The long-term sustainability of Nuclear Energy

The main points that the World Nuclear Association wishes to make are:

- **Relative to alternatives, nuclear energy is sustainable as a long-term means of supplying most of a country's electricity.**
- **This is most clearly shown by France, which embarked on its civil nuclear program in order to achieve security of supply, and now enjoys abundant low cost electricity, is the world's largest net exporter of electricity and has minimal greenhouse gas emissions from that sector.**
- **Nuclear energy as deployed in most of the world has an impeccable safety record. Management of wastes is straightforward and the only impediments to final disposal of high-level wastes are political.**
- **The resource base for greatly expanded nuclear power generation is available**.

Among the 13 questions posed by the Green Paper, the WNA is best able to address the following:

5, re stockpiling of fuel reserves
8, re nuclear energy concerns
9, re Kyoto commitments
13, re evolving a sustainable system of energy supply.

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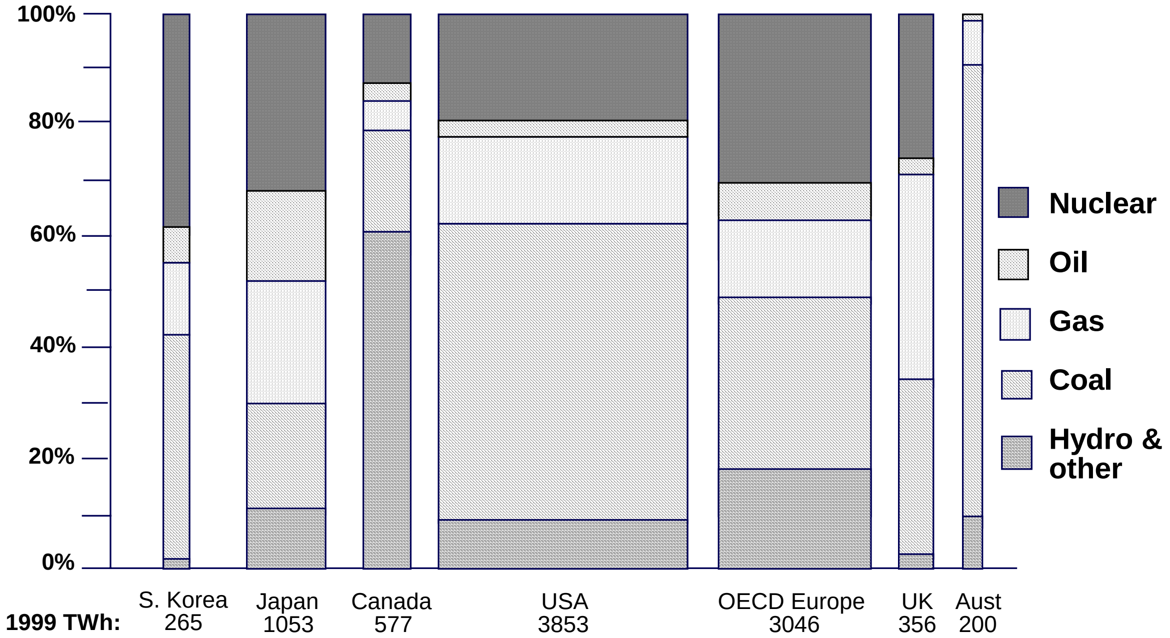
Introduction: a world perspective on nuclear energy.

Fifteen countries derive at least a quarter of their electricity from nuclear power. France gets more than three quarters of its electricity from nuclear energy, while Belgium, Bulgaria, Hungary, Japan, Lithuania, Slovakia, South Korea, Sweden, Switzerland, Slovenia and Ukraine get 35% or more from nuclear.

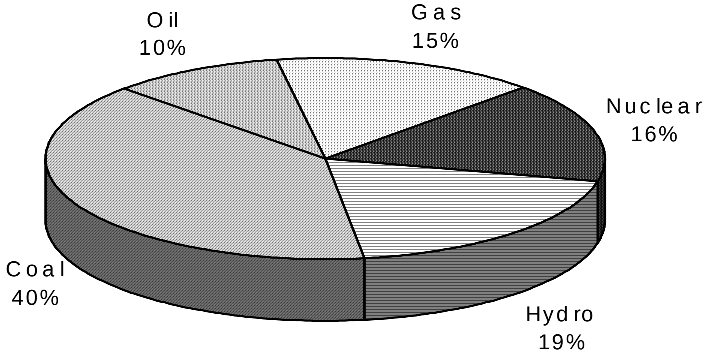
Fuel for electricity generation (percent)



Width of each bar is indicative of power generated (gross production)
Source: OECD/IAEA 2000: *Electricity Information 2000 with 1999 Data*

As of September 2001, 31 countries have a total of 438 commercial nuclear power reactors producing over 16% of the world's electricity. A further 30 commercial power reactors were under construction and six (in Canada) were undergoing major refurbishment. A list of the countries with nuclear power projects is appended (WNA reactor table). In addition, 56 countries have 284 civil research reactors operating.

World Electricity



The generating capacity of the nuclear power reactors currently operating is some 353 000 MWe. The reactors under construction total 8.5 percent of existing capacity, and those ordered or planned, a further 11.6 percent.

New Reactors under Construction

Some 31 power reactors are currently being constructed in 11 countries (see Table), notably China, the Republic of Korea and Japan. Construction is well-advanced on many of them and, based on reported progress and allowing for delays in some countries, 16 with a total net capacity of over 11,000 MWe are expected to be in operation before the end of 2004.

Power Reactors Under Construction

YEAR †	COUNTRY	REACTOR	TYPE	MWe
2001	Czech Republic	Temelin 2	PWR	912
2002	Japan	Onagawa 3	BWR	796
2002	Korea RO	Yonggwang 5	PWR (KSNP)	950
2002	Korea RO	Yonggwang 6	PWR (KSNP)	950
2002	China	Qinshan 2	PWR	610
2002	China	Lingao 1	PWR	935
2002	Argentina	Atucha 2	PHWR	692
2003	Romania	Cernavoda 2	PHWR	650
2003	Iran	Bushehr 1	PWR	950
2003	China	Lingao 2	PWR	935
2003	China	Qinshan 3	PWR	610
2003	China	Qinshan 4	PHWR	665
2004	China	Qinshan 5	PHWR	665
2004	Russia	Kalinin 3	PWR	950
2004	Russia	Kursk 5	RBMK	925
2004	Ukraine	Khmelnitski 2	PWR	950
2004	Taiwan	Lungmen 1	ABWR	1350
2004	Korea RO	Ulchin 5	PWR (KSNP)	950
2004	China	Tianwan 1	PWR	950
2005	Korea RO	Ulchin 6	PWR (KSNP)	950
2005	Japan	Higashidori 1	BWR	1067
2005	Japan	Hamaoka 5	ABWR	1325
2005	Taiwan	Lungmen 2	ABWR	1350
2005	Russia	Rostov-2	PWR	950
2005	China	Tianwan 2	PWR	950
2005	India	Tarapur 3	PHWR	450
2006	Ukraine	Rovno 4	PWR	950
2006	Japan	Shika-2	ABWR	1315
2006	India	Tarapur 4	PHWR	450
2006	Russia	Balakovo 5	PWR	950

† Latest announced year of proposed commercial operation. Onagawa-3 has started up.

