Nuclear Power Generation

By Tarjei Kristiansen*

Nuclear power is defined as the controlled use of nuclear chain reactions to free energy for work, including momentum, heat, and the generation of electricity (Energy Information Administration, 2007). Nuclear power generation is currently limited to nuclear fission and radioactive decay; energy is generated when a sufficiently concentrated fissile material like uranium creates nuclear fission in a controlled chain reaction which also generates heat. The heat can be used to boil water, produce steam, and drive a steam turbine — the turbine can be used for mechanical purposes and to produce electricity.

Nuclear power generation provides 7% of the world's energy and 15.7% of the world's electricity (IEA, 2006). The U.S. produces the most nuclear energy, with nuclear power supplying 20% of consumption, and France generates the highest share of its electrical energy from nuclear reactors — 80% as of 2006 (EIA, 2004 and Beardsley, 2006).

Currently, there is somewhat of a political groundswell in several countries where "nuclear" substitutes for fossil-fuel-generated electricity. A key issue is its low emissions of greenhouse gases which can assist governments to reach targets specified in the Kyoto Protocol.

Additional rationales to support further growth of nuclear capacity:

- Transparent cost structure and low exposure to the variations in global fuel prices; nuclear is the *only* power generating technology where all costs are explicitly priced
- Support for price stability by providing inexpensive baseload generation
- Security of natural gas supply which may be weakened in the future due, for example, to "unstable" deliveries from Russia.

The World Nuclear Association (2006a) categorizes price stability and security of supply as national benefits and non-zero greenhouse gas emissions as a global environmental benefit. The World Nuclear Organization encourages governments to combine their regulatory and safety-oversight responsibilities with efficient licensing procedures for new plants and to introduce incentives to accelerate the transformation to clean-energy economics provided by nuclear generation.

The "800-pound gorilla" issue for the public is the still-unresolved problem of safe, secure waste storage for indefinite periods. Post 9-11, the likelihood of severe radioactive contamination caused by accidents or sabotage, including the possibility that rogue organizations or nations can produce or purchase nuclear weapons is a universal concern. Proponents believe that such risks are small and can be contained or diminished by utilizing new reactor technology. Critics claim that nuclear power is an uneconomic, unsound and potentially dangerous energy source, especially compared to renewable energy, and that new technology cannot be relied on to reduce risk.

Development of Generation Capacity

Most of the existing nuclear power generation is located in Europe, the U.S. and Japan. Globally there are about 440 existing nuclear power plants with a total installed capacity of 368 GW. Worldwide 20 countries have new plants under construction or development. The majority of new build capacity in the next two decades is likely to occur in Russia, the U.S., India, China and Japan.

Global installed nuclear capacity increased relatively quickly, from less than 1 GW in 1960 to 100 GW in the late 1970s, and 300 GW in the late 1980s. Since the late 1980s, capacity has increased at a lower rate, only reaching 366 GW in 2005 (primarily due to Chinese expansion of nuclear power). During the 1970s and 1980s, more than 50 GW of capacity was under construction, but by 2005, only about 25GW of new capacity, mostly baseload, was planned (2006a).

China remains the biggest potential growth market for nuclear reactors and nuclear materials including other commodities. It is expected that new build will be concentrated in Asia (China, India, Japan, South Korea) and Russia. At some point, however, Ukraine, Brazil, Mexico and other countries will consider new generation. Russia's ambitious plan to build 40 GW of new nuclear capacity by 2030 would increase its share of nuclear energy in electricity generation to 25%. Plans in the EU include two 1600 MW European pressurized water reactors (one coming online in 2011 in Finland and another in 2012 in France). The UK's energy review of July 2006 favors nuclear power to replace the coming retirement of its existing nuclear fleet and to meet commitments under the Kyoto Protocol.

In a longer perspective, from 1990 to 2004, world capacity increased by 39 GW (12%, due both to net addition of new plants and uprating of some existing) and elec-

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See footnotes at end of text.

tricity production increased by 38% (Uranium Information Centre, 2007). The relative contributions to this increase were new capacity 36%; capacity uprates 7%; and availability increases 57% (see Figure 1).

