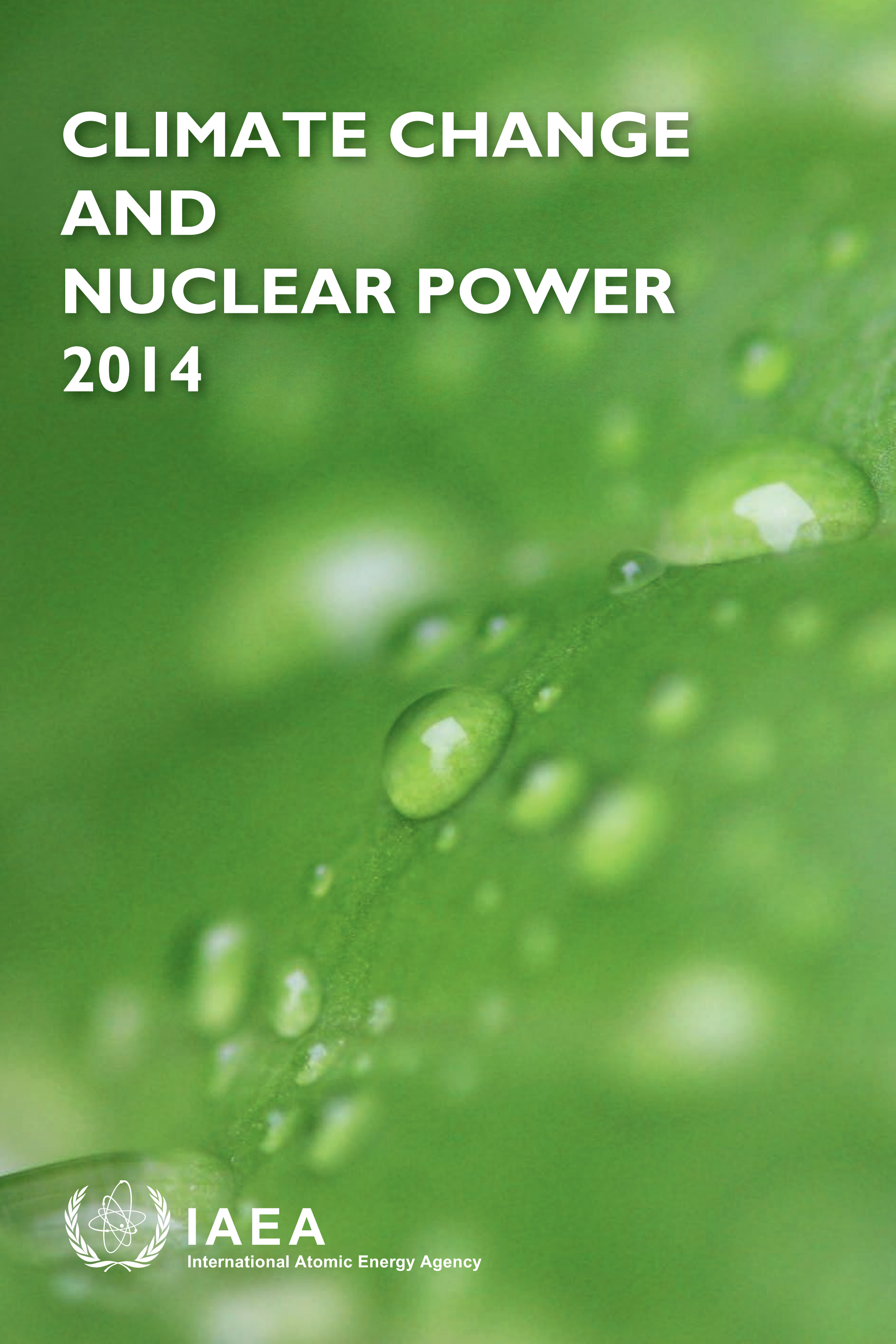

CLIMATE CHANGE AND NUCLEAR POWER 2014

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CLIMATE CHANGE AND NUCLEAR POWER 2014

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
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FOREWORD

Climate change is the foremost global environmental issue today. Nuclear power is one of the low carbon technologies that can contribute to reducing greenhouse gas emissions while delivering energy in the increasingly large quantities needed for growing populations and 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. Nuclear power fosters energy supply security and industrial development by providing electricity reliably at stable and foreseeable prices.

The accident at the Fukushima Daiichi nuclear power plant in 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, more than three years after 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 IAEA provides assistance and information to countries that wish to introduce nuclear power. It also provides information for broader audiences engaged in energy, environmental and economic policy making.

This report provides a comprehensive review of 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 costs, investments, financing, safety, waste management and non-proliferation. Recent developments in resource supply, changes in energy markets and technological developments are also presented.

This edition has been substantially amended since the 2013 report. Most sections have been completely revised on the basis of new scientific information, new analyses, and technical reports and other publications that have become available in 2014. Sections on topics where the available information has not substantially changed within the past year have been omitted and will be updated if necessary in future editions. Short summaries of these sections are provided in the Appendix, but interested readers are referred to the 2013 edition for information on nuclear energy applications beyond the power sector, the thorium option, fast reactors and fusion. New sections explore emerging issues that will affect the relationship between climate change and nuclear power in the coming decades.

EDITORIAL NOTE

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SUMMARY

New evidence put forward by climate scientists indicates that the climate system of the Earth is changing owing to increasing concentrations of greenhouse gases (GHGs), especially of carbon dioxide (CO_2), resulting from emissions from human activities, mainly the burning of fossil fuels and land use change. Global mean surface temperatures are increasing; precipitation volumes and spatial and temporal distribution patterns are changing; the oceans are warming and sea level is rising; features of extreme weather and climate events are changing. Keeping the increase in global mean temperature below 2°C relative to pre-industrial levels would be required to avoid distressing impacts of climate change in ecological and socioeconomic systems, as agreed in the Copenhagen Accord of the United Nations Framework Convention on Climate Change (UNFCCC). This means that global GHG emissions will need to peak within the next decade or so and then fall by at least 90% below the 2010 emission levels by the middle of the century.

Energy is indispensable for development. Enormous increases in energy supply will be required over the next few decades to support industrial and broader socioeconomic development and to lift 2.6 billion people out of energy poverty. Without a major transformation of the global energy system, however, GHG emissions will increase further. Even after accounting for continuing improvements in energy efficiency, global primary energy demand is projected to increase to over 15 gigatonnes of oil equivalent (Gtoe) by 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 about 20% by 2035 and of more than 60% in 2050 relative to 2011. The twin challenge over the next 10–20 years will be to keep promoting socioeconomic development by providing safe, reliable and affordable energy while drastically reducing GHG emissions.

Nuclear power belongs to the set 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 (less than 15 grams CO_2-equivalent (g CO_2-eq) per kW·h (kilowatt hour), median value of 60 reviewed sources). Across a large number of stringent mitigation scenarios consistent with the Copenhagen Accord, nuclear electricity is assessed as avoiding approximately 3.3 to 9 Gt CO_2/year in 2050, depending on assumptions about the relative costs and performance of low carbon technologies.

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 about 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. Including nuclear power in the energy supply mix 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 that are not accounted for in the price of electricity.

Nuclear power is economically competitive. Recent assessments indicate that the ranges of levelized costs of electricity (LCOE) from natural gas, coal and nuclear sources largely overlap between 30 and 80 $/megawatt hour (MW·h) at a 5% discount rate and between 40 and 120 $/MW·h at a 10% discount rate. LCOE from renewable sources are declining but are still significantly higher. The choice of technologies depends on local circumstances, such as the availability of cheap domestic fossil resources and renewable energy potentials, techno-economic capabilities and policy priorities. System costs (resulting from investments required to ensure electricity supply at a given load and level of reliability) are low for nuclear power at 1.40–3.10 $/MW·h (slightly more than other dispatchable sources such as coal and gas), whereas the grid level system costs of intermittent renewables are higher by a factor of 10–20. This means that the system costs alone of renewables are close to the total levelized costs of gas, coal and nuclear electricity and should be considered together with their higher levelized costs. Among the dispatchable technologies, 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. When nuclear investments start increasing, manufacturing and construction capacities will expand as required.

The accident at the Fukushima Daiichi NPP that was caused by the Great East Japan Earthquake and Tsunami that struck Japan on 11 March 2011 prompted a round of stress tests of NPPs around the world. The IAEA's Action Plan on Nuclear Safety (henceforth referred to as 'the Action Plan') includes 12 main actions in key areas of nuclear safety such as assessments of safety vulnerabilities of NPPs, strengthening of the IAEA's peer review services, and improvements in emergency preparedness and response capabilities. The 2013 International Ministerial Conference on Nuclear Power in the 21st Century (St. Petersburg, Russian Federation) reaffirmed the commitment of the IAEA 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. The IAEA is preparing a major report to present an authoritative, factual and balanced assessment of the accident and the lessons learned, which will be finalized by the end of 2014.

Concerns about nuclear energy regarding radiation risks, waste management and proliferation still exist and influence public acceptance. Radiation risks from normal plant operation remain low, 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 sectors 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 spent nuclear fuel and high level radioactive waste are expected to start operation in fewer than ten years. Institutional arrangements are being improved and further technological solutions sought to prevent the diversion of nuclear material for non-peaceful purposes. Public acceptance, following a decline in acceptance in most countries after the Fukushima Daiichi accident, is slowly recovering in some countries, but it is also influenced by a broader range of issues on the public policy agenda in any given country. The nuclear sector needs to improve further and to provide adequate responses to these concerns in order to realize its full potential.

Projections of future nuclear generating capacity point to a continued increase in the use of nuclear power in the longer term. The Fukushima Daiichi accident slowed the projected growth rate of nuclear capacities — the IAEA 2014 high projection for 2030 is about 3% lower than what was projected in 2013 — but did not reverse the upward trends of nuclear power capacities and output. Nuclear capacity is estimated to expand to 401 GW(e) in the low and to 699 GW(e) in the high IAEA projection by 2030 and reach 413 GW(e) in the low and 1092 GW(e) in the high projection by 2050. The principal reasons for the growing 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 mitigation targets and implementation mechanisms in the new UNFCCC agreement currently being negotiated in the Ad Hoc Working Group on the Durban Platform for Enhanced Action (ADP) which is to be finalized by the end of 2015. The final decision to introduce or expand nuclear energy in the national energy portfolio rests with sovereign States.

1. INTRODUCTION

Anthropogenic climate change has dominated the global environmental policy agenda over the past two decades. A principal source of GHGs, and particularly of CO_2 emissions, is the fossil fuels burned by the energy sector. Energy demand is expected to increase considerably in the twenty-first century, especially in developing countries, where population growth is fastest and where, even today, some 1.3 billion people have no access to electricity. 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. All energy sources and technologies will be required to face the twin challenge of climate change and global energy supply. This report explores the possible contribution of nuclear energy to resolving the climate–energy conundrum. It is an updated and extended version of the previous edition [1].

It is increasingly recognized that climate change can impair the achievements of past efforts towards sustainable development and undermine the outcomes of future efforts. United Nations Secretary-General Ban Ki-moon stated that "climate change is an obstacle to the future security, prosperity and sustainable development of humankind" and concluded that "we need a meaningful, robust, universal, legal climate agreement by 2015" [2]. As part of a global effort to mobilize action and ambition on climate change, the Secretary-General invited Heads of State and Government along with business, finance, civil society and local leaders to a Climate Summit in September 2014. The Summit aimed to catalyse action by governments, business, finance, industry and civil society towards new commitments and substantial, scalable and replicable contributions to help the world shift toward a low carbon economy.

As an initial step to reduce the risk of global climate change, developed countries (listed in Annex I of the Convention) 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.

The Doha Amendment to the Kyoto Protocol, adopted at the 18th Conference of the Parties to the UNFCCC (COP 18) and the 8th session of the Conference of the Parties serving as the Meeting of the Parties to the Kyoto Protocol (CMP 8) in 2012, includes new commitments for Annex I Parties who agreed to take on commitments in the second commitment period from

1 January 2013 to 31 December 2020 to reduce GHG emissions by at least 18% below 1990 levels between 2013 and 2020. 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 ADP aim to reach a comprehensive global agreement by the end of 2015 to enter into force in 2020.

"Nuclear energy can help to improve energy security, reduce the impact of volatile fossil fuel prices, mitigate the effects of climate change and make economies more competitive", as IAEA Director General Yukiya Amano has explained [3]. 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 has already been an important contributor to the world's electricity needs. It supplied 12.3% of global electricity in 2011. 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, changed 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 2 presents climate change and global energy supply challenges and demonstrates the need for nuclear power to resolve them. The potential contribution of nuclear energy to easing supply security concerns and reducing local and regional air pollution problems, and its role in supplying low carbon energy for industrial development and economic and employment growth, are also discussed. Section 3 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 4 is devoted to concerns surrounding nuclear power including radiation risks, safety, proliferation and waste management, and to current efforts to address them. Recent trends in public acceptance in selected countries are also discussed. Section 5 looks to the future. In addition to presenting the latest projections of the IAEA, recent developments in relevant energy markets and prospects for nuclear energy technology options that may become important contributors to mitigating climate change in the coming decades are discussed.

2. THE NEED FOR NUCLEAR POWER

2.1. THE CLIMATE CHANGE CHALLENGE

In its Fifth Assessment Report (AR5), Working Group (WG) I of the Intergovernmental Panel on Climate Change (IPCC) confirms at a higher level of confidence than ever before that the climate of the Earth is changing as a result of anthropogenic GHG emissions. “Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia” (Ref. [4], p. 4). Over the period 1880–2012, globally averaged surface temperature increased by 0.85°C. The upper layer of the ocean is warming, the Greenland and Antarctic ice sheets are losing mass, glaciers continue to shrink and global mean sea level rose by 0.19 m between 1901 and 2010.

The AR5 adopted a new approach to projecting anthropogenic climate change for the next decades to the next few centuries. Abandoning the traditional pathway of tracking changes from scenarios of socioeconomic development and associated GHG emissions from energy use and land use changes through atmospheric GHG concentrations and radiative forcing to climate attributes such as temperature and precipitation, the new projections are based on alternative assumptions about radiative forcing values for the year 2100.