China, with three operating reactors, is well into the next phase of its nuclear power program. Construction is advanced on Qinshan 2 & 3 (2 x 600 MWe, PWRs), two French 900 MWe units for Lingao, Guangdong, two 700 MWe Canadian-designed CANDU reactors at Qinshan, and two Russian 950 MWe PWRs at Jiangsu Tianwan in Lianyungang. These are expected to start up from 2002 to 2006, and to add some 6200 MWe to the existing 2167 MWe nuclear capacity.

Increased Capacity of Existing Reactors

Increased nuclear capacity in some countries is resulting from the uprating of existing plants.

Power reactors in USA, Belgium, Sweden and Germany, for example, have had their generating capacity increased. In Switzerland, a program is being undertaken to increase the capacity of its five reactors by 10%.

Spain has a program to add 606 MWe (8.2%) to its nuclear capacity by 2003 through upgrading six of its nine reactors by up to 15%. For instance, the Almarez nuclear plant is being boosted by more than 5% at a cost of US$ 50 million.

Finland has recently boosted the capacity of the Olkiluoto plant by 23% to 1680 MWe. This plant started with two 660 MWe Swedish BWRs commissioned in 1978 and 1980. It is now licensed to operate to 2018. The Loviisa plant, with two VVER-440 (PWR) reactors, has been uprated by almost 100 MWe (11%).

Plant Life Extension

Most nuclear power plants originally had a nominal design lifetime of up to 40 years, but engineering assessments of many plants over the last decade has established that many can operate longer. In the USA the first few reactors have been granted licence renewals which extends their operating lives from the original 40 out to 60 years, and operators of some 80 more are expected to apply for similar extensions. In Japan, plant lifetimes up to 70 years re envisaged.

When the oldest commercial nuclear power stations in the world, Calder Hall and Chapelcross in the UK, were built in the 1950s they were very conservatively engineered, though it was assumed that they would have a useful lifetime of only 20-25 years. They are now authorised to operate for 50 years, and most other Magnox plants are licensed for 40-year lifetimes.

Longer Term Plans

After about 2006 and until orders are placed or construction commenced, forecasts of installed nuclear capacity become much less certain. When the present construction programs are completed, most significant nuclear power growth has been expected to continue only in the Asian region, though with rising gas prices in Europe and North America, nuclear growth may be more widespread.

The International Atomic Energy Agency (IAEA) forecasts that the total installed nuclear capacity in 2015 will be little more than that in 2000, - 370 GWe, with the nuclear share of world electricity output decreased from 17% in 1997 to 13% in 2015.

At least six countries with existing nuclear power programs (Finland, Russia, China, India, Japan & South Korea) have plans to build new power reactors (beyond those now under construction). In addition, the program to provide North Korea with two South Korean 1000 MWe pressurised water reactors is proceeding. Of countries without any present nuclear capacity, Iran has construction well advanced on its first unit.

In all, 44 power reactors with a total net capacity of about 41,000 MWe are planned. None of these is in western Europe or the Americas.

However, rising gas prices and greenhouse constraints on coal have combined to put nuclear power back on the agenda for projected new capacity in both Europe and North America.

Outside of Europe, there are plans for new reactors in many countries.

In addition to the four reactors under construction, **South Korea** plans to bring a further eight, with a total capacity of 13,100 MWe, into operation by the year 2015. Yonggwang-5 & 6 are due for completion in 2002, with Ulchin-5 & 6 in 2004-5. All are 1000 MWe Korean Standard Nuclear Plants (KSNP). Following them are planned Shin-Kori-1 & 2 and Wolsong-5 & 6, to be improved KSNP designs. Then come Shin-Kori-3 & 4, the first of the Advanced PWRs of 1400 MWe, and two more near Ulchin. These APR-1400 designs have evolved from the US System 80+ which has US NRC design certification, and have been known as the Korean Next-Generation Reactor. Cost is expected to be US$ 1400 per kilowatt, falling to $1200/kW in later units with 48 month construction time.

Japan has plans and, in many cases, designated sites and announced timetables for a further 20 power reactors, totalling over 25,000 MWe, and some of these are negotiating the governmental approval process. Earlier this year the major utility Tepco deferred plans for 12 major fossil fuel power plants but maintained the schedules for four new nuclear plants.

Some Power Reactors planned or on order

start operation	start construction	COUNTRY	REACTOR	TYPE	MWe (each)
2006	2002	India	Kudankulam	PWR (VV-1000)	950
2006-7	2002	Japan	Fukushima 7 & 8	ABWR	1325
2007-8		North Korea	Sinpo 1 & 2	PWR (KSNP)	950
2008	2003	Japan	Ohma	ABWR	1350
2007-8		Russia	Sosnovy Bor 1	PWR (VV-640)	600
2010		Russia	Balakovo 6	PWR	950
2010-11	2003?	RO Korea	Shin-Kori 1 & 2	PWR (KSNP)	950
2009-10	2003?	RO Korea	Wolsong 5 & 6	PWR (KSNP)	950
2008	2003	Japan	Tomari 3	PWR	912
2010	2003	Japan	Tsuruga 3 & 4	APWR	1500
2010	2003	Japan	Shimane 3	ABWR	1375
		India	Rajasthan 5 - 8	PHWR	450
		India	Kaiga 3 - 6	PHWR	450
2010-11	2003	RO Korea	Shin-Kori 3 & 4	APR (KNGR)	1350
		RO Korea	near Ulchin	APR (KNGR)	1350
2010-11	2003-5	Japan	Higashidori 1-2, 2	ABWR	1320
2012-15	2007-10	Japan	Kaminoseki 1-2	ABWR	1320

according to announcements 1998-2001

China's tenth Five-Year Plan (2001-2005) incorporates the construction of nuclear power plants. New facilities under consideration include two more 900 Mwe units at Lingao, and up to six 1000 MWe reactors at Yangjiang, Guangdong province. Further developments are to take place in Shandong province, with two 1000 MWe units planned for Haiyang. Also proposed are two 1000 MWe reactors at Hui An, Fujian province, and two 1000 MWe units at Sanmen, near Qinshan in Zhejiang province, the latter to be Westinghouse-based Chinese standard PWRs. Overall the total capacity envisaged is more than 20,000 MWe.

India has announced plans for 11 power reactors (4980 MWe) of its larger reactor type, in addition to the two under construction, but financing difficulties are expected to continue to cause delays. There are also plans to build two large Russian reactors at Kudankulam and the construction contract for these is expected to be signed later in 2001.

Stockpiling of Fuel Reserves (Q. 5)

With nuclear energy, it uniquely simple and cost effective to stockpile fuel, either in its raw state as uranium oxide concentrate, or as finished fuel assemblies. Foratom has already pointed out that an average of three years of fuel is already stockpiled in Europe at the expense of the utilities concerned.

