

CLIMATE CHANGE AND NUCLEAR POWER 2012



IAEA

International Atomic Energy Agency

CLIMATE CHANGE AND NUCLEAR POWER 2012

**INTERNATIONAL ATOMIC ENERGY AGENCY
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Foreword

Climate change is one of the most important issues facing the world today. Nuclear power can make an important contribution to reducing greenhouse gases while delivering energy in the increasingly large quantities needed for global economic development. Nuclear power plants produce virtually no greenhouse gas emissions or air pollutants during their operation and only very low emissions over their full life cycle.

The Fukushima–Daiichi accident of March 2011 caused deep public anxiety and raised fundamental questions about the future of nuclear energy throughout the world. It was a wake-up call for everyone involved in nuclear power — a reminder that safety can never be taken for granted. Yet, in the wake of the accident, it is clear that nuclear energy will remain an important option for many countries. The advantages of nuclear power in terms of climate change are an important reason why many countries intend to introduce nuclear power in the coming decades, or to expand existing programmes. All countries have the right to use nuclear technology for peaceful purposes, as well as the responsibility to do so safely and securely.

The International Atomic Energy Agency (IAEA) provides assistance and information to countries that wish to introduce nuclear power. It also provides information for broader audiences engaged in energy, environmental and economic policy making.



This report, which revises and updates the 2011 edition, summarizes the potential role of nuclear power in mitigating global climate change and its contribution to other development and environment challenges. It also examines issues such as cost, safety, waste management and non-proliferation.

I hope it will make a useful contribution to the deliberations of international policy makers in the United Nations Climate Change Conference and other forums.

Yukiya Amano
Director General

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Introduction

The twin challenges of global climate change and global energy poverty share at least one significant feature — each will require very carefully designed policies if it is to be solved without making the other worse. Significant decarbonization of the global energy system is essential if the goal of meeting global energy aspirations is to be reconciled with that of reducing greenhouse gas (GHG) emissions in order to limit global temperatures. It is in this context that this report highlights nuclear power's potential to help mitigate global climate change while meeting growing global energy needs.

In the period following the accident at TEPCO's Fukushima-Daiichi Nuclear Power Plant, which was caused by the earthquake and tsunami that struck Japan on 11 March 2011, 'stress tests' and peer reviewed safety tests of nuclear power plants have been carried out around the world. In September 2011, an Action Plan on Nuclear Safety was adopted by the IAEA's Board of Governors and subsequently unanimously endorsed by the IAEA General Conference. In September 2012, the first annual progress report was submitted. The accident at Fukushima-Daiichi set off a debate that has offered an opportunity to strengthen the nuclear safety regime. While long term growth projections for nuclear power are now 8–16% lower than they were before the accident, nuclear power is still projected to grow by 25%–100% by 2030. The arguments for nuclear power as a potential mitigator of GHG emissions have not gone away; nor has the need for such mitigators.

The countries attending the 2011 G8 Summit in Deauville, France, confirmed their commitment to long term efforts to limit "the increase in global temperatures [to] below 2°C above pre-industrial levels, consistent with science" and their support for "reducing emissions of greenhouse gases in aggregate

by 80% or more by 2050, compared to 1990" in developed countries [1].

In calling for such dramatic reductions in GHG emissions, the G8 countries are reflecting the major concerns which have been expressed in recent decades about global climate change resulting from increasing anthropogenic emissions of GHGs. 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 where, even today, some 1.4 billion people have no access to modern energy services. Without significant efforts to limit future GHG emissions, especially from the energy supply sector, the expected global increase in energy production and use could well trigger "dangerous anthropogenic interference with the climate system", according to Article 2 of the United Nations Framework Convention on Climate Change [2].

Nuclear power has the potential to continue to play a significant role in the effort to limit future GHG emissions while meeting global energy needs. Nuclear power plants produce virtually no GHG emissions during their operation and only very small amounts on a life cycle basis. This report summarizes nuclear power's potential role in mitigating global climate change. It also highlights nuclear power's contribution to addressing development and environment challenges, as well as its current status, including the issues of cost, safety, waste management and non-proliferation. Nuclear power's current — and potential future — contribution to meeting the twin challenges of climate change and energy poverty make it especially important to deal effectively with any concerns about nuclear power.

Executive Summary

Energy is indispensable for development. Enormous increases in energy supply are required to lift 2.7 billion people out of energy poverty. Without a shift in the global approach to energy, however, GHG emissions will increase even further. Meeting the acute growth in energy demand would require a 75% growth in primary energy supply by 2050. In the absence of sweeping policy interventions, this would lead to an increase in energy related CO₂ emissions of 95% by 2050. Yet the scientific consensus is that GHG emissions will need to peak within the next decade or so and then *decline* by 50%–85% from today's levels by 2050 in order to avoid adverse climate change impacts in ecological and socioeconomic systems. The twin challenges over the next 10–20 years will be to keep promoting economic development by providing reliable, safe and affordable energy services while significantly reducing GHG emissions.

Nuclear power is among the energy sources and technologies available today that could help meet the climate-energy challenge. GHG emissions from nuclear power plants are negligible and nuclear power is among the lowest CO₂ emitters together with hydropower and wind based electricity when emissions throughout the entire life cycle are considered.

In the electricity sector, nuclear power has been assessed as having the greatest potential (1.88 Gt CO₂-equivalent (CO₂-eq.)) to mitigate GHG emissions at the lowest cost: 50% of the potential at negative costs due to co-benefits from reduced air pollution, the other 50% at less than \$20/t CO₂-eq. Nuclear energy could account for about 15% of the total GHG reduction in electricity generation by 2050.

Nuclear energy can contribute to resolving other energy supply concerns and has non-climatic environmental benefits. Nuclear power can help alleviate concerns about energy security and

increased volatility in fossil fuel prices. Ample uranium resources are available from diverse sources, and the cost of uranium is a small fraction of the total cost of nuclear electricity. Nuclear power can also help reduce local and regional air pollution.

The economics of nuclear power are competitive and will be further enhanced by the increasing CO₂ costs of fossil based electricity generation. The estimated ranges of leveled electricity costs from natural gas, coal and nuclear sources largely overlap between 5 and 10 US cents/kW•h. Including the costs of CO₂ capture and geological disposal and increasing charges for CO₂ emissions would further improve the competitiveness of nuclear power.

The accident at TEPCO's Fukushima-Daiichi Nuclear Power Plant, which was caused by the earthquake and tsunami that struck Japan on 11 March 2011, prompted a round of 'stress tests' of nuclear power plants around the world and, in September 2012, the first annual progress report on the IAEA's Action Plan on Nuclear Safety was made. Key areas of progress highlighted in this report include assessments of safety vulnerabilities of nuclear power plants, the strengthening of the IAEA's peer review services, improvements in emergency preparedness and response capabilities, strengthening and maintaining capacity building, and widening the scope and enhancing communication and information sharing with Member States, international organizations and the public. Significant progress has also been made in reviewing the IAEA's Safety Standards, which continue to be widely applied by regulators, operators and the nuclear industry in general, with increased attention and focus on vitally important areas such as accident prevention, in particular of severe accidents, and emergency preparedness and response. In addition the IAEA also convened international experts' meetings on reactor and

spent fuel safety, enhancing transparency and communication effectiveness in the event of a nuclear emergency, and protection against extreme earthquakes and tsunamis.

Radiation risks from normal plant operation and waste management are small. Radiation risks from normal plant operation remain at a negligible level relative to natural and medical sources of public radiation exposure. The scientific foundations for the safe geological disposal of radioactive waste are well established.

Projections of future nuclear generating capacity point to the continued growth of nuclear power in the longer term. The Fukushima–Daiichi accident slowed growth — the 2030 projection is 9% lower than last year's projection — but did not reverse the upward trend in the growth of nuclear power reactors. Nuclear capacity is expected to expand by an additional 87–371 GW by 2030. The principal reasons for increased interest in nuclear power in recent years have not changed.

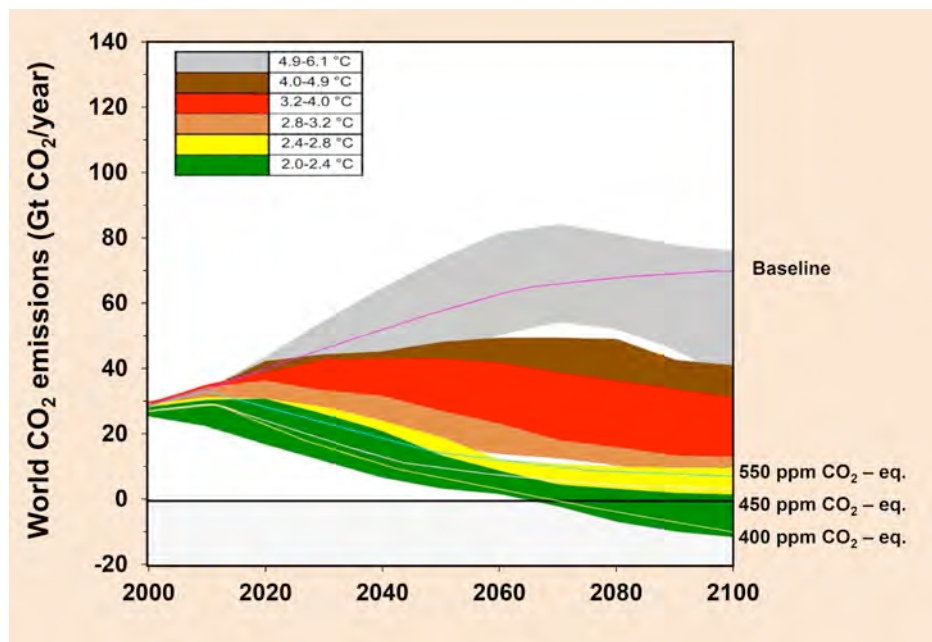
The climate change challenge

According to the findings of the Intergovernmental Panel on Climate Change (IPCC), the biophysical changes resulting from a global warming of more than 3°C will trigger increasingly negative impacts in all climate sensitive sectors in all regions of the world [3]. In mid-latitude and semi-arid low latitude regions, decreasing water availability and increasing drought will expose hundreds of millions of people to increased water stress. In agriculture, cereal productivity is expected to decrease in low latitude regions and to be only partly compensated for by increased productivity in mid-latitude and high latitude regions. Natural ecosystems will also be negatively affected: up to 30% of species will be at a growing risk of extinction in terrestrial areas, and increased coral bleaching in the oceans is forecast. In coastal areas, damage from floods and storms will increase. Human health will also be affected, especially in less developed countries, by the

increasing burden from malnutrition and from diarrhoeal, cardiorespiratory and infectious diseases. Increased morbidity and mortality are foreseen from heat waves, floods and droughts.

