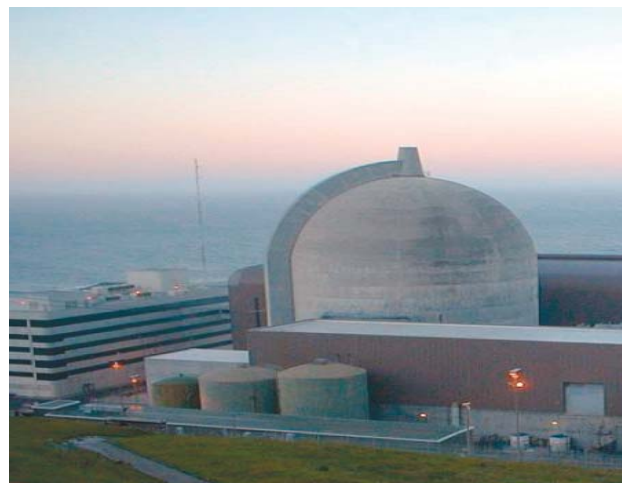


Nuclear Power

- **PROCESS** – Nuclear reactors use heat generated by nuclear fission reactions to drive a turbine-powered electricity generator. Nuclear electricity generation is nearly carbon-free. When replacing coal-fired power, a 1-GW nuclear power plant can avoid emission of some 6-7 million tonnes of CO₂ per year.
- **STATUS** – Existing power plants (370 GW) are mostly 2nd generation light-water reactors (LWR) built in the 1970s and 1980s. The 3rd generation was developed in the 1990s to improve the safety and economics of nuclear power. Following the Chernobyl accident (1986), demand for new nuclear power plants declined; a limited number of 3rd generation reactors have been built since, mainly in Asia. Several countries are now reconsidering nuclear power. The 4th generation of nuclear reactors (GEN-IV) is being developed in an international framework to improve safety and economic performance, to minimise nuclear waste and to enhance proliferation resistance.
- **COSTS** – Nuclear power is a capital-intensive technology. Recent studies point to a cost of nuclear electricity from new power plants ranging from \$30 to \$57/MWh, depending on investment cost (\$1200-\$2500/kW); discount rate (10%-15%); construction time (5-7 years); economic lifetime (25-40 years); load factor and technology learning. The incremental cost of the *first-of-a-kind* reactors or unfavourable economic parameters would raise the electricity cost to \$47-\$81/MWh. In the absence of a carbon price, nuclear power costs are comparable with coal- or natural gas-based power at current price, or slightly higher. A carbon price of between \$10 and \$25/tCO₂ makes nuclear power economically competitive.
- **POTENTIAL & BARRIERS** – With a carbon price of \$25/tCO₂, nuclear electricity's share of global electricity could increase from the current 16% to between 19% and 22% by 2050 (IEA, 2006). If that were the case, nuclear capacity would at least double by 2050 and nuclear power could be making a contribution of 6% to 10% to reducing global CO₂ emissions to sustainable levels by mid-century. Uranium reserves are large enough to support this expansion. But competitive costs and CO₂ mitigation potential are not the only precondition for nuclear power's expansion. Public acceptance, final waste management and proliferation risk are important areas to further address and develop. If not addressed, nuclear power is unlikely to expand and its share in electricity generation might be dropping in the future. In most countries, the perception of investment risk is limiting private investment in nuclear power.

PROCESS – Nuclear energy is a nearly carbon-free source of heat and electricity. When it replaces coal-fired power, the operation of a 1-GW nuclear power plant can avoid about 6-7 million tonnes of CO₂ per year, as well as related airborne pollutants. Several countries are reconsidering the role of nuclear power in the future energy mix. A new generation of safer, more cost-effective reactors is being developed. Inside a nuclear reactor, the energy released by uranium (U) fission reactions provides heat to a coolant fluid that drives a turbine-powered electricity generator. The fluid may directly drive the turbine or provide heat to a secondary coolant. The fuel is natural U or enriched U to some 3-5% of U235 isotope. Natural U is mostly U238 with 0.7% of U235. Nuclear reactors are classified by their neutron energy level (thermal or fast reactors), by their coolant (water, gas, liquid metal¹), also by their neutron moderator (water, heavy water², graphite). Most existing plants are thermal reactors using pressurised (PWR) or boiling water (BWR) as a coolant and moderator. Some reactors use heavy-water (PHWR). In the past years, fast-breeder reactors (FBR) have received renewed attention because their fast neutrons can convert U238 into Pu239 (a usable fuel) and produce fuel in excess of

their own consumption. This could increase by 30 times or more the energy extracted from natural U. There is also interest in high-temperature gas-cooled reactors (HTGR). They offer high efficiency, safety, small size and modularity to adapt to different needs and electricity grids.



