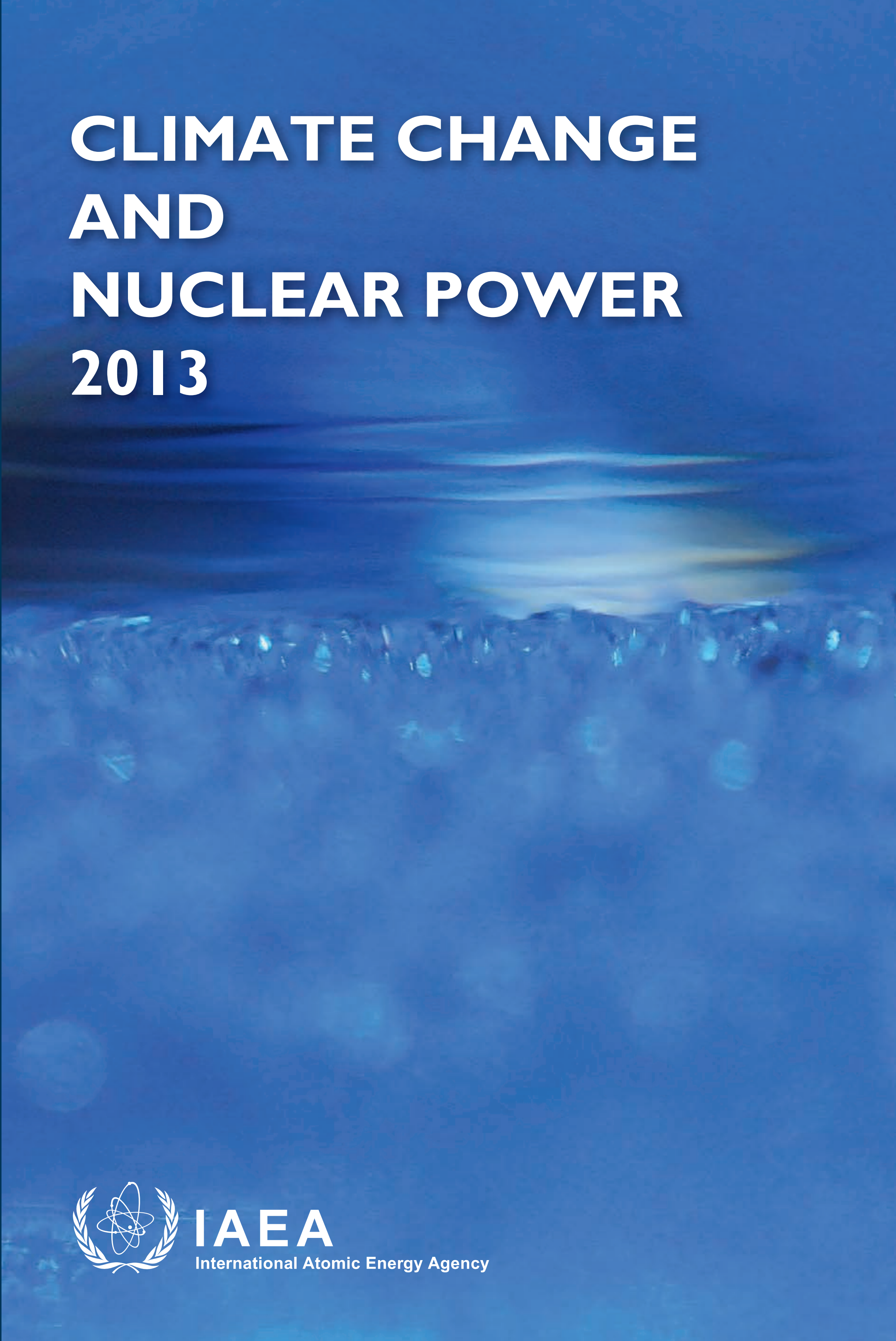

# CLIMATE CHANGE AND NUCLEAR POWER 2013

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# CLIMATE CHANGE
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# CLIMATE CHANGE AND NUCLEAR POWER 2013

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2013

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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 gas emissions while delivering energy in the increasingly large quantities needed for global socioeconomic development.

Nuclear power plants produce virtually no greenhouse gas emissions or air pollutants during their operation and only very low emissions over their entire life cycle. The accident at the Fukushima Daiichi nuclear power plant 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. Its advantages in terms of climate change mitigation 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 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 has been substantially revised, updated and extended since the 2012 edition. It summarizes the potential role of nuclear power in mitigating global climate change and its contribution to other development and environmental challenges. The report also examines broader issues relevant to the climate change–nuclear energy nexus, such as cost, safety, waste management and non-proliferation. New developments in resource supply, innovative reactor technologies and related fuel cycles are also presented.

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# 1. SUMMARY

In order to implement the Copenhagen Accord of the United Nations Framework Convention on Climate Change (UNFCCC) and to keep the increase in global mean temperature below 2°C relative to pre-industrial levels, global greenhouse gas (GHG) emissions will need to peak within the next decade or so and then fall substantially below the 2000 emission levels by the middle of the century. Managing anthropogenic climate change is one of the foremost environmental challenges facing humanity in the twenty-first century. The body of evidence put forward by climate modellers that the climate system of the Earth is warming due to increasing concentrations of GHGs, especially carbon dioxide ($CO_2$), resulting from human activities, mainly the burning of fossil fuels, has grown over the past few years. A rapid reversal of the increasing emissions trends and reductions of 50–85% are required by 2050 to avoid distressing climate change impacts in ecological and socioeconomic systems.

Energy is indispensable for development. Enormous increases in energy supply are required to lift 2.4 billion people out of energy poverty. Without a paradigm shift in the global approach to energy, however, GHG emissions will increase even further. Meeting the soaring global energy demand will require primary energy of the order of 16 gigatonnes of oil equivalent (Gtoe) in 2035 and around 21 Gtoe in 2050. In the absence of sweeping policy interventions, this would lead to an increase in energy related $CO_2$ emissions of 40% in 2030 and of 100% in 2050 relative to 2007. The double challenge over the next 10–20 years will be to keep promoting economic development by providing safe, reliable and affordable energy while significantly reducing GHG emissions.

Nuclear power belongs to the range of energy sources and technologies available today that could help meet the climate–energy challenge. GHG emissions from nuclear power plants (NPPs) are negligible and nuclear power, together with hydropower and wind based electricity, is among the lowest $CO_2$ emitters when emissions over the entire life cycle are considered. In the electricity sector, nuclear power has been assessed as having the largest potential (1.88 Gt $CO_2$-equivalent ($CO_2$-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 $CO_2$-eq. Nuclear energy could account for about 15% of the total GHG reduction in power generation in 2050.

Nuclear energy can contribute to resolving other energy supply concerns, and it has non-climatic environmental benefits. Significant increases in fossil fuel prices in recent years, fears of their sustained high levels in the future and concerns about the reliability of supply sources in politically unstable regions are fundamental considerations in present day energy strategies. Nuclear power can help alleviate these concerns because ample uranium resources are available from reliable sources spread all over the world and the cost of uranium is only a small fraction of the total cost of nuclear electricity. Nuclear power can also help reduce local and regional air pollution. Among the power generation technologies, it has one of the lowest external costs — costs in terms of damage to human health and the environment which are not accounted for in the price of electricity.

Nuclear power remains economically competitive and its position will be further enhanced by the increasing $CO_2$ costs of fossil based electricity generation. Recent assessments indicate that the ranges of levelized costs of electricity from natural gas, coal and nuclear sources largely overlap between $0.05 and $0.10/kW·h, hence the choice between them depends on local circumstances, such as the lack of availability of cheap domestic fossil resources. The costs of $CO_2$ emissions reduction by $CO_2$ capture and geological disposal and the charges for the emitted $CO_2$ from fossil based electricity give a competitive advantage to nuclear power. Despite increasing construction costs, financing nuclear power investments will be feasible under stable government policies, proper regulatory regimes and adequate risk allocation schemes. Once the business case for increasing nuclear investments is established, manufacturing and construction capacities will expand as required.

The accident at the Fukushima Daiichi nuclear power plant that was caused by the earthquake and tsunami that struck Japan on 11 March 2011 prompted a round of stress tests of NPPs around the world and, in September 2012, the first annual progress report on the IAEA Action Plan on Nuclear Safety (henceforth referred to as ‘the Action Plan’) was made. Key areas of progress highlighted in this report comprise assessments of safety vulnerabilities of NPPs, strengthening of the IAEA’s peer review services, improvements in emergency preparedness and response capabilities, strengthening and maintaining capacity building 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 and emergency preparedness and response. Enhancing nuclear safety was also an important item on the agenda of the 2013 International Ministerial Conference on Nuclear Power in the twenty-first century (St. Petersburg, Russian Federation), which reaffirmed the commitment of the Member States to the Action Plan. Participants agreed that all countries have a common interest in the continuous improvement of nuclear safety, emergency preparedness and the radiation protection of people and the environment worldwide, taking into account all the lessons learned from the Fukushima Daiichi accident.

Other concerns about nuclear energy regarding radiation risks, waste management and proliferation are easing. This is also reflected in increasing public acceptance, following a decline in many countries after the Fukushima Daiichi accident. Nevertheless, the nuclear sector needs to improve further and to provide adequate responses to these concerns in order for it to realize its full potential. Radiation risks from normal plant operation remain low, that is, at a level that is virtually indistinguishable from natural and medical sources of public radiation exposure. Concerted efforts by international organizations, such as the IAEA, and by operators of nuclear facilities, have made NPPs one of the safest industrial branches for their workers and for the public at large. Geological and other scientific foundations for the safe disposal of radioactive waste are well established. The first repositories for high level radioactive waste will start operation in about 10 years. Institutional arrangements are being improved and further technological solutions sought to prevent the diversion of nuclear material for non-peaceful purposes.

Projections of future nuclear generating capacity point to a continued increase of nuclear power in the longer term. The Fukushima Daiichi accident slowed projected growth rate of nuclear capacities — the IAEA 2013 high projection for 2030 is 2.8% lower than what was projected in 2012 — but did not reverse the upward trends of nuclear power capacities and output. Nuclear capacity is expected to expand to 435 GW(e) in the low and to 722 GW(e) in the high projection of the IAEA by 2030. The principal reasons for the increased interest in nuclear power in recent years have not changed.

Climate change mitigation is one of the salient reasons for increasingly considering nuclear power in national energy portfolios. Other reasons include fears of sustained high fossil fuel prices, price volatility and supply security. Nuclear power is also considered in climate change adaptation measures, such as seawater desalination or hedging against hydropower fluctuations. Where, when, by how much and under what arrangements nuclear power will contribute to solving these problems will depend on local conditions, national priorities and on international arrangements, such as the flexibility mechanisms under the post-2012 protocol of the UNFCCC currently being negotiated. The decision to introduce or expand nuclear energy in the national energy portfolio rests with sovereign States.

# 2. INTRODUCTION

Among the many challenges the world is facing in the early twenty-first century, climate change remains one of the major problems. The possibility of global climate change resulting from increasing anthropogenic emissions of GHGs has been a major concern in recent decades. A principal source of GHGs, and particularly of carbon dioxide ($CO_2$), is the fossil fuels burned by the energy sector. Energy demand is expected to increase dramatically in the twenty-first century, especially in developing countries, where population growth is fastest and where, even today, some 1.6 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", to use the language of Article 2 of the UNFCCC.

To take initial steps in reducing the risk of global climate change, developed countries (listed in Annex I of the Convention) have made commitments under the Kyoto Protocol to the UNFCCC to reduce their collective GHG emissions during 2008–2012 to at least 5.2% below 1990 levels. Since the United States of America (USA) has not ratified the Kyoto Protocol, the actual reduction was only about 3.8% of the 1990 Annex I emissions. This reduction is far outweighed by increases of emissions in other countries not included in Annex I in the same period. However, much greater global emissions cuts will be necessary in the next few decades to achieve the 2°C goal declared by the Copenhagen Accord. Negotiations under the UNFCCC and the Kyoto Protocol aspire to reach a comprehensive global agreement for the post-2012 period. Yet the fifteenth session of the Conference of the Parties to the UNFCCC merely "took note" of the Copenhagen Accord, which provides a framework for voluntary GHG emissions reductions by 2020 but involves no firm commitments.

NPPs produce virtually no GHG emissions during their operation and only very small amounts 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. It supplied 14% of global electricity and a significant 27% of electricity in Western Europe in 2008. Despite this substantial contribution, the future of nuclear power remains uncertain. In liberalized electricity markets, there are several factors which may contribute to making nuclear power less attractive than fossil fuel power plants, including the high upfront capital costs of building new NPPs, their relatively long construction time and payback period, the lack of public and political support in several countries and renewable portfolio requirements. These factors have, however, altered in recent years owing to concerns about climate change, fossil fuel prices and energy security.

This report summarizes nuclear power's potential role in mitigating global climate change and its contribution to addressing other development and environment issues. Section 3 presents the climate change challenge and demonstrates the need for nuclear power to resolve it. The potential contribution of nuclear energy to easing supply security concerns and reducing local and regional air pollution problems are also discussed. Section 4 addresses issues pertinent to supplying nuclear power, ranging from economic competitiveness and investment costs to financing and construction capacity as well as the availability of uranium to secure the contribution of nuclear energy to low carbon development over the long term. Section 5 is devoted to concerns surrounding nuclear power including radiation risks, safety and waste management, and to current efforts to resolve them. Recent trends in public acceptance in selected countries are also discussed. Section 6 looks into the future. In addition to presenting the latest projections of the IAEA, the current status of promising nuclear energy technology options that may become important contributors to mitigating climate change in a few decades are discussed.

# 3. THE NEED FOR NUCLEAR POWER

## 3.1. THE CLIMATE CHANGE CHALLENGE

The Intergovernmental Panel on Climate Change (IPCC) concludes that 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 [1]. 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 affected negatively: 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 diarrhœal, cardiorespiratory and infectious diseases. Increased morbidity and mortality are foreseen from heatwaves, floods and droughts.

The Copenhagen Accord, the outcome of the Fifteenth Conference of the Parties (COP-15) to the UNFCCC held in 2009, recognizes "the scientific view that the increase in global temperature should be below 2 degrees Celsius" [2], in order to prevent dangerous anthropogenic interference with the climate system. This means that "deep cuts in global emissions are required according to science" [3] and international cooperation is needed for peaking global and national GHG emissions "as soon as possible".

Recent experiments with a coupled climate carbon cycle model found that anthropogenic $CO_2$ emissions to date add up to about 50% of the total amount of cumulative emissions permissible for keeping global mean temperature increase below 2°C relative to the pre-industrial level [4, 5]. Accordingly, emissions of $CO_2$ (and other GHGs) will need to decrease significantly. Given the constraint for cumulative $CO_2$ emissions and assuming a median climate sensitivity of 3°C, even an immediate start of reducing $CO_2$ emissions to eventually reach 10% of their current level would not prevent a warming of more than 2°C by the end of this millennium. Postponing the start of emission mitigation by 20 years and cutting emissions at the rate of 3% per year thereafter would result in reaching the 2°C limit by 2100 [6]. This implies that immediately available technologies with large mitigation potential, such as nuclear power, will be required to avoid more than 2°C warming over the long term.

An international initiative of the scientific community involved in climate change research resulted in new scenarios for assessing climate change impacts, adaptation and mitigation and has produced a set of so-called representative concentration pathways (RCPs) for exploring the near and long term climate change implications of different emissions pathways of all GHGs [7]. The RCPs indicate radiative forcing[1] values for the year 2100 in the range 2.6–8.5 $W/m^2$. The low end of this range is associated with limiting the global mean temperature increase to less than 2°C [8].

Figure 1 shows the baseline (without climate policy) and the RCP2.6 mitigation pathways for all GHGs included in the Kyoto Protocol to the UNFCCC and for energy and industry related $CO_2$ emissions alone. The chart indicates an enormous mitigation challenge: total GHG emissions will need to start decreasing at a fast rate in less than a decade while energy and industry related $CO_2$ emissions will need to become negative beyond 2070. The latter will

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[1] Radiative forcing is the change in energy flux caused by drivers (natural and anthropogenic substances and processes that alter the Earth's energy budget). It is quantified in watts per square metre ($W/m^2$), and it is calculated at the tropopause or at the top of the atmosphere.

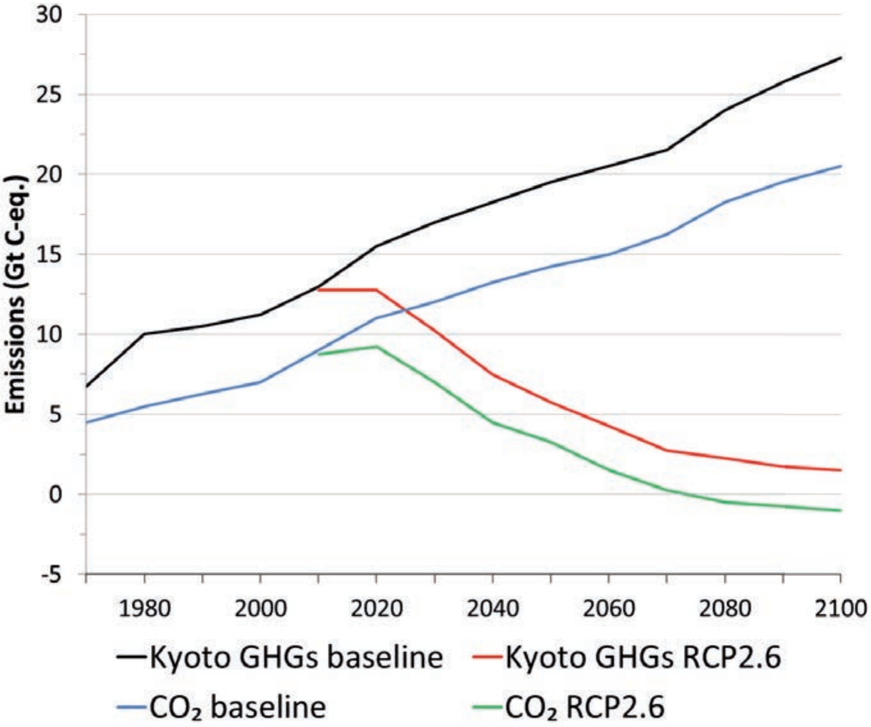

*FIG. 1. Baseline and RCP2.6 emissions paths of all GHGs included in the Kyoto Protocol and of energy and industry related* $CO_2$*. Data source: Ref. [8].*

require a fast decarbonization of the energy system by adding carbon capture and storage (CCS) to a large fraction of fossil fuel and bioenergy use, and drastically increasing the contribution of nuclear energy [8] to the global energy mix.

In its latest report released in September 2013, the IPCC Working Group I [9] concludes that across all RCP scenarios assessed, the increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to be in the range of 0.3–4.8°C. This wide range reflects the extensive range of the underlying radiative forcing scenarios resulting from anthropogenic GHG emissions, from an immediate and fast reduction pathway to a continuation of the trend of recent decades.

Considering the emissions pathways shown in Fig. 1, the world faces an enormous mitigation challenge over the next decades. The IPCC Working Group III report maintains that many mitigation technologies and practices that could reduce GHG emissions are already commercially available. According to the IPCC [10], technical solutions and processes could reduce the 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.

## 3.2. THE GLOBAL ENERGY CHALLENGE

Energy is generally recognized as a central issue in sustainable development. Several high level conferences and declarations have emphasized that the provision of adequate energy services at an affordable cost, in a secure and environmentally benign manner, and in conformity with social and economic development needs, is an essential element of sustainable development. Reliable energy services are the preconditions for investments that bring about economic development. Among other things, they facilitate the learning and study and improved health care that are crucial for developing human capital. They also promote gender equity by allowing women to use their time for more productive activities than collecting firewood, and social equity by giving the less well off the chance to study, thus providing a possible escape from poverty. Energy is therefore vital to alleviating poverty, improving human welfare and raising living standards. Yet, worldwide, 2.6 billion people rely on traditional biomass as their primary source of energy, and 1.3 billion people do not have access to electricity [11] — conditions which severely hamper socioeconomic development.

All recent socioeconomic development studies project major increases in global energy demand, driven largely by demographic and economic growth in today's developing countries. Of the world's 6.9 billion people in 2010, approximately 82% live in non-OECD countries [12] and consume only 55% of global primary energy [11]. Alleviating this energy inequity will be a major challenge. A growing global population will compound the problem. The medium variant of the latest population projections of the United Nations estimates an additional 1.5 billion people by 2030, and another 1.1 billion by 2050, bringing the world's population to about 9.55 billion by the middle of this century [13].

It is also anticipated that the rising population will enjoy increasing economic welfare over the next decades. The World Bank projects an average annual growth rate for the world economy of 2.2% in 2013, 3.0% in 2014 and 3.3% in 2015 [14]. Developing countries will grow the fastest, though their long term growth rates will decline over time from 5.5% at present to 4.5% in the 2030s, while OECD countries will grow at the slowest rate and maintain a consistent ~2.3% long term growth rate [15].

The International Energy Agency (IEA) of the OECD makes similar assumptions about these two main drivers of global energy demand in its World Energy Outlook (WEO) 2012. The world's population is projected to increase to 8.6 billion by 2035, while the global economy is assumed to grow at an annual average rate of 4.0% up to 2015 and 3.5% between 2010 and 2035 [15]. Based on these two main drivers of energy demand, and on additional assumptions about technological development and resource availability for the energy sector, in the 2012 edition of Energy Technology Perspectives (ETPs) the IEA projects in its 6°C reference scenario (6DS) that total world primary energy demand will grow to approximately 21 Gtoe by 2050 [16]. The evolution of the resulting global primary energy mix and the corresponding global energy related $CO_2$ emissions are shown in Fig. 2.

The new ETP study presents global energy prospects up to the middle of the century. The most notable changes projected in the 6DS scenario for the next half-century include the following:

— Fossil fuel use and $CO_2$ emissions almost double in 2050 from 2009 levels.
— Investments in energy system are very high, with a large share directed toward new coal-fired generation; coal use for electricity generation more

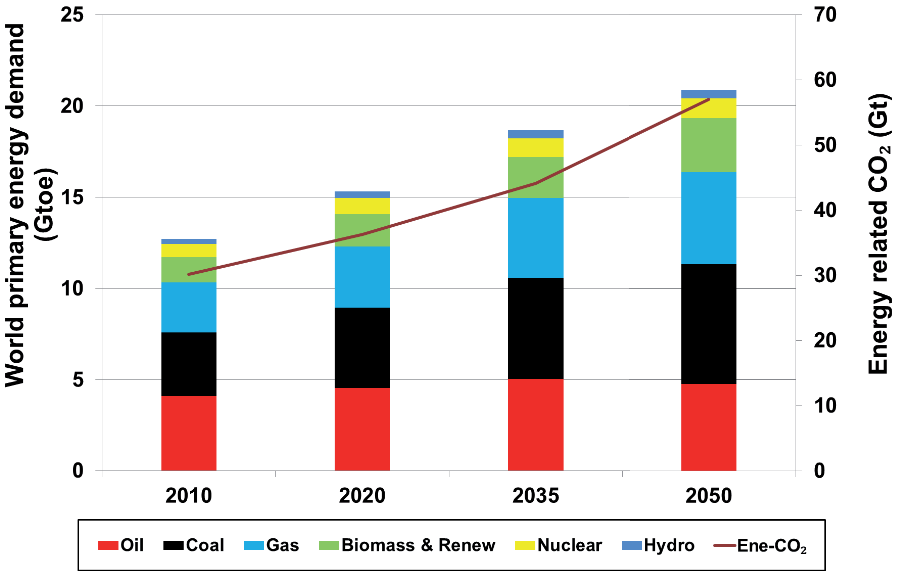

*FIG. 2. Global primary energy sources (left axis) and energy related $CO_2$ emissions (right axis) in the IEA's WEO 2012 Current Policies scenario (up to 2035) [11] and in the ETP 2012 (2050) 6DS [16]).*

than doubles in 2050 from 2009 levels, and carbon capture and storage is not implemented.

- The share of electricity generation from nuclear declines from 13% in 2009 to 9% in 2050.
- Renewable energy increases its share of electricity from 19% to 24%, far lower than in policy scenarios.
- Transport energy use almost doubles by 2050 with little adoption of plug-in electric vehicles or other alternative technologies and fuels.

The climate change implications of the 6DS are severe. Energy related $CO_2$ emissions — the largest component of global GHG emissions — increase by about 66% in 2050 relative to 2010 (see Fig. 2). Assuming that other GHG emissions increase at comparable rates, this would put the Earth on track towards an equilibrium warming of over 6°C in terms of global mean temperature increase above the pre-industrial level. Thus these trends stand in sharp contradiction to the Copenhagen Accord of the UNFCCC to keep the global mean temperature increase below 2°C and point to the urgent need for deploying low carbon technologies.

### 3.3. NUCLEAR POWER: A LOW CARBON TECHNOLOGY

In a carbon constrained world the importance of energy technologies emitting small amounts of GHGs per unit of energy service provided will increase. Because of this heightened importance, carbon emissions need to be accurately identified and attributed. The appropriate method to quantify the total GHG emissions is life cycle analysis, pinpointing carbon emissions that are inherently related to a certain stage in the development of an energy technology.

Life cycle assessment (LCA) is defined as the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a production system throughout its life cycle, from raw material acquisition to final disposal [17]. The LCA of an electricity production system will reflect its high complexity, encompassing many processes within its chosen system boundary that contribute to the final product. The system boundaries for the LCA calculations can vary between different studies. Furthermore, adding to this LCA complexity is (a) the uncertainty associated with characterization factors in the conversion of separate inventory results into one common category unit; (b) the somewhat arbitrary allocation rules in the case of cogeneration systems (producing electricity and heat simultaneously); and finally, (c) the uncertainty stemming from data sources that may be imprecise or extrapolated from data found in LCAs of similar systems or processes.

