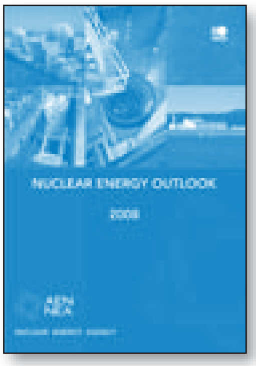
Nuclear Energy Outlook 2008



To celebrate its 50th anniversary, the OECD Nuclear Energy Agency launched its first *Nuclear Energy Outlook* (NEO). It responds to the changing dynamics and renewed interest in nuclear energy and arrives at a moment when energy security, climate change and the cost of energy have become priorities in both short-term and long-term energy policies.

Using the most current data and statistics available, the NEO provides projections up to 2050 to consider growth scenarios and potential implications on the future use of nuclear energy. It also offers unique analyses and recommendations on the possible challenges that lie ahead.

Topics covered by the NEO include:

- nuclear power's current status and projected trends;
- environmental impacts;
- uranium resources and security of supply;
- costs, safety and regulation;
- radioactive waste management and decommissioning;
- non-proliferation and security;
- legal frameworks;
- infrastructure;
- stakeholder engagement;
- advanced reactors and advanced fuel cycles.

The publication is available in English and French and can be purchased online at www.oecdbookshop.org. A Japanese translation will be available shortly.

NEO Executive Summaries can be downloaded free of charge from the NEA website (www.nea.fr/neo) in Chinese, English, French, German, Hungarian, Italian, Japanese, Korean, Russian and Spanish.

We are pleased to offer readers a copy of the Executive Summary in English in the pages that follow.

Nuclear Energy Outlook 2008

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Key messages

Balancing growth of world energy demand with its resulting environmental, social and political impacts

Balancing energy requirements for continued social and economic progress against the potential resulting environmental and socio-political impacts is widely acknowledged to be a significant global challenge in the 21st century. By 2050, global electricity demand is expected to have increased by about a factor of 2.5.

Energy, and particularly electricity, is essential for economic and social development and for improved quality of life, but the last century's global trend in energy supply is generally recognised as being unsustainable. The world faces environmental threats from climate change caused by anthropogenic CO_2 emissions and socio-political threats from rising energy prices and the possible lack of secure energy supplies.

- Electricity generation accounts for about 27% of global anthropogenic CO_2 emissions and is by far the largest and fastest-growing source of greenhouse gases.
- Security of supply has become a major concern around the world, particularly for countries that have limited indigenous fossil fuel resources and are therefore dependent on imported energy.

In "business-as-usual" scenarios, strong economic growth in many developing countries, leading to a more energy-consuming lifestyle, and the projected 50% increase in the world population, primarily in the developing regions, are the drivers for growing energy demand. Fossil fuel use will continue its inexorable rise to meet this increase unless governments' energy policies change worldwide. Nuclear energy has a potentially strong role to play in alleviating these problems.

Current and likely future contributions to global energy supply from nuclear power

In 2006, nuclear energy supplied 2.6 billion MWh: 16% of the world's electricity and 23% of electricity in OECD countries.

- In June 2008, there were 439 nuclear reactors operating in 30 countries and one economy, with a total capacity of 372 GWe.
- France, Japan and the United States have 57% of the world's nuclear generating capacity; in 2007, sixteen countries relied on nuclear energy to generate over a quarter of their electricity.

In June 2008, 41 nuclear power reactors were under construction in 14 countries and one economy; average construction times of 62 months are consistently being achieved in Asia; of the 18 units connected to the grid between December 2001 and May 2007, three were constructed in 48 months or less.

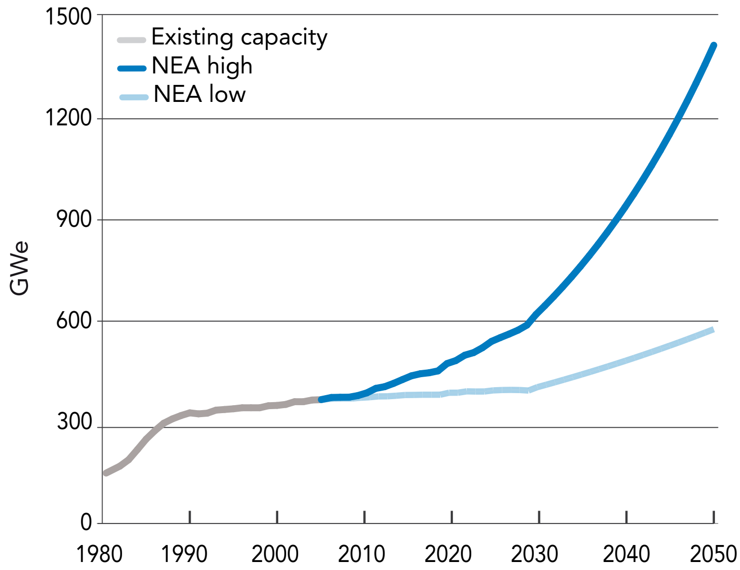
Current national plans and authoritative statements of intent suggest that the countries having the largest installed nuclear capacity in 2020 will be the United States, France, Japan, the Russian Federation, China and Korea. China and the United States plan the largest increases in capacity.

The NEA has projected global nuclear capacity to 2050 using low and high scenarios. The outcome is:

- By 2050, global nuclear capacity is projected to increase by a factor of between 1.5 and 3.8.
- Under the high scenario, the nuclear share of global electricity production would rise from 16% today to 22% in 2050.
- Under both scenarios, nuclear generation would continue to be heavily based in the OECD countries.
- Although a number of countries currently without nuclear power have plans to join the nuclear energy community, they are likely to add only about 5% to global installed nuclear capacity by 2020.

These projections are in broad agreement with those from other organisations. Historic evidence suggests that the world could construct nuclear power plants at a rate more than sufficient to meet the NEA high scenario projections during the period up to 2050.

