Nuclear Development

OECD OCDE

Nuclear Power and Climate Change

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NUCLEAR • ENERGY • AGENCY

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EXECUTIVE SUMMARY

Background and Introduction

In the Kyoto Protocol, agreed upon by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in December 1997, Annex I countries committed to reduce their greenhouse gas (GHG) emissions. Also, the Protocol states that Annex I countries shall undertake promotion, research, development and increased use of new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies. One important option that could be covered by the last phrase, and is not specifically mentioned, is nuclear energy which is essentially carbon-free.

In this connection, the Nuclear Energy Agency (NEA) has investigated the role that nuclear power could play in alleviating the risk of global climate change. The main objective of the study is to provide a quantitative basis for assessing the consequences for the nuclear sector and for the reduction of GHG emissions of alternative nuclear development paths. The analysis covers the economic, financial, industrial and potential environmental effects of three alternative nuclear power development paths ("nuclear variants").

- ***Variant I, "continued nuclear growth",*** assumes that nuclear power capacity would grow steadily, reaching 1 120 GWe* in 2050.
- ***Variant II, "phase-out",*** assumes that nuclear power would be phased out completely by 2045.
- ***Variant III, "stagnation 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 variant I.

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* Note: GWe = 1 000 MWe.

Findings of the NEA Study

Each of the three variants would create challenges for the nuclear sector, but all of them would be feasible in terms of: construction rate; financing; siting and land requirements; and natural resources.

The nuclear industry can achieve the required rate of nuclear power plant construction. In variant I, nuclear power capacity would more than treble between 1995 and 2050, reaching 1 120 GWe in 2050. However, the nuclear unit construction rate would remain rather modest globally, not exceeding 35 GWe per year in the period 2010-2050. Past experience has shown that this construction rate is achievable. For example, the actual rate of nuclear plant grid connections was 32 GWe per year in 1984 and 1985. The higher construction rate in variant III might pose challenges for the nuclear industry, in particular following a long period of low activity.

Cumulative investment requirements can be met. When viewed in absolute magnitudes, the investment requirements of the energy sector appear enormous; however, they would represent only a small fraction of the total capital flows available up to 2050. The real challenge in raising funds for energy investments, and in particular for nuclear facility investments, is not the level of funding requirements, but rather the perceived financial risks to investors and the need for adequate rates of return on energy investments. In the case of developing countries, implementation of variants I and III would require international co-operation, including technology transfer and financing support from OECD countries.

Siting of nuclear power plants and fuel cycle facilities will not be a constraint at the global level, although some countries might have difficulties in finding adequate sites meeting the seismicity characteristics and cooling capacities required for nuclear units. 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.

Natural resources of nuclear fuel can support the projected levels of nuclear power development. In the medium term, fuel availability might be a concern in some cases. However, natural resource levels, technological means and industrial capabilities are adequate to give a reasonably high degree of assurance that all resource demands of the three variants considered can be met to 2050. Breeder reactors could make nuclear power an essentially renewable energy source, through the replacement of fissile material consumed.

Nuclear power can contribute significantly to reducing emissions of greenhouse gases. In variant I, annual reductions in GHG emissions (expressed as CO_2 equivalent) would reach some 6.3 Gigatonnes (Gt) in 2050, i.e. around one-third of the total GHG emissions from the energy sector. Cumulative avoided GHG emissions to 2050 would be nearly 200 Gt in variant I, around 100 Gt in variant III and some 55 Gt in variant II. The factor of four greater reduction in GHG emissions from variant I (continued nuclear growth), relative to variant II (nuclear phase-out), highlights the significant role that an expanded use of nuclear energy could play in helping to alleviate the risk of global climate change. In variant III (stagnation followed by revival) the cumulative avoided GHG emissions to 2050 are only about half of those in variant II, even though both variants reach the same level of nuclear electricity generation in 2050. This illustrates clearly the importance of timely implementation.

Challenges for the Nuclear Industry

- ***Variant I:*** The main challenges would be to ensure that nuclear power retains and improves it economic competitive position relative to alternative energy sources, and to enhance public understanding and acceptance of nuclear power.

- ***Variant II:*** The nuclear sector will be challenged to meet the need for maintaining capabilities and know-how to ensure the safe decommissioning of nuclear units and final disposal of radioactive wastes. Nuclear industries in a number of OECD countries have demonstrated already that capability. This variant might exacerbate challenges within the non-nuclear energy sectors, in regard to long-term security of supply and meeting UNFCCC commitments.

- ***Variant III:*** would challenge the nuclear industry to ensure that technical and economic preparedness would be maintained and enhanced during more than two decades of stagnation, in order to keep the nuclear option open. A revival of nuclear power by 2015 is assumed to be based upon technologies that are able to compete favourably with advanced fossil-fuelled technologies, renewable sources and other options for alleviating the risk of global climate change.

Conclusions

Nuclear power is one of the options available for alleviating the risk of global climate change and its potential contribution to GHG emissions reduction could be significant. Keeping the nuclear option open in order to realise this potential will require a number of actions by governments and by industries in the nuclear sector.

In a longer-term perspective, non-electrical applications of nuclear energy, such as heat, potable water and hydrogen production, could be developed, and these applications could enlarge significantly nuclear power's contribution to GHG emission reduction. Research and development would be necessary in order to assess fully the technical feasibility of those applications at the industrial level and the economic competitiveness of nuclear versus fossil fuels and renewable sources. Governments could play an important role by supporting such research and development, and international organisations could assist in this process by promoting and facilitating exchange of information.