Figure 1 presents the pathways towards stabilizing climate change in various ranges of global warming as established by the IPCC [4]. The underlying calculations imply that in order to prevent a global mean temperature increase of more than 2.0–2.4°C above the pre-industrial level, GHG concentrations should not exceed the range of 445–490 ppm CO₂-eq. This means that global CO₂ emissions would need to peak by 2015 and return to the 2000 level by 2030 at the latest, and should be reduced by 50–85% relative to 2000 by 2100. The Synthesis Report of the 2009 Copenhagen Conference on Climate Change [5] presents three emission pathways for energy related CO₂ emissions

FIG. 1. CO₂ emissions and equilibrium temperature increase for a range of stabilization levels. (Sources: Based on IPCC [4] and Richardson et al. [5].)



towards stabilizing GHG concentrations at three levels (400, 450 and 550 ppm CO₂-eq., shown as coloured lines in Fig. 1) that imply three confidence levels for keeping the global mean temperature increase below 2°C: at 15%, 50% and 75% probability, respectively. The lowest trajectory entails negative global emissions after 2070 (implementation of carbon capture and storage (CCS) and biomass).

The world thus faces an enormous mitigation challenge over the next decades. Both the report of the IPCC Working Group III (WGIII) and the Copenhagen Synthesis Report maintain that many mitigation technologies and practices that could reduce

GHG emissions are already commercially available. According to the IPCC [6], technical solutions and processes could reduce energy intensity in all economic sectors and provide the same output or service with lower emissions. Fuel switching and modal shifts (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 and the increased use of renewables and nuclear power and of CCS in the energy sector could result in significant GHG reductions.

The global energy challenge

All recent socioeconomic development studies project major increases in energy demand, driven largely by demographic and economic growth in today's developing countries.

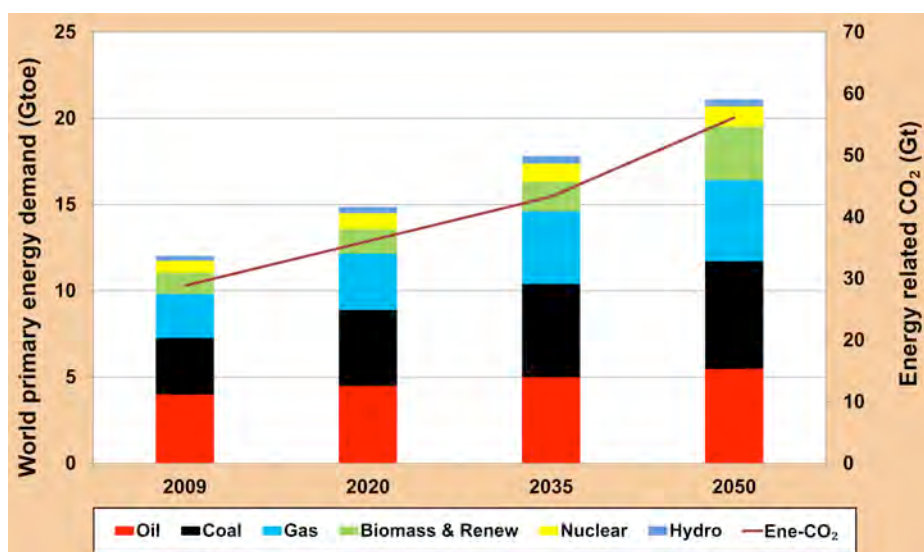
Worldwide, 2.7 billion people rely on traditional biomass as their primary source of energy and 1.3 billion people do not have access to electricity [7] — conditions which severely hamper socioeconomic development.

Of the world's 7 billion people [8], about 82% live in non-OECD countries and consume only 54% of global primary energy [9]. Alleviating this energy inequity will be a huge task. A growing global population will compound the problem. The medium variant of the latest population projections of the United Nations estimates an additional 1.4 billion people by 2030, and another 1 billion by 2050, bringing the world's population to about 9.3 billion by the middle of this century [10]. Regarding economic growth, the World Bank projects an average annual growth rate

for the world economy of 2.5% in 2012, 3% in 2013 and 3.3% in 2014 [11]. Developing countries will grow the fastest, though their long term growth rates will decline over time from 6.9% now to 3% in the 2030s, while OECD countries will grow at the slowest rate and maintain a consistent ~2% long term growth rate [12]. On the basis of these two main drivers of energy demand, the International Energy Agency (IEA) projects that, without substantial changes to current energy policies, total world primary energy demand will grow from 12.15 Gtoe (tonnes oil equivalent) in 2009 to about 18.3 Gtoe by 2035 with current policies in place [9] and 22 Gtoe by 2050 [13]. (See Fig. 2.)

The climate change implications are severe. If energy related CO₂ emissions increase by about 40% in 2030 and roughly double by 2050 relative to 2008 (Figure 2), the Earth would be on track towards atmospheric GHG concentrations of the order of 800 ppm CO₂-eq. and an equilibrium warming of over 5°C above pre-industrial levels.

FIG. 2. Projections of world total primary energy demand and energy related CO₂ emissions. (Source: IEA [9] and IEA and OECD Nuclear Energy Agency (NEA) [14]).



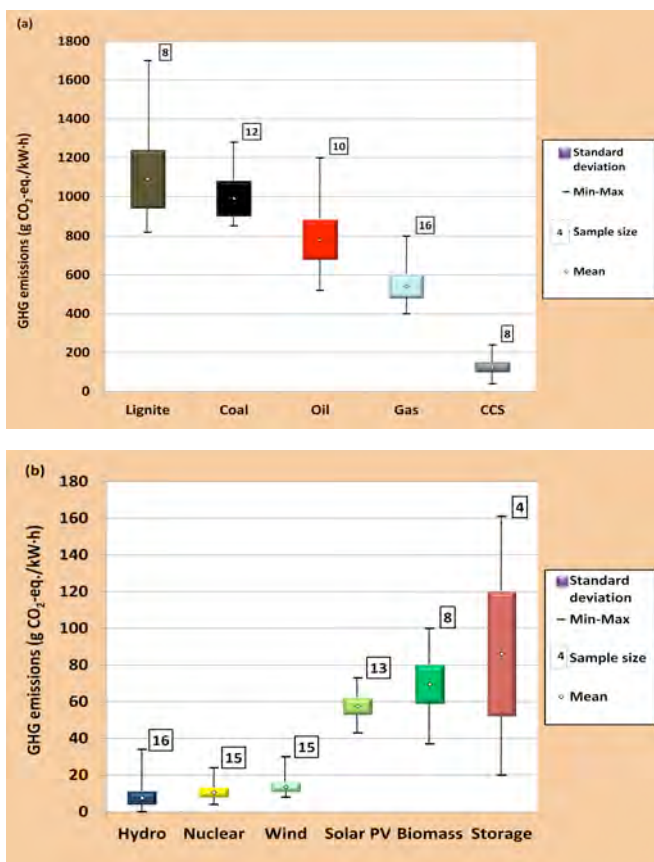
Nuclear power is a low carbon technology...

Many studies in recent years have estimated the life cycle GHG emissions from different power generation technologies.

Figure 3 shows that, on a life cycle basis, **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.** Coal based generation, even if equipped with CCS technology, is estimated to emit about one order of magnitude more GHGs per unit of electricity (note the different vertical scales in Fig. 3(a) and (b)).

GHG emissions from nuclear energy technologies will be even lower in the future owing to four important trends: (i) a shift from electricity intensive gaseous diffusion uranium enrichment technology to centrifuge or laser technologies that require much less electricity; (ii) the increased share of electricity (also for enrichment) that is based on low or non-carbon fuels; (iii) extended nuclear power plant lifetime (which means reduced emissions per kilowatt-hour associated with construction) and (iv) increased burnup (which means reduced emissions per kilowatt-hour associated with uranium mining and manufacturing fuel).

FIG. 3. Life cycle GHG emissions for selected power generation technologies: (a) fossil technologies; (b) non-fossil technologies [15].



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

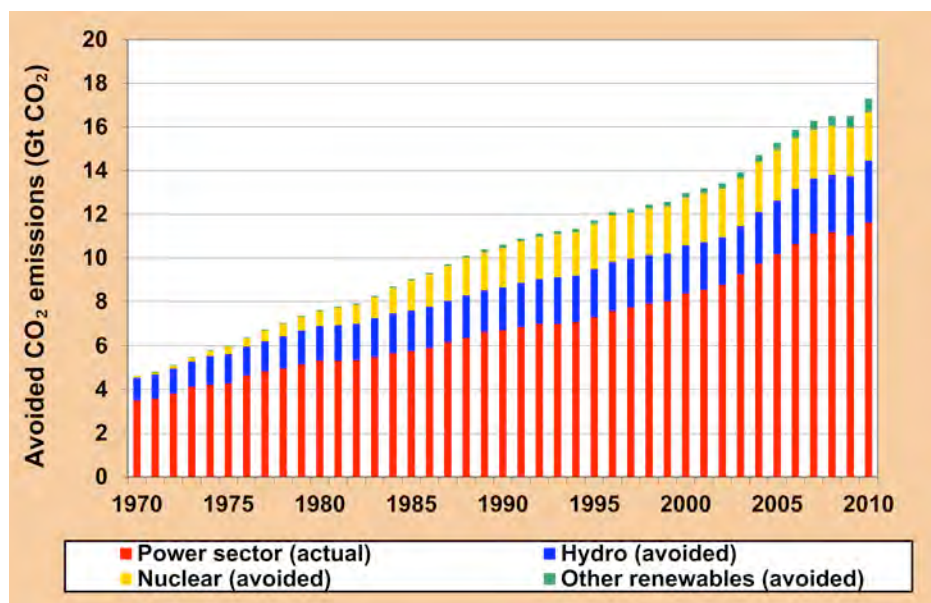
Over the past 50 years, the use of nuclear power has resulted in the avoidance of significant amounts of GHG emissions around the world. Globally, the amount of avoided emissions is comparable to that from hydropower.