Projected nuclear capacity in the NEA high and low scenarios



Nuclear energy's role in minimising the negative consequences of growing energy demand

Nuclear energy could play a significant role in avoiding CO_2 emissions, providing greater energy security and reducing the serious health effects that result from fossil fuel combustion.

Climate change

The United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) concludes that CO_2 emissions, including those from electricity generation, must be halved to contain the consequences of climate change at a tolerable level.

- On a whole life cycle basis, nuclear energy is virtually carbon-free.
- A combination of technologies is needed to meet this demanding target, but nuclear energy is the only carbon-mitigating technology with a proven track record on the scale required.
- Nuclear energy could make an increasing contribution to electricity generation, as well as to virtually carbon-free heat in the future; a potentially important development is global R&D aimed at producing hydrogen to fuel the transport sector, using nuclear heat.

Most potential external costs (i.e. those not represented in the price, including the consequences of climate change) have already been internalised for nuclear power, whereas for fossil fuels, external costs are around the same size as direct costs.

Energy security

Nuclear energy is more able than oil or gas to provide security of supply because the fuel – uranium – comes from diverse sources and the main suppliers are operating in politically stable countries.

- Identified uranium resources are sufficient to fuel an expansion of global nuclear generating capacity, without reprocessing, at least until 2050. Based on regional geological data, resources that are expected to exist could increase uranium supply to several hundreds of years.
- A significantly expanded global nuclear energy programme could potentially be fuelled for thousands of years using the currently defined uranium resource base; however, this would require fast breeder reactors, a technology that is well-developed but not yet in commercial operation.
- Uranium's high energy density (1 tonne of uranium produces the same energy as 10 000-16 000 tonnes of oil with current practices) means that transport is less vulnerable to disruption and storage of a large energy reserve is easier than for fossil fuels.

Health effects

Nuclear energy could contribute to reducing the significant health effects that arise from fossil fuel consumption.

- The health effects of operational emissions from nuclear power are negligible compared to those resulting from fossil fuel use.
- Loss of life from the health effects of emissions from burning fossil fuels far outweighs that from accidents involving all sources of energy.
- Comparison of full energy chain frequency/consequence data for real accidents shows that, contrary to popular belief, nuclear energy presents a far lower accident risk than fossil energy sources.

Meeting the challenges to nuclear energy growth

Nuclear energy offers the opportunity of meeting a significant part of the anticipated increase in electricity demand whilst reducing the potential environmental, political and economic concerns associated with fossil fuels. However, a significant fraction of public opinion perceives that the risks of nuclear energy outweigh its advantages. The nuclear industry and governments wishing to use nuclear power need to manage the real and/or perceived issues of safety, waste disposal and decommissioning, non-proliferation and security, and cost.

Safety

Nuclear safety is a global issue: a serious event in one country may have a significant impact on its neighbours; the nuclear industry has, and must keep, safety and environmental protection as its top priorities. Effective regulatory control will continue to be a key requirement.

- The safety performance of nuclear power plants and other nuclear facilities in OECD countries is excellent, as reflected in a number of safety performance indicators. This strong safety record reflects the maturity of the industry and the robustness of the regulatory system.
- The nuclear industry's safety performance has continued to improve over recent decades. Reactors of new designs have passive safety features that can maintain the plant in a safe state, in particular during an unexpected event, without the use of active control.
- The international community has initiatives in progress to increase regulatory effectiveness and efficiency, in view of the growing interest in new nuclear build and the next generation of designs.
- Countries with no previous experience must be helped to institute satisfactory industrial, regulatory and legal practices if they construct nuclear power plants.

Waste disposal and decommissioning

The delay and failure thus far of some major disposal programmes for high-level radioactive waste continue to have a significant negative impact on the image of nuclear energy; governments and the nuclear industry must work together to deliver safe disposal.

- Because disposal of spent nuclear fuel and high-level waste from reprocessing has not yet been implemented, it is thought by some to be technically difficult or even impossible.
- In practice, the volumes of radioactive waste produced are small, the technologies to manage them are available and there is an international consensus that geological disposal of high-level waste is technically feasible and safe.
- A variety of nuclear facilities has been successfully decommissioned, including several US power plants with capacities larger than 100 MWe that have been fully dismantled.
- Waste management and decommissioning costs for nuclear power plants represent only some 3% of overall nuclear electricity generation costs. Funding schemes exist to finance waste and decommissioning liabilities.

Non-proliferation and security

The global nuclear community must work together to prevent the spread of nuclear weapons by states and the malevolent use of radioactive materials by criminal or terrorist groups.

- For nearly four decades the Treaty on the Non-Proliferation of Nuclear Weapons has been the successful legal and political foundation of the international regime for restraining the spread of nuclear weapons.
- Multilateral approaches to the nuclear fuel cycle currently under discussion have the potential to

provide enhanced assurance to the international community that proliferation-sensitive nuclear technologies are kept contained.

- The technical characteristics of advanced nuclear technologies are designed to enhance their resistance to proliferation threats and their robustness against sabotage and terrorism threats.

Cost

On a levelised cost basis, building and operating new nuclear plants is economically viable in most circumstances; however, governments wishing to encourage investment in nuclear plants may need to mitigate the financial risks associated with licensing and planning, and those perceived by the financial community for radioactive waste management and decommissioning.

- A 2005 international comparison of the levelised costs for nuclear, coal and gas power plants showed nuclear to be competitive with coal and gas, with some dependence on local circumstances; since then, oil prices have quadrupled (as of June 2008) with other fossil energy prices following them upwards.
- The cost of uranium amounts to only about 5% of the cost of generating nuclear electricity.
- The economic challenges of nuclear power relate to investment funding rather than the levelised cost of generation.
- Returns from existing nuclear energy investments have in many cases been increased through improved availability, power uprates and licence renewal; world average availability has increased by 10 percentage points in the last 15 years, now reaching 83%. Many plants have been uprated, some by as much as 20%; a significant number of reactors have had lifetimes extended from 40 to 60 years.