The new IPCC scenarios consists of four so-called representative concentration pathways (RCPs) for exploring the near and long term climate change implications of different paths of anthropogenic emissions of all GHGs, aerosols and other climate drivers. The four RCPs present approximate total radiative forcing values for the year 2100 relative to 1750 ranging from 2.6 to 8.5 watts per square metre (W/m^2). RCP2.6 assumes strong GHG mitigation actions resulting from stringent but unspecified climate policies. Radiative forcing along this pathway peaks and declines during the twenty-first century, and leads to a low forcing level of 2.6 W/m^2 by 2100. In RCP4.5, radiative forcing stabilizes by 2100 at a significantly higher level. The other two concentration pathways (RCP6.0 and RCP8.5) imply increasing emissions throughout the twenty-first century and lead to stabilizing radiative forcing beyond 2100 at 6.0 and 8.5 W/m^2, respectively. The RCPs were converted into corresponding GHG concentrations and emissions that served as inputs to more than 50 global climate models used in the Coupled Model Intercomparison Project Phase 5 (CMIP5) to assess the changes they trigger in the climate system globally and regionally [4].

Figure 1 shows the projected global annual mean surface air temperature anomalies — or simply: the triggered global warming — relative to the 1986–2005 mean values from the CMIP5 concentration driven experiments for all RCPs. Relative to the 1850–1900 period, the increase in global surface temperature is likely to exceed 1.5°C by the end of this century for all but the RCP2.6 scenario. Relative to the IPCC AR5 reference period (1986–2005), global surface temperature is expected to rise between 0.3°C and 1.7°C (RCP2.6) at the low end and between 2.6°C and 4.8°C (RCP8.5) at the high end of the scenario spectrum. The low end of the range is associated with limiting the global mean temperature increase to less than 2°C above the preindustrial level corresponding to the target of the Copenhagen Accord (see below).

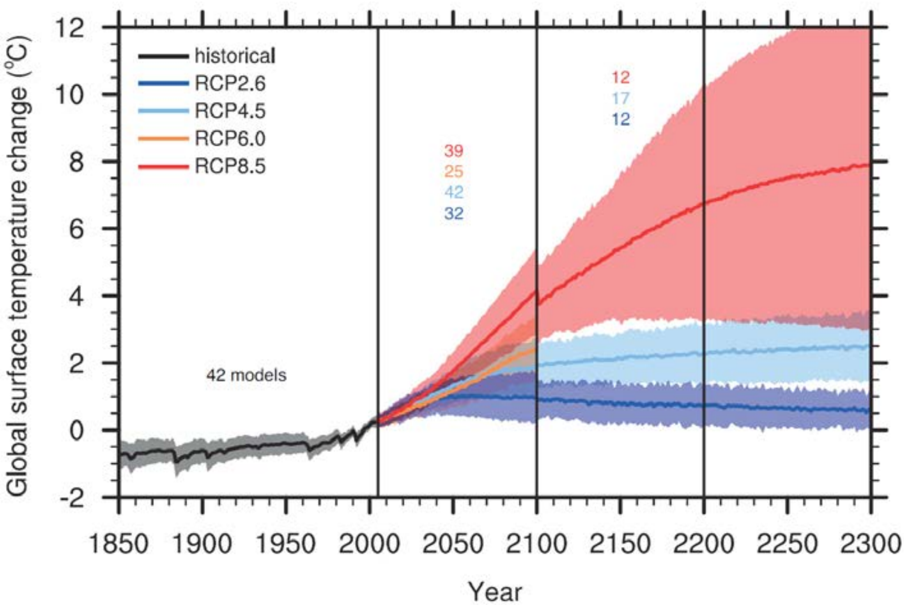

FIG. 1. Global annual mean surface air temperature change relative to the 1986–2005 mean values from the CMIP5 concentration driven experiment. Source: Figure 12.5 in Ref. [4]. Note: Solid lines indicate multi-model means, shaded areas represent 95% ranges. Numbers in colour indicate the number of models that provided input to CMIP5 for a given RCP. Discontinuities at 2100 are due to the smaller set of models running beyond 2100. RCP — representative concentration pathway.

The projected spatial pattern of temperature changes for RCP6.0 (approximately corresponding to the continuation of recent GHG emissions trends) indicates that, in the near term (2016–2035), the increase in annual mean temperature is projected to be modest: 0.5 to 1.5°C in most regions. Over the long term (2081–2100), however, a rather different picture emerges: 2 to 6°C temperature increases are foreseen in most regions of the world. The warming is projected to be much higher in the high latitude regions, especially in the north, than around the Equator.

The contribution of WG II to the IPCC's AR5 [5] assesses the patterns of risks and potential benefits resulting from the above changes in the climate system. The key risks include: death, injury, ill health and disrupted livelihoods in low lying coastal zones and small islands, due to storm surges, coastal flooding and sea level rise, and for large urban populations due to inland flooding in some regions; extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services; mortality and morbidity during periods of extreme heat; food insecurity and the breakdown of food systems caused by warming, drought, flooding, and precipitation variability and extremes; loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity; loss of terrestrial, marine and coastal ecosystems, biodiversity, and ecosystem goods, functions and services. These key risks create particular challenges for the least developed countries and vulnerable communities owing to their limited ability to adapt.

In order to reduce the potentially severe risks of climate change, Parties to the UNFCCC adopted the Copenhagen Accord at the COP 15 held in 2009, recognizing "the scientific view that the increase in global temperature should be below 2 degrees Celsius" [6]. This means that global GHG emissions will need to peak in the next few years and then be reduced at an accelerating rate. Nuclear power and other low carbon technologies will be fundamental in putting the world on this ambitious mitigation pathway.

Considering the emissions pathways shown in Fig. 1, the world faces an enormous mitigation challenge over the next decades. The latest report of the IPCC WG III [7] concludes that mitigation scenarios consistent with the Copenhagen Accord (reaching GHG concentrations around 450 ppm CO_2-eq by 2100) involve large-scale reductions of CO_2 emissions from the energy supply sector in order to reach a level of 90% or more below 2010 emissions between 2040 and 2070, declining to below zero thereafter. These scenarios also feature efficiency improvements and behavioural changes to reduce energy demand in the transport, building and industry sectors and thereby provide more flexibility for reducing carbon intensity in the energy supply sector and avoid lock-in to carbon intensive infrastructures. Nevertheless, low carbon energy technologies such as nuclear power will play a decisive role in reducing the carbon intensity of global energy supply and addressing the climate change challenge.

2.2. THE GLOBAL ENERGY CHALLENGE

Energy is generally recognized as a key driver of sustainable development. The overall consensus in the research community, which is also reflected in political decisions of several high level conferences and declarations, is that in order to embark on a sustainable development path, 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 vitally important. Reliable energy services are the precondition for modern economic growth, attracting investments to national economies and stimulating economic development. Access to energy positively affects the level of education in a society, allowing children to spend more time on their studies — both by decreasing the need for child labour and by providing the artificial light necessary to study during the hours of darkness. Among other things, energy services crucially improve access to modern health care through the uninterrupted provision of medical services after sunset and better storage conditions of medications and vaccines. They also promote gender equality by allowing women to use their time for more productive activities than collecting firewood, and social equality by giving disempowered groups of population a chance to obtain a more advanced level of education, thus providing a possible escape from poverty.

All of these factors are fundamental for the development of human capital. Energy is therefore vital for alleviating poverty, improving human welfare and raising living standards. Yet, according to the 2013 World Energy Outlook (WEO) of the International Energy Agency (IEA) of the Organisation for Economic Co-operation and Development (OECD), in 2011 over 2.6 billion people relied on traditional biomass as their primary source of energy (an increase by 54 million in comparison with 2010), and nearly 1.3 billion people (or 18% of the global population) did not have access to electricity (9 million decrease from 2010) [8]. The majority of these people are living in Sub-Saharan Africa and in developing regions of Asia, with a growing proportion residing in rural areas. This increases inequality and severely hampers socioeconomic development in these parts of the world.

Of the world's 7.16 billion people in May 2014 (according to United States Census Bureau estimates) [9], approximately 82% live in non-OECD countries [10] and consume only 57% of global primary energy [8]. Alleviating international inequality in energy consumption will be a major development challenge in the next decades. The challenge will become even greater — considering the projected growth of the global population, mainly in developing countries. The medium variant of the latest population projections of the UN estimates an additional 1.5 billion people by 2030 relative to 2012, and another 1.1 billion by 2050, bringing the world's population to about 9.55 billion by the middle of this century [11]. The IEA projections are similar: the world population is expected to increase to 8.7 billion by 2035, with the level of urbanization increasing to 62% from the current 52% [8].

It is also anticipated that the rising population will enjoy increasing prosperity over the next decades — and so will naturally need more energy. The World Bank estimate of real gross domestic product (GDP) growth of the world economy in 2013 is 2.4% with significant acceleration of growth projected over the next three years: up to 3.2% in 2014, 3.4% in 2015 and 3.5% in 2016 [12]. Developing countries will continue growing at a fast rate, though their long term annual growth rates will decline over time from 5.8% in the 2010s to 4.5% in the 2020s and 3.2% during the 2030–2050 period, while OECD countries are expected to grow by 2.2% in the 2010s, 2.1% in the 2020s and 1.7% between 2030 and 2050 [13].

Significant population growth and persistent expansion of the global economy will put upward pressure on global energy demand. Those who have access to modern energy services today will continue using them, and those without access will gradually start getting it, so the overall number of consumers will increase over time. In the 2014 edition of Energy Technology Perspectives (ETP), the IEA uses these two factors and some assumptions about technological progress for scenarios to project global energy demand. The direct continuation of existing trends is shown in the so-called 6°C scenario (6DS), which projects that total world primary energy supply will increase by approximately 70% between 2011 and 2050 [13]. Scenarios assuming more intense efforts to limit climate change still show significant increases in global energy supply over the same period: over 50% growth in the 4°C scenario (4DS) and over 25% growth in even the most stringent climate change mitigation case, the 2°C scenario (2DS). The evolution of the global primary energy mix and the corresponding global energy related CO_2 emissions in the 6DS are shown in Fig. 2.

The most important changes projected by the IEA scenarios for the period 2011–2050 include the following [13]:

— CO_2 emissions grow from 34 Gt CO_2 in 2011 to 55 Gt CO_2 (62% increase) in the 6DS, to 41 Gt CO_2 (21% increase) in the 4DS, and decline to 15 Gt CO_2 (a drastic 56% decline) in the 2DS by 2050.

— Fossil fuel use increases by 62% in the 6DS and by 29% in the 4DS, and it decreases by 34% in the 2DS during 2011–2050.

— Nuclear energy production grows by 25% in 2011–2050 in the 6DS, by 72% in the 4DS and by 162% in the 2DS. Considering the differences in energy consumption growth across these scenarios, in the 6DS the share of nuclear in total primary energy supply will actually decline: from 5.1% in 2011 to 3.8% in 2050. In the 4DS, the share of nuclear will slightly increase (to 5.8%), and it will more than double (to 10.9%) in the 2DS.

— Production of energy from renewable sources is expected to significantly increase in all scenarios: by 128% in the 6DS, by 186% in the 4DS and by

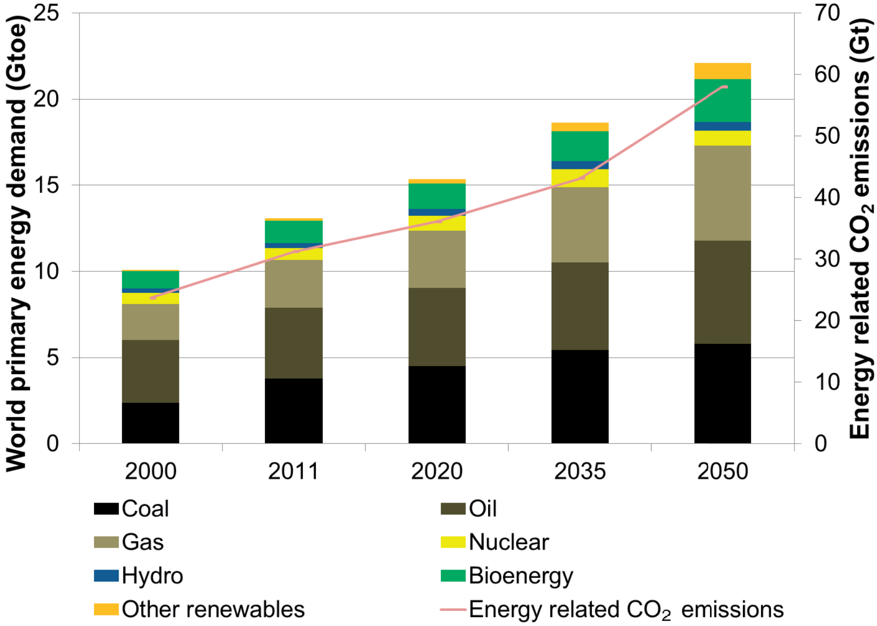

FIG. 2. Global primary energy sources (left axis) and energy related CO_2 emissions (right axis) in the IEA's WEO 2013 Current Policies scenario (up to 2035) and in the ETP 2014 6DS (2050). Sources: Refs [8, 13].

329% in the 2DS in the 2011–2050 period. This will change their share in the total primary energy supply from 13.3% in 2011 to 17.9% in the 6DS, to 25% in the 4DS and to 46% in the 2DS by 2050.

— The global economy will be predominantly fuelled by non-fossil sources of energy by 2050 in the 2DS (56% of total primary energy supply), while the share of renewables and nuclear will be around 30% in the 4DS, and it will remain nearly constant in the 6DS: 22% in comparison with 18% in 2011.

— Realization of the 2DS is strongly associated with the introduction of 'best in class' technologies affecting improvements in energy efficiency, intense use of renewables and the introduction of carbon dioxide capture and storage (CCS). Sub-scenarios of the IEA show possible ways of realizing the 2DS through the expanded role of renewables (2DS-High Renewables), massive electrification of transport (2DS-Electrifying Transport) and deployment of heat-pump technology for space and potable water heating (2DS-Electrified Buildings).

Implications of the continuation of current trends without major climate policy interventions as depicted by the 6DS are severe. Global mean temperature is projected to increase by 6°C above the pre-industrial level, sharply contradicting the Copenhagen Accord of the UNFCCC. In order to keep global warming below even 4°C, significant efforts of the international community will be needed, specifically, strong policy actions to shift away from fossil fuels. Keeping the increase of global mean temperature below 2°C will require extremely stringent climate policy actions in a number of areas, including the development of systems based strategies, support of innovation from research and development, programmes to significantly improve energy efficiency, drastic changes in the construction industry and strategic planning in transport. In general, a sustainable response to the increase in global energy demand driven by population growth and economic development should be twofold: limitation of the growth of energy consumption through the deployment of more energy efficient technologies, and changes in the energy mix in favour of low carbon energy sources. Nuclear power is an important component of the low carbon energy portfolio in most of the stringent GHG mitigation scenarios and the related ambitious climate policies.

