

The Future of Nuclear Energy

The future of nuclear energy depends on the interplay between four factors – growth in energy demand, cost-competitiveness with other fuel sources, environmental considerations, and questions of public attitude and perception.

Depending on the satisfactory resolution of these factors and on technical advances, many new and enlarged applications of nuclear energy can be envisaged, including hydrogen production, seawater desalination and expanded production of isotopes for medical purposes.

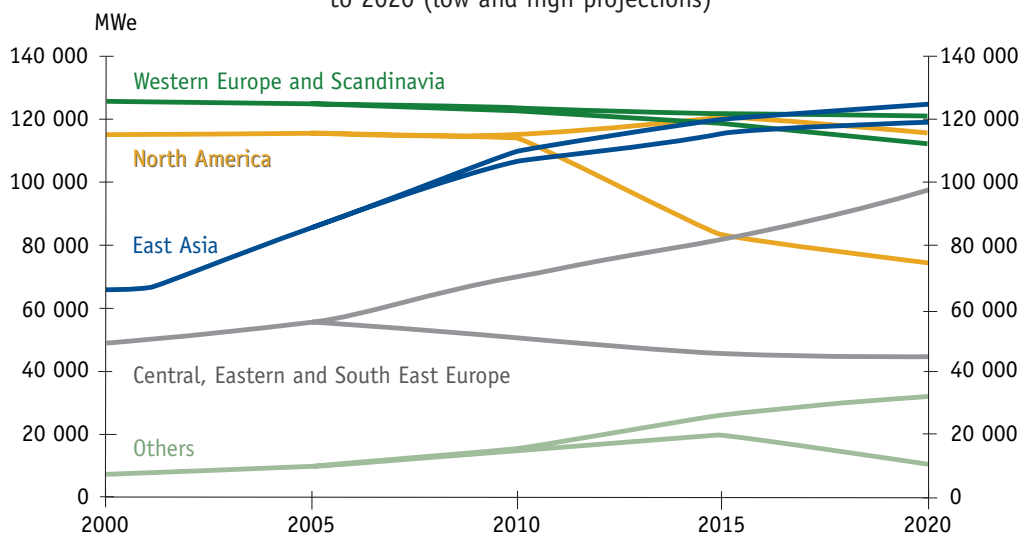
Much research is under way to develop these potential applications and to improve the performance of nuclear energy systems.



At the end of 2000, world nuclear generating capacity represented about 17% of the world's electricity. Most of this capacity had, however, already been installed by 1990 (see Figure 1.1). Since then, though new plants continue to come online, there have also been withdrawals due to the ageing of existing plants, and very little net capacity has been added. Capacity forecasts by

national governments suggest a fairly stable picture up to and perhaps beyond 2020, with projections of installed nuclear capacity ranging between 334 and 466 GWe, compared with 362 GWe at present. Figure 10.1 shows, however, the considerable regional variations implicit in these projections. In Western Europe at least, it will only be a matter of time before a gradual

Figure 10.1: Projected installed nuclear generating capacity to 2020 (low and high projections)



Source: NEA. *Uranium 2001: Resources, Production and Demand* (Paris: OECD, 2002).

Where will future nuclear plants be built?

- As of January 2003, there were 33 reactors under construction in 10 countries: India (8), China (6), Republic of Korea (4), Ukraine (4), Japan (3), Islamic Republic of Iran (2), Russia (2), Slovak Republic (2), Argentina (1) and Romania (1).
- There are 26 reactors firmly committed or planned for construction in OECD countries, 24 of which are in Japan and the Republic of Korea.
- When its parliament voted on 24 May 2002, Finland became the first country in Western Europe in over ten years to authorise the construction of a new nuclear reactor.
- Though not yet formally committed, the United States government is working with utilities to plan for new nuclear power plants, with construction beginning before 2005.
- Conversely, Belgium and Germany have committed to phasing out nuclear power over the next several years.

reduction in installed capacity begins to take place, based on present trends and despite the increasing longevity of the existing stock. The Far East, by contrast, is experiencing strong growth that is projected to continue, with China, the Republic of Korea and Japan all building multiple plants. Eastern Europe – particularly Russia and Ukraine – are experiencing strong growth, though planned retirements of older plants in other countries will offset these gains. The outlook in North America is uncertain with a significant re-evaluation of nuclear energy under way, the results of which remain unclear.