Nuclear energy and society

If nuclear energy is to expand, an ongoing relationship between policy makers, the nuclear industry and society that develops knowledge building and public involvement will become increasingly important.

- Surveys show that over half of European Union citizens think that the risks of nuclear power outweigh its advantages.
- However, people are more concerned about some aspects surrounding nuclear energy (radioactive waste, terrorism and proliferation) than about the actual operation of nuclear power plants.
- Increased knowledge of nuclear energy leads to increased levels of support – but most people feel that they have inadequate levels of knowledge.
- Scientists and non-governmental organisations (NGOs) are the most trusted groups to provide information.
- Processes for stakeholder engagement and building public trust are likely to become increasingly important if nuclear energy is to be an accepted part of a country's energy policy.

Developing the technology

The present generation of reactor designs is capable of excellent performance. They will provide the basis for nuclear energy growth for the next two or three decades. International co-operation on both reactor designs and fuel cycles promises even further advances for the future.

Advanced reactors

Future light water reactors – the likely main reactor types until the middle of the century – will be Generation III+ designs with improved safety characteristics and better economics; four Generation III+ reactors are operating now and more are being constructed.

- Future high-temperature gas-cooled reactors – likely to be commercially available around 2020 – can operate at temperatures sufficiently high to produce hydrogen fuel for the transport sector and for other process heat applications.
- Small reactors being designed for developing economies have inherent and passive approaches to safety, especially advantageous in countries with limited nuclear experience; however, the technologies are not yet commercially established.
- Generation IV energy system concepts, for commercial operation after 2030, offer improved proliferation resistance and physical protection; global initiatives aim to support safe, sustainable expansion of competitively priced and reliable nuclear energy that minimises waste production.

- Fusion energy is still at the experimental stage and is not likely to be deployed for commercial electricity production until at least the second half of the century.

Current and advanced fuel cycles

Current practice divides between those countries which reprocess nuclear fuel and those that do not. Of the three countries with the largest nuclear fleets, France and Japan currently reprocess spent fuel and the United States currently does not. Advanced reprocessing cycles are under consideration and development in many countries, including the United States.

- The reprocessing of the spent fuel existing today could provide fuel for about 700 reactor-years in light water reactors. Additional existing potential fuel sources could provide fuel for over another 3 000 reactor-years.
- Fast reactors with closed fuel cycles, such as those considered by the Generation IV International Forum, can be designed to burn existing stocks of plutonium, or to breed plutonium from non-fissile uranium isotopes. In the latter case, the energy extraction from a given quantity of uranium can be multiplied by up to a factor of 60, enabling uranium resources to last for thousands of years.
- Reprocessing also has an advantage for spent fuel management, allowing a significant reduction in the volume of high-level waste requiring geological disposal.
- Advanced fuel cycles hold the promise of commercial scale separation of long-lived isotopes and their re-irradiation to eliminate them. The radioactivity of waste materials arising from spent nuclear fuel would then naturally decay to below that of the uranium from which the fuel was produced within a few hundred years.

Extended summary

Social, political and environmental consequences of the world's energy demand in the 21st century

Energy, and particularly electricity, is essential for economic and social development and for improved quality of life, but the last century's global trend in energy supply is widely recognised as being unsustainable. The world faces environmental threats from climate change caused by anthropogenic CO_2 emissions and socio-political threats from rising energy prices and the possible lack of secure energy supplies.

Balancing energy requirements for continued social and economic progress against potential environmental and socio-political impacts is acknowledged to be a significant global challenge in the 21st century.

Strong economic growth in many developing countries, leading to a more energy-consuming lifestyle, and the projected 50% increase of the world population, primarily in the developing regions, are expected to drive energy demand in the 21st century. Current annual per capita energy consumption differs markedly by country and region; today's developing countries, with some three-quarters of the world's inhabitants, consume only one-quarter of global energy. By 2050, with current government policies, both total primary energy supply and global electricity demand are expected to have increased by about a factor of 2.5.

By 2050, global electricity demand is expected to have increased by about a factor of 2.5.

If current government policies in most countries remain unchanged, fossil fuel use will continue its inexorable rise to meet this increasing demand for energy, whilst nuclear power is not likely to make a significant contribution. This increase in fossil fuel usage will lead to increased CO_2 emissions, which science and recent history show will have consequent impacts on our climate, and lead to political and economic instability resulting from reduced security of supply and increased energy prices.

The United Nations Intergovernmental Panel on Climate Change, in its most recent major report published in 2007, showed that environmentally sound sources of energy are imperative to control atmospheric emissions of greenhouse gases, particularly CO_2. Electricity generation accounts for 27% of global anthropogenic CO_2 emissions and is by far the largest and fastest-growing source of greenhouse gases.

If projections hold true, by 2050 the average CO_2 emissions per unit of energy consumption must be reduced by a factor of 4.

In 2005, most of the world's population used significantly less than 4 000 kWh of electricity per capita, the threshold below which life expectancy and educational attainment are observed to fall rapidly. Over the period to 2030, the biggest growth in electricity demand is expected to occur in India and in China. Electricity demand in the United States has grown continuously over the past 55 years, with no obvious sign of slowing. As other countries aspire to the level of economic development in OECD countries, it is likely that their energy demands will eventually follow the same pattern – electricity demand is unlikely to level out.

If UN population and IPCC gross domestic product (GDP) per capita and energy intensity projections hold true, the carbon intensity of the world's energy system must be reduced by a factor of four to achieve the 50% reduction in CO_2 emissions by 2050 that the IPCC considers necessary to stabilise climate change. This is tremendously challenging; IPCC data show that carbon intensity has improved by less than 10% in the last 35 years.