The reason that such stockpiling is easy and cost effective is that fuel comprises a lower proportion of electricity cost than with any fossil fuels. It follows incidentally that a doubling of its price (ie of mined uranium) would cause les than a ten percent increase in electricity cost. Thus even five or more years supply of uranium can be stockpiled with little financial inconvenience, if desired.

Nuclear Energy Concerns (Q. 8)

Wastes

A major concern when applying Sustainable Development considerations is wastes – both those produced and those avoided.

With solar energy wastes are mainly produced in manufacturing the conversion equipment, with nuclear energy they are operational and in decommissioning, and with fossil fuels they are primarily operational. There seems no reason why manufacturing wastes cannot be dealt with, nuclear energy contains and manages its wastes, and the focus today is on greenhouse gases from fossil fuels combustion. With nuclear energy the waste question is political, regarding final disposal, rather than technical, and all civil wastes are managed without environmental impact. **Nuclear power remains the only energy-producing industry which takes full responsibility for all its wastes, and costs this into the product - a key factor in sustainability.**

Electricity generation from fossil fuels produces substantial amounts of carbon dioxide, a greenhouse gas of prime concern. As a rule of thumb, every thousand kilowatt hours (1 MWh) of electricity generated from nuclear energy avoids the emission of one tonne of carbon dioxide, relative to generating that electricity from black coal.

Ethical issues surrounding nuclear wastes are topical. However, prominence of the issue has tended to obscure the fact that these wastes are a declining hazard, whereas other industrial wastes retain their toxicity and hence hazard indefinitely.

Regardless of whether particular wastes are nasty for centuries or millennia or forever, there is a clear need to address the question of their safe disposal. If the wastes cannot readily be destroyed or denatured, this generally means removal or isolation from the biosphere, although, the alternative view is frequently put. This asserts that indefinite surface storage of wastes under supervision is preferable to geological disposal, since progressing the latter would simply give encouragement to continued use and expansion of nuclear energy. It is often made very plain that ideological opposition to nuclear energy is more important to its detractors than dealing properly with wastes so as to achieve high levels of safety and security. The wider question of alternative low-CO_2 means of producing base-load electricity tends not to be addressed.

In a 1999 OECD article, *Long-term management of radioactive waste, ethics and the environment,* Claudio Pescatore outlines some ethical dimensions of the question. He starts on a very broad canvas by quoting four fundamental principles proposed by the US National Academy of Public Administration. This proposal followed a request from the US Government to elucidate principles to guide decisions by public administration on the basis of the international Rio and UNESCO Declarations concerning responsibilities for future generations:

- The Trustee Principle says that "Every generation has obligations as trustee to protect the interests of future generations".
- The Sustainability Principle states that "No generation should deprive future generation of the opportunity for a quality of life comparable to its own."
- The Chain of Obligation Principle says that "Each generation's primary obligation is to provide for the needs of the living and succeeding generations," the emphasis being that "near-term concrete hazards have priority over long-term hypothetical hazards."
- The Precautionary Principle is expressed as "Actions that pose a realistic threat of irreversible harm or catastrophic consequences should not be pursued unless there is some countervailing need to benefit either current or future generations."

These are then applied to the question of nuclear wastes, and in particular to geological disposal of these which is noted as having intrinsic passive safety. In the light of the IAEA and the NEA 1995 publications on the matter, Dr Pescatore summarises the principles in this context as follows:

- The generation producing the waste is responsible for its safe management and the associated costs.
- There is an obligation to protect individuals and the environment both now and in the future.
- No moral basis exists for discounting future health and risks of environmental damage.
- In particular, our descendants should not knowingly be exposed to risks which we would not accept today. Individuals should be protected at least as well as they are today.
- The safety and security of repositories should not be based on the presumption of a stable social structure for the indefinite future or on a presumption of technological progress.
- Waste should be processed in such a way as not to be a burden for future generations. However, we should not unnecessarily limit the capacity of future generations to take over management control, including the ability to recover the waste.
- We are responsible for passing on to future generations our knowledge concerning the risks related to waste.
- There should be enough flexibility in the disposal procedures to allow alternative choices. In particular information should be given to the public to enable it to take part in the decision-making process which, in this case, will proceed in stages.

He points out that "geological disposal is considered as the final stage in waste management, ensuring security and safety in such a way as not to require surveillance, maintenance, or institutional control. Although such measures are not necessary to ensure safety and security, they are not, however, excluded. Society will still be able to choose to use them as management tools."

Safety

The safety of nuclear energy has been well demonstrated, and its record is unsurpassed by any technology capable of delivering a comparable amount of power. This safety picture is notwithstanding the continued operation of a small number of reactors which are, by western standards, distinctly unsatisfactory (in particular, 11 VVER-440/230 types and 13 RBMK types have serious design deficiencies, and one of the latter type precipitated the 1986 Chernobyl disaster). Over 10,000 reactor-years of operation have shown a remarkable lack of problems in any of the reactors which are licensable in most of the world.

There is probably no other large-scale technology used worldwide with a comparable safety record, this being largely due to the fact that safety was given a very high priority from the outset of the civil nuclear energy program, at least in the west. About one third of the cost of a typical reactor is due to its safety systems and structures, including containment and back-up provisions. This is a higher proportion even than in aircraft design and construction.

Any statistics comparing the safety of nuclear energy with alternative means of generating electricity show nuclear to be the safest. In fact Chernobyl is the only event detracting from an almost impeccable record in commercial nuclear power, and Chernobyl is of very little relevance to the actual safety of most of the world's reactors.

Improved Performance From Existing Reactors

Although there are not as many nuclear power plants being built now as there were during the 1970s-1980s, the plants now operating are producing more electricity. In 2000, production was 2447 billion kWh, an increase of 15% over the previous six years. This increase (317 TWh) is equal to the output from over thirty large new nuclear power plants, but in fact over 1995-2000 there was a net increase of only five reactors and 3% in capacity. The balance is due to better performance from existing power reactors.

In a 1999 Siemens study, a 50% increase in PWR burn-up (on a thermal, not electrical basis) is charted, from 30 MWd/kg U in 1974 to 45 MWd/kg in 1998. For the BWR the increase is from 23 to 40 MWd/kg over the same period, coupled with increased physical reliability of the fuel.

Two thirds of the world's nuclear reactors outside Russia and Ukraine have load factors over 75%, compared with only 39% operating at this level in 1990. For the past 15 years Finnish plants have been at the top of the performance tables, now with average load factors around 92%. Belgian, Czech, German, Hungarian, Japanese, South Korean, Spanish, Swiss, Taiwanese and US reactors range down to about 80%.

US nuclear power plant performance has shown a steady improvement over the past ten years and at 85% average load factor, has moved (from 65% in 1990) into the top bracket, with some of the best (17 of top 25) reactors. The USA accounts for nearly one third of the world's nuclear electricity.

Advanced Reactors

The nuclear power industry has been developing and improving reactor technology for almost five decades and is preparing for the next generation of reactors to fill orders expected in the next five years.

About 85% of the world's nuclear electricity is generated by reactors derived from designs originally developed for naval use, and which have been found to be safe and reliable. But just as the DC-3, for all its virtues, gave way to more sophisticated and economical aircraft, so the first-generation nuclear power reactors is making way for better ones.