For reasons discussed earlier in this book, the future course of nuclear energy depends on factors that are particularly hard to predict, including public attitudes. If the equation consisted only of economic factors with no change in current attitudes, nuclear energy's characteristic high construction and low generating costs could lead, in a deregulated and highly competitive market, to a situation where existing plants are run profitably to exhaustion and not replaced. However, increasing world energy demand will continue to require decisions on building new power plants and this limiting scenario could, then, be shifted positively or negatively, by other factors such as:

- environmental considerations, depending on the extent that nuclear energy is seen to be beneficial in meeting greenhouse gas reduction targets;
- concerns about security of fuel supplies;
- concerns about the proliferation of nuclear weapons;
- the cost-competitiveness of new nuclear power plants with other fuel sources, including "renewable" energy sources;
- public attitudes towards the safety of nuclear energy and proposed waste disposal plans;
- the extent that advanced technologies can alter the relative competitiveness of the various energy sources.

Alternative uses of nuclear energy

So far, nuclear energy has been applied almost exclusively to the production of electricity. There are other potential uses and the extent to which these other uses become important will also influence the future of nuclear energy.

Hydrogen production

Hydrogen is already an important industrial commodity with an annual world consumption of some 45 million tonnes. Its uses are primarily in the production of chemicals, fertiliser and in oil refining, where demand for it is expected to increase significantly as high quality oil stocks diminish and cleaner fuels are mandated.

Hydrogen also has a large potential as a "clean" fuel in its own right. A great deal of research is currently taking place on the possibility of hydrogen replacing carbon fuels used in motor vehicles – currently the fastest expanding component in world energy demand. If this were to prove successful, the demand for hydrogen would expand dramatically. However, its production currently involves the use of natural gas, itself a carbon-emitter. Before it can pass the "sustainability" test, and notwithstanding its inexhaustible availability, more economic methods for producing hydrogen directly from water without using carbon fuels are required.

Nuclear energy could become an important source of "sustainable" hydrogen either through producing the necessary high-temperature heat, or through electricity. The NEA report on *Nuclear Production of Hydrogen* (2001) concluded that:

Nuclear production of hydrogen holds the potential to significantly contribute to the global energy supply of the 21st century. Production of hydrogen through water-cracking and through nuclear-assisted conversion of fossil feedstock is technically feasible and could provide energy in a way that would diminish global greenhouse gas production.

Several types of high-temperature reactor could provide the near-1 000 °C temperatures necessary for the direct production of hydrogen, such as high-temperature gas reactors or molten metal reactors. Research and development into the use of nuclear energy to produce hydrogen is being conducted in a number of countries and through several international agencies, including the NEA and the IAEA, which are tracking and supporting this potentially important future role for nuclear energy.

Seawater desalination

Fresh water of the requisite quality is essential to life. In many parts of the world, particularly in

Africa, Asia and the Middle East, there is increasing difficulty in meeting growing demands from agriculture, industry, urban development and growing population.

The purification of seawater requires considerable heat, and nuclear-powered desalination plants are already operating in Japan and the United States. These mainly provide pure water for onsite uses rather than large-scale consumption. They have nevertheless successfully demonstrated that, as the demand for desalination grows, nuclear energy is a viable alternative to fossil fuels as the heat source. Argentina, China, India, Morocco, Pakistan, the Republic of Korea, and the Russian Federation have shown interest in this possibility.