Security of supply has also become a major concern around the world, particularly for countries that have limited indigenous fossil fuel resources and are therefore dependent on imported energy. Most of the world's readily recoverable oil and gas reserves are concentrated in a few countries in the Middle East and in the Russian Federation. Over the past few decades, this has proved to be a significant source of tension, both economic and political.

Current and likely future contributions to global energy supply from nuclear power

In principle, nuclear energy could meet much of the anticipated increase in electricity demand.

Nuclear energy offers the opportunity of meeting a significant part of the anticipated increase in electricity demand whilst reducing the potential global environmental, political and economic concerns associated with fossil fuels.

The current contribution to global energy from nuclear power

The first civil nuclear power plants were built in the 1950s and this led to a major expansion in the nuclear industry in the 1970s and 1980s. Rapid growth ended following the accidents at Three Mile Island (1979) and Chernobyl (1986), and the collapse in fossil fuel prices in the mid-1980s.

In 2006, nuclear energy provided 16% of the world's electricity and 23% of electricity in OECD countries, from 439 reactors.

There were 439 nuclear reactors operating in 30 countries and one economy as of June 2008, with a total capacity of 372 GWe. Nuclear energy supplied 2.6 billion MWh in 2006: 16% of the world's electricity and 23% of electricity in OECD countries. Global operating experience of nuclear power reactors now exceeds 12 700 reactor-years. France, Japan and the United States have 57% of the world's nuclear generating capacity; in 2007, sixteen countries relied on nuclear energy to generate over a quarter of their electricity.

In June 2008, 41 power reactors were under construction in 14 countries and one economy: these units will increase global nuclear capacity by 9.4%. Average construction times of about 62 months are consistently being achieved in Asia; of the 18 units connected to the grid between December 2001 and May 2007, three were constructed in 48 months or less.

The energy output from existing nuclear energy investments has been increased through improved availability, power uprates and licence renewals. Energy availability factors for nuclear plants worldwide increased significantly over the past decade; although generating capacity rose by only 1% per year, nuclear electricity production increased by 2.5% per year. Power uprates to existing plants have increased global nuclear generating capacity by around 7 GWe, and in the United States, as of May 2008, 48 reactors had been granted licence renewals, extending their operating lives from 40 to 60 years, the longest out to 2046.

Although most nuclear fuel cycle services are concentrated in France, the Russian Federation, the United Kingdom and the United States, 18 countries have the capability to fabricate fuel, importing enriched uranium as necessary.

The likely future contribution of nuclear energy

There are plans for significant further nuclear power plant construction, particularly in China, India, the Russian Federation, the Ukraine and the United States. There are currently no firm plans to build additional capacity in Western Europe, other than the units currently under construction in Finland and France. Nuclear build is being encouraged by the UK government, but without firm orders to date. More recently the newly elected Italian government has also expressed an interest in new nuclear build. Several European countries – Belgium, Germany, Spain and Sweden – project significant reductions in their dependence on nuclear energy because they have adopted phase-out policies. However, in several of these countries political opinion is divided and nuclear power will still form a part of the energy mix for some considerable time: current final shutdown dates are 2022 in Germany and 2025 in Belgium and Sweden. Nuclear energy is regarded much more favourably in the countries of Eastern Europe, where some countries have firm intentions to add new nuclear capacity.

Current national plans and authoritative statements of intent suggest that the countries having the largest installed nuclear capacity in 2020 will be the United States, France, Japan, the Russian Federation, China and Korea. China and the United States have the largest planned increases in capacity. The countries that produce the largest amount of nuclear electricity in the world are not, with the exception of France, those that are most dependent on it. Among the probable top five producers in 2020, the United States and China are expected to have only 20% and 5% nuclear shares respectively. Although a number of currently non-nuclear countries have plans to join the nuclear energy community, they are likely to add only about 5% to global installed nuclear capacity by 2020.

The NEA has developed low and high scenario projections of nuclear electricity supply showing that global installed nuclear capacity could increase from 372 GWe in 2008 to between 580 and 1 400 GWe by 2050. Under the high scenario, nuclear energy's share of global electricity production would rise from 16% today to 22% in 2050. These projections are in broad agreement with those from other organisations.

The NEA projections suggest that nuclear electricity generation will continue to be dominated by the OECD countries out to 2050.

To achieve this increase, between 2030 and 2050 an average of between 23 (low scenario) and 54 (high scenario) reactors per year would need to be built both to replace plants to be decommissioned and to increase nuclear generation. Historic evidence suggests that the world could construct nuclear power plants at a rate more than sufficient to meet the NEA high scenario projections during the period up to 2050. History also suggests a global capability to construct nuclear plants at a rate that would allow 30% or more of global generating capacity to be nuclear by 2030, should that be what countries around the world were to require, compared with

NEA assumptions

Low scenario	High scenario
New plants are built only to replace retirements in the two decades to 2030. Capacity is maintained or slightly increased via life extension, uprating and higher power replacements. Between 2030 and 2050: • Carbon capture and storage are successful. • Energy from renewable sources is successful. • Experience of new nuclear technologies is poor. • Public and political acceptance of nuclear power is low.	Life extensions and plant upratings continue. Current national plans and authoritative statements of intent for additional capacity by 2030 are largely implemented. Between 2030 and 2050: • Carbon capture and storage is not very successful. • Energy from renewable sources is disappointing. • Experience of nuclear technologies is good. • Public concern about climate change and security of supply increases, significantly influencing governments. • Public and political acceptance of nuclear power is high. • Carbon trading schemes are widespread and successful.

the International Energy Agency (IEA) reference scenario projection of 10%.

The NEA low and high scenarios both project that nuclear electricity generation will continue to be dominated by the OECD countries. Despite the rapid economic growth expected in India and China, their projected share of global nuclear capacity is still relatively small by 2050.

