

CLIMATE CHANGE AND NUCLEAR POWER 2008



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Introduction

The possibility of global climate change resulting from increasing anthropogenic emissions of greenhouse gases (GHGs) is a major concern. A principal source of GHGs, particularly carbon dioxide (CO₂), is the fossil fuels burned by the energy sector. Energy demand is expected to increase dramatically in the 21st century, especially in developing countries, where population growth is fastest and, even today, some 1.6 billion people have no access to modern energy services. Without significant efforts to limit future GHG emissions from the energy sector, therefore, the expected global increase in energy production and use could well trigger “dangerous anthropogenic interference with the climate system”, to use the language of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) [1].

To reduce the risk of global climate change, industrialized countries (listed in Annex I of the Convention¹) have made commitments to reduce their collective GHG emissions under the Kyoto Protocol to the UNFCCC during 2008–2012 by at least 5.2% below 1990 levels. Since the USA did not ratify the Kyoto Protocol, the actual reduction level will be only about 3.8% of the 1990 Annex I emissions, even if all Parties achieve full compliance. This reduction is by far outweighed by increases of emissions in non-Annex I countries in the same period. However, much deeper global emissions cuts will be necessary over the next few decades to stabilize atmospheric GHG concentrations at levels such that the increase in the mean annual surface temperature of the Earth will not exceed 2.5°C [2] relative to the pre-industrial level.

Nuclear power plants produce virtually no GHG emissions during their operation and very low amounts of emissions on a life cycle basis. Nuclear energy could, therefore, be an important part of future strategies to reduce GHG emissions. Nuclear power is already an important contributor to the world’s electricity needs. In 2007, it supplied about one seventh of global electricity and a significant 27% of electricity in western Europe. Despite this substantial contribution, the future of nuclear power was overcast by uncertainty until recently. In an increasingly liberalized electric power industry, return on the investment needed to build a new power plant is critical in deciding which power technology to invest in. The high upfront capital costs for building new nuclear power plants, their relatively long construction time and payback period, and the lack of public and political support in several countries for new construction can make nuclear power a less attractive alternative than fossil fuelled power plants. These factors have changed in recent years.

The nuclear industry is working to reduce costs and improve safety and waste management in order to increase political and public acceptance for nuclear power. The very low amount of GHG emissions from nuclear power could further enhance its future competitiveness. This booklet summarizes nuclear power’s potential role in mitigating global climate change and its contribution to other development and environment challenges, as well as its current status, including the issues of cost, safety, waste management and non-proliferation.

¹ Annex I includes the OECD (membership of 1990) plus Belarus, Bulgaria, Croatia, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, the Russian Federation, Slovakia, Slovenia and Ukraine.

The global energy challenge

All recent energy studies project major increases in energy demand, driven largely by demographic and economic growth in today's developing countries. Of the world's 6.6 billion people, 82% live in non-OECD countries and consume only 53% of global primary energy. Worldwide, 2.4 billion people rely on traditional biomass as their primary source of energy, and 1.6 billion people do not have access to electricity [3]. A growing global population will compound this problem. The latest projection of the United Nations estimates an additional 1.65 billion people by 2030, and another billion by 2050, bringing the world's population to about 9.2 billion by the middle of this century [4]. The rising population will enjoy increasing economic welfare. The World Bank [5] projects a 4.2% average annual growth rate for the world economy up to 2015, 3.3% between 2015 and 2030, and 2.6% for the subsequent two decades up to 2050. Developing countries will grow

fastest, while OECD countries will grow at the slowest rate.

Based on these two main drivers and additional assumptions about technological development and resource availability for the energy sector, the International Energy Agency (IEA) of the Organisation for Economic Co-operation and Development (OECD) projects world total primary energy demand to grow to over 17.7 billion tonnes of oil equivalent (Btoe) by 2030 and to exceed 23 Btoe in 2050 [6]. The shares of main energy sources in the global primary energy balance are shown in Fig. 1.

The most notable changes in the IEA Reference Scenario for the next half century include the following:

- Coal is expected to surpass oil as the largest primary energy source by 2040, due to the persistent high growth in

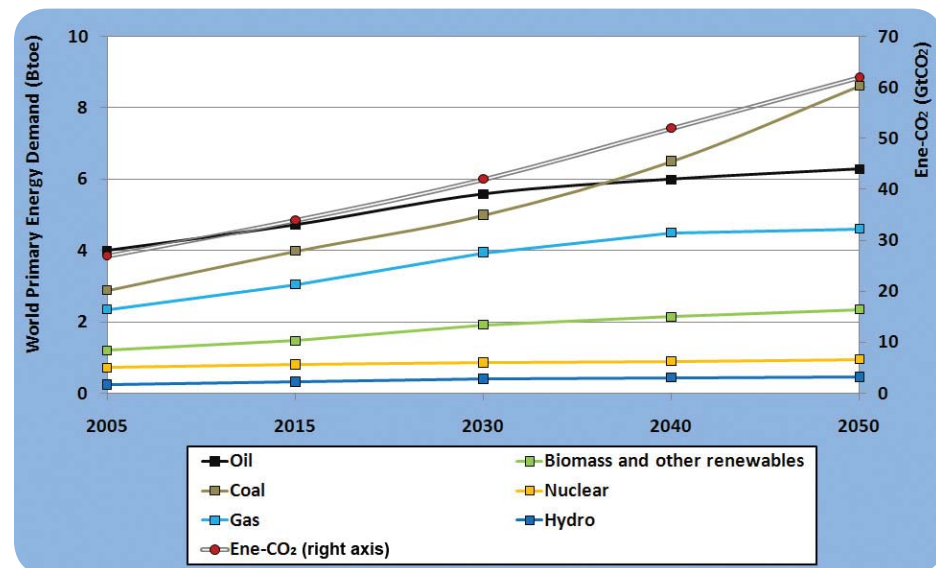
demand for electricity in coal-rich countries such as China and India.

- Gas is projected to level out at around 4.5 Btoe by the middle of the century.
- Despite a 31% increase in volume between 2005 and 2050, the nuclear share in the global primary energy balance is projected to decline from 6.3% in 2005 to 4.8% by 2030 and to 4% by 2050.

The climate change implications of the Reference Scenario are severe. Energy related

CO₂ emissions, the largest component of global GHG emissions, increase by 55% in 2030 and by 130% in 2050 relative to 2005 (see Fig. 1). Assuming that other GHGs increase at comparable rates, this would put the Earth on track towards atmospheric GHG concentrations of the order of 1000 ppm CO₂ equivalent (CO₂-eq.) and an equilibrium warming of over 5°C in terms of global mean temperature increase above the pre-industrial level.

FIG. 1. Global primary energy sources (left axis) and energy related CO₂ emissions (right axis) in the IEA's WEO and ETP reference scenarios [6, 7].



The climate change challenge

The global emissions trend of the IEA Reference Scenario [7] is in sharp contrast to what scientists find to be the type of modest climate change impacts that would be straightforward to cope with and what politicians aspire to as targets for tolerable levels of climate change. According to the findings of the Intergovernmental Panel

on Climate Change (IPCC), the biophysical changes resulting from a more than 3°C warming trigger increasingly negative impacts in all climate sensitive sectors in all regions of the world [8]. Table I summarizes the main features of the pathways towards stabilizing climate change in the low warming range.

TABLE I. ATTRIBUTES OF STABILIZING THE CLIMATE SYSTEM BELOW 4°C WARMING RELATIVE TO THE PRE-INDUSTRIAL CLIMATE [2]

GMT ^a increase (°C)	CO ₂ -eq. concentration (ppm)	CO ₂ concentration (ppm)	CO ₂ emissions peak between	CO ₂ emissions back at 2000 level	CO ₂ emissions in 2050 relative to 2000 (%)
2.0–2.4	445–490	350–400	2000–2015	2000–2030	–85 to –50
2.4–2.8	490–535	400–440	2000–2020	2000–2040	–60 to –30
2.8–3.2	535–590	440–485	2010–2030	2020–2060	–30 to +5
3.2–4.0	590–710	485–570	2020–2060	2050–2100	+10 to +60

^a GMT increase: global mean temperature increase above the pre-industrial level at equilibrium, using best estimate climate sensitivity (3°C).

Over the time horizon up to 2050, an immense gap can be observed between the IEA Reference Scenario involving a 130% increase in global energy related CO₂ emissions relative to 2005 and the 50–85% reductions required for keeping global warming below 2.4°C. This illustrates the enormous mitigation challenge the world will face over the next four decades.

In the Fourth Assessment Report (AR4) of the IPCC, Working Group III (WGIII) [2] analysed GHG mitigation options and costs in large world regions (OECD, economies in transition (EIT) and non-OECD/EIT) across a range of sectors (energy supply, transport, buildings, industry, etc.) and over two time horizons: medium term (up to 2030) and

long term (through to 2100). The report concludes that many mitigation technologies and practices that could reduce GHG emissions are already commercially available. Technical solutions and processes could reduce the energy intensity in all economic sectors and provide the same output or service with lower emissions in transport, buildings and industry. Fuel switching and modal shift (from road to rail, from private to public) in the transport sector; heat recovery, material recycling and substitution in industry, improved land management and agronomic techniques and energy crop cultivation in agriculture, and fuel switching, efficiency improvements, the increased use of renewables and nuclear power as well as carbon capture and storage (CCS) could

result in significant GHG reductions in the energy sector.

Chapters 4–10 of the WGIII report review a large number of bottom-up studies that assessed mitigation potential in seven sectors (energy supply, transport, buildings, industry, agriculture, forestry and waste) by focusing on specific technologies and regulations. Aggregating the options in each sector, the economic mitigation potential is estimated to be between 0.7 (waste management) and 6 (buildings) gigatonnes of CO₂ equivalent² (Gt CO₂-eq.) annually on the basis of carbon prices below \$100/t CO₂-eq. in 2030. The global economic mitigation potential in 2030 amounts to some 16–31 Gt CO₂ eq./year at carbon prices below \$100/t CO₂-eq. out of total baseline GHG emissions of about 56 Gt CO₂-eq. About 6 Gt CO₂-eq. of the total mitigation potential could be realized at negative cost, since the associated benefits (reduced energy costs and less damage due to lower

local and regional air pollution) exceed their costs.

The IPCC AR4 confirmed that, compared with other anthropogenic sources, GHG emissions from the energy supply sector grew at the fastest rate between 1970 and 2004. Currently, energy related CO₂ emissions (including feedstocks) comprise by far the largest share (about 60%) of total global GHG emissions, and this is likely to remain the case over the coming decades. In the absence of additional policy interventions (relative to those already in place), annual GHG emissions from energy production and use are projected to reach 34–52 Gt CO₂ by 2030 (cf. the 42 Gt CO₂ projected by the IEA [6] for 2030). This implies, as chapter 4 of the WGIII puts it, that “[T]he world is not on course to achieve a sustainable energy future. To reduce the resultant GHG emissions will require a transition to zero- and low carbon technologies” (Ref. [6], p. 255).

² The definition of carbon dioxide equivalent (CO₂-eq.) is the amount of CO₂ emission that would cause the same radiative forcing as an emitted amount of a well mixed GHG (CO₂, methane (CH₄) and nitrous oxide (N₂O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF₆) and ozone depleting substances (ODS; chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons) or a mixture of well mixed GHGs, all multiplied with their respective greenhouse warming potentials to take into account the differing times they remain in the atmosphere.

Nuclear power is a low carbon technology...

Dozens of studies in recent years have estimated the life cycle GHG emissions from a suite of power generation technologies. The results of serious technical studies tend to diverge somewhat, due to varying assumptions about the different components of the technology, conversion efficiencies and GHG emissions factors of the energy sources involved, and other features of the fuel chain.

For nuclear power, the most important component in determining the life cycle emissions is the technology used to enrich uranium. Gaseous diffusion, the technology widely used in the past and still in use in several countries, requires a substantial amount of electricity: “roughly 3.4% of the electricity generated by a typical US reactor would be needed to enrich uranium in the reactor’s fuel” [9]. However, the industry has been increasingly switching to gaseous centrifuge technology, which requires only about 2% of the energy input needed for gaseous diffusion (less than 50 kW-h/SWU³ in contrast to the 2400 kW-h for gaseous diffusion), thereby drastically reducing the life cycle GHG emissions from nuclear power, even if the electricity is supplied from fossil sources. The share of centrifuge based enrichment is approaching 70% globally; hence there is still room to improve the life cycle emission balance of the nuclear fuel cycle. All other GHG emissions from generating nuclear power, including cement, iron and steel production for constructing the power plants, are very low when spread over the lifetime of the reactor.

A recent paper by Weisser [10] reviews a set of life cycle GHG assessments pub-

lished between 2000 and 2006. The studies reviewed represent the state of the art with respect to the details, methods and complexity of the assessments and the electricity generation technologies, including upstream (before generation) and downstream (post-generation) processes. The full technology chain for nuclear energy includes uranium mining (open pit or underground), milling, conversion, enrichment (diffusion or centrifuge), fuel fabrication, power plant construction and operation, reprocessing, conditioning of spent fuel, interim storage of radioactive waste, and the construction of the final repositories. Weisser finds that for the most widely used reactor technology (light water reactors), GHG emissions during the operational stage of the reactor, relative to cumulative life cycle emissions, are of secondary importance — ranging between 0.74 and 1.3 g CO₂-eq./kW·h. The bulk of the GHG emissions arise in the upstream stages of the fuel and technology cycle, with values between 1.5 and 20 g CO₂-eq./kW·h. As noted above, this span is largely due to which enrichment process the various assessments considered and to what extent they accounted for nuclear fuel recycling. The GHG emissions associated with downstream activities, such as decommissioning and waste management, range between 0.46 and 1.4 g CO₂-eq./kW·h. Cumulative emissions for the studies reviewed by Weisser lie between 2.8 and 24 g CO₂-eq./kW·h. Figure 2 presents a summary of life cycle GHG emissions for a range of power generation technologies and fuels.

Figure 2 shows that nuclear power, together with hydropower and wind based electricity, is one of the lowest emitters of GHGs

in terms of g CO₂-eq. per unit of electricity generated on a life cycle basis. Coal based generation, even if equipped with CCS, is estimated to emit about one order of magnitude more GHGs per unit of electricity than the three truly low carbon generating technologies. These results are consistent with the conclusions of similar studies by respected authors and organizations [11–13].

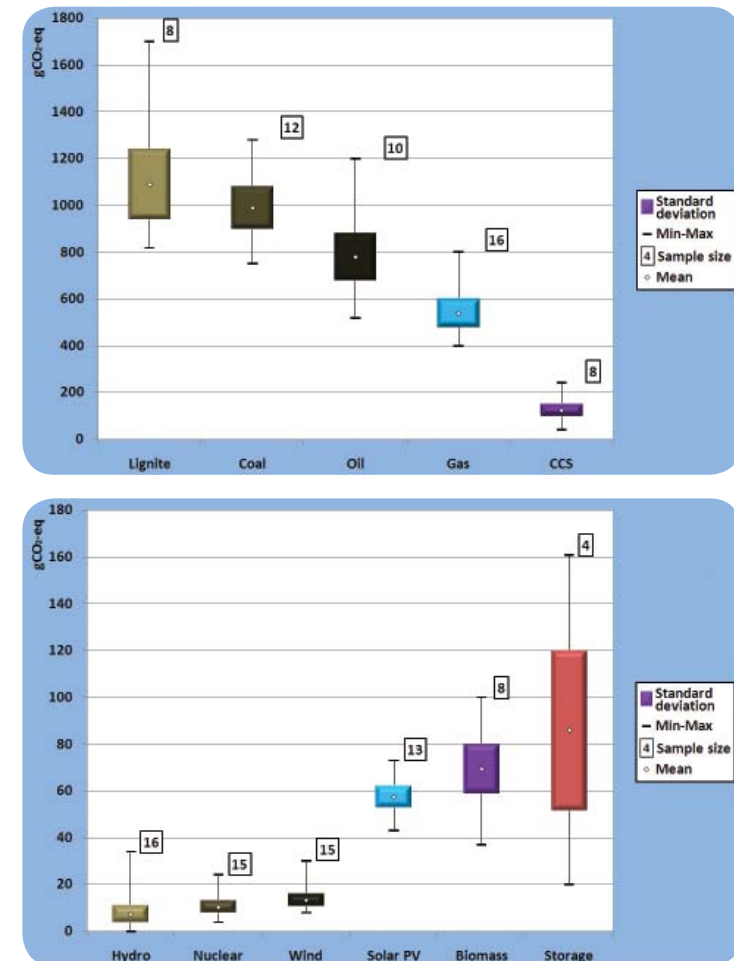
It is possible to reduce GHG emissions from nuclear energy technologies even further. Dones et al. [14] highlight three key areas of improvement:

- Reduce electricity input for the enrichment process (e.g. replacement of diffusion by centrifuges or laser technologies);

- Use electricity based on low or non-carbon fuels;
- Extend lifetime and increase burnup.

While the technology based life cycle assessments provide useful information about the relative merits of power generation technologies in terms of GHG emissions, the real proof of the competitiveness of technologies in a carbon constrained world will be the introduction of a uniform price on all GHG emitting activities via a carbon tax or emission permit trading. This arrangement will also demonstrate the relative merits of the technologies in the broad context of market competition.

FIG. 2. Summary of life cycle GHG emissions for selected power generation technologies [10].



³ The separative work unit (SWU) combines the amount of uranium processed, the composition of the starting material and the degree to which it is enriched into a single indicator. The SWU indicates the amount of energy used in enrichment, when feed, tails and product quantities are expressed in kilograms. For example, processing 100 kg of natural uranium takes about 61 SWU to produce 10 kg of low enriched uranium with 4.5% ²³⁵U content, at a tails assay containing 0.3%.