The capacity factor is similar to availability; it is a measure of the amount of electricity generated versus the maximum amount a unit can generate in the same period. The capacity factor is a function of the technology, the cost structure (i.e., a strong relationship between the capital costs and the capacity factor), the downtime (the length of time to maintain and refuel a plant) and the wholesale price level (including the steepness of the supply curve). We note that in some cases the calculation of the capacity factor is flawed by using a unit's original nameplate capacity rather than its capacity after upgrades, improvements, and the like, thus creating an "inflated" capacity factor. As an example, although it generates a large share of its electricity from baseload nuclear, France's capacity factor is smaller because it uses nuclear power for regulating purposes (Stricker and Leclercq, 2004).

The average capacity factor over the last five years for the world's major nuclear plants has been higher than the cumulative average because during the start-up phase of new plants, unplanned outages are more frequent, and reliability usually increases over time (Morgan Stanley, 2005).

Figure 1
Reasons for Increased Nuclear Generation Worldwide Since 1990

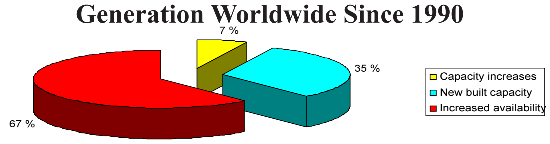
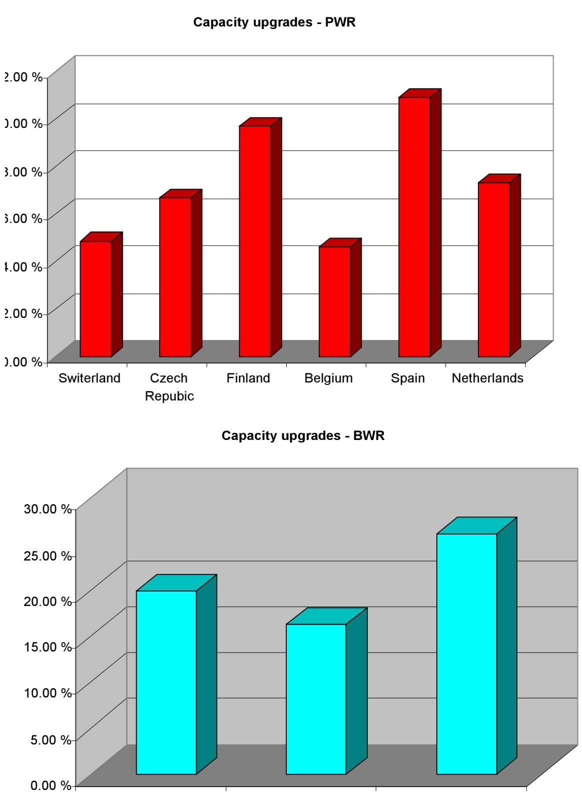


Figure 2
Nuclear Capacity Upgrades by Technology (PWR and BWR) and Country.



Nuclear Uprates

Rising fossil fuel prices and mandatory pollution control equipment when added to fossil power plants including CO_2 allowances drive up the cost of fossil-fueled electricity generation. In the meantime, the cost of nuclear generation has remained relatively stable and has become competitive with fossil generation. Owners have realized increased returns on investment (ROI) in nuclear plants from power uprates and modernizing equipment to achieve higher efficiencies in the steam cycle (Carter, 2006). *Nuclear plants have increased electricity output through power uprates* by increasing the heat output of their 1960s-1980s-era reactors. *Nuclear plants have increased electricity output through modernizing* by taking advantage of design advances in components including reactor cores, steam turbines, moisture separators, steam generators, and fluid flow instrumentation (Carter, 2006).

Figure 2 shows historic and planned capacity upgrades by technology (pressurized water reactor - PWR and boiling water reactor - BWR) for selected countries. The available data (Uranium Information Centre, 2006) is limited but we note that BWR technology appears to have a larger potential for upgrades. Hence it would be desirable to see applications for capacity upgrades in other countries that have these technologies. However, France prefers to invest in new capacity rather than upgrades while Germany still operates under its moratorium with specified nuclear outputs until the phase-out of its major capacity by 2020. EU political experts and investment banks such as Morgan Stanley, UBS and Deutsche Bank believe that Germany must abolish its nuclear moratorium if it wishes to meet its targets under the Kyoto Protocol.

Power uprates are normally undertaken during regular maintenance periods to avoid keeping units out of operation for longer periods. Power uprates were unusual in the 1970s, 1980s, and early 1990s. However, improved technology, rising fossil fuel prices and growing demand have made uprating attractive. In some jurisdictions, the consolidation of nuclear units resulting from mergers and acquisitions encourages power uprates to achieve higher ROI. In the U.S., the Energy Policy Act of 2005 increased government subsidies to encourage new construction.[1] Capacity uprates are significant for Sweden, the U.S. and East European countries. All of the remaining reactors in Sweden will most likely be uprated in the near future, and in the U.S. as much as 5GW could be added between 2005 and 2010.