INTRODUCTION

The energy sector, from primary energy extraction to end-use, is one of the main sources of greenhouse gas (GHG) emissions, in particular carbon dioxide (CO_2), that raise concerns because of their potential risk to induce global warming and climate change. The carbon dioxide emissions related to energy use are estimated to represent some 75 to 90 per cent of the anthropogenic CO_2 emissions. Climate change is a major global issue on the agenda of policy-makers. Accordingly, a key policy-making objective will be the implementation of measures aiming towards reducing GHG emissions from the energy sector in the medium and long term.

At the third meeting of the Conference of the Parties (COP-3) to the United Nations Framework Convention on Climate Change (UNFCCC), that was held in December 1997 in Kyoto, decision-makers agreed on provisions for reducing GHG emissions. A key provision of the Kyoto Protocol[1] is that Annex I countries shall, individually or jointly, reduce their emissions according to country-by-country targets with a view of reducing their overall emissions by 5.2 per cent below 1990 levels in the commitment period 2008 to 2012. Another provision is that Annex I countries shall undertake promotion, research, development and increased use of new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies.

Owing to the fact that the burning of fossil fuels contributes about three-quarters of man-made GHG emissions, the implementation of less carbon intensive energy systems is high in the list of possible measures for reducing GHG emissions. In this connection, "new and renewable forms of energy" are mentioned explicitly in the Kyoto Protocol. However, one important option that is essentially carbon-free, nuclear energy, is not specifically mentioned in the Protocol.

Indeed, there are a number of technical options that could help in reducing, or at least slowing the increase of, GHG emissions from the energy sector. The list of options includes: improving the efficiency of energy conversion and end-use processes; shifting to less carbon intensive energy sources (e.g. shifting from coal to natural gas); developing carbon-free or low-carbon energy sources; and carbon sequestration (e.g. planting forests or capturing and storing carbon dioxide). However, when the technological readiness and costs of the various options are taken into account, there are only a few options that could be implemented in the short and medium term at an acceptable cost. Nuclear power is one of the few options that are: currently available on the market; competitive in a number of countries, especially if global costs to society of alternative options are considered; practically carbon-free; and sustainable at large-scale deployment (i.e. large energy supply can be supported by natural resources which are plentiful and have no other use).

In this context, the Nuclear Energy Agency (NEA) has investigated the role that nuclear power could play in alleviating the risk of global climate change. The main objective of the study is to provide a quantitative basis for assessing the consequences for the nuclear sector and for the reduction of GHG emissions of alternative nuclear development paths. The total greenhouse gas emissions avoided by nuclear power were estimated at the world level and, therefore, do not provide insight into the role of nuclear power as compared with alternative options that individual countries might consider in order to fulfil their UNFCCC commitments. The analysis covers the economic, financial, industrial and potential environmental effects of alternative nuclear power development paths ("nuclear variants"). The illustrative nuclear variants used in the study are consistent with the "ecologically driven" energy demand scenario to 2050 (case C) developed by the International Institute for Applied System Analysis (IIASA) in its study for the World Energy Council (WEC)[2].

Nuclear Power and the Environment Today

At the end of 1996, there were 442 nuclear reactors being operated in 32 countries, with a total capacity of 351 GWe (some 85 per cent of the world's nuclear power capacity is located in 16 countries of the OECD). In 1996, nuclear power plants generated 2 312 TWh, which accounted for 17 per cent of the electricity produced world-wide. This equates to almost 6 per cent of total commercial primary energy used. In 18 countries, the shares of nuclear power in total electricity supply equalled or exceeded 25 per cent.

Nuclear power contributes already to the lowering of carbon intensity in the energy sector. A comprehensive analysis of GHG emissions from different electricity generation chains shows that nuclear power is among the less carbon intensive generation technologies, emitting only about 25 g of carbon dioxide equivalent per kWh (gCO_2-equiv./kWh) as compared with some 450 to 1 250 gCO_2-equiv./kWh for fossil fuel chains[3]. 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 per cent (for the electricity sector, the reduction is about 17 per cent). Indeed, the Executive Director of IEA stated at the second Conference of the Parties of the UNFCCC that "nuclear power accounted for the greater part of the lowering of the carbon intensity of the energy economies of the OECD countries over the last 25 years".

