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The Role of Nuclear Energy in a Low-carbon Energy Future

NUCLEAR ENERGY AGENCY

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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The mission of the NEA is:

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- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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Foreword

World demand for energy is set to increase significantly in the next decades, spurred by economic and demographic growth, especially in developing countries. Unless current trends are reversed, this demand for energy will be met mainly by burning fossil fuel, at the cost of escalating emissions of carbon dioxide and the associated risk of global warming. To curb these emissions, action is needed more than ever to switch to low-carbon energy technologies.

In the decade preceding the TEPCO Fukushima Daiichi accident, nuclear energy had increasingly been considered as a key electricity generation technology to support the transition of fossil-based energy systems to low-carbon systems. Since the accident, several energy scenarios have been published by international organisations such as the International Energy Agency which continue to project a significant development of nuclear energy to meet energy and environmental goals, albeit at a somewhat slower rate than previously projected. At the same time, a large number of countries, including developing countries wishing to launch nuclear power programmes, have confirmed their intention to rely on nuclear energy to meet electricity needs and objectives to reduce carbon emissions.

In this context, this report provides a critical analysis of the contribution that nuclear energy can make to the reduction of greenhouse gas emissions, and evaluates the construction rates needed to reach projected nuclear capacities based on different assumptions regarding the lifetime of existing power plants. It then assesses the barriers to such projected expansion, in terms of technical, economic, societal and institutional factors. Another challenge for nuclear power lies in its capacity to address the constraints of an electricity mix with a high share of renewables, in terms of flexibility and load-following. The impact of new "smart grid" technologies on nuclear energy demand and supply is also analysed.

Long-term prospects for nuclear energy are discussed in terms of technological developments, non-electrical applications of nuclear energy and new operational challenges which power plants could face in terms of environmental and regulatory constraints linked to climate change. A summary and conclusions are presented in the final chapter.

Acknowledgements

This report was produced by an expert group (see list in Annex 2) under the Chairmanship of Jürgen Kupitz from Germany, William D'Haeseleer from Belgium and Steve Herring from the United States, with support from Martin Taylor, Henri Paillère and Ron Cameron of the NEA Secretariat. The active participation of the expert group members is gratefully acknowledged.

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Executive summary

Nuclear electricity generation is virtually free of direct (i.e. during operation) greenhouse gas emissions, but as with any generation technology, there are indirect emissions associated with mining, fuel fabrication, construction and decommissioning of the power plant, and disposal of the waste. Some of these activities can be energy intensive, and depending on the carbon footprint of the energy system where this activity takes place, lead to non-negligible emissions of greenhouse gases. This report provides an in-depth analysis of different studies of current and future fuel cycles, based on life-cycle assessments or environmental product declarations. The analysis considers various parameters: quality of the uranium ore (low grade *vs.* high grade), enrichment technology (gas diffusion *vs.* centrifugal), carbon intensity of the energy used during the processes, etc. and concludes that nuclear power is a low-carbon technology, with overall emissions of the same magnitude as wind or hydro electricity.

The report begins by looking at various scenarios, published by international organisations and aimed at modelling transitions to low-carbon energy futures. In most cases, constraining the evolution of an energy system by limiting carbon levels in the most cost-effective way leads to a high share of nuclear energy. Projections published after the Fukushima Daiichi accident continue to show an important role for nuclear energy as a key contributor to low-carbon systems, even if its contribution is slightly reduced compared to previous estimates. The Blue Map scenario of the International Energy Agency (IEA) *2010 Energy Technology Perspectives*, which foresees 1 200 GWe of nuclear capacity by 2050, is then taken as a case study to evaluate the necessary new build construction rates that would be needed to meet this expansion. These rates depend on assumptions concerning the long-term operation of the existing nuclear fleet. These rates are compared to historical data concerning construction starts or capacity connected to the grid, and it is concluded, based on that data, that a large expansion of nuclear capacity is feasible.

However, data from the past can only give a partial insight into the way nuclear energy can evolve in the future. The perception of nuclear energy by the public, and the constraints associated with this technology, differ greatly from those that were at play in the 1970s. The report therefore reviews all the potential barriers that could prevent nuclear energy from expanding to the levels foreseen by the case study projections. Financing and investment represent

probably the greatest challenges, since the upfront capital investment needed for the most advanced nuclear power plants represents a huge investment for a potential owner, especially a private utility in a deregulated market. The economics of nuclear power plant depend strongly on discount rates, the duration of construction, as well as political risks and electricity market characteristics that affect the operation of the plant as a baseload provider of electricity for 60 years or more. The report also reviews other issues which are often cited as challenges for the future of nuclear power: the set up of the necessary industrial infrastructure and supply chain, the availability of skilled labour, the issue of uranium resources, the siting of new plants – especially in a post-Fukushima Daiichi world, the issue of appropriate management of radioactive waste, the need for standardisation of reactor designs, and finally, public acceptance and institutional, regulatory and legal frameworks without which nuclear energy cannot develop.

The report then addresses the specific challenge of operating nuclear power in a future energy system characterised by a large share of renewable technologies. In such an electrical grid system, frequency control, or stability, and balancing become issues. The case is made that an electric grid is more stable if it includes generating units with high inertia, such as thermal power plants and their turbo-generator sets. Nuclear would then be preferred to coal or gas from the point of view of emissions, and possibly security of energy supply too, if gas is imported as it is in Europe. As far as balancing is concerned, it is argued that even if nuclear is usually operated as a baseload technology, it is also capable of load-following, though this is less cost effective for nuclear power. Smart grid technologies, which could help reshape the electricity demand curve to level the load, would help to increase the proportion of baseload in the system, and this would be beneficial to nuclear power.

Before concluding, the report examines the long-term perspectives for nuclear energy. Technological developments in the area of nuclear systems (Generation IV concepts such as fast neutron reactors and high-temperature reactors, small modular reactors, accelerator-driven systems) and associated fuel cycles (recycling, partitioning and transmutation) are ongoing. If successful, these developments would lead to an improved efficiency of nuclear power and use of natural resources. They would also open the way to new applications of nuclear energy which have the potential to displace processes that are currently based on fossil fuel, and therefore contribute further to the transition to a low-carbon energy future. But new challenges also lie ahead if global warming effects cannot be avoided: heat waves and droughts for instance represent a challenge for thermal power plants sited along rivers, and which require large amounts of water for cooling. Increased environmental and regulatory constraints leading to the limitation of water withdrawal or limitation of thermal

releases will need to be addressed, and this may require new technology developments and reduce the competitiveness of nuclear power.

Finally, the report draws conclusions on the contribution that nuclear energy can make to the transition to a low-carbon energy future. It highlights the main barriers or challenges it needs to overcome to enable its expansion to levels where it can make even more significant contributions than it does today.

1. Introduction

The need to cut emissions of greenhouse gases (GHG), notably carbon dioxide (CO_2) from the burning of fossil fuels, is central to global energy and environmental policy-making. Despite the lack of a global consensus on future emissions reductions to follow the Kyoto Protocol to the UN Framework Convention on Climate Change, many OECD countries have adopted or are considering ambitious targets for emissions reductions in the period to 2050.

This is largely driven by scientific consensus in the 2007 report of the Intergovernmental Panel on Climate Change (IPCC, 2007), which found that the concentration of CO_2 in the atmosphere will need to be stabilised at no more than 450 ppm to have a 50% chance of limiting the global world temperature increase to 2°C. This implies global cuts of 50% or more in emissions by 2050 compared to the levels of year 2000, requiring nothing less than a revolutionary shift away from fossil fuels for energy supply, and particularly for electricity generation.

Nuclear energy already plays an important role in limiting greenhouse gas emissions in the power sector. In 2009, it represented 13.4% of the world electricity production, the second largest low-carbon source behind hydro's 16.4% share. In OECD countries, nuclear energy is by far the largest source of low-carbon electricity, with a share of over 21% of the electricity production (IEA, 2011). Even in the aftermath of the Fukushima Daiichi accident, many governments consider that nuclear power can continue to play an important role in a low-carbon energy future, alongside renewable and carbon capture and storage (CCS) technologies. However, the share of nuclear energy in tomorrow's low-carbon future will depend on many factors, which include national energy policies, public acceptance, economic environment, investment conditions, as well as the rate of commercial deployment of CCS and renewable energies. The Fukushima Daiichi accident in Japan in March 2011, caused by an unprecedented earthquake and tsunami, has certainly clouded the prospects for nuclear energy. Belgium, Germany and Switzerland have announced or confirmed phase-out policies. Italy has abandoned plans for re-introducing nuclear power. Many more countries on the other hand have confirmed their intention to continue with new build plans, albeit at a somewhat slower pace than initially planned. This is the case for China, the Czech Republic, India,

Poland, the Republic of Korea, the Russian Federation, Turkey, the United Kingdom, the United States and Vietnam.

Under those circumstances, it is important to revisit the contribution that nuclear energy can make to the reduction of GHG emissions from the power sector. This report aims precisely at addressing issues that will determine the share of nuclear energy in tomorrow's low-carbon future. It also aims at providing factual answers to criticisms concerning the effective contribution of nuclear energy to the fight against climate change. For instance, it has been argued by some that nuclear is largely irrelevant to reducing emissions, because capacity could not be expanded quickly enough or because of constraints on uranium supply or other inputs. It has also been argued by others that CO_2 emissions from fossil energy use in the nuclear fuel cycle could become significant, making overall emissions comparable to those from fossil power plants.

To address these issues, the OECD/NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) established the ad hoc Expert Group on Climate Change and Nuclear Energy Build Rates in 2009 to carry out a study. This report is the final result of the expert group's deliberations, and is addressed primarily at OECD governments considering the use of nuclear energy as part of their overall national strategy to meet energy and environmental policy goals.

The project builds on existing work by the IEA and other organisations that have prepared energy supply scenarios which foresee a role for nuclear power in reducing CO_2 emissions. The report aims to establish whether the assumed contributions of nuclear power are realistically achievable, or whether constraints on nuclear build rates or fuel cycle capacities will limit the role of nuclear energy. The interaction between increasing nuclear capacity and other developments in energy supply, such as the growth in intermittent renewables, is also examined. The study also addresses the question of how much indirect CO_2 is produced in the overall nuclear cycle, and the extent to which this could rise given the assumed increases in nuclear generating capacity.

The report is organised as follows.

In Chapter 2, various published estimations of indirect GHG emissions from nuclear power are analysed and compared. It is concluded that apart from studies which consider nuclear fuel cycles involving extraction of very low-grade ore in a carbon-intensive electricity supply environment, nuclear power has indeed very low indirect GHG emissions, and these will become even lower in the future as the overall carbon intensity of the national energy mix decreases.

In Chapter 3, scenarios of nuclear energy capacity expansions are reviewed, including projections published after the Fukushima Daiichi accident which foresee a decrease of the order of 10% compared to projections made prior to the accident. The building rates for new plants needed to reach those projections are calculated, under different assumptions on long-term operations of the existing nuclear reactor fleet.

In Chapter 4, issues that are key to the projected capacity expansions are analysed: financing and investment, industrial infrastructure, human resource and knowledge management, uranium supply and fuel cycle, siting aspects, radioactive waste management policies, standardisation of designs and public acceptance.

Chapter 5 analyses the capabilities and limitations of nuclear power operating in an electricity system with a high share of renewables. The load-following capabilities of present and future nuclear reactors are analysed, and the impact of "smart grid" technologies on the level of demand for baseload capacities is discussed.

In Chapter 6, long-term perspectives for nuclear energy are given, from the point of view of its further contribution to a low-carbon energy future, as well as from the point of view of adaptation to new climatic conditions, in the event that significant climate change cannot be avoided. Technology developments, e.g. Generation IV or small modular reactor (SMR) designs are reviewed, operational and environmental constraints and new applications of nuclear energy are analysed.

Finally, conclusions are drawn in Chapter 7.

The overall objective of the report is to present a factual analysis of the technical potential for an expanded nuclear capacity to contribute to reductions in CO_2 emissions in the period to 2050. In doing this, it aims to contribute to the ongoing policy debates at national and international levels on the optimum way to achieve a low-carbon energy future in response to the threat of climate change.

References

IEA (2011), *Electricity Information 2011*, IEA Statistics, International Energy Agency, OECD, Paris, France.

IPCC (2007), *Intergovernmental Panel on Climate Change Fourth Assessment Report: Climate Change 2007*, available at www.ipcc.ch/.

2. Greenhouse gas emissions from the nuclear cycle

Electricity generation from nuclear power plants is virtually free of direct greenhouse gas emissions, i.e. emissions from the nuclear power plant itself. However, as with all electricity generating options, there are some indirect emissions from the full nuclear energy cycle, i.e. those associated with mining and milling of uranium ore, the manufacture of enriched fuel elements, the construction and decommissioning of the nuclear power plant and the disposal of waste. These activities require power and fuel, and the associated emissions are indirect emissions from the nuclear fuel cycle.

Most studies show that the overall indirect emissions from nuclear energy are rather small and comparable to renewable energy sources, such as wind power. However, there are some studies that suggest these emissions are, or could become, much greater than those from renewables, to the extent that nuclear power would not be able to contribute significantly to emissions reductions. This chapter aims to clarify some of the issues surrounding these studies.

Assessments of GHG emissions from different energy sources fall into two main types: life-cycle analysis (LCAs) and environmental product declarations (EPDs). LCAs exist in different forms, but most evaluate all non-negligible inputs and outputs from each process involved in the relevant cycle throughout the lifetime of the facilities employed (e.g. including construction and decommissioning operations as well as operation), and assess the related emissions. The aim of an LCA is usually to produce an average or typical value for a particular technology. For electricity plants and their associated fuel cycles, the result is expressed in terms of emissions per unit of electricity produced.

This necessarily involves setting some system boundaries, and the result depends strongly on the accuracy and completeness of the available data and on the assumptions made. One major source of variable results is that the same type of facilities in different locations or using different technologies may have very different inputs and outputs. As a result, different LCAs, even when prepared using credible methodologies and peer-reviewed, can often produce widely varying results.

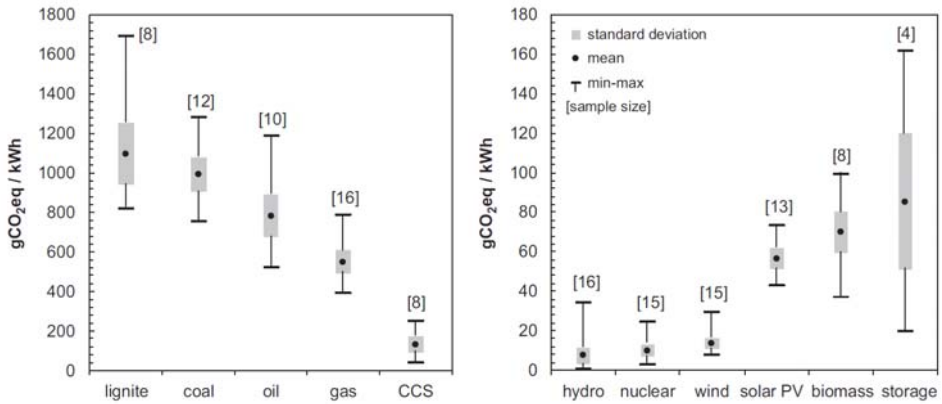
EPDs have been developed by industry to assess the emissions and other impacts that can be directly and indirectly attributed to a particular product (e.g. the electricity from an individual generating plant). Such an analysis includes actual data from the facilities that are actually used to provide the product concerned, rather than taking average or typical data for a class of facility.

2.1. Life-cycle assessment of emissions from nuclear power

Many contributions on the life-cycle assessment of nuclear power and other electricity generating plants have been published in the open literature. In some cases, the results of these studies contradict each other, as do the conclusions drawn from them. Most of the referred publications show that the overall indirect emissions of nuclear plants are quite limited, but a few studies argue that these emissions are heavily underestimated. In this section, a brief overview of published results as well as some qualifying remarks are given.

A comprehensive review of published studies has been undertaken by Weisser (Weisser, 2007). A summary of his results is shown in Figure 2.1.

Figure 2.1: Range of GHG emissions for indicated power plants



Note: Figures in brackets are the number of studies considered for that type of technology. Note the factor 10 difference in the ordinate of the two charts.

Source: Weisser, 2007, reprinted with permission from Elsevier.

Another comparison has been made by the World Energy Council (WEC, 2004). This sample of studies gives a range for emissions from nuclear power of between 3 and 40 g CO_2/kWh. The European Nuclear Energy Forum's SWOT analysis (ENEF, 2010) also provides several examples from the literature, such as the WEC study and an earlier study performed by the International Atomic

Energy Agency (IAEA, 2000) which found a range for emissions from the nuclear fuel cycle between 9 and 21 CO_2/kWh. Fthenakis (Fthenakis *et al.*, 2007) include low, intermediate and high results for lifetime GHG emissions from nuclear life cycles and conclude that the largest differences can be explained by different assumptions with respect to enrichment, construction and operation. However, detailed input data for these process steps are lacking.

Important to mention is the work by Sovacool (Sovacool, 2008), who sets out to calculate a mean value for the overall emissions by averaging the global results of 19 LCA studies forming a subset of, as stated by the author, "the most current, original and transparent studies" of the 103 studies initially identified. However, a critical assessment reveals that a majority of the studies representing the upper part of the emissions range can be traced back to the same input data prepared by Storm van Leeuwen and Smith (Storm van Leeuwen, 2005).

Storm van Leeuwen and Smith make use of data related to the extraction of uranium from very low-grade ores, which makes the extraction stage both very energy and GHG intensive. Their figures show a nuclear fuel cycle consuming more energy than the overall electrical energy output over a nuclear plant's lifetime when relying on very low-grade ores in the long term.

After careful analysis, it must be concluded that the mix of LCAs selected by Sovacool gives rise to a skewed representation of the different results available in the literature. Furthermore, since different studies use different energy mixes and other varying assumptions, averaging the GHG emissions of these studies is not a sound method to calculate overall emission coefficients, as it does not consider any site-specific information. Therefore, for current plants, the previously mentioned attributional approach used in EPDs is to be preferred.

Beerten (Beerten *et al.* 2009), being aware of these earlier reviews, have tried to shed some light on the discrepancies between the different studies. They aim to give a detailed picture of the GHG emissions in the different process stages of the nuclear fuel cycle by comparing the results of selected case studies, reflecting the range of results available in the literature: Torfs (Torfs, 1998), a Belgian study by Voorspools (Voorspools, 2000), Storm van Leeuwen and Smith, and an Australian study by Lenzen (Lenzen, 2006; 2008).