Figure 4 shows the historical trends of CO₂ emissions from the global power sector and the amounts of emissions avoided by using hydropower, nuclear energy and other renewable electricity generation

technologies. The height of the red columns indicates the actual CO₂ emissions in any given year. The total height of each column shows what the emissions would have been without the three low carbon electricity sources. The blue, yellow and green segments of the bars show the emissions avoided by hydropower, nuclear power and renewables other than hydropower, respectively.

Figure 5 confirms these global trends by depicting the CO₂ intensity and the shares

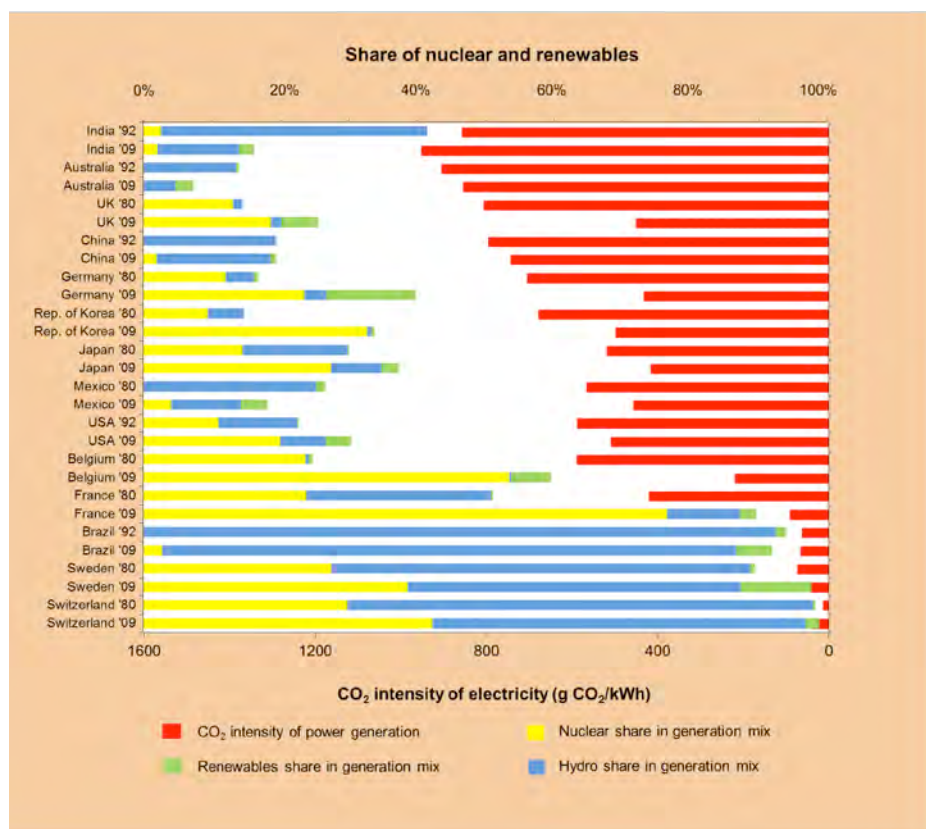
FIG. 4. Global CO₂ emissions from the electricity sector and emissions avoided by using three low carbon generation technologies. (Source: IAEA calculations based on Ref. [13].)



of non-fossil sources in power generation for selected countries. The top scale shows, from left to right, the relative contributions of nuclear, hydropower and other renewable (wind, solar, geothermal, etc.) technologies to the total amount of electricity generated in 1980 (or later years for some countries) and in 2009. The bottom scale measures, from right to left, the average amount of CO₂ emitted from generating 1 kW•h of electricity in the same year. The chart demonstrates

that countries with the lowest CO₂ intensity (less than 100 g CO₂/kW•h, below 20% of the world average) generate around 80% or more of their electricity from hydropower (Brazil), nuclear (France) or a combination of these two (Switzerland and Sweden). The chart also shows that expanding the share of nuclear power in the electricity mix contributed to the reduction of the CO₂ intensity of the power sector in several countries (e.g. Belgium, Germany, Republic of Korea, UK).

FIG. 5. Carbon dioxide intensity and the share of non-fossil sources in the electricity sector of selected countries (IAEA calculations based on IEA data [14]).



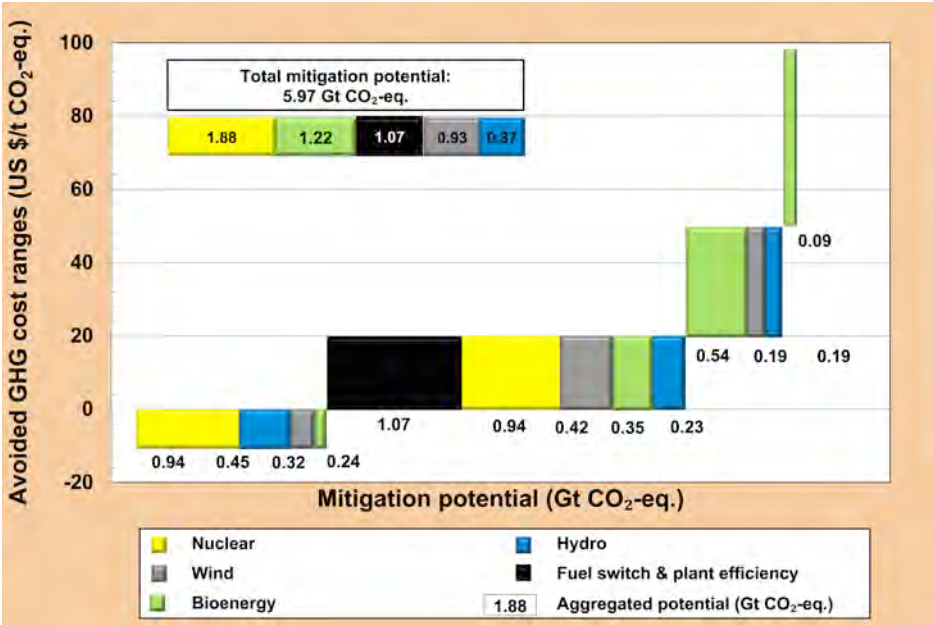
The IPCC estimates that nuclear power has the greatest and lowest cost GHG reduction potential in power generation

The IPCC [4] has estimated the mitigation potential of various electricity generating technologies. Figure 6 shows the results for low carbon power generation technologies with a mitigation potential of more than 0.5 Gt CO₂-eq. The figure shows the potential GHG emissions that can be avoided by 2030 by adopting the selected generation technologies. The width of each rectangle is the mitigation potential of that technology for the carbon cost range shown on the vertical axis. Each rectangle's width is shown below it. Thus, nuclear power (yellow rectangles) has a mitigation potential of 0.94 Gt CO₂-eq at negative carbon costs¹ plus another 0.94 Gt CO₂-eq for carbon costs up to \$20/t CO₂. The total for nuclear

power is 1.8 Gt CO₂-eq, as shown on the horizontal axis.

The figure indicates that nuclear power represents the greatest mitigation potential at the lowest average cost in the energy supply sector, essentially electricity generation. Hydropower offers the second cheapest mitigation potential but its size is the smallest of the five options. The mitigation potential offered by wind energy is spread across three cost ranges, yet more than one third of it can be utilized at negative cost. Bioenergy also has a significant total mitigation potential but less than half of it could be harvested at costs below \$20/t CO₂-eq by 2030.

FIG. 6. Mitigation potential in 2030 of selected electricity generation technologies in different cost ranges. (Source: Based on data in Table 4.19 of Ref. [4].)



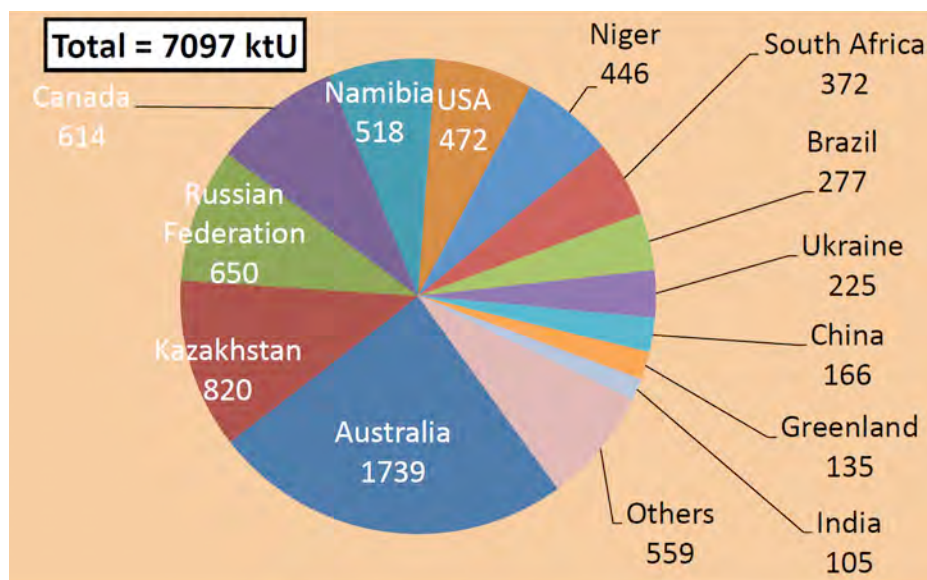
¹ In the IPCC report, mitigation options with net negative costs are defined as those options whose benefits such as reduced energy costs and reduced emissions of local/regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change.

Nuclear power contributes to energy supply security

The best way to strengthen a country's energy supply security is diversification: increasing the number and resilience of energy supply options. For many countries, introducing or expanding nuclear power would increase the diversity of energy and electricity supplies. In addition, the currently known and reported resources and reserves of the basic fuel, uranium, are found in a number of countries across six continents (Fig. 7). Moreover,

compared with fossil fuels, the small volume of nuclear fuel required to run a reactor makes it easier to establish strategic inventories. In practice, the trend over the years has been away from strategic stocks towards supply security based on diverse and well-functioning markets for uranium and fuel supply services. However, the option of relatively low cost strategic inventories remains available for countries that consider it important.