Process and district heating

One application of nuclear energy that has existed from the outset and has the potential to grow in future is to use reactor heat to produce hot water or steam for industrial or residential heating purposes – usually, but not necessarily, in conjunction with the generation of electricity. Significant experience in this use of nuclear energy has been gained in Bulgaria, Canada, China, Germany, Hungary, Japan, Kazakhstan, the Russian Federation, the Slovak Republic, Switzerland, Ukraine and the United States. About 1% of the heat generated in **nuclear reactors** worldwide is applied in this way, and the development of small or medium-sized reactors especially for heat production could stimulate further growth. This

possibility is being pursued in China and the Russian Federation.

Isotope production

Both radioactive and stable **isotopes** are very widely used, particularly in medicine, industry, agriculture, food processing and research. In 2000, isotopes were produced by more than 70 research and power reactors in over 60 countries.

In many applications, isotopes have no substitute and in most, they are more effective and cheaper than alternatives. So far they have principally been produced as by-products of research activity, but a number of purpose-built isotope production reactors are now planned or under construction. A brief look at representative uses will illustrate their importance and diversity.

Medical applications

Isotopes have been routinely used in medicine for over thirty years, and are now applied in over 30 million critical medical procedures annually worldwide. They are used extensively in the detection of tumours and a wide variety of other ailments (e.g. cardiological diseases) through diagnostic gamma-imaging cameras. The primary isotope for these purposes is reactor-produced **technetium-99**.

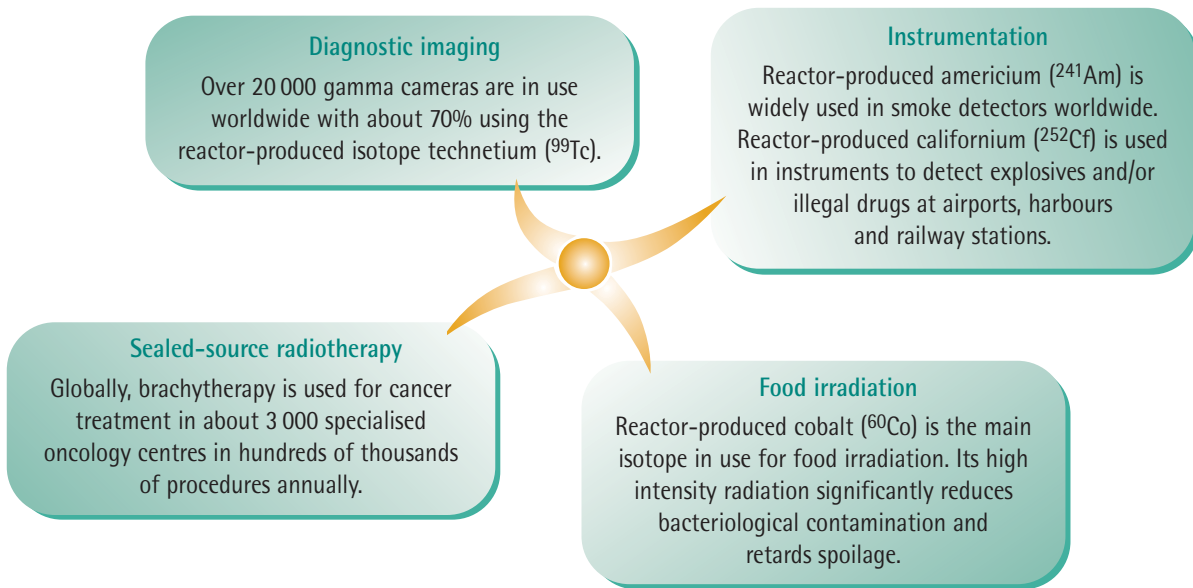
In therapy, the implantation in the body of sealed radioactive sources (brachytherapy) has been used to treat cancers of the cervix, uterus, breasts, lung, pancreas, prostate and oesophagus. The important isotopes for this purpose are reactor-produced iodine (^{125}I) and palladium (^{103}Pd).