In Beerten (Beerten *et al.* 2009), the GHG emissions are analysed together with the indirect energy use, since most of the emissions result from the use of energy in the different process stages. In the comparative analysis, the nuclear life cycle considered is that of a pressurised water reactor (PWR) without recycling of nuclear fuel. To disentangle the contributions of the different

process steps to the overall result and to make a detailed comparison of the selected case studies, the consolidated results have been recalculated according to the same methodology, but using the inputs and assumptions of the original studies.

As to the methodology used in the original studies, it was found that the assessment method for computing the energy and GHG intensity is a major cause of the diverging results. Although a high emphasis has recently been put on GHG emissions, the analysis in two studies was carried out using an energy analysis. One method to perform such an energy analysis is a process chain analysis (PCA). Such an analysis is detailed in that it considers energy used and emissions produced in each step of the chain, but can lead to a systematic error due to the arbitrary selection of the system boundaries.

A second method is the input-output analysis (IOA), using cost and energy intensity data for each industrial sector involved. A simplified method based on an average energy intensity, in which the overall monetary cost is multiplied by an economy-wide energy intensity, is used by Storm van Leeuwen for a number of process steps. In addition, the scope of the studies is another important factor determining the overall result: not all of the studies take into account every process step.

In two of the studies investigated, the GHG emissions themselves are calculated as a by-product of an energy analysis. Making a clear distinction between different primary energy carriers for all process steps involved, and identifying the GHG emissions for each step, as done by Torfs and Voorspools, results in a more accurate assessment of the GHG emissions. Computing the GHG emissions by multiplying the overall thermal and electrical energy inputs with single average GHG intensities, as performed in the two other studies, makes the results highly dependent on assumptions about the background energy system.

When the GHG intensities are changed in line with other established studies, the results from Lenzen are significantly lowered from 57.7 g CO_2/kWh (being their best estimate) to 32.3 g CO_2/kWh (assuming an average European electricity mix and the use of natural gas for thermal power generation). For the Storm van Leeuwen study, compared to their own results of 117 g CO_2/kWh for current day practices and up to 337 g CO_2/kWh when relying on low-grade ores (presuming an all-nuclear electricity input), when the coal intensive background economy from Lenzen is used, the results become 236 to 800 g CO_2/kWh. This illustrates the large dependence of the results on the GHG intensity of the background economy.

The most important reasons for the very high emissions in the study by Storm van Leeuwen and Smith, in the case where low-grade uranium ores are used, are the high energy inputs for mining and milling, the hypothetical model used for mine site clean-up, and the very low extraction yield assumed. This results in GHG emissions from the uranium mining and milling stage contributing up to 70% of the overall result of 337 g CO_2/kWh.

In analysing the result for higher-grade ores (117 g CO_2/kWh), it was found that the highest contributions stem from the construction of the power plant, the operation of the plant, and all downstream life-cycle steps, such as waste storage, decommissioning and final waste disposal. The main reason for these high contributions is the assessment method used for the construction stage, in which total construction costs are multiplied by the average energy intensity of the overall energy system. All subsequent downstream process steps, as well as operation and maintenance, are assessed using similar methods or are assumed to use a percentage of the overall construction energy, thereby leading to very high results.

The results obtained by Torfs and Voorspools (7 to 18 g CO_2/kWh, with 7.7 g CO_2/kWh as the best estimate for Belgium) are far smaller than those obtained by Storm van Leeuwen and are in line with other studies available in the literature. However, the scope of the study does not include storage and final disposal of waste. It also assumes an all-nuclear electricity input for enrichment carried out using energy-intensive gas diffusion technology, which results in a rather small GHG contribution from this step in the fuel cycle.

The GHG emissions in Lenzen's study (10 to 130 g CO_2/kWh, with 57.7 g CO_2/kWh as best estimate for Australia) are higher than the results from the Belgian study, primarily due to the assumed GHG intensive high coal use energy economy. Significant emissions result from the enrichment phase (28%) and the operation and maintenance of the power plant (25%). The higher GHG emissions are also reflected in the higher energy use in the different process steps, which is mainly due to the use of an IOA-based assessment method, whereas a PCA was used for the majority of the process steps in the Belgian study. Lenzen bases his analysis on the literature overview provided by Storm van Leeuwen for some process steps in the upstream part of the fuel cycle. However, the resulting overall energy use and GHG emissions in Lenzen's study are smaller due to a more correct assessment method of the energy use in the downstream part of the fuel cycle. When a European-type energy mix is considered instead of the coal economy assumption initially used, Beerten finds that Lenzen's model yields a lower best estimate value of 32 g CO_2/kWh.

Finally, it is worth mentioning the recently published WNA report (WNA, 2011) on life-cycle greenhouse gas emissions for various electricity generation sources. This report is based on a review of over 20 studies published by international organisations, governmental agencies and universities. The conclusions of this report in terms of life-cycle GHG intensity are summarised in Table 2.1. These are in line with the above data, and identify the enrichment phase (choice of technology, gas diffusion or centrifugal, and specificities of the electricity mix powering the process) as the main source of indirect emissions, and the main factor influencing the range of emissions. The report also cites construction of the power plant as an area where emissions are higher in the case of a nuclear reactor than for other comparable generating technologies, since nuclear reactor designs involve multiple safety barriers which represent additional civil works.

Table 2.1: Range of GHG emissions from different electricity generation technologies

Technology	GHG emissions, in tonnes CO_2 eq/GWh		
	Mean	Lower range	Upper range
Lignite	1 054	790	1 372
Coal	888	756	1 310
Oil	733	547	935
Natural gas	499	362	891
Solar PV	85	13	731
Biomass	45	10	101
Nuclear	29	2	130
Hydroelectric	26	2	237
Wind	26	6	124

Source: WNA, 2011.

Table 2.2 summarises the findings of the different studies cited above in terms of GHG emissions of the nuclear fuel cycle.

Table 2.2: Range of GHG emissions from nuclear power
Synthesis of cited studies

Source of data	GHG emissions for nuclear power generation, in tonnes CO_2 eq/GWh		
	Mean	Lower range	Upper range
IAEA (2000)	–	9	21
Lenzen (2008)	57.7	10	130
Lenzen (2008)/ Beerten *et al.* (2009)	30		
Torfs (98)/Voorspools (2000)/ Beerten *et al.* (2009)		7	18
WEC (2004)	–	3	40
Weisser (2007)	–	2.8	24
WNA (2011)	29	2	130

2.2. Emissions from future nuclear fuel cycles

As is clear from the above discussion, the most important factors influencing the future CO_2 levels of different nuclear fuel cycle alternatives are the quantity of fresh uranium needed, the ore grade and the carbon intensity of the electricity used in the different process steps in the life cycle. The ore grades of exploited uranium deposits could decline over time, which would increase energy use in mining and milling. Conversely, diffusion enrichment technology, which uses more than 25 times more energy than centrifuge enrichment technology, will be phased out over the next few years. The generation mix of the electricity used in the different steps in the nuclear fuel cycle will most likely change towards lower-carbon emissions. The recycling of plutonium and actinides could reduce the need for uranium mining, and also reduce volumes of high-level nuclear waste for repository disposal. This would, however, require an extra stage in the cycle, that of reprocessing of spent fuel.

The work by Wiberg (Wiberg, 2009) helps to clarify the issues on the fuel cycle. A slightly modified version of the emission profile for the Forsmark nuclear power plant (NPP) (as presented in its EPD, with once-through cycle) was used as the reference scenario in a set of future fuel cycle scenarios prepared by the OECD Nuclear Energy Agency (NEA, 2006). These scenarios include different combinations of Generation III+ reactors and Generation IV reactor types chosen from the six selected by the Generation IV International Forum (GIF). Based on the emission profile of the reference scenario, the mass flows in the different fuel cycles and different carbon intensity of the electricity

feeding the life cycle, Wiberg has made estimates of the CO_2 emissions (Wiberg, 2009).

The reference scenario has the following characteristics: Forsmark NPP, 3 boiling water reactors (BWR), total capacity 3 158 MW, once-through cycle, uranium from the Rössing mine in Namibia with ore grade 0.028% U, centrifuge enrichment and electricity input based on national generation mixes; spent fuel is prepared for final repository in line with the Swedish concept; transmission and distribution to a 130-kV customer, distribution losses 3% (input data from 2006).

If future ore grades follow historical trends, they will decline with higher CO_2 emissions as a possible consequence. Hence, Wiberg has set up scenarios for two different ore grades, 0.01% and 0.001% (recall that in the reference scenario, the uranium originates from the Rössing mine, with ore grade 0.028% U) (Wiberg, 2009). Furthermore, for the scenarios below, a best-case and a worst-case estimates are computed, based on different (opposing) assumptions.

The studied scenarios are (Wiberg, 2009):

- Open cycle Forsmark: The once-through cycle; spent fuel is prepared for final repository. “Similar” to the reference case, but now subject to different ore grades and other assumptions (worst and best cases).
- Open cycle EPR: The once-through cycle, slightly smaller fuel requirements than Forsmark but higher enrichment; spent fuel is prepared for final repository.
- Pu LWR: A partially closed cycle where plutonium is multi-recycled in light water reactors (LWR) reactors; other actinides are prepared for final disposal.
- LWR+FR: A fully closed cycle, with LWR and fast reactors (FR); the nuclear waste consists of reprocessing losses and is practically free of actinides.

Assumptions applied to design best- and worst-case scenarios are presented below:

- *Electricity generation mixes and fuels*: In the worst-case scenarios, fossil-based electricity feeding is assumed. In the best-case scenarios, electricity is provided from low CO_2 emitting sources, such as hydro and nuclear power. Fuels used on site, the share of electricity in relation to gross

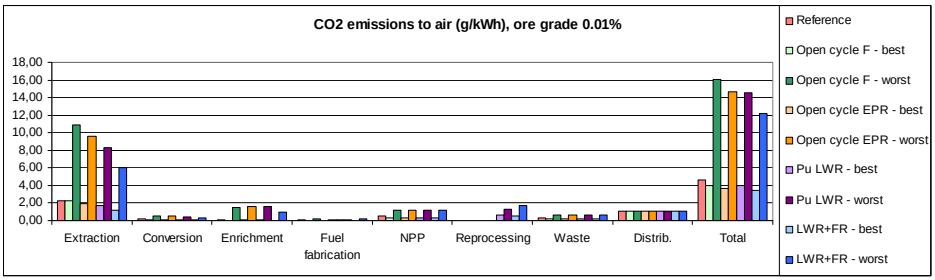
energy use and electricity used to produce input substances are the same as in the reference scenario as well as all transportation.

- *Mass flows*: The number of process operations required is assumed to be proportional to the uranium need in the different scenarios. For example, if the uranium need is 60% compared to the reference scenario, then the amount of conversion operations required has been set to 60%. The enrichment levels proposed in NEA (2006) are taken into account when estimating the separative work unit (SWU) requirements.
- *Energy use, mining and milling*: To estimate energy use at the suggested ore grades, a simple regression equation has been applied in the best-case scenarios. In the worst-case scenarios, it has been assumed that the energy use was inversely proportional to ore grade.
- *Energy use, advanced fuel cycles, fuel fabrication and reprocessing*: Fabrication of fast reactor fuels and mixed-oxide fuels (MOX) will probably be more complex than fabrication of uranium oxide fuels (UOX) due to technical challenges. Since no better guidance has been found, it has been assumed that the energy use associated with fuel fabrication corresponds to future cost estimates of that process in the worst-case scenarios, but would be equivalent to the energy use of UOX fabrication in the best-case estimates. A similar approach has been used for reprocessing with reprocessing of LWR fuel at La Hague, France (Ecoinvent database)[1] as reference data.
- *Energy use, other processes*: No detailed assessment has been made for operations such as conversion and fuel fabrication for once-through cycles. Instead, the energy use is assumed to be doubled in the worst-case and halved in the best-case scenarios. The same applies to the operation/ construction of the NPP and the waste management (for all fuel cycle alternatives). Energy use associated with electricity distribution has been assumed to stay at the reference level, as it is not directly dependent on the fuel cycle.

For an average ore grade of 0.01%, the highest value obtained in the worst-case scenarios is 16 g CO_2/kWh electricity delivered to the customer for the open cycle with LWR reactors only. However, in the best-case scenarios, the computed emissions stay close to the value of the reference scenario. The contribution of CO_2 emissions associated with reprocessing is small but noticeable for the advanced cycles. The results are summarised in Figure 2.2.

1. Available at www.ecoinvent.ch.

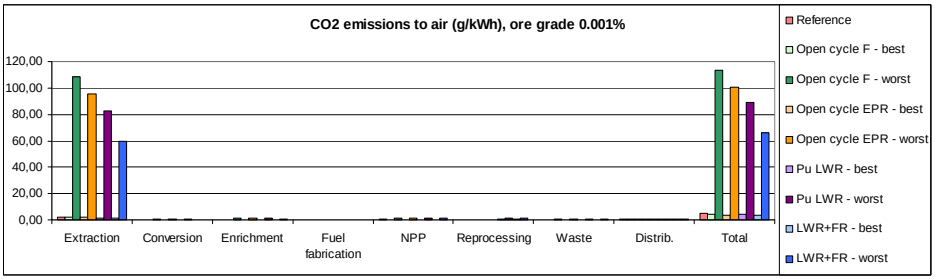
Figure 2.2: CO_2 emissions for different fuel cycles for ore grade 0.01%



Source: Wiberg, 2009.

Uranium extraction completely dominates in the worst-case scenarios at ore grade 0.001 %. Nevertheless, in the best-case scenarios, the results remained close to the reference level (see Figure 2.3).

Figure 2.3: CO_2 emissions for different fuel cycles for ore grade 0.001%



Source: Wiberg, 2009.

At an ore grade of 0.01%, nuclear power clearly belongs to the low-carbon technologies of today, even in a society dominated by fossil fuel electricity generation. In the case of an extremely low ore grade of 0.001% and fossil-based electricity use, the nuclear fuel cycle will still emit one order of magnitude lower CO_2 emissions than coal power. However, if society moves towards a CO_2-lean or -neutral energy economy, the indirect emissions of nuclear power generation will gradually diminish. The same applies to most renewable energy conversion technologies.

As discussed above, the life-cycle CO_2 emissions per kWh end-use electricity from current nuclear power plants are low. Future technology development and decrease of ore grades may lead to different results, for better or for worse.

Looking towards the future, it is important to distinguish between the near- to mid-term or transitional energy evolution (from now till 2030-2040 or so), on the one hand, and the longer term (> 2050 or so) when the energy economy is supposed to be grossly CO_2 neutral, on the other hand.

Current and near-term nuclear investments will be operational in a near-future and transitional energy system, in which there will still be a considerable fossil fuel component in the energy mix. During that period, NPPs will not have to rely on extremely low ore grades, so that the indirect emissions will still be low to moderate. But even these non-zero emissions are negligible compared to the fossil-fired plants they will replace. Indeed, even modern fossil-fuelled plants without CCS emit of the order of 0.4 to 0.8 kg CO_2/kWh (for natural gas CCGTs and coal-fired USCs, respectively; for lignite, the results are of the order of ~1 kg CO_2/kWh). Even with CCS, which is not expected to be *routinely commercially* available before 2030,[2] fossil fuel-fired plant emissions will still emit several tens of g CO_2/kWh. In the time frame 2030-2040, nuclear power will still be a low-carbon technology, and what is more, the nuclear fuel cycle will profit from the CCS application in the electricity generation fuel mix.

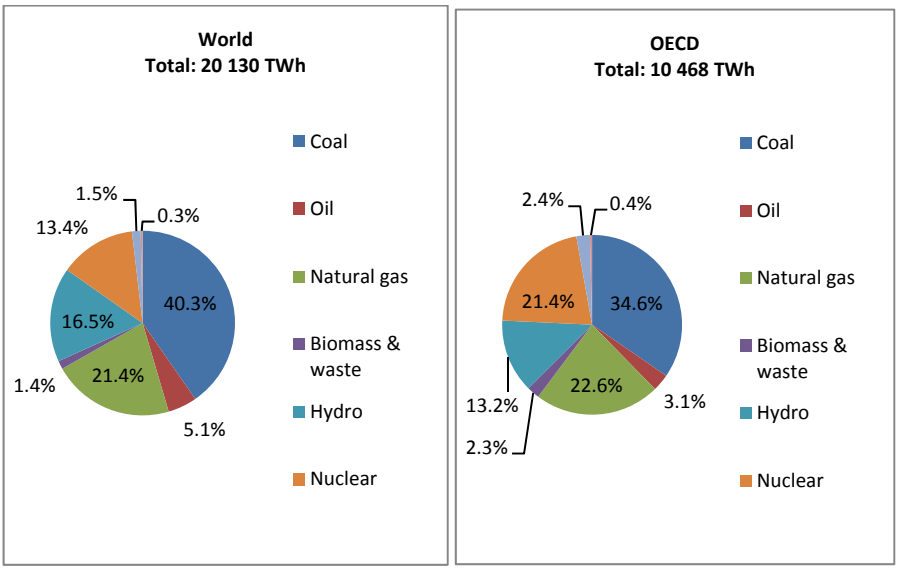
For the ***long-term future***, even if there is a need for low grade ores, the nuclear fuel cycle becomes *de facto* carbon free since the background energy economy will be carbon neutral or almost carbon free. In the long run, nuclear remains a low-carbon technology.

2.3. Nuclear energy's contribution to today's emissions reductions

In 2009, nuclear represented 13.4% of the world's total electricity generation, and over 21% of the OECD's electricity generation (see Figure 2.4). The same year, direct CO_2 emissions from burning fossil fuel (coal, natural gas or oil) for electricity and heat amounted to about 12 Gt (CO_2), 4.7 Gt produced in OECD countries, and over 7 Gt produced in non-OECD countries (IEA, 2011a; 2011b).

2. In the period 2015-2030, a reasonable number of pilot plants with CCS will be operational worldwide, which is different from being "routinely commercial" available, with a completely laid out CO_2 transport grid and storage sites commercially accessible.

Figure 2.4: Share of electricity production by technology in 2009, at world level (left) and at OECD level (right)



Note: Nuclear represents 13.4% of the world's electricity generation, and over 21% of the OECD electricity generation.

