The Uranium Institute

Twenty-Third Annual Symposium
10–11 September 1998: London

Alternative Nuclear Paths To 2050

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The circumstances surrounding nuclear power worldwide and the importance that may be given to issues affecting its future development point toward very different alternative paths over the next 50 years. Economic deregulation, lack of competitiveness in some countries, negative public perception and concerns about waste issues suggest that nuclear power might decrease progressively with a potential phase-out of the technology in the long term. Conversely, rapid growth in electricity demand worldwide and accelerated environmental concerns, coupled with timely solutions to problems affecting nuclear technology today, may allow a continuing market penetration of nuclear power. A third alternative may be a progressive reduction in nuclear generation through the medium term, followed by a dramatic revival once nuclear advantages are recognised.

This paper explores in detail these three potential nuclear paths to 2050. The conditions that could lead to these nuclear paths, as well as the challenges and implications are outlined. The study is based on activities at the OECD Nuclear Energy Agency (NEA) related to future nuclear power developments and climate change. It is important to note that the nuclear paths illustrate possible but not predictive futures, depending on specific conditions and factors affecting nuclear development including policy measures and institutional developments.

The analysis of the implications resulting from these three possible paths illustrates the potential contribution of nuclear power to sustainable development and its role in alleviating the risk of global climate change.

Nuclear Power and GHG Emissions

At the end of 1997, there were 437 nuclear reactors being operated in 32 countries, with a total capacity of 352 GWe (some 86% of the world's nuclear power capacity is located in 16 countries of the OECD). In 1997, nuclear power plants generated 2276 TWh, which accounted for 17% of the electricity produced worldwide and 24% of that in OECD countries. This equates to almost 6% of total commercial primary energy used. In 17 countries, the shares of nuclear power in total electricity supply exceeded 25%.

Nuclear power contributes already to the lowering of carbon intensity in the energy sector. A comprehensive analysis of greenhouse gas (GHG) emissions from different electricity generation chains shows that nuclear power is among the least carbon intensive generation technologies, emitting only about 25 g of carbon dioxide equivalent per kWh, compared with some 450 to 1250 gCO_2-equiv/kWh for fossil fuel chains.[1] Assuming that the nuclear units in operation have substituted for modern fossil-fuelled power plants, nuclear energy is reducing carbon dioxide emissions from the energy sector by about 8% (for the electricity sector, the reduction is about 17%).

A comparison of the GHG intensity of total energy production in various countries having different nuclear and hydro shares in total energy supply illustrates that point (see Figure 1). For example, in the United States, where 12% of the total energy was produced by nuclear and hydropower (6% from nuclear), GHG emissions in 1990 were about 66 million tonnes of CO_2

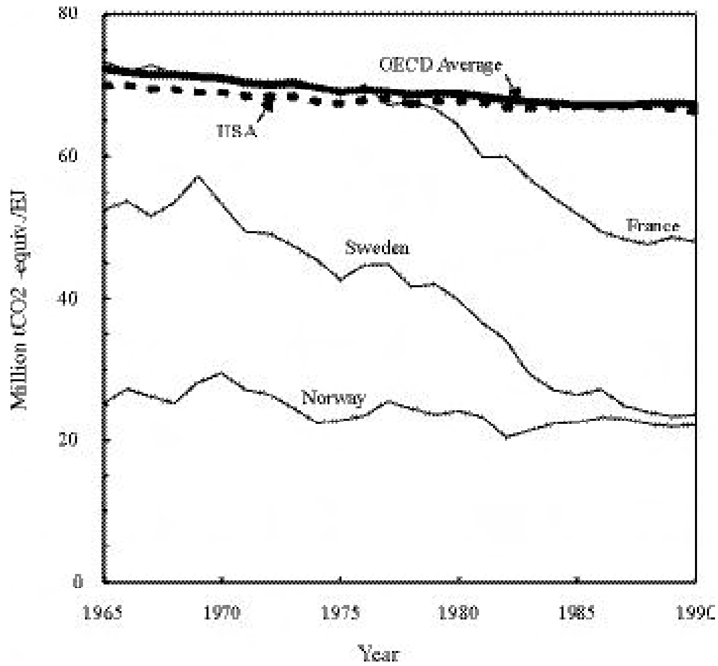


Figure 1. Greenhouse gas (GHG) intensity of energy production.

equivalent per exajoule (1 exajoule (EJ) equals 23.9 million tonnes of oil equivalent). In France, with a 35% share of nuclear and hydro in total energy (30% from nuclear), GHG emissions were about 48 million tCO_2-equiv / EJ. In Sweden, with 66% of its energy from nuclear and hydro (31% from nuclear), GHG emissions were about 24 million tCO_2-equiv / EJ. In Norway, with hydro power contributing 71% of total energy, emissions were 22 million tCO_2-equiv / EJ.

Averaged over the OECD countries, the average emission factor in 1990 was about 67 million tCO_2-equiv / EJ. These emission factors can be put into context by noting that the combustion emission factors for fossil fuels are about 90 million tCO_2-equiv / EJ for coal, 75 million tCO_2-equiv / EJ for oil, and 53 million tCO_2-equiv / EJ for natural gas. It should be noted further that the decrease of emissions in France and Sweden shown in Figure 1 is attributable to the expansion of nuclear share in energy production, as the hydropower share remained almost constant over this period.