Nuclear energy's potential role in minimising the negative consequences of the world's growing energy demand

Consequences for climate change

IPCC analysis concludes that annual CO_2 emissions must be halved from 2005 levels if the consequences of climate change are to be contained at a tolerable level. Emissions have to be cut to around 13 Gt/yr by 2050. Assessments suggest that emissions will be around 60 Gt/yr in 2050 unless serious ameliorative actions are taken. Electricity generation currently accounts for 27% of global anthropogenic CO_2 emissions and is by far the largest and fastest-growing source of greenhouse gases. On a total life cycle basis, nuclear energy is virtually CO_2 free.

Electricity generation is the largest and fastest-growing source of greenhouse gas emissions.

The IEA has suggested that a combination of technologies is needed to meet this very demanding target, including extremely high efficiency gains in both production and use of energy, a massive expansion of renewable energy, introduction of significant quantities of carbon capture and storage and a very significant expansion of nuclear energy.

Nuclear energy is the only virtually carbon-free technology with a proven track record on the scale required. In the NEA's low and high scenario projections, CO_2 emissions would be reduced by between 4 and 12 Gt/yr in 2050 if nuclear were used instead of coal, significant in terms of the 13 Gt/yr target level that the IPCC recommends.

Nuclear energy can provide electricity with almost no CO_2 emissions – it is the only nearly carbon-free technology with a proven track record on the scale required.

The concept of external costs applied to electricity generation accounts for consequences not represented in the price, including the consequences of climate change. Assessments that account for external costs in electricity production chains show that nuclear and hydroelectric power generation are the least expensive on a full life cycle basis.

However, the Kyoto Protocol did not recognise nuclear energy as an accepted technology under its Clean Development and Joint Implementation mechanisms, and the protocol's period of application was too short to have significant influence on investor decisions for power plants. The process of negotiation for a follow-on treaty has begun. Because electricity plants are the largest carbon dioxide emitting sector, with emissions growing faster than in any other, any new treaty must allow a much longer-term view and consider all available options.

Consequences for energy security

Nuclear energy is more able than fossil energy to provide security of supply because the fuel – uranium – comes from diverse sources, the main suppliers being in politically stable countries. Uranium's high energy density (one tonne of uranium produces the same energy as 10 000-16 000 tonnes of oil with current practices) also means that transport is less vulnerable to disruption. Furthermore, the high energy density and the low contribution of uranium to the cost of nuclear electricity production make the storage of a large energy reserve practical and affordable.

A significantly expanded global nuclear energy programme could potentially be fuelled for thousands of years using the currently defined uranium resource base – but this would require fast breeder reactors that are not yet commercially available.

Identified uranium resources are sufficient to fuel an expansion of global nuclear generating capacity employing a once-through fuel cycle (i.e. without reprocessing) at least until 2050, allowing decades for further discoveries. The current resource to consumption ratio of uranium is better than that for gas or oil. Based on regional geological data, resources that are expected to exist could increase uranium supply to several hundreds of years.

Reprocessing of existing irradiated nuclear fuel, which contains over half of the original energy content, could provide fuel for about 700 reactor-years, assuming 1 000 MWe light water reactors (LWRs) operating at an 80% availability factor. Additional existing resources, such as depleted uranium stocks and uranium and plutonium from ex-military applications, could provide nuclear fuel for about another 3 100 reactor-years.

Converting non-fissile uranium to fissile material in fast breeder reactors with closed fuel cycles can multiply the energy produced from uranium by up to 60 times. This technology could extend nuclear fuel supply for thousands of years, but fast breeder reactors are not yet in commercial operation. France, the Russian Federation, India and Japan have operable fast reactors (some of which are research reactors).

Consequences for health effects

The increasing use of energy carries with it significant health effects. The health impact of outdoor air pollution is uncertain, but has been estimated at currently almost one million premature deaths per year in the *OECD Environmental Outlook to 2030*. Nuclear energy could make a contribution to reducing the health effects of fossil fuel consumption.

A rational evaluation of the health effects of alternative electricity production technologies should consider both the long-term health effects of possible radioactivity releases from accidents and the far more dominant operational emissions from fossil sources. Gaseous and particulate emissions from fossil fuel use (SO_X, NO_X and fine particulates) are known to have significant deleterious health effects. Life cycle analyses of electrical energy production chains show that nuclear power (including the effect of radioactive emissions) is one of the best power production technologies for avoiding emission-related health effects. Loss of life from emission-related health effects far outweighs that from accidents in energy supply chains.

Comparison of frequency-consequence curves of real accident data for full energy chains in OECD countries for the period 1969-2000 shows nuclear to be very considerably safer than oil, coal and natural gas which are, in turn, notably safer than liquefied petroleum gas (LPG). However, public and political concern focuses on the very low probability of large accidents, which could lead to fatalities in the long term as a result of released radioactivity.

Meeting the challenges to nuclear energy growth

Despite nuclear energy's potential to reduce global environmental and socio-economic threats, a significant fraction of public opinion perceives that the risks of nuclear energy outweigh its advantages. If nuclear power is to achieve its full potential in the coming decades, the public and politicians will need to be convinced about a number of aspects of the technology, in particularly safety, waste disposal and decommissioning, physical security and non-proliferation, and cost.

If nuclear power is to achieve its full potential, the public must be convinced about safety, waste disposal, non-proliferation and costs.

Safety

The nuclear industry must keep safety and environmental protection as its top priorities. The rapid expansion of nuclear power in the 1970s and 1980s ended principally as a result of the Three Mile Island and Chernobyl accidents. At the same time, low fossil prices made new nuclear plants uneconomic in many countries. Despite current high fossil fuel prices, another serious accident, whether or not it released significant quantities of radioactivity to the environment, could have severe implications for the future of nuclear energy.

Nuclear safety is a global issue: a serious event in one country may have an impact on its neighbours. Although the responsibility for ensuring nuclear safety clearly resides within each country, the international nuclear community is seeking to increase harmonisation between national safety practices via the Multinational Design Evaluation Programme (MDEP) and other international initiatives.