Assuming indirect emissions of 30 tonnes of CO_2 eq/GWh[3] for nuclear energy, the total emissions produced by nuclear power plants in 2009 would represent 0.08 Gt CO_2 globally and 0.07 Gt at the OECD level. This is insignificant compared to the direct emissions produced by burning fossil fuel. Furthermore, replacing nuclear by coal (~1 000 tonnes CO_2 eq/GWh), gas (~500 tonnes CO_2 eq/GWh) or a nuclear-free mix such as that of a country like Denmark (~300 tonnes CO_2 eq/GWh[4]) would represent additional emissions of:

- 2.6 Gt CO_2 (coal), 1.3 Gt CO_2 (gas) or 0.8 Gt CO_2 (mix) at the world level, representing respectively 22%, 11% or 7% of the world's CO_2 emissions from the power sector;

3. This value corresponds to the mean value of emissions for nuclear which appears in Table 2.1, and is higher than the mean value found by Weisser (about 10 tonnes CO_2-eq/GWh) shown in Figure 2.1. Taking the lower range and upper range values appearing in Table 2.1, indirect annual emissions from nuclear power would represent between 0.03 and 0.35 Gt CO_2.

4. In 2009, Denmark produced 36.4 TWh from a mix consisting of 18.5% renewables, essentially wind, 70.3% fossil – coal and gas, and 11% biofuel and waste, and with CO_2 emissions representing 303 tonnes CO_2 eq./GWh (IEA, 2011a, 2011b).

- 2.2 Gt CO_2 (coal), 1.1 Gt CO_2 (gas) or 0.7 Gt CO_2 (mix) at the OECD level, representing respectively 47%, 23% or 15% of the OECD's CO_2 emissions from the power sector.

In conclusion, even taking into account pessimistic evaluations of its indirect emissions, nuclear energy is today a major contributor to the reduction of CO_2 emissions in the power sector.

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3. Status of nuclear power and outlook to 2050

3.1. Current status

At the end of 2010, there were 441 power reactors in operation in 30 countries, totalling almost 375 GWe of installed capacity (IAEA/PRIS). Overall, nuclear power provides around 13.4% of global electricity, and 21% of electricity in OECD countries. In addition, 67 new power reactors were officially under construction in 15 countries at the end of 2010.[1] Of these, China had 27 units under construction, and the Russian Federation had several large units under construction. Among OECD countries, the Republic of Korea had the largest expansion underway with 5 units, but Finland, France, Japan and the Slovak Republic were each building one or two new units. In the United States, a long-stalled nuclear project has been reactivated. In total, these new units can be expected to add around 60 GWe of new capacity over the next few years.[2]

In March 2011, a Level 7 (INES scale) accident occurred at the Fukushima Daiichi nuclear power plant following a major earthquake and tsunami. As a consequence of this accident, several countries reversed their policy towards nuclear energy, choosing either to phase out their existing fleet over the next two decades (Belgium, Germany and Switzerland), or abandoning plans to reintroduce nuclear energy into the country (Italy). A majority of countries have on the other hand, confirmed their plans to continue the development of nuclear energy, albeit at a slower pace than initially anticipated. In June 2011, an IAEA ministerial conference on nuclear safety adopted a declaration calling for an

1. Out of those 67 reactors under construction, 11 were started before 1988 and had their construction halted or delayed for several reasons. Construction has now resumed for all but 3 – so overall 64 reactors could be considered as being actively constructed at the time.

2. The overall situation changed slightly during 2011 mainly as a result of the Fukushima accident: as of 1st March 2012, 436 reactors are in operation representing a capacity of over 370 GWe, and 60 reactors are under construction, representing a capacity of 57 GWe. In February 2012, the United States Nuclear Regulatory Commission approved a Combined Operating License for the construction and operation of two new units. These are the first licenses issued in the United States since 1978.

improvement in global nuclear safety, and asked the IAEA to prepare a safety action plan. This plan was endorsed at the IAEA General Conference in September.

In nearly all countries that have nuclear power, governments ordered safety reviews – so-called "stress tests" – to be performed under the authority of the nuclear regulators, to assess, *inter alia*, the resistance of nuclear power plants (including those under construction) to major earthquakes and flooding. International reviews and sharing of best practices are foreseen before final recommendations are issued by the regulators (in 2012). Preliminary information published by the regulators themselves indicate that in the majority of cases, existing nuclear power plants can operate safely under foreseeable seismic loads or flooding. Some safety upgrades (e.g. in the area of emergency power generation, flooding prevention, essential core cooling, seismic resistance of some equipment) and updates of regulations and procedures may still be required in some cases to further enhance the safety of nuclear power plants. These recommendations may also limit the extent of the licensing of long-term operation for some of the older nuclear power plants.

For Gen III/III+ plants that are under construction or planned, the cost implication of the requirements emanating from the lessons learnt from the Fukushima Daiichi accident is believed to be limited, since many of these designs already incorporate safety systems against severe accidents (NEA, 2011). This means that the investment estimates corresponding to future nuclear new build published before March 2011 can still be considered realistic. However, more extensive siting work and more demanding regulatory approval processes will undoubtedly lead to some additional costs and delays, which cannot be quantified at this stage.

Many energy roadmaps published over recent years had foreseen that nuclear energy would play a key role alongside renewable technologies and CCS in the transition to a low-carbon energy future. Projections and scenarios are currently being revised as a consequence of the Fukushima Daiichi accident and its impact on energy policies and public acceptance of nuclear energy. The current world economic crisis is also having an effect on electricity demand and the ability to finance large capital investments in the energy sector, so near- and mid-term nuclear energy projections are likely to be affected for those reasons too. In the long term for countries willing to pursue the nuclear option, the fundamental reasons for having nuclear power in terms of greenhouse gas emission reductions, competitiveness of electricity production and security of supply still apply, and overall capacity is still expected to grow in the coming years to match rising electricity demands while moving to low-carbon energy sources.

In the next sections, scenarios published before and after the Fukushima Daiichi accident will be considered, and building rates to achieve those projections will be assessed, taking into account various assumptions on long-term operations of the existing nuclear reactor fleet. It is recalled that these scenarios are by no means predictions, but rather projections of how the energy mix of various regions of the world could evolve taking into account economic development and demographic growth assumptions, enacted or planned energy policies and commitments to reduce greenhouse gas emissions, as well as financial, social and technological constraints.

3.2. Scenarios for nuclear energy expansion to 2050

To assess the potential contribution of nuclear power to reducing greenhouse gas emissions by 2050, it is necessary to consider scenarios for overall energy and electricity supply over the next several decades, as well as scenarios for the growth of nuclear generating capacity. The present study will not attempt to prepare new scenarios, but will consider existing published scenarios. Given that the intention is to assess the maximum contribution that nuclear could make, the study will concentrate on those scenarios that have the highest component of nuclear power in the energy supply mix.

The principal scenarios considered in this study will be those prepared by the IEA. Like the NEA, the IEA is part of the OECD system, and produces comprehensive energy scenarios to 2030 (or 2035) and 2050. These regularly updated scenarios take into account a wide range of economic and technological factors in modelling possible energy futures, including the need to reduce CO_2 emissions from the energy system at the lowest cost.

The IEA scenarios will also be compared with energy and nuclear power scenarios prepared by other organisations, to provide additional perspectives. The various scenarios are each described and summarised below.

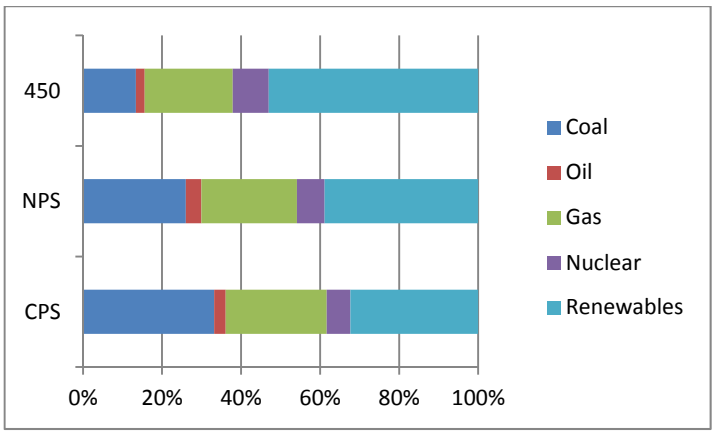
World Energy Outlook

The *World Energy Outlook* (WEO) is published annually by the IEA, and has become one of the most authoritative reports on the future of energy supply. In 2011 (IEA, 2011), the WEO presents a reference, or business-as-usual, scenario, essentially based on a continuation of existing (i.e. enacted) policies and trends (Current Policies Scenario). The New Policies Scenario (NPS) takes into account announced commitments and plans. Given the importance now placed on reducing greenhouse gas emissions, the WEO's other major scenario is the "450 policy" case, that examines the changes in the energy system that

would be needed to bring the concentration of CO_2 equivalent in the atmosphere to below 450 parts per million by 2050. This is the level considered to be necessary to avoid the worst effects of global warming.

In its 2011 edition, published in November (IEA, 2011), the WEO scenarios extend to 2035, by which time nuclear capacity is seen as reaching 865 GWe in the 450 policy scenario, up from 393 GWe in 2009. In other words, it is seen that nuclear capacity could more than double over the next 20 years. In the New Policies Scenario, the nuclear capacity is projected to reach 633 GWe. In the baseline case (CPS), nuclear capacity would grow more modestly, to some 549 GWe, which still represents an increase of nearly 40% compared to 2009. The additional growth in the 450 ppm scenario can be seen as the direct result of efforts to control CO_2 emissions. Figure 3.1 shows the breakdown of electricity supply sources in the WEO 2011, 450 policy scenario.

Figure 3.1: Composition of electricity generation capacity by fuel in 2035 for different scenarios (CPS, NPS and 450 ppm)



Source: IEA, 2011.

Energy Technology Perspectives

The *Energy Technology Perspectives* (ETP) study, updated every two years, is the IEA's main effort to assess the longer-term energy trends, based principally on an assessment of the potential of different energy technologies. It builds on the WEO scenarios, extending the analysis to 2050. It also has a business-as-usual scenario, called the baseline case, as well as a scenario illustrating the contribution of different energy technologies in reaching the overall target of limiting CO_2 equivalent concentration in the atmosphere to 450 ppm. The latter is known as the "Blue Map" scenario. An important driver

of this scenario is reducing CO_2 emissions in the most economically efficient manner.

The ETP 2010 Blue Map scenario (IEA, 2010) projects an installed nuclear capacity of almost 1 200 GWe[3] in 2050, compared to 370 GWe at the end of 2009, making nuclear a major contributor to cutting energy-related CO_2 emissions by 50%. This nuclear capacity would provide 9 600 TWh of electricity annually by that date, or around 24% of the electricity produced worldwide. By 2050 nuclear power would become the single largest source of electricity, surpassing coal, natural gas, hydro, wind and solar. Given that it can be expected that most existing capacity will have been retired by that date, even with lifetime extension, the great majority of this capacity would need to be constructed over the coming 40 years.

The ETP Blue Map scenario assumes that nuclear capacity can be added at an average rate of some 30 GWe per year over the period. A high nuclear variant that removes this assumed limit postulates that as much as 2 000 GWe of nuclear capacity could be added, according to other economic factors. This implies nuclear construction at an average rate of around 50 GWe per year. The IEA's modelling finds that such a large nuclear contribution would reduce the overall cost of reducing CO_2 emissions, compared with the central Blue Map case.

The Blue Map scenario will be taken as the reference case in the rest of the report to evaluate the required nuclear build rates to 2050 under various assumptions of long-term operation of the existing nuclear fleet, and to assess whether such build rates can be realistically achieved. This scenario has been chosen, not because it is more likely than others, but because it projects a large development of nuclear power. Potential barriers to this development will be examined in the following chapter.

Other scenarios

The NEA itself published scenarios for future nuclear generating capacity, in its *Nuclear Energy Outlook 2008* (NEA, 2008). To 2030, these were based on an assessment of the plans and policies of all countries with existing nuclear programmes and those considering new nuclear programmes. The NEA scenarios were also extended to 2050, with the later two decades based on assumptions about the rates of construction of new nuclear plants. The result of

3. The 2012 edition of *Energy Technology Perspectives* is currently in preparation. The projection of 1 200 GWe nuclear capacity by 2050 is likely to be decreased by about 10%.

this analysis was a global nuclear capacity of about 620 GWe by 2030, rising to over 1 400 GWe by 2050. This assumes that by far the most rapid nuclear expansion comes after 2030.

The World Nuclear Association (WNA) produces nuclear generating capacity scenarios to 2030, principally for the purpose of forecasting uranium and nuclear fuel demand. These are also based on a "bottom-up" approach, considering the policies of individual countries and the prospects for nuclear expansion in each case. The WNA's 2009 upper scenario (WNA, 2009) has over 800 GWe by 2030, with 600 GWe in the reference case. In its 2011 edition (WNA, 2011), the WNA projected 790 GWe by 2030 for its upper scenario, and 614 GWe for its reference case.

The IAEA publishes electricity and nuclear power scenarios annually in a publication known as Reference Data Series 1 (RDS1). Until 2009, these covered the period to 2030, with a high and a low scenario. From 2010, the projections cover the period up to 2050. The latest projections, published in August 2011 (IAEA, 2011), consider for the high scenario, 746 GWe in 2030 and 1 228 GWe in 2050 (representing about 13.5% of world electricity generation). For the low scenario, the IAEA considers 501 GWe in 2030 and 561 GWe in 2050. The 2011 projections to 2050 were reduced by 5% and 13% respectively for the low and high scenarios compared to the 2010 projections (590 GWe and 1 415 GWe).

The US Energy Information Administration also publishes projections in its *International Energy Outlook*. In the latest edition (EIA, 2011), published in September 2011, the nuclear capacity is projected to reach 644 GWe in 2035, above the 633 GWe value of the New Policies Scenario of WEO 2011.

Projections for the period between 2030 and 2050, published after the Fukushima Daiichi accident are generally down by 5 to 10% compared to the projections published before 2011. The various scenarios still project a significant nuclear capacity increase over the next decades, with the highest projections corresponding to policies aimed at a transition to low-carbon generation mix.

Overall, there is good agreement between the scenarios that about 800 GWe of nuclear capacity could be in place by 2035, if ambitious policies designed to control greenhouse gas emissions are put in place within the next few years in many large energy consuming nations (if there is no commitment to implement such policies, many projections foresee a nuclear capacity of about 600 GWe by 2035). Fewer scenarios consider the outlook to 2050, and inevitably the outlook a further 20 years into the future is more uncertain.

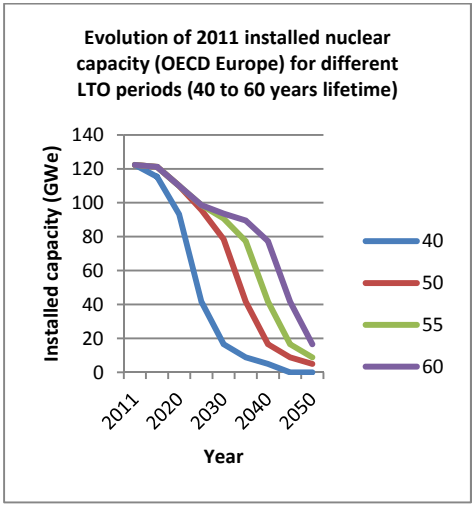
However, the ETP scenarios indicate that there is a role for nuclear capacity in the range of 1 200 to 2 000 GWe by that date, provided that sufficient industrial capacity can be developed to construct and fuel such a capacity.

3.3. Required rates of construction of nuclear power plants

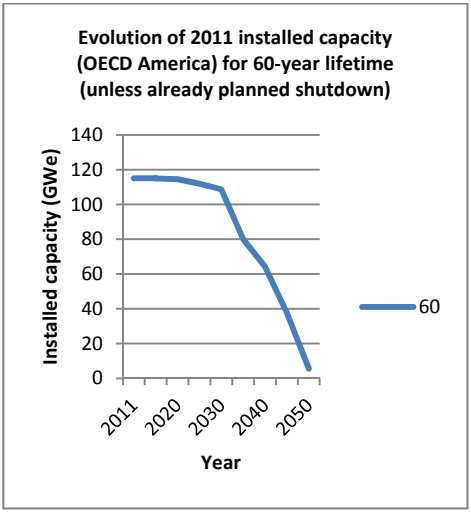
If nuclear energy is to make a significant contribution to the transition to a low-carbon energy system, as set out in the scenarios discussed above, clearly the rate of construction of nuclear power plants will need to increase considerably from present levels. As noted above, 64 nuclear plants with a total capacity of 64 GWe were actively under construction at the end of 2010. In 2010 alone, 16 new construction starts were announced. On the assumption that construction of a new nuclear plant takes approximately 5 years, this is equivalent to an annual rate of construction of about 13 GWe.

The rate of construction required to reach the nuclear capacity included in the various energy scenarios will depend partly on the remaining lifetimes of the existing reactor fleet, most of which will retire at some point before 2050. Most existing reactors began operating in the 1970s and 1980s, with relatively few having entered operation after 1990. It can be expected, therefore, that most of these plants will also close down over a period of about 20 years. The technically feasible operating lifetime of most types of existing reactor is now thought to be up to 60 years. In the United States where 104 reactors are in operation, the nuclear regulator had, as of July 2011, granted licence renewals to 70 reactors allowing them to operate for 60 years, with 14 further applications under review. In Europe, where the issue of long-term operation (LTO) is also very important given the age of the fleet (about a quarter of the reactors are more than 30 years old), different regulatory frameworks are in place to address long-term operation licensing. For example regulators generally give a position on continuation of operation through the process of periodic safety reviews, which are performed every ten years. Such a process should realistically allow most reactors to operate between 40 and 60 years.