2.3. NUCLEAR POWER: A LOW CARBON TECHNOLOGY

In a world with fast growing demand for energy and increasing constraints for GHG emissions, the importance of energy technologies emitting small amounts of GHGs per unit of energy service provided will increase. GHG emissions will therefore need to be accurately identified and quantified. 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 [14]. The LCA of an electricity production system is complex, 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 the importance of LCAs in the climate change decision making process and the possible consequences of errors, consistency and credibility are of the utmost importance in LCAs. Aiming to enhance quality, but without prescribing specific methodologies, relevant International Organization for Standardization (ISO) standards were introduced and currently represent 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 [15], but also presents the findings of the recent meta-analysis performed by the United States National Renewable Energy Laboratory (NREL) [16], as well as results from a broad selection of scientific publications [17].

Summarizing the life cycle GHG emissions results for various electricity generating technologies from all these studies, Fig. 3 presents fossil sources with and without CCS. The figure shows that even by adding CCS to fossil fired power plants, life cycle emissions remain relatively high at about 190 g CO_2-eq/kW·h for coal and about 130 g CO_2-eq/kW·h for gas. Figure 4 presents emissions for renewable energy sources and nuclear power. Aligned left to right from smallest to highest emissions, the figure demonstrates that, according to the available scientific research, nuclear power, together with hydropower and wind based electricity, are the lowest emitters of GHGs per unit of electricity generated. Note the one order of magnitude difference in the vertical scales between Figs 3 and 4.

As presented in Fig. 4 and Table 1, GHG emissions from nuclear power (light water reactors) have a median value of 14.9 g CO_2-eq/kW·h, with a range

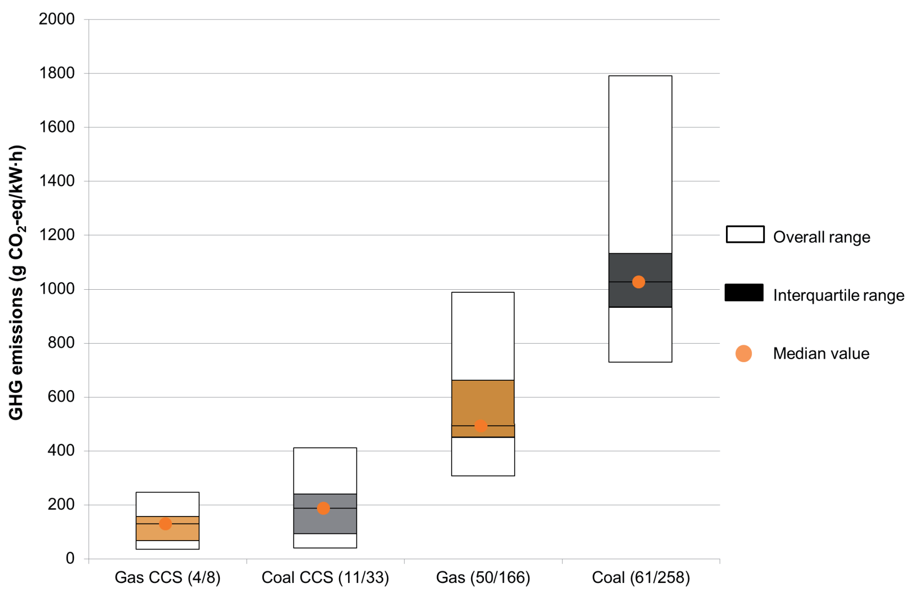

FIG. 3. Life cycle GHG emissions from electricity generation: fossil fuels and carbon capture and storage. Data source: IAEA [17]. Note: The numbers in parenthesis indicate the number of sources/estimates. The interquartile range includes half of the calculations around the median of the overall range. CCS – carbon capture and storage.

of 5.6–19.7 g CO_2-eq/kW·h of generated electricity. This was estimated on the basis of more than 200 individual calculations published in the literature [17]. The lowest value was reported through the Environmental Product Declaration system for an operating NPP [18], while the highest value is part of a highly theoretical worst case scenario [16]. It should be noted that the majority of these studies use some degree of generalization for the life cycle processes and use estimated data to overcome the lack of empirical data. 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.

CCS technologies are considered a viable option in many GHG mitigation studies, despite the fact that they have not been deployed on an industrial scale so far. However, LCA results for CCS in Fig. 3 and Table 1 indicate that GHG emissions per kW·h of electricity generated are often an order of magnitude higher than those from nuclear power generation [17]. The median value, based on a relatively small number of sources and calculations (15 studies and 41 results

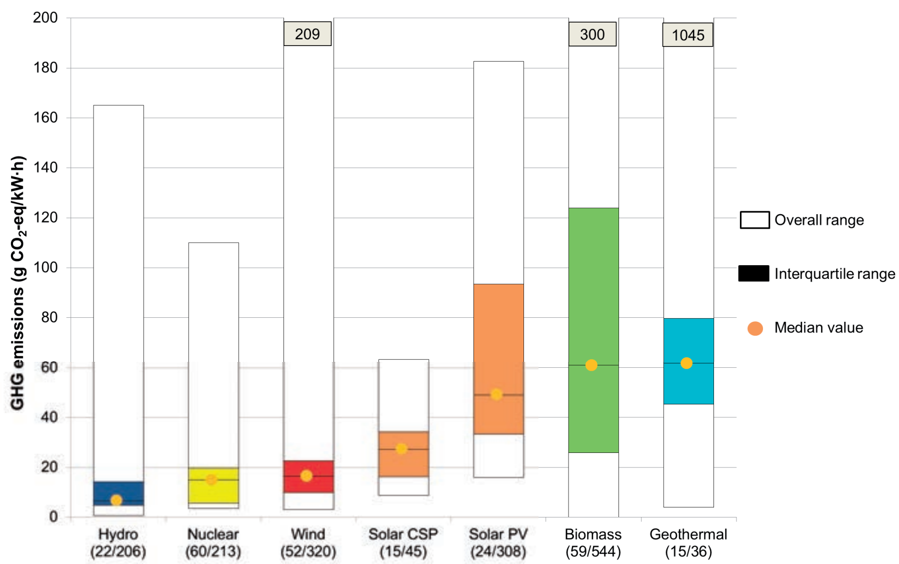

FIG. 4. Life cycle GHG emissions from electricity generation: renewable technologies and nuclear power. Data source: IAEA [17]. Note: The numbers in parenthesis indicate the number of sources/estimates. The interquartile range includes half of the calculations around the median of the overall range. CSP — concentrated solar power, PV — photovoltaic.

TABLE 1. LIFE CYCLE GHG EMISSIONS FROM ELECTRICITY GENERATION (g CO_2-eq/kW·h)

Technology	Hydro	Nuclear	Wind	Solar CSP	Solar PV	Biomass	Geothermal	Gas CCS	Coal CCS	Gas	Coal
Max	165.1	110.0	209.2	63.3	182.6	300.0	1045.0	245.0	410.0	987.5	1790.7
75th	14.1	19.7	22.6	34.3	93.5	123.9	79.8	156.0	240.0	662.1	1131.9
Median	6.6	14.9	16.4	27.3	49.2	60.9	61.7	128.5	186.0	491.8	1024.8
25th	4.8	5.6	9.9	16.3	33.4	25.8	45.3	66.3	92.0	449.0	931.9
Min	0.7	3.5	3.0	8.8	16.0	-3.0	4.0	34.0	39.0	306.8	729.0
Sources (calculations)	22 (206)	60 (213)	52 (320)	15 (45)	24 (308)	59 (544)	15 (36)	4 (8)	11 (33)	50 (166)	61 (258)

Note: Sources indicate the number of publication sources, calculations indicate the total number of calculations presented in all sources. 75th and 25th indicate the corresponding percentile values. CSP — concentrated solar power, PV — photovoltaic, CCS — carbon dioxide capture and storage.

in total), was found to be 128.5 g CO_2-eq/kW·h for natural gas and 186 g CO_2-eq/kW·h for coal, which are in both cases roughly in the middle of both the interquartile range and the overall range. A significant portion of the impacts of CCS systems is due to the transport and storage of the captured CO_2, and the manufacturing of the necessary chemicals. It must be noted that the values given for CCS in Fig. 3 represent a compilation from various sources that have not used exactly the same process to calculate life cycle emissions. Nevertheless, the results are credible and characterize well the carbon intensity of CCS systems.

Solar photovoltaic (PV) has always been promoted as a technology with no GHG emissions during operation. However, when other lifecycle stages are taken into account for both the crystalline silicone and the thin film technologies, the results from more than 300 individual calculations amount to a median value of 49.4 g CO_2-eq/kW·h. Compared to nuclear power, that is on average four times higher. Currently, the market is dominated by the more efficient crystalline silicone technology, but its energy intensive manufacturing results in higher median GHG emissions [15]. The broader interquartile and overall ranges reflect the uncertainties resulting from solar radiation, lifetime, efficiency and performance ratios of PV systems. Concentrated solar power shows noticeably better results of median (27.3 g CO_2-eq/kW·h), interquartile and overall range values, though this may be explained by higher capacities that usually tend to reduce the GHG emissions per unit of output in an LCA framework.

Wind generated electricity has also been the focus of over 50 published sources and 320 reported individual calculations. Combined, they point to a median value for GHG emissions that is comparable to those from nuclear power, at 16.4 g CO_2-eq/kW·h, though with somewhat broader ranges (Fig. 4). Interestingly, some of the calculations indicate that for the same class of wind turbines, onshore siting has a lower median value than offshore siting, though with a much larger GHG emission range [15]. This reflects the fact that higher wind availability for offshore turbines may be offset by the higher material and energy requirements during construction, compared to onshore turbines.

Hydropower generated from alpine and non-alpine reservoirs, as well as run-of-the-river systems, also has comparable life cycle GHG emissions to nuclear power. The GHG emission differences between these systems individually tend to be small but the studies included in Fig. 4 predominantly assess smaller capacity hydroelectric dams, making it difficult to identify their category. Tropical reservoirs, on the other hand, have a markedly higher GHG intensity and the highest GHG emissions values for hydropower. This is mainly due to biomass decomposition and the resulting methane releases. Nonetheless, as seen in Fig. 4, the median value for hydropower in general is 6.6 g CO_2-eq/kW·h, based on 22 published sources with 206 individual calculations [17]. Finally, pumped storage systems show a very wide range of GHG emissions that can be even higher than coal, depending on the carbon footprint of the electricity used to power the pumps that drive the water back to the reservoir for storage [15].

A multitude of LCA studies on biomass have found that median GHG emissions are not much better than geothermal or solar PV technologies. At 61 g CO_2-eq, and an overall range of up to 300 g CO_2-eq/kW·h, the results are highly sensitive to the type of biomass, transport schemes, generating technology and product structure in the plant (heat, fertilizer, gas, electricity). On the other hand, a handful of LCA studies on geothermal power show the same median GHG emissions as biomass, but they indicate potential for a higher impact than coal power, due to the release of GHG emissions from the geothermal fluid. As seen in Fig. 4, the maximum reported value in the calculations is 1045 g CO_2-eq/kW·h [17].

Expectations that nuclear energy technologies may achieve even lower GHG emissions in the future are supported by (a) further improvements in 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, allowing higher burnup that reduces emissions per unit of electricity in the fuel supply part of LCA; and (d) extended NPP lifetime from 40 to 60 years, spreading emissions associated with construction and decommissioning over a longer period, while more electricity (kW·h) is generated.

Without doubt, the very low CO_2 and total 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 alternative energy resources, as well as political, economic and social conditions.

2.4. CONTRIBUTION TO AVOIDED GHG EMISSIONS

Over the past 50 years, the use of nuclear power has prevented significant amounts of GHG emissions. Globally, only hydropower has avoided larger cumulative emissions. 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. The height of the black 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 dark orange segments of the bars show CO_2 emissions avoided by hydropower (2.8 Gt in 2011), nuclear power (2.1 Gt in 2011) and renewables other than hydropower (0.8 Gt in 2011), respectively.

Figure 5 is based on data from the IEA [19]. The latest version of the IEA database includes information on global electricity generation up to and including 2011. The underlying assumption in calculating the amounts of avoided emissions is 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 tends to underestimate the emissions avoided by nuclear power because in the historical context of the 1970s, most of the nuclear capacity expansion occurred with the specific aim to reduce dependence on imported oil and gas, so coal would probably have been the predominant non-nuclear alternative at that time. Nonetheless, this approach allows for conservative estimates of avoided GHG emissions.

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 in later years for some countries) and in 2011. 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

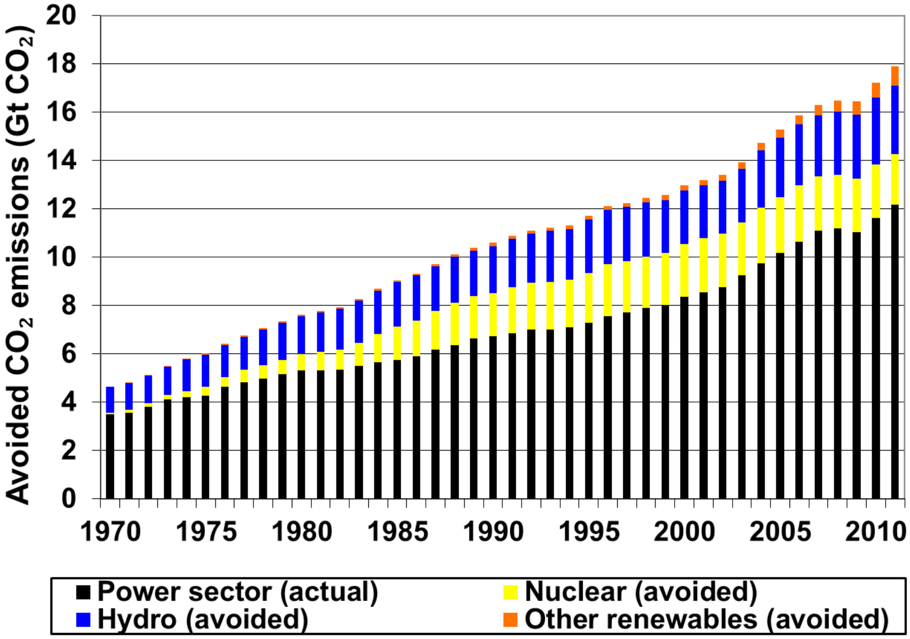

FIG. 5. Global CO_2 emissions from the electricity sector and emissions avoided by using three low carbon generation technologies. Data source: Ref. [19].