Another comparison of the CO_2 intensity, based on emissions from electricity and combined heat and power generation in 1995 in selected countries, also illustrates the nuclear contribution (see Table 1). In countries with no nuclear power, such as Australia and Denmark, the CO_2 emissions per capita are several times greater in magnitude than the corresponding CO_2 emissions in countries with large nuclear shares, such as France, Sweden and Belgium (see Figure 2).

Other environmental benefits are related to the fact that the nuclear electricity generation chain does not release gases or particles that cause acid rains, urban smog or depletion of the ozone layer.

Energy Demand and Supply Outlook

The global energy demand scenario adopted as a basic context for establishing the three nuclear paths is the Case C of the 1995 joint study by the World Energy Council (WEC) and the International Institute for Applied Systems Analysis (IIASA), *Global Energy Perspectives to 2050 and Beyond*.[2] This "ecologically driven" scenario is characterised by:

Table 1. CO_2 emissions per capita from electricity and combined heat and power generation, 1995.

	Nuclear share	Hydro/ renewable share	CO_2 emissions (tCO_2/capita)
Australia	0%	11%	7.44
Denmark	0%	0%	5.65
Netherlands	5%	2%	3.35
Belgium	56%	1%	2.53
Sweden	48%	48%	0.97
France	77%	18%	0.48

Source: 'CO_2 Emissions from Fuel Combustion', International Energy Agency, 1997.

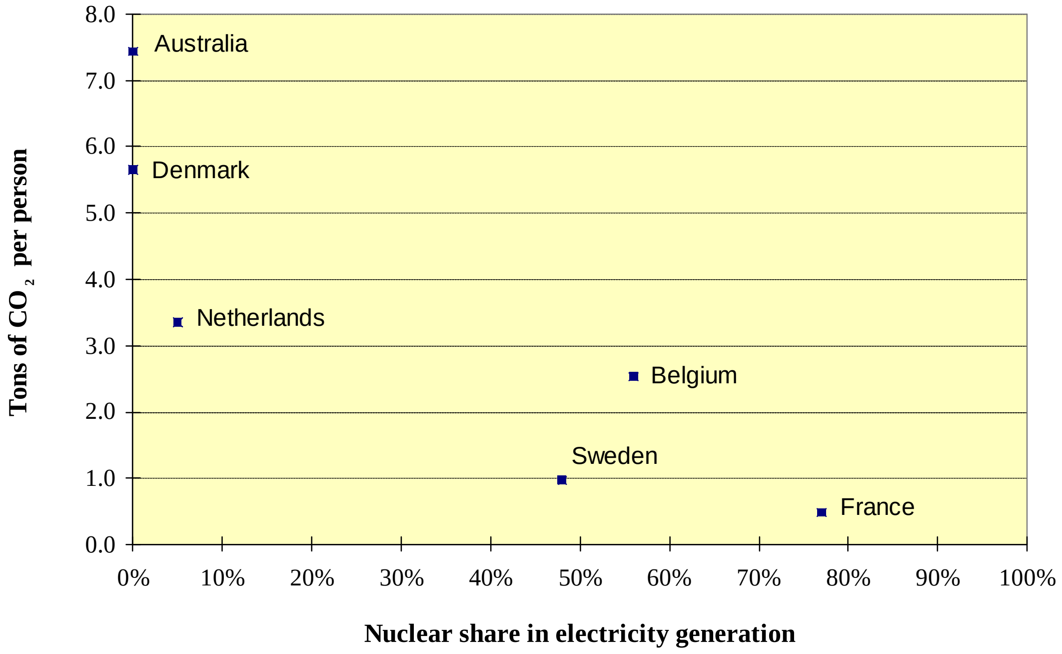


Figure 2. CO_2 emissions per capita from electricity and combined heat and power generation, compared with nuclear share, 1995.

- energy policies focusing explicitly on environmental protection, sustained technological progress and enhanced international co-operation;
- world population growing to slightly more than 10 billion inhabitants in 2050;
- economic growth being moderate, but with significant technology adaptation and transfer from industrialised to developing countries, reducing present regional economic disparities;
- technological progress, technology adaptation and transfer, and policy measures which together result in a continuous reduction in the energy intensity of the world economy by some 1.4% per year up to 2050 (compared with an average reduction of 1% per year over the past decade or so).

In this scenario, world primary energy demand would reach some 586 EJ per year (14 000 million tonnes of oil equivalent, Mtoe) by 2050, and electricity consumption would reach some 23 000 TWh. By way of comparison, in the IIASA / WEC Case A, which assumes that energy policies would not reflect environmental concerns explicitly, primary energy demand would reach some 1046 EJ per year (25 000 Mtoe) by 2050.

Three Nuclear Paths

Within the primary energy demand scenario represented by Case C, three nuclear paths are considered. These are set out in Table 2 and Figure 3. They are intended to cover three different potential nuclear power developments:

- ***Path I, "phase-out",*** assumes that nuclear power would be phased out completely by 2045.
- ***Path II, "continued nuclear growth",*** assumes that nuclear power capacity would grow steadily, reaching 1120 GWe in 2050.
- ***Path III, "progressive reduction followed by revival",*** assumes early retirements of nuclear units in the short term (to 2015) followed by a revival of the nuclear option by 2020 leading to the same nuclear capacity in 2050 as in Path II.