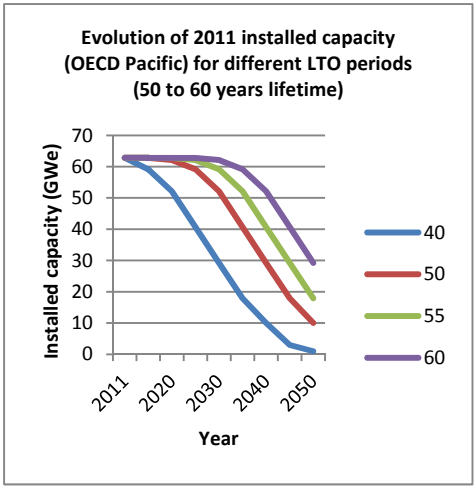
Figure 3.2: Evolution of capacity (GWe) of existing reactors for different long-term operation assumptions by regions



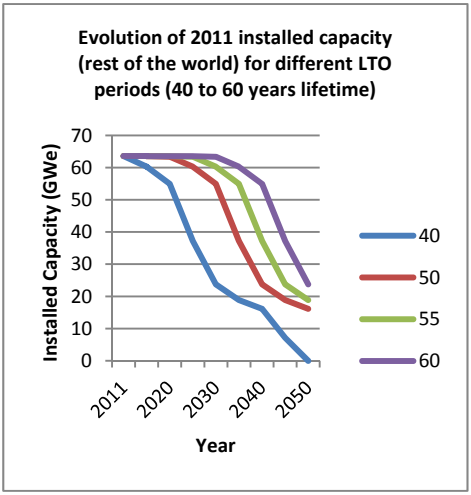
(a) OECD Europe



(b) OECD America



(c) OECD Pacific



(d) Rest of the world

Of course, not all reactors will be licensed for long-term operation. In some cases, the upgrades and refurbishments required to replace ageing equipment and enable the plants to continue to meet regulatory requirements may be uneconomic, given the remaining time for which the considered plant will be operated before final shutdown. In addition to the refurbishments related

to the need to replace ageing equipment, there may also be safety upgrade work required as a consequence of the Fukushima Daiichi stress tests, which will add to the cost of the investment for the plant operator. Reactors may also be shut down due to changes in government energy policy. However, it can be expected that the majority of reactors in operation today will operate for 50 to 60 years. Figure 3.2 shows the capacity provided by the existing reactor fleet in OECD Europe (taking into account planned phase-outs in Belgium, Germany, and Switzerland as well as planned shutdowns for the United Kingdom's AGR and MAGNOX reactors), OECD Pacific (assuming for Japan the permanent shutdown of Fukushima Daiichi units 1-4), OECD America (assuming 60-year lifetime for all PWRs and BWRs in the region and taking into account planned shutdowns for Canada's CANDU reactors) and the rest of the world for different lifetime assumptions (typically 40 to 60 years).

Figure 3.3: Evolution of capacity provided by existing reactors (2011) assuming a 55-year operating life for all regions except 60 years for OECD America
(PWR and BWR)

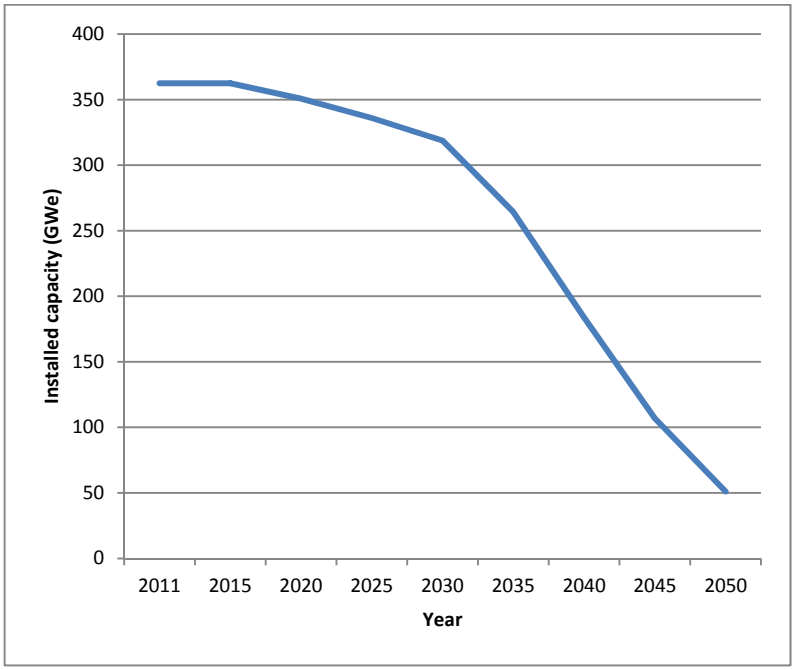
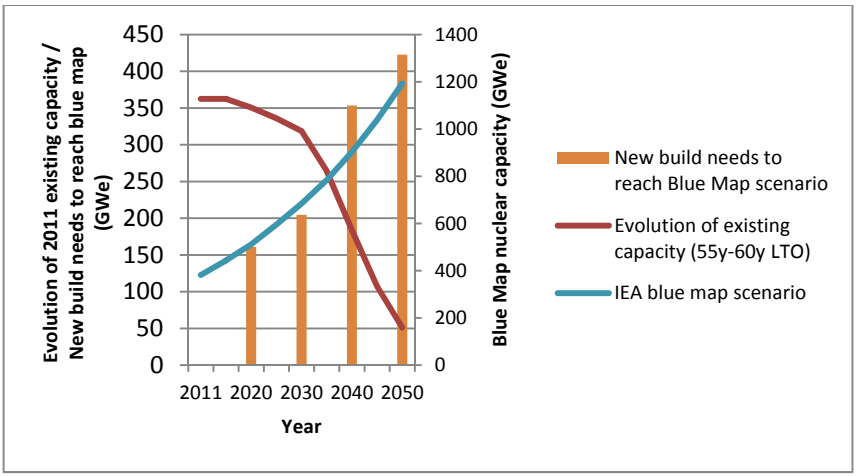


Figure 3.3 shows the overall capacity for the world nuclear reactors assuming 60-year operation for reactors in the United States, and 55 years for the rest of the world. This figure shows that by 2050, only about 50 GWe capacity remains from today's operating reactors (9 GWe in OECD Europe,

5 GWe in OECD America, 17 GWe in OECD Pacific, and 19 GWe in the rest of the world). This does not include reactors under construction.

The target of 1 200 GWe of nuclear capacity by 2050 projected by the IEA's ETP 2010 Blue Map scenario is therefore essentially reached through new build. The extent of long-term operation of existing power plants does not really change the amount of new capacity that needs to be built by 2050, it only delays the time when the construction rate needs to increase substantially. Figure 3.4 shows the nuclear capacity growth projected in the Blue Map scenario (IEA, 2010), i.e. rising to 512 GWe by 2020, 685 GWe by 2030, 900 GWe by 2040, and 1 200 GWe by 2050. The figure also shows the new build rates that are needed to reach that capacity, taking into account the assumed evolution of the capacity existing in November 2011.

Figure 3.4: New build rates needed to reach Blue Map projections, assuming 60 years of operation for existing reactors in the United States and 55 years elsewhere

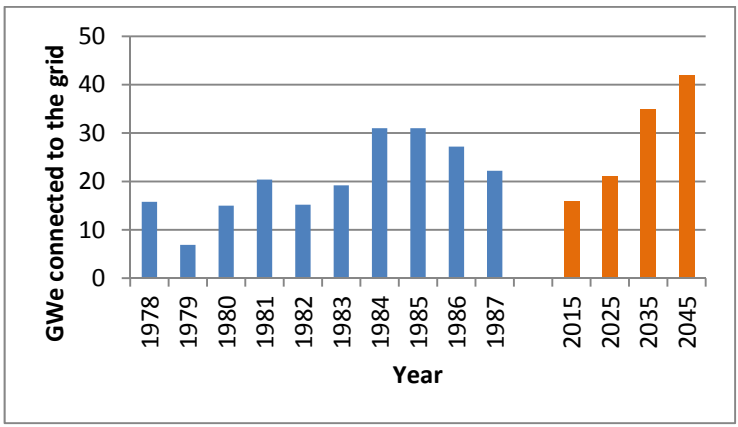


Note that the evolution of the existing capacity and the construction rates refer to the scale on the left vertical axis, whereas the projected capacity evolution of the Blue Map scenario refers to the scale on the right.

To meet the level of nuclear generating capacity mentioned above for 2020, new nuclear power plants will need to be built at the rate of close to 16 GWe per year over the current decade. This is only slightly greater than the presently achieved rate of about 13 GWe. Given that there is clearly some under-utilised capacity for nuclear construction (for example, in the United States and several European countries), it would appear that achieving an installed nuclear capacity of around 512 GWe by 2020 is certainly feasible with a gradual build-up of industrial capabilities and human resources.

However, the longer-term picture is more challenging. If nuclear capacity is to reach around 685 GWe by 2030, the rate of construction will need to grow to around 20 GWe per year on average between 2020 and 2030.

Figure 3.5: World nuclear construction rates between 1978 and 1987 and required construction rates up to 2050



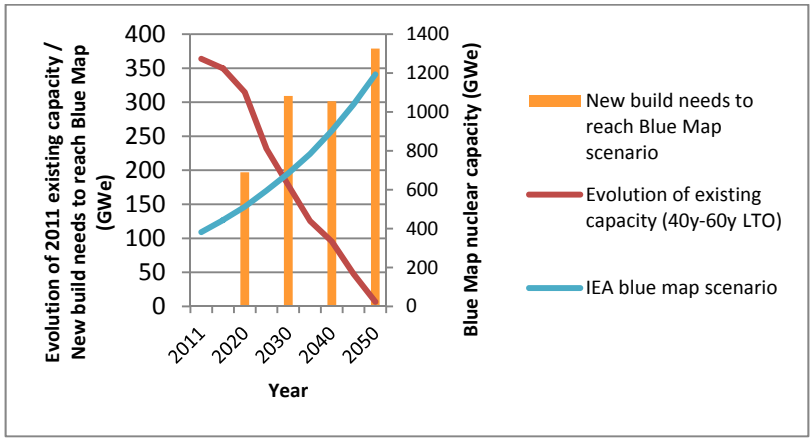
Source: IAEA PRIS.

As a significant number of older plants can be expected to be retired in the 2030s, an increasing proportion of new build will be taken up with replacing existing capacity. Hence, reaching a capacity of 900 GWe by 2040 will require the rate of nuclear construction to rise to an average of 35 GWe per year between 2030 and 2040. To reach a capacity close to 1 200 GWe by 2050 will require that the average construction rate rises to 42 GWe per year between 2040 and 2050, as the remaining reactors that started up in the 1980s retire. These construction rates are challenging, but as shown in Figure 3.5, they should be attainable given the fact that annual grid connections of up to 30 GWe/year were reached between 1978 and 1987, at a time when nuclear construction was limited to a few countries which did not include China. With over 26 GWe of new nuclear capacity currently under construction, China boasts today one of the largest supply chains for nuclear construction. However, it must also be recognised that most of this new build corresponds to Gen II-type reactors similar to those constructed in OECD countries in the 1970s and 1980s. Newer designs, such as those of Gen III/III+ reactors which will be the main type of reactors deployed in the world in the coming decades are more complex, and may require longer construction times.

To assess the impact of LTO assumptions on new build rates, two cases are considered: In the first one, all nuclear reactors in the world are assumed to have a 40-year lifetime except in the United States where the 60-year lifetime

assumption can be considered valid. In that case, less than 7 GWe from today's existing capacity will remain by 2050, and almost all of the 1 200 GWe of the Blue Map projection will consist of reactors built between 2011 and 2050. To achieve the target, the average building rates need to reach almost 20 GWe/year between 2011 and 2020, about 30 GWe/year between 2020 and 2040, and up to 38 GWe/year between 2040 and 2050. This is illustrated in Figure 3.6.

Figure 3.6: New build rates needed to reach Blue Map projections, assuming 60 years of operation for existing reactors in the United States and 40 years elsewhere



In the second case, 60-year operation is assumed for all reactors. This means that by 2050, about 75 GWe of capacity that existed in 2011 still remains. As can be seen from Figure 3.7, the construction rate only gradually increases until 2030, from today's 13 GWe/year rate: about 16 GWe/year would be needed on average between now and 2020, about 20 GWe/year from 2020 to 2030. In the last two decades, a steep rise in construction rate is needed, with 30 GWe/year needed between 2030 and 2040, and over 46 GWe/year between 2040 and 2050. This level should still be within reach given past building rates in the 1980s.

As can be seen from these simulations, the maximum construction rate that is needed to reach the 1 200 GWe target of the Blue Map scenario is influenced by the assumptions on long-term operations of existing reactors. The longer today's reactors operate, the higher are the building rates in the last decades to catch up with the required new build capacity, since in all cases, most of today's reactors will be shut down by 2050.

Figure 3.7: New build rates needed to reach Blue Map projections, assuming 60 years of operation for all existing reactors

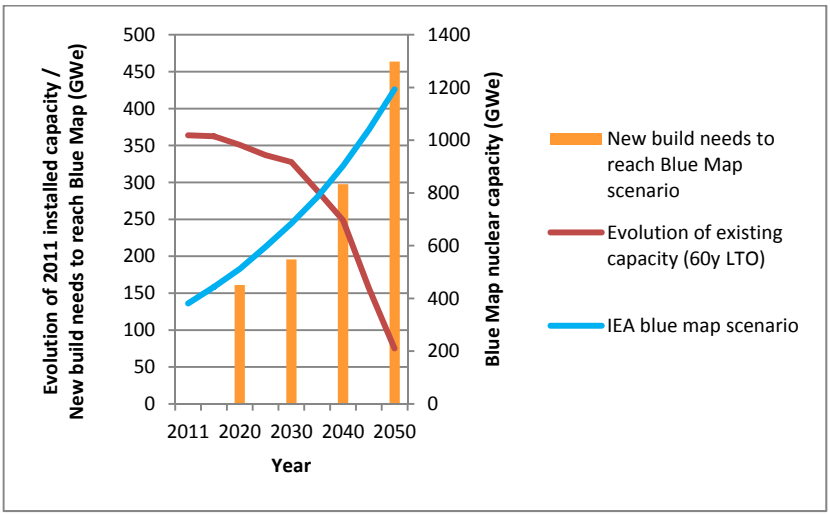


Table 3.1: LTO assumptions and required new capacity additions to reach 1 200 GWe by 2050

Long-term operation assumptions	Remaining capacity by 2050 (GWe)	New build capacity required to reach Blue Map target (GWe)			
		2011-2020	2020-2030	2030-2040	2040-2050
40 years for all reactors (except 60 years in the US)	7	197	309	301	379
55 years for all reactors (except 60 years in the US)	51	161	205	354	423
60 years for all reactors	75	161	196	298	464

Table 3.1 summarises the results of the three LTO scenarios in terms of remaining capacity by 2050, and the amount of new capacity that would need to be added to reach 1 200 GWe installed capacity by 2050. (Note that the results differ slightly from the published IEA/NEA *Nuclear Energy Roadmap* corresponding to the Blue Map scenario of ETP 2010, since the evolution of the capacity takes into account the Fukushima Daiichi accident.)

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4. Economic, technical, societal, institutional and legal factors affecting nuclear expansion

In this chapter, the issues that are key to the projected nuclear capacity expansions described previously are analysed. These include financing and investment needs, supply chain and skilled labour aspects, uranium resources issues, siting, waste management, standardisation of designs and public acceptance of nuclear energy.

4.1. Financing and investment

The investments needed to make large cuts in greenhouse gas emissions from the energy over the next four decades sector will be very large whichever technologies are employed. All options will involve the construction of more capital intensive generating capacity than the traditional coal- and gas-fired plants.

Table 4.1: Investment needs for nuclear to 2050

Region	Investment needs to 2050
OECD Europe	586 USD bn
OECD Pacific	615 USD bn
United States and Canada	883 USD bn
China	893 USD bn
India	389 USD bn
Others	609 USD bn
Total	**3 975 USD bn**

Source: IEA, 2010, Blue Map scenario, 1 200 GWe installed capacity by 2050.

In accordance with the assumptions made, the IEA model used to prepare the Blue Map scenario (IEA, 2010) indicates that increasing the proportion of nuclear power can reduce the overall cost of cutting CO_2 emissions. However, it is clear that constructing well over 1 000 GWe of new nuclear capacity by 2050 will require a very large investment. The IEA estimate of the investment required in nuclear capacity over the period to 2050 is shown in Table 4.1, and amounts to about USD 4 trillion (this only covers the investments needed to

construct new reactors, and does not include the cost of dismantling of retired plants, waste management or fuel cycle facilities).

While the overall investment in nuclear capacity required to provide the expansion foreseen in the scenario may be comparable with that required for other energy and emissions reduction technologies, nuclear power plant construction projects have a number of specific characteristics and circumstances that can make nuclear financing particularly challenging. These include:

- The high capital cost and technical complexity of NPPs, which present relatively high risks during both construction and operation.
- The relatively long period required to recoup investments or repay loans for NPP construction, which increases the risk from electricity market uncertainties.
- The often controversial nature of nuclear projects, which gives rise to additional political and regulatory risks.
- The need for clear solutions and financing schemes for radioactive waste management and decommissioning.
- The need for NPPs to operate at high capacity factors, preferably under baseload conditions.
- The high share of fixed costs which makes nuclear energy particularly vulnerable to price risk in sometimes volatile deregulated electricity markets.

Although some risks can be transferred to or shared with other parties by appropriate structuring of the project, most of them will remain with the utility and other investors in the plant.

The higher capital costs of an NPP mean that its overall economics are more dependent on the cost of capital, or discount rate, which applies to the investment in its construction. With any investment, higher risks demand higher returns. Thus, the cost of capital will depend on potential investors' assessment of the risks involved. This will vary depending on who the investors are, the legal and regulatory framework in which the plant would be built, as well as national energy policy and the political background.

During the previous major expansion of nuclear power in the 1970s and 1980s, many nuclear projects suffered large construction delays and cost overruns. These had several different causes, ranging from licensing and legal problems to technical difficulties. Given also the lack of recent experience with

new NPP construction in most countries, the legacy of such problems increases the risks perceived by potential investors. Of course, such risks will be reduced when there is a successful track record of building a particular design on schedule and within projected costs.

Strong and consistent government support is an essential prerequisite for initiating or expanding any nuclear programme. Given the long time frame involved, a broad-based political consensus is likely to be needed on a nuclear contribution to energy supply as part of a comprehensive long-term national energy strategy. First and foremost, governments need to put in place an efficient regulatory framework, allowing clear and definite decision-making within a reasonable timescale. Stable, legal frameworks dealing with liability issues, radioactive waste management and decommissioning are crucial. In addition, governments have a key role in providing public information and leading national debate on the role of nuclear power, to establish the necessary political consensus.

In addition, governments that wish to see a nuclear contribution to energy supply may need to take a number of steps to enable and facilitate the necessary investment in NPPs. For example, an important factor affecting the competitiveness of nuclear power will be the cost of carbon dioxide emissions under existing and planned carbon trading schemes. The role of governments will be considered further later in this report.