At the beginning of the 21st century over 1.2 billion people do not have access to safe drinking water. Ministerial Declaration, International Conference on Fresh Water, Bonn, December 2001.



A positron emission tomography (PET) imaging device used in medical applications.

Figure 10.2: Various uses of reactor-produced isotopes



Agriculture and industry

Industry is a large user of isotopes, principally in instrumentation and process equipment. The applications include analytical and security instrumentation, pollution measurement, physical measurement, food irradiation and non-destructive testing. Food irradiation has been successfully applied to spices, fruit, grains, meat, fish and poultry-meat. Among others, the World Health Organisation, the UN Food and Agriculture Organisation and the US Food and Drug Administration have endorsed it; the number of countries allowing it as a means to improve the safety and nutritional value of food is increasing.

Trends in isotope uses

Trends in isotope uses are not easily defined as they vary from sector to sector as well as from region to region, with some isotopes declining in importance while others increase. In the medical

field, as a whole, isotopes are increasingly used in an ever-widening range of applications. Trends vary, however, for each specific application. For example, remotely controlled cobalt therapy is projected to progressively decrease while the use of isotopes in brachytherapy is projected to sharply increase. The development of new applications, such as palliative care, create additional demand for isotopes already in use as well as demand for new isotopes.

For industrial applications as a whole, the demand for isotopes is relatively stable. However, if food irradiation becomes widespread it would create a demand for large volumes of radioactive cobalt.

Given that many of these isotopes are capable of being produced in accelerators, it is difficult to predict how changes in isotope demand will be reflected as a need for new reactor-based production capability.

Research and development

Research and development (R&D), which has throughout its existence been central to all applications of nuclear energy, has been the cause of many important advances in human knowledge. Among many areas of R&D interest, three dominant themes are now apparent: advanced reactors and fuel cycles; advanced treatments for waste; and support for safe operation. Research is conducted by academics, governments (including regulatory authorities) and industries, either singly or in combination, and with a growing emphasis on international collaboration in nuclear R&D.

Advanced reactors and fuel cycles

Light water reactors (LWR) are now essentially mature technologies. Consequently, in the near term, new reactor designs under development represent an evolution of existing concepts, in order to improve safety, operational economy and flexibility. Several improved designs likely to be ready for commercial development by or before 2015 include:

- new boiling water reactor (BWR) designs, including the advanced boiling water reactor (ABWR), two of which have already been built

in Japan, plus the BWR 90+ and the simplified water reactor (SWR) 1000;

- advanced pressurised water reactors, such as the AP600, already approved by regulatory authorities in the United States, with its upsized 1 000 MWe version now under regulatory review, plus the European pressurised water reactor (EPR) and the "international reactor, innovative and secure" (IRIS);
- gas-cooled designs, including the pebble bed modular reactor (PBMR) and the gas turbine, modular helium reactor.

For the long term, the focus is on more innovative nuclear energy technologies and fuel cycles. Concepts under investigation include liquid-metal reactors, high-temperature reactors, reactors that use thorium as fuel, and improved recycling technologies to better utilise the uranium and plutonium resources. These advanced technologies offer the promise to greatly improve the sustainability of nuclear energy. For example, fast breeder reactors can, in principle, improve the effectiveness of using uranium resources by about 50-fold (see table 10.1).

Two important international projects, described hereafter, are seeking to make advancements in nuclear energy systems and fuel cycles.

Table 10.1: Effect of technology advances on resource availability¹

Reactor/fuel cycle	Years of electricity production	
	Conventional uranium & thorium resources only	Total uranium & thorium resources
Current fuel cycle (LWR, once-through)	326	8 350
Recycling fuel cycle (plutonium only, one recycle)	366	9 410
Light water and fast reactor mixed with recycling	488	12 500
Pure fast reactor fuel cycle with recycling	10 000	250 000
Advanced thorium/uranium fuel cycle with recycling	17 000	35 500

1. Assumes 1999 world electricity generation from *Key World Energy Statistics* (Paris: IEA, 2001).

Source: "Nuclear Fuel Resources: Enough to Last?", *NEA News*, No. 20.2 (2002).