The paths are not intended to reflect the extremes of all possibilities. Higher scenarios of total primary energy demand could be considered, and this in turn might lead to nuclear electricity generation being higher than any of the three nuclear paths. Furthermore, within the overall primary energy demand scenario adopted, nuclear power penetration into energy supply could be higher or lower than the range represented by the three paths.

Path I: Nuclear Phase-out

This path assumes that no new orders would be placed for nuclear power plants. Only the units already under construction would be completed. All units would be decommissioned after 40 years of operation (or less for the units for which an earlier shutdown has been announced already). This plant lifetime has been chosen in light of the

Table 2. Three paths for world nuclear power capacity up to 2050 (GWe).

Nuclear path	2000	2010	2020	2030	2040	2050
Phase-out	360	354	257	54	2	0
Continued nuclear growth	367	453	569	720	905	1120
Reduction followed by revival	355	259	54	163	466	1120

technical characteristics of nuclear units currently in operation and of the regulatory/licensing framework prevailing in most countries where these plants are operated. Under these assumptions, all nuclear units would be retired by 2045. In Path I, nuclear electricity generation in the world would increase slightly to 2370 TWh in 2005, as plants that are under construction are completed, and decrease steadily thereafter to zero in 2045. Path I is not the lowest extreme of nuclear power evolution that could have been considered. For example, existing nuclear units might be retired earlier than assumed in this path.

This represents the path that most of the world seems to be following at present, given the very high rate of expected retirements and the absence of plans for new orders in the next 17 years in many countries. In fact, in OECD countries, only Japan and Korea have firm plans for adding new nuclear capacity through 2015, although Hungary and Turkey are also considering some reactor orders. Countries with important nuclear programmes, such as the United States, the United Kingdom and Sweden are already planning for many of their nuclear plants to retire by 2015. The cumulative number of nuclear plants retiring by 2015 in OECD countries has been reported as 102 out of 358 currently operating.[3] Retiring capacity is about 58 GWe out of 301 GWe, or 19% (see Figure 4).

Circumstances negatively affecting the future of nuclear power include the perceived disadvantage of its economic competitiveness in many countries, concerns about the safe disposal of long-lived high level radioactive waste, and the low degree of acceptance by the public associated with safety and nuclear proliferation issues. If these circumstances persist, the chances are high for a continued progressive decline in nuclear capacity toward a complete phase out by 2050. Nevertheless, it is difficult to imagine a complete phase out in several countries which are highly dependent on nuclear power and which lack domestic fossil fuel and renewable energy resources.

The consequences of a complete phase-out nuclear path will be increasingly translated into difficulties in meeting policy goals on fuel security, fuel diversity and environmental protection. Nuclear energy would have to be replaced mainly by fossil fuels, since the contribution from renewables would be limited. Countries with low domestic fossil fuel resources would be forced to import even higher levels of fuel. Increasing demand for fossil fuels would put pressure on international markets.

The most likely substitute fuel for nuclear power

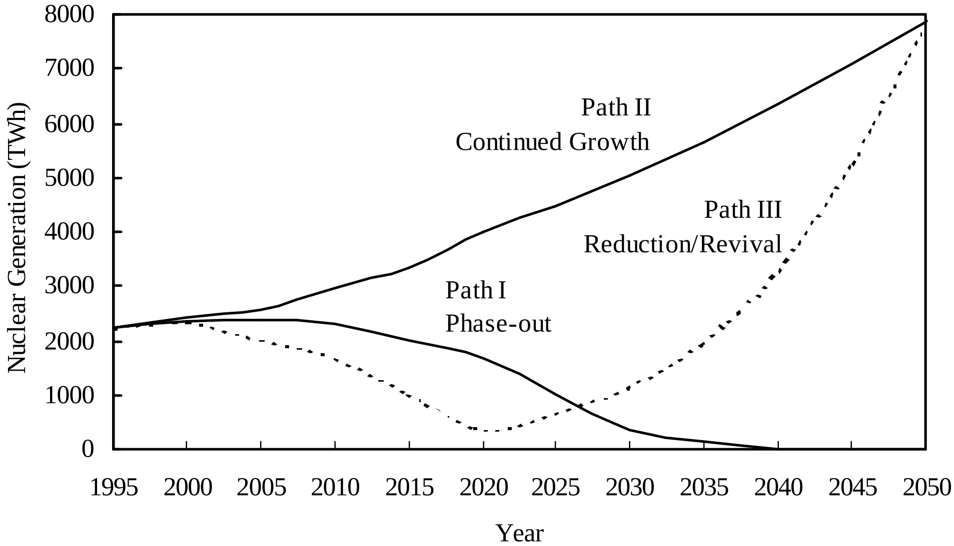
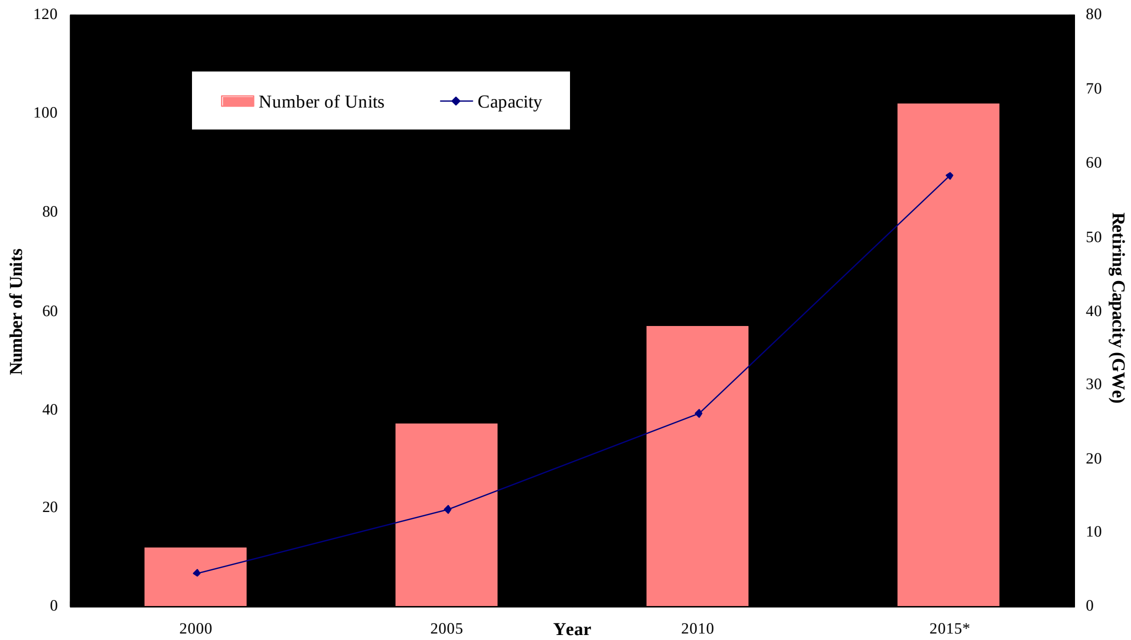