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 (Sweden and Switzerland). The chart also shows that expanding the share of nuclear power in the electricity mix contributed to the reduction of the CO_2 intensity of the power sector in several countries (e.g. Belgium, Germany, Republic of Korea, United Kingdom (UK)) — see the difference between the 1980 and the 2011 bars in Fig. 6. The case of Mexico shows a curious twist – the increase of fossil fuels in the electricity generation mix and the simultaneous decrease of CO_2 emissions. This, however, is the result of cleaner natural gas taking over part of the coal share in the generation mix.

The role of nuclear power in reducing CO_2 intensity will decrease over the next decades in a few countries that have decided to phase out nuclear energy, and increase in several other countries that decided to include or augment its share in their electricity generation portfolio. The expansion of the nuclear fleet in several Asian countries is expected to reduce the carbon intensity of their power sector. In contrast, 2011 data show that the CO_2 intensity of electricity generation in Japan increased by 19.6% as nuclear power's share of the national generation mix fell by 17.1 percentage points from the 2009 level and was mainly

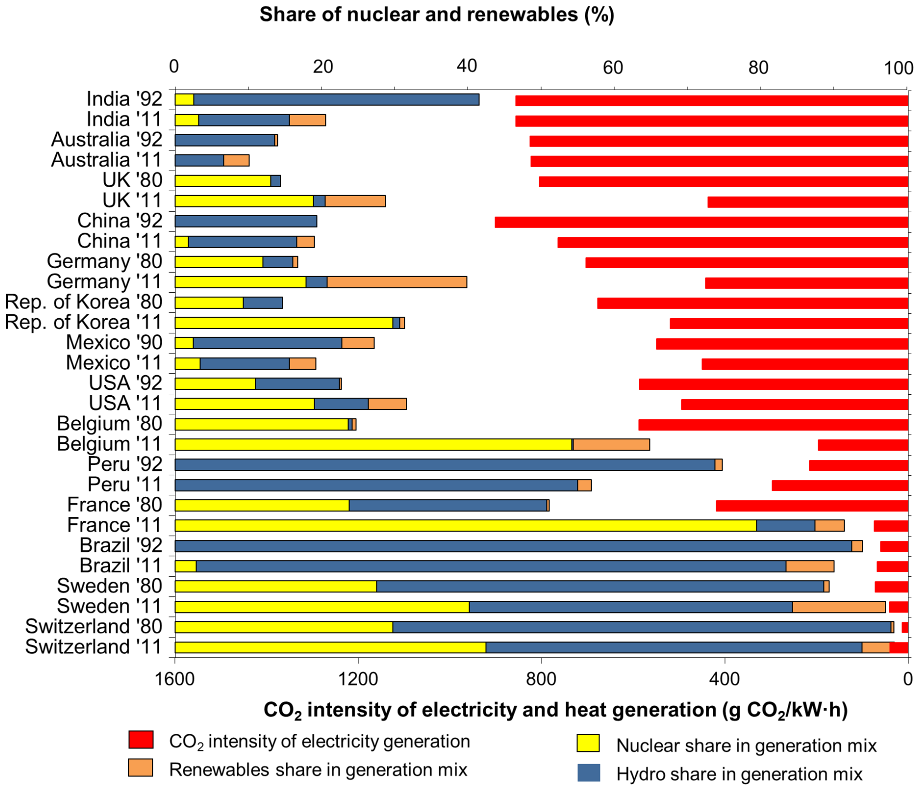

FIG. 6. Carbon dioxide intensity and the share of non-fossil sources in the electricity sector of selected countries. Data source: Ref. [19].

replaced by fossil fuels. In Germany, on the other hand, the 5.1 percentage point reduction of the nuclear share in the generation mix in 2011 (mainly replaced by renewable sources) did not change CO_2 emissions intensity relative to the 2009 levels. However, it must be noted that 2011 is not an ideal year to assess the effects of nuclear phase-out on GHG emissions because economic growth was dampened in most OECD countries and decisions to restrict nuclear energy were implemented mid-year. So far, however, the data support the conclusions demonstrated by Fig. 6.

2.5. GHG MITIGATION POTENTIAL ESTIMATED BY THE IPCC

Stabilizing atmospheric GHG concentrations at a level consistent with the 2°C climate change target requires fundamental changes in global energy supply systems. The portfolio of available measures includes the reduction of final energy demand, fuel switching from high to low carbon intensive energy sources, improvements in the efficiency of fuel use and the introduction of low carbon supply options such as renewables, nuclear and CCS based technologies. Although all of these measures contribute to the mitigation of GHG emissions, the AR4 and AR5 of the IPCC WG III highlight that the decarbonization of the electricity sector is critical and may be achieved at a much faster pace than in the rest of the energy system [20, 21].

The AR4 of WG III estimated 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). The analysis indicates that nuclear power represents the largest single mitigation potential at the lowest average costs [20]. The mitigation volume (1.88 Gt CO_2-eq/year) estimated by the IPCC AR4 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 when fast growth in power generation is considered (see Ref. [1] for details).

The IPCC AR5 WG III report does not provide an update of mitigation potentials in terms of avoided GHG emissions and costs for various electricity technologies. Instead, the new report (a) highlights the lifecycle perspective to be taken into account; (b) discusses the LCOE production; and (c) examines different deployment paths of various supply side mitigation options from a wide range of integrated assessment models. To this end, the WG III report reviews more than 1200 emissions scenarios grouped into baseline (absence of climate policy) and mitigation scenarios in order to analyse the implications for the global energy system. As compared to the AR4, the new ensemble of scenarios encompasses a wider range of assumptions about technologies, international mitigation policy configurations and the timing of global mitigation actions.

The important contributions of nuclear energy to emissions reduction today and in the future are emphasized by the WG III report on the basis of its low life cycle GHG emissions and low operating costs. Nonetheless, safety, investments costs, waste management and proliferation concerns are also discussed and presented as possible constraints to making full use of its mitigation potential.

In the majority of stringent mitigation scenarios analysed by WG III (reaching low atmospheric GHG concentration levels between 430 and 530 ppm CO_2-eq by 2100), the share of low carbon technologies (renewables, nuclear and CCS) in electricity generation exceeds 80% by 2050 and reaches nearly 100% by the end of the century (from around 30% today). Furthermore, when stringent mitigation targets are imposed, the share of electricity in total final energy consumption tends to increase faster; from the current 17% to nearly 40% in some scenarios by 2050 (see fig. 7.13 in Ref. [21]). Electricity generating technologies supporting this decarbonization in a cost effective manner are presented in a wide range of combinations that include renewables, nuclear power and CCS. The role of CCS is found to vary to a high degree across the stringent mitigation scenarios: its cost efficiency depends extensively on assumptions about its future technical and economic improvements. On the other hand, non-biomass renewable energy sources and nuclear power always play an important role in these scenarios.

Figure 7 shows the potential contribution of nuclear power to GHG emissions reductions in energy supply in 2050 for the baseline scenarios and stringent mitigation scenarios (430–530 ppm CO_2-eq GHG concentrations in 2100) across the scenario ensemble of WG III. The range of deployment for nuclear power indicates a great deal of flexibility in the choice of supplying electricity in the baseline scenario and in the choice of competing mitigation technologies in the stringent scenarios. Similarly to other low carbon technologies, the implementation of climate change mitigation policies clearly favours the deployment of nuclear power as it expands to nearly 5000 terawatt hours (TW·h) in the lowest range and to around 13 000 TW·h in the highest range in 2050. Replacing this deployment potential of nuclear with coal fired power plants emitting on average 600–800 g CO_2/kW·h by 2050 (based on Refs [22, 23]), would contribute between additional 2.8 and 10.4 Gt CO_2/year. This is admittedly a rather simplistic way of calculating CO_2 emissions avoided

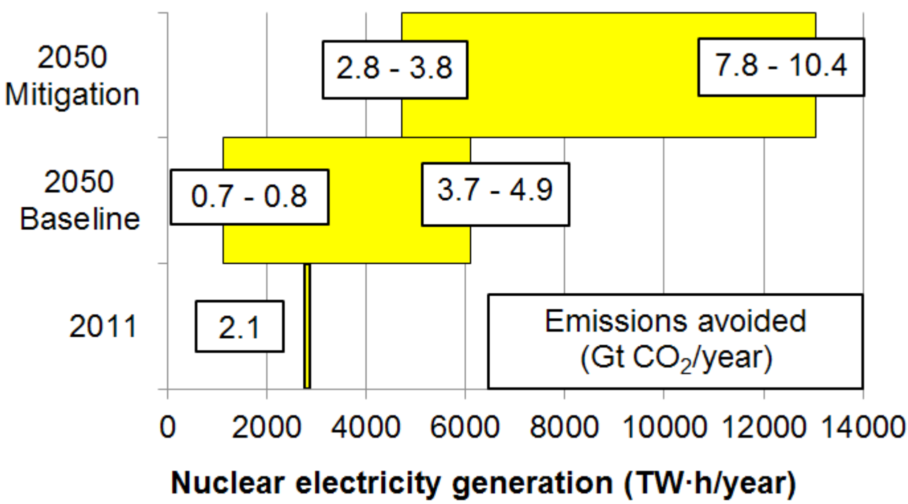

FIG. 7. The range (25th to 75th percentile interquartile) of nuclear power deployment in 2050 in the baseline and stringent mitigation scenarios (430–530 ppm CO_2-eq GHG concentration in 2100) and the avoided CO_2 emissions. Source: Based on deployment data in table 6.7 in Ref. [21] and original calculations. Note: See Section 2.4 for details about CO_2 emissions avoided by the use of nuclear power in 2011.

by the deployment of nuclear power but it provides an indication of the significant magnitude. That said, even without any climate policy, a great number of baseline scenarios project an expansion for nuclear power (by more than a factor of two in the case of the higher end of the range) and its contribution to some degree to the decarbonization of the electricity sector. This means that the absence of a carbon price does not play the same role for the deployment of nuclear power as for CCS based technologies for which zero deployment is projected in the baseline scenarios (see table 6.7 in Ref. [21]).

The decarbonization of the electricity sector and the potential of nuclear power to mitigate GHG emissions depend considerably on the increase in global energy demand (see Fig. 8). In general, the expansion of low carbon options is less rapid and pervasive in scenarios projecting large amounts of energy savings (hence slower growth in demand) whereas high energy demand scenarios are usually accompanied by a more rapid phase out of fossil based technologies without CCS and higher deployment rates of low carbon technologies. The comparison for up-scaling low carbon technologies to produce electricity in 2050 in stringent mitigation scenarios with low and high global energy demands is shown in Fig. 8.

As can be seen from Fig. 8, nuclear power is projected to increase from the current production levels by about a factor of two in many mitigation scenarios with low demand and by a factor of three to four in scenarios of high energy demand. Independently of demand projections, significant increases from their relatively low current levels are expected in the deployment of renewable energy sources such as solar and wind in stringent mitigation scenarios. Similarly, the decarbonization paths also involve CCS based technologies, in particular CCS from gas fuelled plants, given the projected expansion of unconventional fuels. The GHG mitigation potential among low carbon technologies, presented by ranges of their deployments in Fig. 8, depends largely on the assumptions on effective policies, costs and life cycle GHG emissions assessments. For instance, if carbon price reached about \$100–150/t CO_2, a significant fraction of power sector decarbonization would be achieved by CCS based technologies, although their share is not expected to exceed half of the power generation. Thus, at a lower carbon price, a higher fraction of decarbonization would be provided by nuclear and renewable energy sources. However, the WG III report also points to the controversies regarding the cost assessments of intermittent renewable technologies that exclude significant system integration costs (balancing costs, capacity adequacy costs and transmission/distribution costs) [24] from the LCOE.

In addition, delays in climate change mitigation can alter the timing of the deployment of nuclear power and other low carbon technologies. A more gradual transformation of the global energy system is achieved in scenarios reaching comparatively lower global emissions by 2030 (<50 Gt CO_2-eq), whereas higher

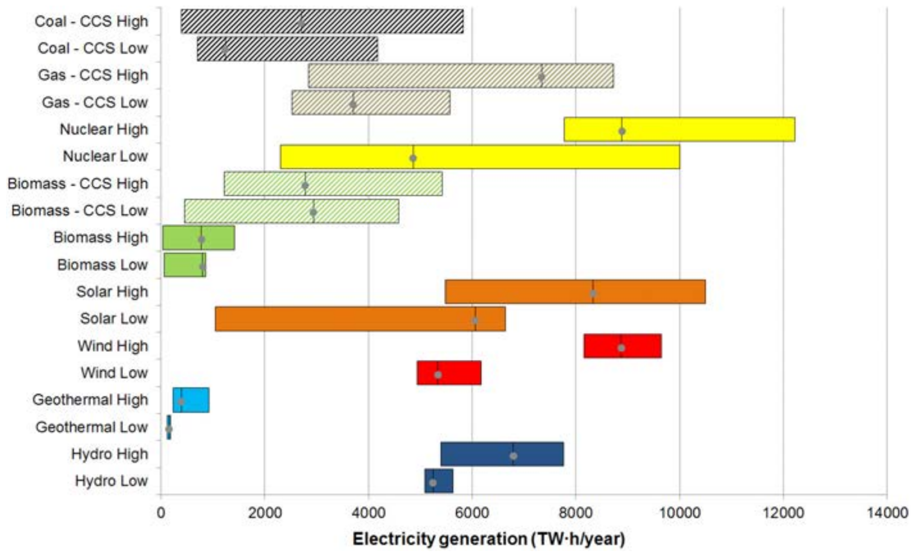

FIG. 8. Influence of energy demand on the deployment of low carbon technologies for electricity generation in 2050 in stringent mitigation scenarios (430–530 ppm CO_2-eq GHG concentration in 2100). Source: Based on fig. 7.11 in Ref. [21]. Note: For each technology the bars represent the 25th to 75th percentile interquartile deployment range, the vertical lines with a dot in each bar indicate the median. 'Low' bars refer to growth in final energy demand in 2050 by less than 20% of the demand in 2010 whereas 'high' bars denote the growth in final energy demand in 2050 by more than 20% of the demand in 2010.

emissions scenarios involve lock-in of emission intensive technologies, which consequently require a much faster scale up of low carbon energy sources between 2030 and 2050 [21]. For instance, a study analysing the impact of delays in near term emission mitigation shows that in the period 2030–2050, 29 to 107 new NPPs per year would need to be constructed [25]. The higher end of this range, explained by the non-availability of CCS based technologies, would be unique in history, but is conceivable. As regards the lower end, expected in the portfolio of full deployment of all low carbon options [25], this rate of nuclear deployment has already been observed in the mid-1980s [26] (see also Section 3.4).