FIG. 7. The distribution of reported uranium resources (Kt U) in 2011. (Source: NEA and IAEA [16].)



Nuclear energy has applications beyond the power sector

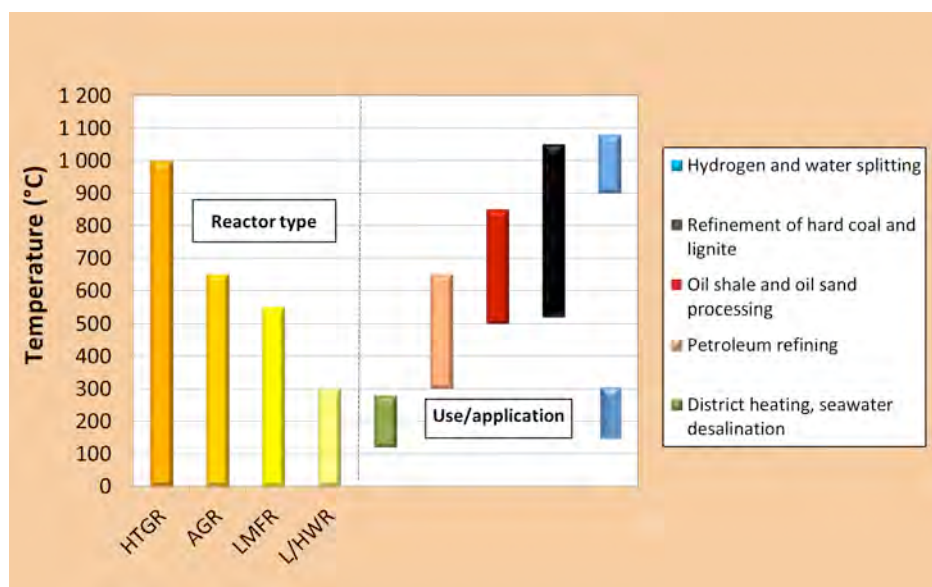
Nuclear energy is used in several non-electric applications, including seawater desalination and district heating. It has the potential for expanded use in desalination, in extracting non-conventional oil, in co-generation with coal and in hydrogen production for transport. The required temperature ranges and the corresponding reactor types are presented in Fig. 8.

Freshwater availability is a severe problem in many countries: 2.3 billion people currently live in water stressed regions, including 1.7 billion living in water scarce areas. Adding to other impacts 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. Currently, around 40 million m³/d of water are distilled in some 15 000 plants, most of which are located in the Middle East and North Africa.

Nuclear desalination is already in operation in several countries and can make use of excess power beyond that required for baseload operation. Most desalination plants today use fossil fuels as their primary energy source, thus contributing to GHG emissions because the process is very energy intensive. Two nuclear desalination plants operate in India, a 6300 m³/d nuclear desalination demonstration plant coupled with a power station, and a low

FIG. 8. Possible uses of nuclear energy beyond power generation. (Source: IAEA [18]) **Note:** HTGR — high temperature gas cooled reactor; AGR — advanced gas cooled reactor; LMFR — liquid metal cooled fast reactor; L/HWR — light/heavy water reactor.



temperature desalination plant (the first of its kind) coupled with a research reactor. China started operation of its first seawater desalination system associated with a nuclear power plant in June 2010. It can provide 10080 m³/d of fresh water. In Japan, several desalination facilities linked to power reactors each provide 1000–3000 m³/day of fresh water for the reactors' own cooling systems. Looking to the future, 20% of the electrical capacity of a 600 MW(e) nuclear reactor operating in co-generation mode could produce 500 000 m³/d of potable water [17].

Nuclear energy can help extract high viscosity oil such as that in the oil sands of Canada's Athabasca region. Currently, substantial CO₂ is released due to energy use and hydrogen production for oil extraction and refining from these oil sands, since the present major source of the energy used is natural gas. Using nuclear reactors to supply energy and produce hydrogen would significantly reduce the carbon emissions resulting from oil recovery from the oil sands.

Nuclear energy is not simply an alternative to coal as an energy source, but **can also help reduce carbon emissions from coal burning**. Given the world's huge coal resources, the gasification of coal

for integrated gasification combined cycle combustion might be an important GHG emission mitigation technology. Nuclear heat from high temperature gas cooled reactors can be used for the gasification of coal along with the generation of electricity, which would reduce carbon emissions significantly [19].

Nuclear energy can potentially also be used to generate hydrogen for direct use by energy consumers. As hydrogen powered fuel cells can be used to power transport in place of internal combustion engines, they could help reduce growth in both fossil fuel consumption and associated GHG emissions.

There are different processes for producing hydrogen. Thermochemical water splitting (water plus heat yields hydrogen and oxygen) is highly efficient and more economical than electrolysis of water with electricity [20]. Thermochemical water splitting requires the high temperatures (750–1000°C) that some nuclear reactors can provide. As with nuclear desalination, nuclear hydrogen production would allow the use of excess nuclear power beyond that required to serve baseload demand.

Nuclear power has non-climatic environmental benefits

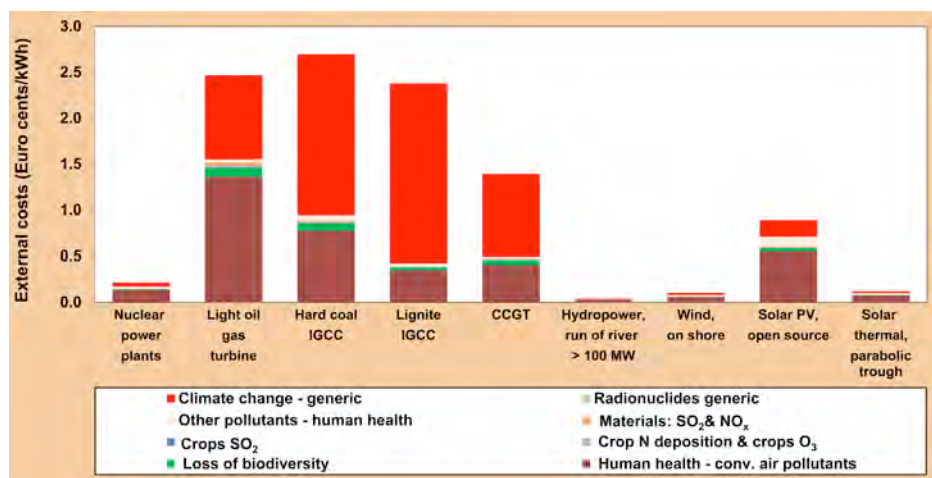
In addition to helping mitigate climate change, the use of nuclear power plants can also reduce emissions of air pollutants with negative health and environmental impacts other than GHGs at local and regional scales.

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 two million premature deaths worldwide each year [21]. Air pollution also contributes to health disorders from respiratory infections, heart disease and lung cancer. In many cities in developing countries, the level of particulate matter in the air exceeds $70 \mu\text{g}/\text{m}^3$, and by

reducing it to $20 \mu\text{g}/\text{m}^3$ (the air pollution concentration level recommended by WHO), air quality related deaths could be cut by around 15%.

At the regional scale, air pollutants travelling long distances cause acid rain. Acid rain disturbs ecosystems, leading to adverse impacts on freshwater fisheries and on natural vegetation and crops. Acidification of forest ecosystems can lead to forest degradation and dieback. Acid rain also damages certain building materials and historic and cultural monuments. It is caused by sulphur and nitrogen compounds, and fossil fuel power plants, particularly coal power plants, are the primary emitters of the precursors of these compounds. Sulphate and nitrate, transported across national borders, also contribute to

FIG. 9. Estimated average EU external costs for selected electricity generation technologies in 2005–2010 (Source: Ref. [23]).



the occurrence of haze, strongly limiting visibility and reducing sunlight, and possibly changing the atmospheric and surface temperatures as well as the hydrological cycle [22]. Technological solutions exist to reduce these emissions, but at a cost.

Environmental and health damages due to electricity production but which are not reflected in the price of electricity are called external costs. The latest systematic analysis of such external cost monetized damages due to (1) climate change; (2) the impacts on human health, biodiversity loss, crops, and materials of familiar air pollutants such as ammonia (NH_3), nitrogen oxides (NO_x),

sulphur dioxide (SO_2) and particulates (3) health impacts of heavy metals and (4) health impacts of radionuclides [23]. Figure 9 shows the estimated average monetized external costs in the EU over the period 2005–2010 for a range of electricity generation technologies. The estimated external costs cover the entire life cycle, i.e. construction and decommissioning as well as the fuel cycle.

Fossil based electricity generation has considerably higher external costs than nuclear power and renewable technologies. Through safety and environmental regulations, the nuclear industry has already internalized the bulk of its potential external costs.

Nuclear power is economically competitive

The estimated range of electricity generating costs for new nuclear power plants overlaps with the ranges estimated for other power generating sources. The investment choice, whether by a government or private investor, will depend on many factors, but the overlap in cost estimates means that in some investment situations nuclear power will be the least-cost option and in other investment situations it will not be. The complexity and capital cost of nuclear power still make it a less frequent investment choice than gas and coal fired power stations, although in recent years nuclear power has been chosen more often. Currently, 63 new reactors are under construction, about twice as many as in 2001. Through 2010, the number of new reactors on which construction started in each year grew for seven years in a row. The accident at the Fukushima–Daiichi Nuclear Power Plant led to some delays in planned nuclear construction starts for 2011, resulting in only 4 starts, down from 16 in 2010. This section addresses distinctive features of nuclear power's costs relative to those of alternatives.

Nuclear power plants have a 'front loaded' cost structure, a feature they share with most renewables; that is, they are relatively expensive to build but relatively inexpensive to operate. Moreover, the low share of uranium costs in total generating costs means that significant volatility in uranium costs results in only minor volatility in generating costs. Thus, nuclear power plants currently in operation are generally a competitive and profitable source of electricity.

For new construction, however, the economic competitiveness of nuclear power is more variable. Firstly, it depends on the alternatives available. Some countries are rich in alternative energy resources, others less so. Secondly, it depends on the overall electricity demand in a country and how fast it is growing. Thirdly, 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 consider the longer term, particularly in a regulated market that ensures attractive returns. Private investments in liberalized markets will also depend on the extent to which external costs and benefits, such as 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 and political support for nuclear power. All these factors vary between countries.