Reactor suppliers in North America, Japan, Europe, Scandinavia and South Africa have a dozen new nuclear reactor designs at advanced stages of planning, while others are at a research and development stage.

The next generation reactors will

- have a standardised design for each type to expedite licensing, reduce capital cost and reduce construction time,
- be simpler and more rugged in design, easier to operate and less vulnerable to operational upsets,
- have higher availability and longer operating life,
- further reduce the possibility of core melt accidents,
- have minimal effect on the environment,
- have higher burn-up to reduce fuel use and the amount of waste,
- often use burnable absorbers ("poisons") to extend fuel life.

The greatest departure from current designs is that many new generation nuclear plants will operate on 'passive' safety features which rely on gravity, natural convection, etc, requiring no active controls or operational intervention to avoid accidents in the event of malfunction.

Light wWater Reactors

In USA, the federal Department of Energy (DOE) and the commercial nuclear industry have developed three advanced reactor types. Two of the three fall into the category of large "evolutionary" designs which build directly on the experience of operating light water reactors in the United States, Japan and Western Europe. These reactors are in the 1300 megawatt range.

One is an advanced boiling water reactor (ABWR), two examples of which are in commercial operation in Japan, with two more under construction in Taiwan. The other type is known as System 80+, an advanced pressurised water reactor (PWR), which is ready for commercialisation. Eight System 80 reactors in South Korea incorporate many design features of the System 80+, and it is the basis of the Korean Next Generation Reactor program.

The US Nuclear Regulatory Commission (NRC) gave final design certification for both in May 1997, noting that they exceeded NRC "safety goals by several orders of magnitude".

Another, more innovative US advanced reactor is smaller - 600 MWe - and has passive safety features. The AP-600 gained final design certification from the NRC in December 1999, and a scaled-up AP-1000 is likely to be submitted to the NRC for approval in 2002. The AP-600 is expected to be economical and quick to build.

These are the first such generic certifications to be issued and will be valid for 15 years. Following an exhaustive public process, it means that safety issues within the scope of the certified designs have been fully resolved and hence will not be open to legal challenge during licensing for particular plants. Utilities will be able to obtain a single NRC licence to both construct and operate a reactor before construction actually begins.

Separate from the NRC process and beyond its immediate requirements, the US nuclear industry selected one standardised design in each category - the large ABWR and the medium-sized AP-600, for detailed first-of-a-kind engineering (FOAKE) work. The US$ 200 million program, half funded by DOE, is now complete. It means that prospective buyers now have firm information on construction costs and schedules.

Beyond these advances, the industry and DOE are starting to define "4th generation" reactor design criteria.

In Japan, the first two ABWRs have started operating, as noted above. Also, a large (1500 MWe) advanced PWR is being developed by four utilities with Westinghouse and Mitsubishi, the first two being planned for Tsuruga. It is simpler, combines active and passive cooling systems to greater effect, and has over 55 GWd/t burn-up. Design work continues and it will be the basis of the next generation of Japanese PWRs.

In Europe, three designs are being developed to meet the European Utility Requirements (EUR) of French and German utilities, with stringent safety criteria.

Framatome ANP is developing a large (up to 1750 MWe) European pressurised water reactor (EPR), which was confirmed in mid 1995 as the new standard design for France. Also Framatome ANP, with German utilities, is developing the more innovative SWR 1000, a 1000 MWe BWR. Westinghouse in Sweden is developing its evolutionary BWR 90+ (1500 MWe) design with Scandinavian utilities to meet EUR requirements.

In Russia, two advanced reactor designs have been developed. Both are advanced PWR with passive safety features.

Construction of the first of four 640 MWe V-407 (VVER-640) units at Sosnovy Bor and Kola is pending. One or two 1000 MWe V-392 (advanced VVER-1000) units are planned for Novoronezh. In addition, the VVER-91 (1000 MWe) has been developed in conjunction with Finland and two have been sold to China for Lianyungang.

Heavy Water Reactors

Canada has had two designs under development which are based on its reliable CANDU-6 reactors. Two improved CANDU-6 units are under construction in China.

The CANDU-9 (925-1300 MWe) is developed from an existing design but is a single-unit plant. It has flexible fuel requirements ranging from natural uranium through slightly-enriched uranium, recovered uranium from reprocessing spent PWR fuel, mixed oxide (U & Pu) fuel, direct use of spent PWR fuel, to thorium, and possibly burning military plutonium or actinides separated from reprocessed PWR/BWR waste. A two year licensing review of the CANDU-9 design was successfully completed early in 1997.

The CANDU-NG is also developed from the CANDU-6. It is nominally 600 MWe but is physically smaller, simpler and more efficient as well as 40% cheaper than the CANDU-6, giving projected operating costs of US$ 3 cents/kWh. It will run on low-enriched uranium (about 1.5% U-235) with high burn-up, and have light water cooling. Units will be assembled from prefabricated modules, eventually cutting construction time to 4 years. Development is under way and the project is expected to be ready in 2005. British Energy has recently signed an agreement with Atomic Energy of Canada Ltd to investigate the possible deployment of these in UK, to be built on existing sites.

High-Temperature Gas-Cooled Reactors

Building on the experience of several innovative reactors built in the 1960s and 1970s, development is proceeding on new high-temperature gas-cooled reactors (HTRs) which will be capable of delivering high-temperature (up to 950°C) helium either for industrial application or directly driving gas turbines for electricity (the Brayton cycle). Technology developed in the last decade makes HTRs more practical than in the past.

Fuel for these reactors is in the form of particles less than a millimetre in diameter. Each has a kernel of uranium oxycarbide, with the uranium enriched up to 8% U-235. This is surrounded by layers of carbon and silicon carbide, giving a containment for fission products which is stable to 2000°C.

There are two ways in which these particles are arranged: in blocks - hexagonal 'prisms' of graphite, or in billiard ball-sized pebbles of graphite encased in silicon carbide, each with about 15,000 fuel particles and 9g uranium. Both have a high level of inherent safety, including negative temperature coefficient whereby fission slows as temperature rises.

The small High-Temperature Test Reactor (HTTR) in Japan started up at the end of 1998. Its fuel is in 'prisms'. China's HTR-10 demonstration reactor started up in 2000 and has its fuel as a 'pebble bed'.

South Africa's Pebble Bed Modular Reactor (PBMR) is being developed by a consortium led by the utility Eskom, drawing on German expertise, and aiming for a step change in safety and economics. Modules with a direct-cycle gas turbine generator will be of 110 MWe and thermal efficiency about 45%. Up to 450,000 fuel pebbles recycle through the graphite-lined reactor continuously (about ten times each) until they are expended, giving an average enrichment in the fuel load of 5-6% and burn-up of 80,000 MWday/t U. Each unit will finally discharge about 19 tonnes/yr of spent pebbles to ventilated on-site storage bins.

Construction cost (for clusters of 10 - 14 units) is expected to be US$ 1000/kW and generating cost 1.6 US cents/kWh. Eskom and the South African Industries Development Corporation hold 55% the project, with BNFL 20% and Exelon (USA) 12.5%. A prototype is due to be built in 2002 for commercial operation in 2006.