Nuclear power clearly belongs to the set of options available to reduce GHG emissions in the electricity sector as confirmed by the latest IPCC report on climate change mitigation [21]. The utilization of its mitigation potential will depend on the stringency of climate policy and on competing, potentially cost effective, low carbon energy sources for which current cost and performance are uncertain (e.g. CCS based technologies). In addition, besides the economic factors, regional circumstances, including both energy resources and broader regional sustainable development goals (e.g. energy security, local air pollution, land use, etc.) might be equally important in the choice of low carbon energy sources [27].

2.6. CONTRIBUTION TO GHG MITIGATION ACCORDING TO THE IEA

How much of the mitigation potential of nuclear energy will be used depends strongly on international and domestic policy decisions in the near future and over the following decades. In general, the more ambitious the climate protection efforts of the international community, the higher the shares of low carbon sources in the global energy mix — and thus the more important the contribution of nuclear power to GHG mitigation — will be. Various scenarios presented by the IEA in WEO 2013 [8] and ETP 2014 [13] draw rather different pictures of the future up to the middle of this century, putting the global economy and climate on track for global warming ranging from 2 to 6°C in terms of global mean temperature increase above the pre-industrial level. (Changes in the global energy mix and energy consumption (scenarios 2DS, 4DS and 6DS) are discussed in Section 2.2.) They imply actions varying from very strict and proactive climate policies (2DS) to no additional mitigation measures and following the current emissions trajectory (6DS) [13].

The prospective role of nuclear power in GHG mitigation can be assessed by analysing the difference between the stringent 2DS (labelled as the 450 Scenario in the WEO reports) and the lax 6DS (labelled as the Current Policies Scenario in the WEO reports) over the next decades. According to the IEA projections, realizing the 2DS would require a decrease in global GHG emissions by 24.3 Gt CO_2 in 2035: from 47.7 in the 6DS to 23.4 Gt CO_2. By 2050, global reductions in the 2DS relative to the 6DS should reach 39.6 Gt CO_2 as a result of decarbonization measures: from 54.6 to 15 Gt CO_2 (see Fig. 9). Therefore, in the 2DS, global GHG emissions in 2050 should be less than half of the 2011 level (33.8 Gt CO_2) — despite intense industrialization projected for the next decades in various regions of the world, primarily in east and south Asia. The projected contribution of nuclear energy to emissions reductions is 2 Gt CO_2 in 2035 and 2.4 Gt CO_2 in 2050, amounting to 8.1% and 6.2% of avoided GHG emissions, respectively [13]. In practical terms, this makes the contribution of nuclear in 2035 comparable to the effect of end use fuel switching.

Current projections of the IEA in ETP 2014 regarding nuclear power reflect a downward change in comparison with ETP 2012 due to the impacts of the Fukushima Daiichi accident on nuclear policies in several countries, limiting its contribution to GHG mitigation [28]. However, the accident has not affected the ability of nuclear power to contribute to achieving global mitigation goals. As public acceptance improves (see Section 4.5) and national governments prepare

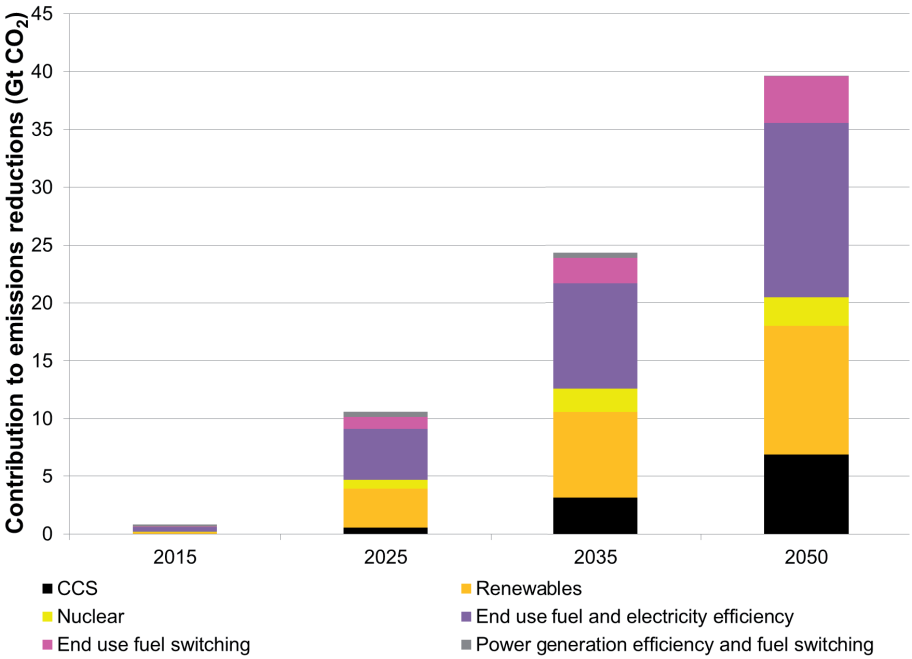

FIG. 9. Global CO_2 emissions reductions by technologies in 2015–2050 as a difference between the current trend (ETP 2014 6DS, WEO 2013 Current Policies Scenario) and the scenario with stringent efforts towards GHG mitigation (ETP 2014 2DS, WEO 2013 450 Scenario). Data sources: Refs [8, 13]. Note: CCS — carbon capture and storage.

to implement policies necessary to limit climate change, these projections may well be reassessed in the future.

In the long term, the role of nuclear power in GHG mitigation will be significant. In order to keep the long term increase of global temperature below 2°C (the 2DS assumes a 50% chance of achieving this goal), best practice technologies should be used in all sectors. Overall stabilization will be achieved after 2100 (450 ppm CO_2-eq concentration of GHGs in the atmosphere), with peak concentration in 2DS reached only in the middle of the century (i.e. at the end of the projection period) [8]. In the case of emissions reductions from the 6DS to the 2DS, nuclear energy will play a major role in the power generation sector that is expected to contribute 43% of total emissions reductions in 2035 and 37% in 2050. Other important contributors to achieving global mitigation goals are expected to be industry, transport and buildings (see Fig. 10). However, in order to move closer to the 2DS trajectory, significant measures will have to be undertaken by 2020. Each year of delay will make this switch harder as increasingly strict measures will be needed owing to the long period of operation

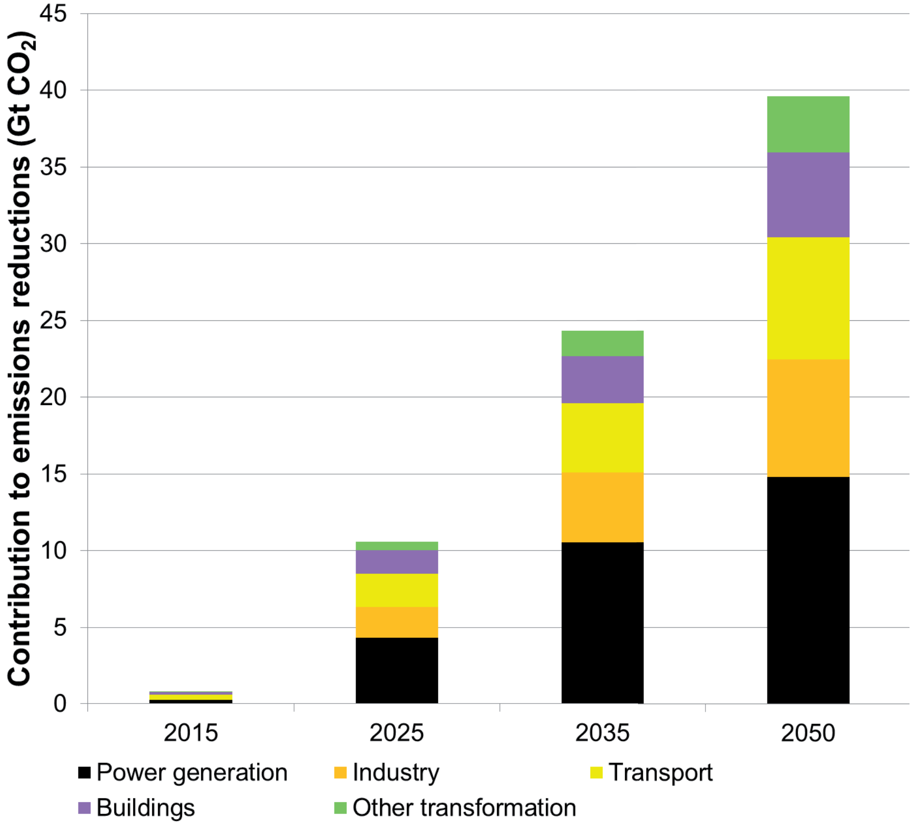

FIG. 10. Global CO_2 emissions reductions by sectors in 2015–2050 as a difference between the current trend (ETP 2014 6DS, WEO 2013 Current Policies Scenario) and the scenario with stringent efforts for GHG mitigation (ETP 2014 2DS, WEO 2013 450 Scenario). Data sources: [8, 13].

of power generation facilities, buildings and other elements of the global economy, contributing to climate change.

In order to leave the window of opportunity open for the full scale implementation of the 2DS after 2020, the IEA proposes the introduction of the following four policies that should provide 80% of the necessary GHG emissions reductions in comparison with the 2DS pathway by 2020 (4-for-2°C scenario) [29]:

— Adopting specific energy efficiency measures (49% of the emissions savings);

— Limiting the construction and use of the least efficient coal fired power plants (21%);
— Minimizing methane (CH_4) emissions from upstream oil and gas production (18%);
— Accelerating the partial phase-out of subsidies to fossil fuel consumption (12%).

Nuclear energy, along with other low carbon technologies, will be among the factors leading to decreasing CO_2 emissions in electricity generation at the global level: from 532 g CO_2/kW·h to 374 g CO_2/kW·h by 2035 (if the intermediate 4DS scenario, labelled as New Policies Scenario in WEO, is realized) [8]. Advanced energy technologies will play a crucial role in GHG emissions reduction in OECD countries. It is expected that in the European Union (EU), CO_2 emissions intensity will decline to less than half of its 2011 level by 2035: from 345 to 160 g CO_2/kW·h.

In the long term, nuclear power is expected to become an increasingly important driver for GHG emissions reduction in developing economies, which, despite some improvements in CO_2 emissions, are likely to face difficulties in limiting overall emissions due to intense industrialization and demand for improved access to energy for their growing populations. In the 4DS, in the 2011–2035 period, CO_2 emissions in India will increase from 0.9 Gt to 1.9 Gt and in China from 3.6 Gt to 4.9 Gt, while in the same period, emissions in the EU will decline from 1.1 Gt to 0.6 Gt, and in the USA from 2.2 Gt to 1.9 Gt [8]. Under the 2DS, the role of nuclear will inevitably increase; for example, in India, its share in power generation is projected to grow from 3% in 2011 to 5% in 2025 (11 GW(e) installed capacity) and to 15% in 2050 (80 GW(e) capacity) [13].

All these scenarios show that, if any meaningful efforts to mitigate GHG emissions are made, nuclear will play an important role as one of the drivers to decarbonize the global economy and allow humanity to manage global climate change. Switching to a sustainable development path associated with limiting global warming to 2°C above the pre-industrial level is highly unlikely without a significant expansion of nuclear energy. The scale of this expansion, and the resulting contribution to GHG mitigation, will depend on policy decisions and on society's perception of the likely impact of climate change on the global environment, economy and society.

2.7. CONTRIBUTION TO ENERGY SUPPLY SECURITY

In addition to nuclear energy's contribution to global climate change mitigation and meeting energy challenges, energy supply security is also important. Since the oil shocks in the 1970s, nuclear energy has been seen as a hedging instrument to decrease the risks associated with the dependency of OECD countries on imported hydrocarbons. Imported oil was important for the stable functioning of OECD economies in the 1950s and 1960s. By the early 1970s, supply had become less reliable owing to fundamental changes in the global energy market: rising energy consumption in OECD countries during the 'Golden Age' of growth, the trend towards the nationalization of oil industries in resource rich countries and better cooperation among them, which eventually led to the establishment of the Organization of the Petroleum Exporting Countries (OPEC). The first oil shock in 1973 was followed by the oil crisis in 1979. Both had a major impact on the economies of OECD countries. Their responses included searching for new strategies and establishing an international organization to foster supply security (IEA), starting oil exploration and extraction in distant regions (such as the North Sea and Alaska) and expanding the use of non-oil energy sources. As a result, nuclear energy became a major element in the diversification of energy supply in the OECD countries. Major drivers of this are the following: a globally even distribution of reserves, lower level of risks associated with transportation and the possibility to accumulate significant stockpiles.

Uranium resources are spread across five continents and are available to satisfy the needs of the global economy in the twenty-first century. However, geological availability of an energy source is not enough to guarantee the security of energy supplies: unpredictable interruptions of extraction and transport and a high level of uncertainty about future supplies due to the high market power of exporting countries can negatively affect the expectations of consumers about future access.

There is little or no likelihood of any uranium producing country or region gaining a monopoly. Uranium resources are distributed evenly and 35% of global uranium resources are located in OECD countries. Australia alone holds 23% of global resources, and around one quarter of global resources are located in Eurasia, alongside significant resources in Africa and Latin America (see Fig. 11). Reported uranium production is also dispersed across many countries (see Fig. 12). Owing to the geographic variety of both uranium rich and uranium producing countries and their sociopolitical stability, it is very unlikely that sudden changes in key supply countries would cause disruptions in global supplies of uranium. This also minimizes the risk of monopolistic pressure on the international uranium market boosting prices.