In the Republic of Korea, for example, the relatively high cost of alternative electricity sources benefits nuclear power's competitiveness. In India and China, rapidly growing energy needs encourage the development of all energy options. In the USA, the 2005 Energy Policy Act strengthened the business case for nuclear power through Government coverage of the costs of potential licensing delays, loan guarantees and a production tax credit for up to 6000 MW(e) of advanced nuclear power capacity.

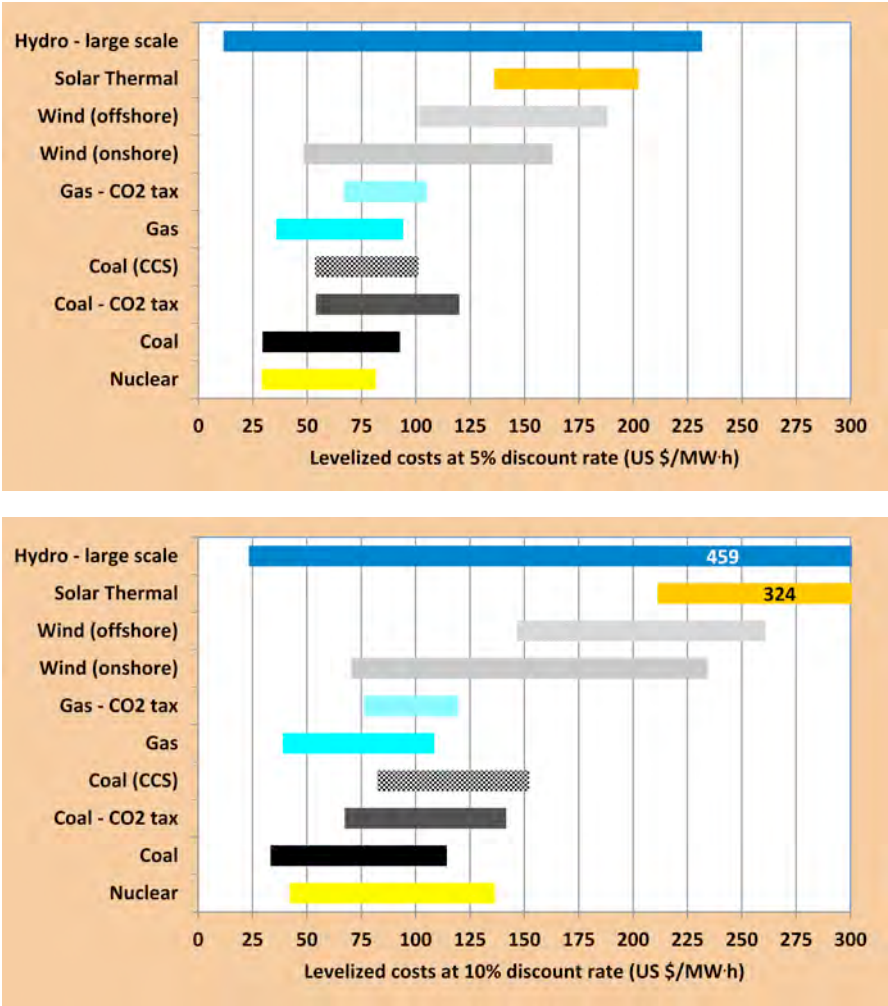
The latest study by the IEA and NEA on the projected costs of electricity generation includes almost 200 power plants in 17 OECD and 4 non-OECD countries [14]. It presents levelized costs of electricity (LCOE) calculated using a common method and using data supplied by countries, companies and industrial organizations. Figure 10 shows the results for six major electricity technologies using two discount rates: 5% and 10%. The former is more relevant for government investments. The latter is more typical of investments by the private sector. Higher discount rates make technologies with large upfront investment costs relatively more expensive. The basic message of the figure is that **the LCOE of the three main current generation technologies (coal, gas and nuclear) largely overlap within**

the \$50–100 per MW·h range. According to current expectations, the incremental costs of revised safety measures after the Fukushima–Daiichi accident will not increase the LCOE of nuclear power significantly. The choice among these technologies in any particular investment decision will be determined according to which of them is more favourable, given the prevailing market, geographical and natural resource conditions,

technological capabilities and sociopolitical preferences.

Figure 10 also shows the impact of increasing CO₂ costs. It is estimated that at a CO₂ price of about \$10/t, the median cost of nuclear electricity becomes lower than that of coal based power, and the gap between the median costs of nuclear and gas based electricity reaches 20% at a CO₂ cost of \$30/t.

FIG. 10. Ranges of LCOE associated with new construction with and without a \$30/t CO₂ tax for 5% (top panel) and 10% discount rates (bottom panel). (Source: Based on IEA and NEA data [14].)



Nuclear investment costs are increasing, but ...

Nuclear power plants are more capital intensive than other large scale power generation plants. The total investment cost typically represents some 60% of the total generation cost of nuclear electricity.

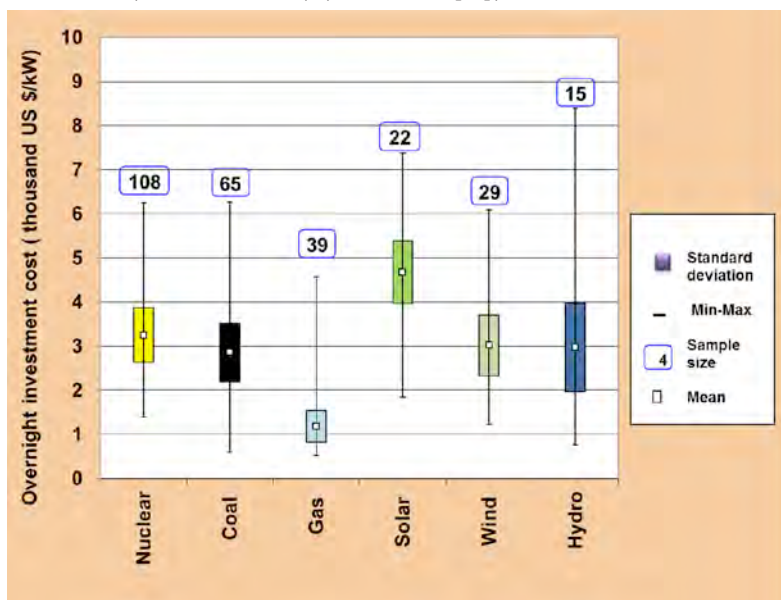
Recent announcements by utilities and power companies show that estimated overnight costs for new nuclear power projects range between \$1400 and \$6300/kW — with most well above \$3000/kW. Even within the same country and for similar technologies, costs can vary due to site characteristics, plant size, localization rate and other factors. The wide range and size of the investments is very challenging, especially for countries considering their first nuclear power plant. For them, a good understanding of the true total investment cost of the project is especially important.

Overnight cost estimates reported vary substantially across countries owing to differences in country specific financial, technical and regulatory boundary conditions. The low

estimates were those reported from Asia, specifically the estimates from China and the Republic of Korea, countries with recent experience in building new reactors, with cost estimates as low as \$1600–1500/kW. When financing costs are low (5%), more capital intensive, low carbon technologies such as nuclear are more competitive than coal and gas fired plants (even without carbon dioxide capture), and, on a longer term basis, nuclear energy delivers stable and low cost electricity [14]. In a more recent study, the Australian Bureau of Resources and Energy Economics found that even at higher financing costs (10%), nuclear power tends to remain competitive with lower cost renewable technologies out to 2050 [24].

Figure 11 presents ranges of the overnight construction costs for six main power technologies. A significant number of the reported nuclear projects are in a relatively narrow range (within one standard deviation of the mean) compared with renewable power technologies.

FIG. 11. Ranges for overnight costs estimates for the main electricity generation technologies, 2008–2010 (in 2008 US dollars). (Source: IAEA [25].)



... financing nuclear power investments is feasible

The traditional methods of government financing (i.e. using State budgets) and corporate financing (using corporate balance sheets) still dominate the industry but the trend towards governments relying more on industry and private sector participation to initiate new innovative financial structures continues. However, initial government support is central to the successful financing of new nuclear power projects under all financing options.

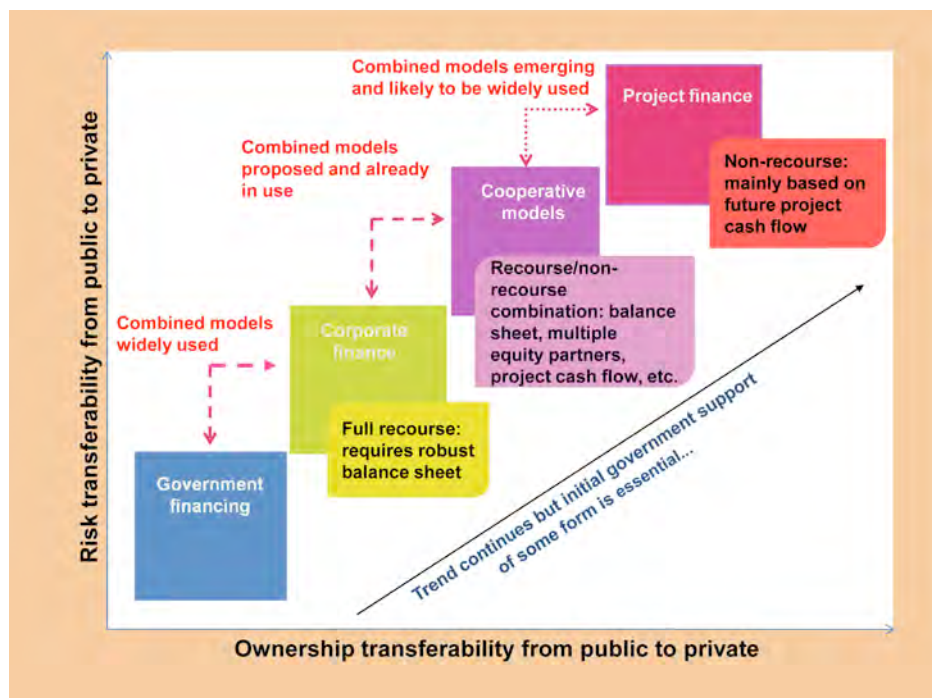
The availability of finance for new nuclear power plants will depend on government support in both mature and emerging countries. By taking on part of the construction risk by awarding loan guarantees, governments can lower the cost of finance. Other salient measures that can assist the nuclear industry are the level and certainty of subsidies and incentives by governments, such

as uniformly applied carbon costs and green credits.