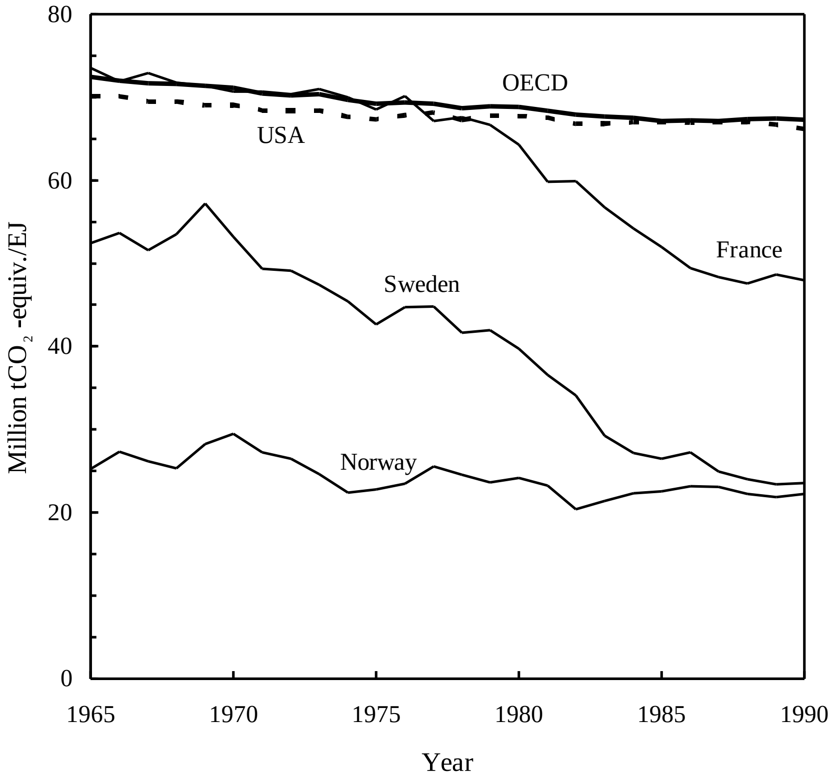

Figure 1**. Greenhouse gas (GHG) intensity of energy production**

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, the GHG emissions in 1990 were about: 66 million tonnes of CO_2-equivalent per exajoule** ($MtCO_2$-equiv./EJ) in the USA where 12 per cent of the total energy was produced by nuclear and hydro power (6 per cent from nuclear); about 48 $MtCO_2$-equiv./EJ in France with a 35 per cent share of nuclear and hydro power in total energy (nuclear contributed some 30 per cent); about 24 $MtCO_2$-equiv./EJ in Sweden, with 66 per cent of its energy production from nuclear and hydro power (31 per cent from nuclear), and 22 $MtCO_2$-equiv./EJ in Norway, with hydro power contributing 71 per cent of total energy. Averaged over the OECD countries, the average emission factor in 1990 was about 67 $MtCO_2$-equiv./EJ. These emission factors can be put into context by noting that the combustion emission factors for fossil fuels are about: 90 $MtCO_2$-equiv./EJ for coal; 75 $MtCO_2$-equiv./EJ for oil; and 53 $MtCO_2$-equiv./EJ for natural gas. It should be noted further that the decrease of emissions in France and Sweden is attributable to the expansion of nuclear share in energy production, as the hydro power share remained almost constant over this period.

With regard to other environmental burdens, the nuclear electricity generation chain does not release gases or particles that cause acid rains, urban smog or depletion of the ozone layer. There are some radioactive emissions from nuclear power plants and fuel cycle facilities, but these are regulated strictly and kept below levels at which health risks might arise. The population doses resulting from nuclear industry emissions of radioactivity are monitored and assessed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). In its 1994 report[4], the UNSCEAR assessment showed that the collective effective dose committed to the world population by a 50-year period of operation of existing nuclear power facilities, i.e. power plants, uranium mining and other fuel cycle facilities, is 2 million man-Sieverts (man-Sv), compared with 650 million man-Sv committed by natural back-ground radiation. That is, the dose commitment from natural background radiation is 325 times higher than that from the world's entire nuclear power industry. Therefore, even if it is assumed that there would be no reduction in the nuclear industry's radioactive emissions per kWh (even though at present there is a trend of decreasing emissions per kWh), the size of the nuclear power industry could be multiplied by this factor (i.e. in excess of 750 thousand TWh of nuclear generation) without leading to a population dose higher than that from the natural background.

** 1 Exajoule (EJ) = 23.9 Megatonne of oil equivalent (Mtoe).

With regard to solid waste, the radioactive waste arisings from nuclear power plants and fuel cycle facilities amount to some 500 cubic metres of intermediate and low-level waste and few tens of cubic metres of high-level waste (with reactors operated on the once through fuel cycle) per GWe-year[5]. These volumes are several orders of magnitude smaller than the waste from the coal chain. The significance of the small volumes of radioactive wastes is that it is possible to isolate them safely and economically from the human environment, whereas this is not possible at acceptable costs with the large volumes of wastes from the coal energy system.

Energy Demand and Supply Outlook

The global energy demand scenario adopted as a basic context for establishing the three nuclear variants investigated below is the Case C of the 1995 IIASA/WEC study "Global Energy Perspectives to 2050 and Beyond". This "ecologically driven" scenario is characterised by:

- energy policies focusing explicitly on environmental protection, sustained technological progress and enhanced international co-operation;

- the world population growing to slightly more than 10 thousand million inhabitants in 2050;

- economic growth being moderate, but with significant technology adaptation and transfer from industrialised to developing countries reducing present regional economic disparities; and

- technology progress, adaptation and transfer, together with policy measures, resulting in a continuous reduction in the energy intensity of the world economy by some 1.4 per cent per year up to 2050 (compared with an average reduction of 1 per cent per year over the past decade or so).

In this scenario, world primary energy demand would reach some 586 EJ per year (14 000 Megatonnes of oil equivalent, Mtoe) in 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 1 046 EJ per year (25 000 Mtoe) in 2050.

The main challenges pointed out in the IIASA/WEC study regarding the scenario represented by Case C are to implement the assumed levels of technology progress and North/South co-operation. The development of nuclear power within this framework would depend mainly on technical and economic preparedness of the nuclear sector and on policy decisions related to nuclear technology transfers, which in turn depend, at least partly, on public acceptance of nuclear power.

Illustrative Nuclear Variants

Within the primary energy demand scenario represented by Case C, three nuclear variants were considered. These are intended to cover a wide range of possible paths (see Table 1 and Figure 2) for nuclear power evolution up to 2050, corresponding to different policies that might be implemented. However, it has to be stressed that the variants considered are not intended to reflect the extremes of all possibilities. For example, 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 variants. 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 variants. The variants are intended to illustrate possible, but not predictive, futures incorporating voluntary policy measures, institutional changes and technological progress that would affect the development of nuclear power programmes.