Figure 3. Three paths for world nuclear electricity generation (TWh).



* Not all OECD countries have reported their retiring capacity for the year 2015.

Figure 4. Cumulative nuclear capacity retirements in OECD countries (as expected in 1997).

would be natural gas, at least in the short term. Assuming that the average efficiency of gas-fired power plants worldwide would be 50%, the additional gas requirements would be around 660 billion cubic metres in 2025 (i.e. 29% of overall 1996 gas production), and 1490 billion cubic metres in 2050 (i.e. 64% of 1996 production). Such large increases in gas demand would not only raise concern about gas price escalation, but also about security of energy supply as gas reserves are not evenly distributed in the world (see Figure 5). In fact, over 70% of the 1996 world natural gas reserves rests in countries of only two regions: the former Soviet Union and the Middle East (15% in Iran). Any signs of instability in these regions could translate into disruption of supplies. Already, there are over 40 countries that are net importers of natural gas. Some of these, including Japan, France, Italy and Germany, have over 65% of their consumption supplied from imports (see Table 3).

At least up to 2025, renewable energy sources are unlikely to contribute substantially to total electricity supply. The 1993 share of renewable energy (excluding hydroelectric power) in

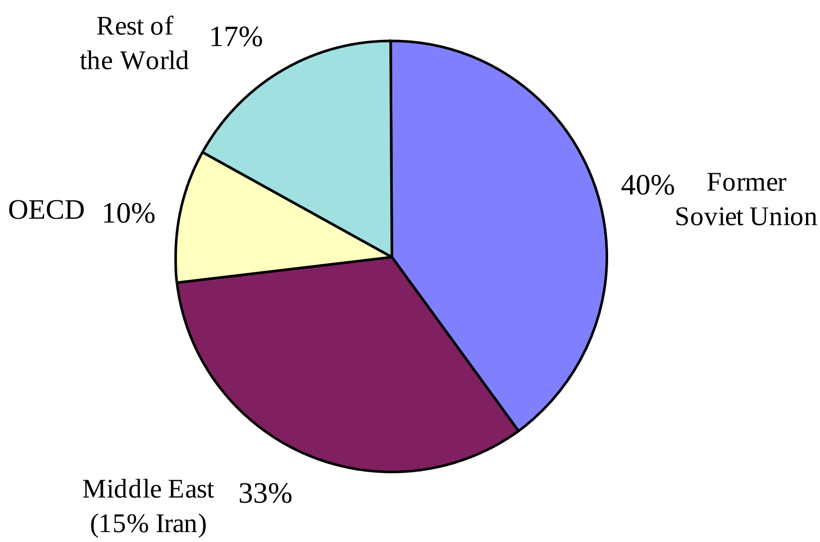


Figure 5. World natural gas reserves by region, 1996.

Table 3. Natural gas consumption and net imports for selected countries, 1996 (million cubic metres).

	Consumption	Net imports	% imports
Japan	67 679	64 972	96%
France	37 520	34 400	92%
Germany	103 804	83 365	80%
Italy	56 100	37 064	66%
United States	619 969	76 789	12%
OECD Pacific	92 943	54 995	59%
OECD Europe	419 088	136 003	32%
OECD America	735 294	-1 927	-0.3%

Source: 'Natural Gas Information', International Energy Agency, 1996.

worldwide electricity production was only 0.4%, and in the OECD region 0.5%.[4] The International Energy Agency (IEA) is expecting this share to increase only slightly to values ranging between 0.8% and 1.7% by 2010, depending on the particular case considered. Hydroelectric power is already fairly saturated in the OECD region, where most of the nuclear reactors will be retired. In OECD countries, the IEA projects the hydroelectric share in electricity in 2010 to either remain at the 1993 level (16%) or to decrease to 14%. Conversely, an increase in hydroelectric power in parts of the developing world is expected, so that the net world share would remain relatively constant between 17% and 19% through 2010.