The current investment climate has been impacted by the global financial crisis of 2008 and the Fukushima–Daiichi accident. In response to the financial crisis, regulations to avoid similar future crises, such as increased capital requirements for banks, which are intended to protect investors, may also add to project financing costs and impact market liquidity.

A new financing model is also emerging that combines project finance with a cooperative approach, including an increased number of equity partners to share the financing risk (see Fig. 12). Pure project finance is still not available for nuclear projects. To explore opportunities in new foreign markets, some corporations are creating new business units

FIG. 12. Financing models.



and plan to open credit lines to finance new nuclear power projects or engage in build-own-operate schemes. Others are forming teams to provide a full complement of services, design, engineering, procurement, construction and operation. Some utilities are strengthening their balance sheets through mergers. To encourage private investment in nuclear power in countries with liberalized electricity markets, investors are exploring mechanisms, such as 'contracts for difference', and governments are proposing legislation, both of which are designed to increase price predictability.

Many countries with nuclear power have reaffirmed their commitment to expanding

nuclear power while incorporating all the lessons to be learned from the Fukushima–Daiichi accident. In countries considering the introduction of nuclear power, interest also remains high. Of the countries without nuclear power that, before the accident, had strongly indicated their intentions to proceed with nuclear power programmes, a few have cancelled or revised their plans, but most have continued their pursuit of introducing nuclear power into their energy mixes. The factors that had contributed to increasing interest in nuclear power before the accident largely remain the same. These factors include increasing global demand for energy, concerns about climate change, volatile fossil fuel prices and security of energy supply.

Construction capacity will expand as needed

Given that nuclear power is competitive and financing is feasible, the demand for new reactors over the last few years — led by China, India and the Russian Federation (all three have reaffirmed plans for expansion after the Fukushima–Daiichi accident) — has already led to an expansion in global reactor production capacity. New nuclear plant construction capacity is being built in China, the Czech Republic, France, Japan, the Republic of Korea, and the Russian Federation, with planned new capacity in the UK, India, and China (World Nuclear Energy Association 2012). **The specialized manufacturing capacity required to build new reactors in the near and long terms is expected to grow in line with the projected growth of nuclear power described below.** The production of most components can be ramped up within a few years and forging capacity for large reactors in approximately five years [26].

Concerns have been expressed in a number of countries about possible shortages of people with the skills needed by an expanding nuclear power industry. Such concerns have prompted initiatives by governments and industry to attract students and expand education and training in nuclear related fields. If the higher projection for nuclear power described below is realized, these successes will have to be replicated several times over. This represents a significant but not unprecedented difficulty. The high projection presented below, for example, would require bringing on-line an average of 22 new reactors each year, compared with the annual average of 16 new reactors during the 1970s. Moreover, even in the high projection, nuclear power's share of global electricity generation remains nearly constant through 2050, meaning that other electricity sources — and their staffing needs — would be growing at the same rate as nuclear power. The challenge faced by nuclear power is not exceptional.

Sufficient uranium is available to fuel increasing nuclear power generation

Every two years, the NEA and the IAEA publish updated estimates of global uranium resources. The latest update, published in 2012, estimates identified conventional uranium resources, recoverable at a cost of less than \$130/kg U, at 5.3 million tonnes of uranium (Mt U). **At the estimated 2010 rate of consumption, these resources would be sufficient for more than 100 years.** This compares favourably with reserves of 30–50 years for other commodities (e.g. copper, zinc, oil and natural gas). For reference, the spot price for uranium on 26 October 2012 was \$98/kg U, down from a peak of about \$190/kg U before the Fukushima–Daiichi accident.

In addition, there are an estimated 1.8 Mt U of identified conventional resources recoverable at costs of between \$130/kg U and \$260/kg U, bringing total identified resources recoverable at a cost of less than \$260/kg U to 7.1 Mt U.

The updated estimate for total undiscovered resources was more than 7.6 Mt U. This included both resources that are expected to occur either in or near known deposits at costs of less than \$260/kg U, and more speculative resources that are thought to exist in geologically favourable, yet unexplored areas.

Unconventional uranium resources and thorium further expand the resource base. Unconventional resources include uranium in seawater and resources from which uranium is only recoverable as a minor by-product. Very few countries currently report unconventional resources. Past estimates of

potentially recoverable uranium associated with phosphates, non-ferrous ores, carbonate, black schist and lignite are of the order of 8 Mt U. Worldwide resources of thorium have been estimated to be about 6 Mt. Although thorium has been used as fuel on a demonstration basis, further work is still needed before it can be considered on an equal basis with uranium.

Reprocessing of spent nuclear fuel, which still contains some 95% of its original energy, can further extend the lifetime of global uranium resources. Annual discharges of spent fuel from the world's reactors total about 10 500 t of heavy metal 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 waste and is stored pending disposal.

Advanced reactor designs, such as fast breeder reactors, and associated fuel cycles could utilize uranium even more efficiently than do current reactors and fuel cycles [27] and extend the lifetime of uranium resources by a factor of 60 to 70. Although there are not yet any fast breeder reactors using reprocessed plutonium operating commercially, more than 200 reactor-years of experience have been accumulated in industry scale breeder reactors in France and the Russian Federation. This provides a good basis for designing and building commercial fast breeder reactors in the future.

In summary, uranium resources per se do not constrain an expansion of nuclear power.

Learning and applying the lessons from the Fukushima–Daiichi accident

In 2012, discussions of nuclear power plant safety focused largely on identifying and applying the lessons that could be learned from the March 2011 accident at the Fukushima–Daiichi Nuclear Power Plant. In the wake of the accident, a Ministerial Conference on Nuclear Safety in June 2011 asked the IAEA to prepare an Action Plan on Nuclear Safety. The resultant plan was adopted by the IAEA's Board of Governors and subsequently unanimously endorsed by the IAEA General Conference in September 2011. It defines 12 main actions:

- Undertake assessments of the safety vulnerabilities of nuclear power plants in the light of lessons learned to date from the accident.
- Incorporate the Fukushima–Daiichi accident's lessons into IAEA peer reviews, apply these more broadly and make the results more transparent.
- Review and strengthen emergency preparedness and response arrangements and capabilities.
- Regularly review (e.g. through IAEA Integrated Regulatory Review Service missions) national regulatory bodies, particularly their independence and resources and strengthen them as needed.
- Regularly review (e.g. through IAEA Operational Safety Review Team missions) and strengthen as needed, the management systems, safety culture, human resources management, and scientific and technical capacities in operating organizations.
- Review and strengthen IAEA Safety Standards and improve their implementation.
- Improve the effectiveness of the international legal framework and work towards a global nuclear liability regime that addresses the concerns of all States that might be affected by a nuclear accident.
- Help countries planning to start a nuclear power programme to create an appropriate nuclear infrastructure based on IAEA Safety Standards.
- Strengthen national capacity building programmes, and incorporate lessons from the Fukushima–Daiichi accident, to ensure sufficient human resources for nuclear power plant safety.
- Cooperate on monitoring, decontamination and remediation, especially for the removal of damaged nuclear fuel and the management and disposal of radioactive waste.
- Improve the transparency and effectiveness of communication and the dissemination of information, including through a fully transparent comprehensive assessment of the accident.
- Undertake research and development in areas highlighted by the accident, such as extreme natural hazards, management of severe accidents, station blackout, loss of heat sink, spent fuel accidents and post-accident monitoring systems in extreme environments.

The first annual report on progress on the Action Plan was submitted to the IAEA Board of Governors and the General Conference in September 2012. Some summary highlights summarized below.

As part of identifying and sharing lessons learned, the IAEA had convened international experts' meetings (IEMs) on:

- Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima–Daiichi Nuclear Power Plant;
- Enhancing Transparency and Communication Effectiveness in the Event of a Nuclear or Radiological Emergency;
- Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima–Daiichi Nuclear Power Plant.

An IEM on Decommissioning and Remediation after a Nuclear Accident is scheduled for January 2013.

To increase transparency, the IAEA has listed on its web site all the facilities and countries where it had completed peer reviews

focused on safety or where such reviews were planned. It posted the results of all completed reviews under its Integrated Regulatory Review Service and summary results of other peer reviews. It adjusted all its peer review services as needed to incorporate lessons learned from the Fukushima–Daichi accident.

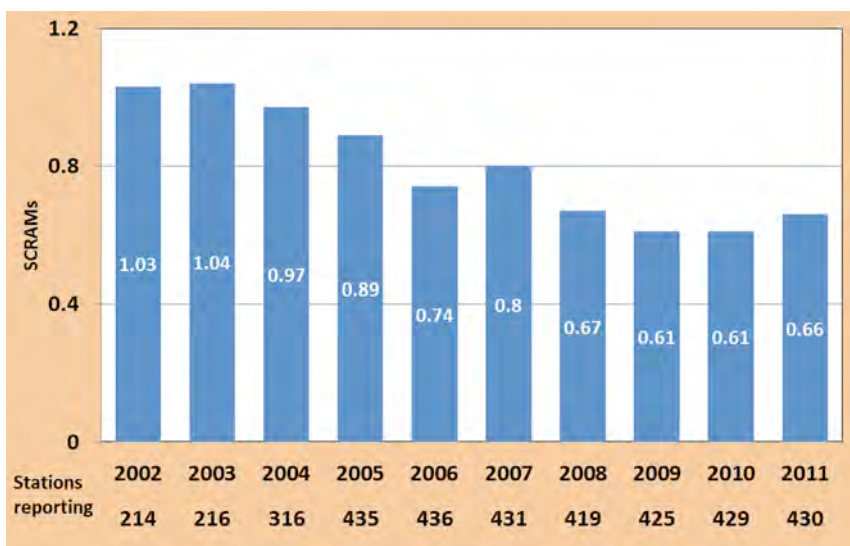
It has upgraded its own emergency response plan to provide better information during an emergency. To strengthen national emergency preparedness and response, it organized 21 national, regional and interregional training events in the first half of 2012. More than 15 more were planned for the second half of the year.