Table 1. **Three variants of world nuclear power capacity (GWe) up to 2050**

Nuclear Variant	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
I. Continued nuclear growth	367	453	569	720	905	1120
II. Phase-out	360	354	257	54	2	0
III. Stagnation followed by revival	355	259	54	163	466	1120

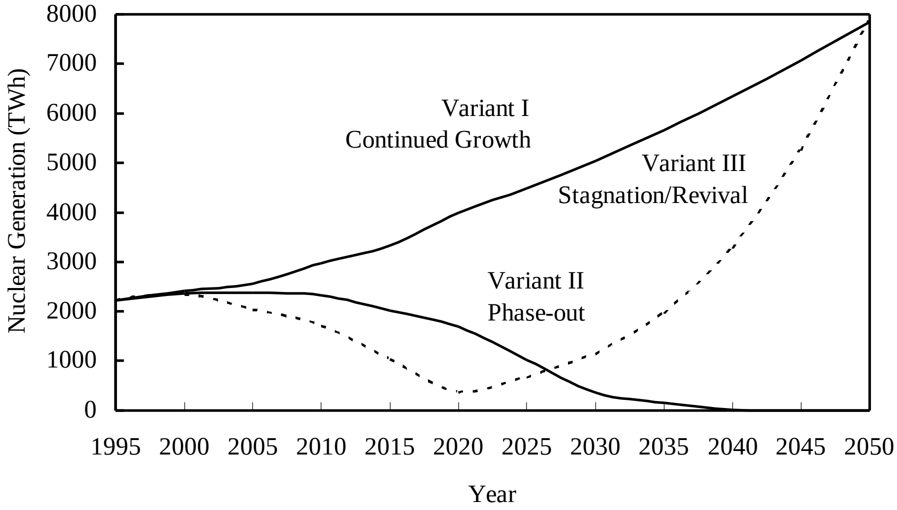

Figure 2. **World nuclear electricity generation (TWh)**

Variant I, "continued nuclear growth", assumes that nuclear power programmes would continue in countries where nuclear units are in operation already, and would be launched in countries which currently are planning to implement nuclear units by 2010-2015. Nuclear units reaching retirement would be replaced by new nuclear units. As a result, nuclear power capacity grows steadily but not at a very high rate because: total energy and electricity demand growth rates are moderate within the energy demand scenario adopted; and the nuclear power share in total energy supply increases 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 7 850 TWh in 2050 as compared with 2 312 TWh in 1996. In 2050, nuclear would supply some 12 per cent of total primary energy demand and some 35 per cent of total electricity consumption, as compared with some 7 per cent and 17 per cent respectively in 1996.

Variant II, "phase-out", 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 technical characteristics of nuclear units currently in operation and of the regulatory/licensing framework prevailing in most countries where those plants are operated. Under these assumptions, all nuclear units would be retired by 2045. Variant II 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 variant; indeed, a shorter lifetime for existing plants has been assumed in Variant III (see below). Nonetheless, variant II is not considered to be a plausible development, owing to the fact that some countries are committed by policy, and by their low endowment with fossil fuel and exploitable renewable energy resources, to continue using a significant amount of nuclear energy. The interest of including variant II in this study is in indicating the stresses that it would place on fossil energy supplies and the environmental problems that it would cause.

In variant II, nuclear electricity generation in the world would increase slightly to 2 370 TWh in 2005, as plants that are under construction are completed, and decrease rapidly thereafter to zero in 2045. The share of nuclear power in energy and electricity supply would decrease continuously during the period.

Variant III, "stagnation followed by revival", assumes that no new nuclear power plants would be ordered until 2015-2020 and that existing units would be retired after 30 years of operation. This lifetime (which is shorter than currently expected) has been adopted in order to illustrate the impact of early retirement of nuclear units for policy reasons (e.g. implementation of political decisions) and/or owing to 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). It is assumed that by 2015 market forces and/or policies would trigger a revival of the nuclear option, leading to an increase in nuclear capacity by 2025. Thereafter, a sustained growth of nuclear power is assumed, which would lead to the same nuclear share in total energy and electricity supply in 2050 as in variant I. The interest of this variant 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 "stagnation followed by revival" scenario.

In variant III, the nuclear electricity generation in the world would start to decrease by the turn of the century owing to retirements of nuclear units after 30 years of operation, or less for the units already planned to be shut down sooner, which would not be replaced by new nuclear units. In 2020, nuclear electricity generation would be around 360 TWh, i.e. less than 16 per cent of the 1996 nuclear generation. After 2025, nuclear electricity generation would grow steadily to reach the same level in 2050 as in variant I, i.e. around 7 850 TWh.

Feasibility of the Nuclear Variants

Each of the three variants would create challenges for the nuclear sector, but all of them would be technically and economically feasible. In particular, it has been assessed in the IIASA/WEC study that the levels of investments and nuclear technology adaptation and transfer required in variants I and III are consistent with the technical, economic and policy assumptions underlying the Case C energy scenario. The feasibility of the nuclear variants is examined below, in terms of the following factors:

- nuclear power plant construction rate;
- investment and financing requirements;
- siting and land requirements;
- natural resource requirements.