...and has been contributing to avoided GHG emissions for decades

Over the past 50 years the use of nuclear power has resulted in the avoidance of significant amounts of GHG emissions in 30 countries of the world. Globally, the amount of prevented emissions is comparable with that of hydropower. This is demonstrated by calculating CO₂ emissions avoided by hydroelectricity, nuclear power and renewables in global electricity generation. Clearly the calculated amounts of avoided emissions depend on the assumptions about which technology and fuels would have replaced the low carbon emitting technologies. For the purposes of this analysis, it was assumed that the electricity generated by hydropower, nuclear energy and renewables would have been produced by increasing the coal, oil and natural gas fired generation in proportion to their respective shares in the electricity mix in any particular year.

This approach underestimates the emissions avoided, as most of the nuclear capacity expansion in the 1970s and early 1980s would have been substituted by coal rather than by oil and natural gas, since the rationale for investing in nuclear power was specifically a reduction in the oil and gas dependence of electricity generation (an effect of the oil crises of the 1970s).

During the 'dash for gas' period after the mid-1980s, only a few nuclear power plants were built and thus there is no overestimation, as the coal share would have been much higher (in the absence of nuclear power and other low carbon electricity sources) than it was in reality (even if only gas had substituted for nuclear power).

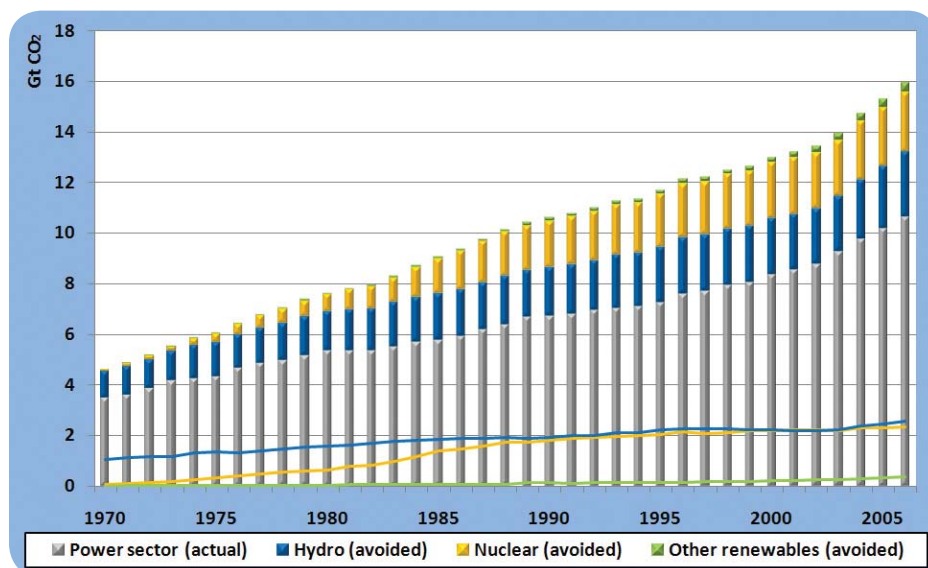
Figure 3 shows the historical trends of CO₂ emissions from the global power sec-

tor and the amounts of avoided emissions by using hydropower, nuclear energy and other renewable electricity generation technologies.

The height of the grey columns indicates the total CO₂ emissions in any given year. The three lines at the bottom show the trends of the amount of CO₂ emissions avoided by the contribution of the three low carbon technologies. Finally, the applicable amounts of avoided emissions in a given year were added to the actual emis-

sions to illustrate the relative contribution of the three low carbon electricity sources and to show the estimated global power sector CO₂ emissions in their absence. In 2006, for example, global CO₂ emissions from electricity generation exceeded 10.6 Gt CO₂, but they would have amounted to 11 Gt CO₂ in the absence of non-hydro renewable sources, 13.2 without hydropower, 13 in a world without nuclear power and almost 16 Gt CO₂ without all these three low carbon sources.

FIG. 3. Global CO₂ emissions from the electricity sector and emissions avoided by three low carbon generation technologies. Source: IAEA calculations based on IEA data [15].



IPCC: Nuclear has the largest and lowest cost GHG reduction potential

The IPCC [2] estimates the mitigation potential in terms of GHG emissions that can be avoided by 2030 by adopting various power generation technologies in excess of their shares in the baseline scenario (the Reference Scenario in the IEA's World Energy Outlook 2004 [16]). The technologies include fuel switching within the fossil portfolio, nuclear, hydropower, wind, bioenergy, geothermal, solar photovoltaic (PV) and concentrating solar power (CSP), as well as coal and gas with CCS.

The IPCC analysis assumes that each technology will be implemented as much as economically and technically possible, taking into account practical constraints (stock turnover, manufacturing capacity, human resource development, public acceptance, etc.). Each technology is assessed in isolation (i.e. possible interactions between deploying various technologies simultaneously are not accounted for). The estimates indicate how much more (relative to the baseline) of each technology could be deployed in major world regions at costs falling in ranges between less than -20 (nuclear, hydro and wind) and more than 250 (PV and CSP) \$/t CO₂-eq. Mitigation costs reflect differences between the cost of the low carbon technology and that of what it replaces. Negative costs indicate reduced energy costs and ancillary benefits arising from reduced local and regional air pollution.

Given the overwhelming share of fossil fuels in electricity generation, the first option is to replace existing fuels and technologies by less carbon intensive fossil fuels and more efficient technologies, respectively.

Another possibility to reduce CO₂ emissions from fossil fuel combustion is CCS. However, as the IPCC notes about CCS, its "[P]enetration by 2030 is uncertain as it depends both on the carbon price and the

rate of technological advances in cost and performance" (Ref. [2], p. 298). For 2030, the potential global emissions reductions from CCS used with coal and gas fired power plants are estimated at 0.49 and 0.22 Gt CO₂-eq., respectively.

Of the low carbon power generation technologies assessed in the IPCC report [2], we take a closer look at those with a mitigation potential of more than 0.5 Gt CO₂-eq. Figure 4 shows the potential GHG emissions that can be avoided by 2030 by adopting the selected generation technologies. The figure indicates that nuclear power represents the largest mitigation potential at the lowest average cost in electricity generation: 50% at negative costs, the other 50% at less than \$25/t CO₂-eq. Hydropower has the second cheapest mitigation potential, but its volume is the smallest among the five options included in Fig. 4. The mitigation potential of wind energy is also significant, but it is spread across three cost ranges, albeit more than one third of it can be utilized at negative cost. Bioenergy too has a significant total mitigation potential, but only less than half of it could be harvested at costs below \$20/t CO₂-eq. by 2030.

The mitigation potential of nuclear power is based on the assumption that it displaces fossil based electricity generation. The mitigation volume estimated by the IPCC for nuclear power reflects the contribution it could make to global climate protection by increasing its share of 16% in the global electricity mix in 2005 to 18% by 2030. This is a small increase in share, yet a major increase in volume if we consider the fast growth of power generation projected for the given time horizon. The potential nuclear share in the electricity mix and the resulting additional (above baseline) power generation are presented in Fig. 5 for the three large global regions and the world.

Nuclear power clearly belongs to the set of options available to reduce GHG emissions in the power sector. A significant part (about 2 Gt CO₂-eq.) of the GHG reduction potential offered by nuclear, hydropower, wind and bioenergy can be realized by displacing fossil fuel power plants at negative cost. Nonetheless, fossil fuels are likely to remain important players even in a

carbon constrained world, especially if they can realize the mitigation potentials arising from fuel switch and plant efficiency improvements and from adding CCS to coal and gas fired power plants. The relative costs of these technologies vary widely according to national and regional conditions that will determine which energy sources and mitigation options will be used.

FIG. 4. Mitigation potential of selected electricity generation technologies in different cost ranges. Source: based on data in table 4.19 of Ref. [2] (p. 300).

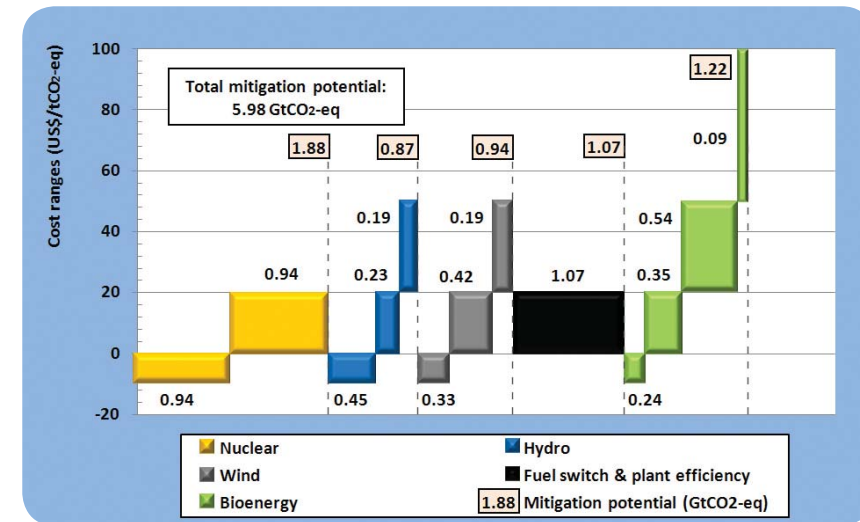
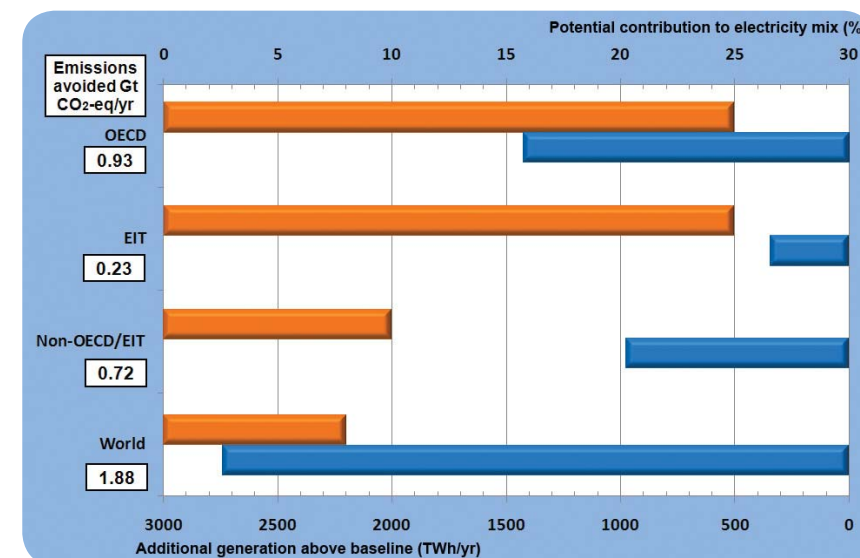


FIG. 5. Nuclear power shares, generation volumes and avoided GHG emissions. Source: based on data in table 4.11 of Ref. [2] (p. 296).



IEA: Nuclear contribution to GHG mitigation can be significant

The 2008 report on Energy Technology Perspectives [7] presents an in-depth survey of energy technologies and prospects for their evolution up to 2050. The study extends the IEA Reference Scenario projection [6] of global energy supply and GHG emissions to 2050. The report's mitigation scenarios involve two targets for reducing energy related CO₂ emissions relative to the Reference Scenario (62 Gt CO₂) by 2050. The so called ACT scenarios stipulate that CO₂ emissions would peak around 2030 at 34 Gt CO₂ and decrease to 2005 levels (27 Gt CO₂) by 2050. In the much more ambitious BLUE scenarios, global emissions need to peak before 2020 and decline to 50% of the 2005 level, to around 14 Gt CO₂.

End use efficiency improvements and changes in the power sector represent the bulk of the low cost mitigation opportunities. End use fuel efficiency and electricity

end use efficiency account for 44% and 36% of the CO₂ emissions reduction under the ACT Map and the BLUE Map scenarios, respectively. End use fuel switching and electrification of some energy supply systems contribute an additional 3% and 7%.

Sorting the two mitigation scenarios according to sectors, the projected CO₂ reductions in buildings are 7 and 8.2 Gt CO₂/year, in the transport sector 8.2 and 12.5 Gt CO₂/year, whereas in industry 5.7 and 9.2 Gt CO₂/year in the ACT Map and BLUE Map scenarios, respectively.

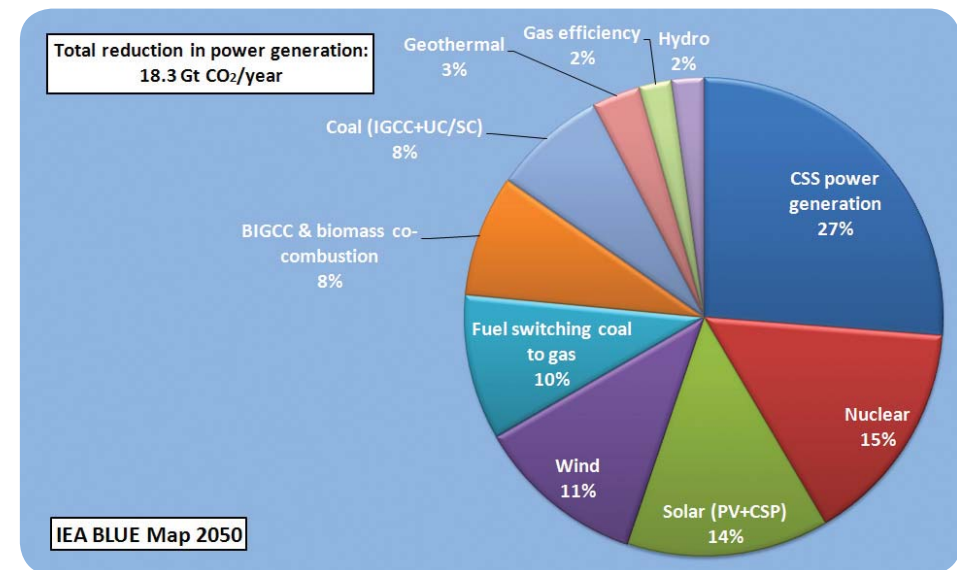
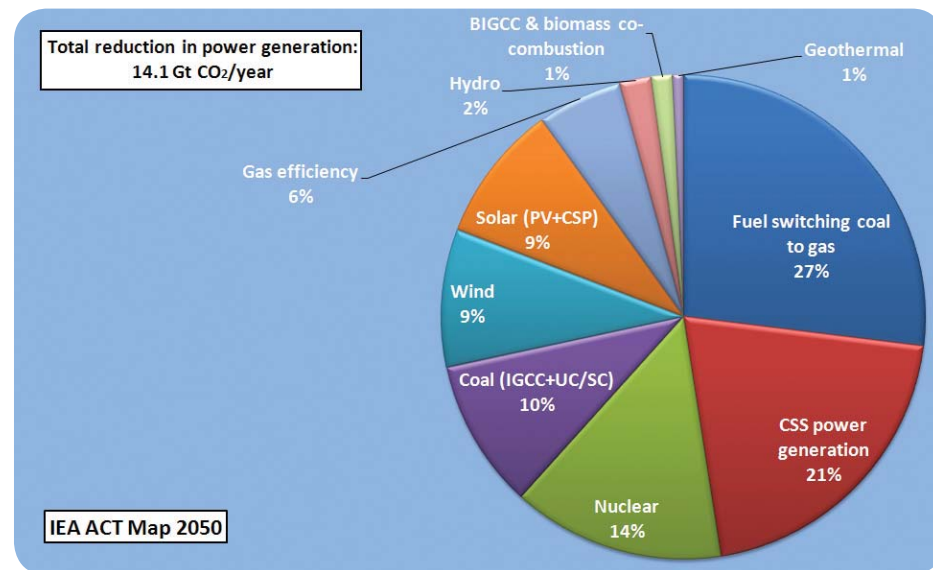
Nevertheless, power generation is projected to contribute most to CO₂ mitigation: about 40% in the ACT Map and 38% in the BLUE Map scenario. Nuclear energy is a significant component of the emission reductions in the power sector, by accounting for about 15% of the CO₂ savings in both mitigation scenarios (see Fig. 6).

The projected amount of CO₂ avoided by nuclear power is estimated at 2 Gt CO₂/year in the main ACT scenario and 2.8 GtCO₂/year in the main BLUE scenario in 2050. This would require expanding the world nuclear fleet by 24 (ACT) and 32 (BLUE) additional 1000 MW(e) units annually above the nuclear investments in the Baseline Scenario without GHG constraints. These rates are 18% (ACT) and 60% (BLUE) above the highest historical expansion rates of the global nuclear energy capacities, but are considered to be feasible according to the IEA scenarios.

Among the variants of the ACT and BLUE scenarios, the IEA report [7] also presents a high nuclear variant, in which the nuclear generation capacity is allowed to grow to 2000 GW(e) in 2050 (compared with the constraints in the ACT and BLUE Map

scenarios limiting nuclear capacity to 1250 GW(e)). The underlying IEA model calculates that almost all of this huge nuclear capacity is used. Total global emissions in this variant are 0.5 Gt CO₂ lower in 2050 than in the BLUE Map scenario (Ref. [7], pp. 88–89). Nevertheless, this variant requires stretching nuclear construction capacities even further, to an average of 50 GW(e) each year between now and 2050. This is 20 GW(e)/year more than the highest recorded construction rate in the past. However, the historical high rates of the 1970s and 1980s reflect nuclear expansions in relatively small regions in terms of global energy demand growth (North America, Japan and Europe), whereas the future expansion will also involve regions with fast growing nuclear manufacturing and construction capacities (east and south Asia).