In the short to medium term, large, financially strong utilities will be best able to finance new NPPs, especially if they are vertically integrated (i.e. they have direct access to electricity consumers). Such utilities presently exist in countries such as France, Japan and the Republic of Korea. In countries where the market is more fragmented, such as the United States, higher levels of direct government support may be required to share in the construction risks.

There is little likelihood at the present stage that a stand-alone project company could finance a new NPP by raising the capital it needs using only the NPP project itself as collateral. Even for hybrid schemes including a significant proportion of equity, debt investors are unlikely to be willing to provide significant funding for a nuclear plant without recourse against the balance sheet of a strong and creditworthy utility.

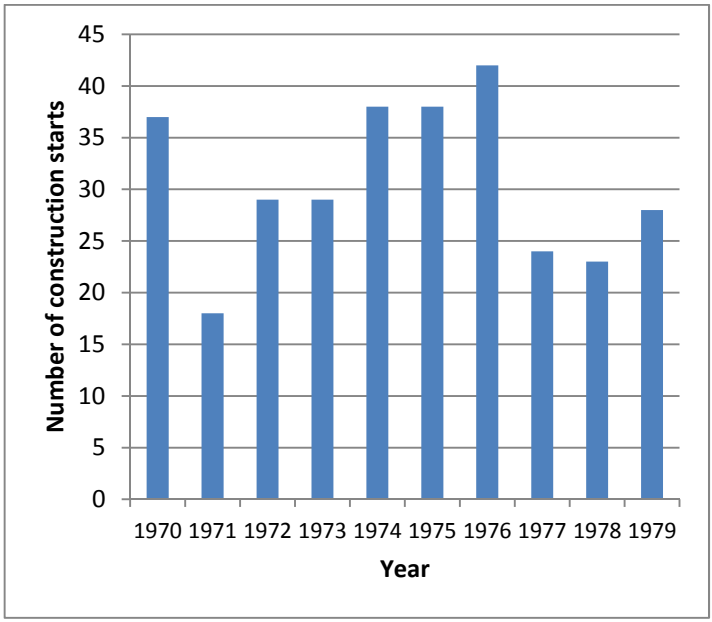
In the longer term, once the successful construction and operation of new nuclear plants has become well established in a particular country, it can be expected that financing by the private sector will become easier to arrange. However, financing is currently one of the major issues facing potential developers of new nuclear plants in many countries.

4.2. Industrial infrastructure

Significantly increasing the rate of nuclear construction by 2020 to reach the levels of deployment envisaged in the Blue Map and other scenarios for rapid nuclear expansion will require large investments over the next few years in additional industrial capacities.

Nuclear plant construction reached considerably higher levels than at present during the 1970s. During that decade, construction starts peaked at over 40 units per year, with an average of over 30 per year (see Figure 4.1). This was a large increase over the preceding decade. Although these units were smaller than current designs, the technology was also less well developed at that time. In addition, relatively few countries were involved in that earlier rapid nuclear expansion, and overall global industrial capacity has increased greatly since the 1970s. A large share of the future expansion of electricity supply, and hence of nuclear new build, will take place in large, rapidly industrialising non-OECD countries (notably China and India). Today, China already boasts a well-established supply chain for its ambitious nuclear programme.

Figure 4.1: Number of construction starts during the 1970s



Source: IAEA PRIS.

However, there are many other factors at work, many of which are different from 30 to 40 years ago. Investment in increased capacities, if it is to

be made on a commercial basis, will only take place once it is clear that sufficient long-term demand exists. Capacities can thus be expected to build up gradually over a period of some years in response to rising demand. A rising level of orders for new nuclear plants over the next few years will be needed not only to achieve an increased nuclear capacity by 2020, but also to allow for the expansion of industrial capacities that will be required for more rapid growth after 2020.

Nuclear power plants are highly complex construction projects. The nuclear supplier, as the designer and technology holder, will supply only the plant's nuclear systems. A wide range of specialist sub-contractors and suppliers is involved in providing and installing the remaining systems and components, including the turbo-generator set and associated equipment that make up the conventional island, and which are specific to nuclear power plants. The "architect-engineering" function, encompassing general engineering, scheduling and cost management, and co-ordination between contractors and suppliers, is also very important in a nuclear project.

Hence, complex global supply chains would need to be developed and managed to ensure the successful completion of nuclear projects. As more orders are placed for new nuclear plants, supply chains would become broader as suppliers seek to expand their capacity to serve markets around the world. This could mean involving local and regional construction and engineering firms as nuclear energy expands into new markets.

The production of most reactor components can be increased within, at most, a few years in response to market demand. The longest lead time for capacity additions is expected to be for large steel forgings, which are used in greater numbers in the latest nuclear plant designs. While there is adequate capacity to produce many of these forgings, the largest forgings for some designs can presently be produced in a very limited number of facilities throughout the world. It can take five years or more to expand such heavy forgings capacity, as it requires a very large investment and only a few companies have the necessary expertise. Plans to expand very large forgings capacity are now being developed, although going ahead with these is likely to depend on receiving firm customer commitments.

4.3. Skilled labour and knowledge management

The nuclear energy sector, which includes the nuclear industry itself, plus utilities, regulators and other governmental agencies, requires highly qualified and skilled human resources. Expanding nuclear energy will require a larger pool of highly trained scientists and engineers, and skilled crafts-people, all of

which are potentially in short supply. Many nuclear industry companies have in recent years expanded their recruitment and training programmes, and there is also a role for governments and universities in ensuring the availability of appropriate courses and training.

The long lifetimes of nuclear power plants, extending over several human generations, make knowledge management an important consideration. Preservation of knowledge is important for achieving safe and effective lifetime extension of existing units, as well as for designing and building new plants that benefit from experience. Important know-how may be lost as the scientists and engineers who implemented the ambitious nuclear programmes of the 1970s and 1980s reach retirement age. Hence, knowledge management and transmission of know-how to younger specialists will need to be high priorities in the nuclear sector.

4.4. Uranium and the nuclear fuel cycle

If nuclear energy is to expand significantly over the coming decades, supplies of nuclear fuel will need to expand commensurately. This will include increased production of uranium, greater capacity in nuclear fuel cycle facilities and, in the longer term, the increased use of recycling and advanced fuel cycles.

Table 4.2: Approximate ratios of uranium resources to present annual consumption for different categories of resources

	Known conventional resources	Total conventional resources	With unconventional resources
With present reactors and fuel cycles	100	300	700
With fast reactors and advanced fuel cycles	> 3 000	> 9 000	> 21 000

Source: NEA, 2008a.

Despite limited exploration over the last 20 years, the ratio of known uranium resources to present consumption is comparable to other mineral energy resources, representing about 100 years' supply. Additional resources that are expected (on the basis of existing geological information) to be discovered could increase this to around 300 years' supply. Inclusion of estimated "unconventional" resources, notably uranium contained in phosphate rocks, could extend resources to about 700 years (Table 4.2). The estimated 4 billion tonnes of uranium contained in seawater would constitute a virtually inexhaustible supply, if a method to extract it economically were to be

developed. A recent evaluation of the cost of uranium recovered from seawater was reported in 2011 (Schneider, 2011) and calculated a baseline cost of uranium of USD 1 230/kgU. While this cost is about nine times the current market price of uranium, the overall impact on the cost of electricity is about 20%.

If nuclear capacity reaches around 1 200 GWe by 2050, on the basis of current fuel cycle technology and practice this would consume about 5.6 million tonnes of uranium between 2010 and 2050. However, several technological developments could increase the amount of energy produced from each tonne of uranium over the coming decades, thereby reducing total uranium consumption. These include improved operating and fuel management practices, advances in fuel design and materials, and higher thermal efficiencies in new and upgraded nuclear plants.

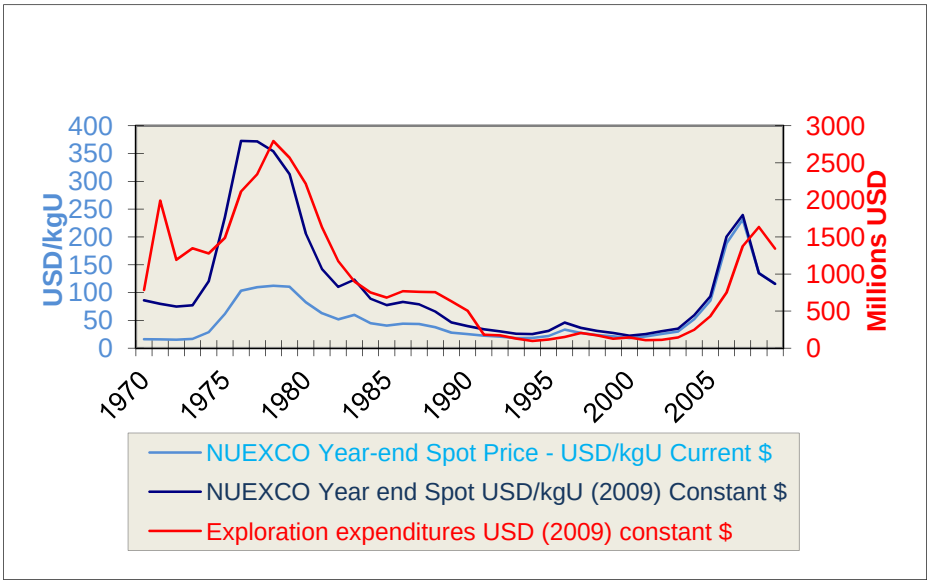
In addition, deployment of new enrichment technologies will have an impact. As there is a trade-off between the amounts of natural uranium and enrichment work required to produce a given quantity of enriched uranium, the proportion of the ^{235}U extracted from natural uranium depends largely on the relative costs of enrichment and natural uranium. The wider use of centrifuge enrichment technology, which has lower operating costs than older diffusion technology, is expected to lead to increased efficiency of uranium use.

As well as new centrifuge plants, more efficient advanced centrifuges will gradually replace older models within existing centrifuge plants. In addition, new enrichment technology using lasers is now being tested and plans are being considered to have the first commercial laser enrichment plant in operation by around 2015. Such developments could potentially allow more ^{235}U to be extracted from existing stocks of depleted uranium, as well as permitting the more efficient use of newly mined uranium in the future.

Nevertheless, in such a scenario, demand for newly mined uranium would still represent a large part of currently known conventional uranium resources of about 6.3 million tonnes (NEA, 2010). However, as noted above, additional and unconventional resources could greatly extend the amount of uranium available. In response to higher uranium prices, annual uranium exploration expenditures have risen three-fold since 2002, from a low base. Figure 4.2 shows for example the correlation between uranium spot prices and exploration expenditures between 1970 and 2009. As nuclear power expansion gets underway, a further sustained increase in uranium exploration activity can be expected as in the past, with many regions having the potential for further major discoveries to replace exploited resources. As for unconventional resources, including phosphate deposits that could be utilised to significantly lengthen the time that

nuclear power could supply energy demand using current technologies, considerable effort and investment would need to be devoted to better defining the extent of this potentially significant source of uranium.

Figure 4.2: Correlation between uranium spot price and exploration expenditures between 1970 and 2009



If uranium resources themselves are unlikely to be a limiting factor for the expansion of nuclear programmes, the timely availability on the market of adequate uranium supplies could be a cause for concern. Developing new mines, both to replace exhausted existing mines and expand overall production capacity, will require large investments over the coming decades. Licensing and developing new mines, often in remote areas, can take many years. The lesson of the recent past is that, even with the stimulus of higher uranium prices, production can take some years to respond.

Existing uranium mining companies and new entrants will be ready to invest in new capacity given the right price signals, and sufficient policy and regulatory certainty. Developers of nuclear power plants may seek to secure at least some of their uranium supply in advance of construction, through long-term contracts or even through direct investment in new production capacity. Governments of countries with commercially viable uranium resources have a role to play in ensuring a supportive policy environment and effective regulatory procedures.

Several different technologies exist for uranium extraction, and advances in mining technology could improve the viability of some uranium resources. Conventional underground and open-pit mining presently account for about 60% of production. *In situ* leach (ISL) techniques have been more widely deployed in the last decade, now providing almost 30% of production. The advantages of ISL include lower up-front capital costs, the ability to exploit smaller deposits and lower environmental impacts. Uranium production as a by-product (usually of gold or copper) is also significant, and could be extended in future.

In the longer term, the commercial deployment of advanced reactors and fuel cycles that recycle nuclear fuel could permit much greater amounts of energy to be obtained from each tonne of uranium (Table 4.2). The development of such advanced nuclear systems will be further discussed later in Chapter 6. Given the expected availability of uranium resources, a large increase in nuclear capacity by 2050 can be achieved without their large-scale deployment. However, if lower cost uranium resources become scarcer, the economic attractiveness of recycling nuclear fuel will increase.

Existing nuclear fuel cycle facilities for UF_6 conversion, enrichment and fuel fabrication are adequate for levels of demand expected in the next few years, and there are near-term plans for replacing and expanding capacities as required. In addition, countries where significant nuclear power programmes are underway, such as China and India, are planning to increase their domestic nuclear fuel capabilities. In general, nuclear fuel cycle capacities can be expanded in less time than it takes to build new nuclear generating capacity. Hence, security of supply for nuclear fuel cycle services should not, in principle, be a significant concern.

However, if nuclear capacity expands significantly after 2020 there will be a need for new large-scale facilities in additional countries. Building new conversion and fuel fabrication facilities as required should not cause difficulties. But the technology involved in enrichment is sensitive from a non-proliferation perspective, which will limit the potential locations for new facilities. For some countries concerned about security of energy supply, this may be a disincentive to rely on nuclear energy.

One solution could be to establish “black box” enrichment plants, where the host country would not have access to the technology. Discussions are also underway in international forums on creating mechanisms to provide assurances of nuclear fuel supply to countries that do not have their own enrichment facilities. Progress with such proposals could facilitate nuclear expansion in a broader range of countries after 2020. In the longer term, the development of

proliferation-resistant advanced nuclear systems may offer technological solutions to this issue.

4.5. Siting considerations

The selection of suitable sites for new nuclear power plants is subject to a number of criteria, established to ensure the safety and security of the plants and hence the protection of the population. Requirements for siting in each country will depend on local legislation and regulations. There are also guidelines developed at the international level by the International Atomic Energy Agency, for instance the Safety Requirements and the Safety Standards publications (IAEA, 2003, 2010a). In addition, the siting of any electricity generation plant has to take into account the location of major demand centres and the existence of suitable transmission lines or the ability to construct these.

This suggests that the number of suitable sites for nuclear plants may not be unlimited. Although there may be a large number of suitable sites globally, their availability in any particular country or region could be restricted. If nuclear power were to expand rapidly over the next few decades, a question could arise over the availability of sufficient sites in suitable locations.

The accident at the Fukushima Daiichi nuclear power plant in Japan in March 2011 has highlighted the particular requirements for siting nuclear plants in zones of high seismicity and in zones prone to flooding, whether caused by earthquake-related tsunamis, or from dike breaks or other causes. Where plants are to be sited in such zones, clearly special precautions need to be taken and the design features of the plant and its associated equipment modified accordingly. The accident has also highlighted the risk of “common mode failure” when a single event affects several reactors built on the same site.

Multiple nuclear units are often situated on the same site, or on closely adjacent sites. In addition, many existing sites have space available for further units to be co-located. Many countries with existing nuclear plants are thus planning to build new reactors on existing sites (including sites where the existing reactors have already closed or will do so in the near future). Of course, if the option to build on existing sites is limited, then selection of new sites will be required.

The siting process generally consists of an investigation of a large region to select one or more candidate sites, followed by a detailed evaluation of each of those sites before making a final decision. Factors considered in site selection include the availability of cooling water, distance to populated areas, seismic

and flooding risks. Analyses for the site selection process take considerable time and resources, which is also a limitation for providing a precise estimate on how many sites may be available. Once selected, the suitability of the site is considered as part of the licensing process for the plant. The suitability of the site is reassessed periodically when a new licence has to be issued, for instance when long-term operation is requested. Over a period of 40 years for instance, changes in the natural environment or the climate can occur so that the suitability of the site has to be reassessed. Industrial and urban development also needs to be taken into account.

4.6. Radioactive waste management

Management of radioactive waste arising from nuclear power production has long been considered an important issue due to the political, economic and societal implications associated with it. The development and implementation of a strategy to manage long-lived high-level waste (HLW) associated with spent fuel is seen in particular as a condition to enable the further development of nuclear energy. There is an international consensus that technical solutions exist (NEA, 2008b), and some countries are leading the way in implementing those solutions.

Like any industrial activity, nuclear electricity generation produces waste, but some of this waste is radioactive and requires appropriate management processes. The radioactive waste can be classified within two main categories: short-lived waste, the radioactivity of which will decrease by a factor of 2 every 30 years; and long-lived waste, the radioactivity of which will decrease but over a much longer duration.

All radioactive waste resulting from nuclear electricity generation are managed according to four principles:

- limiting the quantity of waste;
- conditioning and preparing long-term waste management;
- sorting according to the nature of waste and the radioactivity level;
- isolating from man and the environment.

Short-lived waste

The operation of the nuclear facilities produces short-lived waste. Those waste, of low and medium activity, represent more than 90% of the total

quantity, but they contain only 0.1% of the radioactivity of the waste. Their radioactivity decreases very rapidly and proven industrial solutions exist for their disposal.

Long-lived waste

After having produced its energy during four to five years, the nuclear fuel is used. Current progress has increased the energy efficiency of fuel assemblies and reduced the quantity of used fuel for the same energy output.

The used fuel content (fuel material) is formed by: about 96% of valuable material – uranium (95%) and plutonium (1%) – which can be recycled; and about 4% of high-level long-lived waste, mainly constituted of fission products (caesium, cadmium, tin, molybdenum, etc.) and for a smaller part (0.1%) of minor actinides produced through neutron capture by heavy nuclei (e.g. americium).

The metallic structure of the fuel assembly (metallic tubing containing the fuel material), which is activated in reactor due to neutron flux, is by itself an intermediate-level long-lived waste (ILW).

Whatever the long-term policy chosen for spent fuel management (i.e. direct disposal or reprocessing), the spent fuel management begins with a storage period of several years for cooling, first under water in the spent fuel pool for some years at the reactor site, and then either in another wet storage facility (or in the same pool), or in a dry storage facility in metallic casks or concrete vaults, waiting for the final management choice.