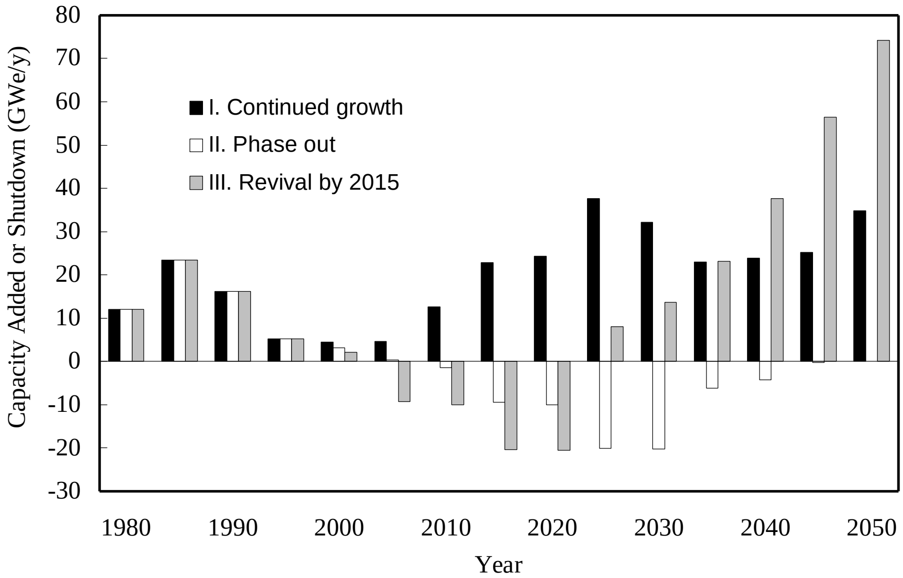

Figure 3. **Gross nuclear capacity additions or shutdowns (GWe/y)**

The nuclear industry can achieve the required rate of nuclear power plant construction. In variant I, nuclear power capacity would more than treble between 1995 and 2050, reaching 1 120 GWe in 2050. However, the nuclear unit construction rate would remain rather modest globally. 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 variant I would not exceed 35 GWe in the period 2010-2050 (see Figure 3). Past experience has shown that this construction rate is achievable. For example, the actual rate of nuclear plant grid connections was 32 GWe per year in 1984 and 1985, and, as can be seen in Figure 3, averaged 23 GWe per year during the period 1981-1985. At the country level, with 47 countries assumed to have nuclear units in operation by 2040-2050, the global construction rate (35 GWe per year) would correspond to less than 1 000 MWe being constructed per year in each country.

In contrast to variant I, which assumes a continuous growth of nuclear power capacity, variant III assumes a stagnation until 2015-2020, followed by rapid growth that reaches the same nuclear capacity in 2050 as in variant I. As a consequence, the nuclear power plant construction rate in the later part of the period (2045-2050) would be much higher in variant III (55 to 75 GWe per year) than in variant I (25 to 35 GWe per year). The nuclear industry would likely face challenges to meet this rate, following a rather long period of low activity. In particular, it might be difficult to maintain adequate research and development efforts, necessary *inter alia* to support advanced reactor designs, in a sector where activities would be stagnant during nearly two decades. Furthermore, the education and training of qualified manpower for operating and, in the revival phase, constructing nuclear units could raise some issues owing to the lack of students' interest in a field that does not seem promising over a long period.

Cumulative investment requirements can be met. When viewed in absolute magnitudes, the investment requirements of the energy sector appear enormous; however, they would represent only a small fraction of the total capital flows available up to 2050. During the period 1990-2020, energy sector investment requirements represent only some 1.5 per cent of world gross domestic product (GDP) and only 1.1 per cent of GDP during 2020-2050. The global average savings rate has tended to remain relatively stable at around 20 per cent of GDP. Assuming this savings rate to be maintained in the future, the investment requirements for the entire energy sector could be financed by around 5-7 per cent of the global savings. The IIASA/WEC study concludes that the real challenge in raising funds for energy investments is not the level of funding requirements, but rather the perceived financial risks to investors and the need for adequate rates of return on energy investments. These two key factors also have implications for investments in nuclear power plants and fuel cycle facilities.

In the case of developing countries, the IIASA/WEC study noted that implementation of the nuclear power programmes that were projected in their Case C scenario would require international co-operation. Such co-operation agreements for the construction of nuclear units have been implemented already, in China and Romania for example. This requirement would also apply to variant I in this study, which is similar to the nuclear component of scenario C2 in the IIASA/WEC study.

For the power plants alone, investment costs of combined-cycle, gas-fired power plants, which are the less capital intensive option at present, vary between 30 and 60 per cent of those of nuclear power plants depending on country specific conditions. The investment costs of coal-fired power plants equipped with pollution abatement systems are about 75 per cent those of nuclear power plants. The investment requirements for fuel cycle infrastructures, e.g. fossil fuel production, transport and handling facilities or nuclear fuel cycle facilities, vary widely from technology to technology and from country to country. Those investments tend to be higher for fossil fuel energy systems than for nuclear power, for which the fuel cycle facility investment costs are always marginal when expressed in terms of cost per kWe, especially in developing countries.

Siting of nuclear power plants and fuel cycle facilities will not be a constraint at the global level, although some countries 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. 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. The land use requirements of the nuclear fuel cycle are not penalising in comparison with other fuel chains.

Natural resources of nuclear fuel can support the projected levels of nuclear power development. At present, nuclear reactors are fuelled mainly with uranium and, in some cases, with recycled plutonium; in the longer term, thorium could become an additional natural resource for fuelling nuclear reactors, and breeders could make nuclear power an essentially renewable energy source, through the replacement of fissile material consumed. However, in the medium term, fuel availability might be a concern in some cases, as discussed below. Nevertheless, natural resource levels, technological means and industrial capabilities are adequate to give a reasonably high degree of assurance that all resource demands of the three variants considered can be met 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 ^{235}U content of the enrichment plant tails (commonly called "tails assay") would remain at the present level of 0.3 per cent, annual uranium requirements (see Table 2 and Figure 4) would grow from less than 60 000 tU/y around the year 2000 to 175 000 tU/y in 2050. Those requirements exceed both the present level of production of fresh uranium (slightly more than 30 000 tU/y in the mid-1990s) and the production capability expected to exist early in the next century (below 40 000 tU/y). However, demand growth would be likely to stimulate an expansion of production capacity, as was the case in the late seventies. Also, at present uranium supply is met partly by drawing from excess civil inventories, and this is expected to continue in the coming five to ten years. Dismantling of nuclear weapons will provide additional supply of fissile materials for power reactors. On the demand side, uranium consumption per kWh can be reduced by[6]:

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

Table 2. **Natural uranium requirements in variant I (once-through strategy)**

	2000	**2010**	**2020**	**2030**	**2040**	**2050**
Annual requirements (1 000 tU)*	54	70	88	112	141	175
Cumulative requirements from 1995 (million tU)	0.34	0.94	1.75	2.75	4.0	5.6

* Annual production in the world was nearly 58 000 tU in 1988 but only about 31 500 tU in 1994.