Nuclear Power Plant

1) Sodium, Na; 2) D₂O, deuterium water

STATUS - Some 443 nuclear power plants (370 GW) are in operation world wide providing 16% of global electricity supply (25% in OECD countries). Roughly 85% of this capacity is in the United States (104 plants), France (59 plants, 78% of electricity generation) Japan, Russia, the United Kingdom, Korea and India. Some 24 units are under construction mostly in China, India, Russia, Ukraine, Finland, Korea and Japan. Nuclear capacity grew by 17% per year from 1970 to 1990 (200 GW installed in the 1980s) and slowed to 2% from 1990 to 2004, following the Chernobyl accident. Market liberalisation and cheap fossil fuels contributed to reducing nuclear power's attractiveness in the 1990s. Since then, however, nuclear electricity has been growing in pace with global electricity generation because of improved operating availability (from 76% to 83%) and power uprating in existing plants. ■ **Current Reactors** - Most of the existing nuclear reactors belong to the 2nd generation that appeared in the 1970s. The 3rd generation, developed in the 1990s, includes evolutionary reactors with passive safety (reactor shut-down in accident conditions without active intervention), longer lifetime and modular design to reduce costs, licensing and construction time, and high fuel burn-up to optimise fuel use and minimise waste. Several such reactors have been built, mainly in East Asia. Three General Electric advanced BWR reactors have been built in Japan. The Westinghouse 1-GW advanced PWR (AP1000) is under consideration for construction in China and in the United States. AREVA is marketing a 1.6-GW PWR (EPR) with 36% efficiency, 92% availability and a 60-year lifetime. The first EPR is being built in Finland. A second unit is planned in France. Canada's AECL offers an advanced HWR. Small-size, high-temperature gas reactors (HTGR) such as the pebble bed modular reactor (PBMR) and the gas-turbine modular helium reactor (GT-MHR) are being developed in Japan, Russia, China, India, South Africa and the United States. ■ **Future Reactors** - The 4th generation of nuclear reactors (**GEN-IV**) is expected to enter the market after 2030. It includes three fast reactor concepts cooled by liquid lead, sodium or gas (LFR, SFR, GFR), and three thermal reactor concepts cooled by high-temperature helium (VHTR), molten-salt (MSR), and supercritical water (SCWR). All concepts are designed to improve passive safety, to minimise long-life radioactive waste production and to reduce costs. Fast reactor concepts run on closed fuel cycles to burn actinides, recycle Pu and use U238. Thermal reactors use high fuel burn-up to extract more energy from U. All concepts have high cooling temperature (500°C to 1000°C) to achieve high efficiency (40% to 50%). In-factory manufacturing and modularity (plant size from 100-200 MW to 1 GW) help minimise costs and adapt to different markets. The **GFR** (helium-cooled, 850°C, 48% efficiency) includes on-site spent fuel treatment and re-fabrication plant. **LFR** variants include the *nuclear battery concept*, a small-size reactor with long refueling intervals (several years) that builds on nuclear submarine technology. The **SFR** builds on vast experience with sodium-cooled fast reactors (e.g., Superphenix, France). The **SCWR** (water-cooled, 510°C, 44% efficiency) uses super-critical water cooling to increase efficiency against that of existing water-cooled reactors. The **VHTR**

(helium-cooled, 950-1000°C, 50% efficiency) is designed for combined production of electricity and hydrogen via thermo-chemical processes or natural gas reforming. The **MSR** uses molten salt (Na, Zr fluorides with dissolved U or Pu) as a coolant/fuel. All these concepts require further R&D.