The IAEA began revising its Safety Standards to incorporate lessons from the accident and had already revised its guidance for countries introducing nuclear power. It published an Operations Manual for Incident and Emergency Communication to improve the implementation of the Early Notification and Assistance Conventions and made available a protected web-based Unified System for Information Exchange in Incidents and Emergencies. It also published ‘Communication with the Public in a Nuclear or Radiological Emergency’ with guidance for those responsible for keeping the public and media informed during an emergency.

The accident had an impact on worldwide prospects for nuclear power. Projections made in 2012 for global nuclear power capacity in 2030 are 8–16% lower than projections made before the accident [28]. But even in these lower projections, nuclear power is projected to grow by 25%–100% by 2030. Thus, globally, the accident is expected to delay growth in nuclear power but not to reverse it. In many countries that had been considering the introduction of nuclear power, interest also remains strong. In 2012, the United Arab Emirates became the first country in 22 years to begin the construction of a first nuclear power plant.

Operationally, nuclear power plant safety around the world remains high, as indicated by safety indicators collected by the IAEA and the World Association of Nuclear Operators. Figure 13 shows the total number of unplanned scrams, or shutdowns, per 7000 hours of critical power reactor operation. This is commonly used as an indicator of success in improving plant safety. As shown in Fig. 13, steady improvements, although not as dramatic as those attained in the 1990s, have been achieved in recent years. The increase from 2010 to 2011 is related to the high number of scrams triggered by the March 2011 earthquake in Japan.

FIG. 13. Total number of unplanned scrams, including both automatic and manual scrams, that occur per 7000 h of critical power reactor operation. Source: IAEA [28].



Putting radiation risks in context

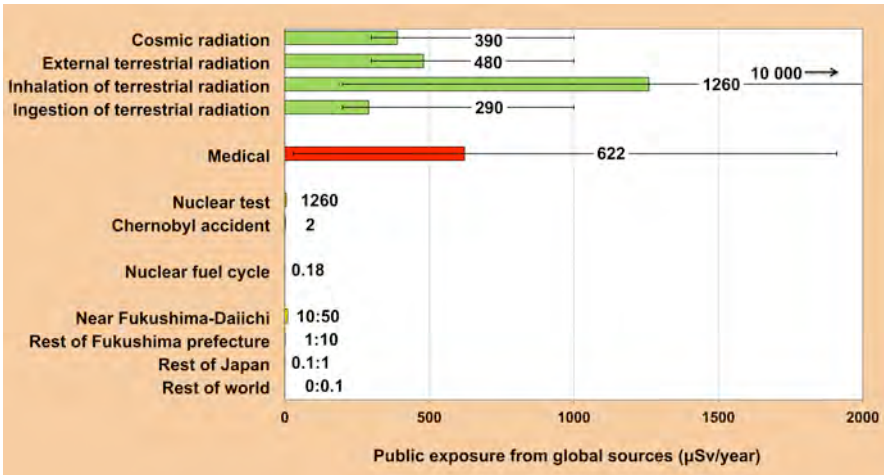
The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) periodically carries out assessments of exposures of the public and workers to various sources of radiation, including natural sources, enhanced sources of naturally occurring radioactive material, manufactured sources for peaceful purposes such as nuclear power production and medical use of radiation, and manufactured sources for military purposes including nuclear testing. According to UNSCEAR's latest report [30], the average worldwide public exposure from globally dispersed radionuclides from nuclear fuel cycle installations is estimated to be 0.18 μSv per person per year of operation. Average annual exposure to local populations is 25 μSv for mining and milling (within 100 km of the site), 0.2 μSv for uranium enrichment and fuel fabrication, 0.1 μSv for nuclear power reactors and 2 μSv for fuel reprocessing (within 50 km of the site).

The World Health Organization released a report on 23 May 2012 assessing radiation exposure for the first year following the Fukushima–Daiichi accident. In the two areas with the highest impact within Fukushima prefecture, the dose is between 10 and 50 μSv . Outside of these two areas, but within Fukushima prefecture, the dose is estimated to be between 1 and 10 μSv . Estimates

for exposure in the rest of Japan are between 0.1 and 1 μSv and for the rest of the world are below 0.01 μSv [29].

To put these numbers into context, Figure 14 shows the levels of exposure that people are subjected to. Radiation exposure levels stemming from uranium mining, refining and nuclear power generation facilities are significantly lower than naturally occurring radiation exposure levels. In the case of a major nuclear accident, radioactive contamination of the environment close to the site can be severe, but exposure levels within areas nearest Fukushima–Daiichi are significantly below natural background radiation levels. The global averages are shown in the coloured bars, and regional variations are indicated with error bars. Major sources of external exposure are cosmic rays from outer space and natural terrestrial radionuclides existing in the Earth's soil and in building materials such as granite and marble. The level of exposure to cosmic rays depends primarily on latitude and altitude. Exposure also arises from the intake of radionuclides in the Earth's soil by inhalation (mainly radon) and ingestion (in the form of food and drinking water). Altogether, worldwide exposure to natural radiation sources for an average individual is 2420 μSv per year, with a typical range of between 1000 and 13 000 μSv per year [30].

FIG. 14. Public exposure to radiation from global sources (average shown by a bar, and typical range shown by a line). (Source: UNSCEAR [30] and WHO [29].)



Making progress on waste management and disposal solutions

Another concern surrounding nuclear energy is radioactive waste, which can create hazards for humans and the environment lasting for centuries — or millennia. **The nuclear industry has provided for the safe temporary surface storage of spent fuel for more than 50 years.** Over the past two decades, major advances have been made towards the first operating final disposal facilities.

During the nuclear fission process in the reactor, the fuel becomes intensely radioactive due to the formation of new radionuclides, known as fission products. After removal from the reactor, spent fuel is temporarily stored under water while the fission products decay and both radiation levels and heat generation decrease.

The disposal of radioactive waste in geological media is considered to be a safe method for isolating these substances from the hydrosphere, the atmosphere and the biosphere. The fundamental principles involved in geological disposal are well understood [31, 32]. Geological repositories are designed to be passively safe, based on multiple engineered and natural barriers, against any release of radionuclides. They are sited in suitable rock formations chosen principally for their long term stability and effectiveness as natural barriers [33].

Programmes to dispose of spent fuel are well advanced in several countries [34]. In Sweden in March 2011, with broad public support, the Swedish Nuclear Fuel and Waste Management Company (SKB) submitted its application for a final spent

fuel geological repository to be located in Östhammar. Construction should start in 2015 and disposal operations are expected to start in 2025. At the Olkiluoto site in Finland, the Onkalo access tunnel was excavated, by the end of 2010, to a length of 4570 m and its final disposal depth of 434 m. Initially, Onkalo will function as an underground rock characterization facility to ensure the suitability of the site. Then the access tunnel and other underground structures will be used for disposal. The construction licence application is expected to be submitted by the end of 2012 and the operating licence process is expected to be completed by around 2020.

An issue associated with final repositories is that of retrievability; whether it should be possible to retrieve waste from a repository if required and, if so, for how long. On the one hand, future generations may consider the buried waste to be a valuable resource. On the other, permanent closure might increase the long term security of the repository. Relevant policies in most countries require retrievability for at least 100 years.

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 political reasons require the establishment of final disposal facilities.

Preventing the proliferation of nuclear weapons

Nuclear power must not only be safe but must also be used solely for peaceful purposes. Unlike other energy forms, nuclear energy was first harnessed for weapons purposes. The non-destructive applications of nuclear energy, such as civilian nuclear power generation, only followed afterwards. The IAEA was established in 1957 to help States reconcile the dual nature of the atom, so that nuclear energy could be put squarely in the service of peace and development. The IAEA Statute directed the IAEA to “enlarge the contribution of atomic energy to peace, health and prosperity throughout the world” and that “...assistance provided by it ...is not used in such a way as to further any military purpose”.

Over the course of several decades, the international community has put in place a number of international political and legal mechanisms to help stem the spread of nuclear weapons. They include the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and regional nuclear weapon free zone treaties, export controls, nuclear security measures, and importantly, the safeguards system of the IAEA. **The purpose of the safeguards system is to provide credible assurances to the international community that nuclear material and other specified items are not diverted from peaceful nuclear activities, and, by the risk of early detection, to deter proliferation.**

States accept the application of safeguards measures through the conclusion of safeguards agreements. Some 180 States have safeguards agreements with the IAEA. Although there are various types of safeguards agreement, the majority of States have undertaken to place *all* of their nuclear material and activities under safeguards. Article III of the NPT requires each

non-nuclear-weapon State to conclude an agreement with the IAEA to enable the IAEA to verify the fulfilment of the State's obligation not to develop, manufacture or otherwise acquire nuclear weapons or other nuclear explosive devices. Under such ‘comprehensive safeguards agreements’, a State commits to provide information on its nuclear material and activities, and to allow inspections.

Over time, and in response to new challenges, the safeguards system has been strengthened. The IAEA's experience in the early 1990s in Iraq and in the Democratic People's Republic of Korea led to important strengthening measures, including the adoption of the Model Additional Protocol, which provides the IAEA with important supplementary tools that provide broader access to information and locations. To date, some 118 States have brought such additional protocols into force.

The IAEA's inspection activities are supported by advanced technology and techniques. It takes special expertise, equipment and infrastructure to carry out the IAEA's verification activities. The IAEA designs customized safeguards approaches for individual States and uses dedicated equipment for carrying out verification activities at different stages of the nuclear fuel cycle. When inspecting nuclear installations in the field, safeguards inspectors use specialized equipment to carry out their work. To help detect possible undeclared nuclear material and activities, IAEA inspectors take environmental samples in the field which are then analysed at the IAEA Safeguards Analytical Laboratories in Austria and by the IAEA's global Network of Analytical Laboratories. The IAEA constantly monitors innovative technologies that enable it to carry out its verification activities, not only more effectively but also more efficiently.

The IAEA also participates in international efforts to make future nuclear technologies more proliferation resistant to begin with. The final product of the IAEA's safeguards implementation activities are the so-called 'safeguards conclusions', which are published annually in the IAEA's Safeguards Implementation Report [35]. The report includes a yearly safeguards statement for each State with a safeguards agreement in force.

The IAEA plays an instrumental verification role, providing assurances to, and on behalf of, States that nuclear non-proliferation commitments are being respected. A resilient safeguards system that provides credible assurances to the international community is the ultimate stamp of confidence that enables the promotion of the peaceful use of nuclear energy.