Life-time Extensions

Most nuclear plants were originally licensed for a period of 30-40 years with potential extensions. The license period is based on economic analyses, and a pay-back time according to the projected ROR based on the electrical rate structure of the era (Carter, 2006).

Earlier experience demonstrated that several aging phenomena observed in nuclear power plants were manageable and that life extension was technically feasible. Similarly, research was conducted to determine the effects of aging on the passive long-lived components in light water reactors. Utilities provide experience, data and component samples on topics vital to license renewal/decommission procedures, such as thermal aging, embrittlement of cast austenitic stainless steel, environmentally assisted cracking, and steam generator tube integrity (Carter, 2006).

Most reactors in Europe are about 20-25 years old and companies usually have 40-year operating licenses. Experts believe the technical limit of their common designs is about 60 years. Generally, existing plants seek to obtain lifetime extensions because it makes sense economically to operate them as long as possible since the construction costs are largely sunk.

Lifetime extensions produce different benefits depending on the owners' options, for example, not replacing retired plants, replacing nuclear with fossil-fuel, or newbuild (nuclear or fossil). The replacement of a nuclear plant with fossil fueled capacity could increase the electricity prices, thus contributing to company profits (Morgan Stanley, 2005).

Economics of Nuclear Power Generation

Prices for uranium have more than tripled. However, since variable costs are small compared to the capital costs, the impact is limited. More important is any incremental change in generation capacity imposed by commissioning, decommissioning, capacity upgrades or availability reductions/increases.

Uranium Markets

Unlike other metals, uranium is not traded on an organized commodity exchange but in most cases through contracts negotiated directly between buyer and seller (Cameco, 2007). Fewer than 100 companies buy and sell uranium in the West.

The structure of uranium supply contracts may vary as:

- A single fixed price or is
- Based upon various reference prices with intrinsic economic corrections.

Contracts normally specify a base price (for example the uranium spot price) including rules for escalation. In these contracts, buyer and seller agree on a base price that escalates over time based on a predetermined formula, depending on macroeconomic indices including GDP or inflation (Cameco, 2007).

A spot market contract usually entails a single delivery and is normally priced at or near the published spot market price at the time of purchase (Cameco, 2007). However, 85% of all uranium has been sold under long-term, multi-year contracts with deliveries starting one to three years after the contract is signed. Long-term contract terms range from two to ten years, but typically run three to five years, with the first delivery occurring within 24 months of contract award. They may also include a clause that allows the buyer to freely choose the size of delivery within specified limits (for example annual volume plus/minus a percentage).

The nuclear fuel cycle is characterized by utilities purchasing enriched uranium in intermediate forms (Cameco, 2007). Sometimes the utility's buyer will purchase enriched uranium product but contract separately for fabrication. Many utilities will typically invite two or three suppliers to submit competing offers for each stage in the four-stage fuel cycle. Sellers consist of suppliers in each of the stages as well as brokers and traders.

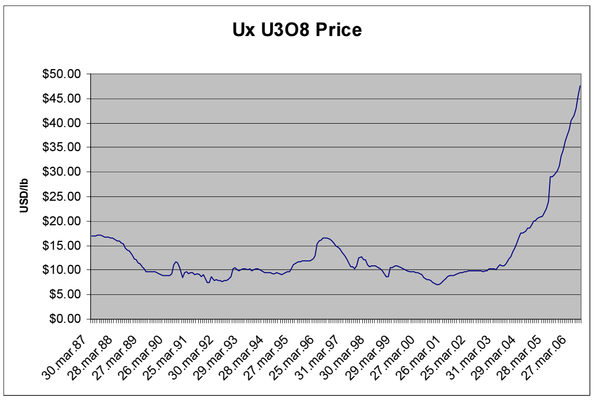
Uranium markets are thus differentiated by intermediate forms but also geographical location. The major marketplaces include the Americas, Eastern and Western Europe, the Far East, the Commonwealth of Independent States (CIS), and China. Most of the fuel requirements for nuclear power plants in the CIS are supplied from the CIS's own stockpiles. Often producers within the CIS also supply uranium and fuel products to western purchasers, increasing competition.