The conflicting trends of diminishing emissions and phasing out nuclear may imply that some countries will have "mono-fuel" electricity sectors. If coal and oil continue following reducing trends, many countries will have to depend almost entirely on natural gas. In the UK, there is already concern about a mono-fuel future in which the country will depend largely on imported Algerian and Russian gas.[5] Nevertheless, in the long term (after 2025), substitutes to nuclear power could include, in addition to gas-fired plants, coal-fired power plants based on advanced "clean coal" technologies, and economically competitive renewable energy sources.

Increasing the combustion of fossil fuels for electricity generation will make it more difficult to meet the commitments made under the UN Framework Convention on Climate Change (UNFCCC) to reduce GHG emissions. In Path I, the avoided GHG emissions per year resulting from nuclear electricity generation would remain at around 1.8 gigatonnes / year until 2010, decreasing to some 0.8 Gt / y in 2025, and to zero in 2045. The reducing trend in GHG, NO_X and SO_X emissions observed in many countries with nuclear programmes would most likely be reversed. Consequently, higher levels of emissions per person and per MWh generated should be expected, depending on the mix of fossil-fuelled technologies used to substitute for nuclear.

The progressive phase-out of nuclear power after 2010 would pose challenges to the nuclear industry, because of the need to maintain capabilities and know-how for the safe decommissioning of nuclear units and final disposal of radioactive wastes. However, nuclear industries have already demonstrated that they can adapt to no-growth and / or domestic phase out perspectives while maintaining high levels of qualification and expertise. Examples of such adaptation are provided by the evolution of nuclear industries in Italy, Finland, Sweden and the United States.[6] Also, the regulatory frameworks, mechanisms and systems in place in countries operating nuclear power plants provide for funding to be available for dismantling nuclear facilities and final disposal of radioactive waste. Furthermore, significant know-how and technical expertise has been accumulated already on decommissioning of nuclear facilities, including power plants, and on waste management.

Path II: Continued Nuclear Growth

The continued nuclear growth path assumes that nuclear power programmes would expand in countries where nuclear units are in operation already (32 countries in total, 16 OECD, 16 non-OECD), and would be launched in countries which currently are planning to implement nuclear units by 2010–15 (1 OECD and 15 non-OECD). The penetration of nuclear power in the electricity market is assumed to continue to follow the historical trend observed in the last 40 years. Nuclear units reaching retirement would be replaced by new nuclear units.

As a result, nuclear power capacity would grow steadily but not at a very high rate, because total energy and electricity demand growth rates are moderate in the energy demand scenario adopted. The nuclear power share in total energy supply also would increase slowly, reflecting economic competition from other energy sources and long lead times to implement nuclear power programmes. Nuclear electricity generation in the world would reach 7850 TWh in 2050 as compared with 2312 TWh in 1996. In 2050, nuclear would supply some 12% of total primary energy demand and some 35% of total electricity consumption, as compared with some 7% and 17% respectively in 1996.

This is the path that the world, in general, does not seem to be following at the present time. Negative circumstances affecting nuclear power would need to be changed for this growth path to continue into the future, and the changes would have to occur in the near term . The industries and governments in countries with nuclear programmes or with plans to develop nuclear programmes would be challenged to maintain, or to create, the conditions that would permit the progressive penetration of nuclear power in their electricity markets. In particular, it would be necessary to ensure that nuclear power retained and improved its economic competitiveness relative to alternative energy sources, and to enhance public understanding and acceptance of this proven technology. In addition, issues related to the safe operation of nuclear reactors and the final disposition of nuclear waste would have to be addressed at a level that would satisfy the public in general.

Rapid growth in electricity demand worldwide coupled with increasing environmental concerns, particularly with respect to climate change, could enhance the chances for nuclear growth. Recently, there have been some signs indicating a renewed recognition of the benefits that can be derived from nuclear power in the areas of environment, and security and diversity of supplies. For example, the US Department of Energy released in early 1998 a "Comprehensive National Energy Strategy" that stresses the importance of continued reliance on nuclear power as the largest source of emission-free electricity.[7] In the UK, a recent report released by a government committee on energy policy indicated that nuclear energy should not be ruled out of the country's energy future.[8]

The consequences with respect to security and diversity of supply are evident. Assuming a 35% nuclear share in total electricity by 2050, many countries would enjoy more diversified electricity sectors with respect to supply, and less dependence on fossil fuels.

Annual avoided GHG emissions (expressed as CO_2 equivalent) resulting from Path II would reach some 6.3 Gt in 2050, i.e. around one third of total GHG emissions from the energy sector expected according to the IIASA/WEC Case C scenario (about 19 Gt/y). Cumulative avoided GHG emissions to 2050 would be near 200 Gt. The factor of four greater reduction in GHG emissions from Path II (continued nuclear growth), relative to Path I (nuclear phase-out), highlights the significant role that an expanded use of nuclear energy could play in helping to reduce CO_2 emissions.