FIG. 6. Nuclear contribution to mitigation by 2050 [7].



Contribution to resolving other energy supply concerns

In addition to staggering increases in demand for all forms of energy, particularly electricity, and the need to reduce GHG emissions, there are several other concerns on the current energy policy agendas of many countries that nuclear energy might contribute to resolve.

The first factor is the price of fossil energy sources. The rate of infrastructure development in fossil resource extraction and delivery in key supply regions is lagging behind the fast growing energy needs, and this exerts a sustained upward pressure on international oil and gas prices. This in itself is a strong motivation for countries with high shares of imported fuels for their electricity generation to look for substitutes. Political conflicts in key supply regions exacerbate the price pressure and raise severe concerns over the security of supply per se, even at high prices. This is yet another reason for considering alternative electricity sources.

Energy importing developing countries tend to be more worried about the sustained high price level because it would severely increase their energy import bills, affect their current account balances and undermine the competitiveness of their export industries. In contrast, developed countries are more worried about direct losses due to supply disruptions, probably because energy is a relatively smaller fraction of their total import bills and the energy content of their exports is lower.

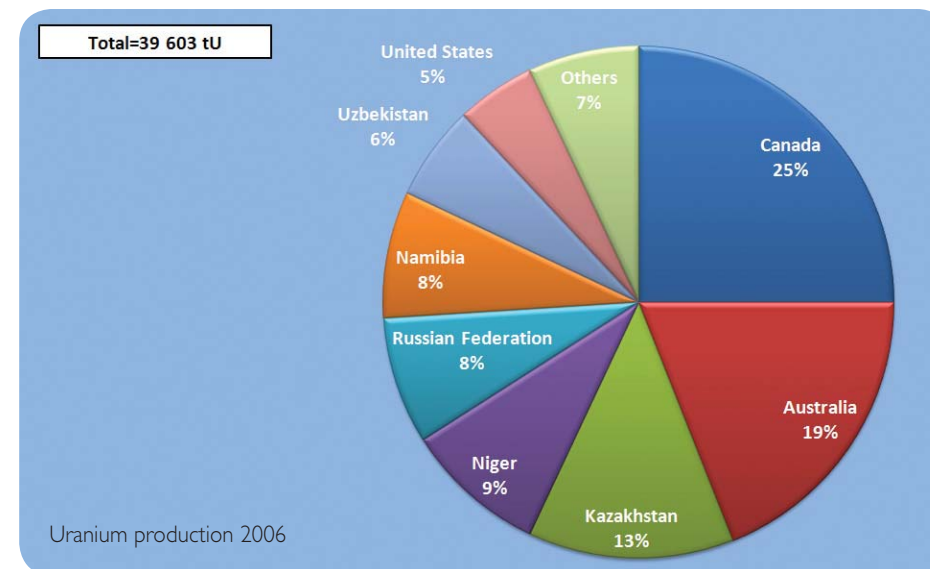
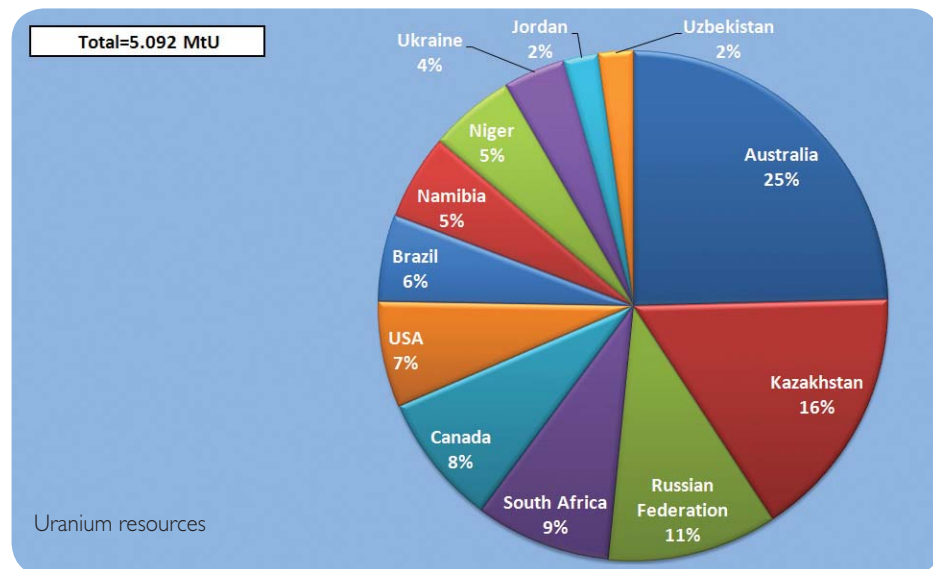
The third, but closely related, factor is price volatility. All elements of the energy supply infrastructure are long lived. Similarly, energy intensive industries base their investment decisions on cautious expectations about future energy and electricity prices. A reasonable degree of stability and predictability of resource prices is crucial for such decisions. The price of uranium is a small fraction of nuclear based electricity, as opposed to power costs from coal

and especially gas based generation. Doubling the price of uranium would increase the nuclear electricity price by about 4%, whereas doubling the price of coal would lead to about a 40% increase and a doubled gas price to an almost 70% increase in the corresponding electricity prices.

The best way to strengthen a country's energy supply security is diversification: increasing the number and resiliency of energy supply options. For many countries, introducing or expanding nuclear power would increase the diversity of energy and

electricity supplies. Nuclear power has one additional feature that generally further increases resilience. The basic fuel, uranium, is available from diverse producer countries (see Fig. 7), and small volumes are required, making it easier to establish strategic inventories. In practice, the trend over the years has been away from strategic stocks towards supply security based on a diverse well functioning market for uranium and fuel supply services. However, the option of relatively low cost strategic inventories remains available for countries that find it important.

FIG. 7. Other energy supply concerns — supply security [17].



Nuclear energy applications beyond the power sector

In recent years, utilization of nuclear energy beyond the power sector has been increasingly considered. The emerging potential of its use in several non-electric applications is due to two special characteristics: the extremely high energy content of nuclear fuel and the wide temperature range in which different reactor designs can operate (200–1000°C). These two features offer various options for humanity to resolve resource constraints, ranging from freshwater supply to liquid and solid fossil fuel extraction, and to provide a new fuel for the transport sector. Among these non-power applications, water desalination, extraction of non-conventional oil sources, cogeneration with coal and hydrogen production for transport are discussed here. The required temperature ranges and the corresponding reactor types are presented in Fig. 8.

Fresh water availability is already a constraint in many countries, as 2.3 billion people live in water stressed areas and among them 1.7 billion live in water scarce areas [19]. Adding to the impact of climate change, more frequent or longer lasting droughts will require alternative ways to provide potable water in many semi-arid and drought-prone areas. Nuclear desalination is already a method used by several countries in order to meet fresh water requirements, supplying about 32.4 million m³/d [20]. According to the IAEA [21], using 20% of the electrical capacity of a 600 MW(e) nuclear reactor operating in cogeneration mode can purify 500 000 m³ of water per day. Another option for nuclear desalination is using deep pool reactors that provide heat as a source for seawater desalination and cogeneration of heat for district heating if needed. Economic analy-

sis of this desalination system shows that it will decrease the total specific capital investment and levelized water cost [22].

As the availability of sweet crude is declining, the remaining hard crude has to be extracted in order to meet oil demand. Refining hard crude needs more energy and hydrogen, in which nuclear energy can play a significant role. Donnelly and Pendergast [23] propose a process in which hydrogen produced by nuclear power might have high importance, especially in the extraction of oil from the tar sands of the Athabaska region in Canada and hard crude in other regions of the world. Currently, a lot of CO₂ is released due to energy use and hydrogen production for oil extraction and refining from the tar sands of Alberta, since the present major source of energy is gas. Using nuclear reactors for supplying energy and producing hydrogen will significantly reduce the carbon emissions from recovering oil from the tar sands.

there has been increasing attention to the options to reduce emissions from the transport sector without constraining the mobility of people and goods. Increasing the fuel efficiency of internal combustion engines still holds considerable reduction potential. Another option is to look for alternative fuels and engine technologies. Using hydrogen as a fuel has been on the research and development agenda for some time, but the ample availability of cheap fossil fuels stalled the progress of its commercial utilization.

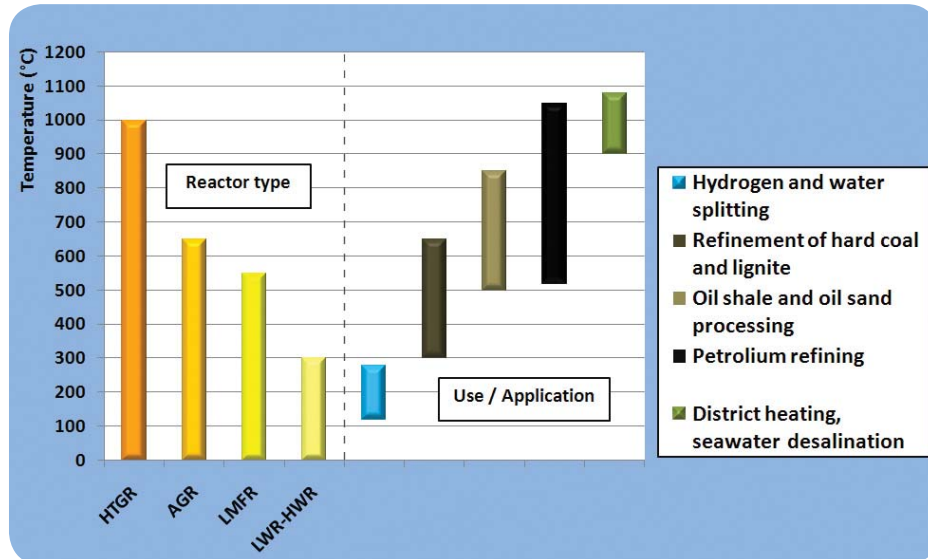
There are different processes to produce hydrogen. Among them, thermochemical water splitting (heat plus water yields hydrogen and oxygen) is considered as highly efficient and more economical than electrolysis of water with electricity [25]. This process needs a high temperature (750–1000°C). Nuclear reactors can provide the heat required to split water to produce hydrogen. This offers many possibilities, because reactors could be installed with peak load capacities and the excess power during the baseload operation could be used for producing hydrogen that can be stored and used for transport and other applications.

It is not possible to predict which of these non-electric options will be used in the energy hungry 21st century, and to what extent, but evidence has been accumulating in recent years that promising opportunities might emerge for using nuclear energy beyond base load electricity generation.

Rather than as a rival energy source for coal, nuclear energy can help to reduce the carbon emissions from coal burning. Given the huge coal deposits in several world regions (China, India, Australia, South Africa, North America), the gasification of coal for integrated gasification combined cycle (IGCC) combustion might be a feasible GHG emission mitigation technology. Nuclear heat from high temperature gas cooled reactors (HTGR) can be used for the gasification of coal along with the generation of electricity, which would reduce carbon emissions significantly [24].

GHG emissions from transport have been growing at a fast rate globally. As a result,

FIG. 8. Possible uses of nuclear energy beyond power generation [18].



Note: HTGR=high temperature gas cooled reactor; AGR=advanced gas cooled reactor; LMFR=Liquid metal cooled reactor; LWR=light water reactor; HWR=heavy water reactor

Nuclear power has non-climatic environmental benefits

In addition to helping to mitigate climate change, displacement of fossil based power plants by nuclear power can also reduce the emissions of other air pollutants that lead to negative human health and environmental impacts at local and regional scales.

Nuclear power plants emit virtually no air pollutants during their operation. In contrast, fossil based power plants are major contributors to air pollution. The World Health Organization (WHO) has estimated that air pollution causes approximately 2 million premature deaths worldwide per year [26]. Air pollution also contributes to diseases from respiratory infections, heart disease and lung cancer. In many cities in developing countries, the level of particulate matter in the air exceeds 70 micrograms per cubic metre ($\mu\text{g}/\text{m}^3$), and by reducing it to 20 $\mu\text{g}/\text{m}^3$ (which is the air pollution concentration level recom-

mended by the WHO), air quality related deaths could be cut by around 15%. Currently, the energy supply sector accounts for one quarter of the total particulate matter (PM_{10}) emissions in the European Union (EU) [27]. Although the air quality in Europe has improved significantly in recent years, particulate matter in the air decreases life expectancy of every European by, on average, almost one year.

A recent study [28] analyses the consequences (including the implications for local air pollution) of lifting the restrictions on a potential expansion of the nuclear capacity in Europe (projecting a 45% nuclear expansion by 2030). According to the analysis, the resulting reduction of particulate matter concentration in Europe would lead to significantly lower chronic diseases (-3% in the number of people with bronchitis and -2.5% in restricted activity days),

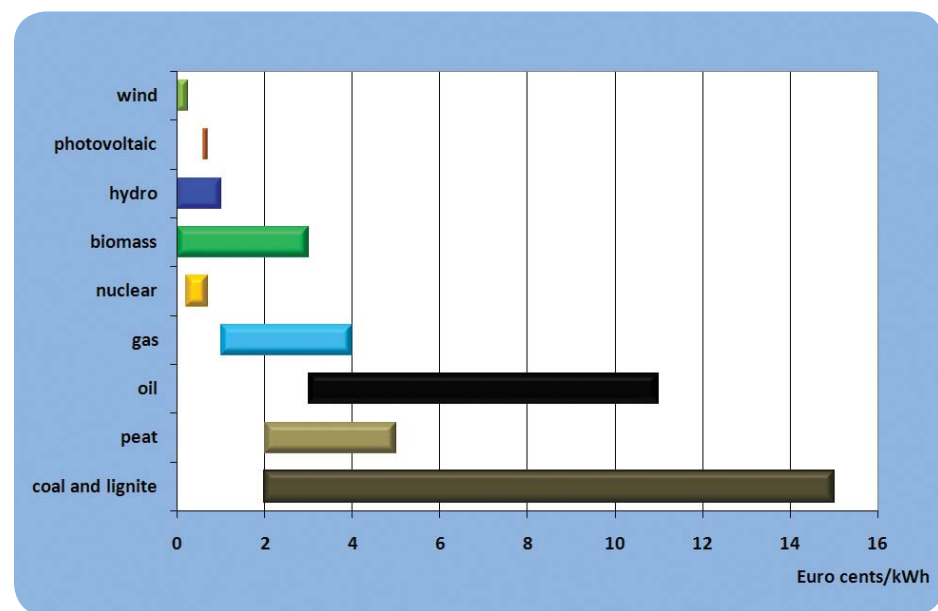
as well as premature deaths (-1.9%) by 2030, amounting to a welfare gain equal to €32–559 billion (median estimate equals €165 billion).

At the regional scale, air pollutants travelling long distances cause acid rain, harming nature at large. Acid rain disturbs ecosystems, leading to adverse impacts on freshwater fisheries and on natural vegetation and crops. In particular, acidification of the forest ecosystems could lead to deforestation. Furthermore, it causes damage to certain building materials, including historic and cultural monuments. Acid rain is caused by sulphur and nitrogen compounds, and fossil fuel based power plants, particularly coal power plants, are the major source of the emission of the precursors of those compounds. Sulphate and nitrate, transported across national borders, also contribute to the occurrence

of haze, strongly limiting visibility and reducing sun light, and possibly changing the atmospheric and surface temperature and the hydrologic cycle [29].

An extended study was coordinated by the EU within the framework of the ExternE study, comparing the externalities (positive and negative side effects not reflected in the price of electricity) of different power supply options in monetary terms. The results are presented in Fig. 9. The assessment includes the effects of air pollution on human health, accidents affecting workers and/or the public, effects of air pollution on materials, crops, forests, freshwater fisheries and unmanaged ecosystems (acidification and eutrophication), and the impacts of noise and of global warming. In the case of Germany, for example, air pollution accounts for 34–47% of the external costs of fossil based electricity generation [30].

FIG. 9. Health and environmental effects of power generation technologies, expressed in monetary terms, estimated by the ExternE project, shown in euro cents/kW·h [30].



Economics of nuclear power getting favourable

The economics of nuclear power needs to be addressed at two levels. First, the direct explicit costs of generating 1 kW·h of electricity levelized across the lifetime of the power plant and, second, the social costs, including all externalities (see previous section) that happen to be predominantly positive in the case of nuclear power. The costs of decommissioning and waste disposal are collected and accumulated through the operating lifetime of the power plant, whereas the social benefits of avoided CO₂ emissions or increased supply security remain unaccounted for in the absence of comprehensive GHG taxes or emissions permit markets. In addition to regulatory uncertainties, both in the nuclear sector and in the electricity market in general, the unrewarded social benefits (equivalent to the gap between private and social costs of fossil competitors) represent another factor that discourages potential investors.

Nuclear power plants have a 'front loaded' cost structure; that is, they are relatively expensive to build but relatively inexpensive to operate (compared with fossil based generating capacities). The low share of uranium costs in total generating costs protects plant operators and their clients against resource price volatility. Thus existing well run operating nuclear power plants continue to be a generally competitive profitable source of electricity, but for new construction the economic competitiveness of nuclear power depends on several factors. First, it depends on the alternatives available. Some countries are rich in alternative energy resources, others less so. Second, it depends on the overall electricity demand in a country and how fast it is growing. Third, it depends on the market structure and investment environment.