Cumulative uranium requirements in variant I would reach 5.6 million tonnes of uranium in 2050 if all reactors were operated on the once-through fuel cycle and enrichment plants would operate at 0.3 per cent tails assay throughout the period. With those assumptions, present uranium reserves (reasonably assured resources recoverable at less than US$80/kgU) would be exhausted by 2025 and presently known uranium resources would run out by shortly after 2040 (see Figure 4). However, the cumulative uranium requirements would be far below total conventional resources recoverable at less than US$130/kgU

(15.5 million tonnes U)[7]. Within a period of several decades, with additional exploration efforts, a significant part of the known uranium resources could become reserves and additional resources could be discovered. In response to growing demand and rising uranium prices, exploration efforts and new mine developments would be possible. Owing to the small contribution of natural uranium cost to total electricity generation costs, rising uranium prices would not affect significantly the cost of nuclear generated electricity.

Also, as mentioned above, uranium requirements could be reduced significantly by reducing enrichment plant tails assay and/or reprocessing spent fuel and recycling the recovered plutonium and uranium. Lowering enrichment plant tails assay from 0.3 to 0.15 per cent would reduce cumulative uranium requirements by 2050 from 5.6 to 4.2 million tonnes U. Reprocessing all light water reactor (LWR) spent fuel and recycling the uranium and plutonium in mixed-oxide fuel (MOX) for light water reactors (loaded with 30 per cent MOX and 70 per cent uranium oxide fuel) 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 would reduce cumulative uranium requirements by more than 30 per cent.

Spent fuel arisings would increase steadily if all reactors would be operated on the once-through fuel cycle, reaching nearly 19 500 tHM/year by 2050, i.e. more than twice the 1995 annual spent fuel arisings (around 9 300 tHM). Reprocessing and recycling strategies would reduce significantly non-reprocessed spent fuel arisings. Assuming that all LWR spent fuel would be reprocessed and recycled in LWRs accepting up to 30 per cent MOX in core, annual non-reprocessed spent fuel arisings in 2050 would be reduced to around 5 000 tHM/y (see Table 3 and Figure 5), i.e. less than half of the arisings in 1995.

In that strategy, reprocessing requirements would reach around 8 360 tHM/y in 2025 and 14 690 tHM/y in 2050, and MOX fuel fabrication requirements would be around 1 000 tHM/y in 2025 and 1 900 tHM/y in 2050. The existing and planned capacities for reprocessing LWR fuel and for

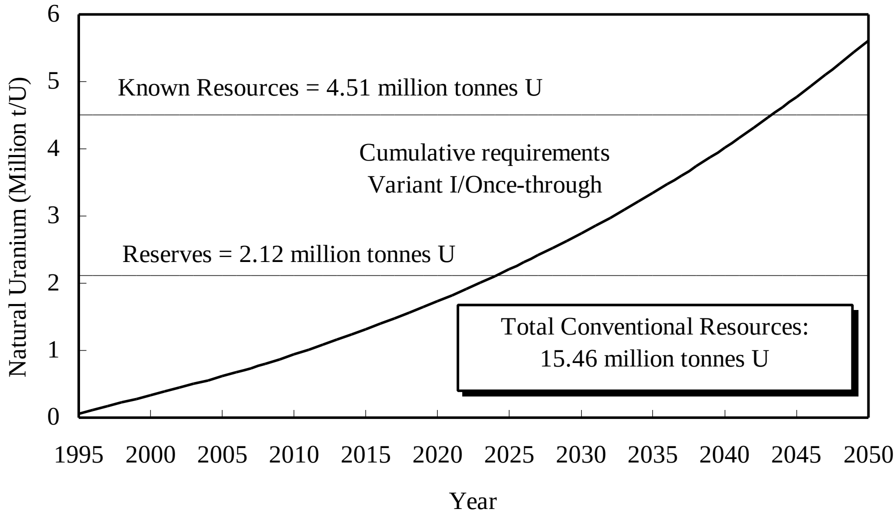

Figure 4. **Cumulative natural uranium demand and resource levels (Million tonnes U)**

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.

Table 3. **Spent fuel arisings and reprocessing and MOX fuel fabrication requirements**
in variant I (reprocessing and recycle strategy)

	2000	**2010**	**2020**	**2030**	**2040**	**2050**
Non-reprocessed spent fuel arisings (10^3 tHM/y)	7.9	7.2	5.1	4.5	4.8	5.0
Reprocessing requirements (10^3 tHM/y)	2.5	3.5	7.0	9.8	12.2	14.7
MOX fuel fabrication requirements (10^3 tHM/y)	0.27	0.40	0.70	1.2	1.6	1.9