Because of its importance in the decision making process and the possible consequences of errors, consistency and credibility are of the utmost importance in LCA. Aiming to enhance quality, but without prescribing specific methodologies, relevant ISO standards were introduced and currently present the norm for developing LCA studies. Among them are the many LCA studies on GHG emissions of different electricity generation technologies that have been published in recent years and continue to be updated. This section draws on data from a large international LCA database called Ecoinvent [18], but also presents the findings of the recent meta-analysis performed by the US National Renewable Energy Laboratory (NREL) [19], as well as results from a broad selection of scientific publications [20].

Summarizing life cycle GHG emissions results for various electricity generating technologies, Fig. 3 presents fossil sources and pumped storage reservoirs. The figure shows that even by adding CCS to fossil fired power plants, life cycle emissions remain high at about 200 g $CO_2$-eq. per kW·h for coal and about 150 g $CO_2$-eq. per kW·h for gas. Figure 4 presents emissions for renewable energy sources and nuclear power. The figure demonstrates that nuclear power, together with hydropower and wind based electricity, remains one of the lowest emitters of GHGs in terms of g $CO_2$-eq. per unit of electricity generated. Note the one order of magnitude difference in the vertical scales between Figs 3 and 4.

As can be seen in Fig. 4, for GHG emissions from nuclear power (light water reactors) the median value is estimated at 14.9 g $CO_2$-eq. per kW·h, with a range of 13.5–19.8 g $CO_2$-eq. per kW·h of generated electricity. The entire life cycle from uranium mining to waste disposal was taken into account for that calculation.

The life cycle assessment performed by the Japanese Central Research Institute of Electric Power Industry (CRIEPI) concurs with these results, with a calculated 19.5 g $CO_2$-eq. per kW·h for pressurized water reactors and 20.2 g $CO_2$-eq. per kW·h for boiling water reactors [21]. A similar median value for nuclear power, 12 g $CO_2$-eq. per kW·h, was reported by the NREL after harmonizing the underlying assumptions and stages for various studies published in the scientific literature [19]. The range of values reported in the studies reviewed by NREL was 4–110 g $CO_2$-eq. per kW·h, with an interquartile range, or half of all LCA results around the median value, of between 7–25 g $CO_2$-eq. per kW·h. However, the majority of these studies use some degree of generalization for the life cycle processes and use estimated data to overcome the lack of information. Assessments of specific life cycles, such as those performed by utilities for the Environmental Product Declaration system, involve a lesser degree of generalization owing to data obtained from known uranium ore suppliers and fuel manufacturers. Based on more precise studies, British,

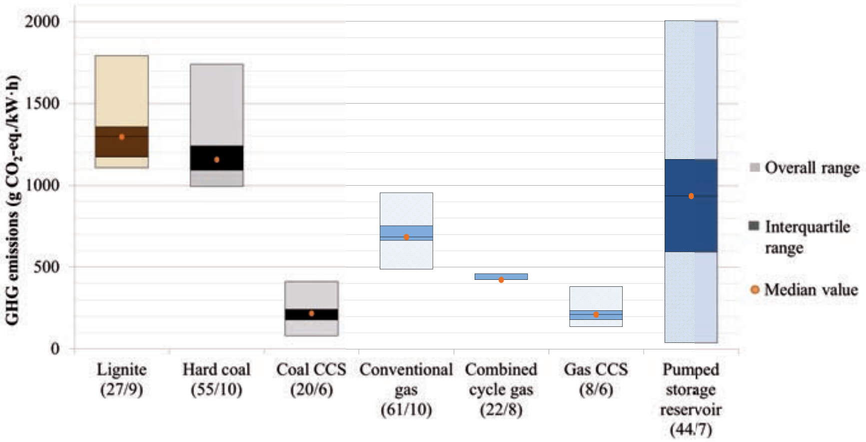

*FIG. 3. Life cycle GHG emissions from electricity generation: fossil fuels and pumped storage reservoir. Data source: Ecoinvent [18]. Note: numbers in parenthesis indicate the number of LCA calculations and the number of global regions in which those locations can be found. The interquartile range includes half of the calculations around the median of the overall range.*

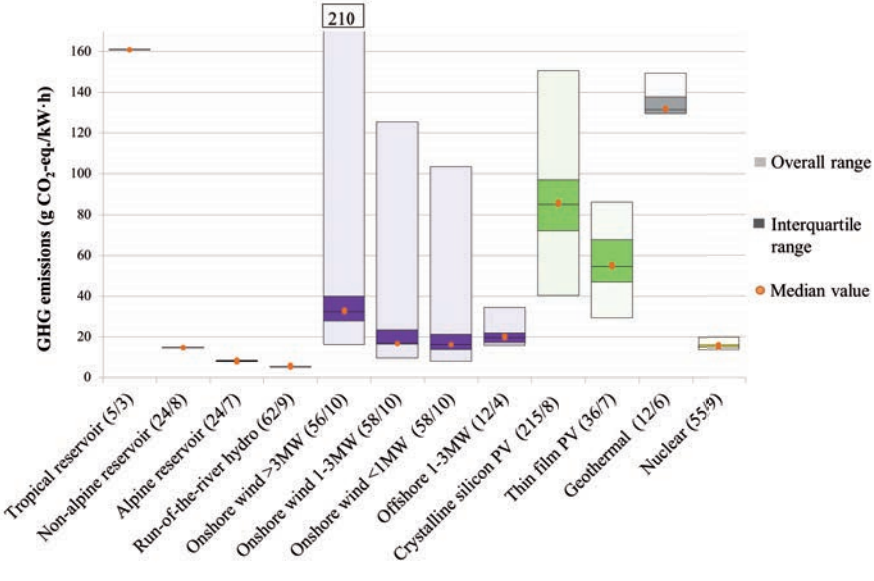

*FIG. 4. Life cycle GHG emissions from electricity generation: renewable technologies and nuclear power. Data source: Ecoinvent [18]. Note: the numbers in parenthesis indicate the number of LCA calculations and the number of global regions in which those locations can be found. The interquartile range includes half of the calculations around the median of the overall range.*

Swedish and Swiss nuclear power LCA studies have calculated considerably lower emissions, 4–6 g $CO_2$-eq. per kW·h [22].

Despite the fact that CCS technologies have not been deployed on an industrial scale so far, they are considered a viable option in many GHG mitigation studies. However, LCA results for CCS in Fig. 3 indicate that GHG emissions per kW·h often amount to an order of magnitude higher values than for nuclear power generation [20]. For example, the US National Energy Technology Laboratory (NETL) calculated 137 g $CO_2$-eq. per kW·h GHG emissions over the life cycle for combined cycle power plants using domestic natural gas with CCS and 241 g $CO_2$-eq. per kW·h for supercritical pulverized coal power plants with CCS in the USA [23]. Singh et al. confirm these results in their study with estimated 140 g $CO_2$-eq. per kW·h for the life cycle of natural gas combined cycle plant and 220 g $CO_2$-eq. per kW·h for supercritical pulverized coal power plant using the best available technology and CCS [24]. Similar values for coal fired power plants with CCS are reported by Liang et al. (213 g $CO_2$-eq. per kW·h [25]) and Hurst et al. (225–229 g $CO_2$-eq. per kW·h [26]). It should be noted that the values given for CCS in Fig. 3 present a compilation from various sources that may not have used exactly the same methodology to calculate life cycle emissions as those for other technologies. Nevertheless, the results are comparable and credible.

Median values for solar photovoltaic (PV), compared to nuclear power, range between 4 times higher (54.5 g $CO_2$-eq. per kW·h for thin film) and 6 times higher (85.2 g $CO_2$-eq. per kW·h for crystalline silicon), with typical ranges of 29.4–86.23 g $CO_2$-eq. per kW·h and 40.3–150.6 g $CO_2$-eq. per kW·h, respectively [18]. Other studies also indicate results that are comparative or fall within this range, such as, for example, Refs [19, 21, 27].

Wind as an electricity generating source shows median values for GHG emissions that are comparative with those from nuclear power up to the class of 3 MW(e) wind turbines (Fig. 4). Above that, life cycle GHG emissions practically double, reflecting the higher use of energy and materials per unit of capacity for the construction of turbines with a capacity larger than 3 MW(e). The lower end of the GHG emissions range is comparable to nuclear, but the high end values can reach up to one order of magnitude larger emissions (209.2 g $CO_2$-eq. per kW·h) [18]. The Japanese CRIEPI calculates 25.4 g $CO_2$-eq. per kW·h for wind turbines with a nominal capacity between 1 and 2.5 MW(e) [21], while Vattenfall's environmental product declaration for its wind generated electricity (onshore and offshore) specifies 15 g $CO_2$-eq. per kW·h [22], falling within the range given in Fig. 4. Comparative values have been reported by NREL's meta-analysis, with 11 g $CO_2$-eq. per kW·h as the median value [19].

Hydropower from alpine and non-alpine reservoirs, as well as run-of-the-river systems, also has comparable life cycle GHG emissions to nuclear power.

Using tropical reservoirs for hydropower generation entails the decomposition of biomass and release of the resulting methane from the reservoir, so it is not surprising to see 160 g $CO_2$-eq. per kW·h calculated for this case. Interestingly, pumped storage systems show a very wide range (40.3–2004.6 g $CO_2$-eq. per kW·h), depending on the carbon footprint of the electricity used to power the pumps that drive the water back to the reservoir for storage [18]. NREL has not yet harmonized the hydropower LCA results, but as reported in the scientific literature, the ranges are of similar magnitude (1–165 g $CO_2$-eq. per kW·h, median value 7 g $CO_2$-eq. per kW·h) [19]. Environmental product declarations for European hydropower facilities range from 2.2 to 9.9 g $CO_2$-eq. per kW·h [22]. A United Nations Environment Programme (UNEP) sponsored study calculated 6.45 g $CO_2$-eq. per kW·h for hydropower generation in Peru [28], while CRIEPI calculated 10.6 g $CO_2$-eq. per kW·h for Japan [21]. It should also be noted that all of these studies predominantly assess smaller capacity hydroelectric dams.

Expectations that nuclear energy technologies may achieve even lower GHG emissions in the future are valid due to further improvements in: (a) uranium enrichment technologies, shifting from electricity intensive gaseous diffusion to centrifuge or laser technologies that require much less electricity; (b) the increased share of electricity used for enrichment based on low carbon technologies; (c) improvements in fuel manufacturing, such as higher burnup, which reduces emissions per kilowatt hour associated with the fuel cycle; and (d) extended NPP lifetime from 40 to 60 years reducing emissions per kW·h associated with construction and decommissioning.

Without doubt, these very low $CO_2$ and GHG emissions on a life cycle basis make nuclear power an important technology option in climate change mitigation strategies for many countries. To what extent it will be used depends on many other factors, including the availability of resources, as well as political, economic and social conditions.

### 3.4. CONTRIBUTION TO AVOIDED GHG EMISSIONS

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. This is demonstrated by calculating $CO_2$ emissions avoided by hydroelectricity, nuclear power and renewables in global electricity generation. Figure 5 shows the historical trends of $CO_2$ emissions from the global electricity sector and the amounts of emissions avoided by using hydropower, nuclear energy and other renewable electricity generation technologies, respectively. The height of the red columns indicates the actual $CO_2$ 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 (2.8 Gt, in 2010), nuclear power (2.2 Gt, in 2010) and renewables other than hydropower (0.6 Gt, in 2010), respectively.

Figure 5 is based on data from the IEA [29]. The latest version of the IEA database includes information on global electricity generation up to 2010.

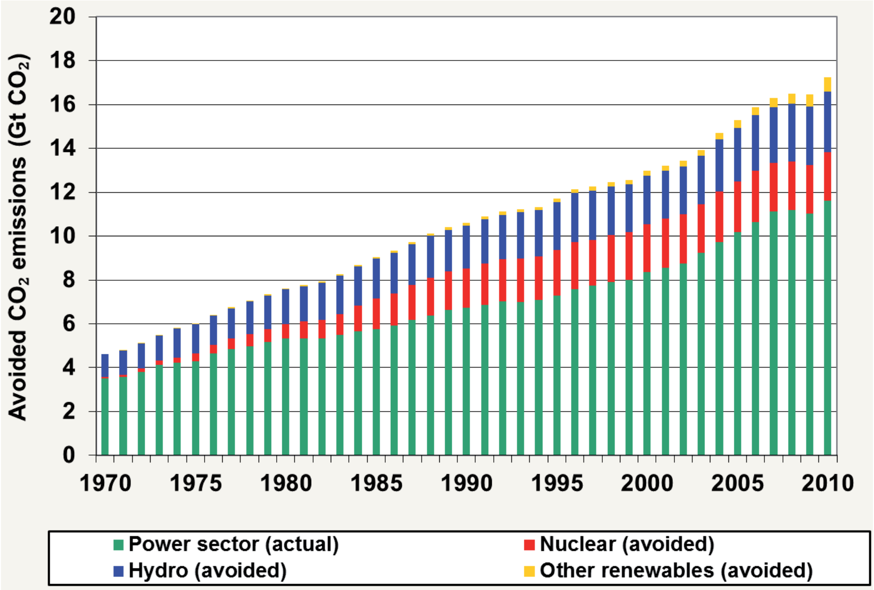

*FIG. 5. Global $CO_2$ emissions from the electricity sector and emissions avoided by using three low carbon generation technologies. Data source: Ref. [29].*

Clearly, the calculated amounts of avoided emissions depend on the assumptions about which technologies 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 can be considered as conservative, if the historical context of the 1970s is taken into account: most of the nuclear capacity expansion was specifically aimed at reducing in oil and gas dependence — and coal would have likely been the predominant alternative at the time. On the other hand, during gas capacity expansion in the 1980s, only a few NPPs were built which probably did not have a profound effect on the total carbon emissions from electricity sources substituting for nuclear power.

Figure 6 confirms the global trends, showing the $CO_2$ intensity and the shares 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 $CO_2$ emitted from generating 1 kW·h of electricity in the same year. The chart demonstrates that countries with the lowest $CO_2$ intensity (less than 100 g $CO_2$/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 $CO_2$-eq. intensity of the power sector in several countries (e.g. Belgium, Germany, Republic of Korea, UK) — see the difference between the 1980 and the 2009 bars.

The role of nuclear energy in shaping $CO_2$ intensity will decrease over the next decade or so in a very few countries that decided on a fast phase out of nuclear energy, and increase in several other countries that decided to include or augment the nuclear power share in their electricity generation portfolio.

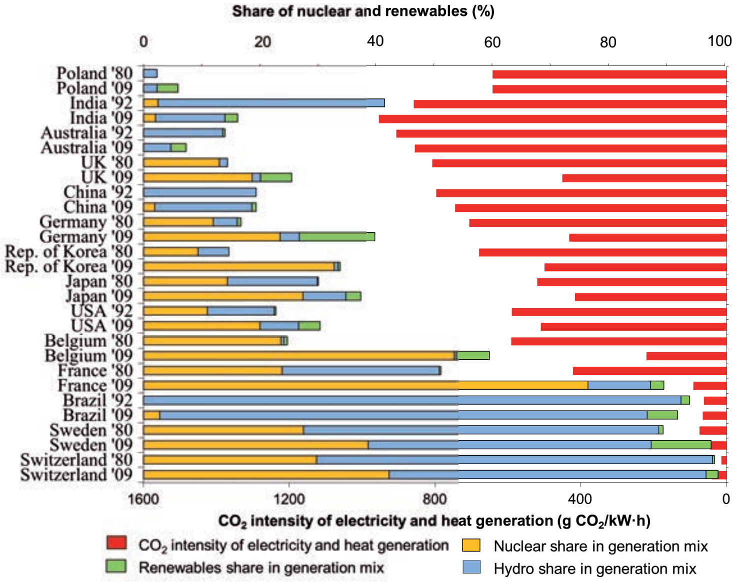

*FIG. 6. Carbon dioxide intensity and the share of non-fossil sources in the electricity sector of selected countries. Data source: Ref. [29].*

## 3.5. GHG MITIGATION POTENTIAL OF NUCLEAR POWER

The IPCC Fourth Assessment Report (AR4) presents GHG mitigation potentials for seven sectors (energy supply including the power sector, transport, buildings, industry, agriculture, forestry and waste management) [10]. This section focuses on the power sector. The IPCC AR4 estimates the mitigation potential in terms of GHG emissions that can be avoided by 2030 by adopting various electricity generating technologies in excess of their shares in the baseline scenario (the Reference Scenario in the IEA's WEO 2004 [30]). The technologies include fuel switching within the fossil portfolio, nuclear, hydropower, wind, bioenergy, geothermal, 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 far 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 various technologies deployed simultaneously are not accounted for). The estimates indicate how much more (relative to the baseline) each technology could be deployed in major world regions at costs falling in the following ranges: less than 0 (possible for nuclear, hydropower, wind, bioenergy and geothermal sources), 0–20, 20–50, 50–100 and more than \$100/t $CO_2$-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 plus ancillary benefits arising from reduced local and regional air pollution.

In reducing $CO_2$ emissions, the first steps to consider are shifting from carbon intensive fossil fuels to less intensive fossil fuels and improving conversion efficiency. Another option to reduce $CO_2$ emissions while continuing to use fossil fuels is CCS. CCS technology is currently in the demonstration phase and may not be commercially available in the near term. According to the IPCC, "Penetration by 2030 is uncertain as it depends both on the carbon price and the rate of technological advances in cost and performance" ([10], p. 298). For 2030, the global mitigation potential of CCS used with coal and gas fired power plants is estimated to be 0.49 Gt $CO_2$-eq. and 0.22 Gt $CO_2$-eq., respectively.

Figure 7 shows the potential GHG emissions that can be avoided by 2030 by adopting the generation technologies highlighted in the IPCC AR4. The figure indicates that nuclear power represents the largest single mitigation potential at the lowest average cost for electricity generation. However, the IPCC acknowledges that "assessments of future potential for nuclear power are uncertain and controversial" and that there is "controversy regarding the relatively low costs shown by comparative life-cycle analysis assessments" used

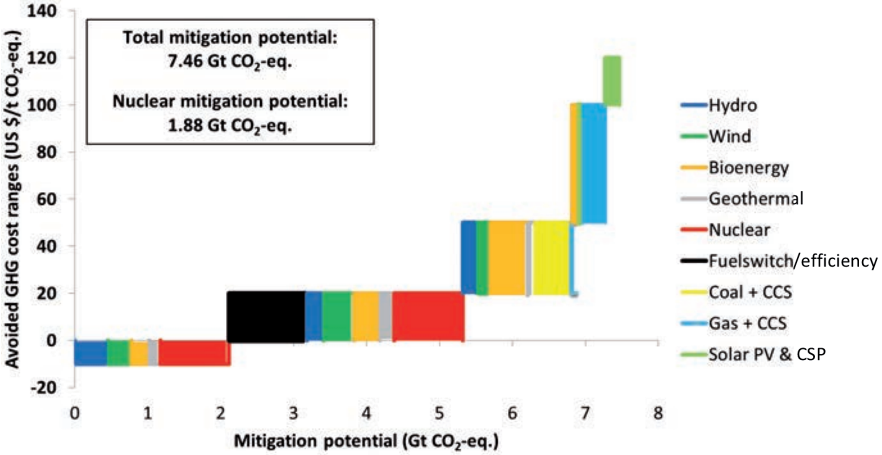

*FIG. 7. Mitigation potential in 2030 of electricity generation technologies in different cost ranges. Source: Based on data in table 4.19 of Ref. [10].*

in the AR4 [10]. Taken together, all renewables combined account for double the mitigation potential of nuclear power. Yet nuclear accounts for almost half the mitigation potential that could be realized at negative cost and for about 29% of the low cost mitigation potential (below \$20/t $CO_2$-eq.). Fuel switching and plant efficiency improvements account for another 33% of low cost mitigation potential. CCS with coal as well as some CCS with gas and higher cost wind, hydro, and bioenergy fall within the middle cost range of \$20 to \$50/t $CO_2$-eq. CCS with gas and solar technologies comprise the bulk of the mitigation potential above \$50/t $CO_2$-eq.

The mitigation potential of nuclear power is based on the assumption that it displaces fossil based electricity generation. The IPCC AR4 methodology for calculating avoided emissions is performed one technology at a time. To the extent that nuclear may compete with another technology, the actual mitigation may be less than the reported potential for nuclear and any of the other technologies evaluated. The mitigation volume estimated by the IPCC for nuclear power reflects the contribution it could make to global climate protection by increasing its share in the global electricity mix from 16% 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. 8 for three large global regions and for the world.

Nuclear power clearly belongs to the set of options available to reduce GHG emissions in the electricity sector. A significant part (about 2 Gt $CO_2$-eq.) of the

GHG reduction potential offered by nuclear, hydropower, wind and bioenergy can be realized at negative cost if these technologies displace fossil fuel power plants. 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 switching 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, which will determine which energy sources and mitigation options will be used in different parts of the world.

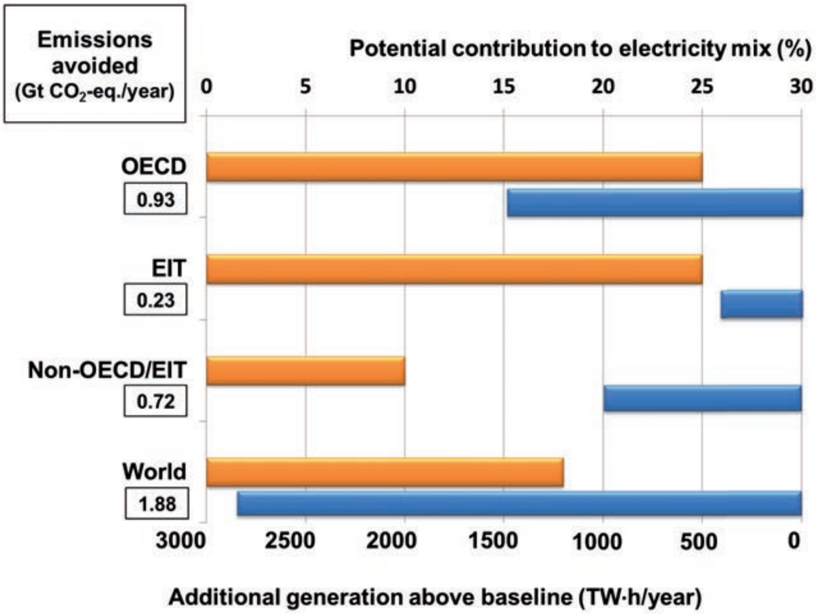

*FIG. 8. Nuclear power shares (orange bars), generation volumes (blue bars) and avoided GHG emissions. Note: EIT — economies in transition. Source: Based on data in table 4.11 in Ref. [10].*

### 3.6. CONTRIBUTION TO GHG MITIGATION

The IEA publishes a detailed energy technology assessment for the world every two years. The 2012 report on Energy Technology Perspectives (ETP) presents an in-depth survey of energy technologies and prospects for their evolution up to 2050. The report presents an overview of a reference case scenario called the 6°C Scenario (6DS) in which current policies and trends are extended into the future. Two policy scenarios — the 4°C scenario (4DS) and the 2°C scenario (2DS), reflecting the policy targets of limiting global mean temperature increase to 4°C and 2°C, respectively — are evaluated, with an emphasis on the 2DS. The 2DS is consistent with the Copenhagen Accord of the UNFCCC (see Section 3.1). The 2DS stipulates an ambitious pathway along which global emissions peak before 2020 and decline to almost 50% of the 2009 level — that is, to around 17 Gt $CO_2$ — by 2050 [16].

Sorting the 2DS according to sectors, the projected $CO_2$ reductions relative to the 6DS are: 8% in buildings, 23% in the transport sector and 24% in industry (see Fig. 9). Nevertheless, power generation is projected to contribute most to $CO_2$ mitigation: about 46% in the 2DS.The projected amount of $CO_2$ avoided by nuclear power is estimated at 3.2 Gt $CO_2$/year in the 2DS in 2050 for about 9% of total $CO_2$ savings.

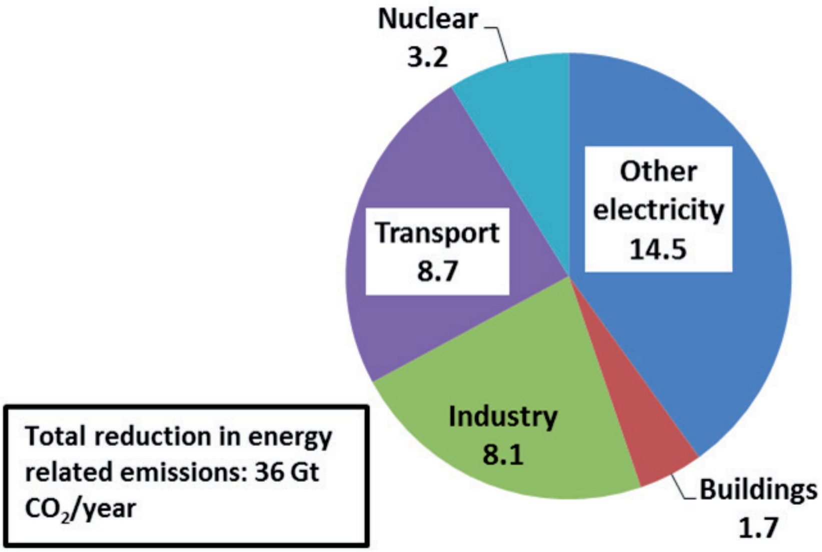

*FIG. 9. Nuclear contribution to the mitigation of energy related $CO_2$ emissions by technology in the IEA 2DS in 2050. Data source: Ref. [16].*

According to the 2DS, the electricity sector will be substantially decarbonized by 2050. The contribution of various electricity generation technologies to this extraordinary development is presented in Fig. 10. End use efficiency improvements, CCS and nuclear represent the largest of the low cost mitigation opportunities within the power sector. End use electricity efficiency

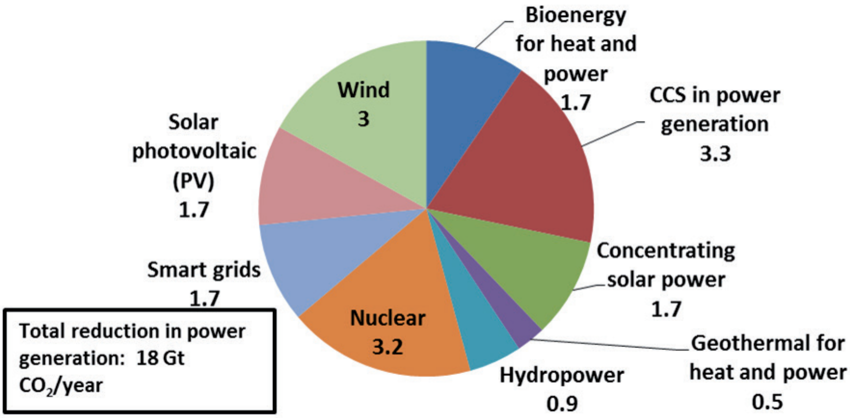

*FIG. 10. Nuclear contribution to $CO_2$ emissions reduction in the power sector in 2050. Data source: Ref. [16]. Note: the difference between the total given and the sum of the individual values is due to rounding.*

accounts for 28% of the power sector $CO_2$ emissions reduction by 2050. CCS accounts for 18% and nuclear 14% of the power sector's $CO_2$ reductions. Combined, renewables account for 35%, but individually, PV accounts for the largest share of power sector $CO_2$ reductions among renewables, at 7%.