A larger US design, the Gas Turbine - Modular Helium Reactor (GT-MHR), will be built as modules of 285 MWe each directly driving a gas turbine at 48% thermal efficiency. The cylindrical core consists of 102 hexagonal fuel element columns of graphite blocks with channels for helium and control rods. Graphite reflector blocks are both inside and around the core. Half the core is replaced every 18 months. It is being developed by General Atomics in partnership with Russia's Minatom, supported by Framatome ANP and Fuji (Japan). Initially it will be used to burn pure ex-weapons plutonium at Tomsk in Russia. The design stage is due to be completed in 2001. Plant costs are expected to be less than US$ 1000/kW.

HTRs can potentially use thorium-based fuels, such as HEU with Th, U-233 with Th, and Pu with Th. Most of the experience with thorium fuels has been in HTRs. See also WNA information paper on Thorium.

Fast Neutron Reactors

Several countries have research and development programs for improved Fast Breeder Reactors (FBR), which are, generically, Fast Neutron Reactors. These generate power by using the uranium-238 in the reactor fuel assembly instead of just the fissile U-235 isotope used in most reactors.

About 20 liquid metal-cooled FBRs have already been operating, some since the 1950s, and some supply electricity commercially. Over 290 reactor-years of operating experience have been accumulated.

Natural uranium contains about 0.7 % U-235 and 99.3 % U-238. In any reactor the U-238 component is turned into several isotopes of plutonium during its operation. Two of these, Pu-239 and Pu-241, then undergo fission in the same way as U-235 to produce heat. In a fast neutron reactor this process is optimised and it therefore 'breeds' fuel so that the FBR can utilise uranium about 60 times more efficiently than a normal reactor. FBRs are however expensive to build and could only be justified economically if uranium prices were to rise to pre-1980 values, about four times the current market price.

For this reason research work on the 1450 MWe European FBR has almost ceased and the 1250 MWe French Superphenix FBR has closed down. Research continues on the Indian FBRs, and Japan's Monju prototype commercial FBR was connected to the grid in August 1995 (but was then shut down due to a sodium leak).

The Russian BN-600 fast breeder reactor has been supplying electricity to the grid since 1981 and has the best operating and product-ion record of all Russia's nuclear power units. The BN-350 FBR operated in Kazakhstan for 27 years and about half of its output was used for water desalination. Russia plans to reconfigure the BN-600 to burn the plutonium from its military stockpiles, and construction has started on the first BN-800.

In the USA, GE was involved with designing a modular 150 MWe liquid metal-cooled inherently-safe reactor - PRISM. GE and Argonne have also been developing an advanced liquid-metal fast breeder reactor (ALMR) of over 1400 MWe, but both designs are still at an early stage and have been withdrawn from NRC review. No US fast neutron reactor has so far been larger than 66 MWe and none has supplied electricity commercially.

Accelerator-Driven Systems

A recent development has been the merging of accelerator and fission reactor technologies for generating electricity and transmuting long-lived radioactive wastes.

A high-energy proton beam hitting a heavy metal target produces neutrons by spallation. The neutrons cause fission in the fuel, but unlike a conventional reactor, the fuel is sub-critical, and fission ceases when the accelerator is turned off. The fuel may be uranium, plutonium or thorium, possibly mixed with long-lived wastes from conventional reactors.

Many technical and engineering questions remain to be explored before the potential of this concept can be demonstrated. See also WNA information papers on *ADS* and *Thorium*.

Kyoto Obligations (Q. 9)

There has been a concerted attempt recently to question the net energy benefits of nuclear energy by asserting that it requires so much energy input, and incurs so much longer-term energy debt, that it is not viable, and that the greenhouse gas emissions from those inputs and debts cancel out any advantage on that score.

This broader question is fully addressed in a WNA Information Paper *Energy Analysis of Power Systems*. The charge does not stand up, and in fact energy inputs on a lifetime basis are typically about 2% of the lifetime outputs. No reputable figures put the total higher than 8.7% of output, and we would want to challenge some of the components even of that.

The question of greenhouse gas emissions incurred in the energy inputs depends of course on the source of energy for those inputs, but is arguably more about sophistry than science. If it is assumed that most of the energy inputs come from coal, then the greenhouse emission attributable will be typically about 2% of those from a coal-fired power plant. In fact the Swedish utility Vattenfall's life cycle analysis shows 6g/kWh for nuclear, compared with 5.5g for wind, 450g for gas combined cycle and 980g/kWh for coal. Published Finnish data are similar, and Japanese data published recently give 22g/kWh – about 2% of coal's.

The following table sets out the data from the three most recent thorough studies:

g/kWh CO_2	Japan	Sweden	Finland
coal	975	980	894
gas thermal	608	1170 (peak, reserve)	-
gas combined cycle	519	450	472
solar photovoltaic	53	50	95
wind	29	5.5	14
nuclear	22	6	10-26
hydro	11	3	-

The Japanese gas figures include shipping LNG from overseas, and the nuclear figure is for boiling water reactors, with enrichment 70% in USA, 30% France & Japan, and one third of the fuel to be MOX. The Finnish nuclear figures are for centrifuge and diffusion enrichment respectively.

Evolving a Sustainable System of Energy Supply (Q. 13)

The economics of nuclear power

The relative costs of generating electricity from coal, gas and nuclear plants vary considerably depending on location. Nuclear energy is, in many places, competitive with fossil fuel for electricity generation, despite relatively high capital costs and the need to internalise all waste disposal and decommissioning costs. If the social, health and environmental costs of fossil fuels are also taken into account, nuclear is outstanding.

The report of a major European study of the external costs of various fuel cycles, focusing on coal and nuclear, was released in mid 2001. It shows that in clear cash terms nuclear energy incurs about one tenth of the costs of coal. The external costs are defined as those actually incurred in relation to health and the environment and quantifiable but not built into the cost of the electricity. If these costs were in fact included, the EU price of electricity from coal would double and that from gas would increase 30%. These are without attempting to include global warming.

This ExternE project was launched by the European Commission in 1991 in collaboration with the US Department of Energy, and it was the first research project of its kind "to put plausible financial figures against damage resulting from different forms of electricity production for the entire EU". The methodology considers emissions, dispersion and ultimate impact. With nuclear energy the risk of accidents is factored in along with high estimates of radiological impacts from mine tailings (waste management and decommissioning being already within the cost to the consumer). For external costs only, nuclear energy averages 0.4 euro cents/kWh, much the same as hydro, coal is over 4.0 cents (4.1-7.3), gas ranges 1.3-2.3 cents and only wind shows up better than nuclear, at 0.1-0.2 cents/kWh average. These all need to be added to the conventionally-quoted costs, such as those (the most recent international figures available) in the table below.

The OECD does not expect investment costs in new nuclear generating plants to rise, as advanced reactor designs become standard. The future competitiveness of nuclear power will depend substantially on the additional costs which may accrue to coal generating plants.