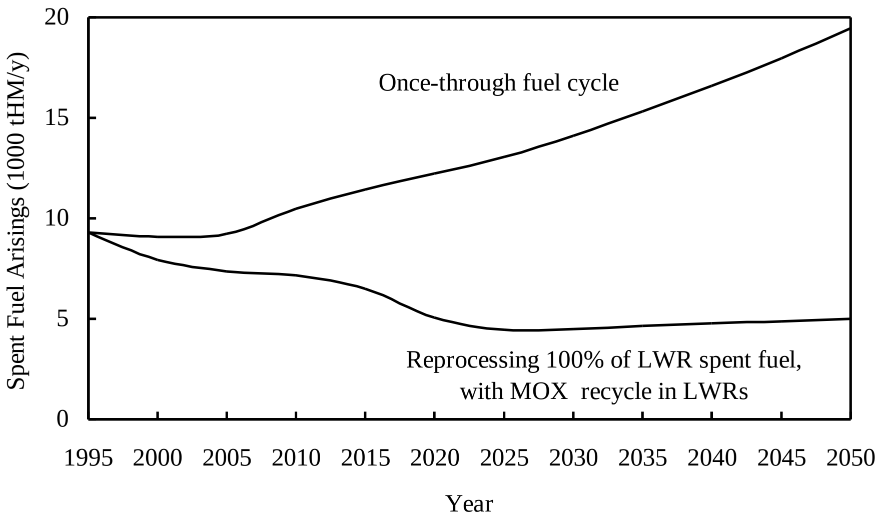

Figure 5. **Non-reprocessed spent fuel arisings in Variant I (1 000 tHM/y)**

Challenges for the Nuclear Industry

Variant I assumes that nuclear power programmes will continue in countries where nuclear units are in operation already, and will be launched in countries that have definite plans to introduce nuclear power into their energy systems. The industries and governments in both groups of countries will be challenged to maintain, or to create, conditions that permit this to occur. In particular, it will be necessary to ensure that nuclear power retains and improves it economic competitive position relative to alternative energy sources, and to enhance public understanding and acceptance of nuclear power. With regard to the latter, international organisations have a role to play in making available objective information of the significant role that nuclear power can play in mitigating the risks of global warming and climate change.

Variant II, owing to the progressive phase-out of nuclear power after 2010, will pose challenges to the nuclear industry in order to ensure that it will remain able to meet the need for maintaining capabilities and know-how to ensure the safe decommissioning of nuclear units and final disposal of radioactive wastes. However, nuclear industries have demonstrated already that they can adapt to no-growth and/or domestic phase-out perspectives while maintaining high levels of qualification and know-how. Examples of such adaptation are provided by the evolution of nuclear industries in Italy, Finland, Sweden and the United States[8].

The regulatory frameworks, mechanisms and systems in place in countries operating nuclear power plants ensure that funding will be available for dismantling nuclear facilities and final disposal of radioactive waste. Funds are accumulated from present beneficiaries of nuclear activities and protected in order to be available when needed. In many countries, existing institutional arrangements assign responsibilities for carrying out all of the operations needed after shut down of nuclear power plants and fuel cycle facilities. Furthermore, significant know-how and technical expertise has been accumulated already on decommissioning of nuclear facilities, including power plants, and on waste management.

Variant II might pose challenges within the non-nuclear energy sectors, owing to the fact that this variant assumes that nuclear power will be replaced by alternative energy sources. At least up to 2025, renewable energy sources are unlikely to contribute more to the total electricity supply than was assumed in variant I, and nuclear energy will very largely have to be substituted by fossil fuels. Increasing demand for fossil fuels would put pressure on international markets and, especially for gas, might raise concerns about possible insecurity of supplies and instability of prices[9] Also, increasing the combustion of fossil fuels for electricity generation will make it more difficult to meet the UNFCCC commitments on reducing GHG emissions.

If nuclear power would be phased out, as assumed in variant II, natural gas would be the most likely substitute fuel, at least in the short term. Assuming that the average efficiency of gas-fired power plants world-wide would be 50 per cent, the additional gas requirements would be around 660 billion cubic meters in 2025, i.e. 29 per cent of the 1996 gas production, and 1 490 billion cubic metres in 2050, i.e. 64 per cent of the 1996 production. Such large increases in gas demand would not only raise concern about gas price escalation but also about security of energy supply since gas reserves are not evenly distributed in the world. However, in the long term, substitutes to nuclear power could include, in addition to gas-fired plants, coal-fired power plants based on advanced “clean coal” technologies and renewable energy sources.

Variant III would pose challenges to the nuclear industry in order to ensure that technical and economic preparedness would be maintained and enhanced during more than two decades of stagnation, in order to keep the nuclear option open. A revival of nuclear power by 2015 is assumed to be based upon technologies (reactor designs and fuel cycle strategies) that are able to compete favourably with advanced fossil-fuelled technologies, renewable sources and other options for alleviating the risk of global climate change. Ensuring technical preparedness and economic competitiveness of nuclear power in order to permit the revival by 2015 might be difficult for nuclear industries in the absence of market opportunities in the short term. In the light of their commitment to sustainable development, governments could consider various policies and mechanisms to meet these challenges, including by providing support to research and development in the field of nuclear energy, as well as on renewable energy sources and other climate change mitigation options.

Impact of the Nuclear Variants on Greenhouse Gas Emissions

Reductions in GHG emissions resulting from the three nuclear variants have been estimated, under the assumption that nuclear power would substitute for a mix of fossil-fuelled power plants emitting 800 gCO_2/kWh, which is an average value for a mix of state-of-the-art coal and gas-fired power plants, approximately equivalent to the mix existing today. This is a plausible assumption at the world level since the most likely substitute to nuclear power during the period considered would be gas-fired power plants in OECD countries and coal-fired power plants in developing countries. However, technology improvements might lead to reducing progressively greenhouse gas emissions from fossil-fuelled power plants during the first half of the next century and a larger share of gas-fired power plants in the mix would also result in lower average emissions of greenhouse gases per unit of electricity generated.