Other things being equal, nuclear power's front loaded cost structure is less attractive to a private investor in a liberalized market that values rapid returns than to a government that can look longer term, particularly in a regulated market that assures attractive returns. Private investments in liberalized markets will also depend on the extent to which energy related external costs and benefits (e.g. pollution, GHG emissions, waste and energy supply security) have been internalized. In contrast, government investors can incorporate such externalities directly into their decisions. Also important are regulatory risks. Political support for nuclear power varies across countries, and, within a given country, it can change over time. An investor must weigh the risk of political shifts that might require cancellation of the project midstream or introduce delays and costs that would vitiate an originally attractive investment. Different countries also have different approval processes. Some are less predictable than others and create greater risks, from the investor's perspective, of expensive interventions or delays.

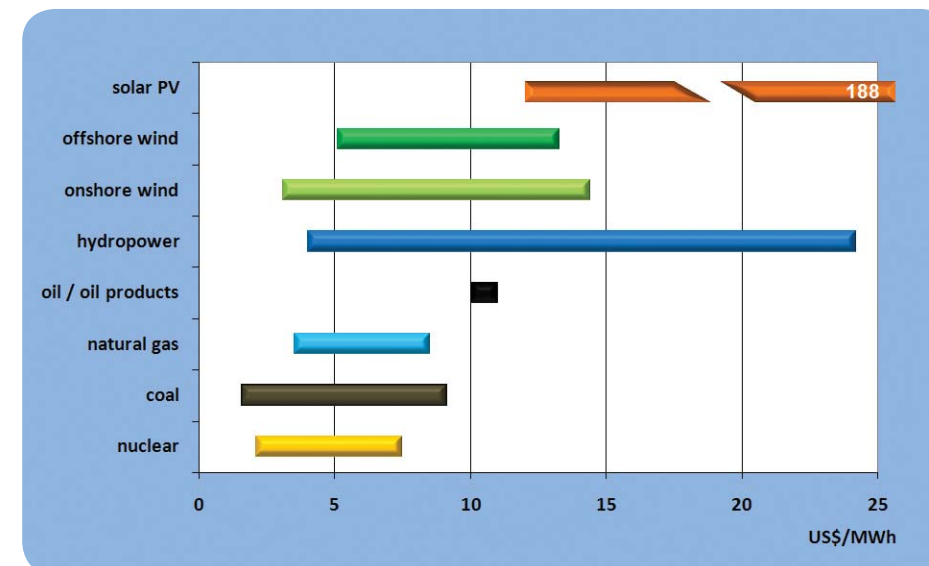
In Japan and the Republic of Korea, the relatively high cost of alternatives benefits nuclear power's competitiveness. In India and China, rapidly growing energy needs encourage the development of all energy options. In Europe, high electricity prices, high natural gas prices and GHG emission limits under the European Union Emission Trading Scheme (EU ETS) have improved the business case for new nuclear power plants. In the USA, the 2005 US Energy Act significantly strengthened the business case for new construction. Previously, new nuclear power plants had not been an attractive investment given plentiful low cost coal and natural gas, no GHG emission

limits, and investment risks associated with the lack of recent experience in licensing new nuclear power construction. The provisions of the Energy Act, including loan guarantees, government coverage of costs associated with certain potential licensing delays and a production tax credit for up to 6000 MW(e) of advanced nuclear power capacity, have improved the business case enough for nuclear firms and consortia to announce applications for combined construction permit–operating licences involving approximately 25 possible new reactors in the USA.

for new power plants with different fuels. Except for oil fired electricity generation (estimated in only one study), the high end of each cost range is at least 100% higher than the low end. This is due partly to different technoeconomic assumptions across the studies, but also to the factors listed above. Moreover, the ranges in Fig. 10 incorporate only internalized costs. If sufficiently high priority is given to improving national energy self-sufficiency, for example, the preferred choice in a specific situation might not be the least expensive on a pure cost basis.

Figure 10 summarizes estimates from seven recent studies of electricity costs

FIG. 10. Ranges of levelized costs associated with new construction as estimated in seven recent studies for electricity generating technologies in different countries [31].



Nuclear investment costs increasing, but...

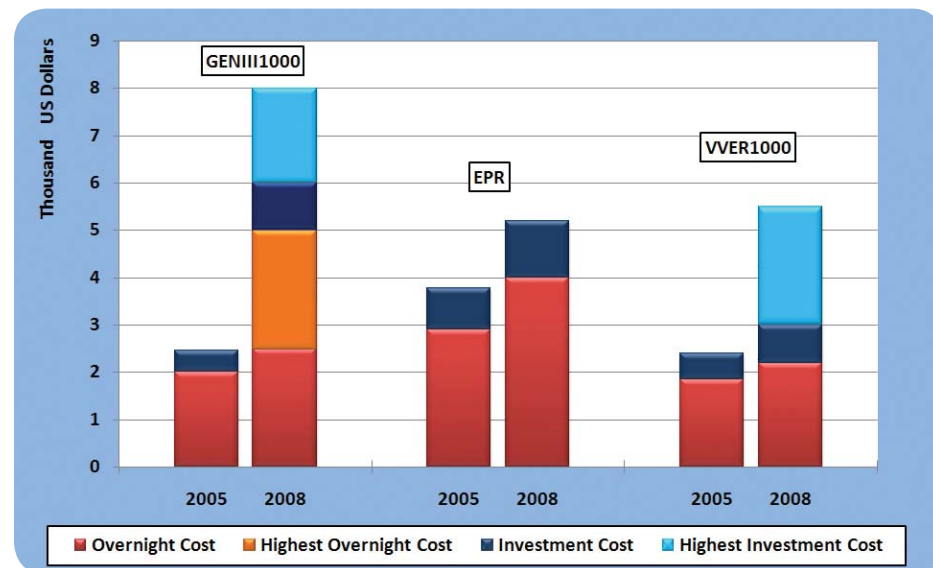
The cost schedule of nuclear power is different from that of fossil fuel generation such as coal, natural gas and oil plants. The capital costs comprise the single largest component of nuclear power costs, approximately 80%. This makes financing complex, especially if the funds are constrained and if the project's investments needs amount to more than \$9 billion (see the next section on financing nuclear power).

Recent studies, publications and news releases have quoted a sizable upsurge in the investment cost estimates of new nuclear power plants (the main investment costs include the engineering–procurement–construction cost, owner's costs, contingency costs, finance cost and escalation costs). The range of the total investment costs varies also depending on the region, project type, technology, size and financing cost. Generally, the new cost estimates are higher than prior industry estimates, cre-

ating an air of ambiguity around what the true costs are.

Studies conducted between 2002 and 2005 quote an overnight capital cost range of \$1200/kW(e) to \$2300/kW(e). Recent estimates prepared in 2007 and 2008 show an overnight cost range from \$1500/kW(e) to \$6000/kW(e) and the total investment cost ranging from \$2000/kW(e) to \$8000/kW(e) (see Fig. 11). The high variation of \$6000/kW(e) of investment cost is alarming for investors. Some of the uncertainties are due to the preconstruction capital cost estimates, which might not entirely be reflective of the final construction cost, especially if vendors cannot predict what the next reactor will cost. It is also not in the interest of vendors and manufactures to reveal the true investment cost, due to commercial confidentiality, therefore some investment costs quoted by the vendors might have an element of 'appraisal opti-

FIG. 11. Nuclear investment costs by technology [32–35].

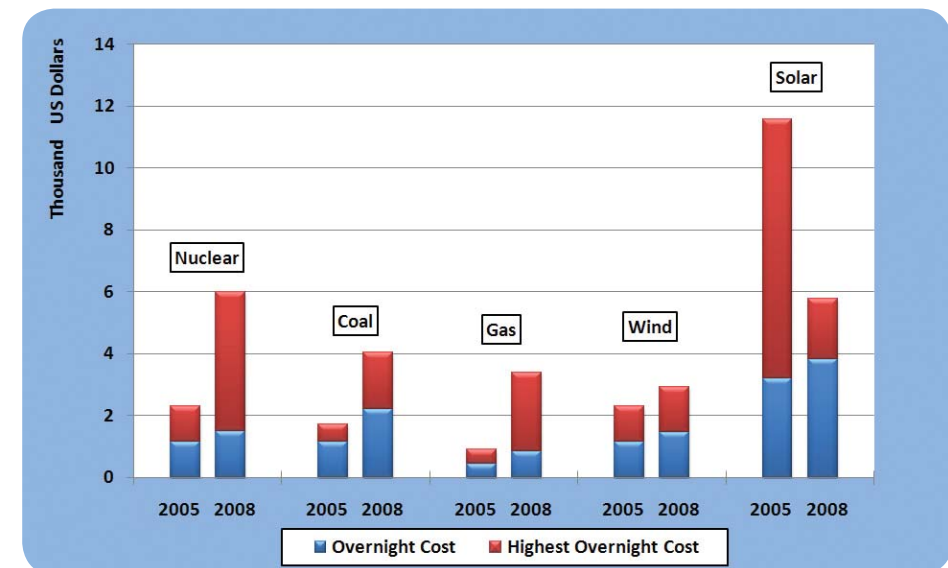


mism', leading to underestimation of the actual cost.

Since the main investment cost elements are equipment, material and labour, the recent escalation of commodity prices and wages has also contributed to the excessive costs (see Fig. 12 for the investment cost increase by technology). However, the increase in input cost has not only had an impact on the nuclear industry but the entire generation industry, each competing for the available resources. Figure 12 displays the overnight generation cost for nuclear, coal, gas, wind and solar for 2005 and 2008. The shades represent the ranges of costs and the entire bar represents the maximum cost. The high end costs for coal and gas represent carbon storage options, which make these technologies more comparable with nuclear. The 2005 and 2008 cost comparison reveals that the costs have nearly doubled for all the generation types, not only for nuclear (except that solar shows declining costs, due to technical improvements).

Although the large upfront capital cost and long project schedule of nuclear plants are possible impediments to investment in building them, once constructed they are remarkably competitive with other generation plants. Various studies show that the levelized cost of nuclear is lower than other low carbon options such as offshore wind, coal fired generation with CCS or solar power. Also, the gap between nuclear and gas may narrow, but since gas requires much less upfront capital cost it is more attractive to investors [37]. An increase in carbon taxes, and if nuclear qualifies for green credits, will make nuclear a more attractive investment option.

FIG. 12. Changes in generation costs between 2005 and 2008 [32, 36, 37].



...financing nuclear power investments is feasible

For decades in most countries, governments have invested public sector funds either using tax revenues or electricity tariff charges to finance nuclear power. However, recent trends show that, worldwide, governments are increasingly looking to the private sector to finance new infrastructure investments.⁴ Cognizant of this fact, the utility industry and the financial sector have devised some incentives to invest in nuclear projects. The utilities are using their balance sheets to invest in joint ventures, such as build-own-operate schemes. The financial sector is also catering to investors' need and interest in nuclear through ventured funds such as Van Eck's Market Vectors Nuclear Energy Exchange Traded Fund and nuclear indices (such as the Global Nuclear Energy Index and Standard and Poor's Global Nuclear Energy Index), evidence that the financial markets do recognize an interest for investment in the nuclear industry.

To secure successful financing, it is critical to have well structured nuclear projects to reduce uncertainties to the extent possible and to identify the risks upfront, such as regulatory uncertainty, which is cited as one of the main deterrents to investment in a new nuclear power plant. Since most of the previous nuclear plants were built in a regulated market with long term contracts, the change in the structure of electricity markets over the years to semi or fully deregulated markets, with competition among generators, has amounted to regulatory market risk. An efficient regulatory body with effective regulatory procedures will mitigate this risk. There are also other risks, such as unknown costs, first of a kind, licensing, delayed construction, pub-

lic acceptance and legal risks, but most of these can be contained by setting a well structured project schedule with appropriate risk allocation. Well reputed vendors, operators and project managers, along with some form of government guarantee, will give assurance to the finance industry to venture into new financing schemes for nuclear power plants.

In general, financing of new nuclear power plants can be either by governments (sovereign) or industry (corporate or balance sheet and limited recourse). In terms of government financing, the traditional approach to funding new nuclear power plants has changed. Governments in developed and developing countries alike have increasingly found government resources insufficient to meet all competing demands, and increasingly must turn to capital markets for financing specific projects. Construction of new nuclear power plants would most likely fall into this category. On the industry side, in the past project sponsors could assure return of, and on, equity by virtue of government guarantees, guaranteed rates and captive electricity markets. Under current conditions, in the absence of such protection, sponsors of new nuclear power plants may not be able to pay the yield needed to attract equity holders. For commercial investors and lenders, concern about delays and cost overruns in the face of the industry track record is a major factor.

The possible solution to lack of government funds, if national budget resources are unavailable to built new nuclear power plants, is creating government equity. There are many ways that a government can create equity, for example by pledge receive-

bles from credible government owned industries. Other examples of possible government funding mechanisms include earmarked surcharges on all electricity sales, use of national funds (e.g. infrastructure funds or postal savings), creation of a government-run private bank to help finance clean energy projects (including nuclear), banks financing infrastructure, asset pooling (in countries or by utilities with other significant power generation assets) and (in developing countries) use of remittances from expatriates. On the industry side, project sponsors do have some options for generating equity among themselves, either as good faith money or to supplement available investment. One source of equity could be balance sheet financing. Another possibility could be to expand the number of equity partners to include partners who could provide equity in kind, or for principal customers to become major shareholders as a way of assuring security of supply. Another mitigating option is for sponsors to recruit local equity financing for local content. One suggested hedge for containing construction cost overruns is phased financing. This approach (already implemented in China and proposed for

new plants in the USA) involves financing a project in tranches, starting with construction. The cost of capital for each phase will reflect the risks only of that phase, so that the high costs of construction risks are not carried over throughout the project.

In summary, for both government and industry, it is imperative to explore new options and approaches that might facilitate new nuclear plant financing in today's environment with stable and efficient regulatory and tax regimes. The initial financing arrangements for a new nuclear plant might include some government funding; for plants in developing countries, additional resources could include directly allocated development funds from international aid organizations and development banks, other government sponsored aid programmes, export credit agency insurance schemes or institutions such as the Overseas Private Investment Corporation and the Multilateral Investment Guarantee Agency (although these only ensure that the suppliers of the equipment, not the project sponsors, get paid in the event of delays or default), and equity investments and commercial loans.

The Ohi nuclear power plant in Japan.



⁴ Even if government is not the direct sponsor of a project, it has a lead role in establishing stable regulatory policy, legal frameworks, fiscal regimes, ensuring commitment to non-proliferation and IAEA safeguards, and commitment to substantial international nuclear liability regimes.

Construction capacity will expand as needed

Assuming that nuclear power is competitive and financing new construction will be feasible, the next question is: will there be sufficient specialized manufacturing capacity to build new reactors at the required rate? Moreover, a considerable amount of specialized knowledge is required to control the entire construction process and, later, to operate the plants. Therefore, a major challenge for the nuclear industry over the next decade will be to satisfy the increasing demand as well as to transfer nuclear knowledge to the next generation.

Growth in energy demand and the need to reduce GHG emissions in order to tackle climate change has created new prospects for the nuclear industry. China, India and the Russian Federation have all recently made the political decision to launch large scale nuclear programmes to add significant amounts of new generating capacity to their national grids. Several OECD countries (e.g. France and the United Kingdom) that have not built nuclear plants for decades are now considering replacing their ageing plants with new reactors. By the end of 2008, the number of applications for a combined construction permit–operating licence in the USA might exceed 15, involving over 25 possible new reactors in total [38].

Reactor pressure vessels, pump cases and other components must be manufactured to the highest standards to ensure safety. The most demanding items are the pressure vessels, which require high capacity presses for producing heavy forgings. Japan Steel Works has been considered by many in the industry as the leader in heavy forgings. In recent years, many other companies established such capacities in preparation for meeting the rising expectations

for nuclear power. The Japanese company Mitsubishi Heavy Industries and the Russian OMZ Izhora have both announced the doubling of their capacities, the latter providing large forgings for Russian reactors to be built domestically and abroad. Doosan Heavy Industries in Korea has also established itself as an important actor in this market. Still in east Asia, companies in emerging countries such as the Dongfang Boiler Group, Shanghai Electric Group and Harbin Boiler Works in China are getting ready to enter the very large forgings market. In south Asia, India's Larsen and Toubro are increasing their scope in this area to satisfy both domestic and international demand.

In western Europe, the nuclear industry is already adapting its production capacity to match the upcoming market. To take part in the UK's new nuclear programme, Sheffield Forgemasters is considering expanding its heavy forging capacity with a 15 000 t press that would allow the production of large scale reactor pressure vessels, including Areva's 1650 MW(e) European Pressurized Reactor, currently the largest on the market [39]. Meanwhile, Areva is also increasing its large forging capacity at Le Creusot in Burgundy.

Regarding nuclear staffing, the booming demand for energy experts, nuclear engineers and technicians and the fast pace of the nuclear power industry will generate higher demand for skilled workers in the industry. University programmes and industrial training capacities are expanding to meet the increasing demand. For example, the UK's British Energy's flagship training facility will provide courses in nuclear technology and excellence in technical leadership to both new and experienced

nuclear professionals [40]. Other nuclear expansion countries have already begun revitalizing their nuclear education or plan to do so in the near future.

It is obvious that the global nuclear supply chain will be able to satisfy even the most ambitious nuclear programmes, but this will certainly require further investment. Once the signals of reliable and persistent demand are sufficiently strong, companies will undoubtedly invest in new production capacities, since this is how the market responds and works. There may be some bottlenecks at the early stages, but the market will react and adjust itself to bring forward the required material, staff, components and services. Since the process of planning, licensing and preparing a new construction takes years, this will give sufficient time for manufacturers to establish the required capacities.