COSTS – A few countries have encountered long construction periods for nuclear plants because of licensing and public acceptance issues. Adding to high investment costs, this has resulted in final costs higher than initial estimates and uncertainties over the real cost of nuclear power and investment risk. Recently, costs have been re-assessed by several studies. ■ In 2004, a study supported by the **US Department of Energy**, *The Economic Future of Nuclear Power* (University of Chicago) suggested a projected cost of electricity from new, first-of-a-kind nuclear power plants between **\$47 and \$71/MWh**, including a first-of-kind extra cost of 35%, an incremental 3% financing risk premium and taxes applicable in the United States. After building the first few plants, technology learning (3%-10% learning rates) is expected to reduce the cost to **\$31-\$46/MWh even** without policy incentives. The study assumed an overnight investment cost of \$1200/kW for mature designs, \$1500/kW for new designs with first-of-kind penalty, and \$1800/kW for advanced designs also bearing first-of-kind extra costs. Other basic assumptions were: lifetime of 40-60 years; construction in 5-7 years; capacity factor 85%; 50% investment financed by debt and 50% by equity with return rate of 10% and 15%, respectively; fuel cost of \$4.3/MWh; O&M cost of 10\$/MWh; decommissioning \$350/kW; waste fee of \$1/MWh. Electricity from first-of-kind nuclear plants emerged as considerably more costly than fossil-based electricity (then quoted between \$33 and \$45/MWh). Technology learning, however, can bring the cost of nuclear closer to that of fossil fuel plants. In addition, placing a value on avoided CO₂ emissions makes nuclear power economically competitive. ■ In 2005, a joint **IEA/NEA** study, *Projected Costs of Generating Electricity*, placed the cost of nuclear electricity in the range between **\$30 and \$50/MWh** (70% capital, 20% O&M, 10% fuel cycle) with a 10% discount rate and no tax. The overnight investment cost ranged from \$1000 to \$2000/kW and construction time from 5 to 7 years. The study estimated costs of coal-based electricity at \$35-\$60/MWh (investment costs \$1000-\$1500/kW, 4-years construction) and costs of gas-based electricity at \$40-\$63/MWh (gas price 4.5/GJ, investment cost \$400-\$800/kW, 2-3 years construction). ■ **The IEA World Energy Outlook 2006** compares projected (2015) nuclear, coal, gas and wind electricity costs assuming nuclear investment costs of \$2000/kW and \$2500/kW and two discount rates: low (debt/equity return rate of 8/12%, capital recovery in 40 years); and high (debt/equity return rate of 10/15%, capital recovery in 25 years). Other key figures include projected investment costs for coal, gas and wind power plants (1400, 650, 900 \$/kW, respectively); costs of nuclear fuel, coal and natural gas (0.5, 2.2 and 6.0 \$/GJ, respectively); nuclear capacity factor (85%) and construction time (5 years). Using a low discount-rate and investment costs, nuclear emerges as the cheapest option (**\$49/MWh**). Using the

high investment cost, nuclear costs **\$57/MWh**, which is cheaper than gas-fired power, but more expensive than coal so long as coal prices do not exceed \$2.8/GJ (\$70/t). A 50% increase in uranium, gas and coal prices would raise the electricity cost by 3% (nuclear), 20% (coal) and 38% (gas), thus making nuclear the cheapest option, even with high capital costs (\$2500/kW). Using the high discount rate, nuclear energy (**\$68-\$81/MWh**) tends to be more expensive than the other options. If a value is given to avoided CO₂ emissions, then nuclear becomes more competitive. At a low discount rate, a CO₂ price of \$10/t would make nuclear competitive with coal and gas even with a capital cost of \$2500/kW. With a high discount rate, carbon prices of \$10 and \$25 are needed to make nuclear competitive with coal (low and high capital costs, respectively). It should be noted that the average CO₂ price in the EU emissions trading market in 2005 was some \$23/tCO₂ and that the typical cost of **CO₂ capture & storage (CCS)** in coal power plants is currently quoted at around \$50/tCO₂, with an impact on the electricity cost of \$20-30/MWh (see ETE01). The cost of CCS is expected to decrease to \$25/tCO₂ over coming decades. The comparison is also sensitive to the nuclear capacity factor (a change from 90% to 80% results in further \$10/MWh) and to duration of the construction. In Japan, Korea, China and India, nuclear power plants have been built in less than four years, but construction has taken more than five years in many other cases. Other costs relate to fuel cycle and decommissioning. The **fuel cycle** cost includes basic uranium 25%, conversion into oxide 5%, enrichment 30% (for LWR), fuel manufacturing 15% and up to 25% for waste treatment (direct disposal or reprocessing and recycling). In some countries, the **cost of direct disposal** (on-site storage and ultimate disposal) is estimated at \$1/MWh. **Decommissioning** costs may range from \$200 to 500/kW (\$1-2/MWh). In nuclear power plants, all external costs are internalised and collected up-front.