The driving force behind $CO_2$ mitigation in the electricity sector are renewables, which grow to a 57% share of generation in 2050 in the 2DS. Nuclear energy is also a significant contributor to generation in the electricity sector in the 2DS with a 19% share by 2050, and carbon capture and storage (CCS) is close behind at 14% (see Fig. 11). In the 6DS or reference scenario, the share of nuclear generation actually declines relative to 2009 levels and is replaced primarily by coal fired generation. The ETP also briefly presents a high nuclear case combined with a 2DS, and in this scenario, nuclear reaches a 34% share by 2050, largely by crowding out some renewables and coal with CCS. According to the ETP, this high nuclear scenario "reflects a world with larger public acceptance of nuclear power" and assumes average construction rates of almost double the 27 GW/year of the 2DS: 50 GW/year for the high nuclear case. This variant also assumes a larger nuclear fuel supply through recycling spent fuel and/or unconventional uranium sources.

## 3.7. CONTRIBUTION TO ENERGY SUPPLY SECURITY

In addition to staggering increases in demand for all forms of energy, particularly electricity, and the need to reduce GHG emissions, there are several

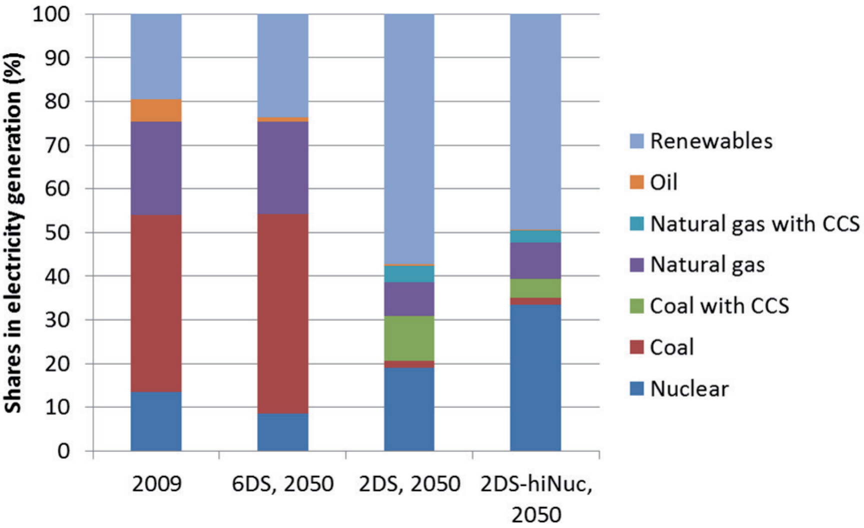

*FIG. 11. Shares of electricity generation technologies in 2009 (actual), in the 6°C scenario (6DS), which is the reference case, in the 2°C scenario (2DS), which is the primary policy scenario, and in a high nuclear variant of the 2°C scenario (2DS-hiNuc), as given in the IEA's Energy Technology Perspectives 2012. Data source: Ref. [16].*

other issues on the current energy policy agendas of many countries that nuclear energy might contribute to resolving.

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 fast growing energy needs, and this is exerting a sustained upward pressure on international oil and gas prices. This in itself is a strong motivation for countries with high shares of imports in the fuels they use for their electricity generation to look for substitutes. Political conflicts in key supply regions exacerbate the price pressure and raise serious concerns regarding 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 concerned about the sustained high price level because of the prospect of its severely increasing their energy import bills, affecting their current account balances and undermining the competitiveness of their export industries. In most developed countries (except those with very small energy resource endowments), energy is a relatively small fraction of the total import bills and the energy content of their exports is lower. These countries are more concerned about direct losses due to supply disruptions, especially if these might render expensive capital and labour capacities idle for some time.

Another closely related factor is price volatility. All elements of the energy supply infrastructure are long lived. Energy intensive industries base their investment decisions on cautious expectations of future energy and electricity prices. A reasonable degree of stability and predictability of resource prices is crucial for such decisions because hedging against large price fluctuations might be vastly expensive.

Nuclear power can help mitigate these concerns. The price of uranium has a small influence on the cost of nuclear based electricity, as opposed to fuel prices in the case of coal and especially gas based generation. Doubling the price of uranium would increase the cost of nuclear electricity by about 4%, whereas doubling the price of coal would lead to an increase of about 40% and a doubled gas price to an increase of almost 70% in the corresponding electricity costs.

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. Nuclear power has one additional feature that generally further increases resilience. Figure 12 shows that currently known and reported resources and reserves of the basic fuel, uranium, are spread throughout politically stable regions over five continents (see Ref. [31]). Figure 13 reveals a similar diversity of uranium production in 2010 (see Ref. [31]). Moreover, the small volume of nuclear fuel required for one load to run a reactor for one year or so makes it easier to establish strategic inventories on or close to the reactor site. 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 find it important.

## 3.8. NUCLEAR ENERGY APPLICATIONS BEYOND THE POWER SECTOR

Nuclear energy has potential applications beyond electricity generation. Some of them, such as desalination and hydrogen production, have a potential to significantly advance climate friendly global economic and technological development.

Currently, about one third of the world population lives in water stressed areas, mostly in Sub-Saharan Africa, the Middle East and South Asia. During the next decades, owing to climate change and continuing population growth in these regions, the problem of access to fresh water will become increasingly more acute. To solve the fresh water challenge, many countries already have to look for alternative ways of providing it, primarily through desalination [32].

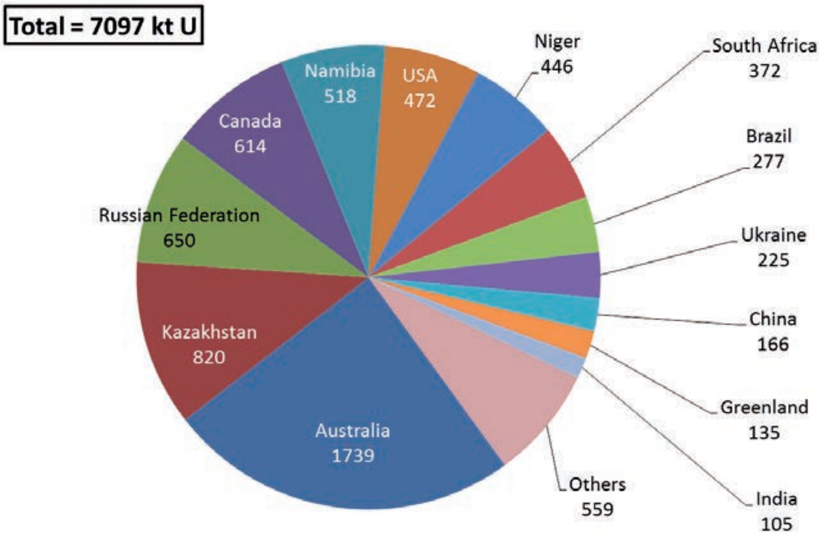

*FIG. 12. The distribution of reported uranium resources and reserves in 2011. Data source: Ref. [31]. Note: the difference between the total given and the sum of the individual values is due to rounding.*

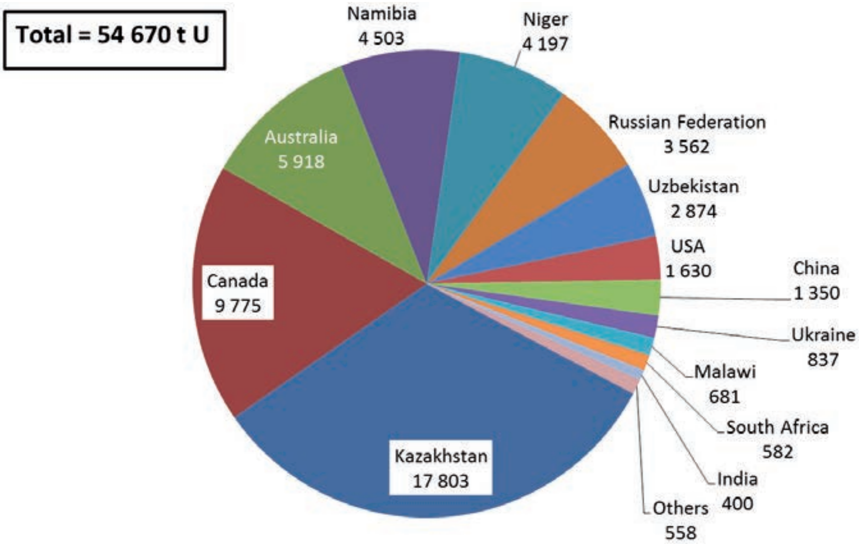

*FIG. 13. The distribution of reported uranium production in 2010. Data source: Ref. [31].*

Global desalination capacity has increased immensely during the last decades — from nearly zero in the 1960s to approximately 80 million m$^3$/day at present (see Fig. 14). Between 2004 and 2012, global installed capacity more than doubled. This growth is expected to continue in the future. According to the projections published by Global Water Intelligence, global capacity is expected to reach 112 million m$^3$/day [33], while the World Bank expects an increase to over 120 million m$^3$/day by 2016 (see Fig. 15). Nuclear energy offers one of the possible solutions to this problem based on the successful experience of implementation at various types of reactors: pressurized water reactors in Japan (Ohi, Takahama, Ikata and Genkai), a fast reactor in Kazakhstan (Aktau) and a heavy water reactor in India (Kalpakkam) [34]. Existing experience allows fast and large scale implementation of nuclear desalination techniques around the globe.

Currently the majority of the approximately 16 000 existing desalination plants operate on fossil fuels [33]. To a large extent, this is because some of the countries facing the most severe shortages of water are rich in oil and gas, specifically in the Middle East region (the largest desalination facility in the world is the Jebel Ali Desalination Plant in the United Arab Emirates). The low costs of oil and gas extraction in these countries stimulate them to make a choice in favour of fossil fuelled desalination. However, nuclear desalination will become an increasingly more attractive solution as contemporary highly energy intense desalination plants operating on fossil fuels significantly contribute to climate change, thus further increasing water scarcity in many regions over the

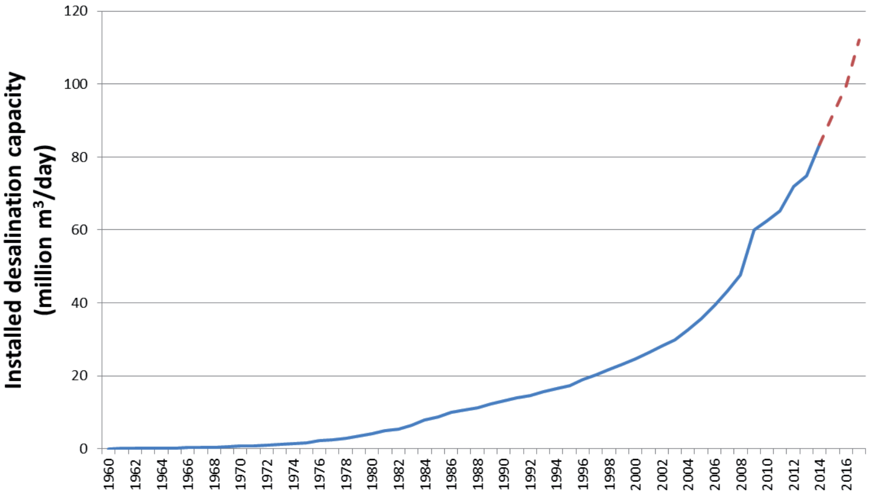

*FIG. 14. Cumulative installed desalination capacity 1960–2016. Source: Global Water Intelligence [33]. Note: 2012 data are for June, 2013–2016 data are projections.*

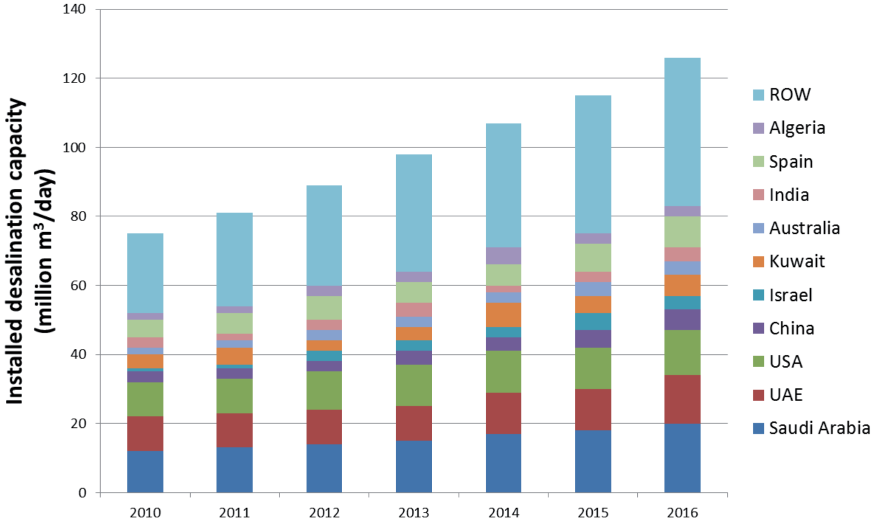

*FIG. 15. Cumulative installed desalination capacity, country specific projections, 2010–2016. ROW — rest of world. Source: Ref. [35]. Note: compound annual growth rate (CAGR) is 8.9%.*

long term. Increasing domestic energy consumption and growing demand in the global market stimulate oil rich and water scarce countries to consider the nuclear alternative in their energy sector, which, if chosen, can be followed by the use of nuclear energy for desalination [36].

Nuclear desalination is being seriously considered in South Asia due to its fast growing population and scarcity of fresh water resources. The ambitious three stage nuclear power programme in India is expected to provide the country with a lot of NPPs, many of which will be located near the seashore [37]. The Nuclear Desalination Demonstration Plant in Kalpakkam comprises two units operating with different technologies at a capacity of 6.3 million litres per day. Operational experience of both units of this plant as well as of a low temperature nuclear desalination plant in Trombay will demonstrate the prospects for nuclear desalination in India. It will also significantly affect the future plans of the Indian government for the development of its national nuclear desalination programme. Similar efforts are being made by Pakistan, which in 2010 launched its own nuclear desalination plant, connected to the Karachi NPP.

So far, the most significant experience in nuclear desalination has been accumulated in Japan, where this technology has been successfully applied at four NPPs [34]. However, the future of nuclear desalination in Japan strongly depends on the strategic decision about the overall prospects for the nuclear industry after the Fukushima Daiichi accident. Another country that might be interested in nuclear desalination in the future owing to the scarcity of water resources and advanced level of development in nuclear technologies is China, especially in northern and north-eastern regions.

An important expansion of desalination technology is the construction of floating nuclear powered desalination plants that can supply water to areas facing abrupt and severe shortages due to natural disasters or conflicts. An example of the role such plants can play is the use of the nuclear reactor of the USS Carl Vinson aircraft carrier to provide a water supply in Port-au-Prince (Haiti) after the devastating earthquake in 2010. Coastal areas naturally have unlimited access to salt water — and they are the areas most vulnerable to various natural disasters that are expected to become more frequent as a result of climate change. As currently around 44% of the global population lives within 150 km of the coast [38], these prospective changes could make floating desalination facilities important for the development of the world economy and international humanitarian efforts.

Nuclear energy can potentially be applied for hydrogen production in order to replace contemporary internal combustion engines with hydrogen fuel cells. Such changes would imply a major transformation in the transport sector and contribute to the achievement of global mitigation goals. The large scale deployment of hydrogen fuel cells will allow the gradual substitution of oil by hydrogen with near zero pollutant emissions [39]. In contrast to massive $CO_2$ emissions from modern transport driven by fossil fuels, the products of hydrogen fuel use will be only water and heat. The limiting factor for the introduction of hydrogen driven transport on an industrial scale is the lack of infrastructure such as fuel stations and production facilities.

Another possible application of nuclear energy is district heating, usually combined with electricity generation. The costs of such central heating systems, based on the experience of the Beznau and Gösgen NPPs in Switzerland, were proved to be comparable with those from fossil fuelled plants [40]. District heating with the use of nuclear power will become increasingly attractive if the costs of fossil fuels increase due to GHG mitigation policies.

Nuclear energy is expected to be applied to the extraction of hard crude oil as even in a hydrogen based economy there will be a need for fossil energy sources, e.g., in the petrochemical industry. Specific applications are tar sands in Canada (Athabasca tar sands in Alberta province) which comprise a significant share of global reserves [41]. Currently, the major energy source for oil extraction from tar sands is natural gas that is expected to provide the required heat and contribute to the growth of GHG emissions, owing to the projected fast increase of tar sands extraction. Nuclear energy offers a low carbon alternative. Possible options include the construction of conventional large reactors (such as the Canadian CANDU reactors) serving large tar sands extraction territories with energy or small reactors to be located closer to specific extraction areas. A design of a small reactor to power tar sands extraction was proposed in 2013 with the expectation of putting the first unit in operation by 2020 [42].

Another possible application could be a broader use of nuclear energy in maritime transport, specifically, for large tankers and container ships. The nuclear industry has had significant experience in maritime applications in navy programmes for many decades: in submarines (the first nuclear submarine entered service in 1955) and in aircraft carriers (the first launch was just a few years after the submarine). A specific application of nuclear technology is nuclear icebreakers, the first of which was constructed in 1959 to support transportation in the Arctic. Since the 1960s, nuclear technology has been applied in cargo ships (in the German built Otto Hahn, the Japanese built Matsu and the US built NS Savannah) and has demonstrated a perfect safety record. However, in recent decades nuclear powered ships have not found wide civilian applications for economic reasons. Since the late 2000s the interest in them has been gradually reviving, due to the necessity to limit GHG emissions from maritime transport [43]. To this end, the regulation of $CO_2$ emissions under the UNFCCC to mitigate climate change can make the use of nuclear powered maritime shipping economically more competitive.

Nuclear energy is expected to be used in space exploration as well, especially in Earth orbit applications (energy for launching and operating satellites); as an energy supply for space stations (mainly electricity); and to provide energy for outer space missions (of short, medium and long durations) [44]. Nuclear technology will be able to provide spacecraft and rovers with a long lasting energy source operational even in unfavourable conditions in distant parts of the solar system. The first step towards the use of nuclear reactors as engines is the application of radioisotope power systems to fuel space devices. The latest expedition to Mars by the Curiosity rover launched by NASA demonstrated the prospects for this technology in the exploration of other planets of solar system [45]. Curiosity operates on energy produced by a radioisotope power system using plutonium ($^{238}$Pu). Plutonium-238 is a non-fissile material and energy is obtained through the conversion of the heat produced from its decay. In contrast to solar batteries installed in the earlier rover Opportunity, such systems offer a steady energy supply and are therefore key to sending larger vehicles to Mars (Curiosity weights five times as much as Opportunity).

## 3.9. NON-CLIMATIC ENVIRONMENTAL BENEFITS

Apart from its contribution to climate change mitigation, the use of NPPs has other environmental benefits such as reducing the emissions of air pollutants which have negative health and environmental impacts on both local and regional scales.

NPPs emit virtually no air pollutants during their operation. In contrast, fossil fuel power plants are among the major contributors to air pollution. According to the World Health Organization (WHO), air pollution is a major human health risk factor. Outdoor air pollution due largely to fossil fuel burning causes over one million premature deaths worldwide each year. Air pollution also contributes to health disorders from respiratory infections, heart disease and lung cancer [46]. New evidence indicates that the adverse health effects of air pollutants occur in some cases at lower air pollution concentrations levels than previously thought. The range of health effects is also broader. They now include impacts on neurodevelopment and cognitive function. Air pollution is increasingly linked to chronic diseases such as diabetes [47].

A recent joint study from the NASA Goddard Institute for Space Studies and Columbia University's Earth Institute examined the historical and potential future role of nuclear power in preventing air pollution related mortality. The study estimates that globally, nuclear power has prevented over 1.8 million air pollution related deaths that would have resulted from fossil fuel burning between 1971 and 2009. The largest shares of prevented fatalities are estimated for European OECD Member States and for the USA. Furthermore, the calculations show that the deployment of nuclear power can make an even higher contribution to reducing air pollution related deaths in the future. Projections from a simulation model assess hypothetical scenarios in which all nuclear capacity would be phased out and substituted by fossil fuels. If all nuclear electricity production projected by the IAEA in 2011 (that is, after the Fukushima Daiichi accident) [48] for the period 2010–2050 were to be delivered by coal fired power plants, the number of premature air pollution related deaths could increase by 4.4 million for the low IAEA projection and by 7.0 million for the high projection. The large scale expansion of natural gas use would likewise cause far more deaths than the expansion of nuclear power. In the all gas case (generating the projected nuclear electricity by gas fired power plants instead), the resulting additional human deaths are estimated at 0.4 million (low projection) and 0.7 million (high projection). The overall conclusion of the study emphasizes the importance of retaining and expanding the role of nuclear power in the near term global energy supply [49].

Apart from health damages and increased mortality, air pollutants travelling long distances cause acid rain. At the regional scale, 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. Acid rain is caused by sulphur and nitrogen compounds, and fossil fuel power plants, particularly coal power plants, are the primary emitters of the precursors of those compounds. Sulphate and nitrate, transported across national borders, also contribute to haze, strongly limiting visibility and reducing sunlight, and possibly changing the atmospheric and surface temperatures as well as the hydrological cycle [50].

An analysis of the Ecoinvent database [18] shows that nuclear power is among the power generating technologies with the lowest acidification potential. The Ecoinvent database contains up to date Life Cycle Inventory (LCI) data. Figures 16 and 17 present the acidification potential in g $SO_2$ equivalent per kW·h electricity generated by types of fossil and renewable or nuclear technologies, respectively. The underlying calculations take into account already implemented technical solutions to reduce emissions from energy technologies with high acidification potential, while any further reductions can be achieved at costs varying significantly across countries.

Environmental and health damages which occur due to electricity production but are not reflected in the price of electricity are called external costs. The latest systematic analysis of such external costs monetized damages due to (a) climate change; (b) 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; (c) health impacts of heavy metals; and (d) health impacts of radionuclides [51]. Figure 18 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,

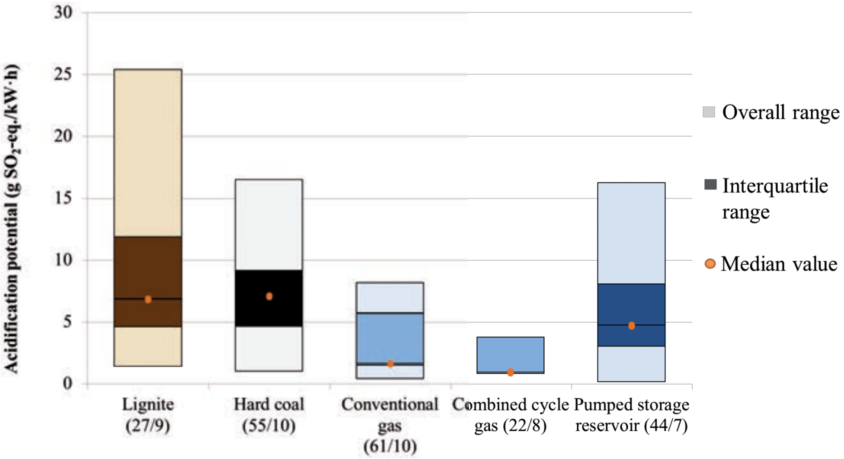

*FIG. 16. Acidification potentials of emissions from fossil technologies in g $SO_2$-eq. per kW·h by type of technology. Data source: Ref. [18]. Note: The interquartile range includes half of the calculations around the median of the overall range..*

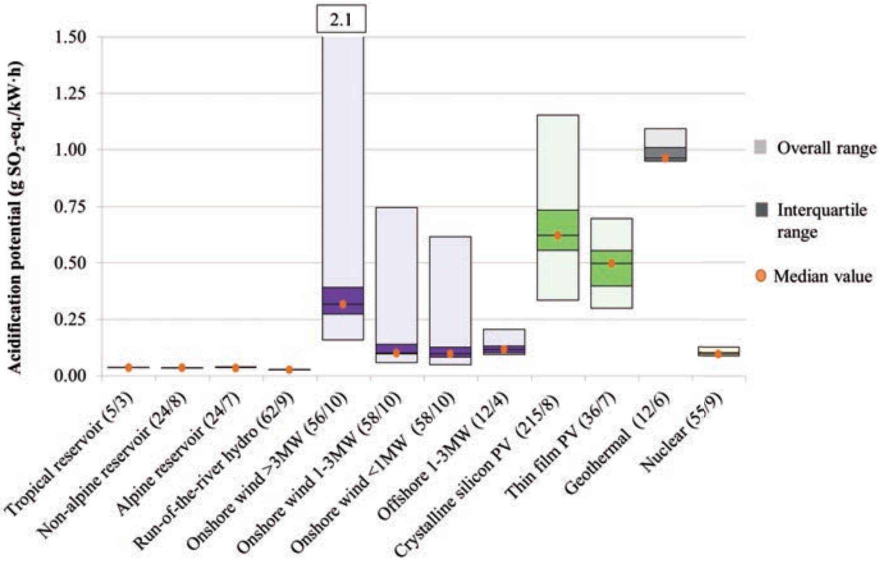

*FIG. 17. Acidification potentials of emissions from renewable and nuclear technologies in grams of $SO_2$-eq. per kW·h by type of technology. Data source: Ref. [18]. Note: The interquartile range includes half of the calculations around the median of the overall range.*

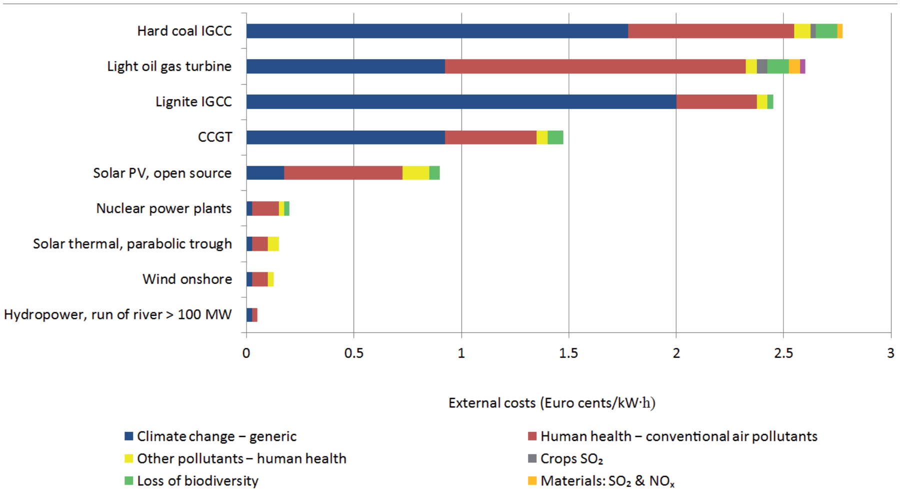

*FIG. 18. Estimated average external costs in the EU for selected electricity generation technologies between 2005 and 2010. IGCC: Integrated Gasification Combined Cycle; CCGT: Combined Cycle Gas Turbine. Based on: Ref. [51].*

i.e., from construction to decommissioning, as well as the fuel cycle from mining to waste disposal.