A reduction should also be expected in other types of emissions, such as SO_X, NO_X and particulates, in countries with increasing nuclear shares, or at least less draconian measures would be needed in non-nuclear sectors in order to achieve policy goals. The situation would be similar to the experiences of countries which have developed large nuclear programmes in the last 20 years. For example, in France, sulphur dioxide and particulate emissions from the power sector were reduced by factors of nine and ten respectively between 1980 and the mid 1990s, while electricity generation roughly doubled during the same period. This reduction resulted from an increase in the nuclear share of total electricity generation from less than 25% in 1980 to more than 75% in 1995. Sweden has also accomplished significant reductions in sulphur dioxide and nitrogen emissions during the last two decades owing to increases in nuclear and hydroelectric shares.

The projected levels of nuclear power development in Path II imply higher consumption of nuclear fuel. At present, nuclear reactors are fuelled mainly with uranium and, in some cases, with recycled plutonium. In the medium term, fuel availability from surplus defence inventories will be able to complement the supply of fissile material. In the long term, thorium could become an additional natural resource for fuelling nuclear reactors, and breeder reactors could make nuclear power an essentially renewable energy source, through the replacement of fissile material consumed. In general, natural resource levels, civil and surplus defence inventories, technological means and industrial capabilities are expected to be adequate to meet required resources in this path up to 2050.

Natural uranium requirements would depend on the fuel cycle strategy adopted. Assuming that reactors would be operated on the once-through cycle, and that the U-235 content of the enrichment plant tails (commonly called the "tails assay") were to remain at the present level of 0.3%, annual natural uranium requirements (see Table 4) would grow from less than 60 000 tU/y around 2000 to 175 000 tU/y in 2050. Those requirements would exceed both the present level of production of fresh uranium (around 36 000 tU/y in 1996) and the production capability expected by 2010 (about 66 000 tU/y).

However, demand growth would be likely to stimulate an expansion of production capacity, as was the case in the late 1970s. Also, at present uranium supply is met partly by drawing from excess civil and surplus defence inventories, and this is expected to continue in the coming five to fifteen years. In particular, dismantling of nuclear weapons could provide additional supply of fissile materials for power reactors in the medium term. A recent report estimates that surplus defence inventories could supply 20% of the world's commercial nuclear fuel by 2001 and about 50% of projected US uranium requirements by 2010.[9]

Cumulative uranium requirements in Path II would reach 5.6 million tU in 2050 if all reactors were operated on the once-through fuel cycle and enrichment plants were operated at 0.3% tails assay throughout the period. With those assumptions, presently known uranium resources would run out shortly after 2040 (see Figure 6). However, the cumulative uranium requirements would be far below the current estimation of total conventional resources recoverable at less than US$130 / kgU (15.5 million tU),[10] and it could be expected that additional exploration effort would identify the required ore deposits.

On the demand side, uranium consumption per kWh can be reduced[11] by:

- increasing fuel burnup (thereby producing more energy per unit of nuclear fuel);
- lowering enrichment plant tails assays (thereby recovering more of the U-235 present in natural uranium);
- recycling plutonium and uranium recovered from reprocessed spent fuel (thereby reducing the needs for fresh natural uranium).

Lowering enrichment plant tails assay from 0.3% to 0.15% would reduce cumulative natural uranium requirements by 2050 from 5.6 to 4.2 million tU. Reprocessing all light water reactor (LWR) spent fuel and recycling the plutonium in mixed oxide (MOX) fuel for LWRs (loaded with 30% MOX fuel and 70% UO_2 fuel), and also recycling the uranium, would lead to a cumulative saving of some 600 000 tonnes of natural uranium by 2050. The combined effect of lowering tails assay and recycling could reduce cumulative uranium requirements by more than 30%.

If all reactors were operated on the once-through fuel cycle, spent fuel arisings would increase steadily, reaching nearly 19 500 tHM / year by 2050, i.e. more than twice the 1995 annual spent fuel arisings of around 9300 tHM. Assuming, however, that all LWR spent fuel was reprocessed and recycled in LWRs accepting up to 30% MOX fuel in core, annual non-reprocessed spent fuel arisings in 2050 would be reduced to around 5000 tHM / y (see Table 5 and Figure 7), i.e. less than half of the

Table 4. Natural uranium requirements in Path II (once-through strategy).

	2000	2010	2020	2030	2040	2050
Annual requirements (thousands tU)	54	70	88	112	141	175
Cumulative requirements from 1995 (millions tU)	0.34	0.94	1.75	2.75	4.0	5.6

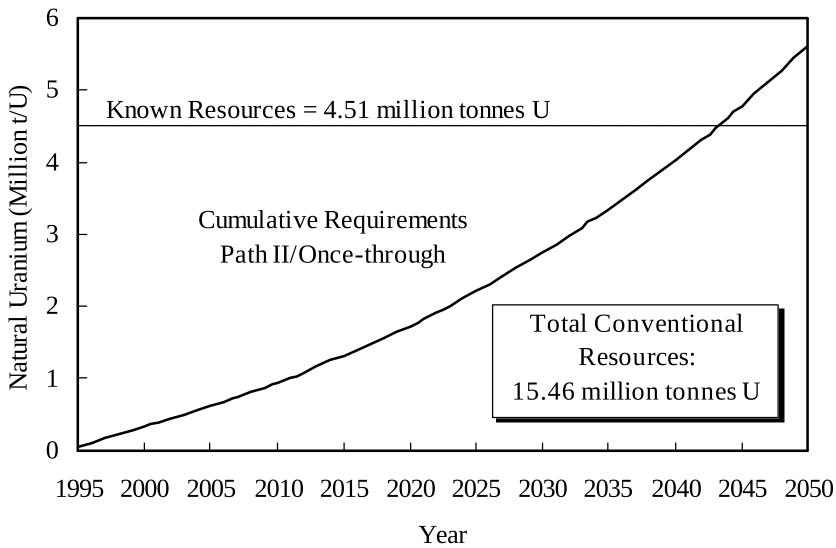


Figure 6. Cumulative natural uranium requirements of Path II, and resource levels.