The international community has initiatives in progress to increase regulatory effectiveness and efficiency, in view of the growing interest in new nuclear build and the next generation of designs.

The MDEP is an initiative undertaken by ten countries with the support of the NEA, to develop innovative approaches to make best use of the resources and knowledge of the national regulatory authorities that will be tasked with the review of new nuclear power plant designs. The main objective of the MDEP effort is to establish reference regulatory practices and regulations to enhance the safety of new reactor designs. The resulting convergence of regulatory practices and regulations should allow for enhanced co-operation among regulators, improving the effectiveness and efficiency of the regulatory design reviews that are part of each country's licensing process.

New designs of reactor have passive safety systems that are intended to maintain the plant in a safe state, in particular during an unexpected event, without the use of active control. Some advanced designs for smaller-sized reactors – not yet built – have an integral cooling system, with the steam generators, pressuriser and pumps all located within the reactor pressure vessel to reduce the probability and consequences of loss-of-coolant accidents.

Nuclear energy may be developed in countries where previous experience in nuclear power and its regulation is very limited. Ensuring that these "new" nuclear countries follow appropriate industrial and regulatory approaches and implement adequate legal procedures will be a duty of the international community and, in particular, of the vendor countries.

Waste disposal and decommissioning

Low-level and short-lived intermediate-level wastes account for the largest volumes of radioactive waste, but are only a small proportion of its total radioactivity. Technologies for disposal of such wastes are well developed and most countries with major nuclear programmes operate facilities for their disposal or are at an advanced stage in developing them.

Failure so far to build high-level waste disposal facilities is a significant factor in negative perceptions of nuclear energy – but there is now an international consensus for geological disposal.

The delay or failure thus far of some disposal facility programmes for high-level radioactive waste (HLW) continues to have a significant negative impact on the image of nuclear energy. Governments and the nuclear industry must work together to deliver safe disposal. Because HLW disposal has not yet been implemented, this has given the impression to some that it is technically very difficult or even impossible. In addition, waste management and decommissioning are sometimes believed to be prohibitively expensive.

The quantities of HLW arising are small and can be stored safely for extended periods of time. A 1 000 MWe light water reactor produces about 25 tonnes of spent nuclear fuel (SNF) per year which can be packed for disposal as HLW; alternatively, where spent fuel is reprocessed, about 3 m^3 of vitrified high-level waste is produced.

The consensus approach being pursued worldwide for ultimate management of SNF and HLW is geological disposal, for which the technological basis is well established. So far no facilities for disposal of SNF and HLW have been licensed, but progress is being made through participative national decision-making processes. In the United States a site has been selected and considerable investigation work conducted. In Finland the selected site has received political and local support, and it is possible that Sweden may be in that position soon. Numerous other countries, including France, Japan and the United Kingdom are currently engaged in the search for an acceptable HLW disposal site. If all countries investigating geological disposal succeed in operating a repository before 2050, only about one quarter of the SNF and HLW generated under the NEA high scenario would be without a defined disposal route at that time.

There is experience of successfully decommissioning a variety of nuclear facilities, including several US power plants with capacities larger than 100 MWe that were fully dismantled, with disposal of the resultant waste. An analysis by the United Kingdom Department of Trade and Industry showed that waste management and decommissioning costs for nuclear power plants represent only 3% of overall nuclear generation costs. Funding schemes exist to finance decommissioning liabilities.

It is estimated that 70% of today's worldwide nuclear decommissioning liabilities are associated with military activities from the Cold War rather than with civil nuclear power plants.

Non-proliferation and security

The possibility of materials or technologies developed for civil use in electricity production being diverted for military purposes is a concern to many people. The International Atomic Energy Agency (IAEA) safeguards system under the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) has served the international community well in helping to prevent the diversion of civil nuclear materials and technologies into military uses. The NPT has 191 Parties and came into force in 1970; it was extended indefinitely in 1995. The safeguards arrangements are backed up by diplomatic, political and economic measures and complemented by controls on the export of sensitive technology.

The Treaty on the Non-Proliferation of Nuclear Weapons has successfully restrained the spread of nuclear weapons for four decades.

The NPT has been the legal foundation of the international regime for restraining the spread of nuclear weapons for nearly four decades. Yet its future effectiveness and support could be in jeopardy as a result of various political, legal and technical developments. To ensure its continued success, it needs to be enhanced.

Concerns about the spread of reprocessing and enrichment technologies have led the IAEA to propose multilateral nuclear approaches to increase non-proliferation assurances for nuclear fuel cycle facilities. These are aimed at reinforcing existing commercial arrangements for enrichment and reprocessing via a range of possible mechanisms: implementing international nuclear fuel supply guarantees; promoting voluntary conversion of existing nationally controlled facilities to multinational facilities; creating new multinational facilities based on joint ownership for enrichment and for disposal of spent fuel.

Several other proposals are also under discussion or development. These include the Global Nuclear Energy Partnership (GNEP) promoted by the United States, which has 21 participating member countries as of August 2008, and the Russian Federation's project to establish an International Uranium Enrichment Centre (IUEC). Proposals from Japan, Germany and a group of six countries with commercial enrichment facilities have also contributed to the international debate.

While the international safeguards regime is an important component of proliferation resistance, design measures may facilitate the implementation of safeguards controls. Advanced nuclear technologies are being designed with enhanced resistance to proliferation threats and robustness against sabotage and terrorism threats.

Cost and funding

A 2005 international comparison of the levelised costs for nuclear, coal and gas power plants, carried out by the NEA and the IEA, shows nuclear to be competitive with coal and gas, with some dependence on local circumstances. Since then, the price of oil has quadrupled (as at June 2008) with other fossil energy prices following it upwards. Building and operating new nuclear plants is clearly economically viable in the right circumstances. However, sensitivity analysis of nuclear electricity generation costs show that they are particularly dependent on overnight construction cost and on the cost of capital (financing charges). The large up-front cost is also a discouragement to investors. The economic challenges of nuclear power therefore relate more to investment funding than to levelised generation costs.