The even distribution of uranium reserves positively affects the transportation costs of this type of fuel. Also, owing to the extremely high energy density of uranium — 50 000 kW·h of electricity from 1 kg fuel (in comparison with 3 kW·h from coal and 4 kW·h from oil) — the physical amounts needed for

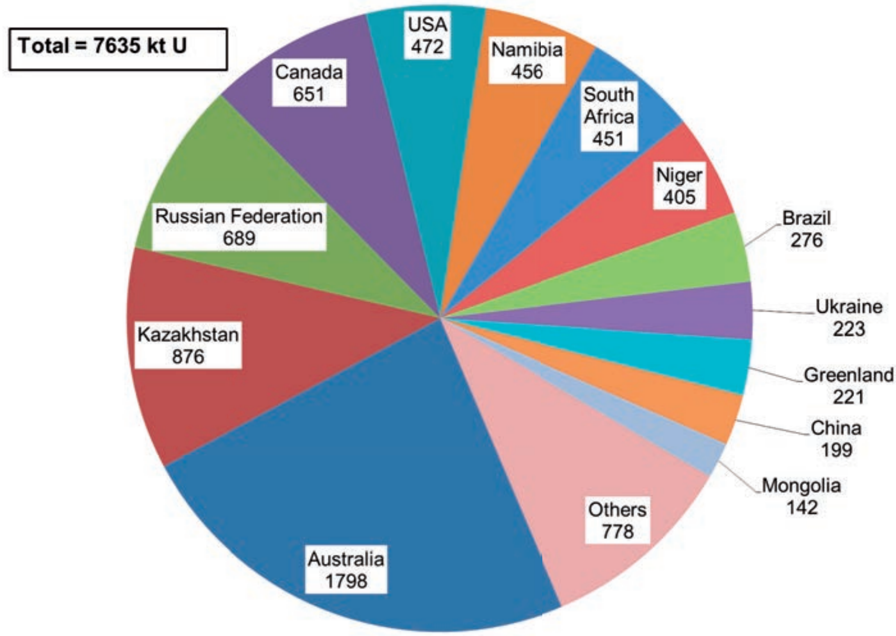

FIG. 11. Reported uranium resources in 2013. Data source: Ref. [30]. Note: The difference between the total given and the sum of the individual values is due to rounding.

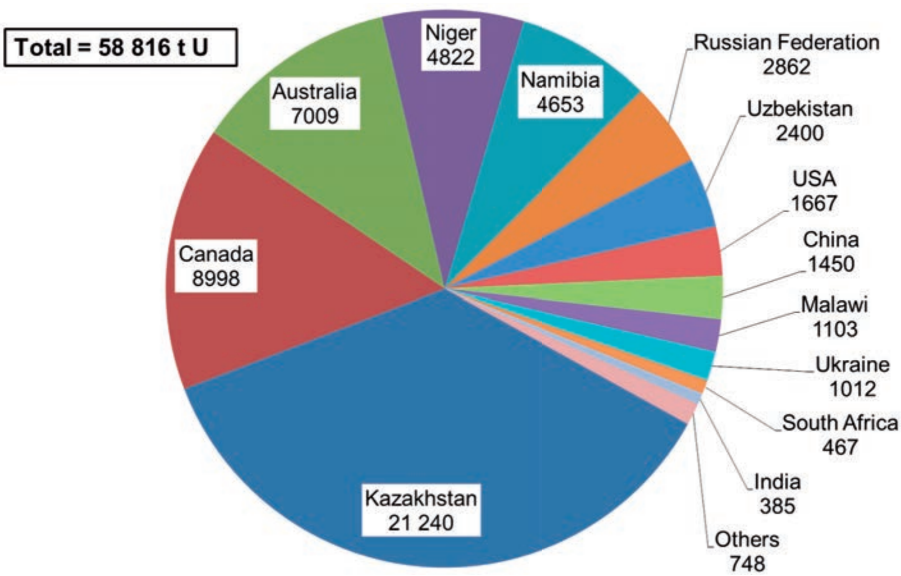

FIG. 12. Reported uranium production in 2013. Data source: Ref. [30]. Note: The difference between the total given and the sum of the individual values is due to rounding.

industry are much lower than those of hydrocarbons. In terms of energy security, supplies of uranium are much less likely to be disrupted by international conflicts.

Another difference in supply security between uranium and hydrocarbons is that the latter are often shipped by sea, using a limited number of transport corridors crossing a few major points such as the Strait of Hormuz, the Strait of Malacca, the Bosporus and the Suez and Panama canals. Supplies through these transport arteries can be cut relatively easily. Continental supplies of hydrocarbons, mostly using pipelines, are associated with different types of risks, e.g. the problems with the position of intermediary states and significant interdependence of supply and demand sides. These factors are not applicable to the nuclear industry. The necessary amounts of uranium can be transported quickly and safely, using various shipment routes, greatly reducing the risks of transport interruptions.

Well functioning competitive international markets provide a good basis for the safe supply of nuclear fuel. Moreover, the relatively small physical amounts of uranium needed for industry allow the establishment of national reserves in importing countries at a low cost. This is an important advantage in comparison with fossil fuels. Currently, the IEA requires its Member Countries to keep crude oil reserves equal to 90 days of the previous year's imports [8], at considerable cost. Uranium stockpiles can make the operation of the nuclear industry more predictable and encourage positive expectations in markets, thus contributing to economic growth in countries using nuclear energy. Another related development is the emergence of uranium stockpiles at the international level with the establishment of international nuclear fuel banks proposed by the IAEA. The first of these banks became operational in Angarsk, Russian Federation, in 2010 [31]. Such banks are expected to provide IAEA Member States with uranium fuel necessary for their industries on a non-political and non-discriminatory basis. This should further decrease the volatility of fuel markets caused by short term political and economic changes in participating states. In the future, the level of energy supply security supported by nuclear power is expected to increase owing to the introduction of other fuel sources (thorium); the need for fresh uranium will decline owing to the implementation of the closed fuel cycle [31].

2.8. POWERING ENERGY INTENSIVE INDUSTRIES

Industrial energy intensity has declined substantially over the last three decades across all manufacturing subsectors worldwide owing to increases in energy efficiency. Nonetheless, energy use and industrial CO_2 emissions have been growing along with industrial output. An estimated 36% of the world's

CO_2 emission can be attributed to manufacturing industries [32], although the associated energy requirements are dominated by only a few industries.

About half of all energy used in the industrial sector is used in only five branches. With increasing demand, the delivered quantity and fuel mix of the industrial sector in the future will largely be determined by the energy consumption in these energy intensive industries. They comprise the chemical and petrochemical, iron and steel, cement, pulp and paper, and aluminium branches. Together, these branches account for around 75% of total direct CO_2 emissions from industry, and deserve special attention as part of global efforts to combat climate change [33].

To assess the potential role of nuclear power in energy intensive industries, it is necessary to identify the type and volume of energy demand in the predominant manufacturing processes. Since nuclear power mostly provides electricity (and possibly heat), its potential to replace carbon intensive fuels will depend on how much electricity is required by individual manufacturing processes.

The chemical and petrochemical industry represents the largest consumer of energy, requiring a large amount of hydrocarbon feedstock (liquefied petroleum gas, naphtha and natural gas) as intermediary building blocks to synthesize final products. Many different processes exist in this industry, and depending on the final product, a fixed amount of feedstock is required, thus greatly limiting the possibility to decrease fuel consumption without shifting production towards recycling and biobased chemicals [33].

In the iron and steel industry, the amount of energy used depends on the manufacturing process employed. The blast oxygen furnace process produces 70% of global steel. In this process, mined iron ore is purified by blowing super heated oxygen into a furnace containing a charge of coke. Coke acts as a fuel and a reducing agent (the carbon molecules in the coke bind to the oxygen molecules in the iron ore), making a low carbon replacement challenging. More importantly, this iron making process constitutes half of the energy use and CO_2 emissions in steelmaking (see Fig. 13). The remaining 30% of global steel production uses scrap metal in electric arc furnaces. This process has the advantage that it only uses 30–40% of the energy of the conventional blast oxygen furnace [34]. Accordingly, the related CO_2 emissions can be reduced by increasing the shares of low carbon sources, such as nuclear energy, in power generation.

Cement production accounts for close to 80% of energy demand in the non-metallic mineral sector. The production of cement starts by crushing the raw materials (e.g. limestone, clay, sand) to the size of gravel. These ingredients are mixed under intense heat and with lime, silica, alumina and iron to pellets called clinker. The resulting feedstock is proportioned at the cement plant to create different types of cement with specific chemical compositions. Depending on the water content of the feedstock, cement production can be divided into ‘wet’ and

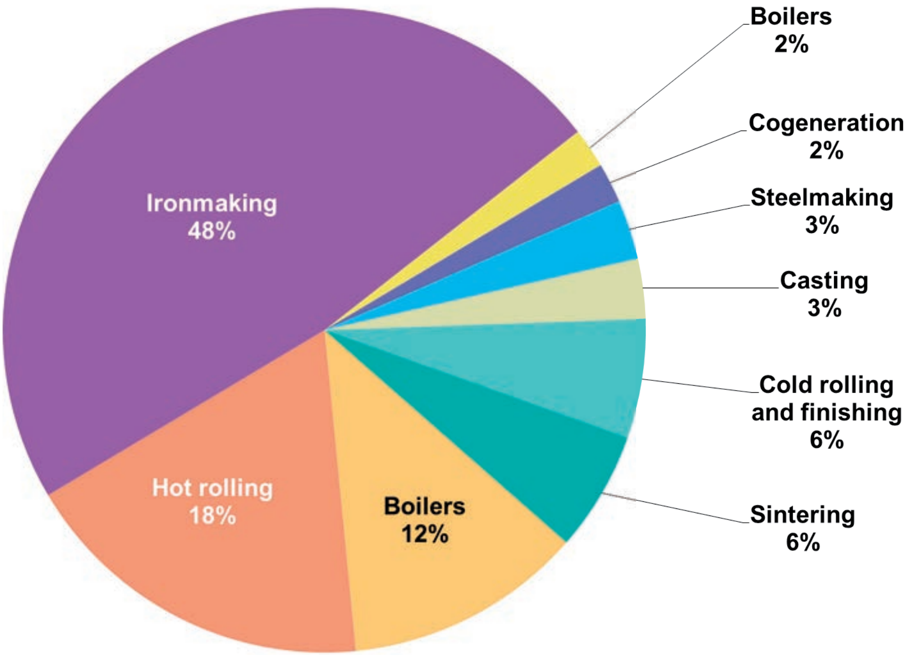

FIG. 13. Breakdown of energy consumption in iron and steel production. Source: Ref. [33].

'dry' processes. The wet process facilitates the control of the chemistry, but it is more energy intensive as slurry water will need to be evaporated [32]. Most of the CO_2 emitted in cement manufacturing is generated during the transformation of limestone (decarbonation) to produce clinker, the basic component of cement. Thus, GHG reductions associated with cement production will depend largely on the substitution of fossil fuels by low carbon sources and increased electrification of the production processes.

The high energy intensity of paper and pulp production has triggered many efforts to increase the use of renewable energy from wood residues. Wood is harvested and chipped before the fibres and lignin are separated. The industry meets almost half of its energy needs from biomass, part of which is a by-product of the industry itself. A multitude of production processes are used in the paper and pulp industry (e.g. chemical pulping, mechanical pulping, paper recycling, paper production) [35]. Nonetheless, electricity constitutes a major component of energy demand in paper and pulp production (see Fig. 14 [36]). Consequently, the key opportunity to reduce the related GHG emissions is to use more nuclear and other low carbon technologies in power generation.

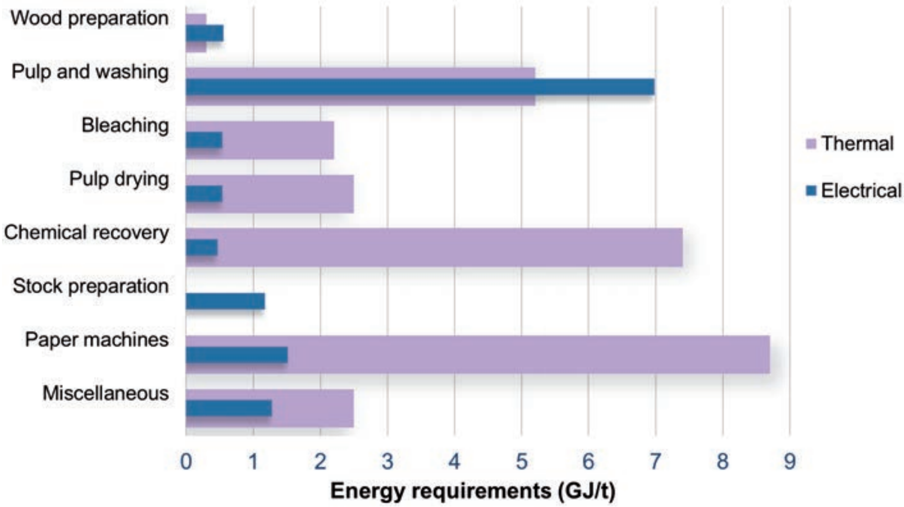

FIG. 14. Energy requirements in paper and pulp production. Data source: Ref. [36].

The aluminium industry is the dominant energy intensive industry in the non-ferrous metal sector. Fuel is combusted in order to mine, move and refine bauxite. The transformation of bauxite into alumina (Bayer process) requires thermal energy, produced in refineries. During the smelting process, fuel is combusted to generate sufficient heat for anode baking, casting and supporting operations to form the metal aluminium. The amount of energy that these processes require, however, is relatively low in comparison to the power requirement of the Hall-Héroult reduction process, which is the standard reduction process in global aluminium production (see Fig. 15). A constant source of power is critical for aluminium smelters, and traditionally it is provided by hydroelectricity. However, hydropower production has been growing slowly in absolute terms over the past 40 years, and its share in global electricity generation declined from 21% in 1973 to 15.8% in 2011 [37], indicating the need for expanding the shares of other constant low carbon power generation sources such as nuclear energy.

While certain processes in the industrial sectors are difficult to decarbonize for technical reasons, nuclear power can help to reduce CO_2 emissions by powering those production processes where large amounts of baseload electricity are critical, especially in metallurgy (e.g. electric arc furnace, electrolytic reduction).

