ **Nuclear Power Outlook** - Assuming a carbon price of $50/t$CO_2$ and the construction of 30-GW nuclear capacity per year between now and 2050, the

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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.

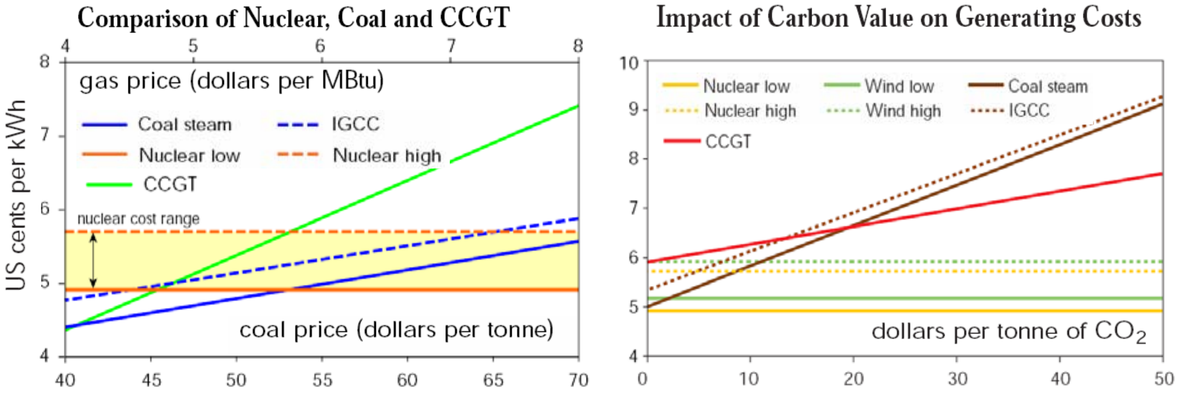
[5] $69/MWh in Japan, where costs are usually higher than in other countries because of high labour and commodities cost

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 2050 CO_2 savings vs. the business-as-usual scenario. 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 definitely addressed. The United Nations IPCC (2007) also suggests that nuclear power could supply 18% of 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 replacement of obsolete plants). The extrapolation does not consider the current status of the nuclear industry, which is under reorganisation in several countries, and the unavailability of appropriate human skills, materials and components. For example, a few companies world wide are able to produce high-quality, ultra-large forgings that are needed for reactor pressure vessels, and these companies have 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 US-launched Global Nuclear Energy Partnership (GNEP) aim to foster the renaissance of the nuclear industry and to develop a new generation of cost-competitive nuclear power plants. ■ **Uranium Resources** – Uranium is produced by a number of countries and major suppliers such as Canada and Australia are politically stable. Uranium resources are plentiful and increasing. With the current demand level of 67,000 tonnes per year (2006), identified uranium reserves (5.47 million tonnes) are sufficient for some 100 years. Recycled and secondary U and Pu^{239} (from fuel reprocessing and military use) could extend conventional reserves to more than 100 years. Resources are more uncertain, but geological evidence points to the existence of an additional 10 million tonnes, which could extend supply to some 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 U ore rose from $13/kg to $95/kg in the period 2001-2006 and has continued to grow recently. 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 the U reserves. However, Th fuel cycle, requires further R&D and considerable investments for industrial deployment. ■ **Safety –** Existing western nuclear reactors already meet high international safety standards, based on multiple safety systems and containment structures that complement the inherent safety features of the reactor (in-depth-defence). The efficacy of this approach has been tested in severe accidents (e.g., Three Mile Island, 1979) which resulted in no fatality and health threat for the population. The Chernobyl accident (1986) dramatically pointed out the serious concerns of the old Soviet Union power plants in contrast with western reactors' safety. Nevertheless, the social acceptance of nuclear energy in the OECD countries remain an issue, and the nuclear industry continues to enhance safety worldwide. ■ **Nuclear Waste** – Nuclear wastes represent less than 1% of total toxic waste from industry and are classified by the radioactivity level. Low-level wastes (LLW) represent 90% of nuclear waste in volume, have short-life radioactivity and require no shielding or geological disposal. Intermediate-level waste (ILW) represent 5 to 7% of nuclear waste volume and require shielding and disposal in shallow repositories. High-level waste (HLW) are fission products and actinides from spent fuel. They have long-life radioactivity, represent 3 to 5% of nuclear waste volume and 95% of the total radioactivity. They require shielding, deep geological disposal and cooling as the decay of radioactive elements generates heat. 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 amounts 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 and 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 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 the original energy content (excluding U^{238}). In addition, its radioactivity decreases significantly in a few decades and storing the spent fuel in cooling pools for several years enables later easy reprocessing. Roughly, 270,000 tonnes of spent fuel are in storage today and some 10,000-12,000 tonnes are added each year, of which some 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 ones. Finland, Sweden and the United States have identified suitable sites. France, Japan and the United Kingdom plan to identify sites in the next future and to have disposal facilities in the next decades. Finland and Sweden plan to dispose of the spent fuel with no reprocessing. Public acceptance of nuclear power plans 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. Today's knowledge suggests that P&T of minor actinides and fission products is technically possible, but commercially questionable, and will 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 UN International Atomic Energy Agency, backed up by diplomatic, political and economic measures, and complemented by controls on import/export of sensitive technologies. The past decades have shown the need for an an additional protocol to enable the IAEA to credibly ensure the absence of undeclared nuclear materials and the non-diversion of declared materials. Some 121 States have signed or ratified the Additional Protocol. In spite of the Treaty, proliferation is seen as one of the risks of nuclear energy. Recent studies (Keystone Center, 2007) find 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 frequency of inspections. International fuel-cycle facilities could guarantee nuclear fuel supply to developing countries and create additional non-proliferation assurances.