International comparison shows nuclear to be competitive with coal and gas – but governments may need to mitigate licensing and planning risks to encourage investment in nuclear energy.

The cost of generating nuclear electricity has three main components: capital investment, operation and maintenance (O&M) and fuel cycle. The capital investment required to construct a nuclear power plant contributes typically 60% to the total cost of nuclear electricity generation, while O&M and fuel cycle contribute about 25% and 15% respectively. The cost of the uranium itself amounts to only around 5% of the cost of generating nuclear electricity. This is markedly different from the cost structure of fossil electricity generation plants, particularly those operating on gas, where fuel costs dominate.

The introduction of competitive wholesale markets for electricity has generally been positive for existing nuclear plants. Competitive pressures have encouraged improvements in operating performance, allowing the full value of the assets to be realised. For both new and existing plants, improved economics can be achieved through uprating power levels, lifetime extensions and increased availabilities. Worldwide, average availability has increased by almost 10 percentage points in the last 15 years, now reaching 83%. Five countries exceeded 90% average availability in 2006 and in 2007 this increased to six countries; the best reactors in the world have availabilities around 95%. Many plants have been uprated to produce more power, some by as much as 20%. A significant number of reactors have had licensed lifetimes extended from 40 to 60 years.

The large initial capital cost of new nuclear plants and the length of time of licensing processes have caused investors to be very cautious of new build. Governments wishing to encourage investment in nuclear may need to remove or mitigate the real or perceived financial risks associated with licensing, planning and radioactive waste management and decommissioning. Achieving a broad national consensus on the nuclear programme would also be advantageous in reducing political risks for investors.

In addition, governments may need to put in place clear, long-term arrangements for carbon pricing or trading. Most potential external costs have already been internalised for nuclear power, whereas for fossil fuels, external costs are around the same size as direct costs. The manner in which a utility's income from electricity generation is taxed can also have the effect of influencing the relative competitiveness of generating technologies, discouraging the construction of capital-intensive facilities such as nuclear and renewables. Governments should ensure that their energy policy objectives and taxation regimes are in harmony.

Legal framework, infrastructure and resources

The current international legal framework consists of a suite of legally binding treaties, conventions, agreements and resolutions supplemented by numerous non-legally binding codes, guidelines and standards. It has undergone significant changes over the past five decades. Whether at national or international level, legal frameworks must be sufficiently flexible to adapt to future developments, including a significant increase in global nuclear energy production. One of the most important challenges will be to persuade countries with new nuclear power programmes to abide by the terms of the current international framework. The same challenge will apply to those countries that already have established nuclear programmes, but which have so far declined to harmonise their regimes with the existing international framework.

One of the most important challenges from an expansion of nuclear power will be to persuade countries with new nuclear programmes to abide by the terms of the international legal framework.

National regulatory bodies are important components of national legal frameworks for which it is essential to keep the following attributes:

- adequate legal authority, technical and managerial competence;
- adequate human and financial resources to fulfil their responsibilities;
- freedom from undue influence and pressure which could conflict with safety interests.

With the anticipated increase in demand for nuclear power, concerned stakeholders may press not only for more comprehensive and definitive national legislation, but for more effective international conventions on public participation. The further development and implementation of good governance is a necessary step towards educating, empowering and engaging society in the policy-making process of deciding and shaping the future of nuclear energy. For this to happen effectively, a legal framework that will support transparency of information and stakeholder involvement is required. Legislators are likely to ensure that stakeholders gain increasing rights to contribute to the nuclear decision-making process by established legal procedures; they are already convinced that increasing stakeholder involvement in nuclear decision making will lead to enforcement of nuclear and environmental policies that are more effective and will help to build public trust and confidence.

Many in the current nuclear workforce received their education and started their careers during the rapid buildup of nuclear programmes in the 1960s and 1970s. These people are now close to retirement, or indeed have already left the industry. The long life cycle of nuclear power plants, together with the requirement for technical competence, means that the nuclear industry in many countries now faces problems in retaining existing skills and competencies and in developing future skills to support any expansion of nuclear power. Availability of adequate human resources is affected by the increasing liberalisation of the electricity market, resulting in pressure to reduce costs as well as a decrease in government funding for nuclear research. Most countries have recognised the need to secure qualified human resources and recent international, regional and national initiatives have been aimed at encouraging and facilitating more students to enter the nuclear field. Although some progress has been achieved, more needs to be done.

An ageing nuclear workforce, the historic slowdown of new build and requirements for specialised competence, mean the nuclear sector now faces human-resource challenges.

Nuclear research is essential in a number of areas, including safety, radioactive waste management, and nuclear science and technology development. Throughout the 1990s, most OECD governments with nuclear programmes reduced the funding dedicated to nuclear fission R&D. This reduction in domestic resources increased the importance of international organisations, such as the NEA and the IAEA, as focal points to pool the expertise and resources of national laboratories, industry and universities. They also play an important role in activities related to the preservation of knowledge.

The reduced number of nuclear power plants built worldwide in recent years has led to a major consolidation of the nuclear construction industry, resulting in a currently limited capacity to construct new plants. If the demand is there, this can be rebuilt. There is some evidence that this is already happening.

Nuclear energy and society

Provided that the nuclear electricity produced is competitive, people are then more concerned about some aspects surrounding nuclear energy (radioactive waste, terrorism and proliferation) than about the actual operation of the power plants. It is likely that opposition to nuclear energy would reduce considerably if the matter of waste disposal sites were resolved.

However, over half of European Union citizens think that the risks of nuclear power outweigh

If nuclear energy is to expand, an ongoing relationship between policy makers, the nuclear industry and society that develops knowledge-building and public involvement will become increasingly important.

its advantages, particularly if they live in countries with no nuclear power and so have little personal experience of it, or if they do not feel well informed. Increased knowledge of nuclear energy leads to increased levels of support – but most people feel they have inadequate levels of knowledge. Scientists and NGOs are most trusted to provide information. National governments, energy companies and nuclear safety authorities are much less trusted. If nuclear energy is to expand, an ongoing relationship between policy makers, the nuclear industry and society that develops knowledge-building and public involvement will become increasingly important.