Table 5. Spent fuel arisings, and reprocessing and MOX fuel fabrication requirements, in Path II (reprocessing and recycle strategy).

	2000	2010	2020	2030	2040	2050
Non-reprocessed spent fuel arisings (thousands tHM/y)	7.9	7.2	5.1	4.5	4.8	5.0
Reprocessing requirements (thousands tHM/y)	2.5	3.5	7.0	9.8	12.2	14.7
MOX fuel fabrication requirements (thousands tHM/y)	0.27	0.40	0.70	1.2	1.6	1.9

arisings in 1995.

In that strategy, reprocessing requirements would reach around 8360 tHM / y in 2025 and 14 690 tHM / y in 2050, and MOX fuel fabrication requirements would be around 1000 tHM / y in 2025 and 1900 tHM / y in 2050. The existing and planned capacities for reprocessing LWR fuel and for fabricating MOX fuel assemblies could meet the requirements during the first two decades of the next century, but new capacity would be needed by 2020. The introduction of fast reactors could reduce even further, and eventually eliminate, the accumulation of non-reprocessed spent fuel and of plutonium in excess of hold-up inventories at reactors and fuel cycle facilities.

Possible constraints that may be faced in Path II (continued growth) include the rate of construction of new nuclear plants, the level of required investments, and siting limitations.

In Path II, nuclear power capacity would more than treble between 1995 and 2050, reaching 1120 GWe in 2050. Taking into account the replacement of nuclear power plants at the end of their lifetime (assumed to be 40 years) the nuclear plant capacity to be constructed yearly in this path would be up to 35 GWe in the period 2010–50. This rate of construction would far exceed that which has been experienced recently. However, past experience has shown that this construction rate is achievable. For example, the actual rate of nuclear plant grid connections was 32 GWe in 1984 and 1985, and averaged 23 GWe per year during the period 1981–85. At the country level, with 47 countries assumed to have nuclear units in operation by 2040–50, the global construction rate (35 GWe per year) would correspond to less than 1000 MWe being constructed per year in each country.

The investment requirements for the construction of the expected nuclear capacity and associated fuel cycle facilities in this continued nuclear growth path are considerable. However, they would represent only a small fraction of the total capital flows expected to be available up to 2050. Potential constraints in raising the funds include the perceived financial risks to investors and the need for adequate rates of return on energy investments. In the case of developing countries, as noted in the IIASA / WEC study, the implementation of nuclear power programmes would require international co-operation. Such co-operation agreements for the construction of nuclear units have been successfully implemented already in some countries, including China and Romania.

Siting of nuclear power plants and fuel cycle facilities may be a constraint, since some countries

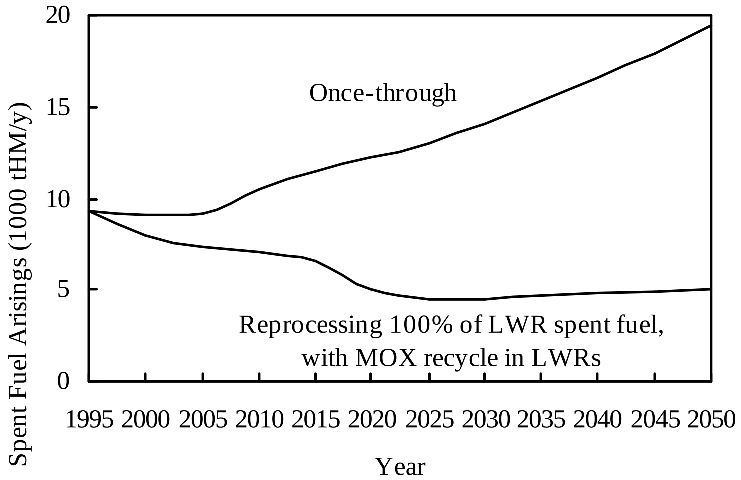


Figure 7. Non-reprocessed spent fuel arisings in Path II, for once-through and reprocessing and recycle strategies.

might have difficulties in finding adequate sites meeting the seismicity characteristics and cooling capacities required for nuclear units. Also, it might be difficult in some countries to overcome public reluctance to accept the implementation of nuclear projects. Nevertheless, most countries that are operating or planning to construct nuclear power plants have enough sites, or capacity on existing sites, to allow them to increase significantly their installed nuclear capacity. New reactor designs, especially small and medium-sized reactors with passive safety features and very low risk of off-site impact in case of accident, would increase the number of sites suitable for constructing and operating nuclear units.

Path III: Reduction Followed by Revival

In Path III it is implied that a combination of energy price structures and a lack of public confidence in nuclear energy would render difficult the continuance of commercial nuclear programmes. Also, it is assumed that problems affecting nuclear power today would not disappear in the next few years, forcing the early retirement of a considerable part of the world capacity and further delaying orders for the construction of new nuclear units. The increasing demand expected for electricity worldwide would, in the absence of a mature technology able to replace the retiring nuclear capacity, eventually cause a return to nuclear power characterised by an accelerated deployment of new nuclear reactors. In addition, increasing concerns about the environment, and security and diversity of supplies, would contribute to the rebirth of nuclear.