Without considering external costs not already included, and under current regulatory measures, the OECD expects nuclear to remain economically competitive with fossil fuel generation, except in regions where there is direct access to low cost fossil fuels. In Australia, for example, coal-fired generating plants are close to both the mines supplying them and the main population centres, and large volumes of gas are available on low cost, long-term contracts.

Comparative electricity generating cost projections for 2005-2010

	nuclear	**coal**	**gas**
France	**3.22**	4.64	4.74
Russia	**2.69**	4.63	3.54
Japan	5.75	**5.58**	7.91
Korea	**3.07**	3.44	4.25
Spain	**4.10**	4.22	4.79
USA	3.33	2.48	**2.33** - 2.71
Canada	**2.47**-2.96	2.92	3.00
China	**2.54**-3.08	3.18	-

US 1997 cents/kWh. Discount rate 5%, 30 year lifetime, 75% load factor. ***OECD 1998***.

The most recent OECD comparative study shows that at a 5% discount rate, in 7 of 13 countries considering nuclear energy, it would be the preferred choice for new base-load capacity commissioned by 2010 (see Table above). At a 10% discount rate the advantage over coal would be maintained in only France, Russia and China, unless the external costs are brought fully into account.

A 1997 European electricity industry study compared electricity costs from nuclear, coal and gas for base-load plant commissioned in 2005. At a 5% discount rate nuclear (in France and Spain) at 3.46 cents/kWh (US), was cheaper than all but the lowest-priced gas scenario. However at a 10% discount rate nuclear, at 5.07 c/kWh, was more expensive than all but the high-priced gas scenario. (ECU to US$ @ June '97 rates)

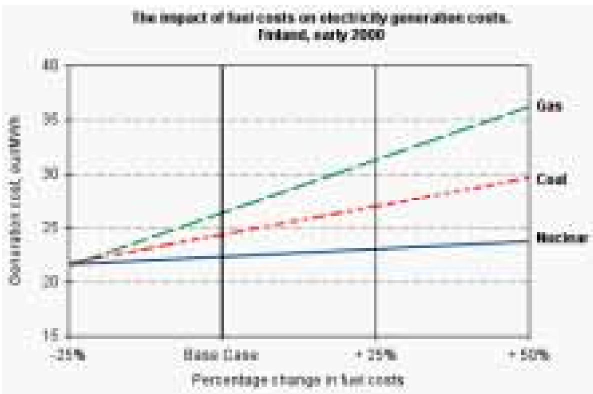
In 1999 Siemens (now Framatome ANP) published an economic analysis comparing combined-cycle gas plants with new designs, including the European Pressurised Water Reactor (EPR) and the SWR-1000 boiling water reactor. Capital costs for these in Germany, at 1750 and 1000 MWe respectively, were both EUR 1250/kW, compared with EUR 1375/kW for a 1550 MWe version of the EPR, and EUR 1500/kW for the 1350 MWe Advanced Boiling Water Reactor, two of which are now operating in Japan.

Looking at power costs, both the 1550 MWe EPR if built as a series in France /Germany and the SWR-1000 (with an 8% discount rate) were competitive with gas combined cycle, at EUR 2.6 cents/kWh. But once depreciated, their costs fall to about 1.5 cents/kWh compared with gas at 2.5 cents (capital being 60% of the nuclear plant costs but only 15% of the gas plant costs).

The current-generation Konvoi plants operating in Germany produce power at 3.0 cents/kWh including full capital costs, falling to 1.5 c/kWh after complete depreciation.

A detailed study of energy economics in Finland published in mid 2000 shows that nuclear energy would be the least-cost option for new generating capacity. The study compared nuclear, coal, gas turbine combined cycle and peat. Nuclear has very much higher capital costs than the others --EUR 1749/kW including initial fuel load, which is about three times the cost of the gas plant. But its fuel costs are much lower, and so at capacity factors above 64% it is the cheapest option. At 80% capacity factor, nuclear fuel costs are EUR 2.36 c/kWh, gas 2.69, coal 2.54 and peat 3.26. At 90% (Finland's norm for nuclear plants) the nuclear advantage increases to 2.15 c/kWh compared with 2.41 for coal and 2.61 for gas. Gas is cheapest only below about 55% capacity. A real interest rate of 4.5% was used in the study.

The Finnish study also quantified fuel price sensitivity to electricity costs:



These show that a doubling of fuel prices would result in the electricity cost for nuclear rising about 9%, for coal rising 31% and for gas 66%. These are similar figures to those from a 1992 OECD report. Gas prices have already risen significantly since the study.

Other figures suggest that a doubling of respective raw fuel prices increases the electricity cost about 5-7% for nuclear and about 70% for gas.

The industry continues to invest and develop new reactor designs in order to improve both safety margins and economic performance. Much progress has been made towards licensing these in the USA and Japan, BNFL's Westinghouse subsidiary has been active in this, and recently an innovative development of an earlier design has been in the news – the Pebble Bed Modular Reactor (PBMR), with production costs projected at a little over 1.6 Euro c/kWh. See also section above on Advanced Reactors.

The long-term sustainability of energy resources

Harnessing renewable energy is an appropriate first consideration in sustainable development, but it cannot be the only option. We can certainly make much more use of solar energy, for direct application (hot water etc) and for conversion to electricity. The fact that we can enjoy our summer holidays in the sun testifies to its low intensity, while bad weather and night-time underline its short-term unreliability. It is these two aspects which provide the challenge. And it is a technological challenge of some magnitude to collect energy at a peak density of about one kilowatt per square metre when the sun is shining and then apply it to the kind of electricity demand which exists, much of it for relatively continuous and large-scale supply. Solar and wind are clearly incapable of meeting this kind of demand reliably.

Beyond renewables it is a question of what is most abundant and least polluting. Today, to a degree almost unimaginable even 25 years ago, there is an abundance of many energy sources in the ground. Coal and uranium (not to mention thorium) are available and unlikely to be depleted this century. Uranium is even available from sea water at costs which would have little impact on electricity prices. In any case the resource can be multiplied 60 to one hundredfold by adopting the kind of technology which our postwar forebears thought would be necessary by now, - fast neutron reactors. The next section considers uranium availability.

The criteria for any acceptable energy supply will continue to be cost and safety, the latter including environmental effects. Grappling with those environmental effects has cost implications, as the current greenhouse debate makes clear. But low-cost electricity with acceptable safety and low environmental impact will depend substantially on harnessing and deploying reasonably sophisticated technology.

Manufacturing high-efficiency solar cells is not a cottage industry, nuclear energy has obvious high-tech requirements for reliability and safety, and even coal-burning becomes a high-tech operation under efficiency and greenhouse constraints.

Fuel cells, which promise so much in extending the utility of solar energy collection, are at an early stage of technological development with substantial R&D input still required. Certainly they promise to be an important technology of the future, but insofar as they depend on hydrogen fuel, that will need to be made from water if carbon emissions are to be avoided, and so a very large increase in electricity demand is foreseeable. However, this electricity need not be continuous base-load supply, and solar or wind generation may well serve the purpose to some degree, since hydrogen can be accumulated and stored. The safety implications of a hydrogen economy (such as might maximise the use of fuel cells) still need to be addressed in the public arena.