NEA Nuclear Safety R&D Projects (as of January 2003):

The **CABRI Water Loop Project** investigates the ability of high-burnup fuel to withstand sharp power peaks.

The **FIRE Project** aims to improve knowledge relating to fire events in nuclear environments.

The **Halden Reactor Project** conducts experiments related to improving fuels and operational safety.

The **International Common Cause Failure Data Exchange** seeks to improve knowledge on important safety system components.

The **MASCA Project** investigates reactor vessel phenomena during a severe accident.

The **Melt Coolability and Concrete Interaction (MCCI) Project** addresses phenomena related to a hypothetical molten core.

The **OECD Pipe Failure Data Exchange (OPDE) Project** investigates the root causes of pipe failures.

The **SETH Project** involves experiments related to nuclear accident management.

Generation IV International Forum

This effort was started at the end of 2000 as a collaboration of interested governments, industry and the research community in an attempt to develop and demonstrate one or more advanced nuclear systems that could be commercially deployed by 2030 ("fourth generation" nuclear systems). The objective is to make advances over existing systems in the areas of economy; safety and reliability; sustainability; and proliferation resistance and physical protection. At the beginning of 2003, the members of the group were Argentina, Brazil, Canada, France, Japan, the Republic of Korea, South Africa, Switzerland, the United Kingdom and the United States.

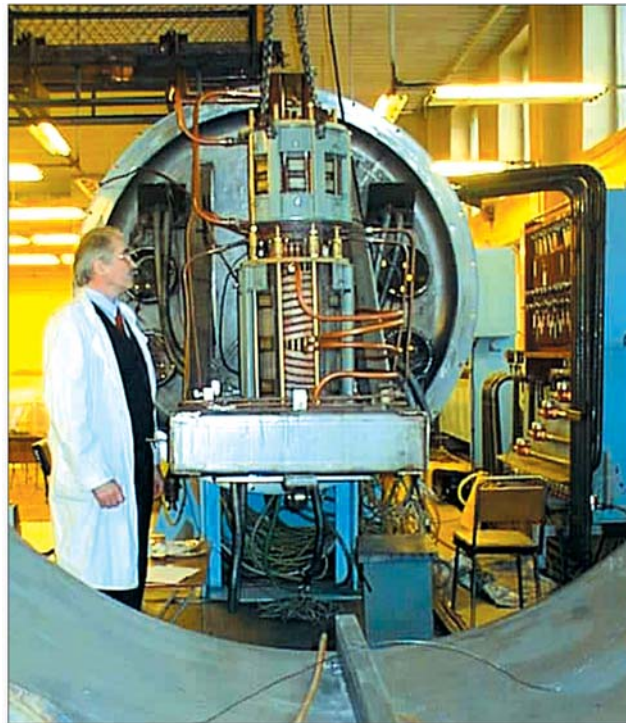
In October 2002, six nuclear energy system concepts were selected to be the focus for collaborative R&D. The concepts include: a sodium-cooled fast reactor, a very-high-temperature reactor, a supercritical-water-cooled reactor, a lead-cooled fast reactor, a gas-cooled fast reactor and a molten salt reactor. All but one of these concepts involve recycling spent nuclear fuel.

International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)

This international collaboration, initiated and supported by the IAEA, was launched in 2001 with the stated objective of supporting the safe, sustainable, economic and proliferation-resistant use of nuclear technology to meet the global energy needs of the 21st century. At the beginning of 2002 the members of the initiative included the European Commission, Argentina, Canada, China, Germany, India, the Netherlands, the Russian Federation, Spain, Switzerland and Turkey.