Fossil based electricity generation has considerably higher external costs than nuclear power and renewable technologies. Through safety and environmental regulation the nuclear industry has already internalized the bulk of its potential external costs. Economic rationale calls for the internalization of all external effects. Policies to include all external costs of all technologies would allow the economic and environmental benefits from nuclear power generation to become more visible. This would be a significant addition to the benefits of using nuclear energy to mitigate $CO_2$ emissions from the energy sector.

### 3.10. MACROECONOMIC BENEFITS

Nuclear power can play an important role in driving sustainable economic growth by meeting growing electricity demand, contributing to GHG emissions reduction and generating economic activity within and beyond the power sector. A vast literature exists on the correlation between energy consumption and change in GDP, while a few studies specifically cover the implications of nuclear power technologies on growth [52]. Despite not being conclusive, the literature shows evidence that the increased consumption of nuclear power has a positive effect on economic growth. There are two mechanisms making this possible. First, nuclear generated electricity fuels the development of a country's economic activity, particularly where nuclear power represents a large share of total electricity consumption. Second, nuclear plant investment and operation directly stimulate economic activity and create new employment.

Nuclear power requires a large upfront investment (see Section 4.2). The estimated overnight capital cost of a 1 GW(e) NPP is about $2–6 billion, a large amount of money compared to the GDP of most developing countries. For a sense of scale, in 2010, fifty countries had a GDP lower than $7 billion, and the GDP of about half of the world's countries is below $20 billion (see Fig. 19 based on Ref. [53]). For these countries, small modular reactors at a cost of about $1 billion would be more appropriate.

A country's GDP will ideally be large enough to allow sufficient savings to cover the investment and the costs associated with establishing and maintaining the necessary physical and institutional infrastructure, and to cover the liability for potential environmental and health damage in case of an accident. To date, Pakistan is the only country with a GDP of less than $50 billion (in 2000) that has ever built an NPP. Moreover, the cost structure of nuclear power implies that its levelized cost is highly sensitive to an increase in the cost of capital. For this reason, the economy of a country building a nuclear plant will ideally be

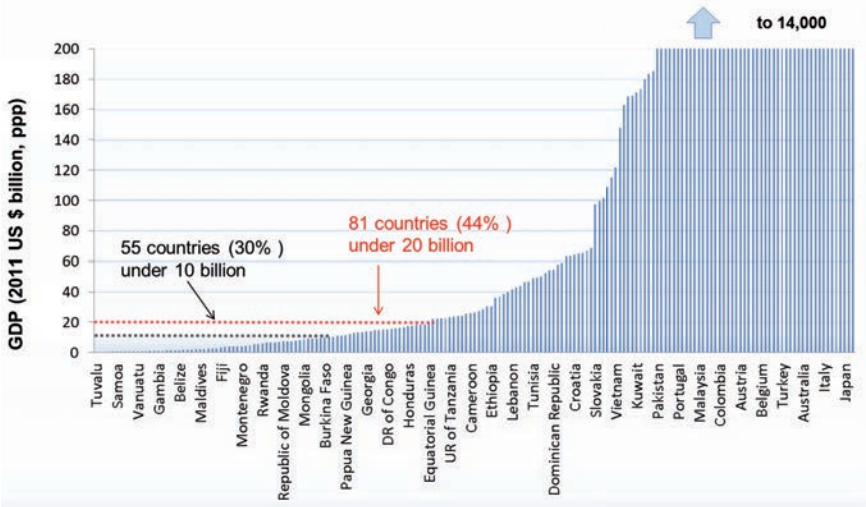

*FIG. 19. Capital investment in nuclear power and countries' GDP. Data source: Ref. [53]. Note: Only selected countries are named along the horizontal axis. DR — Democratic Republic; UR — United Republic.*

strong enough to overcome an unexpected increase in the cost of an NPP. Good macroeconomic conditions also facilitate a country's ability to borrow the funds needed at competitive costs.

Price stability is an important precondition for investing in nuclear power, as it prevents unexpected increases in construction costs and unforeseen changes in future cash flows. Financial calculations are made in real terms, as net-present-value discounting includes expected price changes. With a timeframe of several years, unexpected inflation rates can significantly modify the profitability profile of a nuclear power project. Mitigating mechanisms to reduce inflation risk exist, but at a cost. On the other hand, nuclear power may have positive implications for a country's price stability, due to its potential substitution effect on imported fossil fuels. Nuclear power also boasts low fuel price sensitivity, so electricity prices are not strongly affected by uranium price volatility. The price of nuclear generated electricity is therefore more stable than other baseload technologies. Electricity price stability leads to low inflation and, thus, to a favourable monetary policy context for economic growth.

The employment effects of nuclear power are an important driver for the construction of new facilities. Nuclear investment directly creates high skilled employment in construction, operation, nuclear fuel cycle and supporting industries. Additional jobs are created in areas such as design, siting, licensing, oversight, waste management, decontamination and decommissioning, etc. At the same time, nuclear power also generates indirect employment in induced non-nuclear industries. Estimates of the employment effects of NPPs in the USA [54] indicate that, for each directly created job in construction, manufacturing or operations for a new NPP, four additional indirect or induced non-nuclear jobs are created in the economy. Other studies in various countries [52, 55] stress the job multiplying effect of nuclear power. Despite the fragmentation of available data and the need for further research on the topic, the positive employment effect of nuclear power appears indisputable, especially at the local level. There are estimates that the yearly contribution to the local community of the average NPP in the USA is approximately \$470 million in sales of goods and services, in addition to \$40 million in total labour income [56].

Typically, the construction of a new NPP initially implies a certain stress on a country's current account balance, due to the necessary imports of nuclear technology, expertise and fuel, especially in the case of States building their first NPP. In the medium run, up to the start of operations, the construction of a new NPP is therefore likely to worsen the current account situation of a country (see e.g. Ref. [57]). The negative current account effects of the initial investment are mitigated if the new plant allows for reduced future energy imports (or even for new exports). A country's reserves of foreign currency must also be large enough to cover the imports necessary to undertake a new nuclear power project. Current account benefits may derive when new nuclear electricity displaces some fossil fuels.

If the country is a net exporter of the displaced fuel, it can export more fuel, improving its balance by adding foreign reserves. If the country is a net importer, it can import less fuel, also improving its account balance by reducing the demand for foreign reserves. In the case of fossil fuel importing countries, the potential benefit for improving their current account balance by displacing imported fuel with nuclear power is significant. Global fossil fuel prices followed a rising trend between the late 1990s and 2008. Expenditures on oil and gas imports triggered by a spike in fuel prices reached more than 6% of GDP in countries like India. Fuel diversification strategies, including nuclear power, contribute to reducing fossil fuel dependency and the consequent price risk and to strengthening a country's energy security.

Due to the low fuel price sensitivity of nuclear power's cost structure, uranium price fluctuations have a relatively small balance-of-payments impact, compared to fossil fuel based electricity generation. Case by case analysis is needed to assess the current account effect of a new power plant. In general, the construction phase is likely to generate a negative current account contribution (unless foreign direct investment is involved), due to the large imports of specialized technology and expertise. On the other hand, the operation phase would cause a neutral-to-positive impact (again, without foreign direct investment), depending on the energy trade profile of the country, and the economic impact of the nuclear power programme on the country's productive and consumption structure.

An increase in government debt financing might be necessary, due to the high investment required for a nuclear power project and to the relevant role typically played by governments in its financing scheme. The cost of new debt issued depends on the country's debt rating. Either directly — through new debt emission to finance the project, or indirectly — by determining the discount rate to apply for present value calculations, government debt rating is an essential factor in the profitability of a nuclear power project.

Finally, nuclear power contributes to enhance a country's human capital, as it requires highly educated and trained personnel. Engaging in nuclear power implies a long term human capital investment, with potential driving effects on economic growth, via increased productivity within and beyond the electricity sector. The resulting enhanced human capital in the nuclear sector and induced industries increases labour productivity and has dynamic spillover effects on other related industries.

In summary, macroeconomic stability will ideally be in place for a country to effectively manage the economic risks and challenges of nuclear power. Macroeconomic factors and implications must be considered to make an informed decision on initiating or expanding nuclear power use. With favourable macroeconomic conditions in place, nuclear power can bring important economic benefits to a country's economy.

# 4. SUPPLYING NUCLEAR POWER

## 4.1. THE ECONOMICS OF NUCLEAR POWER

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, which happen to be predominantly positive in the case of nuclear power. The costs of decommissioning and waste disposal can be collected and accumulated throughout the operating lifetime of the power plant, whereas the social benefits of avoided $CO_2$ 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 the private and social costs of fossil competitors) represent another factor that discourages potential investors.

NPPs have a front loaded cost structure (a feature shared with most renewables), that is, they are relatively expensive to build but relatively inexpensive to operate (compared with fossil based generating capacities). The low share of uranium fuel costs in total generating costs protects plant operators and their clients against resource price volatility. Thus, existing well run NPPs continue to be a generally competitive and profitable source of electricity. For new construction, however, 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 the country in question 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 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 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 and political support for nuclear power. All these factors vary across countries.

In the Republic of Korea, the relatively high costs of alternative electricity sources benefit nuclear power's competitiveness. In China and India, 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 Emissions Trading Scheme (EU ETS) have improved the business case for new NPPs. In the USA, the 2005 US Energy Policy Act significantly strengthened the incentives for new construction. Its provisions, including Government coverage of costs associated with certain potential licensing delays, loan guarantees 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 file 18 applications for combined construction permit–operating licences for 28 reactors as of August 2013 [58]. The large volume and low price of shale gas has created a new situation concerning the relative costs and cost competitiveness in the USA.

The OECD IEA and NEA regularly prepare studies on the projected costs of electricity generation. The latest edition includes the largest number of technologies from the largest number of countries in the history of the study: almost 200 power plants in 17 OECD and 4 non-OECD countries. The study presents levelized costs of electricity (LCOE) calculated on the basis of a common methodology using data supplied by countries and organizations [59].

Figures 20 and 21 present an overview of the projected LCOE for six major electricity technologies. The levelized costs are calculated using two discount rates: 5% (Fig. 20) and 10% (Fig. 21). The former is more relevant for government investments while 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 baseload generation technologies (coal, gas and nuclear) largely overlap within the $50–100 per MW·h range [59]. The LCOE for intermittent renewable technologies shown in Figs 20 and 21 do not include energy balancing costs, which add $1–$6 per MW·h to the LCOE for intermittent renewables up to a system penetration of around 20% [59].

The US Energy Information Administration updates the National Energy Modelling System annually with the most recent generic cost estimates for new electricity generating technologies and includes LCOE calculations in a related support document. Although these cost estimates are US specific, they provide another objective source of cost information to compare the LCOE of various generating technologies (see Fig. 22). As with the OECD IEA and NEA study, the US Energy Information Administration finds that nuclear LCOE is well within the range of costs of other baseload technologies, comparable to conventional coal, but less expensive than advanced coal with CCS and more expensive than natural gas combined cycle.

There is insufficient information for estimating the incremental costs of the enhanced safety measures resulting from the international and national safety

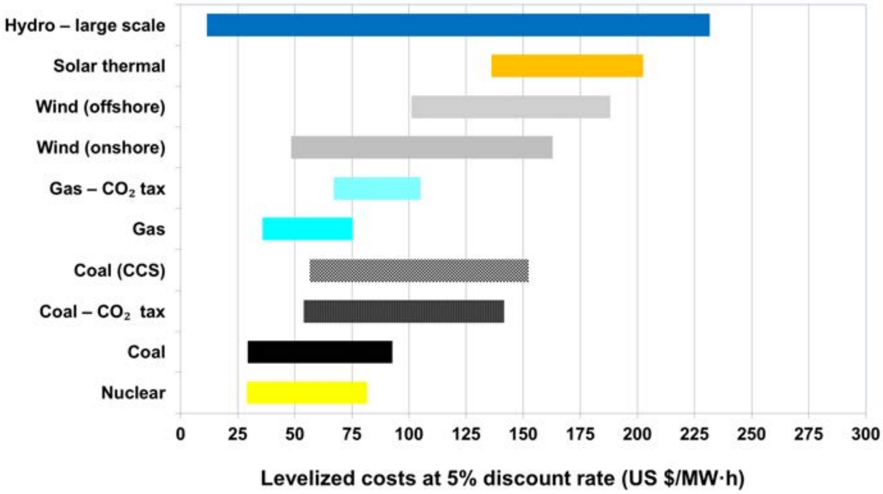

*FIG. 20. Ranges of LCOE associated with new construction at 5% discount rate. Data source: Ref. [59].*

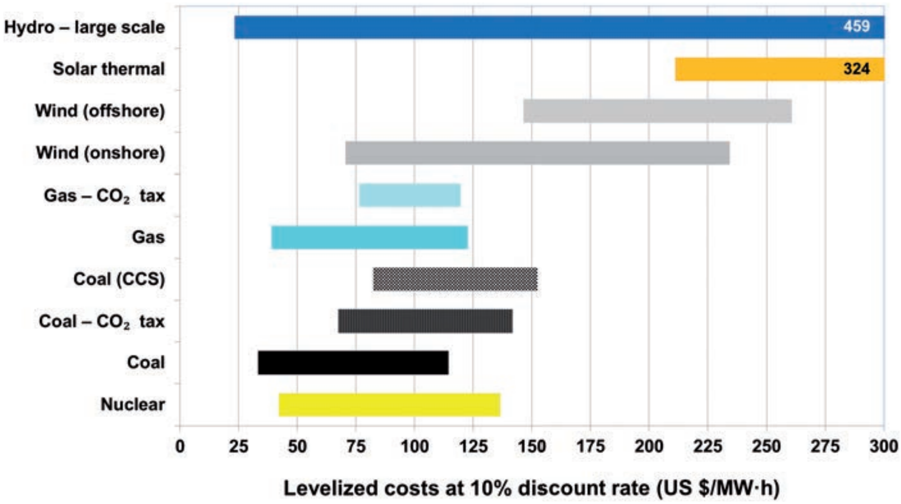

*FIG. 21. Ranges of LCOE associated with new construction at 10% discount rate. Data source: Ref. [59].*

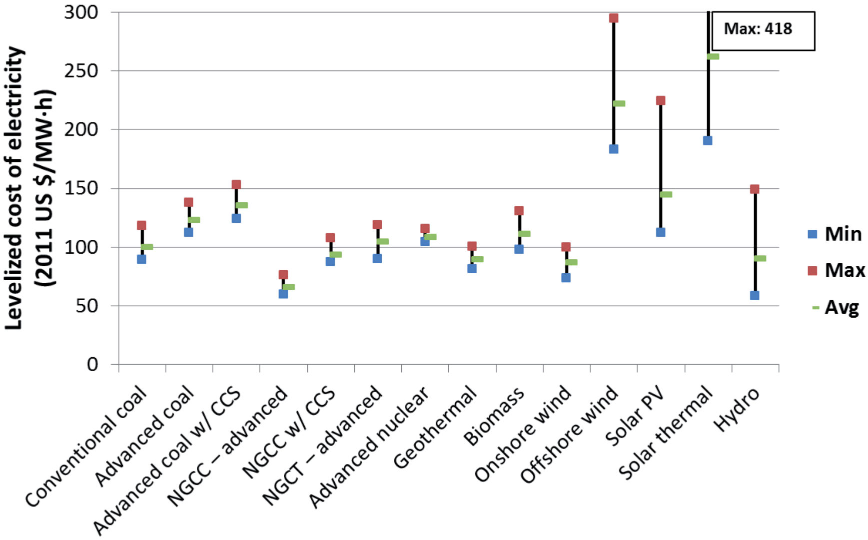

*FIG. 22. LCOE for new electricity generating technologies in 2011 across 22 US regions. Data source: Ref. [60]. Note: the minimum, maximum and average LCOEs across the regions are presented. NGCC: natural gas combined cycle; CCS: carbon dioxide capture and storage.*

action plans after the Fukushima Daiichi accident (see Section 5.2). However, when spreading the one time investment costs of improved safety measures over the long lifetime of NPPs, the LCOE of nuclear power is not likely to increase significantly. The choice among these technologies will be determined by which of them is more favourable under the prevailing geographical and natural resource conditions, technological capabilities, electricity market regulation schemes and sociopolitical preferences.

The impacts of $CO_2$ costs (carbon tax or emission permits) on electricity prices have already become evident in the EU in recent years and are expected to increase with a tightened emissions cap [61]. For example, both the United Kingdom and Germany are establishing compensation schemes to industry to offset the increase in the cost of electricity as a result of the EU ETS. The UK government estimates that industry will receive compensation of £250 million in 2013 [62]. The German government estimates that its industry will receive €350 million [63]. Increasing $CO_2$ costs will also trigger changes in LCOE relative to those depicted in Figs 20 and 21. It is estimated that, at a $CO_2$ 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 coal based electricity reaches more than 20% at a $CO_2$ cost of $30/t.

## 4.2. NUCLEAR INVESTMENT COSTS

In a $CO_2$ emissions reduction portfolio, nuclear energy belongs to the options (together with large hydropower plants) that involve large investments costs but supply mitigation benefits for half a century or longer at low running costs. NPPs have a high upfront capital cost but relatively low fuel costs and operational costs when compared with large scale generating units relying on fossil fuels. The total investment cost typically represents some 60% of the total generation cost of nuclear electricity. A good indicator of the magnitude of investment is the overnight costs, including pre-construction (owner's), construction (engineering, procurement and construction) and contingency costs, but excluding interest during construction (see Section 4.3).

A wide range of cost estimates have been published by diverse sources in recent years. This cost uncertainty and the size of investments are very challenging especially for countries considering their first NPP. For them, a good understanding of the true total investment cost of the project and its dynamics over time is especially important when evaluating the relative competitiveness of generating capacity additions.

Most recent evidence lends support to the estimated overnight costs for new nuclear power projects in the range between $1556/kW(e) and $5863/kW(e)

— with most well above \$3000/kW(e). Within this range, there are marked differences in the overnight cost levels across countries. The lowest estimates at \$1748/kW(e) and \$1556/kW(e) are those reported for China and the Republic of Korea. The high end estimates in Western Europe and the USA range from roughly \$3500/kW(e) upwards. Japan and the Russian Federation take a mid-range position with overnight cost levels of around \$3000/kW(e) [64]. The investment cost structure of a NPP is skewed towards the engineering-procurement-construction (EPC) component which represents around 80% of the total overnight costs. The remaining 20% are owner's costs and various contingencies.

The significant variation in investment cost levels for new nuclear power projects — between and even within countries — has a variety of reasons, ranging from site characteristics and plant size to country specific financial, technical and regulatory boundary conditions. The typically rather high overnight capital costs of a first-of-a-kind reactor tend to decline when moving towards the construction of a fully mature nth-of-a-kind plant. Recent evidence from China, France and the Republic of Korea suggests that both economies of scale and benefits of learning from building multiple units, most importantly accumulated experience in the recent building of reactors and the project management of large civil engineering projects, can lead to lower capital costs [65]. However, the large disparity in estimated overnight costs is not specific to nuclear energy. A similar difference — a factor of one to three — can be observed for other electricity generation technologies such as gas [64].

Rising capital costs for NPP projects have been reported in recent years in academic studies, government reports and the general media. The 2011 University of Chicago study assesses major cost drivers contributing to the overnight cost increases in the US. Current values presented in this study are \$2080/kW(e) higher than the earlier cost estimates published in 2004 [66, 67]. Four key factors account for the higher estimates: (a) increasing technical maturation of the engineering design; (b) improved accounting for the owner's costs; (c) the run-up in supply chain pricing; and (d) significant premium in fixed or firm price engineering-procurement-construction contracts. The authors stress that early stage overnight capital cost estimates in the 2004 study might be significantly underestimated due to the limited amount of information available on the scope of the owner's cost structure at that time. These costs are particularly sensitive to site specific factors required for the construction of roads, warehouses or the provision of security services.

Figure 23 presents ranges of the overnight construction costs for six main power technologies. The majority of the reported nuclear projects are in a relatively narrow range (within one standard deviation of the mean) compared to renewable power technologies. The variation in estimates reflects the importance of country specific conditions.

The competitiveness of nuclear energy depends on several factors, with the cost of capital being among the most important ones. The relevant indicator is the total investment costs, including overnight costs and interest during construction.

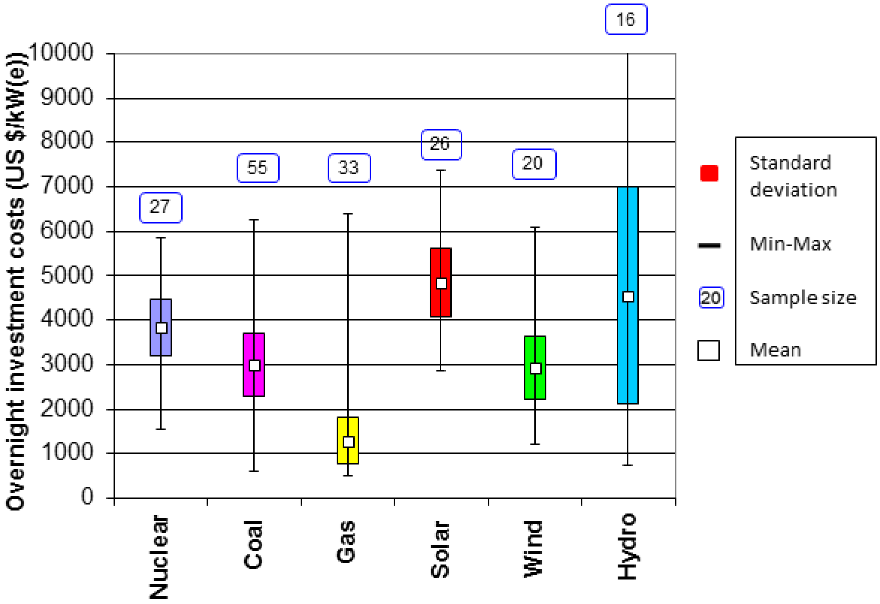

*FIG. 23. Overnight investment cost estimates for the main electricity generation technologies. Data source: Ref. [68]. Note: This chart is based on data compiled from sources published between 2010 and 2013.*

When interest rates 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. Figure 24 presents ranges of the total investment costs for six main power generation technologies at 5% interest rate.

Higher discount rates disfavour energy power investment projects with high front end costs and a long return period such as nuclear power. However, a breakdown by regions shows that nuclear energy remains competitive in OECD Member States in Asia and North America even at the 10% discount rate (see Refs [64, 69]), although new developments in the shale gas market have changed relative competitiveness.

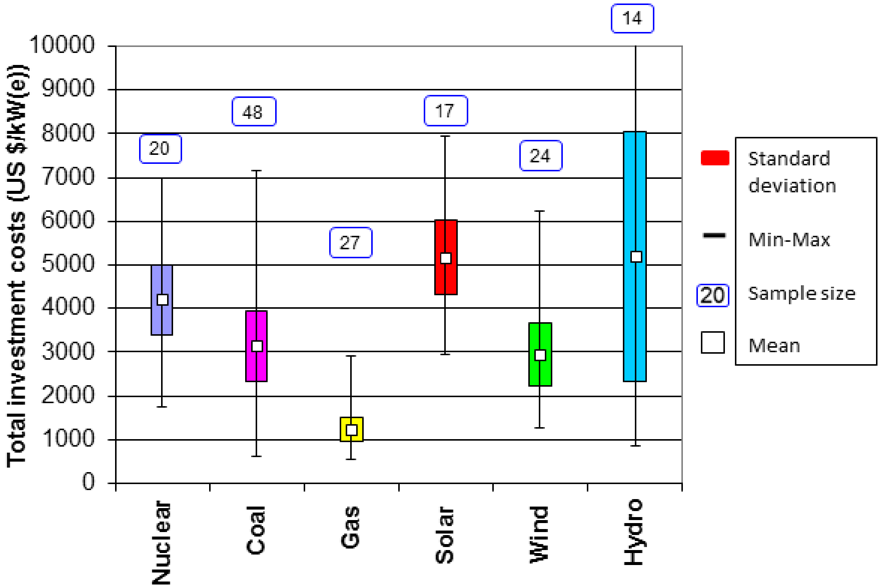

*FIG. 24. Total investment costs for main electricity generation technologies at 5% interest rates. Data source: Ref. [64].*

Some recent calculations confirm that the construction period is an important factor determining the cost competitiveness of nuclear power compared with other energy technologies. Limiting construction time from seven to four years alone (while holding the overnight cost constant) has been shown to reduce the total capital costs by 13% at 10% annual interest rate and by 7% at 5% interest rate [69] (see also Section 4.3).