Therefore, Path III assumes that no new nuclear power plants would be ordered until 2015–20, and that existing units would be retired after 30 years of operation with no replacement. The 30-year lifetime (which is shorter than that currently expected) has been adopted in order to illustrate the impact of early retirement of nuclear units due to policy decisions or economic factors (e.g. privatised utilities could decide not to invest in refurbishment in the face of uncertainties and enhanced competition in deregulated electricity markets). By 2020, nuclear electricity generation would have decreased to 360 TWh, i.e. less than 16% of 1997 nuclear generation. After 2025, nuclear electricity generation would grow steadily to reach the same level in 2050 as in Path II (around 7850 TWh), and the same nuclear share in total energy and electricity supply. The interest of this path is in providing a framework for analysing potential stresses on the nuclear industries, and issues that might merit attention by governments in the context of a "progressive reduction followed by revival" scenario.

A revival of nuclear power by 2015 is assumed to be based upon a satisfactory performance record in nuclear power plant operation, satisfactory implementation of radioactive waste disposal, political recognition that nuclear energy could alleviate a number of environmental concerns, and a restructuring of energy costs through the widespread internalisation of externalities, together with improved nuclear technologies (reactor designs and fuel cycle strategies).

In Path III, the level of annual GHG emissions avoided by 2050 would be the same as in Path II (6.3 Gt), but the contribution of nuclear power to GHG emission reduction would be marginal in the period 2015–30. The cumulative avoided GHG emissions to 2050 would correspond to 100 Gt. These avoided emissions represent only about half of those in Path II (200 Gt), even though both paths reach the same level of nuclear electricity generation in 2050. This illustrates clearly the importance of timely implementation of GHG mitigation technologies.

A major concern related to this path is whether the supporting infrastructure would still exist by the time the revival would start to take place. Technical know-how, industrial capabilities, and availability of regulatory and legal frameworks are all factors that would be necessary to ensure a rapid deployment of nuclear reactors all over the world.

The nuclear power plant construction rate in the later part of the period (2045–50) would be much higher in Path III (55 to 75 GWe per year) than in Path II (25 to 35 GWe per year). The nuclear industry would likely face challenges in meeting this rate, following a rather long period of low activity. In particular, it might be difficult to maintain adequate research and development efforts to support advanced reactor designs in a sector affected negatively for nearly two decades. Furthermore, the education and training of qualified personnel for operating and, in the revival phase, constructing nuclear units could raise some issues owing to the lack of student interest in a field that in the short and medium term would not offer attractive career opportunities.

Conclusions

The future of nuclear power will be driven by a series of factors and circumstances that affect its

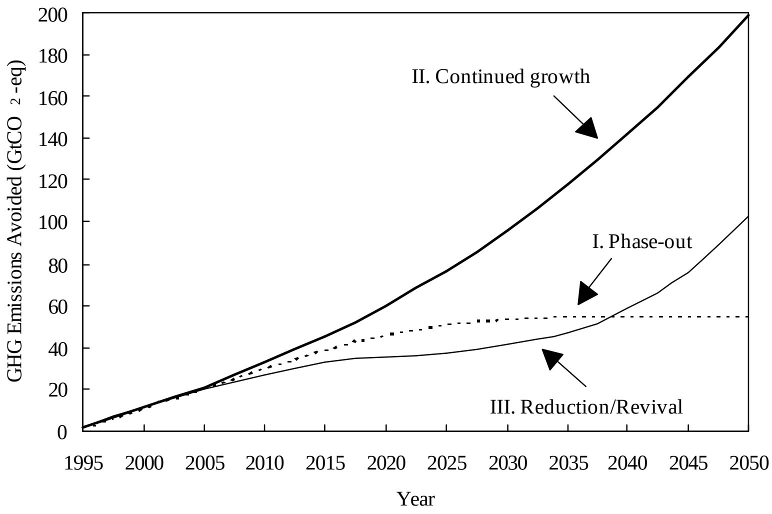


Figure 8. Cumulative greenhouse gas (GHG) emissions avoided in the three nuclear paths.

development, and by the importance given to the debate on climate change and sustainable development. Three possible nuclear development paths illustrate the circumstances, implications and issues that could characterise the future of nuclear power. A complete phase out path may have a significant negative impact on the environment and on the ability of many countries to provide security and diversity of fuel supplies for electricity.

Alternatively, a sustained growth in nuclear power towards a 35% nuclear share in electricity by 2050 illustrates the dramatic contribution that nuclear power could provide to alleviating the risk associated with global climate change and in reducing dependency on fossil fuel utilisation. A progressive reduction in nuclear generation followed by a revival points toward the challenge of maintaining the necessary infrastructure, achieving accelerated construction rates, and ensuring a minimum level of R&D.

In general, there are no physical limitations that could preclude nuclear from following any of the three paths outlined. However, there are institutional implications that would need to be addressed in a timely manner to ensure the proper implementation of future strategies to satisfy world electricity demand.

In general, governments, industry, international organisations and policy makers have important roles to play in defining the baskets of energy technologies that should be considered to ensure the satisfaction of future electricity demand, given the goals of sustainable development. Nuclear power is one of the proven technologies that could be used to achieve this objective.

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