Since power can be generated using a variety of fuels, the emissions of electricity generation depend on the fuel source. Between 1971 and 2010, coal related CO_2 emissions from electricity and heat generation have more than tripled, increasing the relative share of CO_2 emissions from 46% to 68% [38].

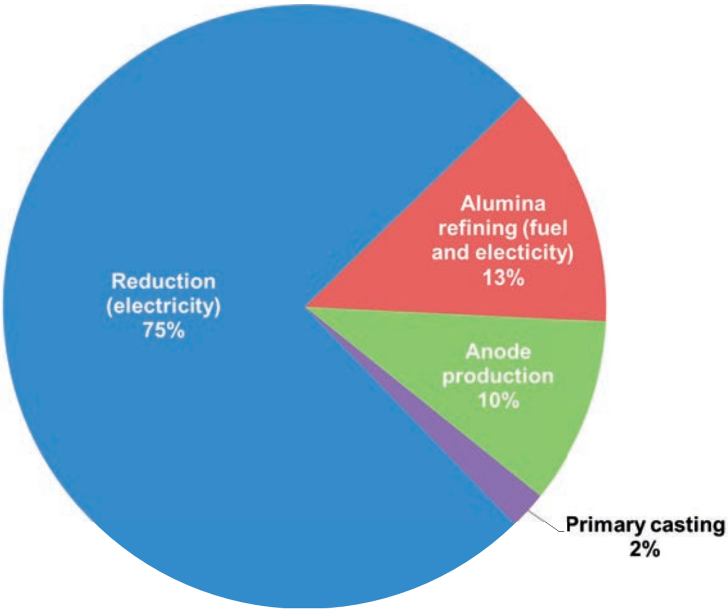

FIG. 15. Energy required in aluminium production. Source: Ref. [33].

As industry consumed 42.6% of world electricity in 2011 [37], major reductions in CO_2 emissions from electricity generation could be achieved by substituting fossil based generation with nuclear energy and other low carbon energy sources.

2.9. NON-CLIMATIC ENVIRONMENTAL BENEFITS

Apart from its contribution to climate change mitigation, the use of nuclear energy has other environmental benefits such as reducing the emissions of air pollutants which have negative health and environmental impacts on both the local and regional level. NPPs emit virtually no air pollutants during their operation. In contrast, fossil fuel power plants are among the major contributors to air pollution.

The latest scientific knowledge establishes a stronger link between both indoor and outdoor air pollution exposure and cardiovascular diseases, in particular strokes and ischaemic heart diseases, as well as between air pollution and cancer. Air pollution also contributes to health disorders from both chronic and acute respiratory diseases, including asthma [39].

According to the latest estimates of the World Health Organization (WHO), in 2012 around 7 million people died as a result of outdoor and indoor air pollution exposure — one in eight of total global deaths. The population in low and middle income countries — in particular in the western Pacific and south-east Asia — experienced the burden of air pollution exposure disproportionately. The new WHO findings more than double previous estimates and confirm that reducing air pollution could save millions of lives [40].

A recent joint study by the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies and Columbia University's Earth Institute examined the historical and potential future role of nuclear power in preventing mortality related to air pollution. 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) [41] 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 4.39 million for the low IAEA projection and by 7.04 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 0.42 million (low projection) and 0.68 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 [42, 43].

Apart from health damages and increased mortality, air pollutants, which can travel long distances, also cause acid rain. At the regional level, 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 (tree mortality noticeably above usual mortality levels). Acid rain also damages certain building materials and historic and cultural monuments. Acid rain is caused by sulphur and nitrogen compounds. 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 [44].

An analysis of the Ecoinvent database [15] 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 data. Figures 16 and 17 present the acidification potential in g SO_2 equivalent (SO_2-eq) per kW·h electricity generated by types of fossil and renewable or nuclear technologies, respectively. The underlying calculations take into account technical solutions that have already been implemented to reduce emissions from energy technologies with high acidification potential, while further reductions can be achieved at costs varying significantly across countries.

Environmental and health damages which occur because of electricity production but are not reflected in the price of electricity are called external costs. The latest systematic analysis of such external costs monetized these damages during normal operation (without accidents) that were 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 [45]. 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, i.e. from construction to decommissioning, as well as the fuel cycle from mining to waste disposal.

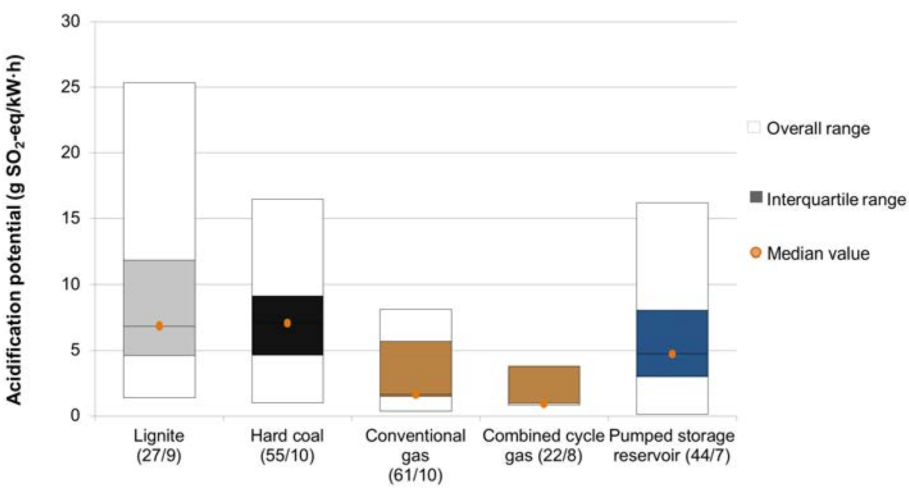

FIG. 16. Acidification potentials of emissions from fossil technologies in g SO_2-eq per kW·h by type of technology. Data source: Ref. [15]. Note: The interquartile range includes half of the calculations around the median of the overall range.

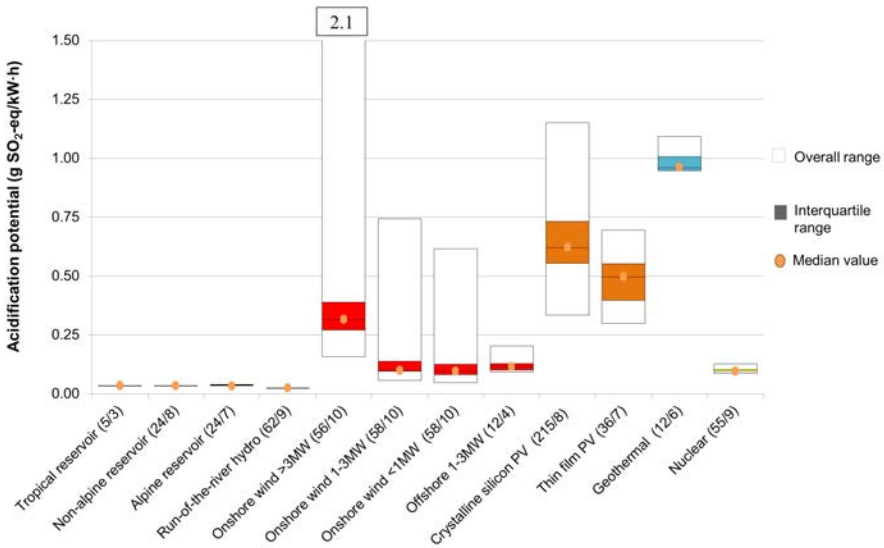

FIG. 17. Acidification potentials of emissions from renewable and nuclear technologies in g SO_2-eq per kW·h by type of technology. Data source: Ref. [15]. Note: The interquartile range includes half of the calculations around the median of the overall range.

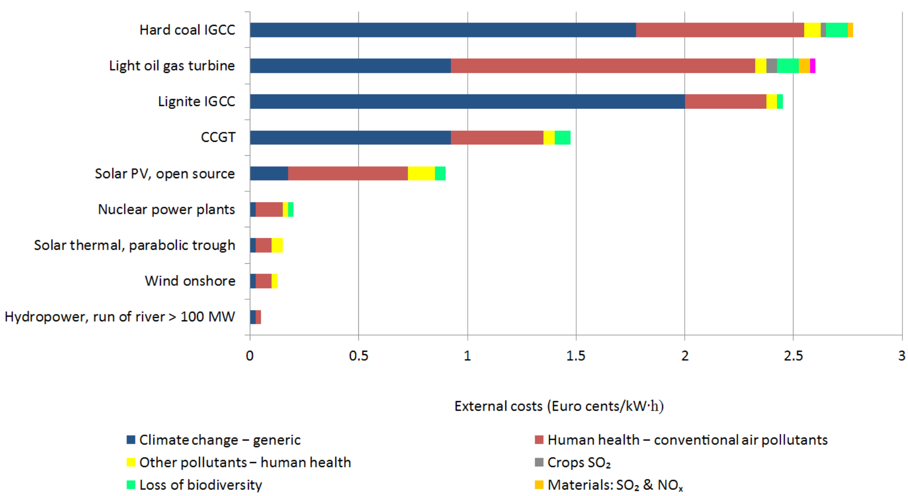

FIG. 18. Estimated average external costs in the EU for selected electricity generation technologies between 2005 and 2010. Data source: Ref. [45]. Note: IGCC — Integrated Gasification Combined Cycle, CCGT — Combined Cycle Gas Turbine.

A recent study [46] estimates the external costs of wind based electricity augmented by combined cycle gas turbine (CCGT) power plants to be higher than that of nuclear, even if catastrophic nuclear accidents with impacts similar to Chernobyl and Fukushima are assumed. The focus of the study is on countries with a well-established culture of safety (Canada, EU member states, Japan, Republic of Korea, Taiwan (China) and the USA). Six cost categories of a nuclear accident were considered: (a) cost of lost reactors, (b) cost of lost power, (c) fatal cases of cancer, (d) lost value of agricultural production, (e) cost of displaced population and (f) cost of cleanup. Under the central set of assumptions, the total external cost of nuclear, related to both normal operation and an accident situation, amounted to €0.0079/kW·h, while those of nuclear substitutes were estimated to be €0.0123/kW·h. The study concludes that the premature shutdown of existing nuclear plants is associated with very high private costs and cannot be justified by external cost reductions [46].

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. Policies to include all external costs of all technologies would allow the economic and environmental benefits from nuclear power generation to become even more visible. This would be a significant addition to the benefits of using nuclear energy to mitigate CO_2 emissions from the energy sector.

2.10. MACROECONOMIC BENEFITS

Energy is vital to economic prosperity. Nuclear power can play an important role in meeting increasing electricity demand and contributing to GHG emissions reduction. With favourable macroeconomic conditions in place, it can bring important benefits to a country's economy, first and foremost by generating economic growth.

A considerable literature exists on the energy–growth nexus, while relatively little is known about impacts of nuclear power on economic growth [47]. The empirical results from the literature are conflicting to a certain degree: the growth hypothesis whereby nuclear consumption has had a positive impact on the economy has been confirmed for the Republic of Korea [48, 49], India [50], Japan, the Netherlands and Switzerland. Conversely, economic growth has had impact on nuclear energy consumption in Canada and Sweden [51]. Bidirectional causality between growth and nuclear energy consumption was detected in France, Spain, the UK and the USA [51]. Finally, the neutrality hypothesis

— no causal relationships — has been reported for the USA and Taiwan, China, respectively [52, 53].

The most recent empirical literature on the nuclear energy–growth relationship seeks to clarify some conflicting conclusions from previous research by applying more advanced statistical techniques. Using a panel dataset for 16 countries in different income categories — including the USA, for which some conflicting results had been previously reported — over the period 1980–2005, nuclear energy consumption has been shown to play an important role in economic growth in the long run [54]. The panel results show that a 1% increase in nuclear energy consumption increases real GDP by 0.32%, while the same increase in real gross fixed capital increases real GDP by only 0.17%. A further relevant and robust result is that increasing the labour force by 1% leads to an increase in real GDP by 0.76%. Though not explicitly discussed in the study, the quantified impact of nuclear energy on real income might be underestimated as it also affects economic growth indirectly, e.g. by boosting employment (see below). Additional studies are, however, needed to provide more robust results.

Nuclear plant investment and operations directly stimulate industrial activity. Countries with existing NPPs opting for nuclear expansion consider these impacts to be significant. In the USA, every dollar spent by the average nuclear plant during one year of operation is estimated to result in the creation of $1.04 of output on the local level, $1.18 in the state economy and $1.87 economy-wide [55]. Each $ spent in NPP construction in Jordan will create additional output of $3.30, which is spread across all industry sectors [56].

Nuclear power enhances 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 related industries increases labour productivity and has dynamic spillover effects on related industries. These effects were particularly pronounced in the Republic of Korea. Following growing demand for nuclear energy and isotope techniques, the government currently envisages increasing national industrial participation by substituting imports as a source of isotopes and related machinery. Over the past decades, the growth of these industries was exponential: as of 2003, almost 160 000 radiological technologists were licensed and more than 25 000 radiation workers were employed in the nuclear industry handling radioisotopes [57].

The employment effects of nuclear power are an important economic driver. Nuclear investment directly creates high skilled employment in construction, operation, the nuclear fuel cycle and supporting industries. Salaries in an NPP in the USA are, on average, 36% higher than in the local area [55]. Additional

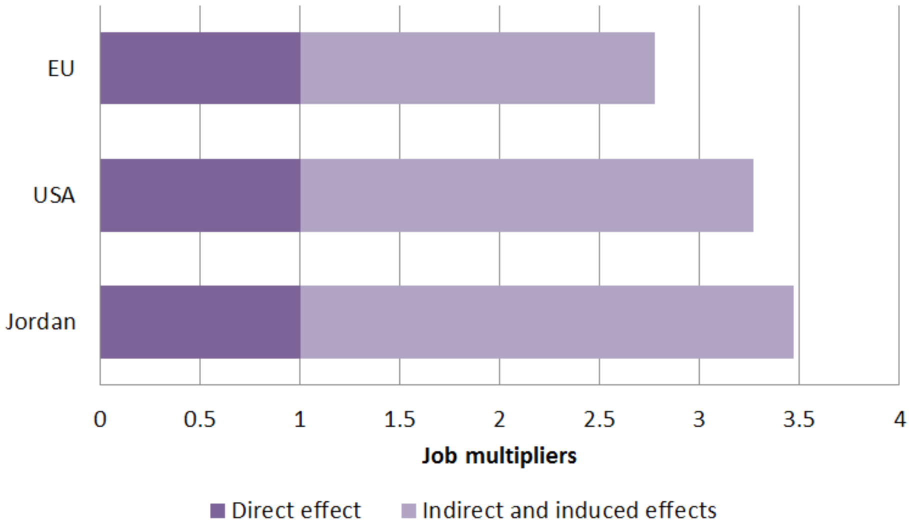

FIG. 19. Direct, indirect and induced job multipliers in proposed nuclear energy investment programmes in the EU, Jordan and USA. Data source: original calculations based on Refs [56, 59, 60].

jobs are created in areas such as design, siting, licensing, oversight, waste management, decontamination and decommissioning.