## 4.3. FINANCING NUCLEAR POWER INVESTMENTS

Even if nuclear power is demonstrated to be an economically efficient option to expand a country's energy supply portfolio and reduce GHG emissions, implementation requires the resolution of several issues, ranging from construction and operation licences to securing skilled labour for construction and operation. One of the key issues to resolve is financing.

Nuclear power generation projects face particular challenges when it comes to financing. Although NPPs enjoy relatively low and stable operating costs, the upfront capital investment costs can be considerable, and are incurred over relatively long construction periods — resulting in potentially significant amounts of interest during construction. Figure 25 compares the relative amounts of interest during construction (IDC) incurred by two projects which are of identical value ($5.75 billion) in terms of overnight costs (costs of materials, equipment, labour, etc.), but which differ in terms of project duration and the rate of interest paid on financing. Each bar in Fig. 25 is composed of two ‘stacked’ parts, a blue part representing the overnight cost expenditure in a given year and a red part representing the total IDC which will have been incurred on that expenditure by the time the project is complete. The darker bars represent a seven year construction project at an interest rate of 10% per year, and the paler bars a five year construction project at an interest rate of 5% per year. The bars on the far right compare the total amounts of IDC incurred by these two projects: almost $2.8 billion in the 7 year at 10% case, versus $1 billion in the 5 year at 5% case.

In addition, the scale of investment required to take a single nuclear power project to successful completion can exceed that to which all but the very largest entities (governments and the largest corporations) are willing to expose their finances. The cost of the ultimate disposal of used fuel has traditionally been a concern to potential investors as well.

In addition to specifically nuclear challenges such as these, putative nuclear investments also face the more general challenges faced by power investments

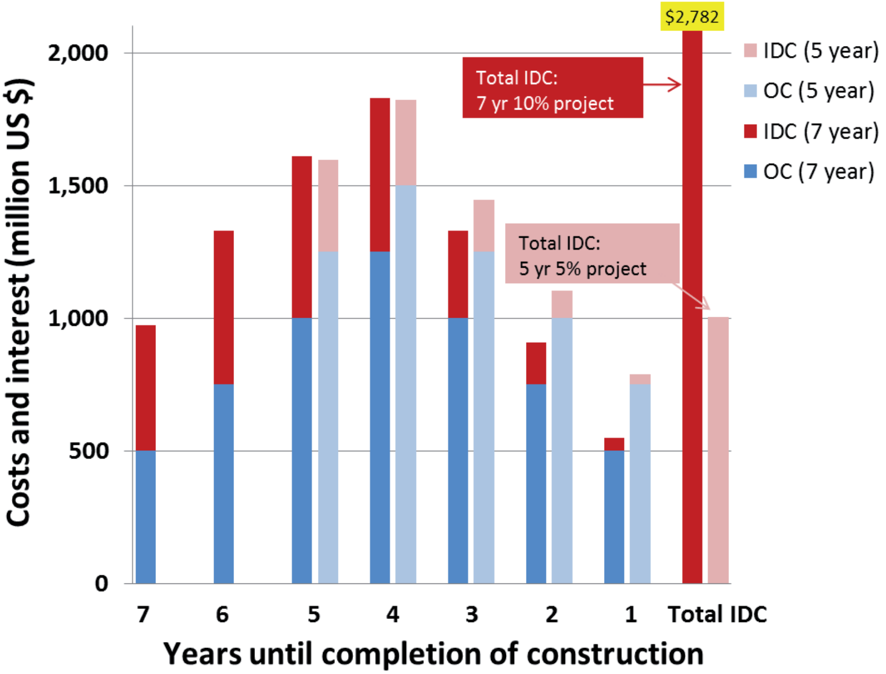

*FIG. 25. Overnight costs (OC) and interest during construction (IDC) for two cases.*

today, many stemming from the crisis of 2008, from which a recovery has not been achieved (particularly in Europe) at the time of writing.

Notwithstanding these specific and general challenges, it is apparent that it is still possible to finance nuclear investments. Indeed, a number of innovative models are beginning to emerge.

The build–own–operate (BOO) model — such as is currently being implemented in Turkey's Akkuyu project — is often associated with project finance, but can be distinct. Amongst global nuclear technology vendors, the Russian Federation's Rosatom has embraced the BOO framework most clearly as a model for its international ventures. In August 2011, Rosatom set up Rusatom Overseas, which will act as the developer of Rosatom's foreign projects which are implemented according to the BOO model. The key to this model is a concession such as a power purchase agreement. In the case of Akkuyu, the state owned electricity wholesaler TETAŞ will be the counterparty to the owner-operator Akkuyu Electricity Generation Joint Stock Company in such a power purchase agreement.

A similar concession type agreement is being contemplated by the UK's Electricity Market Reform legislation, which makes provision for a contract for differences arrangement whereby nuclear operators will effectively be guaranteed a price for the electricity which they generate. Analyses carried out in that context for the UK government suggest that presence of a power purchase agreement can reduce borrowing costs for a power project by as much as 2 percentage points [70].

Another innovation within the context of UK government efforts to ensure a nuclear generation component within its electricity supply mix has been its willingness to provide some certainty on back end liabilities. In particular, the UK has proposed to remove what investors have often viewed as a potentially unlimited downside for the costs of used fuel (and 'intermediate' level radioactive waste) via a mechanism which allows operators to enter into so called 'waste contracts' which will cap these costs on a per unit basis [71]. This represents a significant movement towards improving the nuclear investment proposition.

The role of export credit agencies will continue to be crucial. Traditionally, export credit has played a major role in financing NPPs. Typically, 85% of the value of goods and services exported can be financed, plus a percentage of third party and local costs, and up to 100% of interest during construction can be financed. For multi-country contracts, export credit agencies can cooperate to deliver joint financing, and they can also offer the longer term loans which may be increasingly difficult to obtain from banks under the terms of planned regulatory changes pertaining to that sector. In fact, export credit is becoming increasingly unregulated, in the sense that the volume of potentially available credit which is not subject to the OECD framework (which sets maximum loan durations, and minimum interest rates for loans — see Ref. [72]) now constitutes just one third of global government export credit. The availability of large volumes of export credit from countries such as China which are not subject to OECD restrictions is a significant development.

There is a growing demand on the part of potential nuclear technology customers for vendors of such technology to take an equity stake in projects. For example, a United Arab Emirates contract for the design and construction of four 1400 MW(e) NPPs provides equity shares for ENEC & KEPCO. Lithuania sought equity investors for its Visiganis project in early 2011, and the then Senior Vice President of vendor GE-Hitachi noted in late 2011 that such requests were becoming more the norm [73].

Notwithstanding the emergence of the innovative financing models outlined above, the availability of finance for new nuclear projects will depend on government support in both developed and developing countries. By taking on part of the construction cost by awarding loan guarantees, government can lower the cost of finance. Other measures to assist the financing of building new NPPs could include the uniform application of $CO_2$ emission penalties (carbon tax or tradable permit system) and green credits.

## 4.4. CONSTRUCTION CAPACITY EXPANSION

Concerns have been raised that that nuclear energy cannot play a significant role in climate change mitigation because there is no sufficient manufacturing capacity to supply the necessary equipment, especially the reactor vessels, related machinery and instrumentation and other nuclear specific components for which the manufacturing industry must satisfy the highest safety and quality standards. A related concern is the lack of skilled labour force to build, operate and regulate a fast expanding nuclear industry.

If a massive increase in demand for nuclear energy occurs during the next decades an important question is whether the industry will have enough capacity to construct the required number of power plants within the requested period of time. The last period of large scale NPP construction was in the 1980s and since the 1990s the rate of nuclear expansion has been relatively low, especially in Western Europe and North America.

Currently, the nuclear manufacturing industry is fundamentally different from what it used to be in earlier eras. In the 1970–1980s the components for NPPs came mostly from national producers (usually – from integrated suppliers like Westinghouse) with minimal use of imported components, whereas the modern industry is highly internationalized with the major components being manufactured by companies around the globe. Vendor companies at the current stage of nuclear manufacturing development specialize mostly in design and engineering work. This internationalization often means a high level of technology transfer as major multinational vendors manage the construction of new NPPs in different countries (e.g. the transfer of technology of the project AP1000 from the USA to China) [74].

Among the most significant manufacturing capacities needed for NPP construction are forging presses for the production of the pressure vessels. The capacity of presses needed to produce contemporary designs of pressure vessels is around 15 000 t to handle steel ingots of 500–600 t. Significant capacity in this sphere is currently operated by China, Japan and the Russian Federation. Additional heavy forging capacity is expected to be put in operation in China, the Czech Republic, France, Japan, the Republic of Korea and the Russian Federation as current reactor designs have much more advanced requirements than older ones (around 8000 t presses operating with 300 t ingots). Internationally recognized standards for production of advanced nuclear equipment are the accreditation by the American Society of Mechanical Engineers (ASME) according to the ASME Boiler and Pressure Vessel Nuclear Codes and Standards, the French standard RCC-M and the ISO 9001 standard.

The nuclear industry shows a significant potential for capacity expansion if needed. A major Japanese producer JSW (Japan Steel Works Ltd) in 2007 had the capacity at its Muroran plant to produce four reactor pressure vessels with the necessary additional components per year, but this capacity was increased threefold to twelve vessels by 2011 [75]. Other important Japanese producers are the IHI Corporation, Mitsubishi Heavy Industries Ltd, Kobe Steel, Babcock-Hitachi KK, and the Japan Casting & Forging Corporation (JCFC), which in 2010 launched its 13 000 t press [76]. Among the most important producers of components for nuclear industry in the Republic of Korea is Doosan Heavy Industries, which launched its 17 000 t heavy forging press in 2010. Doosan Heavy Industries is also a major example of the internationalization of nuclear manufacturing as they bought the turbine producer Skoda Power (Czech Republic) in 2009. Chinese industry is expected to be able to produce seven sets of pressure vessels and steam generators per year as of 2013 (in comparison with 3–4 in 2007) and twenty sets per year by 2015. In 2013, the major producers of reactor equipment were China First Heavy Industries, China National Erzhong Group, and Shanghai Electric Heavy Machinery. Despite this impressive growth, China still has some limitations in the production of steam valves and large pumps — equipment for AP1000 reactors is imported from the UK [74]. India also has its own production facilities for nuclear pressure vessels at Larsen & Toubro Ltd, which operates a 9000 t press and plans to construct a 15 000 t facility.

The major Russian Federation producer OMZ’s Izhorskiye Zavody has a capacity to produce 3–4 reactor vessels per year after its modernization in 2011 (previously its capacity was 2 vessels per year), which generally corresponds to the needs of the Russian nuclear state corporation Rosatom [77]. Other producers of nuclear equipment in the Russian Federation are also aiming to manufacture components necessary for four reactor sets per year (e.g. machine building plant ZiO-Podolsk). Another reactor pressure vessel producer is the Energomash plant in Volgodonsk, which is expected to produce necessary equipment for a planned NPP in Belarus.

In Europe, the French conglomerate Areva has significant production facilities for the manufacturing of large forged parts for NPPs, and after the purchase of SFARSTEEL in 2006, it operates 11 300 t (able to forge 360 t ingots) and 9000 t forging presses [78]. A capital spending programme for the construction of another new 9000 t press was launched in April 2012. The UK's main producer Sheffield Forgemasters International operates a 10 000 t press (300 t ingots) and the German producer Saarschmiede commissioned a 12 000 t press (370 t ingots) in 2010. Important nuclear manufacturing facilities are located in Italy (Ansaldo Nucleare, SAFAS) and Spain (Equipos Nucleares SA). Another major European producer is Pilsen Steel (formerly Skoda Steel), which has been owned by United Group S.A. since 2010, and which operates a 10 200 t press and has significant experience of the production of complete sets of equipment for VVER-type reactors (pressure vessels, internals and control rod drive mechanisms) [79]. In general, a recent trend towards the expansion of manufacturing facilities for the production of the most advanced parts of NPPs, especially in East Asia, shows that in case of the major growth of the industry, manufacturing capacity will be increased as needed.

Another prospective limiting factor for the growth of nuclear industry is the labour force. Engineers and skilled workers who were just starting their careers in the 1980s (during the time of a nuclear expansion) are already at pre-retirement age, which inevitably leads to concerns about the ability of the nuclear industry to adequately respond to the energy challenges of the twenty-first century due to the lack of a well prepared labour force. The IAEA estimates that around 2500 workers and over 800 engineering, regulatory, startup, management, quality assurance and control personnel are needed for the construction of a 1000 MW reactor unit [74]. In addition to this, 300–500 companies supply materials and equipment.

Another factor, which can be treated as hampering the expansion of the nuclear industry, is that the major share of its growth is expected in countries with limited or no previous experience in the nuclear sphere. Obviously, such states will have to rely substantially on the help and experience of countries with advanced programmes, which have limited labour resources themselves [80]. Most likely these nuclear newcomers will not be able to manufacture the most technologically advanced parts of the reactor for their first NPPs.

However, this argumentation does not consider the fact that during the period when nuclear was fast expanding (after the oil crisis in 1970s) the industry also lacked the necessary labour force but was able to quickly train it. If the demand for nuclear energy grows in a carbon constrained world, economic incentives would stimulate the prompt expansion of existing companies operating in the nuclear sphere and the creation of new ones. All these organizations will inevitably focus on the formation of the new pool of labour force.

New workers without previous nuclear construction experience will definitely need additional training. However, construction equipment and methods used for many of the NPP structures, systems and components are quite similar to those used for other large industrial projects such as conventional power plants, refineries and chemical plants. Moreover, about 30% of the total NPP investment cost is typically related to civil construction and erection on-site, including site excavation, the construction of utilities and support infrastructure, system installation comprising mechanical and electrical components and other elements [74]. This allows the use of the experience of local companies specializing in the construction of ports, complex buildings and hydro projects. In case of the mass construction, NPPs will likely be standardized, which, coupled with expected design simplification, will ideally make the preparation of workers and engineers easier and faster [81].

Developing countries will, during the next decades, face a strong growth of energy demand and, being located mostly in regions with warm climates, will be severely threatened by the process of climate change. Industrializing economies and the existence of vast reserves of labour force are likely to provide local nuclear programmes with the necessary resources. Positive previous industrialization experience in various branches of the economy shows that in case of real need, certain industry can be advanced within very tight timeframes. There are no special factors that make nuclear an exception to other high tech branches, especially in the case of significant national nuclear programmes, which will make participation in this field attractive to local companies.

Another prospective driver of global nuclear industry expansion should become the enhancement of international cooperation both in manufacturing and skilled labour. Currently, of the 31 Member States of the IAEA with NPPs in operation, none has implemented the industrial part of a national nuclear programme exclusively using the capacities of national organizations [74]. If a high scale expansion of nuclear energy occurs, deeper specialization at the international level will become possible, especially in the field of production of the most technologically advanced equipment (such as reactor pressure vessels or pump cases), resulting in the faster expansion of production facilities and a more focused system of labour force training [82].

Increased competition in a growing market, which will be joined by players from developing nations and medium sized countries that will more actively participate in production chain due to international specialization, will lead to the optimization of construction techniques. A system of international standardization could make the use of components produced in various parts of the globe for standardized NPP designs easier [83]. The accumulation of experience through learning curve effects and more intense flows of labour force in an international market should decrease the construction time allowing the industry to expand at an increasingly faster rate.

## 4.5. AVAILABILITY OF URANIUM

The estimated available uranium and other fissile resources are sufficient to sustain nuclear power generation in the long run. The reference publication containing data concerning uranium resource availability is the joint IAEA/OECD report Uranium: Resources, Production and Demand, commonly known as the ‘Red Book’ [31]. Since 1965, this biennial report has provided estimates of uranium resources based on country surveys covering only locations where a basic degree of exploration and ore concentration estimate has been conducted to a sufficient extent to confirm the existence and the main characteristics of uranium deposits. The Red Book classifies resources based on geological certainty and broadly divides them into identified and undiscovered resources. The dividing line in this broad categorization is whether or not deposit levels have been directly measured by pre-feasibility or feasibility studies.

The identified resources category includes ‘reasonably assured’ and ‘inferred’ resources, depending on the level of confidence — sufficient to determine the decision to undertake mining operations in the case of the former, and immediately prior to that stage in the latter. Undiscovered resources still require significant amounts of exploration to confirm their existence and to identify their grade and available amount. However, geological knowledge of previously discovered deposits and geological mapping provide a scientific base for expecting that undiscovered resources exist. This category is further divided into prognosticated and speculative resources.

The Red Book also provides information on extraction costs. The resources are classified into cost ranges: less than \$40/kg U, between \$40 and \$80/kg U, between \$80 and \$130/kg U, and (in some issues) between \$130 and \$260/kg U. Some analysts (e.g. Ref. [84]) have pointed out how these cost categories are expressed in nominal terms, which would determine real term costs to be considerably larger, and suggested the need for higher cost categories. Nonetheless, the 1965–2005 Retrospective shows that the amount of uranium resources in each cost bracket has not decreased since around 1980 [85]. Although minor reductions have been observed recently, this seems to further support the case that the availability of uranium resources in the economically extractable category will be sufficient for a long time.

The latest Red Book [31] estimates the total identified uranium resource base at around 7.1 Mt U, with an increase of over 12% since 2009. At the same time, a significant increase in extraction costs has been observed, which has caused a reduction in the lower cost brackets. This seems to be in line with a certain decline in productivity in the mining sector, favoured by high commodity prices [86]. The recent decrease in uranium prices following the Fukushima Daiichi accident is likely to lead to the resumption of investments in productivity improvements in uranium mining. Technological advances in mining and enrichment techniques are expected to increase the availability of these resources at lower costs. The 2011 Red Book concludes that the "identified resources are sufficient for over 100 years of supply for the global nuclear power fleet", at 2010 global reactor requirements. Figure 26 summarizes the amount of global identified uranium resources in each cost category.

The 2011 Red Book suggests that normal market price dynamics will lead to the identification of new resources, via new explorations and increased mining effort in both existing and new deposits. Potential undiscovered uranium resources are estimated by the IAEA survey at over 10 million t of uranium

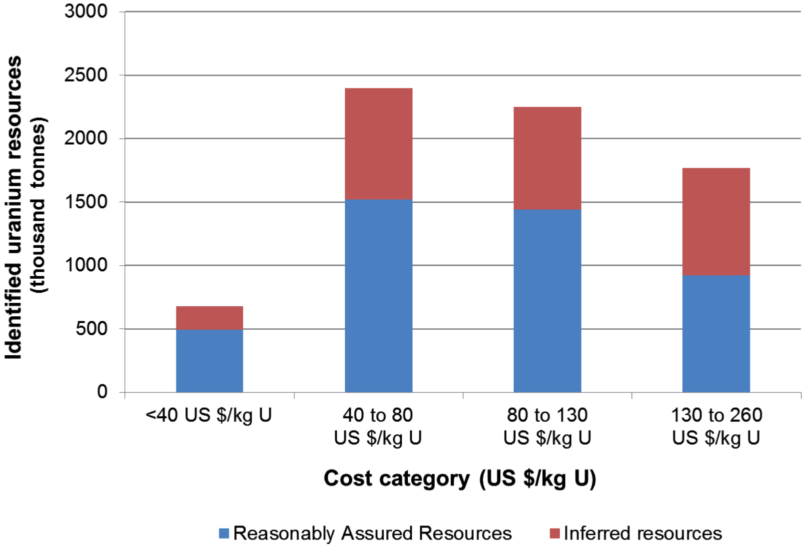

*FIG. 26. World identified uranium resources in different cost categories. Source: Ref. [31]*

(including prognosticated resources and speculative resources) as of 1 January 2011 [31].

Additional uranium resources exist in low grade deposits (black shales, lignites, carbonatites and granites), although these are too expensive and environmentally challenging to extract with current technologies. Uranium can also be obtained as a by-product from the production of other minerals, such as phosphate rocks and non-ferrous ores [87]. In this case, economic benefits can be drawn because the main product would bear a large share of the extraction costs.

The most important unconventional uranium resources are phosphate deposits and seawater. Uranium is abundant in seawater, with about 4 billion t of uranium technically extractable. The operation is technically feasible, but involves challenges which drive up its cost [88]. Although seawater uranium production is often regarded as the upper limit to the uranium production cost, it would suffice for nuclear power generation for thousands of years with the current once-through fuel cycle technologies, which justifies current research activities in the area [31]. In addition, uranium is an integral component of coal, with typical concentrations from around 1 ppm to 4 ppm. After coal combustion, uranium remains in the ash with concentrations ten times higher than in the original coal. Where uranium concentrations in lignite and hard coal deposits are higher than average, the extraction of uranium from coal ash can become economically appealing and be environmentally desirable (see e.g. Ref. [89]).

Other fissile materials are also suitable for nuclear power generation with currently foreseeable advances in fission technology. Thorium is abundant in nature and its resource base is estimated to be around 6 million t. Thorium can be used as a nuclear fuel if alternative fuel cycles are developed and successfully introduced. Thorium fuelled reactors have been demonstrated and operated commercially in the past, although further work is needed before thorium can be considered on a par with uranium [31]. See also Section 6.3.

Another promising technological change in nuclear reactors is the reprocessing of spent nuclear fuel. Current technologies leave about 95% of the original energy content of the uranium resources used for the fission reaction in spent fuel. Reprocessing spent fuel would further extend the lifetime of global uranium resources. Reactors worldwide discharge approximately 10 500 t of spent uranium fuel 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 awaiting final disposal.

Advanced reactor designs, such as fast breeder reactors and the associated fuel cycles (see Section 6.4) are technically able to utilize uranium much more efficiently than current reactors and fuel cycles do [90]. They might extend the lifetime of uranium resources by a factor of 60–70. These types of reactors are not yet commercially available, but 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 will not represent a constraint in nuclear power generation in the next decades, even in the case of strong expansion of current capacity. A timely investment in productivity and in new mining capacities is key to efficiently exploiting existing resources. In the past two decades, annual reactor requirements have been greater than fresh uranium production. Only 40–60% of global uranium demand was met by newly mined uranium, while the remainder came from secondary sources: strategic cold war reserve stocks, down blending of highly enriched uranium from nuclear weapons (the ‘Megatons to Megawatts’ programme), reprocessed uranium and plutonium from spent fuel, etc. Uranium prices determine the economic viability of mining projects. When prices are low, some mines close as their revenues do not cover variable operating costs; global production capacity is below reactor requirements and the industry depends on secondary sources. When prices are high, relatively less productive mines remain in operation and investments in new capacity become economically attractive, as well as the reprocessing of spent fuel or the extraction of low concentration uranium. It is not the geological availability per se that will determine the lifetime of uranium resources, but rather demand, technological change and economics.

## 4.6. TIMELINESS OF SUPPLY

An important aspect of global climate policy is the magnitude and timing of GHG emissions reductions that would allow compliance with the Copenhagen Accord of the UNFCCC to keep the increase of global mean surface temperature at 2°C (see Section 2.1). This raises the question of the deployment rate of low carbon technologies in the energy sector and in electricity generation in particular.

Anthropogenic GHG emissions and their current status in relation to global climate change are the main topics of UNEP’s 2012 Emissions Gap Report [91]. Two important points raised by the report include: (a) the gap between current emissions and those required for achieving the 2°C target is large, but it is still technically possible to close it through concerted and rapid action; and (b) steep emission reductions are needed after 2020 in order to preserve the possibility of limiting warming to 2°C or 1.5°C [91]. Since global electricity generation accounts for 35% of GHG emissions, a fairly large potential for climate change mitigation is presumed in this sector. The IEA explores this question in its World

Energy Outlook Special Report 2013 [92] and envisages a roadmap for achieving the 2°C target presented in Fig. 27.

The current annual production of nuclear energy in the world is approximately 2350 TW·h from 434 reactors with 370 GW(e) installed capacity. As of mid-2013, 69 reactors with a total capacity of 66.5 GW(e) were under construction globally [93]. The latest IAEA report on the global status and prospect for nuclear projects a total installed nuclear capacity in 2020 in a range between 407 GW(e) (low) and 503 GW(e) (high estimate) [94]. The low projection takes into account the scheduled retirement of the older units at the end of their lifetime (see Section 6.1).

However, according to the IEA's roadmap presented in Fig. 27, it would be necessary to maintain a NPP deployment rate consistent with the high estimate of the IAEA 2013 projection for 2020. The construction trends up to 2010 were on an upward slope but they were broken in 2011 in response to the Fukushima Daiichi accident. As UNEP's Gap Report suggests, concerted and rapid mitigation action is needed. If nuclear power is to be part of climate change mitigation efforts, rapid action is needed not only to restore the broken pre-2010 trend, but also to enhance it. It has been done before, when strong political support enabled the

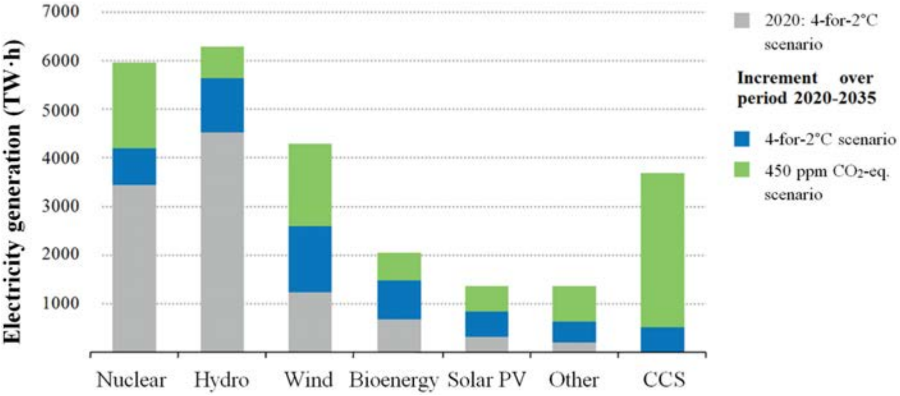

*FIG. 27. World electricity generation from low carbon technologies by scenario. Data source: Ref. [92]. Note: 'other' includes geothermal, concentrated solar power and marine. 4-for-2°C scenario: implementation of four policies that can help keep the door open to the 2 °C target through to 2020 at no net economic cost (energy efficiency, limiting the role of least efficient coal plants, minimizing methane emissions from upstream oil and gas production, accelerating the phase out of subsidies for fossil fuel consumption). 450 ppm $CO_2$-eq. scenario: an energy pathway consistent with the goal of limiting the global increase in temperature to 2°C by limiting the concentration of GHGs in the atmosphere to around 450 parts per million of $CO_2$.*

large expansion of nuclear power and delivered dramatic changes in the energy systems of many countries. The example of France demonstrates how an energy system can be completely changed by adding 56 nuclear power reactors to the grid in fewer than two decades that generate almost 80% of the electricity used in a country.