Industrial machine: Main cylinder for press, JSW Steel Forgings and Castings.



Sufficient uranium to fuel increasing nuclear power generation

Another often heard concern is the 'peak uranium' fallacy. Based on recent surges of uranium prices on the spot market and interpreting resource/production ratios mechanistically, proponents of this view suggest that uranium resources will run out within two to three decades, making large scale nuclear energy expansion a chimera.

Uranium is a metal approximately as common as tin or zinc, and it is a constituent of most rocks and even of the sea. The economically producible occurrences of any mineral are a function of concentration, exploration and production technology, demand and market price. Hence resource availability changes dynamically with improved geological knowledge, advances in production technology and price expectations. At higher prices, lower concentration occurrences may become economically attractive, while new innovative production methods may enable production from deposits previously beyond reach. Low prices may reduce previously economic resources to easy to produce high concentration sources. This does not mean that physical occurrence of the mineral no longer exists — it just delineates the economically recoverable portion of that resource at a given point in time [41]. Thus, any assessment of the future availability of any mineral, including uranium, which is based (a) on current production costs and price data and (b) on existing state of the art technology and geological knowledge (as most resource assessments do) is erring on the conservative side.

Uranium resources are plentiful and per se do not pose a limiting factor to future nuclear power development. As so often, the limiting factor is the timely investment

in new production capacities. The current reactor requirements and uranium production anomaly calls for significant mine development. Given the lead times for turning uranium in the ground into yellow cake, which have become much longer than 30 years ago, global reactor requirements will continue to depend on secondary sources for another decade or so.

Uranium spot prices have been declining over the past three years and were at about \$80/kg U in October 2008. The price level of \$130/kg U is the threshold used for delineating identified uranium resources by 50%. This price level stimulates not only additional exploration and mine capacity development around the world but also promotes the intensified use of secondary sources, especially in the longer run. The future role of secondary supplies will depend on economics and policy, especially with regard to spent fuel reprocessing and high level waste disposal.

According to the latest report published jointly by the Nuclear Energy Agency (NEA) of the OECD and the IAEA [17], approximately 5.5 million tonnes of global uranium resources had been identified by 2007 (considerably higher than the 4.74 million tonnes estimated three years earlier). This amount is equivalent to 130 times the global production of uranium estimated for 2007. The resource abundance of uranium is therefore assessed as one of the advantages of the nuclear power option over oil and gas. In addition, uranium resources are geographically more evenly distributed so that supply is not concentrated in geopolitically unstable regions.

The annual global uranium demand of the presently operating 435 commercial power

reactors is estimated as 66 000 t U. The world uranium production in 2006 provided 60% of the required uranium. The majority of the remainder has been supplied by uranium stockpiles accumulated due to overproduction until about 1990. A minor portion is supplemented by reprocessed spent fuel and re-enrichment of depleted uranium tails, as well as by those that originated in the military sector.

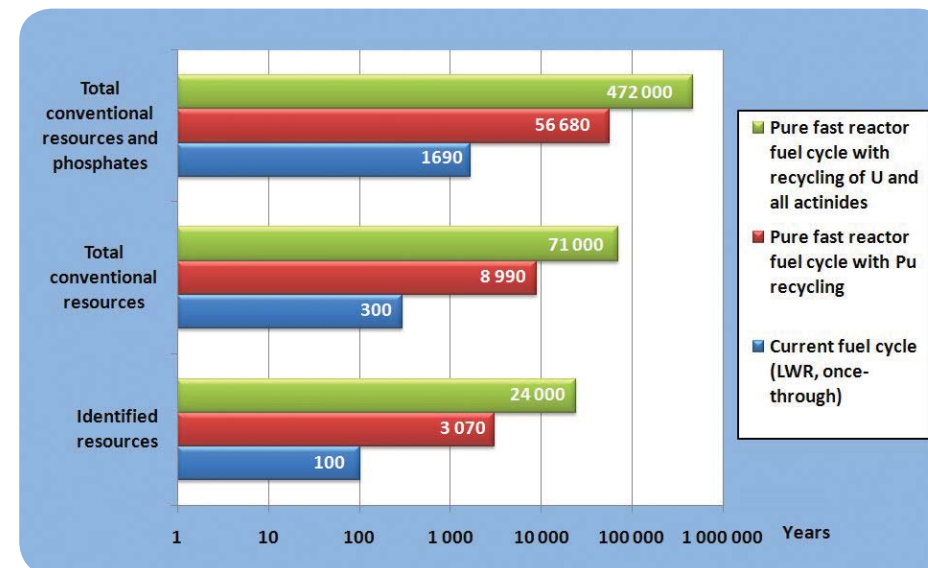
Reprocessing of spent nuclear fuel can contribute to a better uranium demand and supply balance. Annual discharges of spent fuel from the world's reactors total about 10 500 metric tonnes of heavy metal (t HM) per year, approximately one third of which is reprocessed to extract usable material (uranium and plutonium) for new mixed oxide (MOX) fuel. The remaining spent fuel is considered as waste and is stored pending disposal.

This is in addition to advanced (such as fast breeder) reactors and associated fuel cycles, which could utilize uranium more efficiently (by a factor of approximately 60–70)

than current reactors and fuel cycles [42]. The advanced technologies, however, will require reprocessing. There are presently no fast breeder reactors operated commercially anywhere in the world (reprocessing is more expensive than fresh uranium fuel), but more than 200 reactor-years of experience has been accumulated in industry scale breeder reactors (in France and the Russian Federation), which provides a good basis for designing and building commercial fast breeder reactors when they become economically competitive. Figure 13 shows the lifetime of various types of uranium resources under different fuel cycle and reactor technology scenarios.

In summary, the lifetime of uranium resources will be determined by demand, technological change and economics rather than by geology. As and when cheap uranium sources become scarce, uranium prices will increase, which in turn will make reprocessing spent fuel or the extraction of low concentration sources profitable for traditional as well as breeder reactors.

FIG. 13. Estimated years of uranium resource availability for various reactor and fuel cycle scenarios at 2007 nuclear power utilization levels.



Radiation risks are low

The benefits of the lack of emissions of GHGs and air pollutants by nuclear based power generation must be assessed in comparison with the higher levels of radiation associated with nuclear power plants and their entire fuel cycle, from mining and milling, uranium enrichment and fuel fabrication, nuclear reactor operation and fuel reprocessing, to solid waste disposal and transport. A series of reports by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [43] present a full account of radiation emitted by each and every power plant in the world as well as that emitted during fuel cycle operations. Although even a small amount of radiation is believed to increase the risk of cancer, it has been shown that the health risks due to radiation related to nuclear power generation are at a level that is statistically indistinguishable from those due to radiation exposure from radiation sources existing in nature.

Average worldwide exposure to natural radiation sources for an average individual is 2.4 millisievert (mSv) per year, with a typical range between 1–10 mSv. As shown in Fig. 14, radon accounts for half of the public radiation exposure from natural radiation sources, followed by terrestrial radiation, cosmic radiation and radiation in food. In comparison, radiation exposure due to nuclear power production is 0.0002 mSv per year for an average individual.

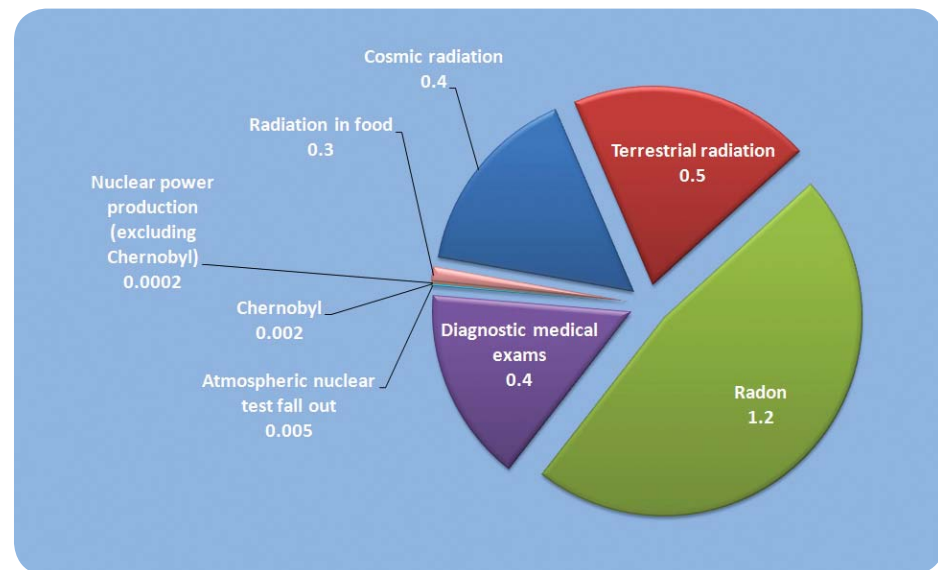
The reported annual dose (the level of exposure) of individuals from a number of reactor sites is in the range of 1–500 μ Sv (1 μ Sv = 0.001 mSv), with the average estimated as 5 μ Sv for pressurized water reactors (PWRs) and 10 μ Sv for boiling water reactors (BWRs). For mining and milling operations, the annual dose is estimated to be about 40 μ Sv, whereas for fuel processing it is estimated as 10 μ Sv. According to an ICRP report [44], the

cancer risk expressed in terms of cancer cases per 10 000 persons per Sv is 1715. Converting this risk into a health indicator, the exposure of 1 μ Sv increases the cancer risk to one in 5.8 million persons.

There are a number of occupations in which workers are exposed to human-made sources of radiation, including those at nuclear installations and at other fuel cycles. UNSCEAR [43] estimates that the average annual effective dose for workers

at nuclear fuel cycle installations (including uranium mining) is 1.8 mSv, with 4.5 mSv for mining, 3.3 mSv for milling, 0.1 mSv for enrichment and conversion, 1.0 mSv for fuel fabrication, 1.4 mSv for reactor operation, 1.5 mSv for fuel reprocessing and 0.8 mSv for research in the nuclear fuel cycle. In comparison, the average annual effective doses for mining workers (excluding coal mining) and the crew in air travel are 2.7 mSv and 3 mSv, respectively.

FIG. 14. Typical sources of public radiation exposure in 2000 (in mSv/year) [43].



Nuclear plant safety keeps improving

The Chernobyl accident in 1986 was clearly a setback to nuclear power. Many lives were lost, thousands suffered major health impacts and there were significant environmental and social impacts. The accident was the result of an old reactor design, compounded by gross safety mismanagement. However, this event also prompted major improvements in the approach to nuclear safety [45].

A key change was the development of a so called international nuclear safety regime. International conventions were put in place, creating legally binding norms to enhance the safety of nuclear activities. The IAEA updated its body of safety standards to reflect best industry practices. And, importantly, both the IAEA and the World Association of Nuclear Operators (WANO) created international networks to conduct peer reviews and exchange operating information to improve safety performance [45]. The outcome is shown in Fig. 15.

“The international nuclear safety regime over the years has produced many insights on how to minimize safety risks. But we should not rest on our laurels. It is essential that existing safety standards, operational practices and regulatory oversight be adapted — and in some cases strengthened — to ensure enhanced levels of safety in the future” [45].

As IAEA Deputy Director General T. Taniguchi pointed out [47], operational safety is one of the most challenging areas that the IAEA deals with. In addition to having to consider sound engineering and technology principles, one must take into account the human and organizational factors that can either contribute to, or detract from, safety. There are also economic, political and social pressures that must be taken into account.

Since the Chernobyl accident, many improvements have been made, and one can

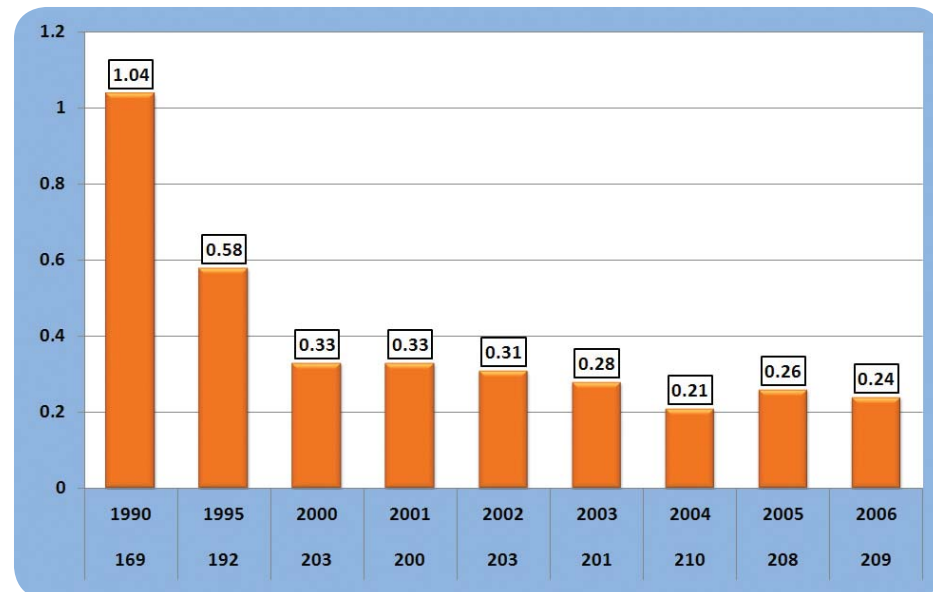
point to a substantially improved nuclear safety situation throughout the world. The way the nuclear industry has coped with severe natural disasters around the world is testament to the level of safety. Tsunamis, floods, hurricanes and earthquakes have affected many parts of the world, and nuclear installations everywhere responded admirably. The design and operational features ensured that the extreme natural conditions would not jeopardize safety. Many of these facilities returned to normal operations very quickly once the extreme situation had passed, providing necessary and much needed infrastructure [47]. However, there is a very real possibility that one will become complacent with the high level of performance. The margin for further safety improvement is smaller than in the past, and it is more of a challenge to find and implement this continuous improvement. Without sustained safety improvement effort, a decline will occur. Therefore, one needs strong safety leadership, effective safety management and sustained safety culture, especially for those nuclear plants facing extended operations. The challenge is immense because of the deep rooted human and organizational nature and complex human-machine interface.

The third review meeting of the Contracting Parties to the Convention on Nuclear Safety [48] identified the fundamental need for openness and transparency in the nuclear industry. There was also special emphasis put on the need for leadership in nuclear safety from both regulators and operators and about the need to contin-

ue and improve communication between them. For operational safety, probabilistic safety assessment is now a mainstream tool in most countries, although every Contracting Party stressed that it is not used in isolation. More and more countries are now requiring periodic safety reviews as part of their regulatory regimes. Knowledge management continues to be important as experienced staff retire and as facilities move into extended operation. It was also noted that peer reviews, such as those offered by the IAEA and WANO, play an important role in maintaining and improving operational safety. Finally, it was reinforced that the IAEA safety standards have matured and now offer a comprehensive suite of nuclear safety standards that embodies good practices and is a reference point to the high level of safety required for all nuclear activities [47].

Reducing safety risks and improving safety performance begin with strong safety leadership, effective safety management and sustained safety culture [49]. When there is a strong safety culture, maintenance staff excel in the preparation and execution of the tasks in compliance with the safety, quality and technical specifications. The personnel element is crucial for the continuous improvement of safety culture, and this in turn enables each individual to contribute towards achieving the overall goals. Therefore, solid emphasis has been put on the proper education of employees in the past years to reinforce this notion.

FIG. 15. Industrial accidents at nuclear power plants per 200 000 person-hours worked [46].



Waste management and disposal solutions emerging

Another persistent concern surrounding nuclear energy is radioactive waste, which can create hazards for humans and the environment for centuries or millennia. Over the past two decades, major advances have been made in the scientific understanding and the technological development towards the safe storage and final disposal of nuclear waste. Here nuclear waste storage means interim storage, which is generally implemented around the waste producing site such as a nuclear plant and located typically above ground or at very shallow depth. Nuclear waste disposal means long term storage located at deep underground sites, generally between 500 and 1000 m.

Most countries with nuclear power plants are currently investigating possible solutions regarding their radioactive waste inventories [50]. The rate of progress varies across countries, but geological disposal seems to be the best currently available option for safe long term disposal. Other factors, such as social, economic, political

or even ethical issues, are also essential in the decision making process. Therefore temporary storage remains the preferred option in most cases, while selection and construction of an ultimate disposal site is discussed among the population and the different stakeholders. In addition, the temporary storage phase remains an important step in the safe management of radioactive waste, since it helps to reduce both radiation and heat generation prior to waste handling and transfer to the final disposal site. In fact, as long as active surveillance and maintenance are ensured, it has been demonstrated over the past decades that interim storage of radioactive waste can be relied upon. Moreover, according to safety standards, storage is considered technically feasible and harmless over a long period of time if monitoring, control and care are properly implemented [51].