Tab.1 - Key Nuclear Data and Figures

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	Some 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 t/GW, cooling water m^3/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	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
Av. employment units/MW	na

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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Major R&D and commercial players - www.iaea.org; www.nea.org; www.iea.org; www.gnep.energy.gov; www.gen-4.org; www.snetp.eu; www.cea.fr; www.ipcc.ch; www.areva.com; www.westinghouse.com; www.gepower.com; www.edf.fr, www.world-nuclear.org; Idaho National Laboratory, Los Alamos National Laboratory.

Tab. 2 - Information on ENEA activities

Processes and Technologies Developed by ENEA (motivation)

● Qualification of passive safety systems and components; ● Liquid Metal-cooled fast neutron systems (critical and subcritical); ● Instrumentation in liquid metals; ● Material coatings against corrosion: ● Pyrochemistry processes for actinides separation.

Demonstration and Experimental Plants and Facilities

TAPIRO 5 kW fast neutron reactor at ENEA-Casaccia Centre; ● TRIGA 1 MW research reactor at ENEA-Casaccia Centre; ● CIRCE at ENEA-Brasimone Centre: lead bismuth large size facility for systems and components qualification in support of LFR and ADS development; ● LECOR at ENEA-Brasimone Centre: corrosion tests in heavy liquid metal environment; ● CHEOPE at ENEA-Brasimone Centre: thermalhydraulic, chemistry and corrosion tests for heavy liquid metal coolants; ● LiFUS5 at ENEA-Brasimone Centre: interaction between heavy liquid metals and water at high temperature and pressure; ● GEST Facility at SIET for testing LWR systems and components at nominal operating conditions (passive containment condenser system, Isolation Condenser system, etc.); ● IETI Facility at SIET: Reactor Core and Steam Generator Thermal-Hydraulics, Critical Heat Flux Experiment, Steam Jet Pumps (or Steam Injectors) performance tests; ● SPES-2 Facility at SIET: Full-height simulator for AP600 certification Program (nominal, transient and accident conditions); ● SPES-3 Facility at SIET (under design/construction): Full-height simulator for IRIS certification program (nominal, transient and accident conditions); ● CETRA and NDA C-43 at ENEA-Casaccia Centre: laboratories for radioactive waste characterization; ● Facilities for waste treatment and characterization.