Nuclear power is projected to continue its steady growth through 2030

The IAEA publishes annually two updated projections for the world's nuclear power generating capacity: a low projection and a high projection. In the updated low projection, the world's installed nuclear power capacity grows from 369 GW(e) today to 456 GW(e) by 2030, down 9% from last year's projection. In the updated high projection, it grows to 740 GW(e) by 2030, down by less than 1% from last year. Most of the growth will occur in countries that already have operating nuclear power plants.

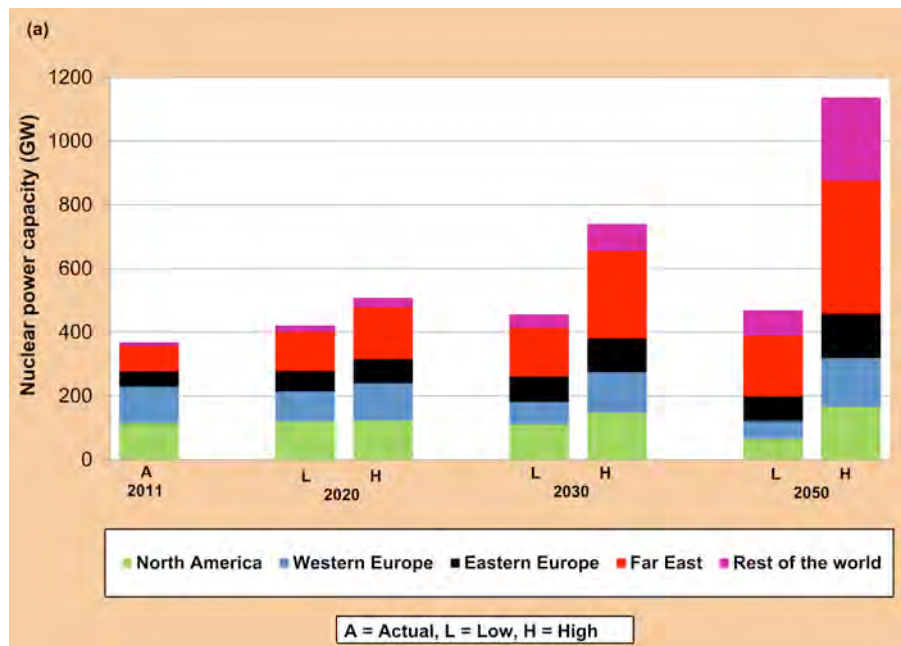
Projected growth is greatest in the Far East (Fig. 15). From 80 GW(e) at the end of 2011, capacity grows to 153 GW(e) by 2030 in the low projection and to 274 GW(e) in the high. The low projections are lower than last year's by 27 GW(e), but the high projections are 19 GW(e) higher than last year's projections.

The low projection assumes current trends continue with few changes in policies affecting nuclear power, although it does not necessarily assume that all national targets for nuclear power will be achieved. The projection is "conservative but plausible."

The high projection assumes that the current financial and economic crises will be overcome relatively soon and past rates of economic growth and electricity demand would resume, notably in the Far East. It also assumes stringent global policies to mitigate climate change.

The low and high projections are developed by experts from around the world who are assembled by the IAEA each spring. They consider all the operating reactors, possible licence renewals, planned shutdowns and plausible construction projects

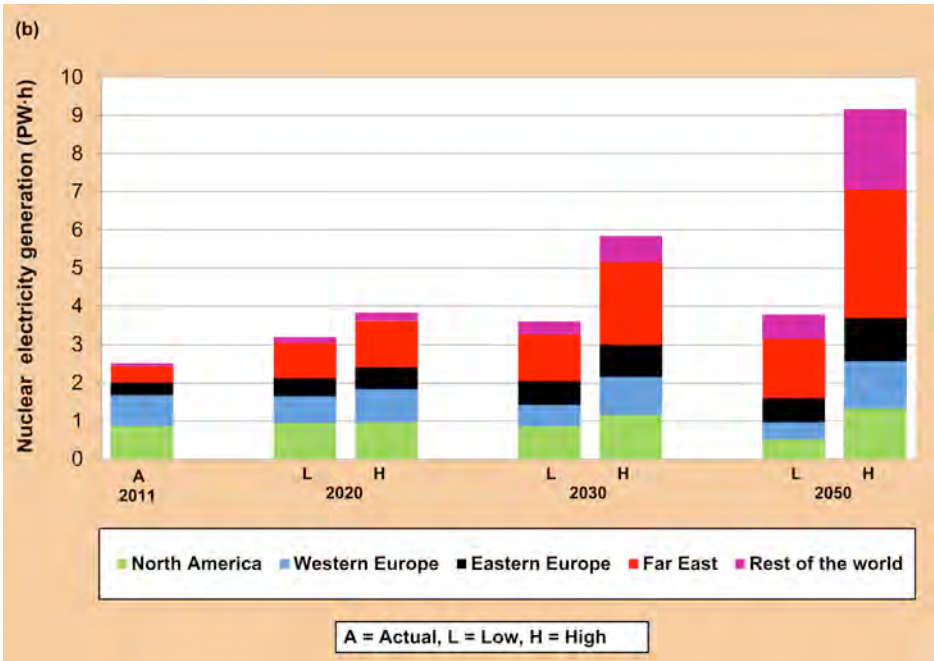
FIG. 15. Prospects for nuclear power in major world regions: (a) estimates of installed nuclear capacity; (b) estimates of nuclear electricity generation. (Source: IAEA [36].)



foreseen for the next several decades. They build the projections project by project by assessing the plausibility of each in the light of, firstly, the low projection's assumptions and, second, the high projection's assumptions.

Since the Fukushima–Daiichi accident, a number of countries have announced reviews of

their programmes; some took steps to phase out nuclear power entirely, whereas others re-emphasized their expansion plans. The continued growth in both the low and high projections suggests that the factors, listed above in the section on Finance, that contributed to increasing interest in nuclear power before the Fukushima–Daiichi accident have not changed.



Fast reactors in a closed fuel cycle can use uranium more efficiently

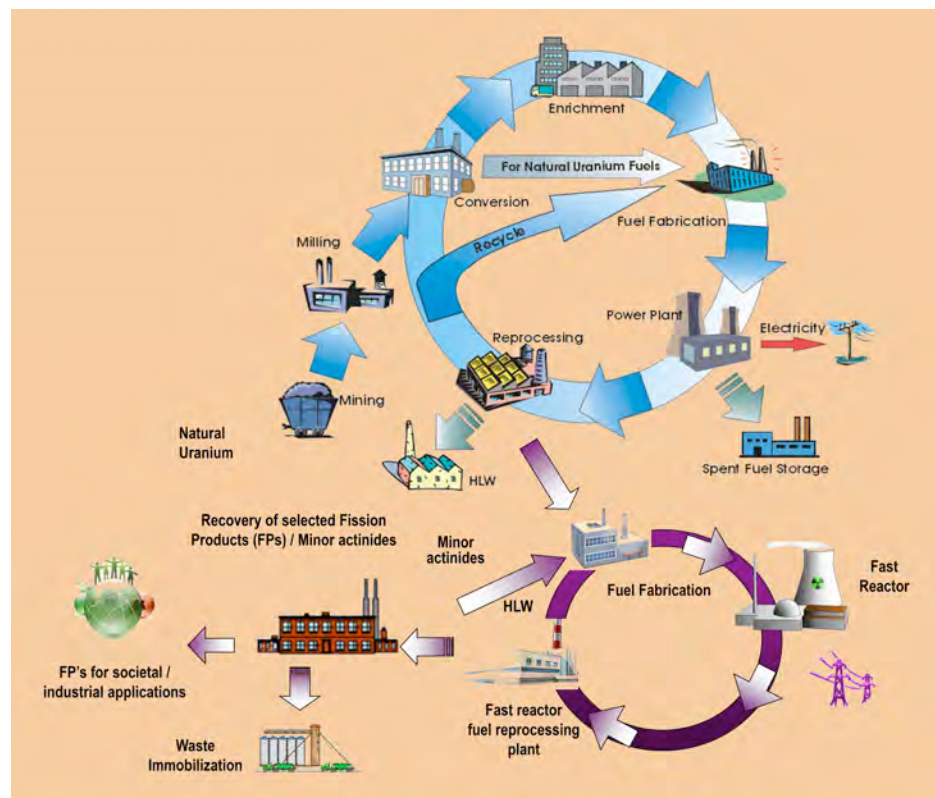
Fast breeder reactors have been developed since the 1960s, with demonstration and prototype reactors being operated in several countries, including China, France, Germany, India, Japan, the Russian Federation, the UK and the USA. **Operated in a closed fuel cycle (Fig. 16), such reactors have the potential both to increase the energy output from a given amount of uranium by a factor of 60–70 and to reduce significantly the quantities, heat load and hazardous lifetime of the ultimate waste to be disposed of [37].**

Twelve experimental fast reactors with thermal power ranging from 10 to 400 MW (th) and six commercial sized prototypes with electrical output ranging from

250 to 1200 MW(e) have been constructed and operated. The closed fuel cycle has been demonstrated and important experience, even in decommissioning such reactors, has been gained.

Research on fast reactor technology continues under a number of initiatives. International initiatives include the Generation IV International Forum (GIF 2002) and the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) of the IAEA [37, 38], which assist participating Member States in assessing, developing and implementing innovative nuclear energy systems. National initiatives include programmes in China, Europe, India, Japan, the Republic of

FIG. 16. Fast reactor fuel cycle.



Korea, the Russian Federation and other countries with the goal of having the first Generation IV fast reactor demonstration plants and prototypes in operation by around 2025–2030.

Europe has defined a strategy and technological pathway for fast reactors that includes development of the sodium cooled fast reactor as a first track aligned with Europe's prior experience and two alternative fast reactor technologies to be explored on a longer

timescale, the lead cooled fast reactor and the gas cooled fast reactor.

The Russian Federation, which currently operates the most powerful commercial fast reactor in Beloyarsk (BN-600) and is constructing the BN 800, has recently launched a Federal Target Program entitled 'New Generation Nuclear Power Technologies for 2010–2015 with Outlook to 2020' aimed at the development of several fast reactor technologies as well as the related fuel cycles.

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