Advanced treatment of waste

A fairly new approach that has the potential to change the nature of the wastes that will require geological disposal is **partitioning and transmutation (P&T)**. This process involves the **transmutation** of long-lived radionuclides into shorter-lived ones through **neutron capture** or **fission**, thereby eliminating those parts of high-level waste that contribute most to its heat generation and **radioactivity**. Partitioning and



View of the RASPLAV cylindrical wall facility during the preparation for the MASCA experimental programme.

transmutation therefore has the potential to reduce the time that waste needs to be kept isolated from several thousand to several hundreds of years – i.e. to periods that are within human experience, thereby reducing the uncertainties associated with predicting repository performance. However, sufficient conversion of the longer-lived isotopes to achieve these aims would require many stages of P&T and a fully developed [reprocessing fuel cycle](#). Therefore, solutions along these lines seem a long way off.

The approaches to P&T that are being researched vary according to each country's fuel cycle practices and policies, but are similar enough to encourage collaboration. The main lines of the research are advanced separation technologies, to better remove the [fission products](#) and transuranic elements from spent fuel, and the use of accelerator-driven and reactor systems for transmutation.

Numerous countries including Belgium, China, France, Italy, Russia and the United States are investigating these research areas. Small-scale collaborative efforts currently involve France, Japan, the Republic of Korea, the United States and the European Commission.

[Nuclear safety R&D](#)

In addition to the R&D aimed at making advances in nuclear technologies, there have always been and continue to be both national and international programmes to support the safe operation of nuclear power plants. At the international level, the NEA manages a number of research projects, for example the Halden Reactor Project in Norway. This project has been in operation for over 40 years and is supported by approximately 100 organisations in 20 countries. Research is conducted on, among other things, fuels and materials, the improvement of plant performance and operational safety.

[Other international R&D](#)

The European Union, through the European Commission and its Joint Research Centre (JRC), sponsors and conducts numerous research projects in support of its member states' programmes. Research related to nuclear energy is conducted at four of the seven JRC centres. Thus, the Institute for Reference Materials and

Measurements (IRMM) at Geel, Belgium, conducts measurements of neutron interactions with materials, including high resolution cross-section measurements. The Institute for Transuranium Elements (ITU) at Karlsruhe, Germany, conducts research related to alpha-immunotherapy, basic actinide research, safety of nuclear fuel, spent fuel characterisation, and partitioning and transmutation. The Institute for Energy (IE) at Petten, the Netherlands, conducts research related to nuclear safety, development of new nuclear energy systems and nuclear medicine. Finally, the Institute for the Protection and Security of the Citizen (IPSC) at Ispra, Italy, conducts research related to non-proliferation and nuclear safeguards.

The IAEA also sponsors other nuclear R&D through its Co-ordinated Research Programme in nuclear energy, radioactive waste safety, waste technology and safeguards.

Partitioning is the separation of undesirable elements, i.e. minor actinides and long-lived fission products, from spent nuclear fuel. **Transmutation** is the changing of one element into another through neutron capture or fission. It can be used to transform these undesirable elements into short-lived or stable elements.

For further information

See the references listed below provided in the "For Further Information" section for more in-depth information on:

- [Projections](#) of future nuclear energy capacities and related uranium resources and demand, see 1.1 and 9.3.
- [Hydrogen](#) as an energy carrier and nuclear energy as a source of hydrogen, see 10.1 through 10.4.
- [Alternative uses](#) of nuclear energy including desalination and process heat, see 10.4.
- [Production and uses of isotopes](#), see 10.5.
- [Advanced reactor types](#), see 10.6 through 10.8.
- [Several international nuclear energy research programmes](#) including the Generation IV International Forum and INPRO as well as other interesting links, see 10.9 and 10.10.
- [Advanced treatments of high-level waste](#), see 10.11.