One of the arguments often heard against using nuclear power in climate change mitigation is that it takes too long to construct NPPs, making it unsuitable for rapid reductions of GHG emissions. Indeed, much time elapses from the initial planning of an NPP to its first grid connection. Construction alone would typically take around 42 months. For first-of-a-kind NPPs, these timeframes can be longer because specific construction management knowledge needs to be accumulated. The total process can typically take around ten years, as shown in Fig. 28. However, once built, NPPs can produce low carbon electricity for 40–60 years.

Figure 28 shows that much of the time in this process is dedicated to activities that are common to any power plant construction: feasibility studies, environmental impact assessments and site preparation activities. But what is also important is that the construction time for fossil fuel or renewable power plants on the scale of 1 GW(e) can easily match the 42–52 months required for a nuclear new build, although in some cases for different reasons. The IEA Energy Technology Systems Analysis Programme [95] estimates the following typical construction times for the installed capacities specified below:

- 18–96 months for construction of hydro dams with an output of more than 10 MW(e);
- 42–54 months for supercritical coal power plants with an output of 600–1100 MW(e);
- 24–30 months for combined cycle gas turbines with an output of 60–430 MW(e);
- 40–72 months for nuclear power with an output of 800–1200 MW(e);
- Typical construction times for solar PV and wind power are not yet provided by ETSAP[2].

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[2] Although the following two examples are not claimed to be representative, they illustrate these time schedules: (a) A construction period of 48 months is planned for the proposed 150 MW(e) Moree solar PV plant in Australia [96], and (b) up to 60 months are planned for the proposed construction of the Caledon wind park in South Africa with 243 MW(e) installed power [97]. Construction times that are shorter or longer than the cases presented can be found in projects around the world.

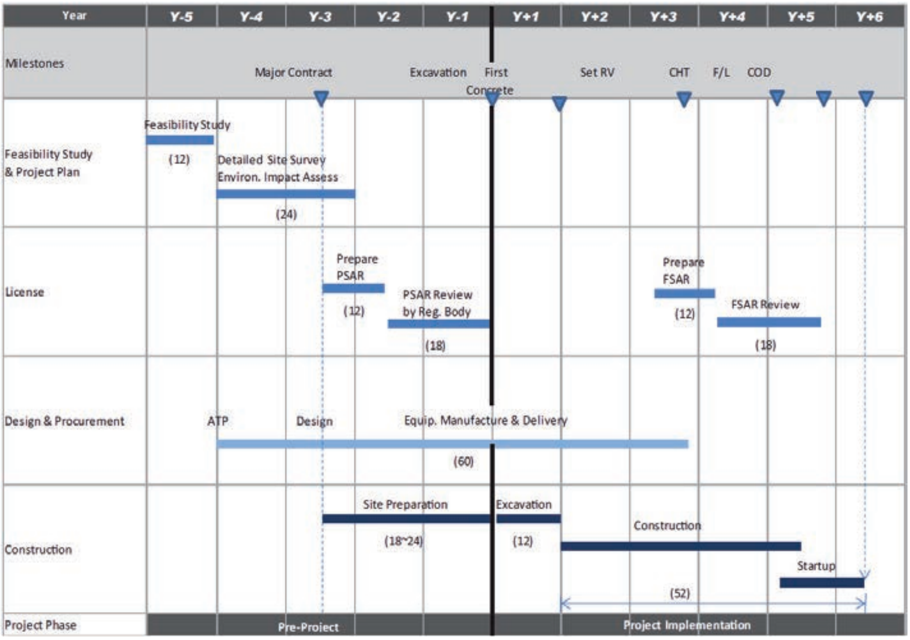

*FIG. 28. Typical durations of the main steps in NPP construction. Source: Ref. [82]. Note: ATP — Authorized to proceed, PSAR — Preliminary Safety Analysis Report, FSAR — Final Safety Analysis Report, RV — Review and verification, CHT — Cold hydrostatic test, FL — Fuel loading, COD — Commercial operation date.*

The conclusion is that NPPs have construction times comparable with other power generating alternatives, and they tend to deliver more low carbon electricity after completion, in most cases much more.

Actually, time constraints for fast transition to a low carbon power sector are likely to be found elsewhere. The commissioning time of new grid assets (typically 7–10 years for a new 400 kV overhead line) exceeds the typical commissioning time of 3–5 years for new generation facilities. This is mainly due to the duration of the authorization procedures, but it creates a situation in which transmission system operators must launch the grid reinforcement process before being sure that the electricity generation projects triggering the need for additional transmission capacity will actually be realized, making the decision making process more complicated [98]. Accordingly, electricity sources and their construction times do not seem to show a crucial link to the speed at which the electricity sector can respond to climate change. The ultimate pace depends rather on the ability to put these sources to use through the transmission grids.

The choice of energy sources can have large impacts on the transmission system. Massive deployment of renewable power generation capacities was identified as the main driver behind larger, more volatile power flows over longer distances across Europe, so that about 80% of all bottlenecks related to grid integration are due to the integration of renewable energy sources. This led the European Network of Transmission System Operators for Electricity to conclude that the integration of renewable energy sources will be a major challenge for grid development in the coming decade [99]. A shift towards a more balanced approach in electricity generation, with stable electricity generating sources such as nuclear power, could prove more effective in climate change mitigation.

Considering the various reasons for inertia in developing and transforming the electricity sector and the deployment time for large capacities regardless of which low carbon technologies, there is no a priori reason to exclude nuclear energy from a climate change mitigation portfolio. NPPs are built within timeframes that are comparable with other electricity generating alternatives. Further improvements in reactor design and construction management (related to size, modularity, standardization and other factors) are likely to further shorten the overall time needed for deployment of nuclear power, enabling it to play an important role in the rapid action on climate change mitigation.

# 5. CONCERNS ABOUT NUCLEAR POWER

## 5.1. RADIATION RISKS

Ionizing radiation is associated with all electricity generating technologies at some stage of their life cycle. However, for nuclear power it is probably the single most important topic. As such, it is part of the continuous assessments performed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). This specialized organization has a mandate from the United Nations to address sources of ionizing radiation and effects of exposure to the public and workers from various sources of radiation. Apart from peaceful uses such as nuclear power production and manufactured sources for the medical use of radiation, the areas assessed include natural sources, enhanced sources of naturally occurring radioactive material and manufactured sources for military purposes including nuclear testing.

Radiation exposure is measured in sieverts (Sv)[3] over a period of one year. Nuclear power has always been indicated as a minute source of ionizing radiation for the public in UNSCEAR's assessments (see Fig. 29). For example, against natural background radiation of 2400 µSv, UNSCEAR's latest report estimates the average worldwide public exposure from nuclear fuel cycle installations due to globally dispersed radionuclides to be 0.18 µSv per person per year of operation [100]. For local populations, the average annual exposure is estimated by UNSCEAR at 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). For comparison, exposure to the local population from oil and gas extraction alone can contribute to an effective dose of 30 µSv, mainly because of the release of radon gas together with the oil or gas; similarly, steel production stack releases can add 100 µSv to the effective dose for people living in the vicinity [100].

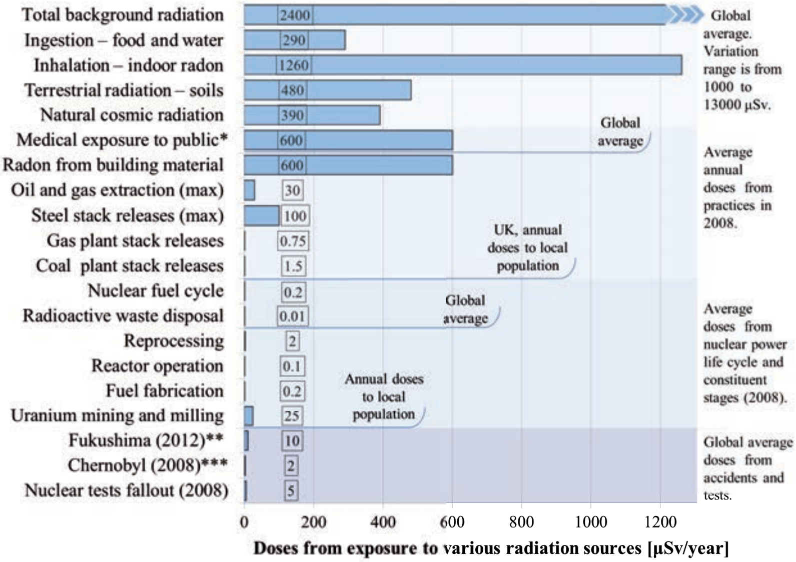

*FIG. 29. Radiation exposure to public in µSv. Source: UNSCEAR [100]. Note: * Estimate for 2008, corrigendum is being prepared by UNSCEAR. ** 2012, decreasing with time. *** Decreasing from 40 µSv in 1986 for the northern hemisphere.*

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[3] 1 Sv is defined as 1 Joule of energy per 1 kg of tissue mass and is used as a unit to express the effective dose. The biological effect of the same radiation dose can be different depending on the types of tissues absorbing it; taking this into account, the effective dose is a measure of dose designed to reflect the amount of radiation detriment likely to result from it.

It is obvious that radiation exposure levels of the population around nuclear facilities are significantly lower than naturally occurring radiation exposure levels. It should be noted that relating such low doses to health effects over large populations and long time periods can be highly uncertain [100]. Nevertheless, calculations of the health impacts of nuclear power from ionizing radiation indicate $2.14 \times 10^{-8}$ disability adjusted life years[4] per 1 kW·h over the entire life cycle due to ionizing radiation [101]. Therefore, one year of nuclear electricity generation in the world is estimated to give rise to approximately 62 000 DALYs per year. What is the meaning of this result in the global mortality and morbidity context?

According to the latest WHO statistics, available for the year 2004, the amount of DALYs due to malignant neoplasms (cancers) is estimated at 77.8 million [101]. In this context, even if uncertainty is ignored, the value calculated above amounts to a negligible contribution of 0.08% of all cancer related DALYs due to the health effects of ionizing radiation from the nuclear power life cycle. Furthermore, the majority of these estimated health effects would be associated with the quantity of radon gas emissions from uranium mining and milling, which is in general accordance with the UNSCEAR calculation premises on exposure for local populations, but seems rather conservative given the fact that: (a) radon has a short half-life, and hence its transport is geographically limited; (b) in open air, radon quickly disperses to insignificant levels; (c) in closed spaces, protective equipment and ventilation can be used to prevent radon inhalation, minimizing occupational health risks; and (d) uranium mines and mills are usually far from populated areas. See also Ref. [102].

In areas of uranium mining and milling, local background radon concentrations can be naturally elevated. Therefore, the radon doses at the mine site can be similar to those in areas not impacted by mining and milling activities. The Canadian Nuclear Safety Commission cites concentration ranges of 1–50 Bq/m$^3$ within the site boundary and 1–20 Bq/m$^3$ for the site boundary as well as for faraway reference sites [103]. A more specific example can be found in the McClean Lake underground mining site in Canada, where the nominal background air concentration of radon ranges between 15–25 Bq/m$^3$, while the incremental radon concentration related to mining and milling activities would typically be less than 10% of this [104].

Even with the change announced by the ICRP of the dose conversion values for radon of around a factor of two [105], the relative impact of the nuclear fuel cycle will remain at minute levels. Furthermore, UNSCEAR mining and milling

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[4] ‘Disability adjusted life years’ (DALY) are the sum of ‘years of life lost’ (YLL) and ‘years of life with disability’ (YLD).

stage calculations are based on an older model mine site. The current situation is somewhat different, with a rapid shift toward in situ leaching, which accounted for the largest share (39%) of global uranium production in 2010 [31]. In this regard, the calculated 25 μSv effective dose can be viewed as an appropriately conservative result.

Comparison between nuclear and fossil fuel power plants operation, or even with other industrial practices (Fig. 29), also indicates the low radiation health risk related to nuclear power. Similar findings were reported by UNSCEAR [102] and the Oak Ridge National Laboratory back in 1978 [106], when the doses of ionizing radiation for individuals receiving the highest effective dose next to a coal power plant were estimated to be at least an order of magnitude higher compared to an NPP. It should be noted, however, that all of them are well below the authorized emission levels for ionizing radiation.

Current average effective doses to the global public from major nuclear accidents and military tests are very low. As the decay of the radionuclides continues, the doses to the public will keep diminishing. On the other hand, radioactive contamination of the environment close to the accident sites of Chernobyl and Fukushima can be severe, contaminating sizeable areas. Again, however, it should be stressed that the inhabitants of the contaminated areas due to the Chernobyl accident have received an average effective dose of 9 mSv for the first 20 years of exposure [100], with decreasing increments over the years. Similarly, for the locations inside the Fukushima prefecture and around it, depending on the deposition, the estimated doses among the non-evacuees of all age groups are between 0.1 and 10 mSv for the first year due to external dose from ground deposition and ingestion [107].

## 5.2. NUCLEAR SAFETY: LEARNING THE LESSONS FROM THE FUKUSHIMA DAIICHI ACCIDENT

The Fukushima Daiichi accident in March 2011 revived old concerns, or amplified existing ones about the safety of nuclear energy in many countries. Although the accident did not cause fatalities and contamination was restricted to Japan, its consequences were global in terms of reviewing and improving nuclear safety. The IAEA, other international institutions and regional and national organizations initiated rigorous programmes to assess the potential vulnerability of NPPs to external hazards, including unlikely but potentially devastating natural threats, and to initiate near term measures and longer term action plans to augment their safety.

In 2012–2013, discussions on NPP safety focused largely on identifying and applying the lessons that could be learned from the Fukushima Daiichi accident. A Ministerial Conference on Nuclear Safety in June 2011 requested the IAEA Director General to prepare a draft Action Plan on Nuclear Safety to define a programme of work to strengthen the global nuclear safety framework. The Action Plan [108] 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 NPPs in the light of lessons learned to date from the accident;
- Incorporate the lessons learned from the Fukushima Daiichi accident 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 the effectiveness of national regulatory bodies (e.g. through IAEA Integrated Regulatory Review Service missions), 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;
- Assist 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 NPP 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, thereby determining the agenda for further developments in this sphere in 2012–2013 [109]. The main progress in the implementation of the Action Plan made since the 2012 annual report can be summarized as follows:

- Significant progress was made in several key areas, such as assessments of safety vulnerabilities of NPPs and strengthening of the IAEA's peer review services. The IAEA Safety Standards were reviewed, with a focus on vitally important areas such as the design and operation of NPPs, protection of NPPs against severe accident(s) and emergency preparedness and response. Additional attention was given to the revision and strengthening of Part 1 of the IAEA General Safety Requirements on government, legal and regulatory work for safety, specifically, the regulations on the independence of the regulatory body, prime responsibility for safety, the role of the regulatory body in emergency preparedness and response, international obligations and arrangements for international cooperation, liaison between the regulatory body and authorized parties, review and assessment of information relevant to safety and communication and consultation with interested parties [110]. The IAEA has continued to analyse the lessons learned from the Fukushima Daiichi accident. It has now prepared the full reports of the three international experts' meetings (IEMs) organized in 2012 and made them available at the Fukushima Ministerial Conference on Nuclear Safety, organized by the Government of Japan in co-sponsorship with the IAEA in December 2012 [111].
- In 2013, the Secretariat organized two further IEMs, one on Decommissioning and Remediation after a Nuclear Accident and one on Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant. The Secretariat also organized an International Conference on Effective Nuclear Regulatory Systems, hosted by Canada in Ottawa.
- In addition to this, in May 2013, the IAEA, in cooperation with the Government of Japan and the Fukushima Prefecture, opened the IAEA Response and Assistance Network Capacity Building Centre in Fukushima City to coordinate training activities that are aimed at enhancing nuclear emergency preparedness and response capacity at regional and international levels. The IAEA established the Emergency Preparedness and Response Expert Group (EPREG) consisting of 16 senior experts representing all regions to provide strategic advice in order to strengthen international preparedness for nuclear and radiological emergencies. EPREG met for the first time in February 2013.

Enhancing nuclear safety was an important item on the agenda of the 2013 Ministerial Conference on nuclear power in the 21st century (St. Petersburg, Russian Federation), which reaffirmed the commitment of the Member States to the Action Plan [112]. Participants agreed that all countries have a common interest in the continuous improvement of nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide, taking into account all the lessons learned from the Fukushima Daiichi accident. As nuclear accidents have no borders, it was recognized that international cooperation is an extremely important component of global nuclear safety and should be further enhanced. The conference recognized the need for a global nuclear liability regime addressing the concerns of all States that might be affected by a nuclear accident with a view to providing appropriate compensation for nuclear damage.

Regional and national stress tests and safety improvements were initiated as well. The EU, in the report of the European Nuclear Safety Regulator's Group (ENSREG) in 2013, noted the high level of safety of European NPPs, as during the reporting period from mid-2011 to mid-2013 there were no events or developments affecting public health and safety in any European country. ENSREG reported that the stress tests it organized following the Fukushima Daiichi accident according to the European Council request (March 24–25, 2011) were successfully carried out and completed by April 26, 2012, making full use of available expertise (notably from the Western European Nuclear Regulators Association (WENRA)). The stress tests focused on three topics directly connected with the Fukushima Daiichi accident: natural hazards (including earthquake, tsunami and extreme weather), loss of safety systems and severe accident management. The peer review process initiated by ENSREG showed the consistency in the identification of strong features, weaknesses and possible ways to increase plant robustness across Europe in spite of differences in national approaches. The general conclusion of ENSREG was that necessary modifications and upgrades to NPP safety systems must be performed without undue delays and to a very high standard [113].

In the USA, the Nuclear Regulatory Commission (NRC) had already provided recommendations to enhance US reactor safety based on the lessons of the Fukushima Daiichi accident in July 2011, focusing on the clarification of the regulatory framework, the improved efficiency of NRC programmes, increased protection measures and emergency preparedness [114]. Specifically, the NRC Task Force recommended requiring its licensees to re-evaluate and upgrade as necessary the design basis for seismic and flooding protection of each operating NPP as well as to evaluate potential enhancements to the capability to prevent or mitigate seismically induced fires and floods. Using the proposals of the Task Force, the NRC developed a hierarchical set of recommendations. The main recommendation requires US NPPs to be designed and built to safely withstand a set of unlikely harmful events such as equipment failure, pipe breaks and severe weather [115]. The background to this recommendation is that the Fukushima Daiichi nuclear plant experienced flooding and seismic events that went beyond the design basis levels set by the Japanese regulator.

Following the Fukushima Daiichi accident, an investigation committee was formed in Japan on May 24, 2011. The committee published its final report in July 2012, suggesting a broad set of measures to prevent recurrences of nuclear disasters and mitigate any damage caused in the future. The recommendations of the investigation committee were grouped in seven categories: basic safety measures and emergency preparedness, safety measures regarding nuclear power generation, nuclear emergency response systems, damage prevention and mitigation, harmonization with international practices, relevant organizations and continued investigation of accident causes and damage [116]. The main recommendation of the investigation committee was to review the existing safety measures at nuclear power stations in order to sufficiently consider the risks of large scale complex disasters, including earthquakes and tsunamis. Specifically, staff should receive special training on the actions to be taken in such situations. Another important conclusion was the necessity to secure a high level of independence and transparency of the nuclear safety regulatory organization.

All these actions of national and international bodies were implemented as a response to the Fukushima Daiichi accident. However, the overall trend towards higher safety of the nuclear industry can be observed for more than a decade as a result of long term and focused safety policy. Progress in this area can be seen in the decrease in the number of unplanned scrams (Fig. 30) in 2002–2012: from around 1 per 7000 hours of critical power reactor operation in the early 2000s to 0.6 in the 2010s.

## 5.3. WASTE MANAGEMENT AND DISPOSAL

A longstanding public concern about nuclear energy is radioactive waste, which can create hazards for humans and the environment lasting for centuries — or millennia. Over the past two decades, major advances have been made towards the safe temporary storage and final disposal of radioactive waste in terms of scientific understanding and technological development. Due to emerging solutions for the long term storage of spent fuel and the ultimate disposal of radioactive waste, nuclear energy can contribute to climate change mitigation without causing additional environmental concerns.

During the nuclear fission process in the reactor, the fuel becomes intensely radioactive due to the formation of new radionuclides, known as fission products, which reduce the efficiency of the reactor and must be removed. Spent fuel

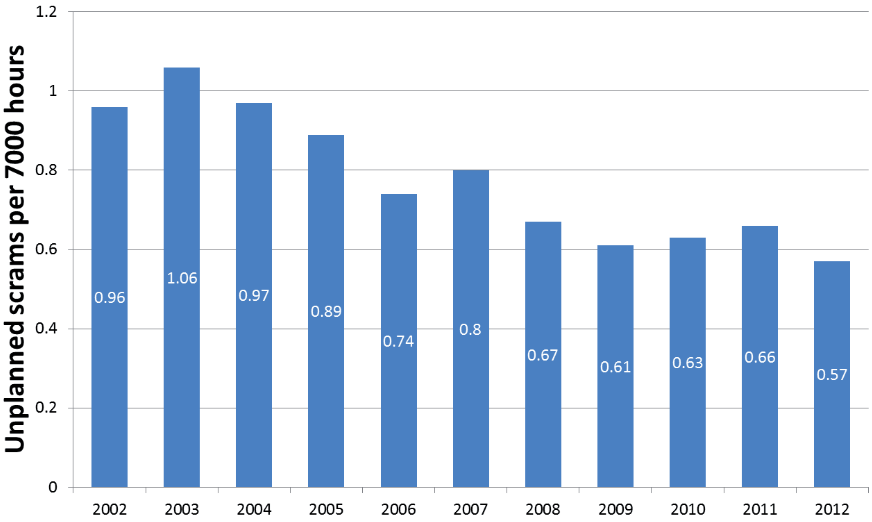


*FIG. 30. Total number of unplanned scrams, including both automatic and manual scrams, that occur per 7000 h of critical power reactor operation. Source: IAEA [93].*

requires a period of storage to reduce its heat output. This temporary storage phase is 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, it has been demonstrated over the past decades that as long as active surveillance and maintenance are ensured, the interim storage of radioactive waste can be relied upon. Moreover, storage is technically feasible and harmless over a long period of time if monitoring, control and care are properly implemented [117].

The disposal of radioactive waste in geological media is considered a safe method for isolating these substances from the hydrosphere, the atmosphere and the biosphere. A crucial but as yet unresolved issue is retrievability; that is, whether the option to retrieve wastes from repositories is required and, if so, for how long. On the positive side, it is possible that future generations will consider the buried waste to be a valuable resource. On the negative side, permanent closure might increase the long term security of the repository. Relevant policies in Canada, France, Japan, Switzerland, the USA and most other countries require retrievability for at least 100 years.

The fundamental principles involved in geological disposal are well understood [118, 119]. Geological repositories are designed to be passively safe. This is ensured by the multibarrier principle, in which long term safety is ensured by the synergy of several engineered and natural barriers. These barriers prevent or reduce the transport of radionuclides in groundwater, which is generally the most important transport mechanism. They also influence the migration of gas, which will arise in radioactive waste repositories from chemical and biochemical reactions and radioactive decay.

In the multibarrier principle, the engineered barrier system comprises the solid waste matrix and the various containers and backfills used to immobilize the waste inside the repository. The natural barrier (the geosphere) is principally the rock and groundwater system that isolates the repository and the engineered barrier system from the biosphere. The host rock is the part of the natural barrier in which the repository is located. Emplacement of the waste in carefully engineered structures placed at depth in suitable rock is chosen principally for the long term stability that the geological environment provides. At depths of several hundred metres in a tectonically stable environment, processes that could disrupt the repository are so slow that the rock and groundwater systems will remain almost unchanged for hundreds of thousands of years, and possibly longer [120].

Programmes to dispose of spent fuel are well advanced in several countries. Site characterization and selection for deep geological repositories have been under way since the 1970s. The two countries closest to licensing and operation are Finland and Sweden. The general principles and designs of the disposal facilities are similar (see Fig. 31).

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

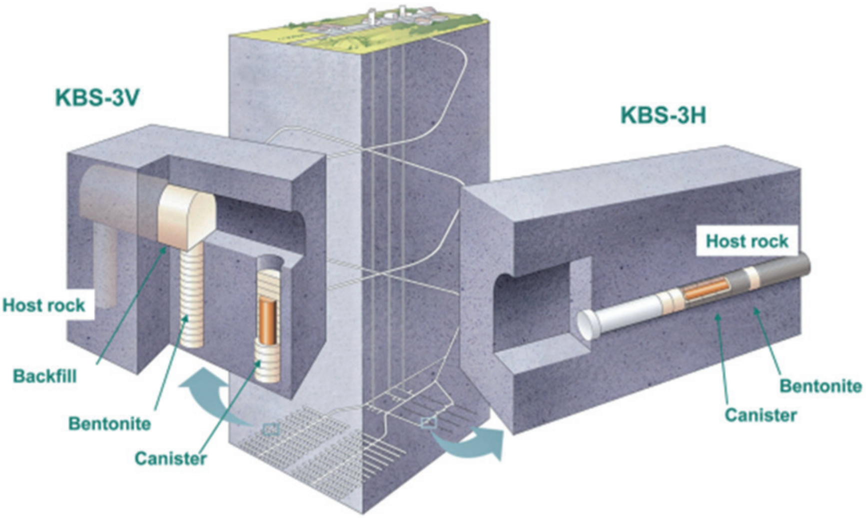


*FIG. 31. The KBS-3 disposal concept. (Sources: Refs [121, 122]) (Note: KBS — nuclear fuel safety; H — horizontal; V — vertical.)*

structures will be used for disposal. The construction licence application was submitted in 2012 and the operating licence process is expected to be completed by around 2020. 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.