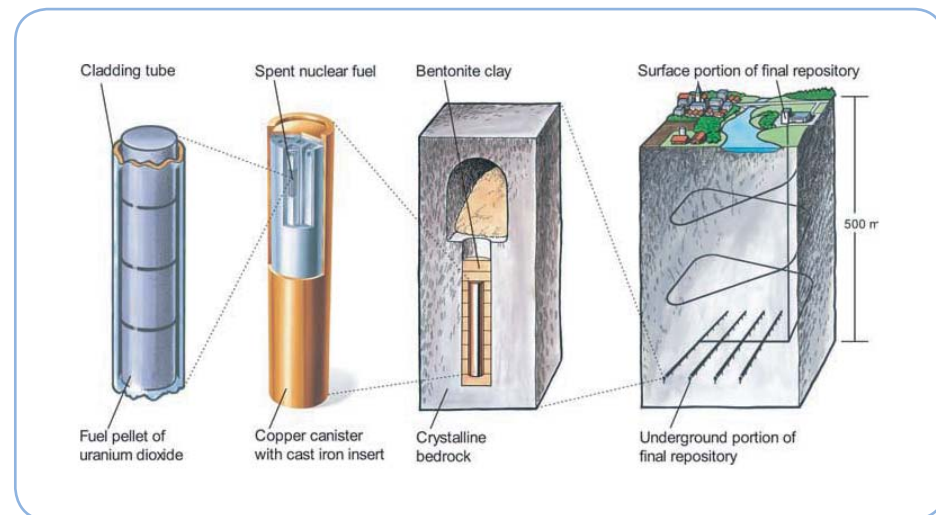
Geological disposal could be the alternative solution in the future as it guarantees long term safety without surveillance and

maintenance [52]. The protection of the present and future generations and the environment will be ensured by engineered and natural barriers. After vitrification, nuclear wastes are placed into corrosion resistant canisters, which would nest in either a bed of granite or bentonite clay. Given their geological characteristics (low groundwater movement rates, geological stability and low economic value) these two formations have been recognized as the most suitable for a long term repository. In addition, geological repositories possess the advantage of reducing considerably the possibility of human intrusion or a terrorist attack, since the usual design depth is between 500 and 1000 m, compared with a few metres below the surface in the case of temporary storage. As opposed to storage, there is no intention to retrieve the waste material, although systems can be developed to handle and retrieve the waste during the operating phase; however, handling and retrieval will not be possible after site closure. Currently, several countries, for example the USA [53], Finland [54], Sweden [55] and France [56], are conducting on-site research in deep underground laboratories, with operation

expected to commence around 2020 and a phased disposal option generally assumed to last between 50 and 150 years from the first waste emplacement. These projects were launched and received approval from the local population after a long period of public consultation and debates with different stakeholders. Encouraged by these achievements, it is likely that other countries, such as the UK and Germany, will move forward with this option.

Storage and disposal are complementary rather than competing activities, and both are needed to ensure safe and reliable nuclear waste management. The timing and duration of these options depend on many factors. Although perpetual interim storage is not feasible because active controls cannot be guaranteed forever, there is no urgency for abandoning it on technological or economic grounds. However, ethical and particularly political reasons require the establishment of final disposal facilities. Such facilities are expected to start operation in 15–20 years and substantially reduce one of the current concerns about nuclear power.

The Swedish concept for the disposal of spent nuclear fuel as an illustration of the multibarrier concept.



Proliferation concerns are being addressed

There is still significant concern that nuclear energy could pave the way for proliferation. The source of such concerns is the possible dual use of nuclear material and fears that the establishment of a nuclear energy programme may lead to nuclear weapon building. Apart from this, there are non-State actors that also pose proliferation risks. An IAEA report, *The International Status and Prospects of Nuclear Power* [57], states that “Though civil nuclear power plants in themselves do not pose an increased proliferation risk, increased nuclear material in use may increase the risk of diversion to non-peaceful uses or terrorism”. Such concern still exists, but has already been taken into consideration.

The non-proliferation regime backed by the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and IAEA safeguards proved successful in limiting the spread of nuclear weapons; the safeguards regime of the IAEA is especially efficient and effective in monitoring and safeguarding nuclear materials and technology from diversion to non-peaceful purposes. To date, 145 States have entered into such agreements with the IAEA, submitting nuclear materials, facilities and activities to the scrutiny of the IAEA’s safeguards inspectors. “Effective IAEA safeguards remain the cornerstone of the world’s nuclear non-proliferation regime aimed at stemming the spread of nuclear weapons and moving towards nuclear disarmament” [58].

Every country has the right to introduce nuclear power, as well as the responsibility to do it right. In the past two years, some 50 Member States have expressed interest in considering the possible introduction of nuclear power and have asked for IAEA support. Twelve countries are actively preparing to introduce nuclear power. In-

creased demand for assistance has been particularly strong from developing countries, which seek expert and impartial advice in analysing their options and choosing the best energy mix [59].

Apprehension over the proliferation of nuclear weapons is likely to persist. The wider use of nuclear energy and the spread of nuclear know-how, technology and material may intensify these concerns. There is a worry about the state of health of the nuclear non-proliferation regime, which the IAEA supports through verifying compliance with relevant legal agreements. Fears are intensifying that the regime is seriously threatened and needs to be bolstered in many ways [60].

Spent fuel reprocessing (for extracting plutonium) and uranium enrichment are the two important stages in the nuclear fuel cycle that can contribute to a weapon building programme. These two key stages in the fuel cycle come under the safeguards regime of the IAEA, which has proven monitoring and accounting standards; this means that there is already an established regime of checks and balances that is capable of detecting the diversion of materials from a power programme [61, 62].

There are other initiatives to reduce the risk of nuclear proliferation, especially with a view to the increasing number of countries considering adopting nuclear power in their energy mix. Plans under the auspices of the Global Nuclear Energy Partnership (GNEP) and Global Nuclear Energy Initiative (GNEI) are aimed to strengthen the non-proliferation regime and to keep nuclear power away from proliferation risks. According to a recent IAEA report “Looking to the rising demand for nuclear energy, the USA has proposed the Global

Nuclear Energy Partnership (GNEP) as a comprehensive strategy to restructure the nuclear fuel cycle and introduce proliferation resistant fast reactor and fuel cycle technologies, using the most advanced international safeguards technologies and systems”. These fuel cycle initiatives offer safeguarded international enrichment facilities, fuel leasing with take back options and other services.

Yet another initiative is that of the IAEA. The Director General of the IAEA, Mohamed ElBaradei [63], proposed a plan to address such issues. The proposal highlighted the necessity of limiting the use, production and reprocessing of weapon usable material in civilian nuclear programmes, avoiding the use of materials in nuclear energy systems that may be applied directly to making nuclear weapons and considering multinational approaches

to the management and disposal of spent fuel and radioactive waste.

In the medium term, projects such as the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and the Generation IV International Forum (GIF) aim to develop more efficient nuclear power systems with proliferation resistance among the development criteria. INPRO intends to develop innovative nuclear power systems by bringing technology holders and users under the auspices of the IAEA [52]. The GIF is pursuing the development of advanced nuclear energy systems with increased safety, improved economics for electricity production and new products such as hydrogen for transport applications, reduced nuclear waste for disposal and increased proliferation resistance [64].

President Dwight D. Eisenhower, of the USA, delivering his speech at the General Assembly of the United Nations in which he proposed the creation of a new UN atomic energy agency.



Public acceptance getting more favourable

There are several concerns associated with the use of nuclear power, but their relative importance varies across regions to some extent. Among these concerns, the most crucial one in shaping public perception is operation safety. This is the uncontested leader and the most frequently mentioned factor in public opinion surveys. The nuclear industry does not seem to be doing a very good job in explaining to the public that the reactor models on sale today that buyers are choosing from are very much improved since the time of the Three Mile Island and Chernobyl accidents. Fortunately, the industry is doing a much better job in technology development by incorporating passive safety features into new editions of the Generation III technologies and making them a basic feature of innovative designs in the future. In addition, the globalization of operation experience in the nuclear industry is strengthening safety even further.

A set of regional papers on the prospects for nuclear energy published in Toth and Rogner [65] show a remarkable disparity in the fears over operation safety between developed and developing countries. Safety concerns appear to be the most severe in Europe (both west-central and eastern Europe), in the long shadows of Chernobyl, and in Japan, fed by recent incidents, but also in Latin America, with very few operating reactors, and in the South Pacific (Australia and New Zealand), with no nuclear facilities at all. In contrast, safety issues cause less anxiety in south and south-west

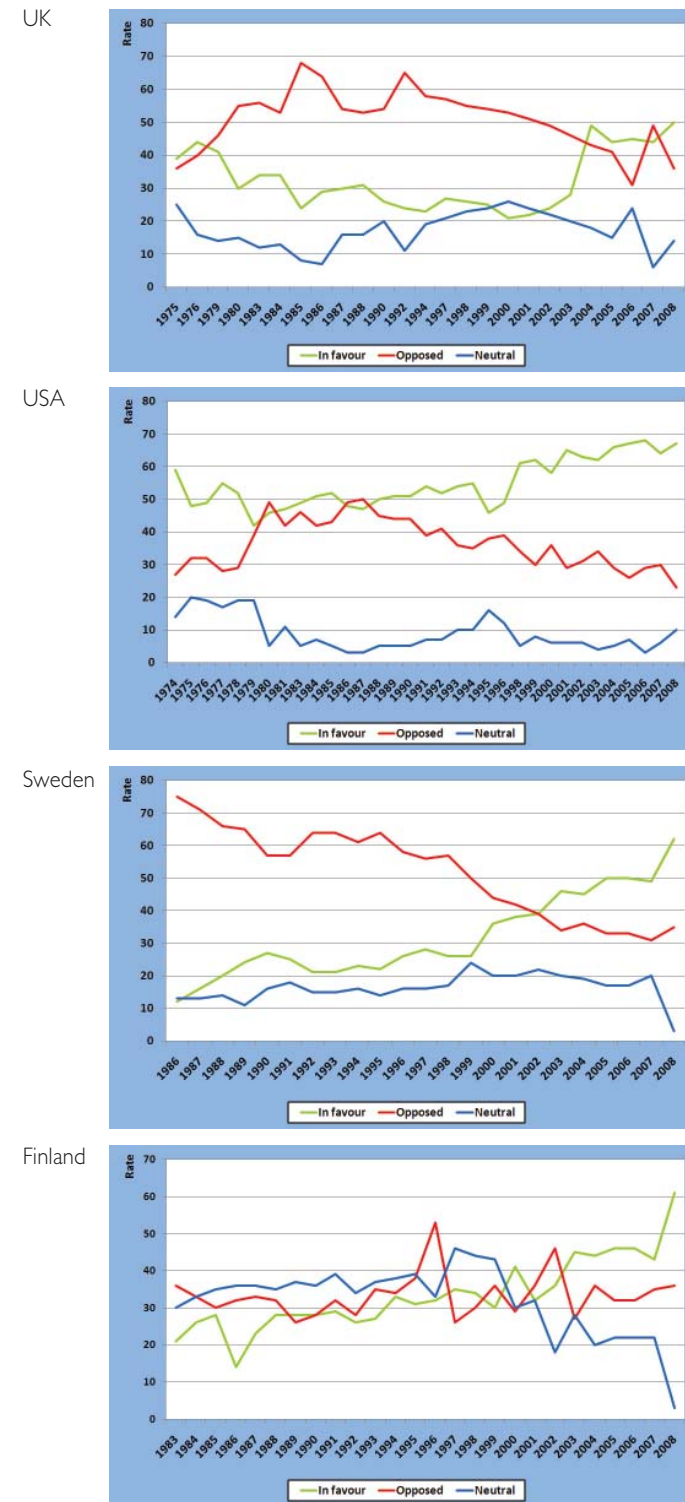
Asia, where almost 20 reactors operate in densely populated areas.

The second most important factor shaping the public perception of nuclear energy is the risks associated with the interim storage of spent fuel and the long term disposal of nuclear waste. Public fears associated with on-site storage are much lower than for reactor operation, but information about the safety properties of wet (underwater) and dry storage facilities available to the public is still sparse. More severe public opposition is witnessed against interim and final repositories of high level waste in some countries. While the preparations of such facilities in Finland and Sweden are progressing well, in a Japanese prefecture merely the expression of interest in a feasibility study for a repository (with no binding commitment irrespective of the outcome) led to the replacement of the local mayor in the ensuing local elections [66].

With concerns over higher fossil fuel prices, supply security and climate change, and with the improved safety record, public acceptance of nuclear energy has been improving in recent years. This is demonstrated by the results of recent surveys conducted in different countries (see Fig. 16).

Higher safety measures and more transparency have encouraged public acceptability towards nuclear power. Including nuclear in the energy mix is a safe option that can perform a crucial role in meeting energy needs.

FIG. 16. Public acceptance of nuclear power in selected countries [67].



Projections reflect rising expectations worldwide

The IAEA has published the annual Energy, Electricity and Nuclear Power Estimates since 1981; these report on the actual status of and future estimates of energy use, electricity production and nuclear power generation in all regions of the world for the near to medium term. The estimates are prepared in close collaboration and consultation with several international, regional and national organizations and international experts dealing with energy related statistics and projections.

The estimates of nuclear power capacities and generation are prepared using the bottom-up approach. Every year, the nuclear power programmes and plans of IAEA Member States are reviewed to prepare low and high estimates of nuclear power capacity expansion for the period up to 20–25 years ahead. These two sets of estimates represent plausible ranges based

on the judgement of energy experts. The low estimates are based on the number of units under construction or firmly planned, current retirement and life extension plans, and the medium term plans announced by governments and power utilities. The high estimates are based on an upward revision of the low estimates, essentially assuming full implementation of the announced medium term plans for nuclear power development.

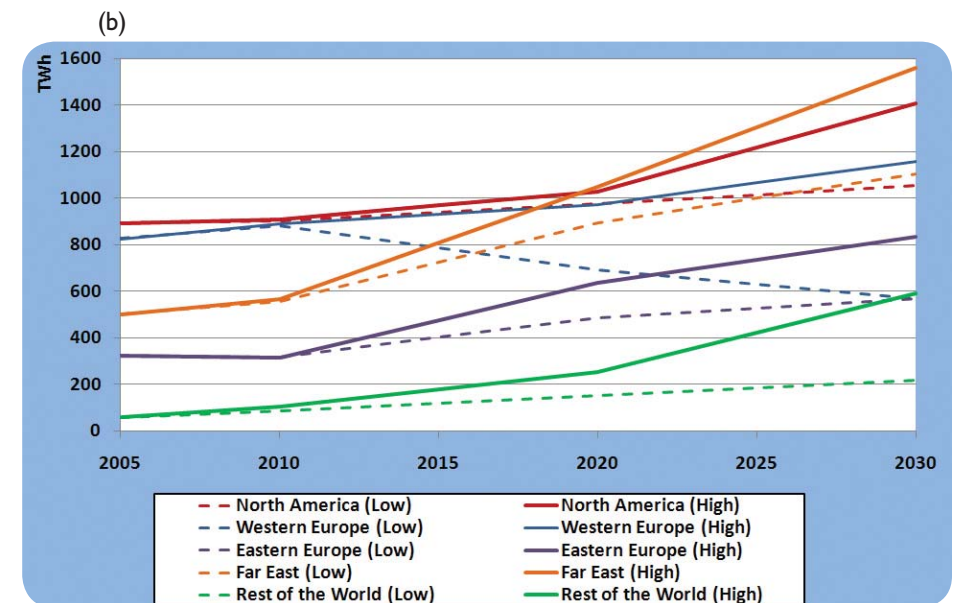
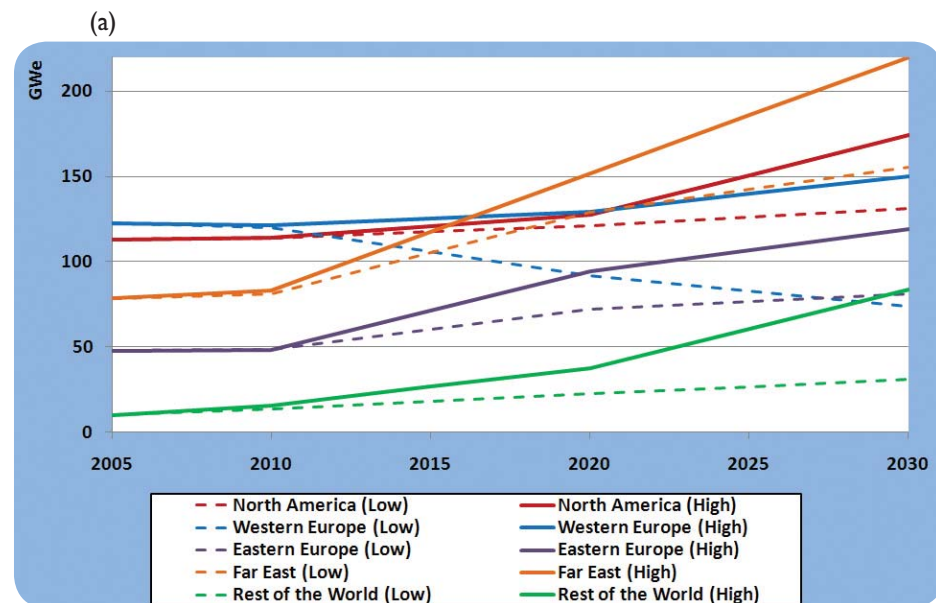
Figure 17 presents the most recent IAEA estimates [57] of the global nuclear generation capacities and the electricity output from the corresponding reactor fleet up to 2030.

There are, however, some open questions concerning the estimates: Will the high economic growth rates in large developing countries continue? How long will high

fossil fuel prices persist? What will be the architecture and flexibility mechanisms of the post-Kyoto regime? Will the industry be able to deliver new reactors on time and on budget? Will public acceptance continue to improve?

Balancing the general and region specific issues, and the high/low projections, nuclear power capacities in the future could exceed the high estimates if positive factors strengthen each other, or they could stay below the low projection if some negative factors coalesce (e.g. collapse of fossil prices, as in the 1980s, poor construction performance or another accident).

FIG. 17. Estimates of installed nuclear capacities (a) and nuclear electricity generation (b) in major world regions [67].