Uranium availability

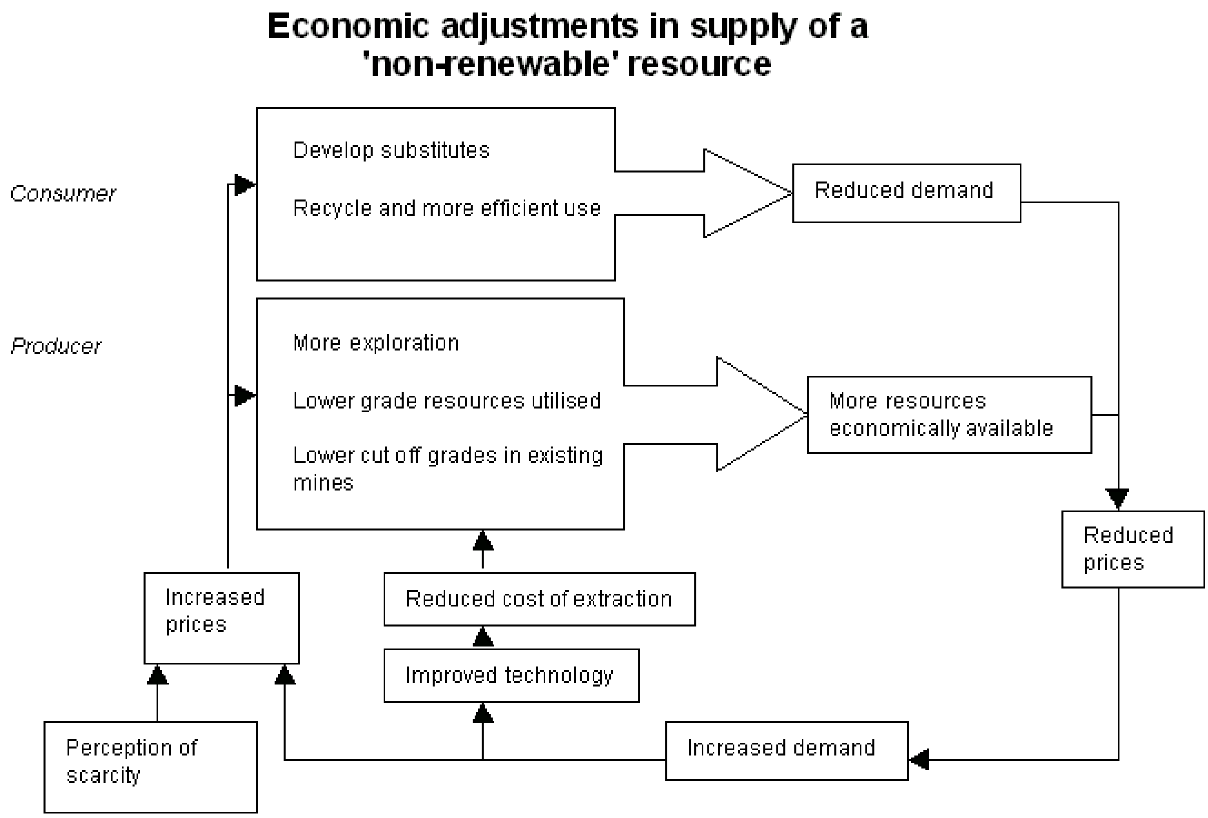
Uranium is ubiquitous on the earth. It is a metal approximately as common as tin or zinc, and it is a constituent of most rocks and even of the sea. Some typical concentrations are:

High-grade orebody	2% U,	20,000 ppm U
Low-grade orebody	0.1% U,	1,000 ppm U
Granite		4 ppm U
Sedimentary rock		2 ppm U
Average in earth's continental crust		1.4 ppm U
Seawater		0.003 ppm U

(ppm = parts per million).

An orebody is, by definition, an occurrence of mineralisation from which the metal is economically recoverable. It is therefore relative to both costs of extraction and market prices. At present neither the oceans nor any granites are orebodies, but conceivably either could become so if prices were to rise sufficiently.

Measured resources of uranium, the amount known to be economically recoverable from orebodies, are thus also relative to costs and prices. They are also dependent on the intensity of exploration effort. Changes in costs or prices, or further exploration, may alter measured resource figures markedly. Thus, any predictions of the future availability of any mineral, including uranium, which are based on current cost and price data and current geological knowledge are likely to be extremely conservative. The following diagram illustrates the dynamic interactions involved:



With the above major qualifications the following Table gives some idea of our present understanding of uranium resources. It can be seen that Australia has a substantial part (about 27 percent) of the world's low-cost uranium, and Canada 15 percent.

World Uranium Resources (known and recoverable)

	tonnes U	percent of world
Australia	754,000	27%
Kazakhstan	474,000	17%
Canada	433,000	15%
South Africa	300,000	11%
Namibia	240,000	8%
Brazil	197,000	7%
Russian Fed.	133,000	5%
USA	106,000	4%
Uzbekistan	106,000	4%
World total	3,002,000	

Reasonably Assured Resources plus Estimated Additional Resources - category 1, to US$ 80/kg U, at 1/1/99. Brazil, Kazakhstan and Russian figures above are 75% of in situ totals.
Uranium: Resources, Production and Demand 1999, OECD NEA & IAEA, July 2000.

The world's present measured resources of uranium, in the lower cost category and used only in conventional reactors, are enough to last for well over 45 years. This represents a higher level of assured resources than is normal for most minerals. Further exploration and higher prices will certainly, on the basis of present geological knowledge, yield further resources as present ones are used up. A doubling of price from present levels could be expected to create about a tenfold increase in measured resources.

Widespread use of the fast breeder reactor could increase the utilisation of uranium sixty-fold or more. This type of reactor can be started up on plutonium derived from conventional reactors and operated in closed circuit with its reprocessing plant. Such a reactor, supplied with natural uranium for its "fertile blanket", very quickly reaches the stage where each tonne of uranium in ore yields 60 times more energy than in a conventional reactor.

Reactor Fuel Requirements

The world’s power reactors, with combined capacity of some 350 GWe, require about 62,000 tonnes of uranium from mines (or the equivalent from stockpiles) each year. While this capacity is being run more productively, with higher capacity factors and reactor power levels, the uranium fuel requirement is increasing but not necessarily at the same rate. The factors increasing fuel demand are offset by a trend for higher burnup of fuel and other efficiencies, so demand is steady. (Over the 18 years to 1993 the electricity generated by nuclear power increased 5.5-fold while uranium used increased only just over 3-fold.) It is likely that the annual uranium demand will grow only slightly to 2010.

Fuel burnup is measured in MW days per tonne U (MWd/t), and many countries are increasing the initial enrichment of their fuel (eg from 3.3 to 4.0% U-235) and then burning it longer or harder to leave only 0.5% U-235 in the fuel. This might mean that burnup is increased from 33,000 MWd/t to 45,000 MWd/t. On the other hand low uranium prices mean that enrichment plants are being operated so as to reduce energy requirements and leave more U-235 in the enrichment tails.

Reprocessing of spent fuel from conventional light water reactors also utilises present resources more efficiently, by a factor of up to 1.3 overall.