Similar site characterization, selection and licensing processes are under way in France and Japan. All these cases demonstrate the long processes (e.g. scientific, political and public participation) of characterizing, analysing and selecting sites. In each case, deep geological disposal of high level waste and used fuel emerged as the best solution.

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 to substantially reduce one of the current concerns about nuclear power.

## 5.4. 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 Statute of the IAEA directs it to “enlarge the contribution of atomic energy to peace, health and prosperity throughout the world” and to ensure that peaceful nuclear energy “is not used 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 control arrangements, nuclear security measures and also, 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 being diverted from peaceful nuclear activities and, by the risk of early detection, to deter proliferation.

States accept the application of technical safeguards measures through the conclusion of safeguards agreements. Over 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 it to verify the fulfilment of the State's obligation not to develop, manufacture or otherwise acquire nuclear weapons or other explosive nuclear devices. Under such comprehensive safeguards agreements, a State commits to provide information on its nuclear material and activities, and to open up for 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 highlighted the limitations of safeguards implementation that is focused primarily on nuclear material and facilities declared by the State concerned. It showed that the IAEA needed to be much better equipped to detect undeclared nuclear material and activities. This 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. Over 120 States have brought such additional protocols into force to date.

The shift in the focus of safeguards implementation, from the verification of declared nuclear material at declared facilities to the consideration of the State as a whole, has resulted in changes to the ways in which safeguards activities are planned and conducted, results are analysed, safeguards conclusions are drawn and follow-up activities are carried out. The framework within which all this work takes place is the so-called State level concept.

Under the State level concept, the IAEA collects and processes safeguards relevant information about a State from a wide range of sources: information provided by the State itself, safeguards activities conducted by the IAEA in the field and at its headquarters and other relevant information. The IAEA conducts ongoing reviews of such information and evaluates its consistency with the State's declarations about its nuclear programme.

The IAEA's inspection activities are supported by advanced technologies and techniques. It takes special expertise, equipment and infrastructure to carry out the IAEA's verification activities. The IAEA develops and implements State level 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 IAEA evaluates the results of its activities in the context of its understanding of the State's nuclear fuel cycle activities and plans. On the basis of this evaluation, the IAEA establishes its independent findings from which an annual safeguards conclusion is drawn for each State with a safeguards agreement in force. These conclusions are published annually in the Safeguards Implementation Report.

In conclusion, the IAEA plays an instrumental verification role, demonstrating 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.

## 5.5. PUBLIC ACCEPTANCE

Factors affecting the public acceptance of any technology, including energy technologies, are classified into two categories: (a) technology specific (technical features, benefits, costs, human health risks, environmental impacts and other characteristics of the given technology); and (b) the socioeconomic context in which the given technology is considered or used. Shifts in both types of factor have affected the evolution of public acceptance of nuclear power in recent years.

Among the technology specific factors, historical and accumulated experience had led to increased public acceptance in most countries until the Fukushima Daiichi accident in March 2011. Not surprisingly, the accident has led to a marked shift in public opinion on nuclear power immediately following the incident. A multicountry poll administered by GlobeScan [123] between July and September 2011 indicated that opposition to nuclear power had increased significantly compared to a 2005 GlobeScan poll conducted in several countries. Results indicated a marked rise from 73% to 90% in Germany, 51% to 82% in Mexico, 76% to 84% in Japan, 66% to 83% in France and 61% to 80% in the Russian Federation. Nevertheless, the public attitude toward nuclear energy has been more favourable over time. Indeed, an Ipsos MORI survey [124] conducted in September 2012 shows a change in global support for nuclear energy (+7%)

since April 2011 with the strongest support in China, France, India, Poland, Saudi Arabia, Sweden, the UK and the USA (50% or above). Argentina, Germany, Italy and Mexico remained the least supportive.

An assessment of the public acceptance of nuclear energy is usually based on public opinion surveys. The results of such surveys should be handled with care, particularly when trying to compare them over time and across countries, because they often differ in scope, coverage, methods and other important aspects. The key determinant of the outcome of such surveys is how the questions are framed and phrased. The number and content of the response options vary across surveys, therefore a simple normalization procedure is used to portray all survey results in this section by a Public Acceptance Index (PAI) on a scale from 0 (complete rejection) to 100 (full acceptance).

In the aftermath of the Fukushima Daiichi accident, however, several large multicountry surveys as well as national country surveys were conducted with the same or very similar, and therefore comparable, basic questions of whether the respondent supports or opposes nuclear power or finds nuclear favourable or unfavourable. The shifts in support for nuclear power since 2010 in selected countries (the Czech Republic, France, the UK and the USA) are presented in Fig. 32.

Overall, opposition to nuclear power increased after the Fukushima Daiichi accident in these four countries. The highest level of opposition was observed in the UK. However, Fig. 32 shows that support for nuclear power recovered within a few months. This trend was confirmed by surveys conducted in 2012 and 2013, the results of which show that close to or more than 65% of the public is now favourable towards nuclear energy. This is a classical phenomenon in social sciences and sociology, illustrating that with the passing of time following an incident, memories tend to fade. A February 2013 poll conducted in the USA found that public support has gradually increased over the past two years to the level of 70% of US citizens now favouring the use of nuclear energy as part of a diverse energy production portfolio. This is compared with 69% in September 2012, almost 66% in February 2012 and close to 64% in September 2011, only a few months after the Fukushima Daiichi accident.

In the UK, Ipsos MORI surveys show that support for nuclear power tumbled in June 2011, but bounced back to almost previous levels within six months. IFOP polls also reveal that the proportion of French people opposed to France’s use of nuclear power has been declining since March 2011. Likewise, a survey conducted by the Czech State Energy Company CEZ shows an increase of public support for the development of nuclear energy in the Czech Republic from 54% in 2011 to 64% in September 2012 and 66% in 2013.

Figure 33 [125–134] shows country specific results of the latest national surveys of public opinion. It clearly demonstrates that the impact of the

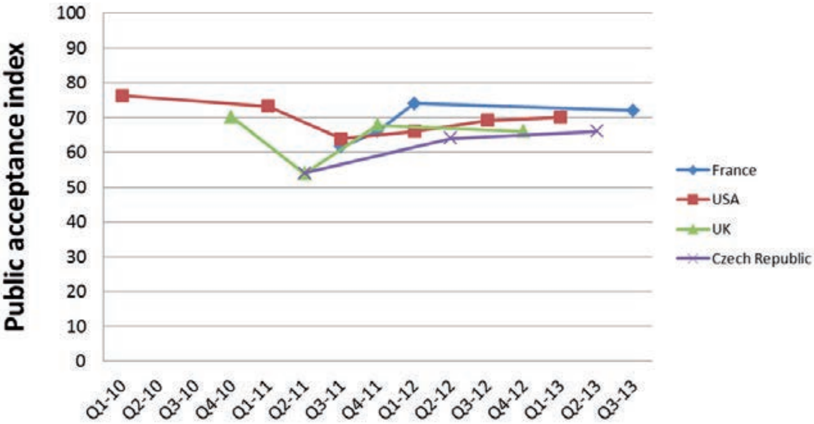


*FIG. 32. Trends of public acceptance of nuclear energy since 2010 in selected countries. Data sources: Refs [125–134].*

Fukushima Daiichi accident on public opinion in these countries (except Japan) is fading. However, close to 77% of Japanese people want nuclear power generation in Japan to be terminated in the next 20 years, according to an Asahi Shimbun opinion poll [135] conducted in February 2013. A 2011 Pew Research Center poll [136] demonstrated that almost 50% of Japanese people were in favour of the increased use of nuclear power before the Fukushima Daiichi

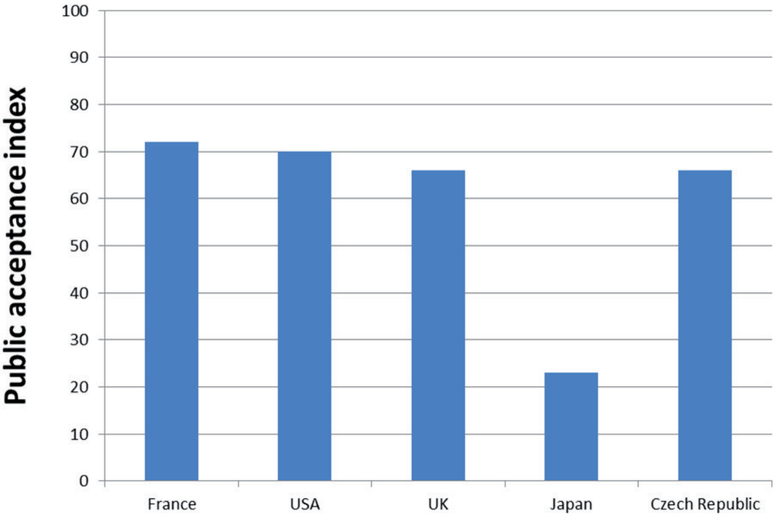


*FIG. 33. Current status of public acceptance of nuclear energy in selected countries. Data sources: Refs [125, 130, 132, 134, 135].*

accident. Japanese support for nuclear power has understandably dropped after the Fukushima Daiichi accident, but is slowly recovering. Indeed, in 2012, 80% of respondents participating in an Asahi Shimbun survey [137] were in support of phasing out nuclear power, yet within one year that percentage had reduced to 70%.

The history of public acceptance of nuclear power is driven by cycles of accidents (e.g. Three Mile Island and Chernobyl) followed by reassessments by the industry on safety. Over time, without serious incidents, public acceptance of nuclear energy improves due to its positive attributes, such as zero emissions, energy security and economics. Given that the nuclear industry, country regulators and the IAEA are refocusing on safety (e.g. plants are undergoing stress tests and safety upgrades, see Section 5.2), the potential for the acceptance of nuclear power to rebound is strong, especially when climate and other benefits of nuclear power are increasingly recognized by the public.

# 6. PROSPECTS FOR NUCLEAR POWER

## 6.1. NUCLEAR POWER PROJECTIONS

Each year the IAEA publishes projections for the world's nuclear power generating capacity. The projections presented in the 2013 edition [94] are based on three major sources:

- National projections submitted by countries for a recent OECD/NEA study;
- Data and indicators published by the World Bank in its World Development Indicators;
- Global and regional energy, electricity and nuclear power projections prepared by other international organizations.

The estimates of future nuclear generating capacities are derived from aggregating country by country data. They are prepared by a group of experts gathered each year for a consultancy meeting on Nuclear Capacity Projections at the IAEA. The projections are based on a review of nuclear power projects and programmes in IAEA Member States. The experts review all operating reactors, possible licence renewals, planned shutdowns and plausible construction projects foreseen for the next few decades. The projections are prepared by assessing the plausibility of each project in the light of the general assumptions for the low and the high case, respectively.

The projections of future energy and electricity demand, and the role of nuclear power, are presented as low and high estimates encompassing the inherent uncertainties involved in projecting trends. The low and high estimates reflect contrasting, but not extreme, underlying assumptions about factors driving nuclear power deployment (see Figs 34 and 35, respectively). These factors, and the ways they might evolve, vary from country to country. The IAEA estimates provide a plausible range of nuclear capacity growth by region and worldwide. They are not intended either to be predictive or to reflect the full range of possible futures from the lowest to the highest feasible cases.

The low case reflects expectations about the future, assuming that current market, technology and resource trends continue and few additional changes in laws, policies and regulations affecting nuclear power are made. This case is explicitly designed to produce a 'conservative but plausible' set of projections. Additionally, the low case does not automatically assume that targets for nuclear power growth in a particular country would necessarily be achieved. These assumptions are relaxed in the high case. The high case projections are much more optimistic, but still plausible and technically feasible. The high case assumes that current rates of economic and electricity demand growth, especially

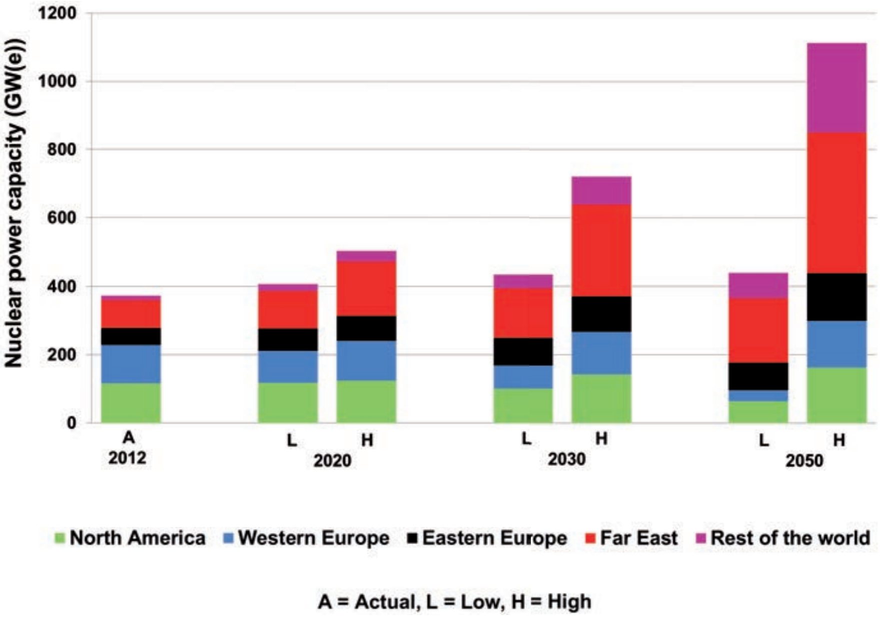


*FIG. 34. Prospects for nuclear power in major world regions: estimates of installed nuclear capacity. Data source: IAEA [94].*

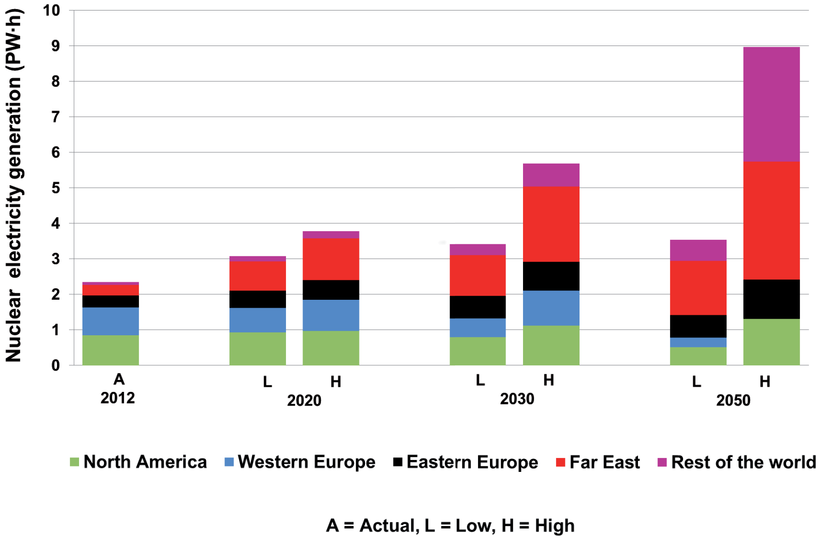


*FIG. 35. Prospects for nuclear power in major world regions: estimates of nuclear electricity generation. Data source: IAEA [94].*

in the Far East, continue. Changes in national climate change policies are also included in the high case.

Over the short term, the low price of natural gas and increasing capacities of subsidised renewable energy sources are expected to affect nuclear growth prospects in some regions of the developed world. These low natural gas prices are partly due to low demand as a result of macroeconomic conditions as well as technological advances. Moreover, the ongoing financial crisis continues to present challenges for capital intensive projects such as nuclear power. The assumption adopted by the expert group was that the above mentioned challenges, in addition to the Fukushima Daiichi accident, may temporarily delay deployment of some NPPs. In the longer run, the underlying fundamentals of population growth and demand for electricity in the developing world, as well as climate change concerns, issues regarding security of energy supply and price volatility of other fuels point to nuclear energy playing an important role in the energy mix over the longer term.

Over the last year, most countries have completed their nuclear safety reviews providing greater clarity for nuclear power development. Nevertheless, challenges remain because policy responses to the Fukushima Daiichi accident are still evolving in some key regions. Once greater certainty about the policy and regulatory responses is established, the projections presented here will likely need to be refined.

Compared to the 2012 global nuclear capacity projections for 2030, the 2013 projections are lower by about 20 GW(e) in both the low and high cases. These reduced projections reflect national responses to the Fukushima Daiichi accident and factors noted above, although the decline of the projected capacities in 2013 relative to those in 2012 is less than the decline between subsequent projections in earlier years since 2011. Effects of the Fukushima Daiichi accident include earlier than anticipated reactor retirements, delayed or possibly cancelled new build and increased costs owing to changing regulatory requirements. Nevertheless, interest in nuclear power remains strong in some regions, particularly in developing countries. The projections for 2050 reflect assumptions about the general rate of new builds and retirements. Considering all uncertainties, the estimates depict a plausible range of actual outcomes.

## 6.2. SMALL AND MEDIUM SIZED REACTORS

The nuclear power reactors currently offered by vendors are typically in the range of 1000–1700 MW(e) of net electric capacity. This makes it less feasible for many countries to consider nuclear energy as part of their climate change mitigation strategy because their power grid is too small to integrate large reactors, their financing capabilities are limited or for other reasons. This might change over the next 10–20 years with the deployment of advanced small and medium sized nuclear power reactors (SMRs). The IAEA defines small reactors as reactors with an electrical output of up to 300 MW(e) and medium sized reactors with outputs up to 700 MW(e).

SMRs have the specific characteristic to match spiralling energy demand by adding incremental capacity with moderate financial commitment for countries with smaller electricity grids. The technology also aims for significant cost reduction through modularization and reduced construction schedules. With lower upfront capital cost, SMRs will offer better financing options (i.e. better affordability for developing countries). By size, SMR designs are better suited for cogeneration (i.e. electricity and heat) in non-electrical applications such as sea water desalination, hydrogen production and heat for industrial processes. This translates to improved thermal efficiency and better return on capital investment.

SMR designs include features not available or in some cases not even achievable in large nuclear reactors. Some SMR designs are based on integral pressurized water reactors, where some key components for nuclear steam supply (e.g., steam generators, pressurizer and reactor coolant pumps) that are normally located outside of the reactor, are instead integrated in the reactor vessel, making for a very compact design. Additional benefits are that the integral vessel configuration eliminates loop piping and external components, thus enabling compact containment and smaller plant size, and thereby lower costs. This configuration also improves safety by eliminating the possibility of a large pipe break resulting in a loss of coolant accident.

Another unique feature of advanced SMR designs is modularity. In these reactor designs (e.g. SMART, mPower, NuScale, FAREM25 and Westinghouse SMR), one plant may include multiple (e.g. 2–12) reactor modules. Each module is operated independently from the other modules. Modularity permits scaling the power plant to larger sizes based on incremental future needs for energy and compatibility with the electrical grid infrastructure. This also reduces the initial capital costs to provide better affordability and reduced financial risk for entry into deployment. The modularity of construction also lends itself better to factory fabrication, shared infrastructure of multiple modules, truck/rail shipment of the largest components and avoids use of large components (e.g., large castings) that are produced by very few global suppliers.

In the 2030–2040 timeframe, innovative SMRs (e.g., SVBR-100, 4S, PBMR, $EM^2$, GT-MHR) including small Generation IV reactors using non-water coolant/moderator will be deployed. Potential advantages of these reactors are higher output temperatures that will increase reactor efficiency and provide a better match with process industry heat requirements of approximately 500ºC.

Some SMRs include converted and modified concepts that include barge mounted floating NPPs (e.g. Russian Federation KLT-40s) and seabed moored submarine-like reactors (e.g. French Flexblue). There are also innovative applications of SMRs that are compatible with renewable energy systems (wind, solar) and SMRs that may be coupled to non-electric applications (e.g. desalination, district heating, hydrogen production). The benefits of coupling to non-electricity applications include improvement of efficiency by harnessing the waste heat, improvement of economics, increased use of off-peak power to provide process heat for enhanced oil recovery, zinc smelter, paper mills, petrochemical refiners and plastic industries. SMRs would displace the energy otherwise produced by fossil energy, thus reducing GHG emissions.

Recent global activities in the design and technology development of SMRs have shifted the paradigm for commercial nuclear power. Currently nine IAEA Member States are developing advanced SMR designs. In the past few years, many of the advanced SMRs for near term deployment are of the light water cooled reactor type, including integral PWRs with modularization; the other are reactors with liquid metal and helium gas as coolant and moderator respectively.

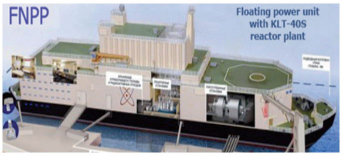
Advanced SMRs, particularly those integral pressurized water reactors with modularization technology, are not yet commercially available although several countries are moving in this direction. A brief update on SMR technology development is provided as follows:

- Argentina has completed the site excavation for the CAREM-25 prototype reactor, for which the first concrete pour for construction is expected to take place at the end of 2013.
- In China, two modules of gas cooled reactors, called HTR-PM, are under construction for domestic use; China is also developing several integral PWR type SMRs for near term deployment, including ACP-100 and CAP-150.
- In the past two years, France has been developing a 160 MW(e) seabed moored type reactor called Flexblue-SMR to be operated from a coastally located control room.
- In India, the Prototype Fast Breeder Reactor has completed construction and is being prepared for startup commissioning. Four units of PHWR-700 are under construction, and four more units are to follow. The AHWR-300 is at final design stage and is being prepared for construction.
- Japan has completed the detailed design of the 4S, a 10 MW(e) sodium cooled fast reactor. The reactor is intended for a deployment in remote arctic areas.
- The Republic of Korea has granted a standard design approval for the 100 MW(e) SMART in July 2012; the reactor is intended for cogeneration of power production and non-electric application.
- In the Russian Federation, the construction of two KLT-40s floating NPPs is near completion, and site excavation for the SVBR-100 reactor has been started; the Russian Federation is also developing dozens of other innovative SMRs for future deployment.
- In the USA, there are at least five modular and integral PWR type SMRs under development, called mPower, NuScale, W-SMR, SMR-160 and EM$^2$. The US Department of Energy sponsors cost sharing programmes aimed to accelerate commercialization. The 180 MW(e) mPower has received the first round of funding for design review by the Nuclear Regulatory Commission.

Approximately 17 countries considering the introduction of nuclear energy (newcomers) have small electricity grids where large nuclear power reactors would not be practical due to grid stability and operational concerns. The SMRs would serve a vital role in enhancing energy supply security and providing clean energy in the imminent future for these countries.

Table 1 provides three examples of SMR designs representing advanced SMRs, innovative SMRs and converted SMRs with modified concepts. Many other reactors fall into each of these categories and more detailed information can be found in IAEA publications [138, 139].

TABLE 1. EXAMPLES OF SMR DESIGNS

| Technology developers and SMR designs | Main technical features | Reactor diagram |
|---|---|---|
| United States of America<br>mPower (advanced SMR) | • 180 MW(e) integral iPWR;<br>• Light water coolant and moderator, forced circulation;<br>• 48 month fuel cycle;<br>• Fuel enrichment below 5.0%;<br>• Passive safety features;<br>• 60 year design life;<br>• Received the US DOE’s funding subsidy for design review with the NRC;<br>• 2 module deployment scheme. |  |
| China<br>HTR-PM | • 200 MW(e) pebble bed modular high temperature reactor;<br>• Helium gas coolant and graphite moderator, natural circulation;<br>• 8.5% fuel enrichment;<br>• Passive safety features;<br>• 40 year design life;<br>• Construction started in December 2012 in Shidao Bay. |  |
| Russian Federation<br>KLT-40S (Modified concept) | • 35 MW(e) PWR module for floating NPP — barge mounted;<br>• Light water coolant, forced circulation;<br>• Fuel enrichment below 20%;<br>• Active and passive safety systems;<br>• 40 years design life;<br>• Construction in the Russian Federation, 2013 deployment. |  |

SMRs have even smaller environmental impacts than large NPPs due to their smaller plant size (i.e. the dimensions of the facility), shorter construction period and smaller amount of construction related and operational materials. These factors result in less traffic during the construction and operation of the plant, resulting in fewer (traffic related) atmospheric emissions, less waste and, due to the smaller facility size, less impact on the landscape and land use. Likewise, the smaller plant size has a beneficial effect on its operational impacts.

The smaller footprint of SMR plants also offers flexibility in geographical locations and lower land and water usage, resulting in lower environmental impact. Most of the current SMRs have an electric capacity of less than 300 MW(e). This power range offers flexibility in generation locations and it contributes to grid stability. In this regard, SMRs can work in synergy with other renewable energy sources promoted particularly in Europe and developed countries. Additionally, the cost of electrical infrastructure could be avoided when an SMR is used to replace other fossil fuelled generators of matching electrical output either owing to environmental concerns or obsolescence.

SMRs have the potential for enhanced safety and security. The SMRs to be built in the future will have to meet at least the level of safety required for the best NPPs currently in operation or being designed. It is expected that their safety will be even more transparent and easier to prove. Their expected level of safety will also be independent of the particular type of reactor or technology. The technical characteristics and safety features of some SMRs indicate that the full application of existing safety requirements, mostly developed for large water cooled reactors, would not be completely appropriate. There is the need to develop a tailored set of safety requirements derived from the general consolidated principles of nuclear safety that better incorporates the specific characteristic of SMRs plus the need to integrate the lessons learned from major nuclear accidents (e.g. the Fukushima Daiichi).