R&D Objectives, Outcomes and Results (achieved and expected)

Development of GENIII+ SMR LWR (IRIS): integral and separate effects testing, seismic isolation, shielding, economic assessment; ● Development of LFR, SFR and VHTR Generation IV systems: nuclear data, core design and performances, advanced fuels, materials and coolant technology, systems and safety analyses, experimental testing for material compatibility and coolant thermal-hydraulics, R&D needs; ● Development of Accelerator Driven Systems for nuclear waste transmutation: nuclear data, core design and performances, spallation targets physics and technology, materials and coolant technology, systems and safety analyses, minor actinides separation processes, experimental testing for material compatibility and coolant thermal-hydraulics, R&D needs; ● Scenario studies ; Safety of advanced LWRs and FRs: ● Advanced fuel cycles assessment; ● Advanced nuclear materials and fuels development; ● Nuclear wastes conditioning and storage; ● Nuclear materials characterization; ● Proliferation Resistance, Physical Protection and Security; ● Nuclear code and methods development.

Human Resources and Budget

Some 150 person-year and 10 M€ / year

Collaborations and External Financing

● Commisariat a l'Energie Atomique (France) ● Karlsruhe Institute of Technology (Germany) ● SCK.CEN (Belgium) ● Argonne National Labs (USA) ● Oak Ridge National Labs (USA) ● IPPE (Russia) ● RIAR (Russia) ● Ministry of Economic Development (Italy); ● Ministry of Science and Education (Italy) ● European Commission (6th and 7th Framework Programmes)

National and International Patents, Major Publications, Articles, Conference Participations, citations and web-sites

● Energia nucleare: l'opzione del futuro (prima e seconda parte) ● IRIS – An advanced grid-appropriate PWR for near-term deployment ● The SPES-3 experimental facility design for the IRIS reactor integral reactor simulation ● The ELSY Project ● The Potential of the LFR and the ELSY project ● ELSY: Neutronic Design Approach ● EUROTRANS European Research Programme for the Transmutation of High Level Nuclear Waste in an Accelerator Driven System ● Status and trend of core design activities for heavy liquid metal cooled Accelerator Driven Systems ● EFIT: The European Facility for Industrial Transmutation of Minor Actinides ● EFIT Fuel cycle analysis by deterministic and Monte Carlo methods ● A-BAQUS: a multi-entry graph assisting the neutronic design of an ADS ● Corrosion experiments in flowing LBE ● ENEA Experience in LBE technology ● Neutronic Analysis of the TRADE Demonstration Facility ● Inert matrix fuel beahviour in test irradiations ● Inert matrix and thoria fuel irradiation at an international research reactor ● Westinghouse AP1000 internals heating rate distribution calculation using a 3-D deterministic transport method ● Failure mode and effect analysis application for the safety and reliability analysis of a thermal-hydraulic passive system ● Resonance capture cross section of 207Pb ● New measurements of neutron capture resonances in 209Bi ● Neutron capture cross section of 232Th measured at the n_TOF facility at CERN in the unresolved resonance region up to 1 MeV ● Fission of light actinides: 232Th(n,f) and 231Pa(n,f) reactions ● NEA-IEMPT - Information Exchange Meeting on Actinides and Fission Products Partitioning and Transmutation ● ARWIF - Workshop on Advanced Reactors With Innovative Fuels ● FISA - EU Research and Training in Reactor Systems ● GLOBAL ● ICAPP - International Congress on Advances in Nuclear Power Plants ● ICENES - International Conference on Emerging Nuclear Energy Systems ● IPASS - International Workshop on Passive Safety Systems in Advanced PWRs ● PHYSOR - International Conference on Reactor Physics ● EURADWASTE – European Commission Conference on the Management and Disposal of Radioactive Waste ● Workshop on Materials for HLM-cooled Reactors and Related Technologies ● AccApp – International Conference on Accelerator Applications ● NEA-HPPA - International Workshop on High Power Proton Accelerators

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