POTENTIAL - ■ Nuclear power outlook - According to *Energy Technology Perspectives* (IEA, 2006), with a carbon price of \$25/tCO₂, the share of nuclear in global electricity generation is projected to increase from the current 16% to 19%-22% by 2050. If this were the case, nuclear capacity would have more than doubled by 2050 and nuclear power could be making a contribution of between 6% and 10% to globally reducing CO₂ emissions by mid-century. But if the key nuclear issues (waste management, proliferation and social acceptance) are not addressed, nuclear power is unlikely to expand and its electricity share in 2050 could drop to only 7%. In the *WEO Reference Scenario* (assuming unchanged current policies), nuclear capacity is projected to attain 415 GW by 2030, with increases in all regions except Europe, where phase-out policies in Germany, Sweden and Belgium would account for a 35-GW reduction. In the *WEO Alternative Scenario*, additional policies to curb emissions would raise nuclear capacity to 519 GW by 2030, but nuclear's share in global electricity generation would still decline to 14%. ■ **Uranium resources** – At the current demand level of 65,000t/year, proven conventional reserves (4.6 million tonnes) are sufficient for some 85 years. Secondary uranium (from military use and fuel reprocessing) and

recycled Pu239 could extend proven reserves to cover more than 100 years. A pure fast reactor fuel cycle would in principle make reserves sufficient for more than 2500 years. Resources are more uncertain. They are estimated to exceed three times proven reserves. Major producers are Canada and Australia, but U reserves exist in many countries. The price of uranium ore rose considerably from \$13/kg to \$95/kg in the period 2001-2006, boosted by expectations of a nuclear renaissance. While only slightly affecting the cost of nuclear electricity, high U prices are expected to trigger new discoveries and production. One option for extending nuclear fuel reserves is the use of thorium (Th) to produce U233. Once started with U235 or Pu239, neutron-efficient reactors such as advanced HWR and HTGR can convert Th232 into U233. India holds 25% of global Th reserves, which are roughly comparable to U reserves. Use of thorium calls for further R&D. ■ **Policies and expansion targets** – Finland, Japan and Korea are the three OECD countries with nuclear plants under construction. Finland's approach for financing the construction of a €3 billion, 1.6-GW EPR reactor is innovative. Construction delay risks are borne by the plant vendor and market risks are mitigated by long-term electricity purchase contracts between the owner and shareholders. Important government incentives to encourage nuclear power growth are in place in the United States. They include a streamlined licensing process (*Early Site Permit, Construction & Operating Licence*), production tax credits for new capacity in the first 8 years, support for construction delays and loan guarantees. While other countries are planning to streamline the regulatory frameworks, Sweden, Germany and Belgium have decided to phase out nuclear power, albeit subject to ongoing debates. Outside the OECD, Russia, China and India have ambitious nuclear programmes. Russia plans to increase nuclear electricity's share from 16% to 25% by 2030. China plans to build 40 GW by 2020. India has announced a new target to reach 40 GW in 2030. New plants are also considered by other non-OECD countries. Two international co-operation frameworks, the Generation IV International Forum and the Global Nuclear Energy Partnership aim to develop a new generation of nuclear plants with attractive cost, safety, waste and non-proliferation features.

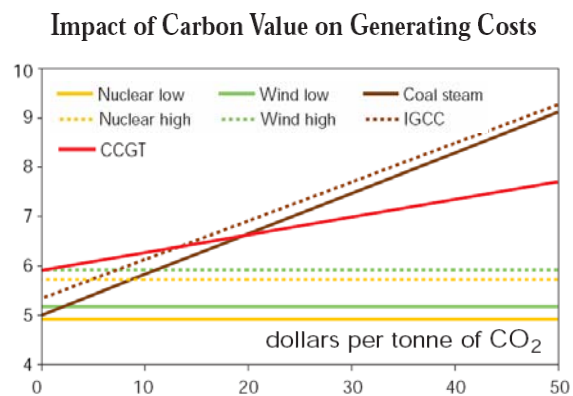
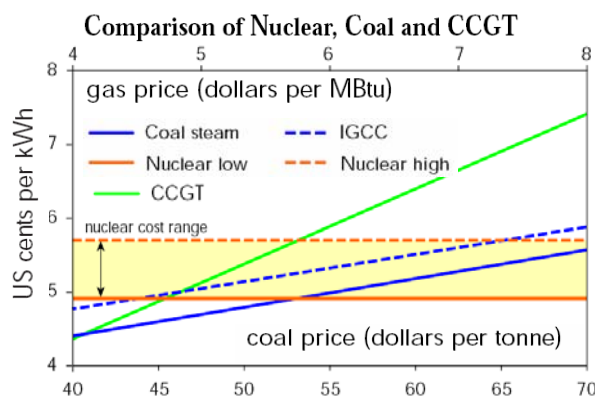
BARRIERS – ■ Investment Risk – Current reactors already meet the internationally defined safety levels. However, regulatory processes and carbon trading schemes need to be further developed and stabilised in order to build investors' confidence in nuclear power. ■ **Nuclear Wastes** - Radioactive wastes are classified as: **low-level wastes (LLW)** with short-life radioactivity requiring no shielding or geological disposal (90% nuclear waste volume, 1% radioactivity); **intermediate-level waste (ILW)**, which requires shielding and disposal in shallow repositories (5%-7% volume, 4% radioactivity); and **high-level waste (HLW)** with long-life radioactivity and heat production (fission products, actinides from spent fuel), thus calling for shielding, cooling and deep geological disposal (3%-5% volume, 95% radioactivity). Nuclear wastes comprise less than 1% of total industrial toxic waste. Typically, a 1-GW