SMRs offer numerous advantages including innovative technology to enhance energy supply security in newcomer countries with small grids and less developed infrastructure. However, there are still considerable technical and institutional challenges that should be resolved in the developmental stages prior to deployment. Some challenges are associated with the advanced specificity and unique features of SMRs that are not incorporated in conventional large reactors, as well as their broader options of utilization, including deployment in remote areas and their utilization for non-electric applications. Other challenges include: limited commercial availability for newcomer countries aiming for immediate deployment (i.e. construction by 2017) since most of the advanced SMR designs are still under design review for certification; regulatory infrastructure (in both expanding and newcomer countries); licensability delay (due to innovative or first-of-a-kind engineering structure, systems and components); first-of-a-kind cost estimate; economic competitiveness; operability; and human factor engineering (e.g. staffing for multimodule SMR, human–machine interface) [140, 141].

The IAEA facilitates the efforts of Member States in identifying key enabling technologies in development and in addressing the key challenges in deployment of SMR. The priority for IAEA SMR programme activities is twofold:

(a) The first is to facilitate Member States with ongoing SMR development activities for near term deployment (i.e. Argentina, China, France, India, Italy, Japan, Republic of Korea, Russian Federation and the USA) in the conclusion of design certification and to have SMR deployed in the countries of origin — by addressing common issues and key enabling technologies.
(b) To facilitate newcomer countries' capacity building particularly in the capability in performing technology self-assessment and selection, and human resource and infrastructure development.

Many newcomer countries have expressed interest in SMRs, but are still in favour of proven technology, so they want SMR technology to be first deployed in the country of origin to minimize licensing and performance risks. Member States also have expressed their wish that technology developers, nuclear regulatory authorities and operating organizations primarily responsible for reactor safety incorporate the lessons learned from the Fukushima Daiichi accident into the operating plants as well as in advanced nuclear new builds including SMRs. In conclusion, as a result of all these, SMRs might become significant constituents of the technology portfolio to mitigate global climate change.

## 6.3. THE THORIUM OPTION

When assessing the potential contribution of nuclear energy to climate change mitigation over the long term, it is important to consider the natural resource base of the technology. Despite the relative abundance of world uranium reserves, their rather even distribution around the planet and significant industrial experience with the uranium fuel cycle, there are factors that might stimulate the transfer to alternative types of fuel. Among such factors is the necessity to achieve a higher level of proliferation resistance and to produce smaller amounts of high level waste. The factor that will drive the search for alternatives to uranium is likely to be the expansion of the nuclear industry caused by the growth of international energy demand and the necessity of achieving global $CO_2$ mitigation goals.

The most realistic alternative to uranium (U) is thorium (Th). Being three times more abundant in nature than uranium, it can become a viable alternative as a fuel for NPPs [142]. The idea to use thorium as a fuel was proposed as early as 1947 by the Oak Ridge National Laboratories in the USA, and since the 1960s, a few thorium fueled reactors have been put into operation [143]. Experience obtained during the last decades with thorium use allows a better understanding of its prospective industrial scale use. Previously, thorium fuel was used only in specifically designed reactors, but in 2013 tests were started at the Halden research reactor, Norway, to analyse the prospects of thorium use in current designs of NPPs (mainly in light water reactors). This experiment, preceded by a feasibility study in 2007–2008, will last for at least five years and may reveal an opportunity to gradually start replacing uranium fuel in existing reactors [144].

The enrichment process for thorium is rather different than for uranium as in nature thorium exists only as a non-fissile $^{232}$Th isotope, which later can be irradiated with neutrons to convert it into $^{233}$Th [145]. $^{233}$Th, as a result of the radioactive decay process, converts into protactinium ($^{233}$Pa) and — later — into $^{233}$U, which has good fissile properties. As an irradiation source, $^{232}$Th can use enriched uranium, plutonium (Pu) and $^{233}$U obtained from a previous cycle of irradiation. The use of thorium fuel in reactors is different from the use of uranium due to its higher melting temperature (3350°C) and chemical stability (significant amounts of corrosive materials are required).

Designs of thorium fuel assemblies usually proposed imply that fuel will stay in the reactor core much longer, which should positively affect the economic competitiveness of the thorium fuel cycle. In comparison with a 1–1.5 year residence time in the core for conventional uranium fuel for thorium, this period can be extended up to 9 years [146] or even 10 years and more [147]. A technological limitation is that fuel rod cladding that could meet such requirements has not yet been developed. If such technology is developed, it would benefit not only thorium fuel but uranium as well. Therefore, the economic benefits of thorium fuel would strongly depend on corresponding changes in uranium fuel technologies.

The physical properties of thorium make it more reliable and safe while being used in the reactor core [147]. It is expected that in the thorium fuel cycle much less long lived minor radiotoxic elements will be produced (neptunium, americium and curium), which would decrease the toxicity of nuclear waste in the long run [148]. Moreover, in this type of fuel cycle, most of these elements can be recycled [149]. The thorium fuel cycle, however, produces some specific long lived radionuclides, which makes estimation of its waste properties more complicated.

Thorium fuel is expected to be economically competitive in comparison with traditional uranium fuel — according to the research conducted jointly by the Kurchatov Institute (Russian Federation) and the Thorium Power Corporation (USA) that contend that the costs of the fuel cycle based on thorium can be at least 20% lower [146] than that of uranium. Moreover, as the thorium fuel cycle is at an early stage of development, it is probable that the price of fuel could be further decreased due to the introduction of innovative technologies. However, the technology of thorium fuel fabrication is more complicated than uranium.

The thorium cycle has favourable non-proliferation properties. The reason is that it would allow plutonium burnup at a rate three times higher than conventional uranium fuel, thus allowing the regulation of the plutonium stockpile. If thorium is used in the fuel matrix in place of uranium, it could allow an increase in plutonium burnup from 20 to 60%. This is, however, only a partial solution as in mixed fuel not all $^{238}U$ can be replaced by thorium due to non-proliferation regulations. Otherwise uranium, if used as a driver of reaction, would have to be enriched up to 100%, which violates 20% level non-proliferation regulation [147]. Therefore, some plutonium will be produced as a result of the reaction anyway, thus decreasing the benefits from plutonium stockpile decrease through the thorium fuel cycle. Another issue is that the necessity to use uranium enriched to 19.95% (well over the 3–5% level used in conventional fuel) will put upward pressure on fuel production costs [146].

A product of the thorium fuel cycle is $^{233}U$, which is more proliferation resistant than plutonium because it is always obtained in a mix with highly radioactive $^{232}U$ (which emits very high energy gamma rays) providing sufficient detectability and self-protection incentives which complicate attempts to violate the international security regime [147]. However, the thorium fuel cycle does not resolve the proliferation issue completely.

Potential large scale introduction of thorium in the global nuclear energy mix will likely be driven not only by resource scarcity issues but by energy security concerns. Though uranium is not accumulated in one region of the globe and a significant share of its reserves is located in the OECD countries, making the probability of the establishment of an organization energy similar to OPEC for uranium exporting countries highly improbable, some countries still do not have sufficient reserves. Therefore, in the longer perspective, the diversification of fuel sources is an attractive option for consuming states in order to decrease prospective risks that can arise from political instability.

Since the countries with the richest thorium reserves are also the major energy consumers (Brazil, India and the USA) the potential for them to develop national thorium fuel cycle programmes during the twenty-first century is high (see Fig. 36). For example, India's three stage nuclear power programme assumes the introduction of thorium based reactors after the high scale development of fast breeder reactors by middle of the century in order to increase reliance on abundant domestic thorium resources rather than on imported uranium [150].

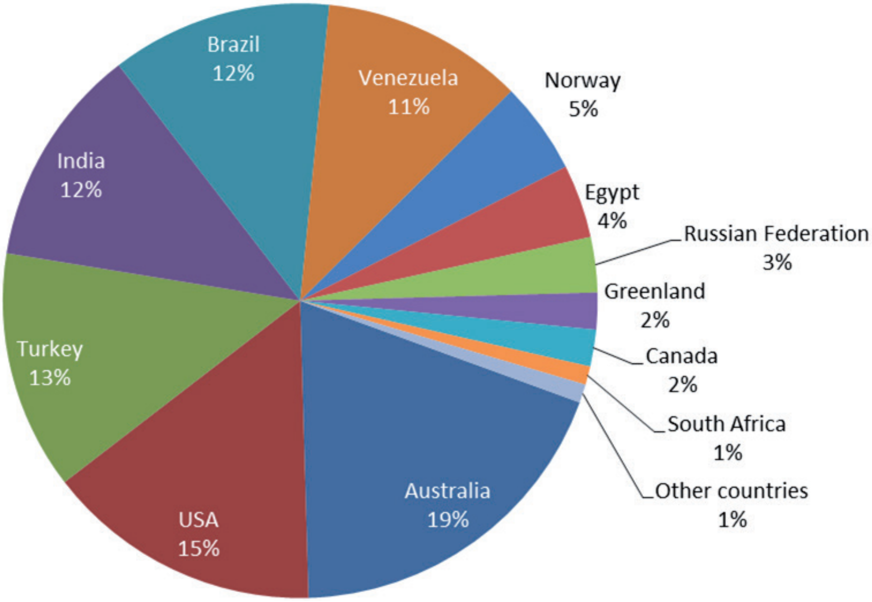


*FIG. 36. Global thorium reserves in 2007. Based on data from Ref. [151].*

Prospectively, the thorium alternative could play a stabilizing role in the market of nuclear fuel, thus making consumers more self-sufficient.

There are no special limitations to the introduction of thorium fuel as an energy source. The current level of technological development allows its industrial use (especially considering existing experience in this sphere, e.g. the German Thorium High Temperature Reactor THTR-300, which was producing electricity for commercial needs as early as 1983–1989) [143], and progress in this area depends more on the growth of energy demand than on technical issues. As thorium fuel can be used in light water reactors, it can be treated as an expansion of contemporary nuclear technologies, allowing the extension of the sources available to industry. This extension will provide the international energy system with more economically efficient and proliferation resistant nuclear fuel fostering global goals of $CO_2$ emissions reduction.

## 6.4. FAST REACTORS: BREEDING THE FUTURE

An important option to enhance the use of natural resources, overcome future resource constraints and reduce the amount of long lived radioactive waste, is closing the nuclear fuel cycle by using fast breeder reactors (FBR) and used fuel recycling. The introduction of fast breeder reactors might have a revolutionary impact on the future of nuclear energy and foster its contribution to mitigating climate change.

The major advancement of fast breeder technology relative to existing reactor designs is that it will prospectively allow the extraction of over 50 times more energy per kilogram of uranium than is possible in current light water reactors. In a fast breeder reactor nearly all the energy contained in nuclear fuel can be used as it can convert fertile non-fuel $^{238}$U into fissile $^{239}$Pu at a faster rate than it consumes the fissile fuel ($^{235}$U or $^{239}$Pu) [152]. As a result, all $^{238}$U will be converted into fissile material over time. The reason for this is that FBRs have a much more efficient neutron economy (ratio of neutrons created during the reaction to neutrons lost) than conventional reactors, which allows them to breed fissile fuel from fertile materials. Fast breeders would extend existing uranium reserves for thousands of years providing a source of low carbon energy.

An important characteristic of breeder reactors is the reduced amount of long lived radioactive waste, as they burn up the most toxic minor radioactive elements, which account for a significant share of long term radioactivity of spent fuel due to long half-life periods [153]. Fast breeders also use plutonium fuel (this is seen as the basis of the second, breeder based part of three stage nuclear power programme in India) [150] thus reducing plutonium stockpiles, which build up in the used fuel of conventional reactors.

A major factor that will determine the future role of FBRs will be their specific breeding characteristics. The breeding ratio is the ratio of new fissile material produced (as the result of reaction) to fissile material consumed from the fuel loaded in the reactor. For the FBRs of current designs the breeding ratio is close to one (‘breakeven’ level), which means that the reactor produces nearly the same amount of fissile material (from fertile material loaded) in spent nuclear fuel as it consumes from the fuel loaded in it.

The general scheme for using nuclear energy dominated by fast breeders is to load the fuel cores of new reactors with fuel bred in existing reactors in order to maximize resource utilization. Therefore, FBRs with a breeding ratio close to one will make such expansion rather slow. The reason is that the doubling time (the period during which the reactor would be able to produce enough fuel to startup another of same capacity) can be significant. Liquid metal cooled reactors are likely to have a breeding ratio close to one, advanced sodium cooled reactors a ratio of around 1.4 and fast reactors with direct loading of fuel elements a ratio of 1.6 [154]. The issue here is that the startup of a FBR requires a significant initial upload of fuel (e.g. for the startup of one fast reactor with a high conversion ratio the amount of plutonium needed is equal to that produced during the 30 year operation of a conventional light water reactor). Another source of fuel for FBRs could be highly enriched uranium (enrichment levels over 20%), which exceeds non-proliferation limits. However, an FBR with a breeding ratio close to the breakeven level can be started with low enriched uranium that is not usable for weapons [152].

Breeding is extremely important for countries planning to fuel their future FBR fleet with the used fuel produced in traditional thermal reactors. With FBRs, industry can rely mostly on domestic resources and reach a significant level of energy independence. An example is India, where a fast breeder test reactor was launched in 1985. The construction of the first full scale prototype fast breeder reactor is now under way and scheduled to be completed in 2014. This will be a major step towards the mass FBR construction in the country [37].

Ideally, the efficiency of the neutron economy of fast breeders could make the industry self-sustainable, which should drastically reduce the need for mining and enrichment — the most energy intensive and, depending on the source of electricity, the potentially most $CO_2$ intensive step in the once-through fuel cycle, thus making nuclear a renewable source of energy in terms of fuel consumption. Fast breeder reactors may become an important technology for mitigating climate change due to their friendliness to the environment and sustainability based on the fuelling of new reactors with fuel produced from existing ones.

The idea of breeders is not a new one — in 1951 the USA launched the first experimental breeder reactor (EBR-I), followed a few years later by the UK and the Soviet Union [152]. The development of the concept of FBRs in early years of the nuclear era was stimulated by concerns about the availability of uranium and high costs of its enrichment. Technological progress as well as the discovery of significant uranium deposits resolved these concerns by the 1960s and, therefore, made the necessity of FBR introduction less acute. Another factor that stimulated the choice of light water reactors was the higher construction costs and more complicated design of FBRs.

Subsequently, efforts were focused on the cost decrease of FBR construction in order to make the technology more competitive. In the 1970s and 1980s, significant successes in R&D and construction experience were achieved in France (the Phénix and Superphénix reactors) and in the former Soviet Union. A partial but positive experience of cost decrease of breeder reactors is the Russian Federation programme of BN reactors. The design specific capital costs of reactor systems for BN-600 were decreased by approximately 20% per kW(e) in comparison with the earlier BN-350 design. The capital cost of BN-800 (now under construction — see Fig. 37) is expected to further decline by 20% compared to BN-600 [155]. BN-800 will use mixed uranium-plutonium fuel, while BN-600 operates with uranium dioxide [153]. It is expected that the fuel for BN-800 will only be 30–40% more expensive in comparison with that used in conventional light water reactors of the VVER-1000 type.

*FIG. 37. The sodium cooled fast reactor BN-800 (Russian Federation).*

Fast breeder technology started to attract additional interest in the 2000s when it was again being seen as a promising way to resolve the problem of radioactive waste and as an important element of prospective closed fuel cycle technology [156]. In the development programme of the Generation IV International Forum (GIF), three out of six prospective systems are fast reactors: the sodium cooled fast reactor (SFR), the gas cooled fast reactor (GFR) and the lead cooled fast reactor (LFR) [157].

Currently, the capital costs of fast reactors are considered to be higher than those of conventional designs [155]. Construction costs are expected to decrease through reduced construction time and simplified design. The issue of FBR technology at this stage is the limited practical experience in construction, which will make the costs of the first commercial units significantly higher. However, the factor that is expected to affect the choice in favour of FBRs is the decrease in the mass of radioactive waste. As the waste disposal is not only costly but also a major factor affecting public concern, the decision in favour of FBRs might be made even before they have become economically competitive with conventional LWRs.

## 6.5. IGNITING THE FUSION SUN

Looking into the long term options of climate change mitigation, nuclear fusion is the technology at the edge of current research efforts and is expected to be commercialized in the second half of the twenty-first century. Fusion differs from fission used in conventional nuclear reactors, as in this case, during the reaction between two atomic nuclei with lower masses, a new nucleus of a heavier element is formed, which is accompanied by the release of energy.

From the rise of nuclear era, fusion was seen as its prospective future, allowing the realization of the concept of providing abundant and cheap energy. Fusion is seen as a carbon free technology offering an adequate response to the challenge of climate change and meeting the energy needs of humanity but being free of the weaknesses of nuclear fission. Power plants operating with nuclear fusion are expected to produce minimal amounts of radioactive waste. The reason for this is that the result of deuterium–tritium (D–T) reaction, which will be used in fusion reactors of the first generation, is environmentally benign helium, in contrast with heavy radioactive isotopes in spent nuclear fuel from existing NPPs [158] (see Fig. 38). Thermonuclear reactors of the second generation are likely to be based on deuterium only (D–D fuel cycle), producing tritium and helium as the result of this reaction. Tritium is an isotope of hydrogen but its half-life is only 12.32 years, making it much more favourable in comparison with radioactive waste from current reactors. Radioactivity will accumulate in the core of the reactor due to the impact of neutrons released during the fusion reaction but, because of the short half-life of isotopes produced, it will decrease to safe levels after only a few decades, compared with thousands of years in fission power plants [158].

Currently, there are two major approaches to the practical realization of nuclear fusion — magnetic confinement and inertial confinement. Magnetic confinement is based on the idea of the use of magnetic fields to confine fusion fuel in the form of plasma (ionized gas). The devices that have been most widely used for this since the 1960s are tokamaks (toroidal chambers with magnetic

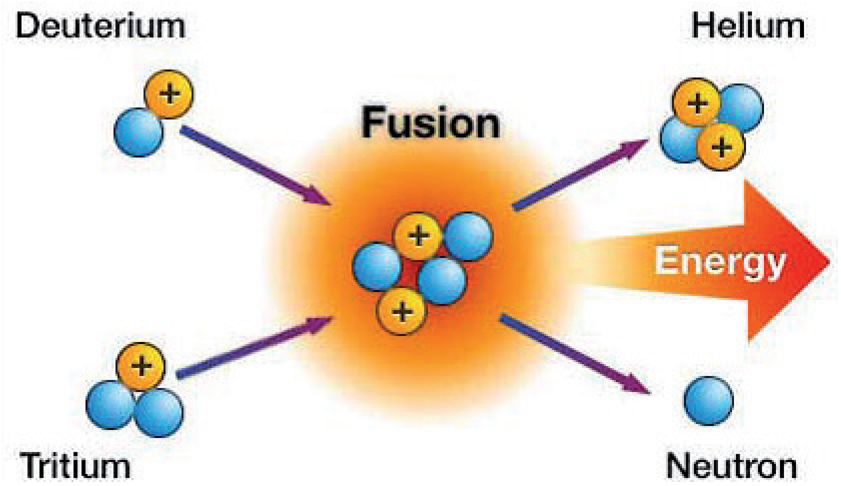


*FIG. 38. The deuterium–tritium fusion reaction. Source: Ref. [159].*

coils — see Fig. 39) [157]. Owing to significant progress in their construction (see Fig. 40), they are considered to be the most likely candidates for industrial implementation of thermonuclear fusion (e.g. the current ITER project). In tokamaks, plasma is kept moving around the torus chamber by magnetic field lines. Magnetic fields in tokamaks are produced by electromagnets: the first set of magnets surrounding the torus chamber produce a toroidal field and the second set induce an electric current flowing in the plasma forming poloidal field. An alternative form of the tokamak is the spheromak (a spherical tokamak with the rod inserted in the centre).

Inertial confinement is based on heating and compressing the fuel pellet using e.g. lasers [160]. To heat the fuel pellet, energy is delivered to its outer layer, which results in an outward explosion and compresses the target. Experiments in the field of inertial confinement started in the 1970s but significant engineering difficulties with the achievement of ignition energies made this direction of research less favourable for industrial implementation in comparison with magnetic confinement. The most advanced inertial confinement device is the National Ignition Facility (NIF) located at the Lawrence Livermore National Laboratory (USA) and completed in 2009. However, it was unable to achieve the level of pressure necessary to achieve ignition (energy levels achieved by NIF were around one third of those needed) [161]. Despite current difficulties

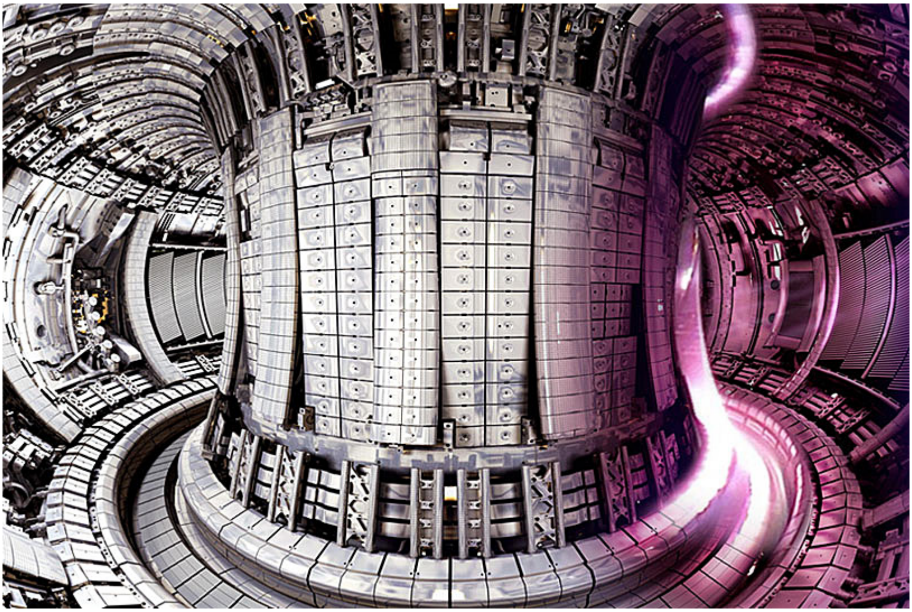


*FIG. 39. Internal view of a tokamak. Source: Ref. [159].*

with NIF and another project in this field — Laser Mégajoule (France), which is currently expected to be launched in 2014 — inertial confinement is still considered by the National Research Council to be a viable alternative to magnetic confinement [160].

Fusion technology is expected to support much higher safety standards as the plasma used in the reactor is burnt under rather specific conditions and any significant deviation will result in the halting of the process thus excluding the possibility of any reactor disasters. The external impact of possible accidents at fusion power plants should not exceed the level of those at non-nuclear industrial facilities. Disrupting fuel delivery in prospective fusion reactor designs will lead to quick suspension of the reaction, while in fission reactors the amount of fuel loaded is enough for years of operation.

The energy system based on fusion will be fundamentally different from existing ones. The concept of energy security in modern understanding, based on resource scarcity, will simply disappear, as the necessary fuel will be produced from abundantly available materials such as water. It will make meaningless any attempts to use some kind of ‘energy weapon’ based on the uneven distribution of energy sources around the globe. The fusion energy system will allow the resolution of current contradictions between consumers and producers of energy sources, making international energy policy much more predictable and collaborative.

Fusion will also contribute to resolving nuclear proliferation issues as the use of neutrons released during the fusion reaction for the production of materials used in nuclear weapons would require a significant redesign of the reactor, allowing the detection of possible proliferation violations already at the stage of construction. Tritium (which is used in the D–T reaction and is a product of D–D

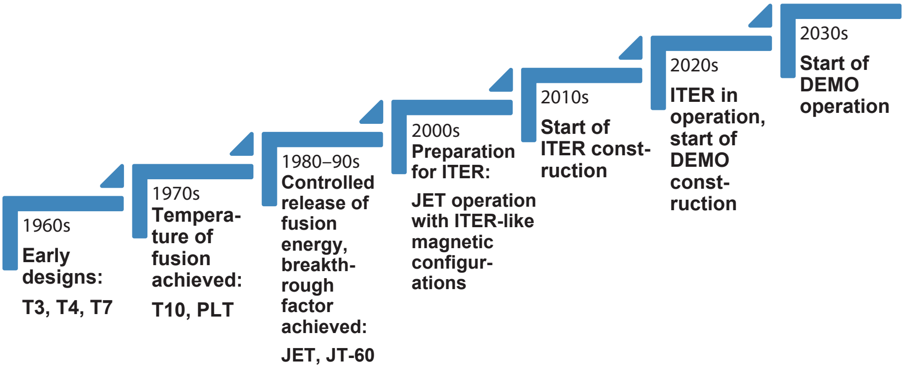


*FIG. 40. Progress in tokamak based magnetic confinement fusion research.*

reaction) is used in thermonuclear weapons but is not a major component and definitely not the hardest one to produce.

Over a half-century of experience of global research efforts in the area of fusion today has been accumulated in the ITER project, which is aiming to construct the first full scale fusion reactor. The project has been jointly developed by a group of countries (China, the EU, India, Japan, the Republic of Korea, the Russian Federation and the USA) and the site chosen is Cadarache, France [158]. The idea of ITER was initially proposed at the Geneva summit in 1985, but it took around twenty years until an international consortium was formed (2006). Site development started in 2008 [162]. It is expected that the first D–T reaction at the site will start in the late 2020s. ITER will operate with magnetic confinement fusion technology and should demonstrate the prospects of fusion on an industrial scale with an input capacity of 50 MW and producing 500 MW, i.e. with a fusion energy gain factor of 10 (i.e. the ratio of energy produced to the energy required to confine plasma). The self-sustaining plasma burning process requires at least a factor of 5. The goal of ITER is to support the fusion reaction for eight minutes. ITER is expected to be succeeded by the DEMO fusion reactor, which should become the prototype of industrial thermonuclear reactors of the future [160]. The goal for the DEMO project would be the continuous production of energy with energy gain factor of 25, making its output comparable to contemporary power plants. The expected timeframe for its commencement is highly uncertain but according to ITER project estimates DEMO is expected to begin operations in the early 2030s with connection to the grid around 2040 [163].

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