Depending on the long-term policy, the used fuel can be either:

- Conditioned in specific casks or packages to be placed in a geological disposal after years or even decades of cooling. The used fuel, including the fissile material still present, is then considered as a whole as a waste. This option – direct disposal of spent fuel, also called “once-through fuel cycle” – has not yet been implemented in any country, but Finland, which has chosen this option, will be the first country to implement geological disposal of spent fuel by 2020, closely followed by Sweden.

- Or, after five to eight years, the used fuel is reprocessed in order to separate the high-level waste and to condition them in a specific and suitable way by vitrification, and to recycle the valuable nuclear material uranium and plutonium to manufacture new fuel, while

maintaining open the long-term energy resources options. This reprocessing recycling strategy is currently working at an industrial and proven scale. Just as for direct disposal of spent fuel, deep geological disposal of the final waste produced after reprocessing is the chosen option. It has not yet been implemented in any country, though France is set to start construction of its geological disposal site around 2015, and first disposal around 2025.

- For countries which have not yet chosen between direct spent fuel disposal or reprocessing, centralised interim storage of spent fuel is another option which gives time to develop a spent fuel strategy. This can be interpreted as a way to postpone a decision on how to deal with the nuclear spent fuel, and is sometimes called the "wait and see" option.

To ensure successful implementation of high-level waste management policies, stakeholder involvement is necessary in the decision-making process. To gain confidence and trust it is important that the stakeholders' concerns are heard and addressed correctly. Key stakeholders are the government, the regulators, the local communities, the waste producers, the scientific communities and the general public (NEA, 2008c).

4.7. Standardisation of reactor designs

In spite of the Fukushima Daiichi accident, nuclear power is still considered by many countries as a major energy source for the future – providing benefits for national energy independence as well as global environmental preservation. For potential investors, however, global expansion of nuclear power continues to be viewed primarily through a financial and economic prism that focuses particularly on nuclear power's competitiveness compared to other sources of baseload power such as coal and gas.

A major opportunity in this equation is the potential for economies of scale which can be achieved by building plants in series. The French nuclear programme which saw the construction of 58 reactors from the middle of the 1970s to the end of the 1980s using a limited series of standardised PWRs is seen as an example in that respect. To achieve progress in this direction at a more global level, it is important that national safety regulations be mutually validated and harmonised. The achievement of harmonisation of nuclear safety standards could overcome this obstacle, facilitating the emergence of a global market that offers a choice of a small number of advanced reactor types that are recognised by regulators as safe and technologically mature. This important step could kick-start serial reactor construction worldwide.

This approach can bring shared benefits, for the industry through increase in efficiency, but also for safety enhancement through intensified experience feedback sharing for similar plants, and also for regulators and customers.

Benefits of standardisation for the nuclear industry

Standardised designs and harmonisation of industrial engineering codes and standards will reduce the overall engineering and construction time and cost, reduce licensing risk and increase predictability of construction, improving the financial feasibility of nuclear new build.

Seen from a vendor perspective, the gain lies in the ability to sell a reactor to any customer (electricity company) in any country without the need for design changes, unless justified by site-specific circumstances. Seen from an electricity company (owner-operator) perspective, standardisation does offer a "fleet" operational concept, whether an electric utility operates in only one country or operates only one plant of a particular design in one country as part of a larger international "fleet" of that design.

This approach should also be of benefit to the supply chain of high-quality nuclear components. Just as in construction, the supply of standard components should be at lower costs and higher quality than supply of custom-made components. This greater volume of standard supply will also encourage more suppliers to invest in quality and enter the supply chain, thus enhancing competition while ensuring availability of components meets the needs of the nuclear new build programmes.

Harmonisation of national nuclear safety standards will enhance the stability of regulatory regimes, thus providing a major prerequisite for investment decisions. Close collaboration among regulators may also lead to a convergence of licensing procedures as well as safety standards. Currently, there are still major differences in licensing.

Finally, harmonisation of safety standards will enhance public confidence not only in regulators (as mentioned earlier) but also in operators, and can thus have a positive impact on public and political acceptance of new nuclear power plant construction.

Benefits of standardisation for nuclear safety

The nuclear industry, with safety as its core principle and responsibility, envisages that standardisation of designs will lead to higher levels of safety. These benefits derive from being able to draw on design and operational

experience in all phases of a plant's life cycle: construction, commissioning and long-term operation, with actual fleet experience and reliability databases providing the underpinning for enhanced safety. In the design phase, new plant designs incorporate the latest technology and lessons learnt from the current operating fleet.

During construction, each subsequent plant of the same design will benefit from the experience accumulated in the construction of previous plants. This will also yield benefits in terms of the quality of construction through repeated application of the same proven construction methods and techniques.

In the operational phase, a global fleet of standardised nuclear plants offers the potential for increased operational excellence, better availability and capacity factors, and improved maintenance efficiency.

Feedback from operational experience will apply directly to all plants of the fleet, thus offering the possibility to strengthen safety in a continuous and uniform fashion. Operation of a fleet of standard plants allows operational support to move easily between plants and provides a clear focus for technical, maintenance and procurement support.

Clearly, if a company fleet is part of a wider national or international family of plants, even greater benefits can be derived from shared experience, internal benchmarking and best practice assessment. This possibility points to an enhanced role for "owners groups" uniting the vendor of a specific design and the operators running this design.

With the deployment of a large number of reactors of one design, a defect can be revealed and potentially affect the whole fleet; in any case, the probability of early detection of any design flaw is much higher due to rapid accumulation of experience and knowledge exchange during evaluation, testing and operation, which can enable the implementation of preventive measures at a precocious stage.

Further, in the unlikely event of a significant generic shortcoming, remedying and backfitting measures could be organised and implemented in a very efficient manner across all plants. Operators, vendors and regulators involved could easily co-operate on the basis of internationally harmonised regulations, voluntary initiatives and reporting requirements.

In this model, backfitting measures are taken quickly and uniformly, offering maximum benefit for safety internationally. Such an approach offers potential benefit both for nuclear regulators and the nuclear industry.

Benefits of standardisation for regulators

A greater convergence and harmonisation of national standards would allow for increased international co-operation among regulators. Regulatory design reviews, which are central to the national licensing processes, would be improved, in both effectiveness and efficiency, by sharing methods and data arising from safety evaluations.

Moreover, knowledge transfer on all regulatory issues, including regulatory practice, could greatly facilitate the development of civil nuclear energy in emerging nuclear countries, which have yet to develop well-established and independent regulatory regimes. Such collaboration will be facilitated if a high degree of convergence of rules and standards is achieved internationally and the process of harmonisation may lead to a common choice of the most reasonable and convincing solutions.

Finally, the harmonisation of safety standards can have a positive impact on public confidence in regulatory decisions. Safety goals will be better understood and more readily accepted if they are internationally aligned.

An area where closer collaboration based on harmonised safety requirements will be very beneficial is in quality inspections in construction and component manufacturing, where collaboration among regulators is essential to an efficient handling of manufacturing oversight issues.

Benefits for electricity consumers

Of primary importance is that the benefits for overall nuclear safety as well as for regulatory and industry efficiency should ultimately redound to the benefit of consumers through the enhanced delivery of safe, affordable, and environmentally cleaner electric power.

The Multinational Design Evaluation Programme

The Multinational Design Evaluation Programme (MDEP) is a multinational initiative of the regulators from Canada, China, Finland, France, Japan, the Republic of Korea, the Russian Federation, South Africa, the United Kingdom and the United States. The IAEA is involved in all generic MDEP activities to ensure consistency with its safety standards. The purposes of the MDEP are to co-operate on specific design reviews and to explore potential harmonisation of regulatory requirements and practices with the overriding goal to make new reactors safer.

As individual regulators review new nuclear reactor designs, MDEP aims to enhance co-operation among them through sharing resources and knowledge, thus improving efficiency and effectiveness of the licensing process. The ultimate goal of MDEP, for which OECD's Nuclear Energy Agency has been chosen to perform the technical secretariat duties, is to explore the achievement of convergence of industry codes, standards and safety goals

The MDEP regulators interact frequently with other stakeholders such as reactor vendors, component manufacturers, mechanical and electrical standards development organisations, non-MDEP regulators and regulatory bodies such as WENRA, and industry organisations such as the World Nuclear Association to obtain important input in carrying out MDEP functions. A key message of the MDEP is that each regulator maintains its sovereign right and responsibility regarding ensuring the safety of new reactors designed, constructed and operated within its borders.

MDEP may thus be seen as an enabler of increased safety and standardisation through potential harmonisation and convergence of regulatory requirements and practices.

4.8. Public acceptance

Although concerns about security of energy supply and the threat of global climate change have tended in recent years to increase public recognition of the benefits of nuclear energy, several factors continue to weaken public support in many countries. These include concerns about nuclear safety, radioactive waste management and disposal, and the potential proliferation of nuclear weapons. Society at large is often reluctant to accept nuclear energy, mainly because its benefits are not perceived to outweigh its drawbacks.

Public acceptance of nuclear energy has suffered of course as a result of the Fukushima Daiichi accident. A quarter of the people polled by IPSOS in June 2011 (IPSOS, 2011) say their opinion was affected by the accident, and this percentage is much higher in South East Asia countries (66% in the Republic of Korea and 52% in Japan and China). According to this poll, only 38% support the use of nuclear energy, though this level of support varies greatly from country to country, with over 48% support in the United Kingdom, the United States, Poland and India, and only 21% support in Germany. According to the BBC Globescan poll of November 2011 (BBC, 2011), support for new build has also decreased in many countries, though it has increased or remained stable in the United Kingdom and the United States. This shows that

there is considerable work to recover a sufficient level of support for nuclear energy to enable new projects to be developed.

Establishing improved communication channels with all stakeholders is a necessary step towards promoting better understanding of the risks and benefits of nuclear energy, and the role it can play alongside other energy options. Beyond this, however, civil society should be engaged in the policy-making process for deciding the future of nuclear energy programmes, in the context of overall national strategy to meet energy and environmental policy goals. Enhancing public involvement in shaping the future of nuclear energy is essential to build trust and ensure broad support.

In addition to nuclear power plants themselves, the siting of related fuel cycle facilities can also lead to public concerns and opposition. In particular, locating radioactive waste storage and disposal facilities has often become highly controversial. In several countries, proposals for such facilities have had to be withdrawn in the face of public opposition.

Lessons have been learnt from such setbacks, and radioactive waste management organisations in most countries are now making much greater efforts to engage with local communities potentially affected. In some cases, notably in Finland and Sweden, this approach has resulted in great progress being made towards the implementation of radioactive waste disposal plans. Other countries will need to adopt similar approaches as they seek to make progress with radioactive waste disposal.

4.9. Institutional and legal frameworks

A successful nuclear programme will always require clear and sustained policy support from the government concerned. The nuclear energy policy can be part of the country's overall long-term strategy to meet its energy policy and environmental objectives, including achieving security of energy supply and controlling greenhouse gas emissions. Examples of countries with such long-term policies to develop nuclear energy include France, Japan, the Republic of Korea and, more recently, China. The need for strong policy support applies equally whether the electricity supply industry is in the public or private sector. No investor would contemplate proceeding with a project to construct a nuclear power plant without clear policy support from the government.

In several cases, nuclear power projects have been delayed or cancelled, or operating plants forced to close prematurely, as a result of policy changes regarding nuclear power. Given that the construction period of a nuclear plant

may include national elections, and that there will be several changes of government during the plant's operating life, there is likely to be a need not only for policy support from the incumbent government, but also a long-term settled strategy with broad-based political support.

For countries launching a new nuclear programme, the government will need to take a particularly active role. In some countries, the electricity supply industry is wholly or mainly under state control, and the decision to proceed with a nuclear programme will be taken directly by the government. In other cases, the government will need to work closely with the private and public sector actors involved to ensure that projects can proceed smoothly. This will clearly include establishing the required legal and regulatory frameworks (as discussed below), but it will often be necessary for the government to take a broader role.

All countries with a nuclear programme need to have in place an appropriate legal framework dealing with nuclear-related matters. This includes a system of licensing of nuclear activities and facilities, overseen by an independent regulatory body. Other necessary legal provisions include defining responsibility for radioactive waste and decommissioning, and establishing a nuclear liability regime (which for most countries is done through an international convention). Many countries have a specific "nuclear energy act" that deals with all aspects of the use of nuclear energy.

For countries with existing nuclear programmes, that also have existing legal and regulatory systems, the main issue in contemplating a further expansion of nuclear power is the effectiveness and efficiency with which the existing system has worked. There are cases where the licensing system proved to be a source of frequent delays in nuclear plant construction. Important reforms to the licensing process in the United States, for example, have resulted in a one-step licensing process, with construction and operating licences combined.

Beyond enhancing the effectiveness of national regulatory frameworks, international co-operation aims at facilitating the licensing of new reactor designs across borders. This will be an important factor in support of the deployment of nuclear power worldwide, allowing established standardised designs to be replicated in different countries with the minimum of changes. The MDEP, described above, is an example of international co-operation in the field of safety.

Countries planning new nuclear programmes that do not have an existing nuclear regulatory and legal infrastructure have the ability to learn from

international best practice. Given that there are different approaches to nuclear regulation and legislation among established nuclear countries, new entrants have typically adopted the main principles of the country from which they plan to acquire nuclear technology. This simplifies the licensing process, as the reference plant will normally already have been licensed in its country of origin, so a similar regulatory approach should proceed smoothly without the need for design changes.

For nuclear energy to play a significant role in the supply mix worldwide, nuclear power programmes will need to be implemented in developing countries where most of the increase in energy and electricity demand will occur. The construction and operation of nuclear power plants in those countries will require technology transfer and capacity building.

The policies of OECD countries and others with established nuclear programmes regarding technical co-operation and assistance in the nuclear field will be very important in this regard. In developing and emerging countries embarking on nuclear power programmes, it is essential to ensure that the necessary regulatory frameworks and legal infrastructures are working effectively before the first units are built and commissioned. Clearly, those countries involved in exporting nuclear plants to new nuclear countries have a particular responsibility to ensure that the necessary legal infrastructure and expertise are in place before proceeding.

There is also an important role here for broader international co-operation, including through intergovernmental agencies. The International Atomic Energy Agency (IAEA) in particular has extensive programmes of technical co-operation which support its member states wishing to embark on nuclear power programmes. At present, the agency is working with several dozen member states that are considering a future nuclear programme, within the Integrated Nuclear Infrastructure Group (INIG) (IAEA, 2011) and the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) (IAEA, 2010b).

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5. Impact of developments in the electricity supply system

In this chapter, the issue of the role of nuclear energy in a future electricity grid characterised by a very large share of renewables is addressed. In most countries where nuclear represents a small percentage of the electricity generation, nuclear power plants are operated in baseload mode. In countries with a large share of nuclear such as France, load-following operation of nuclear power plants has been developed to complement hydro or other technologies as a means to respond to consumption peaks. This chapter shows that nuclear can adapt to a likely future where, in addition to variations in consumption, the electricity grid has to cope with intermittency in electricity production from renewable sources such as wind. Furthermore, it is shown that with "smart grids" which level the load, there is still a need for significant baseload production which large nuclear units can provide.

5.1. Nuclear power plants in a future electricity generation system

The issue of balancing in a future electricity generation system provokes the question whether nuclear power stations still have a role to play if balancing issues of the grid are taken into account (e.g. Greenpeace, 2011; D'haeseleer, 2011). Two issues must be addressed in this context:

- In a world with ample dispersed generation, is there still a need for large generating units, with installed power capacities of the order of 800-1 300 MW? This relates especially to large coal (or lignite) power plants – that will need to be equipped in the future with CCS facilities – and nuclear power plants, the largest units of which exceed today 1 700 MWe capacity.

- Are nuclear power plants flexible enough to be able to cope with the balancing requirements if massive amounts of intermittent sources (with nearly zero marginal cost) feed into the system, even up to a point that supply exceeds demand for certain periods of time?

The issue of large rotating units characteristic of thermoelectric plants (coal, gas or nuclear) in an overall system addresses the point of system inertia and damping. System inertia is necessary to avoid too sudden drops of the system frequency. Traditionally, this inertia is provided by large "working

horses", being the turbo-generator units of large power plants distributed over the entire interconnected system, and the many millions of rotating electric motors. In the future, it is to be expected that many of the rotating motors will be connected to the grid through power-electronics kits to allow so-called frequency or speed control, meaning that they are no longer directly coupled to the synchronised grid. Likewise, many distributed generation sources will feed in via power electronics invertors. This means that the system inertia may decrease to the extent that the passive damping mechanism will be "depreciated". It is possible, in principle, to mimic virtual system inertia and damping with specially designed power-electronic means (Risoe, 2009), but the question remains whether this will allow to replace (even partially) the classical damping mechanism. Furthermore, even if classical passive damping would be replaced by active control mechanisms via some sort of power-electronics intermediary, the issue will remain whether this is sufficiently "reliable" in the broad sense, since the system might in the end be much more "nervous" and less incident robust, so that continued and permanent adjustment would then be necessary. As long as all goes well, few problems should arise, but incident management would have to resort to a completely different paradigm. The jury on this issue is still out, but common wisdom would suggest that the presence of a minimal number of large rotating turbo-generators in the system is not a superfluous luxury. On the contrary, the presence of such large units might expedite the future penetration of large amounts of "perturbing" intermittent and non-dispatchable units.

Having made the case for large rotating masses, can nuclear plants then still play a role in that context? Is it not sufficient to have coal-fired plants or a multitude of CCGTs? Both coal-fired plants and gas-fired plants will have to be equipped with CCS in a carbon-constrained world. The flexibility of some of these CCS-equipped units might be hampered so that their part of the mix may have to be limited (Martens, 2010). Furthermore, if one were to ban both nuclear plants and coal plants from the generation mix, and rely entirely on gas-fired plants, the question of security of supply must be addressed. For security of supply reasons, a well-balanced distribution of generation means seems justified, as e.g., demonstrated through portfolio considerations when instantaneous power delivery and not annual energy amounts are considered (Delarue, 2011). From the system inertia point of view, there is no reason why large nuclear units should not be welcome as part of the mix, quite the contrary.