Annual avoided GHG emissions (expressed as CO_2 equivalent) resulting from variant I would reach some 6.3 Gigatonnes (Gt) in 2050, i.e. around one-third of the total GHG emissions from the energy sector in the IIASA/WEC Case C scenario (about 19 Gt/y). In variant II, the avoided GHG emissions resulting from nuclear electricity generation would remain at about the present level, around 1.8 Gt/y until 2010-2015 and decrease rapidly to some 0.8 Gt/y in 2025 and to zero in 2045. In variant III, the level of GHG emissions avoided in 2050 would be the same as in Variant I, but the contribution of nuclear power to GHG emission reduction would be marginal in the period 2015-2030.

Cumulative avoided GHG emissions (see Figure 6) to 2050 would be nearly 200 Gt in variant I, around 100 Gt in variant III and some 55 Gt in variant II. The factor of four greater reduction in GHG emissions from variant I (continued nuclear growth), relative to variant II (nuclear phase-out), highlights the significant role that an expanded use of nuclear energy could play in helping to reduce CO_2 emissions. In variant III (stagnation followed by revival) the cumulative avoided GHG emissions to 2050 are only about half of those in variant I, even though both variants reach the same level of nuclear electricity generation in 2050. This illustrates clearly the importance of timely implementation of GHG mitigation technologies.

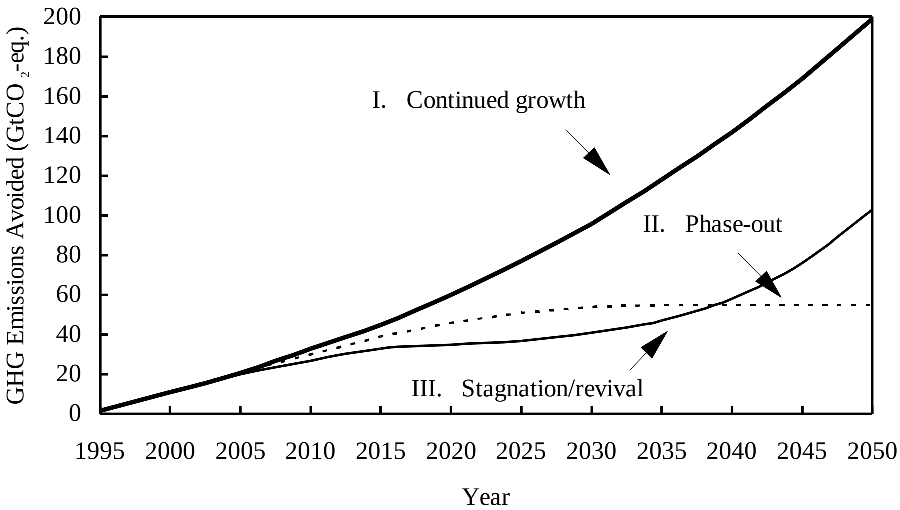

Figure 6. **Cumulated greenhouse gas (GHG) emissions avoided (GtCO2-equiv.)**

Concluding Remarks

The nuclear variants discussed in this paper, as well as results from a number of other studies, show that technically and economically feasible nuclear development paths could contribute significantly to alleviating the risks associated with global climate change. Recognising that up to now it has proven to be difficult to meet the GHG emission reduction targets proposed at international or national levels, it is important to keep open all the options that could help in achieving those objectives.

Nuclear power is one of the options available for alleviating the risk of global climate change and its potential contribution to GHG emissions reduction could be significant. However, the future role of nuclear power will depend on maintaining the high-level of safety achieved by nuclear units operated in OECD countries and implementing high level radioactive waste repositories in order to ensure the sustainability of nuclear power. Keeping the nuclear option open in order to realise its potential will require a number of actions by industries in the nuclear sector and by governments.

In a longer-term perspective, non-electrical applications of nuclear energy, such as heat, potable water and hydrogen production, could be developed, and these applications could enlarge significantly nuclear power's contribution to GHG emission reduction. Research and development would be necessary in order to assess fully the technical feasibility of those applications at the industrial level and the economic competitiveness of nuclear versus fossil fuels and renewable sources. Governments could play an important role by supporting such research and development, and international organisations could assist in this process by promoting and facilitating exchange of information.

REFERENCES

1. United Nations, Kyoto Protocol to the United Nations Framework Convention on Climate Change, FCCC/CP/1997/L.7/Add.1 (10 December 1997), Kyoto (1997).

2. International Institute for Applied Systems Analysis, Global Energy Perspectives to 2050 and Beyond, IIASA, Laxenburg (1995).

3. International Atomic Energy Agency, Comparison of energy sources in terms of their full-energy-chain emission factors of greenhouse gases, IAEA-TECDOC-892, Vienna (1996).

4. United Nations Scientific Committee on the Effects of Atomic Radiation, Ionising Radiation: Sources and Biological Effects, UNSCEAR, New York (1994).

5. International Atomic Energy Agency, Radioactive Waste Management, IAEA Source Book, IAEA, Vienna (1992).

6. International Atomic Energy Agency, International Symposium on Nuclear fuel Cycle and Reactor Strategies: Adjusting to New Realities – Key Issues Paper 1, IAEA, Vienna (1997).

7. Nuclear Energy Agency, International Atomic Energy Agency, Uranium Resources, Production and Demand: Update 1995, OECD, Paris (1996).

8. OECD Nuclear Energy Agency, Infrastructure for Nuclear Energy Deployment – Proceedings of an NEA Workshop held in Paris on 10-11 June 1996, OECD, Paris (1996).

9. International Energy Agency, World Energy Outlook 1996, OECD, Paris (1996).