Uranium Prices

Until 1985 the West supplied more uranium than was reprocessed from commercial nuclear facilities and military programs. By the end of the 1980s, prices had dropped below 10 USD/lb for yellowcake. As producers then began to curtail operations or exited the business entirely, western uranium inventories shrank significantly. Since 1990, uranium requirements have exceeded supply; now global demand for uranium is expected to increase steadily through the next decade to a peak of over 200 million pounds annually of yellowcake (Energy Information Administration, 2007). Figure 3 shows the development of the uranium-U3O8 price from March 1987 to January 2007.

Uranium spot prices reached an all-time low of 7 USD/lb in 2001, but as of January 2007, uranium sells at 72 USD/lb.[2] Uranium is at the highest price (adjusted for inflation) in more than 20 years;[3] its price has risen seven times from July 2003 to January 2007 due to the scarcity of sources. The continuing price escalation has caused significant mining expansion among the uranium majors and the entry of numerous smaller companies.

Figure 3
Spot Price Development of Uranium-U3O8 from March 1987 to January 2007 (Source: The Ux Consulting Company, LLC, http://www.uxc.com/)



However utilities almost exclusively purchase all uranium through long-term contracts. The price for these contracts charged by French Areva was around 23 USD/lb in 2006 and thus substantially lower than the spot price (Areva, 2007).

Capital Costs

The capital costs of a nuclear plant depend on plant size, multiple unit sites, design improvements, standardization, and performance improvement (World Energy Council, 2007). The capital costs are accounted for through depreciation.

In a deregulated market, private companies must accept shorter output contracts and the risks of future competition. These conditions shorten the return on investment (ROI) period and thus support power plants with lower capital costs (Stenzel, 2003). In many countries, licensing, inspection and certification of nuclear plants have created delays and additional construction costs. Gas-fueled and coal-fueled plants are not subject to such regulations. During construction a power plant does not create revenue and, therefore, longer construction times lead to higher interest payments on borrowed construction debts. However, in some regions, the regulatory processes for siting, licensing, and constructing have been standardized to make construction of newer, safer designs more attractive to investors. Examples are Japan and France where construction costs and delays are down because of streamlined government licensing and certification procedures.

The capital costs for a nuclear plant contributes to about 70% of the total costs of nuclear-generated electricity, assuming a 10% discount rate (Grimston, 2005). Capital costs incurred while a plant is under construction include costs for the necessary equipment, engineering and labor. These are often termed “overnight” costs and exclude interest incurred during the construction period and financing costs. The capital costs also include engineering-procurement-construction (EPC) costs, owners’ costs and various contingencies. When electricity sales begin, the owner pays back the sum of the overnight and financing costs.

Variable Costs

Variable costs include operation and maintenance (O&M) costs. O&M costs are influenced by availability of the nuclear plants and by safety regulations and manpower costs (World Energy Council, 2007). Historically, the reductions in O&M resulted from cuts in staffing and downtime. Moreover, nuclear O&M costs have stabilized at levels comparable with other baseload generation (World Nuclear Association, 2006a).

OECF-NEA studies (2005) show that the fuel costs have remained fairly stable over time due to lower uranium and enrichment prices including higher burnups. Typically new fuel rods now last 10-15% longer.

Fuel accounts for approximately 20% of total nuclear generation costs. In recent years, fuel cycle costs have decreased significantly, leading to reduced fuel costs for all types of nuclear power plants globally (World Energy Council, 2007). The nuclear fuel cost components include natural uranium (U3O8), uranium conversion to UF6, uranium enrichment, and nuclear fuel fabrication. Table 1 shows the nuclear fuel cost components as of January 2007. If we assume that one kilogram gives 3.4 GJ or 315 MWh, taking the total cost and dividing it by the energy gives 7.03 USD/MWh or 5.45 EUR/MWh. Currently uranium (U3O8) amounts to approximately 57% of the total fuel cost while enrichment amounts to around 28%. Costs for nuclear waste management are around 2 Euro/MWh (Morgan Stanley, 2005).

Variable costs also include O&M costs which are in the range 3.54 to 5.23 Euro/MWh (World Energy Council, 2007).