Providing citizens with a more in-depth understanding of nuclear issues through direct involvement has been demonstrated to be highly effective. While the provision of information is necessary in order to better educate society about nuclear risks, building public trust must be recognised as equally important. Communication must be open and straightforward, and must be balanced as a priority against conflicting demands such as security and financial pressures.

Developing the technology

Advanced reactors

Advanced reactors are those in Generations III, III+ and IV. Around 80% of today's nuclear power plants use Generation II light water reactors (LWRs), mostly built in the 1970s and 1980s, and LWRs are expected to continue to be the primary form of nuclear power generation until the middle of the century. However, most future nuclear power plants will be Generation III+ designs; four Generation III+ LWRs are operating now and several more are being constructed. These designs offer improved safety characteristics and better economics than the Generation II reactors currently in operation.

Nuclear power could make an increasing contribution to carbon-free heat as well as to electricity production; nuclear production of hydrogen as a transport fuel is an important potential development.

Nuclear power could make an increasing contribution to the supply of electricity as well as to the production of virtually carbon-free heat in the future. Two applications for nuclear heat using LWRs are in current use: district heating and desalination. Most other industrial processes require temperatures that can only be produced by high-temperature gas-cooled reactors (HTGRs). These HTGRs are designed to produce electricity using a gas turbine and to operate at temperatures sufficient for hydrogen production and other process heat applications. Globally, there is significant R&D investment in hydrogen production from nuclear energy, driven by a desire to reduce dependence on imported oil, with commercial exploitation expected around 2020. Hydrogen production could be a significant use of nuclear energy in the coming decades.

Much of the projected growth in world electricity demand will take place in developing economies, where the large nuclear power plants being developed and built in the advanced nuclear energy countries are not necessarily appropriate. Outside of baseload demand in the big and developing economies, such as China and India, large nuclear power plants will not always be well suited. The geographic isolation of some population centres makes them candidates for small or medium reactors (SMRs), particularly if the plants also produce heat and/or potable water. A number of Generation III/III+ SMR designs are under consideration, about half designed without the need for on-site refuelling in order to reduce capital costs and allow easier non-proliferation assurances. These are mostly LWRs with inherent and passive approaches to safety, such as integral primary coolant systems; such design features are especially advantageous in countries with limited nuclear experience. However, SMR technologies are not yet commercially established.

For the longer term, Generation IV energy systems involving advanced reactor designs are expected to be commercialised after 2030. Around the world, many advanced reactor designs are under consideration and it is clear that considerable international co-operation is required to maximise the outcome of scarce R&D funding. An important aspect of Generation IV energy systems is further-improved proliferation resistance and physical protection against terrorist threats.

Fusion energy is still at the experimental stage and is not likely to be deployed for commercial electricity production until at least the second half of the century.

Six energy systems, including their fuel cycles, have been chosen by the Generation IV International Forum (GIF) for detailed R&D, several of which are fast reactors with closed fuel cycles. At least three international initiatives are in progress that aim to support the safe, sustainable and proliferation-resistant expansion of competitively priced and reliable nuclear technology that minimises waste production:

- the GIF, for which the NEA provides the Technical Secretariat;
- the US-led Global Nuclear Energy Partnership;
- the IAEA-led International Project on Innovative Nuclear Reactors and Fuel Cycles.

At a research and development level, controlled nuclear fusion has been realised, although only for a few seconds. Cadarache in France has been chosen as the location of the EUR 5 billion International Thermonuclear Experimental Reactor (ITER) project, the next major development step. The technology is inherently far more complex than fission and the economics of fusion are very uncertain; fusion is not likely to be deployed for commercial electricity production until at least the second half of the century.

Advanced fuel cycles

Current practice in dealing with spent nuclear fuel divides between those nations which reprocess and those that intend to directly dispose of spent fuel to a geological repository after appropriate packaging. Of the three nations with the largest nuclear fleets, France reprocesses fuel and provides reprocessing services to other nations on a commercial basis; Japan reprocesses fuel, buying services from others whilst developing its own domestic capability; and the United States does not reprocess, although it formerly had the capability to do so.

Advanced reprocessing technologies hold the promise of eliminating the long-lived radio-isotopes in nuclear waste.

Existing commercial reprocessing technology enables the recovery of unused uranium, the recovery of plutonium for use in mixed-oxide fuel for LWRs or future fast reactors and the reduction of waste volume for disposal in a deep geological repository. However, the very low price of uranium during the 1990s made reprocessing less attractive in economic terms and the separation of plutonium led to concerns about potential proliferation risks. The price of uranium has recovered in the last few years.

Advanced reprocessing technologies are under development in several countries, and are the subject of international co-operation as part of the Generation IV International Forum and the US-led Global Nuclear Energy Partnership. These hold the potential to provide a number of advantages. Proliferation risks can be reduced by avoiding the separation of plutonium from uranium. Separating the long-lived isotopes from spent fuel (partitioning) for subsequent re-irradiation can eliminate them (transmutation). The radiotoxicity of the waste resulting from the treatment of spent fuel would then reduce by natural radioactive decay to less than that of the natural uranium from which the fuel was originally produced in a matter of only a few hundred years. The volume and heat load burdens on geological repositories could be significantly reduced, allowing the capacity of a given repository to be greatly extended.

The use of thorium for energy production in nuclear reactors is also possible; thorium is believed to be considerably more abundant in the earth's crust than uranium. The naturally occurring isotope of thorium can be transmuted to a fissile uranium isotope. Research and development on thorium-based fuel cycles had been conducted in a number of countries but the technology has not been developed to the commercial scale. ■