The second allegedly thorny issue is that of the balancing flexibility of NPPs. In most instances, nuclear power plants have always been run in baseload, simply because of their cost structure: large investment cost and low variable cost. Economic logic clearly dictates that such plants should run as much as possible, perhaps the whole year (minus some time for scheduled

maintenance). Most nuclear power plants have been optimised to run in that baseload mode. This does not mean, however, that NPPs are technically unable to do load-following. In France, with a large installed nuclear capacity (of about 63 GW in 2009), a considerable fraction of the NPPs participates in load-following. In the French fleet, the power gradients of the participating NPPs are up to 5% per minute in the power range of 30% to 100% of the rated power (Ludwig, 2010; NEA, 2011). At the time of commissioning, it was shown that the German NPPs were able to deal with power gradients of 10%/min. But, according to Luwdig (2010), the existing German NPPs have over the years been modified and optimised for baseload operation, leading to a decreased margin for load-following (by means of control rod adjustment). Nevertheless, there is no technical problem for the existing German PWRs to absorb the currently desired power gradients of 2%/min (meaning about 25 MW per minute). As a matter of fact, negative gradients (i.e. downward regulation to be able to temporarily absorb massive wind power injection in the system) of PWRs can be implemented at almost any rate over the whole range up to a hot standstill or island operation. For BWRs, because of the possibility to modify power output through flow control by means of the circulation pumps, gradients of up to 100 MW/min between 60% and 100% of the nominal power are possible. Below the 60% power output range, BWRs can be modulated also via control rod adjustment, leading to an overall modulation range of 20%-100% of the nominal power. The ramping-rate values for PWR (and BWR) are in line with those quoted by the VGB Scientific Advisory Board (VGB, 2010), which gives ramping rates of 5%/min (even faster than CCGTs). In summary, load-following does not seem to be a problem technically; such fluctuating operation might, however, possibly have consequences for the durability of some components and the operational lifetime of the plants.

With regard to load-following, convincing computer simulations have been provided by Hundt (2009), in which it was shown that the existing German NPPs would be able to absorb large power swings caused by massive renewable power injection by 2030 (up to 40% renewable electricity generation). Furthermore, it was shown that large storage facilities, or wind power curtailment, would be needed if one were to assume a speeded up renewable generation of 50% renewable electricity by 2030, to avoid a generation surplus (Hundt, 2010).

It must be stressed that the above analyses apply to existing power plants. Modern nuclear power plants are also designed for load-following operation. EPRI's Utility Requirement Document for Advanced Light Water Reactors, or in Europe, the European Utilities' Requirements (EUR) state that modern reactors should have significant manoeuvrability capability and be able to operate in the load-following mode, as well as take part in the primary control

of the grid (frequency stabilisation) (NEA, 2011). If needed, operational procedures and design margins for new NPPs could be modified so as to further improve load-following capabilities. At any rate, the fuel for such plants is designed to avoid limitations on the rate of power increase for hot and cold start-ups, so there are no fundamental operational or safety limitations on the load-following capabilities of NPPs. The problem for new NPPs will be of an economic nature. Load-following of a NPP means that its capacity factor (or load factor) will be less than optimal, leading to a more expensive cost of generating electricity for that plant. Additional "wear and tear" is also expected if the plant operates in load-following mode, which will result in slightly higher maintenance costs for the plant's equipment.

As a final point, it is interesting to mention that liberalised markets based on a marginal-cost pricing system will be faced with problems if massive power injection of almost zero-marginal-cost generation takes place. Such massive injection might lead to zero and even negative spot prices in particular control areas. With such price structure, nobody would be interested to invest in balancing capacity. The (whole) market design of liberalised markets will have to be reconsidered, e.g. to include capacity payments into the pricing system. In regulated markets, whereby pricing is based on an overall cost-plus principle, this is less of an issue.

It must be stressed that a good understanding and insight in the functioning of the overall generation system is crucial but not a straightforward exercise. Careful modelling is required to fully grasp the dynamic interactions occurring in the system (Delarue, 2009). After all, power plants face a multitude of technical constraints, characterised by typical indivisibilities (like minimal operating points), resulting sometimes in an unexpected outcome.

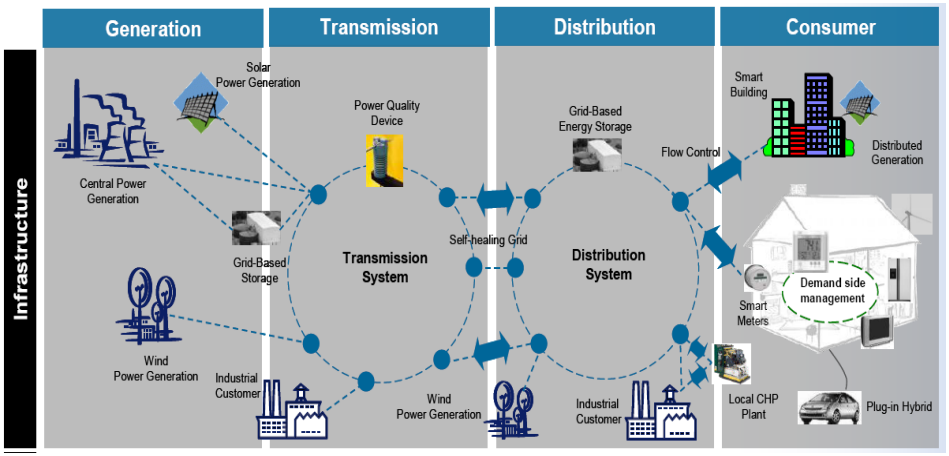
5.2. Nuclear power and "smart grids"

In 2009, electricity (including heat) accounted for 41% of global GHG emissions in the energy sector (IEA, 2011a), although it represented only 17% of the total final energy consumption (IEA, 2011b). This underlines the need to improve the efficiency of the whole electricity system, including production, delivery, and consumption and the need to evolve towards low-carbon technologies in the electricity production.

The term "smart grids" has many definitions and interpretations, depending on the specific country, drivers and outcomes. It generally refers to the entire power grid, including the generation, transmission, and distribution structure, as well as electricity consumers.

Smart grids focus mainly on the efficiency of the electricity system encompassing both supply and demand aspects, which results in GHG emissions reductions. Figure 5.1 shows an example of a smart grid concept.

Figure 5.1: Concept for smart grid for electricity supply



Source: MEF, 2009.

The expected benefits of an electricity supply system which follows the smart grid concept, include:

- the reduction of energy loss through the optimisation of power flow;
- the load levelling (see Figure 5.2) by the rational consumer response to electricity rates. This leads to:
  - decreasing the fluctuation of electric load and hence decreasing the maximum generating capacity required to meet peak demand;
  - increasing the proportion of baseload power plants;
- the increase of renewable and distributed generation sources.

In such systems, energy storage (via pump storage, or compressed air storage or even through batteries in electric vehicles) will gain in importance, and play a major role in homogenising the fluctuating electrical generation from renewable energies.

The optimal power mix in the electric supply system is the one that minimises the total costs (fixed and variable costs). The fixed costs comprise

mainly construction and O&M costs, and variable costs correspond mainly to the fuel cost. The variable costs and generation amounts by electricity-producing units are usually calculated by considering the plants' technical and economic variables on the supply side and a load duration curve on the demand side, resulting in the so-called "merit order" of each unit in the electric system. (The merit order is a way of ranking power generation units, in ascending order of their short-run marginal costs of production, so that those with the lowest marginal costs are the first ones to be brought online to meet demand, and the plants with the highest marginal costs are the last to be brought on line.)

As for the generation cost structure on the supply side, nuclear plants are highly capital-intensive compared to other conventional energy sources such as coal- and gas-fired plants, though the nuclear fuel cost is comparatively very low (about 10% of total generation cost). Therefore the more electricity nuclear power plants generate, that is, the higher the load factor, the better its economics becomes comparatively thanks to the relatively low variable (or fuel) cost.

As for the load curve on the demand side, since the electric loads are usually fluctuating continuously between the maximum and minimum loads, the specific power plants to meet the medium and peak loads, which are economically competitive only under the comparatively medium and low generations for the period, are also needed in the electric system in order to minimise the total electric system cost. In addition, the shape of load duration curve characterised by an average load rate and min/max load ratio also plays an important role in determining the generation shares by each electric technology in the system.

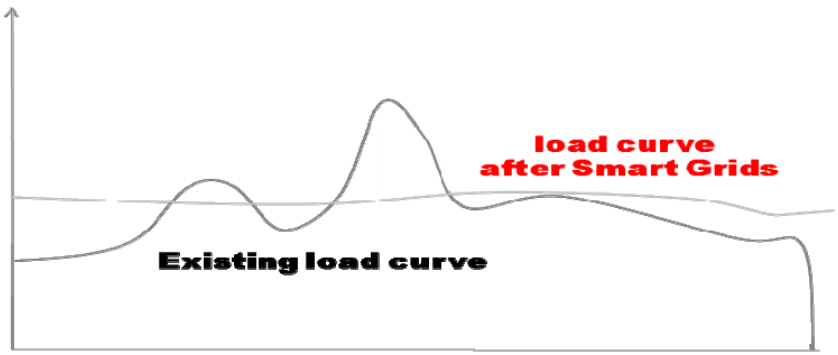
Nuclear, coal and hydro (in some countries) are often classified as baseload power plants with comparatively high capacity factors and natural gas power plants are used for peak loads with lower capacity factors over the period.

Smart grids technologies will be able to flatten the shape of the present load duration curve (LDC) thanks to the effect of the consumer response to price signals from generation plants (see Figure 5.2). This flattening phenomenon in LDC leads to a demand increase for baseload power plants, and simultaneously, to a decrease of demand for peak load or even medium load generation.

In conclusion, some of the present peaking/medium power plants could be substituted by baseload power plants. However, since coal power plants emit CO_2, nuclear power's position and share within the electric system could

increase significantly on the premise that nuclear remains very competitive compared to other energy technologies.

Figure 5.2: The potential effect of a smart grid on the load duration curve



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6. Longer-term perspectives for nuclear energy

In this chapter, the long-term perspectives for nuclear energy are reviewed, from the point of view of reactor technology evolutions (e.g. Generation IV reactors, or small modular reactors), new market applications which could develop in a low-carbon energy future (e.g. non-electric applications such as desalination or fabrication of synthetic fuels to substitute fossil fuels), as well as from the point of view of new operational constraints related to climate change or regulations (e.g. availability or regulation concerning cooling water for power plants).

6.1. Generation IV nuclear systems

The Generation IV International Forum (GIF) was initiated in 2000 and formally established in the middle 2001 with nine countries. It is an international co-operative initiative which today has 13 participants to jointly develop one or more advanced reactor system. Argentina, Brazil, Canada, China, France, Japan, the Republic of Korea, the Russian Federation, South Africa, Switzerland, the United Kingdom and the United States are members of the GIF, along with the EU (Euratom).

In 2002, GIF announced the selection of six reactor systems, which are regarded to represent the future shape of nuclear energy. These reactors were selected out of some hundred reactor concepts and some hundred experts contributed to the evaluation. They are claimed to better respond to the social, environmental and economic requirements of the 21st century and they promise to enhance the future contribution and benefits of nuclear energy. These systems employ advanced technologies and designs to improve the performance of reactors and fuel cycles as compared with current nuclear systems. They would allow meeting increased energy demands on a sustainable basis, while being resistant to diversion of materials for weapons proliferation and secure from terrorist attacks. The reactors are expected to be ready for deployment around 2030-2040.

The following reactor systems were selected for further development.

Sodium-cooled fast reactor (SFR)

The SFR has liquid sodium as the reactor coolant, allowing high power density with low coolant volume. There are about 400 reactor-years of experience with sodium-cooled fast neutron reactors over 5 decades in 8 countries, and the SFR is the main technology of interest in GIF, with prototypes planned in several countries.

Supercritical-water-cooled reactor (SCWR)

This reactor evolves from today's water reactor technology and operates at a very high pressure above the thermodynamic critical point of water (374°C, 22 MPa) to give a thermal efficiency about one third higher than current water reactors. The supercritical water (25 MPa and 510-550°C) is planned to directly drive the turbine, without any secondary steam system, simplifying the plant.

Very-high-temperature gas reactor (VHTR)

These reactors use helium as coolant and graphite as moderator. High-temperature reactors have been operated in China, Germany, Japan, the United Kingdom and the United States. Several reactors are under development, e.g. in China, Japan or the United States. Due to the absence of any metallic material in the reactor core, outlet temperature of over 900°C can be achieved, which allows thermochemical hydrogen production via an intermediate heat exchanger, with electricity cogeneration, or direct high-efficiency electricity generation with a gas turbine (Brayton cycle).

Gas-cooled fast reactor (GFR)

The GFR is a high-temperature helium-cooled fast breeder reactor with temperatures of about 850°C. It is suitable for power generation, thermo-chemical hydrogen production or other process heat applications. The helium will directly drive a helium turbine (Brayton cycle) for electricity generation.

Lead-cooled fast reactor (LFR)

The LFR is a fast neutron reactor cooled by liquid metal (Pb or Pb-Bi eutectic), which operates at low pressure by natural convection (at least for decay heat removal). Coolant temperature of 550°C can be achieved today, but in the longer term a temperature of 800°C is planned with advanced materials. The higher temperature would enable thermochemical hydrogen production.

Molten salt reactor (MSR)

The MSR has an epithermal neutron spectrum. In contrast to other reactor designs with solid fuels the MSR fuel is dissolved in the coolant which circulates through graphite core channels. The MSR has a coolant temperature of 700°C at very low pressure, with development objectives for about 800°C. Electricity generation is done via a secondary circuit, and due to the high-temperature production of hydrogen is also feasible.

Three of the six systems (SFR, LFR and GFR) employ a closed fuel cycle including the reprocessing and recycling of plutonium, uranium and minor actinides to maximise the fuel resource base and minimise high-level wastes. The MSR is designed for an epithermal neutron spectrum, and the remaining two, the SCWR and the VHTR operate with thermal neutrons like most of today's operating nuclear power plants.

The fast neutron reactors were originally conceived to burn uranium more efficiently (typically producing 30 to 60 times more energy from the same quantity of uranium) and breed new fissile fuel in form of plutonium (i.e. fast breeder reactors). Table 4.2 in Chapter 4 shows how uranium resources could be extended through the use of fast breeder reactors and advanced fuel cycles.

The high coolant temperatures of some of the Generation IV systems (up to 1 000°C for the VHTR) also open the possibilities of developing specific non-electric applications of nuclear energy. These are discussed in Section 6.3.

The Generation IV reactor systems are all in various stages of conceptual design, with some systems such as the SFR or the VHTR at a more advanced stage than others. These are expected to move into the detailed design phase by the middle of the decade if decisions to build prototypes (e.g. ASTRID in France for the SFR and the NGNP in the United States for the HTR) are taken.

The 2010 GIF annual report (GIF, 2010) and the GIF website give an overview of the latest developments for these systems (www.gen-4.org).

6.2. Accelerator-driven systems

Accelerator-driven systems (ADS) operate by means of an external neutron source (created through the acceleration of protons that are smashed into a heavy material so as to produce so-called "spallation neutrons") so that the reactor assembly operates sub-critically. Although some ideas were launched in the 1990s to operate ADS systems for electricity production (called "energy amplifiers") based on a thermal spectrum and fed by thorium-232, it is the

current understanding that the first generation of ADS should operate with fast neutrons and should concentrate on nuclear waste incineration (the so-called "partitioning and transmutation" – P&T), with energy production as a useful side product. This can reduce the inventory of long-lived isotopes and facilitate waste management. At present, a prototype ADS project, the MYRRHA project,[1] is being investigated in Europe.

6.3. Small modular reactors

Commercial nuclear power plants under construction are mostly large sized units, with a capacity of more than 700 MWe. But there is also renewed interest in the small- (i.e. below 300 MWe) and medium-sized (between 300 MWe and 700 MWe) category, which is of particular interest to countries with small electricity grids, for energy supply to remotely located areas or for special applications, such as heat supply for various industrial processes, district heating, desalination of seawater, enhanced oil recovery and coal conversion. Lower investment cost compared to large nuclear units is also one of the most attractive features of such reactors. Currently about 40 reactors in the small- and medium-sized category are at different stages of development or design (IAEA, web).

The most recent small reactor designs make extensive use of modularity and scalability, hence the abbreviation SMR for small modular reactor used in particular in the United States.[2] For such reactors, large components can be assembled in workshops, and transported by rail, truck or barge to the construction site, reducing significantly site assembly work. Scalability means that several reactor modules can be added on one site to increase the power output of the nuclear power plant, if necessary.

A recent review of SMR concepts and an analysis of their economic competitiveness compared to large nuclear units and other electricity generation technologies can be found in NEA (2011). It was shown in this report that in

1. MYRRHA: Multipurpose hYbrid Research Reactor for High-tech Applications: http://myrrha.sckcen.be. This project has also been selected as the European Technology Pilot Plant demonstration for the lead fast reactor (LFR) technology, one of the options pursued by Europe's Nuclear Industrial Initiative under the EU SET plan (http://ec.europa.eu/energy/technology/set_plan/set_plan_en.htm).

2. The IAEA uses the abbreviation SMR to describe small- and medium-size reactors. In this report, SMR refers to small modular reactors, which are advanced small-size reactors (typically < 300 MWe) based on modular design and construction. None has been built to this day.

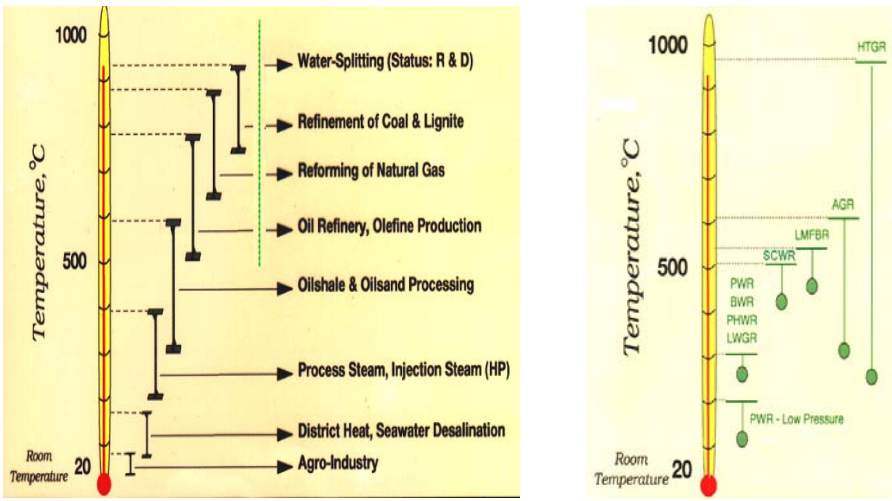
markets where large nuclear units cannot be considered, SMRs may be competitive compared to fossil or renewable energy sources.