Main messages

There is increasing evidence put forward by climate modellers that global GHG emissions need to peak within the next decade or so and then decline to substantially below the 2000 emissions by the middle of the century. However, the global energy system is heading exactly in the opposite direction: in the absence of sweeping policy interventions, energy related CO₂ emissions are projected to increase by 55% in 2030 and by 130% in 2050 relative to 2005 [7]. The double challenge over the next 10–20 years will be to keep promoting economic development by providing reliable, safe and affordable energy while significantly reducing GHG emissions.

A range of energy sources and technologies is available in various stages of research, development, demonstration, deployment and commercialization that could help to meet the challenge. Nuclear power is clearly one of them. The actual mix of energy sources and technologies in a given country will be determined by national resource endowments and economic conditions, as well as political and social circumstances. The extent to which nuclear power will be included in the energy supply portfolio will also be influenced by other concerns, such as hedging against supply security risks and high fossil energy prices in most countries, and by the increasing realization of the health, economic and ecological impacts of local and regional air pollution from fossil fuel use and the need to reduce the related emissions in developing countries. However, these benefits will need to be balanced against concerns over nuclear power that include operation safety, nuclear weapon proliferation, economic performance, nuclear waste disposal and public acceptance, the relative importance of which diverges widely across regions and countries.

The main objective of this booklet is to provide an overview of the linkages between climate change and nuclear power and to put these linkages into the broader context of global development, energy and environmental issues currently on the social and political agendas in many countries. The main conclusion is that the need to mitigate climate change is one of the salient reasons for considering nuclear power in national energy portfolios.

The recent IPCC [2] and IEA [6, 7] assessments and the numerous underlying studies demonstrate and confirm the potential for nuclear power to contribute to solving the GHG mitigation challenge and other energy related concerns. To realize this potential, the nuclear sector needs to provide adequate responses to the concerns still surrounding its use. With that, nuclear energy will certainly not be the universal remedy for all energy related troubles, but it may well become a significant part of the solution.

Where, when, by how much and under what arrangements nuclear power will contribute to solving these problems will depend on national circumstances and priorities. Therefore the decision about introducing or expanding nuclear energy in the national energy portfolio rests with sovereign States.

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National perspectives on climate change and nuclear power

The following pages provide short summaries of how the relationship between climate change and nuclear power are perceived by various stakeholder groups in different countries. The emerging picture concerning the contexts and perspectives in which these countries look at the climate–nuclear nexus is diverse.

In the United Kingdom and the USA, climate change mitigation is coupled with supply security concerns in recent government policies to boost the contribution of nuclear power in the national electricity generation mix. In contrast, climate change considerations are still of lesser importance but the fast expansion of coal based generation is constrained by limits on mining and transport infrastructure in China. The Russian Federation could benefit from exporting natural gas even if international oil and gas prices stabilize at lower levels than the over \$140/barrel oil prices of 2008, and

this is one of the main reasons behind the expansion of nuclear capacities. Two neighbouring countries follow opposite directions in central Europe. Poland is seriously considering adopting nuclear power (supply security and GHG mitigation are the main reasons), whereas Germany is on a phase-out track, but voices to at least slow down the phase-out are increasingly heard from various stakeholders.

The contributions in this Annex are abridged and slightly edited versions of short essays prepared by M. Grimston (UK), C.D. Ferguson (USA), Deshun Liu and Shuwei Zhang (China), E.V. Poplavskaya and V.S. Kagramanyan (Russian Federation), A. Strupczewski (Poland) and S. Rath-Nagel (Germany). The usual disclaimers apply: the views expressed in this Annex do not represent those of the authors' organizations, the IAEA or its Member States.

Climate change and nuclear power in the UK: Full turn in five years

The rapidity with which nuclear energy has returned to the policy table in the UK is quite extraordinary. As recently as 2003, in that year's Energy White Paper (Our Energy Future — Creating a Low Carbon Economy), nuclear power was effectively dismissed. "Nuclear power's... current economics make it an unattractive option for new, carbon free generating capacity and there are also important issues of nuclear waste to be resolved." Uniquely among the major energy options, then, firms were to be prevented from building new nuclear power plants.

Meeting the Energy Challenge — A White Paper on Nuclear Power, published in January 2008, removed an important obstacle to the market delivering on British energy goals in the way it sees as most efficient. In his foreword, Prime Minister Gordon Brown said:

"The Government has today concluded that nuclear should have a role to play in the generation of electricity, alongside other low carbon technologies. We have therefore decided that the electricity industry should, from now on, be allowed to build and operate new nuclear power stations, subject to meeting the normal planning and regulatory requirements. Nuclear power is a tried and tested technology... More than ever before, nuclear power has a key role to play as part of the UK's energy mix."

Why such a striking change in tone? We need three things from our electricity industry.

- Secure supplies — power cuts are hugely expensive in economic and social terms, and even a fall in the quality

of supply (reliable voltage and frequency) can wreak havoc with electronic equipment.

- Environmentally acceptable supplies, most pressingly in relation to climate change.
- And of course we want the lowest costs of production that are consistent with the other goals.

After the 'dash for gas' decade of the 1990s, supplies can be threatened in three ways: a fuel shortage, a shortage of available generating capacity or a breakdown in the transmission or distribution wires. The UK is now a net importer of natural gas. Most developed countries are, but when more immediate sources such as Norway and North Africa are exhausted, the UK will be at the end of some very long pipelines from the Middle East and Former Soviet Union, where most of the world's gas is located.

As for generating capacity, the first generation of nuclear stations (Magnox) is all but over. The second generation (advanced gas cooled reactors (AGRs)), if there is no extension of their lives from current projections, will start to come off line in 2014, and all seven will be closed by 2023. That would leave us with our sole pressurized water reactor, Sizewell B, generating perhaps 3% of Britain's electricity, down from the 18% nuclear share today. At the same time, some of our older coal fired plants will also be reaching the end of their economic lives. The 2007 Energy White Paper estimates that we will need investment in new generation capacity of around 30–35 GW(e) over the next two decades. Undoubtedly some wind generation will be built, but because it is intermittent and unpredictable, such capacity cannot be treat-

ed as 'firm' when it comes to making sure we have enough plant available to cover peak demand.

Environmentally, the UK's record since the Kyoto Protocol of 1997 has been disappointing. After several years of declining CO₂ emissions, they are now rising once again, owing largely to the re-emergence of coal, the fastest growing of the major energy sources both in the UK and globally in each of the last five years.

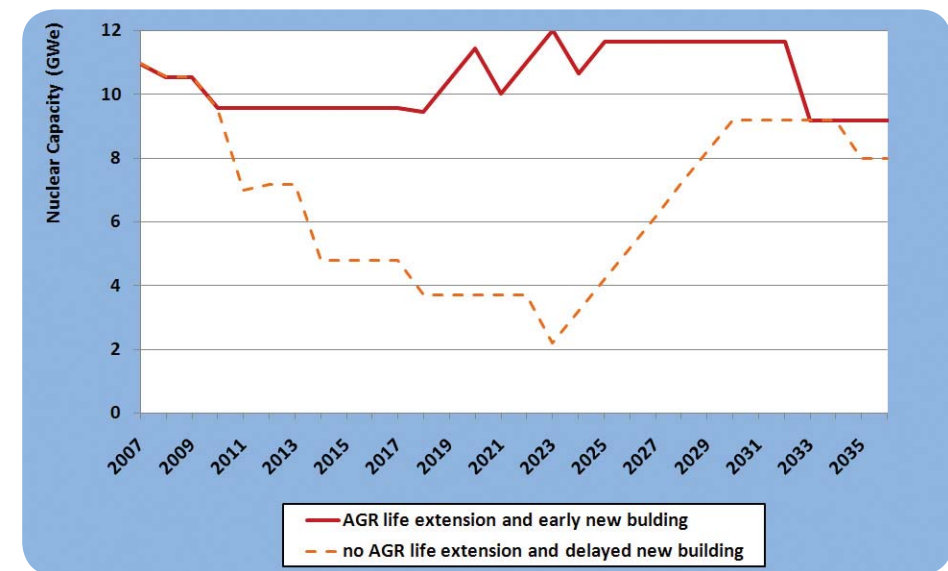
So where does nuclear fit in? The government (rightly) takes the view that the economic risks associated with investment in nuclear energy should be taken by the investor, not the government. The government's role is to create a technology-blind planning and licensing system and to deal with special issues, such as radioactive waste management, which need national policies. Reform to planning and licensing procedures (as presaged in the 2007 planning White Paper), and the pledge by the Opposition not to change the rules for

nuclear energy if elected, are moves in the right direction. Subsidies have not been sought or offered.

But the decision is tight. If, as seems to be a popular proposal among the public, existing nuclear plants are to be replaced by new ones, a start has to be made now. Even with lifetime extensions for the AGRs at their current rate output, an immediate start on new nuclear build, assuming a ten year plan, finance and build cycle, will only just deliver on an orderly retirement and replacement regime if all goes well (see Fig. A-1). With no lifetime extension, a gap appears, but if new build is delayed by five years as well, the gap becomes large.

Clearly the gap would need to be filled with something else, almost certainly CCGT, leaving the UK locked into yet more imports and GHG emissions. The task is therefore urgent — now that all the work of consultation and policy has been done, it is time to get on with it.

FIG. A-1. Two scenarios of the UK nuclear generating capacity: (1) with 10 year AGR lifetime extension and new build (1 GW(e) per year online 2018–2025); (2) with no AGR lifetime extension and delayed new build (1 GW(e) per year on-line 2023–2030).



US views on climate change and nuclear energy

The US approach to both nuclear energy and climate change can be summarized in two words: risk management. Unpacking the layers of risk management, however, requires understanding the characteristics of the US electricity market and the influences that federal and state governments have on that market. The first set of issues to understand is that electric utilities in the USA are relatively risk averse, increasingly subject to competition, acutely aware of their accountability to stock investors and relatively lacking in the large capital needed to build nuclear power plants. Chief executive officers (CEOs) of utilities know that their companies' long term financial futures ride on the decisions that they make today about what types of power plants to build because of the plants' decades long lifetimes. John Rowe, CEO of Exelon, the US based utility with the largest number of nuclear reactors, expressed this point directly: "cost is fundamental" [A-1]. Many other CEOs are receptive to countering climate change, but not at the risk of hurting the US economy. This is the prevailing perception among many US business leaders. In contrast, some experts have argued that on balance such efforts could help the economy and would mitigate catastrophic climate change effects. The bottom line is that the USA can choose to pay in the near term or delay longer — with potentially graver consequences — to address climate change.

While the Bush administration has been slow to recognize the potential perils of climate change, it has been strongly supportive of nuclear power expansion since early 2001. The US Government has essentially three options for influencing the construction of new nuclear power plants: (a) take ownership of utilities; (b) offer subsidies; and (c) set a price on GHG

emissions, with emphasis on CO₂. Owing to major changes in US laws and regulations over the past three decades, the first option is unlikely. Even after considerable deregulation, the USA has a mixed regulatory system. Some utilities in regulated markets may benefit from relatively predictable pricing, which would give them the confidence to invest in new nuclear plants, but they would likely still need subsidies in order to surmount the high financial costs of new construction. Those in deregulated markets may need greater support from government loan guarantees and other incentives before risking large amounts of capital on new nuclear plants.

The 2005 Energy Policy Act (EPAc) provides production, regulatory insurance, liability protection and decommissioning cost incentives for new nuclear power plants. The electricity production tax credit offers up to \$18/MW·h over the first eight years of operation for a maximum of 6000 MW(e) of new nuclear capacity. If more than 6000 MW(e) of new capacity is built, the credit will be proportionally spread over the plants that meet the full set of qualifications: apply for a combined operating licence with the US Nuclear Regulatory Commission by 31 December 2008 and begin construction prior to 1 January 2014. The total credit offered would be \$6 billion. The production credit applies to any no or low carbon emission power source. The second incentive is regulatory risk insurance, which would have the US Department of Energy compensate utilities if, through no fault of their own, regulatory snags or court cases delay the licensing of the first six new reactors. The third incentive limits liability responsibility to the nuclear industry to \$10.6 billion for any plants built through to 2025.

EPAc has, as of late 2008, spurred interest in more than 30 nuclear reactors, but it is not clear how many will actually be built because the full effect of the incentives would only apply to the first 6000 MW(e) of capacity.

The other option to stimulate further nuclear power plant construction is to make it even more cost competitive with fossil fuel power plants. This approach would require placing a price on carbon emissions. According to the non-partisan Congressional Budget Office [A-2], a price of \$45/t CO₂ "would probably make nuclear generation competitive with conventional fossil fuel technologies... even without EPAc incentives".

In recent years, a consensus has been emerging to favour a carbon price signal that would stimulate investment in no and low carbon energy technologies. Notably backing this concept are the Nuclear Energy Institute (NEI) [A-3] and the US Climate Action Partnership (USCAP), which is a coalition of business and envi-

ronmental non-governmental organizations. The main difference between the NEI and environmental groups that belong to USCAP is that the NEI and utilities support US Government subsidies, whereas the environmental organizations oppose subsidies for what they call "a mature industry". While it is likely that a majority of politicians will back some subsidies, there is large uncertainty about whether a carbon pricing scheme will set a high enough and sustainable price to favour significant nuclear power plant construction to make a difference in fighting climate change.

The next several years will be a critical period for the future of new nuclear power plant construction in the USA. If the next few reactors are built on time and within budget, confidence would increase. This activity could set the stage for increased construction in later years. However, the major determining factors will remain capital costs and financial risks, which a long term carbon pricing signal could make more manageable.

Climate change and nuclear power: Chinese perspective

Nuclear power in China is boosted by serious electricity, coal and oil supply shortages and by government policy. The government started advocating nuclear power after serious electricity shortages in 2003. "Proactively promote the development of nuclear power", pronounced first in the 11th five year National Social and Economic Development Plan, has already been adopted by national strategic polices and action plans.

The principle of integrating climate change policy with other policies is emphasized in the national policies to address climate change. China will give full consideration to climate change issues by integrating related measures (both mitigation and adaptation) into its National Social and Economic Development Plan under the framework of sustainable development. Nuclear power can bring multiple benefits by improving the fossil fuel dominated energy mix, reducing associated pollution and alleviating the heavy burden on inter-regional coal transport¹, as well as coping with global climate change.

The nuclear power industry and academics specializing in the electric power sector are preparing for the growth of nuclear energy². There is consensus that nuclear power can help mitigate climate change and is a strategic and realistic choice to satisfy the increase in the demand for electricity and to enhance energy security while reducing environmental pollution. Compared with other advanced technology alternatives in the power sector, nuclear power has a

large unit capacity and is suitable as the stable base load as an alternative to thermal power in the generation mix.

The target of the official nuclear power development plan is to have 40 GW(e) of generating capacity, accounting for 4% of the total installed capacity, by 2020 and to have a further 18 GW(e) under construction by the same date; however, Zhang Guobao, Director of the National Energy Administration, maintains that the total nuclear power capacity could reach 60 GW(e) by 2020 [A-4]. Medium to long term development plans have been adjusted to increase nuclear power further to raise its share in electricity generation from 4% to 5% by 2020³. Nevertheless, due to their long construction time, the contributions of nuclear power to climate change mitigation and the power generation mix are still not very significant in the near term.

According to the medium and long term energy development plan, up to 2020 coal based thermal power will be still dominant, but the share of nuclear and hydropower will be enlarged, and at the same time advanced renewable energy technologies such as wind power and solar PV, and energy efficient technologies on the demand side, will undergo fast development. After 2020, the share of nuclear and renewable energy will be continuously increased, offsetting the decline of coal power. In the longer term, nuclear power is expected to play a proportional role with coal and other sources (mainly renewable energy)

by 2050. The role of natural gas will be minor, because of limited resources and the high cost of the fuel.

Of course, whether or not nuclear energy can play a critical role will be influenced not only by public concerns on nuclear safety, energy security and environment consequences, as well as investment availability, etc., but also by the evolution of the international post-2012 climate regime. China faces great pressure as a giant emitter, and it is addressing global climate change in the national sustainable development strategies and plans.

Large nuclear power investment in advanced nuclear power technology will face considerable financial and technological barriers, so China would like to pursue an innovative clean development mechanism

(CDM) regime in the post-2012 climate system in which nuclear energy technology would be involved as a GHG emission reduction technology option for the CDM, and the improved technology transfer mechanism, by which nuclear power technology transfer could be facilitated.

The effects of the post-2012 agreement on the prospects for nuclear power in China will be positive; that is, the role of nuclear power will be emphasized and its development will be stimulated as an important factor in the national sustainable development strategy that integrates the policies and measures in response to climate change. An innovative CDM is expected in the post-2012 climate regime, in which nuclear power technology could be involved, could foster nuclear power to mitigate climate change in China.

¹ The geographically uneven distribution of resources within China calls for long distance transport of large amounts of energy (mainly coal, oil and gas) from the north and west to the coastal regions.

² "Chinese nuclear energy society: 'Spring coming' for nuclear power development in China": in the 2008 annual conference hosted by China's nuclear energy industry association held on 17 June 2008 in Beijing, participants from government officials, nuclear experts and nuclear power industries were all bullish on the prospects for nuclear power development in China. <http://www.cec.org.cn/>, 2008-6-25.

³ <http://news.cctv.com/xwlb/20080802/105454.shtml>.