power plant produces annually 200-350m³ of LLW and ILW and 10-20m³ of HLW (some 1000 tonnes over a 40-year lifetime). After recycling, final HLW amounts to less than 3m³ of vitrified waste that must be stored for thousands of years³. ■ **Waste Reprocessing** – If 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 5000t/y (30% of world annual output). Recycled U and Pu are used to produce mixed oxide fuel (MOX). ■ **Waste Disposal** - If the spent fuel is not reprocessed, it is treated as HLW for direct disposal. There is reluctance about irretrievable disposal because the spent fuel contains significant amounts of U238, 1% U235, 1% Pu239, and over half of the original energy content (excluding U238). In addition, its radioactivity decreases considerably in a few decades. This provides incentives to delay both reprocessing and final disposal, and to store the spent

fuel in cooling pools for several years. Roughly, 270,000 tonnes of spent fuel are in storage today and some 10,000-12,000 tonnes are added each year, 3000 of which are reprocessed. Site selection for final geological repositories has proved to be a long process. It is under consideration in most countries and well under way in a few. ■ **Partitioning and transmutation (P&T)** processes could convert long-lived radio-nuclides into short-lived elements thus reducing HLW volume. After separation, fission products and transuranic elements are converted in fast reactors or accelerator-driven systems. Transmutation will not eliminate the need for geological disposal and requires further R&D. ■ **Proliferation** - The 1970 Treaty on Non-Proliferation of Nuclear Weapons commits 187 countries. States having no nuclear weapon receive the benefits of peaceful nuclear technology in return for agreeing to forego nuclear weapons. Compliance with the commitment is verified under the international safeguard administered by the International Atomic Energy Agency. The safeguard controls have been strengthened recently to enable the IAEA to provide credible assurances about the non-diversion of declared nuclear materials and the absence of undeclared nuclear material and activities.

Table 1 - Typical Data and Figures for Nuclear Power Plants

Data Confidence – Performance data refer to 3 rd generation LWR (AREVA design). Costs refer to typical ranges estimated in recent detailed studies for new 3 rd -generation LWR.	
Performance	
Size 1.6 GW; Efficiency 36%; Lifetime 60 years; Capacity factor 90%; Construction time 5-7 years.	
Nuclear waste: LLW/ILW: 200-350 m ³ /GWyear; HLW 10-20 m ³ /GWyear (3 m ³ /GWyear after recycling) ¹	
CO ₂ reduction potential: 6-7 million ton CO ₂ /GW year	
Costs	
Cost of electricity (COE)	\$ 30-57/MWh (\$47-81/MWh for first-of-kind power plant) 10-15% discount rate
Investment cost	\$ 1800-2500 ² /kW ≈ 65%-70% COE;
Decommissioning cost	\$ 200-500/kW equal to \$1-2/MWh
O&M cost	\$ 5-10/MWh ≈ 20%-25 % COE
Fuel cost	\$ 4-5/MWh ≈ 10% COE (25% U; 30% enrich.; 20% manufact.; 25% waste disposal)
Competitiveness of nuclear power (Source: IEA WEO 2006)	



Uranium Reserves and Resources	
Uranium proven reserves	4.6 million tonnes ≈ 85 years of current demand (65 000 t/year)
Uranium resources	Estimates amount to some three times proven reserves ³

Further Information - www.iea.org; www.nea.org; *Energy Technology Perspectives*, IEA-2006; *World Energy Outlook*, IEA-2006; *Projected Costs of Generating Electricity*, IEA-NEA-2005; *Economics of Nuclear Power*, US 2004; *Nuclear Energy Today*, NEA-2003; *Uranium-2005: Resources, Production and Demand*, NEA-2005

1 According to EDF (France), long-lived wastes from 58 French power plants in 15 years operation total some 2000 m³

2 Includes 35% first-of-kind extra cost

3 Fast Breeder Reactors (FBRs) could in principle increase by 30 times or more the energy extracted from natural U