At present, no such reactor has been built or licensed, though several utilities, especially in the United States, have expressed interest in building such reactors.

6.4. Non-electric applications

The expected shortages of fossil fuels, the prospects of their rising prices as well as their uncertain availability have created increased attention to substitute forms of energy, which at the same time have less impact on the environment. Developing renewables and nuclear for electricity generation, together with energy storage and smart grid technologies, could help reduce significantly the share of fossil fuel (essentially coal and gas) in electricity generation.

Figure 6.1: Temperature requirements for process heat applications and core outlet temperatures of principal reactor lines



Source: IAEA, 2008.

But nuclear energy could also address non-electric applications by providing both electricity and heat to industrial processes which today use fossil fuel. These applications include district heating, desalination, enhanced oil recovery, coal conversion, synthetic gas production, oil refining, and hydrogen production (IAEA, 2008; von Lensa, 2010). The Figure 6.1 shows temperature requirements for various industrial processes and at the same time outlet

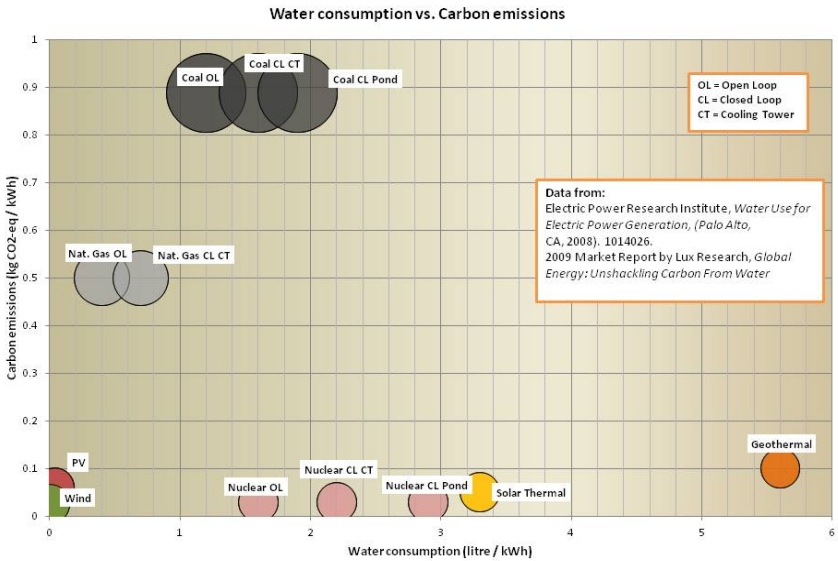
temperatures of principal reactor types. For example, water-cooled reactors (light water and heavy water) can produce hot water or steam up to about 300°C. Gas-cooled reactors cooled by carbon dioxide and liquid metal cooled reactors can produce process steam up to 540°C, and the high-temperature gas-cooled, graphite-moderated reactor (HTGR) can produce process heat up to 950°C.

Hydrogen production using thermochemical splitting and nuclear heat for example is such a process heat application, which could substitute steam reforming of natural gas. Use of hydrogen as a transport fuel, or use of hydrogen to manufacture synthetic fuels, will depend on the development of the "hydrogen economy". In the long term, if such non-electric applications of nuclear energy develop and displace fossil-fuel usages, the contribution of nuclear technologies to the reduction of greenhouse gas emissions could extend beyond the power sector.

6.5. Adaptation to climate change

Besides the barriers to the development of nuclear energy that were cited in Chapter 4, there are other possible constraints which opponents of nuclear energy often cite, especially in the context of evolving environmental and regulatory conditions. One such constraint, related to siting, is the availability of cooling water for nuclear power plants, especially for those situated along rivers. It is well known that nuclear power plants require large quantities of cooling water. This is especially true for once-through cooling plants, where large amounts of water are withdrawn and then returned to the source. Power plants with cooling towers withdraw less water, but consume more than once-through cooling plants, since a significant part is evaporated. Today's nuclear power plants require more cooling water than coal- or gas-fired power plant per kWh produced, essentially because of the lower efficiency of the nuclear Rankine cycle (see Figure 6.2).

Figure 6.2: Carbon and water intensities of different electricity generating technologies



Regulations concerning allowable cooling water heat-up exist to protect the environment and the eco-system of the cooling source, and there are examples where nuclear power plants have had to reduce their power output to limit thermal releases. Other regulations limit the amount of water intake, which effectively imposes the use of cooling towers for nuclear power plants, even for sites situated near large expanses of water (for instance for the projected Calvert Cliff Unit 3 in the United States). In that case, the argument against the use of once-through cooling is not concern over the impact of thermal releases onto the environment, but the impact of large water withdrawal on the life of fish and other wildlife at the filtering screens of the water intake.

In either case, nuclear power plant technology needs to adapt itself to harsher climatic conditions (drought, heat, storms, heavy rain, flooding…) and more stringent regulations. This adaptation will call for technological advances in cooling technologies, which are also required for other thermal power plants. On the reactor side, it should also be mentioned that future nuclear power plants (e.g. Generation IV) have higher operating temperatures and higher efficiencies, and so will have lower water intensity compared to today's reactors. A new study might be carried out by the NEA to address in detail the technological adaptations that nuclear power plants may require to operate in more constrained environmental and regulatory conditions.

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7. Summary and conclusions

The generation of electricity from nuclear power does not result in any direct emissions of CO_2, the most important of the greenhouse gases thought to be responsible for global warming. As with all energy sources, there are some indirect emissions; these result mainly from fossil fuel use for operations in the nuclear fuel cycle. The exact level of these indirect emissions varies according to location and the technologies used, but studies described in this report show that even in the highest cases they remain more than an order of magnitude below the direct emissions from fossil fuel generation, and are comparable to the indirect emissions from most renewable energy sources.

As an established source of low-carbon energy, nuclear power could potentially play a vital role in achieving large reductions in CO_2 emissions while ensuring reliable and affordable energy supplies. This is illustrated by scenarios such as the International Energy Agency's Blue Map scenario, which models a 50% cut in energy-related CO_2 emissions. It includes around 1 200 GWe of nuclear capacity by 2050, or some 24% of global electricity supply. This presumes that a large-scale and broadly-based expansion of nuclear capacity will take place, such as occurred during the first major nuclear expansion of the 1970s and 1980s.

It is clear from this and other scenarios that nuclear energy could make a major contribution to future cuts in CO_2 emissions if it is able to provide around one-quarter of global electricity supply by 2050. To reduce CO_2 emissions from electricity supply by over 90% by 2050 would require this nuclear expansion to occur alongside an even more rapid expansion of renewable energy capacities, the large-scale introduction of carbon capture and storage technology at fossil-fuelled power plants, and major improvements in energy efficiency.

Nuclear presently provides around 13.4% of global electricity, a figure which has been in decline in recent years as its growth has not matched the overall growth in electricity supply. Although this decline may continue for a few more years, the significant upturn in nuclear plant construction starts that was observed between 2008 and 2010 could indicate a halt in the decline in nuclear share of total electricity production. In 2011, the number of construction starts dropped to 4 from 16 in 2010, possibly as a combined effect of the

Fukushima Daiichi accident and the economic crisis. It is too early to assess the trend in 2012, but it is worth noting that for the first time in more than 30 years, the United States has decided to launch the construction of new nuclear build, with the Combined Construction and Operating Licences being granted by the US NRC for 4 Generation III+ reactors in 2 sites.

However, for nuclear energy to provide a growing share of global electricity by 2020 and beyond, the pace of nuclear construction would need to further increase in the next few years. Hence, the key question for the future of nuclear energy is whether it can expand quickly enough over the next decades to provide a growing share of total electricity supply as the use of fossil fuels is cut back in order to reduce CO_2 emissions.

The analysis in this study indicates that to meet the capacity milestones mentioned above towards a nuclear capacity of 1 200 GWe in 2050, new nuclear power plants would need to be built at the rate of close to 16 GWe per year over the current decade to 2020. This is a little greater than the rate that was observed at the end of 2010, when 63 GWe was under construction (equivalent to an annual rate of about 13 GWe, assuming a 5-year construction period). Given that there clearly remains some under-utilised capacity for nuclear construction (for example, in the United States), it would appear that achieving an installed nuclear capacity of around 512 GWe by 2020 is certainly feasible with a gradual build-up of industrial capabilities and human resources.

The rate of nuclear construction would need to grow to around 20 GWe per year on average in the 2020s if capacity is to reach around 685 GWe by 2030. Reaching a capacity of 900 GWe by 2040 would require that the rate of nuclear construction rises to an average of around 36 GWe per year in the 2030s as many existing plants retire, on the assumption that a 55-year lifetime will typically be achieved for existing light water reactors. A further increase in the average construction rate to 42 GWe per year would be needed in the 2040s to reach a capacity close to 1 200 GWe by 2050.

Hence, lifetime extensions for the existing rector fleet would help nuclear capacity to grow strongly until 2030, as new start-ups would mainly represent additional capacity. However, in the 2030s and 2040s the rate of retirements is likely to rise strongly, meaning that much new capacity would simply be replacing older plants. In other words, the rate of nuclear construction would need to increase markedly after 2030 if total nuclear capacity is to continue to grow strongly in the face of increasing retirements. Hence, the growth of nuclear capacity could slow after 2030 unless there is a strong upturn in new construction at that stage.

Factors affecting nuclear expansion

The study has not identified any insurmountable barriers to an expansion of nuclear generating capacity on the scale required over the next 40 years. However, despite the clear opportunity for nuclear energy to expand as the use of fossil fuels is cut back, many challenges to such a rapid expansion remain. If nuclear energy is to realise its full potential, then governments and the nuclear and electricity supply industries would need to successfully address these.

Progress in the near future, to around 2020, will to a large extent set the scene for a potentially more rapid expansion in the following decades. Decisions and actions in the next few years, or the lack of them, will have an important impact on the longer-term development of nuclear generating capacity. Thus, it is important that an early start is made if nuclear capacity is to grow strongly in the 2020s and beyond.

The principal challenges for nuclear expansion over the next ten years include:

- The difficulties of financing the high capital costs of nuclear plants, especially given the risk of delays and cost overruns with first-of-a-kind plants and in countries with no recent experience of nuclear construction.

- Overcoming current constraints on industrial capacities and human resources for the construction of nuclear plants.

- Recovering pre-Fukushima levels of public acceptance of nuclear energy, by addressing people's concern over the safety of nuclear power.

- Demonstrating the safe management of radioactive wastes, and implementing plans for the disposal of long-lived high-level waste.

- Introducing nuclear capacity into additional countries while avoiding the proliferation of sensitive nuclear materials and technologies.

- Increasing the supply of nuclear fuel in line with the expansion of nuclear capacity, and ensuring reliable fuel supplies during reactor lifetimes of 60 years.

The regulatory reviews that were ordered in countries operating nuclear power plants after the Fukushima Daiichi accident are expected to result in

additional requirements on nuclear plant designers and operators. This could lead to delays and increased costs for nuclear construction projects, though it is too early to quantify these impacts. At the same time, it could be beneficial to public acceptance of nuclear power by showing that safety suffers no compromise, and remains the highest priority for governments, regulators and operators.

Another important factor that could affect the future of nuclear energy but which is not discussed in this report, is likely to be the potential availability of much greater reserves of natural gas than previously thought. This would directly affect gas prices, and therefore the competitiveness of nuclear power. Natural gas is a very flexible fuel for power generation, and gas-fired plants can be built quickly and with a relatively modest capital investment. Burning natural gas produces less CO_2 at the power plant than coal or oil burning, and it is sometimes seen as a quick way to achieve some reduction in CO_2 emissions. However, a widespread increase in the use of gas for electricity production will limit the reduction in emissions that can be achieved. Furthermore, significant amounts of methane, a potent greenhouse gas, may be released during gas production and transport. Security of energy supply may also be of concern to countries relying on imported gas.

In the longer term, other issues may come to the fore. Nuclear energy is today a source of baseload electricity, i.e. nuclear plants are mostly in operation constantly at full power. In a largely decarbonised electricity supply system (containing mainly renewables, nuclear energy and fossil fuel plants with CCS), nuclear plants may increasingly need to adapt their output to complement that of intermittent renewable, and it was shown that reactors do have load-following capabilities. The gradual introduction of smart grids at both transmission and distribution levels will also impact the demands on generating plants. New designs of nuclear plant will thus need to take account of these changing requirements.

There is also potential for nuclear energy to meet energy requirements beyond its established role in large-scale grid electricity supply. Designs for small modular reactors are being developed that could allow nuclear energy to be introduced in locations where existing grid infrastructure is inadequate for a large-scale plant, or in remote communities that are isolated from grid connections. In addition, some new designs will be capable of producing the high temperatures needed for direct use in industrial processes, such as in chemical plants, displacing fossil-fuel burning.

The continued development of nuclear technology, including Generation IV reactors and fuel cycles, holds the promise of extending the

resources available for nuclear energy by between 30 to 60 times or more, potentially providing low-carbon energy for several thousand years. Some of the new fuel cycles consider the recycling of minor actinides, and they could offer significant reductions in volumes and heat load of long-lived radioactive waste. Generation IV reactors are aiming at improved safety and performance, as well as increased proliferation resistance. Of course, important technical and organisational challenges will have to be overcome before this can begin to be achieved, but research and development programmes now underway aim to fully demonstrate such technologies over the next 20 to 30 years.

Responding to the challenges

A successful nuclear programme in any country must have the confidence of society as a whole. Nuclear plant operators are responsible for ensuring they achieve high standards of operational safety and performance. This must be backed up by strong and independent regulatory authorities. Furthermore, transparency and public involvement in decision-making are vital to ensure public acceptance for nuclear programmes. This encompasses issues such as radioactive waste management and disposal, nuclear safety, and avoiding the proliferation of sensitive nuclear materials and technologies.

In common with other studies, this report notes that strong and sustained government policy support is a prerequisite for nuclear expansion. Governments must also create the appropriate legal, regulatory and market conditions in which investment in new nuclear capacity can take place if they intend to rely on the nuclear option. They must work with industrial partners to ensure that the decision-making and regulatory processes work effectively and efficiently. Harmonisation of regulatory requirements between countries would have important benefits, helping to reduce construction times and costs by allowing near-identical plants to be built in many countries.

It clearly makes good economic sense for energy supplies to be provided in the most cost-effective manner, including the cost of carbon emissions reductions. This can potentially be pursued through government planning and/or control of energy supply systems and industries, or through the development of open and competitive energy markets with mainly private-sector participants within an appropriate legal and regulatory framework. In the latter case, the aim of governments should be to create a level playing field for competition, which should ensure that the most cost-effective solutions are adopted to the maximum extent.

There is an important role for government support for new energy technologies, including for research and development and for early deployment.

However, as such technologies mature they should be increasingly exposed to competitive pressures. In the longer term, rather than governments choosing particular technologies to support, introducing technology-neutral carbon pricing or trading systems is likely to improve the cost-effectiveness of energy supply and CO_2 emissions reductions.

In general, low-carbon energy sources are more capital intensive than fossil-fuelled sources. Hence, achieving large-scale cuts in CO_2 emissions will require huge investments to be made in all forms of low-carbon energy over the coming decades, as well as in improved energy efficiency and in the upgrading of energy networks. Ultimately it is energy consumers who must pay for this investment. Achieving the most cost-effective reductions will thus be important for maintaining public and political support for the move to low-carbon energy sources.

Although studies have shown that nuclear energy is one of the most cost-effective sources of electricity on a lifetime cost basis, the scale of investment in an individual nuclear power plant, and hence the period required to make a return on investment, is generally much larger than for other types of generating plant. This creates particular problems for those seeking to finance investment in new nuclear plants, driving up the financing costs compared to fossil-fuelled generating capacity. This is especially true where such investment is to be made principally by the private sector and where competitive electricity markets exist. At least in the early stages of nuclear expansion, some form of government support for financing costs may thus be required in some cases.

Decisions to invest in increasing the industrial capacities needed for the construction of nuclear power plants, such as facilities for producing large steel forgings, are largely based on commercial factors, i.e. investments will take place once it is clear that orders will be forthcoming and that the facilities will operate profitably. Hence, new capacity may take several years to come into operation. Clear and consistent policy support for nuclear expansion will also be important in giving investors the confidence to proceed.

Expanding the skilled human resources needed for new nuclear construction will also take place gradually as it becomes clear that the nuclear industry offers attractive long-term career opportunities. Again, stability in government policy on nuclear energy would help achieve this. But the growth of real job opportunities in an expanding nuclear industry is the key to stimulating demand for the relevant university courses and technical training. This reinforces the point that the capacity for nuclear expansion would take some time to increase, and that it is important to develop “momentum” in the next few years to create the conditions for a more rapid expansion in later years.

Annex 1
Abbreviations

BWR	boiling water reactor
CCS	carbon capture and storage
EPD	environmental product declaration
ETP	*Energy Technology Perspectives*
FR	fast reactor
HLW	high-level long-lived waste
IEA	International Energy Agency
ILW	Intermediate-level long-lived waste
IOA	Input-output analysis
IPCC	Intergovernmental Panel on Climate Change
ISL	*in situ* leaching
LCA	life-cycle analysis
LDC	load duration curve
LTO	long-term operation
LWR	light water reactor
MDEP	Multinational Design Evaluation Programme
MOX	mixed-oxide fuel
NDC	Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle
NEA	Nuclear Energy Agency
NPP	nuclear power plant
OECD	Organisation for Economic Co-operation and Development
PCA	process chain analysis
PWR	pressurised water reactor
SMR	small modular reactor
SWU	separative work unit
UOX	uranium oxide fuel
WEO	*World Energy Outlook*

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The Role of Nuclear Energy in a Low-carbon Energy Future

This report assesses the role that nuclear energy can play in supporting the transition to a low-carbon energy system. It begins by considering the greenhouse gas emissions from the full nuclear fuel cycle, reviewing recent studies on indirect emissions and assessing the impact that nuclear power could make in reducing greenhouse gas emissions.

The report provides estimates of the construction rates that would be needed to meet the projected expansion of nuclear power foreseen by many energy scenarios published by international organisations. It then assesses the economic, technical, societal and institutional challenges represented by such an expansion to identify the most significant barriers. The capacity of nuclear power plants to operate in an electricity system with a large share of renewables, and the impact of smart grid technologies are also examined. Finally, long-term prospects for nuclear energy are discussed in terms of development of new reactor and fuel cycle technologies, non-electric applications and new operational and regulatory constraints that could arise as a consequence of climate change.

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