Figure 4 shows the nuclear fuel costs sensitivity when the uranium, enrichment, fuel fabrication and conversion prices are increased with twice the absolute value and decreased with half the absolute value. The greatest impact is from the uranium price and the enrichment price. A 100% increase in the uranium price results in a 57% increase in the total fuel price while a 100% increase in the enrichment price results in a 28% increase in the total fuel price. The component costs of producing nuclear fuel (conversion, enrichment and fabrication) do not vary substantially. Thus the impact of increases in the price of uranium on the total generation cost is small. For a large PWR a five-fold increase in uranium price will only double the fuel cost (World Energy Council, 2007).

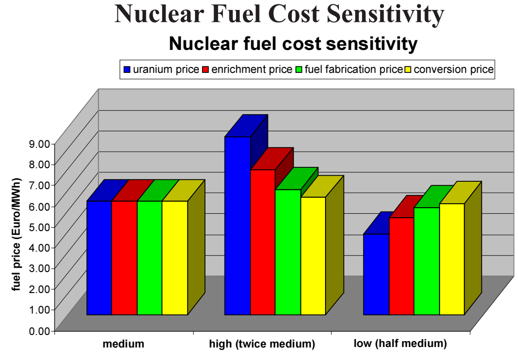
Table 1
Nuclear fuel Cost Components

item	cost	unit	amount	unit	cost USD
U3O8	72,00	USD/lb	8,00	kg	1269,84
conversion	11,50	USD/kg	7,00	kg	80,50
enrichment	130,00	USD/SWU	4,80	SWU	624,00
fuel fabrication	240,00	USD/kg	1,00	kg	240,00
total					2214,34

The variable costs of operating nuclear plants continue to remain low. In the U.S. they were 1.72 cents/kWh in 2003 (World Nuclear Association, 2006a). In Europe a level of 1 euro cent/kWh has been obtained in France and Finland (World Nuclear Association, 2006a).

The balance among O&M costs, fuel, and spent fuel (including waste management) costs correlates with age. O&M costs tend to rise as plants age; spent fuel charges drop as the funds dedicated to it accumulate.

Figure 4
Nuclear Fuel Cost Sensitivity



Full Generation Costs

The World Nuclear Association (2006a) states that nuclear generation has become more competitive primarily due to cost reductions in construction, financing and plant operations, waste management and decommissioning. Construction costs per kW have decreased substantially because of standardized design, shorter construction times and more efficient generation technologies. Financing costs for new plants are expected to decrease with the application of new technology methods, and the streamlining of licensing procedures will reduce regulatory costs and uncertainty by establishing predictable technical parameters and timescales from design certification to construction and operations. Operating costs have decreased with increasing capacity factors. Lower marginal costs (below coal and gas) have made refurbishment and capacity uprates popular. The marginal cost change very little with varying uranium prices and thus accommodate price stability and encourage lifetime extensions for existing units. Waste and decommissioning costs are included in the operational costs and represent a small share of the lifetime operational costs. The bottom line is that even when considering both capital and operating costs, nuclear today is less expensive than fossil-fueled electricity generation.

Several studies (e.g., Morgan Stanley, 2005 and UBS, 2005) estimate the full generation costs of new nuclear power plants to be 42-43 EUR/MWh (a possible reduction in investment costs could give a cost below 40 EUR/MWh). The studies estimate the full generation costs (excluding carbon costs) of a new CCGT and a new coal plant to be 42 EUR/MWh and 39 EUR/MWh respectively.

Table 2 shows the costs in the study by IEA and OECD-NEA (2005); these may even be an underestimate because they do not account for recent increases in fossil fuel prices.

Table 2
Summary of Generation Costs from IEA and OECD-NEA (2005) study.

Generation costs (USD/MWh)	5% discount rate	10% discount rate
Nuclear	23-31	30-50
Coal	25-50	35-60
Natural gas	37-60	40-63

Critics of nuclear power argue that any of the environmental benefits are offset by safety compromises and by the costs related to construction and operations, including costs for depleted-fuel disposal and plant decommissioning and retirement. Proponents of nuclear power argue that nuclear energy is the only power source which explicitly factors the estimated costs for waste containment and plant decommissioning into its overall cost, and that the quoted cost of fossil-fuel units is deceptively low for this reason.

Other issues relevant to nuclear power economics are:

- Nuclear plants are inclined to be most competitive in areas where other fuel resources are not promptly available; for example, France has almost no natural supplies of fossil fuels (Palfreman, 2006)

- Most new natural gas-fired plants are planned for peak load supply. The larger nuclear and coal plants are more difficult to regulate in their instantaneous power production, and are generally considered baseload supply. The market price for baseload power has increased less quickly than peak load supply. Some new experimental reactors, particularly pebble bed modular reactors, are specifically designed for peak load supply
- Current nuclear reactors give back around 40-60 times the invested energy when using life-cycle analysis. This is more efficient than coal, natural gas, and current renewables except large hydropower (World Nuclear Association, 2006b).