Nuclear Weapons as a source of fuel

An increasingly important source of nuclear fuel is the world's nuclear weapons stockpiles. Since 1987 the United States and countries of the former USSR have signed a series of disarmament treaties to reduce the nuclear arsenals of the signatory countries by approximately 80 percent by 2003.

The weapons contain a great deal of uranium enriched to over 90 percent U-235 (ie about 25 to 100 times the proportion in reactor fuel). Some weapons have plutonium-239, which can be used in diluted form in either conventional or fast breeder reactors. From 2000 the dilution of 30 tonnes of military high-enriched uranium is displacing about 11 000 tonnes of uranium oxide per year from mines, representing about 17% of the world's reactor requirements.

Details of the utilisation of military stockpiles are available in WNA Information paper on *Military Warheads as a Source of Nuclear Fuel.*

Thorium as a nuclear fuel

Today uranium is the only fuel supplied for nuclear reactors. However, thorium can also be utilised as a fuel for CANDU reactors or in reactors specially designed for this purpose. Neutron-efficient reactors, such as CANDU, are capable of operating on a thorium fuel cycle, once they are started using a fissile material such as U-235 or Pu-239. Then the thorium (Th-232) captures a neutron in the reactor to become fissile uranium (U-233), which continues the reaction.

The thorium fuel cycle has some attractive features, though it is not yet in commercial use. It is outlined further in WNA Information paper on *Thorium*. Thorium is about three times as abundant in the earth's crust as uranium.

Energy security

Particularly from a national perspective, the security of future energy supplies is a major factor in assessing their sustainability. Whenever objective assessment is made of national or regional energy policies, security is a priority. France's decision in 1974 to expand dramatically its use of nuclear energy was driven primarily by considerations of energy security, though their economic virtues have since become more prominent.

Where fuel supplies are not indigenous, security relates to many factors including abundance, cost, diversity of sources, political relationships, distance from sources, ability to stockpile several years supply if desired, and whether alternatives can be quickly deployed within Europe (eg substituting gas or LPG for oil).

Nuclear energy rates very highly on any likely combination of the above factors.

Opportunity costs

Nuclear energy and renewables have one important feature in common: they give us access to virtually limitless resources of energy with negligible opportunity cost, - we are not depleting resources useful for other purposes. Of course minimising opportunity cost would be very difficult if we preferred to "leave uranium in the ground", as sometimes urged. The question of the technologies involved and our willingness to harness them is central, whatever the preferred course.

Even more fundamental is the ethical consideration of resources, and opportunity costs. What preference should be given to utilising abundant rather than less abundant energy resources?

Those with no significant other uses rather than those which are versatile? Those with least environmental impact from wastes?

Any attempt to answer these from a future-oriented perspective is likely to reaffirm the desirability of utilising renewable energy sources, and it may also suggest that the time is not far off when fossil carbon-based fuels are too valuable to burn on the scale we have been doing.

Recent analyses fail to come up with any 50-year scenario aligned with Sustainable Development principles which does not depend significantly on nuclear fission for large-scale, high energy-intensive needs, along with renewables for small-scale (and especially dispersed) low-intensity needs. The alternative to such a dual approach is either squandering fossil carbon resources or denying the aspirations of many billions of people in our grandchildren's generation.

Nuclear energy's detractors have yet to credibly suggest where the bulk of our future electricity will come from. Certainly all the reputable energy scenarios show the main load being carried by coal, gas, and nuclear, with the balance among them depending on economic factors in the context of various levels of greenhouse constraints.

The notion of sustainability may be expected to assert itself politically before it starts to drive the economics of fuel choice for electricity production in the way that has been seen with oil in the last three decades. The sooner substantial solar and wind capacity is operating on grid systems the sooner their advantages and limitations will become widely evident. That will help focus the public discussion on the real options for base-load electricity.

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Appendix.

Summary of Nuclear Power Reactors

COUNTRY	Nuclear generation 2000		REACTORS OPERATING at Sept 2001		REACTORS BUILDING* at Sept 2001		REACTORS ON ORDER or PLANNED		TOTAL REACTORS	
	TWh	%	No.	MWe	No.	MWe	No.	MWe	No.	MWe
Argentina	5.7	7.3	2	935	1	692	0	0	3	1627
Armenia	1.8	33	1	376	0	0	0	0	1	376
Belgium	45	57	7	5728	0	0	0	0	7	5728
Brazil	5.6	1.5	2	1855	0	0	0	0	2	1855
Bulgaria	18	45	6	3538	0	0	0	0	6	3538
Canada*	69	12	14	9998	6	3598	0	0	20	13596
China	16	1.2	3	2167	8	6370	2	1800	13	10337
Czech Rep.	13.6	19	5	2560	1	912	0	0	6	3472
Egypt	0	0	0	0	0	0	1	600	1	600
Finland	21	32	4	2656	0	0	1	1000	5	3656
France	395	76	59	63203	0	0	0	0	59	63203
Germany	160	31	19	21141	0	0	0	0	19	21141
Hungary	15	42	4	1755	0	0	0	0	4	1755
India	14	3.1	14	2548	2	900	11	4980	27	8428
Indonesia	0	0	0	0	0	0	1	600	1	600
Iran	0	0	0	0	1	950	1	950	2	1900
Japan	305	34	54	44301	3	3696	12	15858	69	63855
Korea DPR (N)	0	0	0	0	0	0	2	1900	2	1900
Korea RO (S)	104	41	16	12970	4	3800	8	9200	28	25970
Lithuania	8.4	74	2	2370	0	0	0	0	2	2370
Mexico	7.9	3.9	2	1364	0	0	0	0	2	1364
Netherlands	3.7	4	1	452	0	0	0	0	1	452
Pakistan	1.1	1.7	2	425	0	0	0	0	2	425
Romania	5.1	11	1	655	1	620	0	0	2	1275
Russia	120	15	30	20793	3	2625	5	4050	38	27468
Slovak Rep.	16	53	6	2472	2	840	0	0	8	3312
Slovenia	4.5	37	1	679	0	0	0	0	1	679
South Africa	13	6.7	2	1842	0	0	0	0	2	1842
Spain	59	28	9	7345	0	0	0	0	9	7345
Sweden	55	39	11	9460	0	0	0	0	11	9460
Switzerland	24	36	5	3170	0	0	0	0	5	3170
Taiwan	37	24	6	4884	2	2600	0	0	8	7484
Ukraine	72	47	13	11195	2	1900	0	0	15	13095
UK	78	22	33	12528	0	0	0	0	33	12528
USA	754	20	104	98060	0	0	0	0	104	98060
=										
WORLD	**2,447**	**16**	**438**	**353,425**	**36**	**29,503**	**44**	**40,938**	**518**	**423,866**

Source: Reactor data: ANSTO, based on information to 1 Sept 2001,
% e = % of total electricity from nuclear (source: IAEA)
Operating = Connected to the grid; Construction = First concrete poured;
Planned = Relatively firm plans. Mwe: nett
** Canadian construction figures are for 4 laid up Pickering A reactors likely to re-enter service by 2003, plus two Bruce A units which are very likely do so later.*