Role of nuclear power in reducing GHG emissions in the Russian Federation

In 2004 the Russian Federation ratified and thus triggered the entry into force of the Kyoto Protocol. The Russian Federation will be able to meet its GHG reduction commitment under the Kyoto Protocol not only by 2012 but also until 2020, despite the expected growth in the economy. A new orienting point for negotiations on international agreement on GHG emissions after 2012 — cutting GHG emissions by 50% below 1990 levels by 2050 — is based on the IPCC Fourth Assessment Report and was discussed at the G8 summit in 2008⁴. The Russian Federation has to cut its current emissions by 25% to reach the corresponding target [A-5].

Among the options to reduce GHG emissions, increasing energy efficiency is the main short term emphasis in the Russian Federation. Other options would be used to achieve the long term targets. Hydro-power had already reached its maximum level of 18%. The contribution of other renewable energy resources (wind, biomass, solar, etc.) at present is negligible and there is little scope for their expansion. According to the ERIRAS (the Energy Research Institute of the Russian Academy of Sciences) estimate [A-6], in the medium term the prospects for the total share of renewable energy resources, including hydropower, would not exceed 15%.

Currently, gas based power generation has the highest share (41%), and there are constraints on replacing coal by gas. The Russian Federation needs to decrease gas based generation for several reasons: to provide a secure energy supply at an acceptable price level, to provide a guaranteed gas supply abroad and to significantly

increase the gas supply domestically. This can be realized by increasing the shares of coal and nuclear energy in power generation.

According to data produced by ERIRAS, the share of coal in power generation will increase to 31–38% and that of nuclear power to 19–20% by 2020. This trend will continue until 2030 (see Fig. A-2).

On the political level, it has been considered that nuclear power could be a key measure in decreasing CO₂ emissions. The Russian President, Dmitry Medvedev, emphasized at the G8 summit in Japan in 2008 that the Russian Federation supports increasing the role of nuclear power. Accordingly, nuclear power development is planned.

In the medium term, the strategic goal is to provide 25–30% of electricity by nuclear power plants (compared with 16% currently), which means commissioning of 2–3 GW(e) per year from 2010 to 2020. It is suggested to achieve this goal on the basis of the existing thermal reactor and open nuclear fuel cycle technologies. In the long term, the strategic goal is to increase the nuclear share to 50% or more, which will require transition to a new technological platform, including the closed nuclear fuel cycle, using fast breeder reactors.

The strategy of nuclear power development up to 2050 considers several scenarios: the maximum scenario foresees 300 GW(e) of nuclear capacity (avoiding 1.5 Gt CO₂/year), while the moderate scenario projects 100 GW(e) (avoiding 0.5 Gt CO₂/year). It is planned that the nuclear share in electricity generation will be up to 30% by

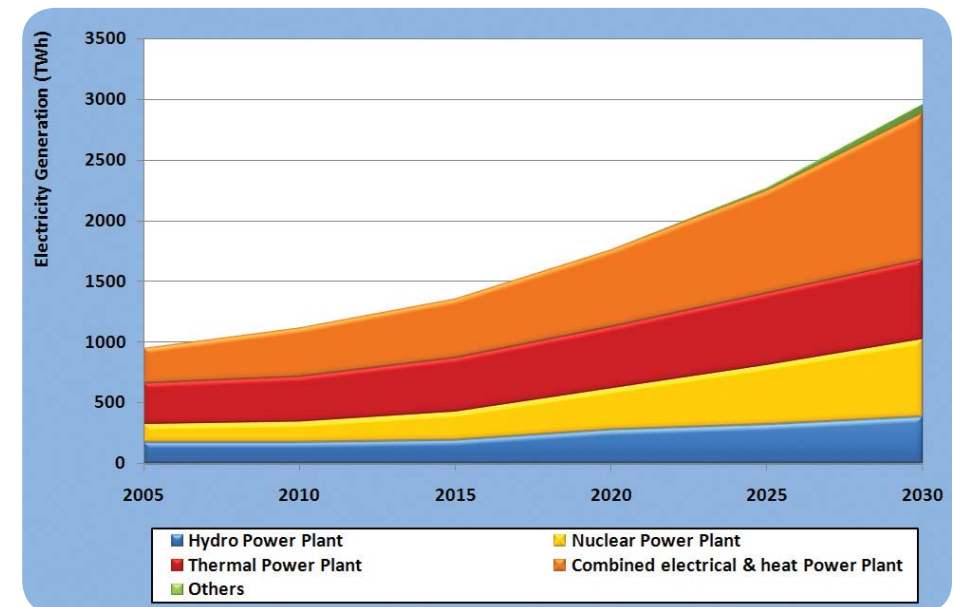
2030, with a possible increase of up to 50% by 2050. The CO₂ emissions avoided by the high scenario are a significant share of the total reduction requirement for the 2050 mitigation objective.

It is necessary to emphasize that nuclear power in the Russian Federation is being developed mainly in order to provide energy security. Nuclear power development is recognized as a strategic goal considering the depletion of fossil fuel resources. Future nuclear power developments will rely on fast reactors and a closed fuel cycle, because fast reactors will allow access to virtually unlimited sources of nuclear fuel, including the energy potential of ²³⁸U

and natural thorium.

The business sector also supports the expansion of nuclear power. However, due to historical reasons, many ecological organizations disapprove of the development of nuclear power, owing to concerns over spent nuclear fuel and high level waste and to the effect of possible accidents at nuclear power plants. However, nuclear power can realize its potential for reducing CO₂ emissions only if it is safe and economically acceptable, can solve as yet unresolved issues such as spent fuel storage, and can increase social acceptance through establishing open and transparent dialogue.

FIG. A-2. Structure of electricity generation by power plant type [A-7].



⁴ The leaders of the G8 confirmed the intention to reduce harmful emissions by 50% by 2050 — joint declaration (<http://www.ami-tass.ru/article/37943.html>).

Climate change and nuclear power development in Poland

In Poland about 94% of electric power is produced by coal fired power plants burning domestic coal. In the rest of the EU nuclear power is a major electricity source, providing about 32% of total electricity needs. Poland has a high energy independence, while the rest of the EU must import a large and ever growing share of its energy sources. However, nuclear power plants ensure clean air and water, do not emit CO₂ and produce low cost electricity. In Poland, emissions of air pollutants have been significantly reduced, but are still a burden on the environment, and CO₂ emissions are very high.

At present, electricity consumption in Poland is about 110 TW·h, and the rate of gross national product increase in the basic scenario is 4–5%/year [A–8]. Even when considering efficiency improvements, electricity demand will be about 240 TW·h/year and the required generation capacity will reach 43 GW(e) in 2030. By then, about 15 GW(e) of the current 34.3 GW(e) capacity will be retired (see Fig. A–3).

Figure A–3 shows that in 2030 some 12 GW(e) of power generation capacity will be missing, even allowing for energy savings. What could be the sources to fill this gap? Total hard coal reserves are very large (43 321 billion tonnes), but reserves in currently operating mines are only 3.8–4.8 billion tonnes (lifetime: 35 years). Similarly, the reserves in operating lignite mines will last for about 30 years. The rest of both resources are available from deeper mines at much higher extraction costs and which result in more environmental degradation. The domestic reserves of natural gas are insufficient for covering the current needs, and gas is not used for electricity production (except for a few cogeneration plants).

Only peak load gas power plants are economically justified. Renewable sources can provide a comparatively low amount of energy. Renewable energy is more expensive than coal or nuclear energy, so high subsidies are needed. Assuming a subsidy level of 240 Polish zloty (2004) (PLN'04)/MW·h (equivalent to €65/MW·h) in addition to the market price, the total amount of renewable electricity could be about 20.4 TW·h/year (8 TW·h hydropower, 2.1 TW·h biomass from wood, 2.5 TW·h from energy crops and 7.8 TW·h from wind farms). The optimistic low cost figures for electricity production quoted by renewable energy advocates and repeated in EU reports are not compatible with the situation in Poland.

Thus assuming that at the cost of much effort and much expense renewable energy will provide Poland with 20.4 TW·h in 2030, the remaining electricity will have to be supplied by coal, gas or nuclear power plants. These considerations were dictating the necessity of the development of nuclear power in Poland even before the full impact of auctioning of emission permits became known. Today the urgency of introducing nuclear power is very clear.

The role of nuclear power as a means of reducing CO₂ emissions was initially not highly appreciated, and generally not much discussed. The necessity of nuclear power has been mostly considered in the light of the security of domestic resources and economic competitiveness, taking into account the environmental advantages of nuclear power, but it should be stressed that it has strong justification even without its positive influence on CO₂ emission reduction. Recently, with the introduction of the EU plan of CO₂ emission permit auction-

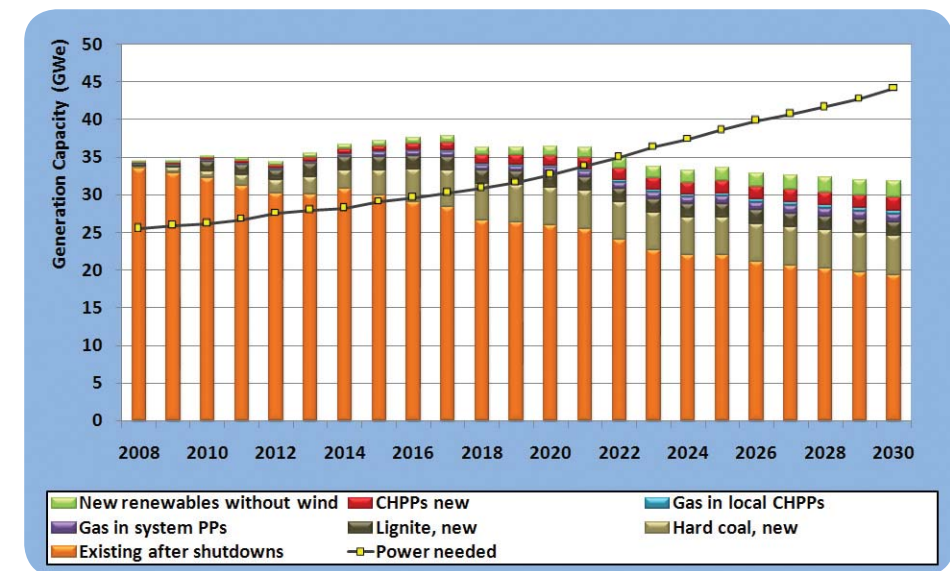
ing, the competitiveness of nuclear power has been strongly stressed.

An earlier (2007) government strategy for the electric power sector proposed the development of nuclear power, with the first nuclear power plants planned to begin operation around 2020. The nuclear power development programme was supported by all technical and scientific organizations, from the Polish Academy of Sciences to the Association of Electrical Engineers, including the Polish chapter of Environmentalists for Nuclear Power [A–9]. The only protests came from anti-nuclear organizations such as Greenpeace and the Green Party Federation.

The new (2008) government draft programme of strategy for the development of the energy sector up to 2030 [A–10]

indicates that nuclear power is an important option, although in the short term it emphasizes energy savings and renewable energy sources. In the longer term, the draft strategic programme states that “it is not possible to limit greenhouse gases emissions without nuclear power. Even significant progress in energy efficiency and renewable energy sources will not be enough to resolve the problem of electricity production. In view of the increasing requirements of environment protection, development of nuclear power seems to be the best way of ensuring security of electrical energy production. Nuclear power plants provide the cheapest way of large scale electricity generation.” The discussion of the draft programme is ongoing. A full public discussion of the nuclear power development programme in Poland is planned for 2009.

FIG. A–3. Planned structure of electric power sources in Poland showing need for nuclear power plants [A–11].



Germany: Climate protection leader and nuclear phase-out

Nuclear energy has been a solid constant for base load electricity generation in Germany since the 1970s. By the end of the 1990s, about 31% of total electricity was generated in 19 nuclear plants. However, a complete turnaround in energy policy commenced in June 2000, when the government entered into a convention with the nuclear power plant operators to decommission reactors after 32 years of operation. With the shutdown of the two oldest (and smallest) reactors in 2003 and 2005, implementation began and the last reactor is estimated to be taken out of service by 2021.

The rationale for the nuclear phase-out has been questioned from the beginning, but came under more heavy attack recently after the government released a very ambitious climate protection programme. Nuclear power has now been re-assessed by a growing number of concerned scientists, managers, consumers and decision makers as a necessary cornerstone against climate change at an affordable cost to society. A series of recent expert assessments provided evidence for this relationship.

In September 2005 the German Physical Society [A-12] highlighted that an additional 100–120 Mt/year of CO₂-eq. GHG would be emitted if nuclear power was replaced by modern and efficient fossil generators. Furthermore, the transition to a non-nuclear energy future would need more time than anticipated. By 2020, in contrast to the prevailing view, a small fraction of nuclear electricity could be substituted by renewables or efficiency measures, but the bulk would have to be replaced by fossil fuel generation. The 2020 goal to reduce GHG emissions by 40% below the 1990 level would clearly be missed.

Since energy has become such a central issue for future industrial location policy

and as climate protection is a cornerstone of energy policy, the Federal Government held an energy summit with the industry in July 2007. A study by EWI/PROGNOS [A-13] prepared for the summit presents three scenarios. One of these considers a 20 year extended lifetime for the 17 nuclear plants, resulting in 45% GHG mitigation annually by 2020 (compared with 1990). This is the highest mitigation volume and the lowest mitigation cost compared with the scenarios with a forced phase-out of nuclear reactors.

A study by the consultancy McKinsey [A-14] for the Federation of German Industry concluded that GHG mitigation of around 26% by 2020 (compared with 1990) would be feasible if the known potentials for mitigation with an avoidance cost of up to €20/t CO₂-eq. were implemented and the nuclear exit plan continued. A 31% GHG reduction by 2020 would require an additional installation of renewable energy sources at higher average avoidance costs: €32/t CO₂-eq. (power generation with renewable energy) and €175/t CO₂-eq. (biofuels). In a slowed down nuclear exit strategy allowing the operation of several reactors beyond 2020, an additional 90 Mt CO₂-eq. could be mitigated (otherwise emitted by a mix of coal and gas power plants) and a €4.5 billion avoidance cost could be saved annually.

The issue of nuclear power in Germany has been recently rediscovered as of central interest for society. With rising concerns about climate change and the tremendous cost of a mitigation programme based solely on renewable energies and efficiency measures, several policy makers have proposed reconsidering nuclear power as a transition technology progressing towards an emissions free energy system and revising the nuclear exit programme. Several

Social Democratic and Green party politicians (the coalition that initiated the phase-out) have now indicated their acceptance of slowing down the nuclear exit plan, without commissioning new reactors.

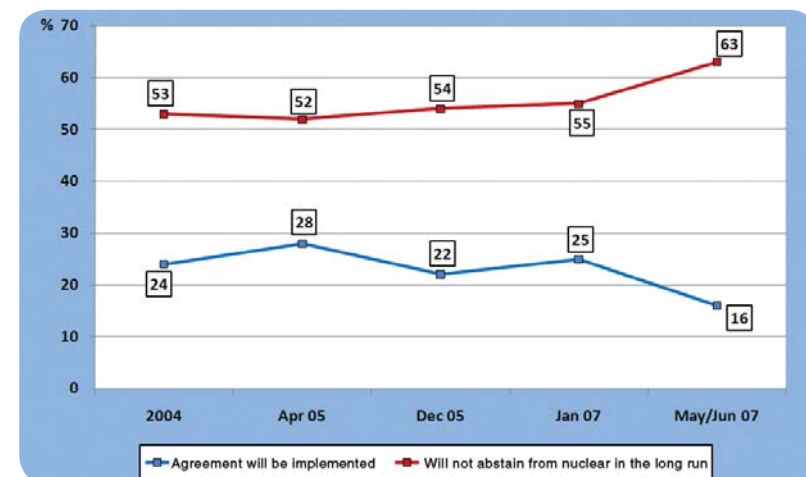
Private stakeholders continue to point out that nuclear energy is an essential technology option for Germany's energy future — evoking low environmental and social costs — which consequently should not be phased out. The position shared by the four utilities operating the 17 nuclear reactors in Germany is that achieving the government's climate goals is possible without nuclear power, but at a much higher price. The Association of German Electric Utilities [A-15] estimated that nuclear energy could save 53 Mt CO₂-eq. GHG emissions by 2020 at a lower electricity cost (10% for residential, 20% for industrial consumers on average) than any other combination of technologies.

According to a recent survey by the Al-lensbach social research institute [A-16], 79% of Germans consider climate change to be one of the world's most pressing problems. Climate protection is, however, widely regarded as something to be achieved through higher efficiency and the use of renewable energy. Yet 32% of respondents believe that extended operation of nuclear reactors will have a substantial impact on GHG mitigation.

As for nuclear power in general, the attitude of the population is more favourable than often thought: a stable majority of 52–55% has stated in recent years that Germany should not reject nuclear power in the long run. The share of this view grew to over 63% in the latest survey (see Fig. A-4).

In summary, with a 40% GHG mitigation goal by 2020 (compared with 1990), Germany strives to position itself as a forerunner in international climate protection. This role can only reasonably be achieved with a sophisticated mix of all energy options: nuclear, fossil and renewable. It is understood by a large section of opinion leaders in Germany that nuclear power is a climate protection driver with low generating costs. It is also recognized as a transitional energy until technology research and development provides better energy forms. The extremely high cost of achieving the ambitious GHG mitigation goals without nuclear power is a key factor stimulating a renewed consideration of the technology by the general public. In this context, international nuclear construction programmes are very closely monitored. The negotiations for the post-2012 international climate protection agreements are considered very important, but do not have any immediate implications for the nuclear power aspirations of Germany as of today.

FIG. A-4. Public opinion about nuclear phase-out in Germany [A-16].



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