Summary

We have described nuclear power generation development including capacity uprates, life-time extensions and the economics of nuclear power. Nuclear power generation has gained public interest due to its economic competitiveness, zero carbon dioxide emissions, and its potential for energy independence. Global consumption is increasing rapidly, creating a need for significant new generation capacity (mainly baseload) in the coming decades. Yet few plans to meet global demand with nuclear exist in the EU, although some plans exist in Asia and Russia.

Plant owners have realized increased ROI by extending the output of their licensed plants (capacity available) through uprating and modernizing equipment to achieve higher efficiencies in the steam cycle. From an economic view it makes sense for owners to run nuclear units as long as possible since construction costs are largely sunk and the plants are profitable. The marginal generating costs of capacity uprates and life-time extensions are roughly only one third of those for new nuclear plants (World Energy Council, 2007).

Uranium is generally traded through contracts negotiated directly between buyer and seller. Uranium spot prices have risen almost seven times from July 2003 to January 2007 due to the scarcity of sources. The continued price escalation has triggered expanded mining by the uranium majors and the entry of numerous smaller companies. However most utilities buy their uranium almost exclusively through long-term contracts priced at substantially lower prices.

The coming decades should create expanded opportunities for nuclear power worldwide. For example, more than 80% of installed European capacity will be over 30 years old by 2020 and will be retired from 2010 to 2030 (World Energy Council, 2007).

Due to global cost reductions in construction, financing and plant operations, waste management and decommissioning, the World Nuclear Association (2006a) forecasts that nuclear will remain competitive. For new nuclear power projects we conclude that:

- Standardized design, shorter construction times and more efficient generation technologies will sharply reduce construction costs per kW,
- Financing costs for new units will decrease as new technologies develop,
- License streamlining will reduce regulatory costs and uncertainty by establishing predictable technical parameters and timescales from design certification to turnkey operation,
- Eventually, regional solutions will arise to safely transport and store global nuclear waste.

Footnotes

[1] See for example, http://www.eia.doe.gov/oiaf/aeo/conf/pdf/rankin.pdf

[2] The price rose especially fast because of recent flooding at Cameco's Cigar Lake mine in Canada; the mine was on track to produce around 15% of the world's supply by 2011 but that now appears unlikely.

[3] The higher price has stimulated new prospecting and reopening of older mines. Cameco and Rio Tinto are the two largest producers (each with 20% of production), followed by Areva (12%), BHP Billiton (9%) and Kazatomprom (9%).

References

Areva (2007). 2006 results presentation, http://www.areva.com.

Beardsley E. (2006). France Presses Ahead with Nuclear Power. NPR.

Cameco, (2007). Uranium Markets, http://www.cameco.com/uranium_101/markets/.

Carter, J. (2006). The Transformation of the Nuclear Power Industry. IEEE Power and Energy Magazine, Vol. 4, No. 6, Nov/Dec 2006.

Energy Information Administration (2007). Nuclear Basics, http://www.eia.doe.gov/basics/nuclear_basics.html

Grimston M. (2005). "The Importance of Politics to Nuclear New Build." Royal Institute of International Affairs.

IEA (2004) - World Energy Outlook.

IEA and OECD-NEA (2005 and earlier editions). Projected Costs of Generating Electricity. http://www.nea.fr/html/pub/ret.cgi?id=new#5968

International Energy Agency (2006). Key World Energy Statistics (pdf).
Morgan Stanley (2005). Nuclear: Core of the matter. Equity Research,
Palfreman J. (2006). Why the French Like Nuclear Power. Frontline. Public Broadcasting Service.
UBS (2005). The future of nuclear. Global Equity Research.
Uranium Information Centre, Melbourne, Australia, (2007). http://www.uic.com.au/nip.htm
Stricker L. and Leclercq J. (2004). An ocean apart. Nuclear Engineering International, December.
World Energy Council (2007). The Role of Nuclear Power in Europe.
World Nuclear Association (2006a). The New Economics of Nuclear Power.
World Nuclear Association (2006b). Energy Analysis of Power Systems. Information and Issue Briefs.