At the same time, nuclear power generates indirect employment in non-nuclear industries through supply chain integration [58]. Studies in various countries stress the importance of the job-multiplying effect of nuclear power, including induced effects which are generated through spending of each dollar associated with direct and indirect employment (see Fig. 19 [56, 59, 60]). Despite the fragmentation of available data and the need for further research on the topic, the positive employment effect of nuclear power appears indisputable.

Furthermore, the operation of nuclear power has positive implications for electricity and aggregate price stability leading to a more favourable policy context for economic growth. Several mechanisms make this possible. Price stabilization can be achieved through the substitution effect on imported fossil fuels. Though price fluctuations are intrinsic to commodity markets, price volatility has been advancing at a faster rate in the crude oil market in comparison to other commodities over the past few decades [61]. There is a growing consensus in the most recent literature that the primary channel whereby energy (oil) price shocks affect a country's economy is through a disruption in private — consumers' and firms' — spending on goods other than energy [62].

Nuclear electricity generating costs are less sensitive to fuel (uranium) price volatility than are the costs of fossil fired generation because uranium represents a smaller fraction of the total cost. Fuel cycle costs — both front and back end

— amount to a range of 9%–16% of the LCOE depending on the discount rate [63]. Moreover, uranium prices have been less volatile in the past in comparison to oil prices.

The introduction of cap and trade regulation for GHG emissions can amplify the price stabilizing effects of nuclear energy [64]. In liberalized electricity markets, fossil fuel based electricity generators subject to a carbon pricing regime tend to fully internalize emissions costs (‘emission costs pass-through’). During the initial trading phases on the largest carbon market in the world — the European Emissions Trading Scheme (ETS) — electricity producers have been shown to pass on opportunity costs of emissions allowances to consumers via increased electricity prices. Nuclear energy is a low carbon production technology and will therefore reduce the volatility of electricity prices related to the carbon price component.

A balanced view requires countries embarking on new nuclear power programmes to objectively gauge the related economic risks and challenges. Nuclear power requires a large upfront investment (see Section 3.2). The estimated overnight capital cost of a 1 GW(e) NPP is approximately $2–6 billion, a large amount of money compared to the GDP of most developing countries. A country’s GDP should 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.

Moreover, the economy of a country building a nuclear plant should ideally be strong enough to overcome an unexpected increase in investment costs. A country’s reserves of foreign currency must also be sufficiently large to cover the imports necessary for building a new NPP.

3. SUPPLYING NUCLEAR POWER

3.1. 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 plus the related system costs; and, second, the social costs, including all externalities, which are 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, and thus fully internalized. The social benefits of avoided CO_2 emissions remain unaccounted for in the absence of comprehensive GHG taxes or emissions permit markets (see Section 2.9). Similarly, increased supply security as a public good is also disregarded. 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 an important factor that discourages potential investors.

NPPs have a front loaded cost structure (a feature shared with most renewables). In other words, they are comparatively 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 remain 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. air 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 demand for electricity encourages the development of all energy options. In Europe, high electricity prices, high natural gas prices and GHG emission limits under the EU ETS have improved the business case for new NPPs, although the collapse of ETS prices in 2009 and again in 2013 significantly weakened the effect of the third driver, GHG emissions limits. In the USA, the 2005 Energy Policy Act significantly strengthened the incentives for new construction. Its provisions, including government coverage of costs associated with 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 for nuclear firms. As of June 2014, two combined construction permit–operating licences have been issued for four new reactors and nine applications for a total of fourteen reactors were under review [65]. However, the large volume and low price of shale gas have created a new situation concerning the relative costs and cost competitiveness of nuclear power in the USA (see Section 5.3).

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 LCOE calculated on the basis of a common methodology using data supplied by countries and organizations [66].

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 figures is that the LCOE of the three main current baseload generation technologies (coal, gas and nuclear) largely overlap within the \$30–120 per MW·h range [66].

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.

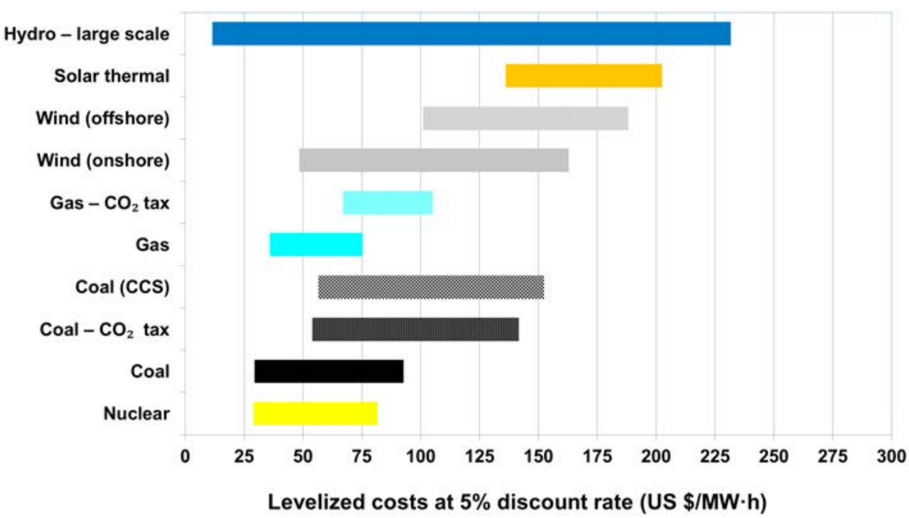

FIG. 20. Ranges of LCOE associated with new construction at 5% discount rate. Data source: Ref. [66].

There is insufficient information for estimating the incremental costs of the enhanced safety measures resulting from the international and national safety action plans after the Fukushima Daiichi accident (see Section 4.2). 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 electricity generation 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 LCOE figures shown in Figs 20 and 21 reflect the full costs of power generation but exclude external costs (uncompensated damages caused by the generation facilities such as various kinds of pollution released from or disamenity caused by them) (see Section 2.9). They also exclude system costs that arise from additional investments and services needed to supply electricity at a particular load and specified level of reliability. System costs include investments required to expand and augment transmission capacities and distribution grids on the one hand, and short term balancing and long term adequacy costs to ensure the stability and reliability of electricity supply on the other.

All electricity generation technologies involve systems costs, but for traditional dispatchable technologies (nuclear, coal, gas), these costs tend to be low and do not vary much with the shares of these technologies in the generation mix. They range between 0.34–0.56 \$/MW·h for gas, 0.46–1.34 \$/MW·h for

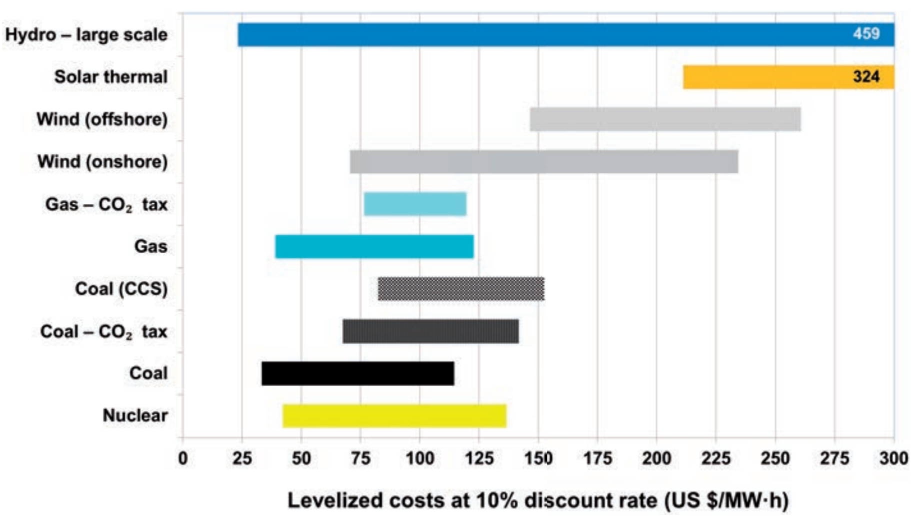

FIG. 21. Ranges of LCOE associated with new construction at 10% discount rate. Data source: Ref. [66].

coal and 1.40–3.10 \$/MW·h for nuclear across six OECD countries involved in a study of the OECD NEA [67]. Increasing the shares of intermittent renewables to significant levels changes the situation dramatically. Their grid connection costs are a factor of 3 to 10 higher than those of dispatchable technologies and their balancing costs increase sharply with their shares in the grid. Using the same methodology as for dispatchable technologies, the OECD NEA study estimates total grid level system costs for onshore wind between 16.3 \$/MW·h (10% share in the USA) and 43.85 \$/MW·h (30% share in Germany), for offshore wind between 20.51 \$/MW·h (10% share in the USA) and 45.39 \$/MW·h (30% share in the UK), and for solar 14.82 \$/MW·h (10% share in the USA) and 82.95 \$/MW·h (30% share in Germany). The large ranges indicate the importance of resource endowments (windiness, insolation), their location and distance to large consuming centres, and other technological and economic conditions. Nevertheless, the system costs of intermittent renewables largely overlap the ranges of total supply costs (levelized costs and system costs) of gas, coal (without CCS) and nuclear electricity and should be added to their levelized costs, which are higher in any case. Ultimately, system costs must be paid by consumers as part of the transmission and distribution costs in their electricity bills. They are partially responsible for the fast growing electricity prices in countries with fast growing shares of variable renewables in the power supply mix.

3.2. 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 higher upfront capital cost but relatively low fuel and operational costs when compared with large scale generating units burning fossil fuels.

Though a variety of metrics exists, overnight costs have proven to be a good indicator of the magnitude of the investments needed. They include pre-construction (owner's), construction (engineering, procurement and construction) and contingency costs, but exclude interest during construction. For countries opting for nuclear programmes, a good understanding of the true total investment cost of the project and the annual outlay schedule is especially important when evaluating the relative competitiveness of generating capacity additions.

The large ranges of uncertainty in nuclear overnight costs prove very challenging. Most recent evidence lends support to the estimated overnight costs for new nuclear power projects in the range between \$1556/kW(e) and

$6607/kW(e) — with most well above $3000/kW(e). (All cost data in this section are presented in 2008 dollars.) Therefore, a large portion of cost variations can be explained by reasons ranging from site characteristics and plant size to country specific financial, technical and regulatory boundary conditions. Comparing the cost estimates across countries, the lowest estimates at $1748/kW(e) and $1556/kW(e) are those reported for China and the Republic of Korea [66]. The most recent high end estimates in western Europe and the USA range between $3564/kW(e) and $4946/kW(e) for Advanced Passive 1000 (AP1000) reactors and between $4364/kW(e) and $6607/kW(e) for European Pressurized Water Reactors (EPRs) (calculations based on Ref. [68]). Both of these reactor types are considered Generation III+ reactor designs. The most recent overnight cost estimates for the Russian Federation reactor designs are somewhat lower in a range between $3133/kW(e) and $4290/kW(e) (calculations based on Ref. [63]).

The typically high overnight capital costs of a first of a kind reactor (FOAK) tend to decline when moving towards the construction of a fully mature nth of a kind (NOAK) plant. In 2012, PricewaterhouseCoopers LLP (PwC) analysed the cost savings potential of establishing a nuclear fleet in the UK with up to eight new reactors to be built by 2030. The study estimated a saving of 10% for the total design and construction costs compared to diversified reactor technologies under a so-called fleet assumption, where a fleet is defined as two or more pairs of reactors relying on the same reactor technology and common design of the conventional island and balance of plant. The construction of a nuclear fleet could generate cost efficiencies through a variety of sources, including discounts through bulk purchases, learning effects which lead to new or improved designs, improved resource planning, absorption of fixed costs associated with design, procurement, etc. These benefits acquired through cost savings could be potentially delivered to electricity users via reduced electricity prices [69]. However, risks might also be involved in the fleet approach, including systematic design (safety) issues resulting in delays (shutdown) of all reactors, insufficient financial capacity to meet contractual obligations for multiple builds and regulatory complexity. The PwC estimates are in line with the previously published Parsons Brinckerhoff's study for the UK, forecasting slightly higher savings of about 15% [70]. Finally, a study conducted for the UK Department of Energy and Climate Change by Mott MacDonald assumed the FOAK markup on capital costs for third generation nuclear reactors to be in a considerably higher (20%–40%) range [71]. Implicitly, this study assumes higher learning effects than others as deployment moves from a FOAK to a NOAK.

In addition to the spatial dimension (cost variation across regions), overnight costs tend also to vary over time. Academic studies, government reports and the general media have consistently documented rising costs for nuclear power over the last few decades. In France, for example, the overnight construction cost almost doubled between the late 1970s, when the first four reactors at Fessenheim and Bugey were commissioned ($1075/kW(e)), and the early 2000s, when the last four reactors at Chooz and Civaux came on-line ($1607/kW(e) and $2102/kW(e), respectively; calculations based on Ref. [72]). In the USA, overnight cost increases were even more pronounced over a shorter period of time. In a detailed analysis from 2011, the University of Chicago corrected its own estimates from $1883/kW(e) to $3964/kW(e) in comparison to earlier published results from the year 2004 (calculations based on Refs [73, 74]).

What is the explanation for the anomaly that nuclear technology seems to display the opposite trend to many other technologies, which experience falling costs over time? The University of Chicago study identified four key factors behind rising overnight costs in the USA: increasing technical maturation of the engineering design, improved accounting for the owner's costs, the run up in supply chain pricing and the significant premium in fixed or firm price engineering–procurement–construction contracts [74]. Increasing technical maturation of the engineering design is to a large extent a response to stricter safety regulations, by far the largest factor in the escalating costs observed in the USA, according to a study by Lévêque in 2013 [75].

Evidence from China, France and the Republic of Korea suggests that a variety of factors in the recent building of reactors and the project management of large civil engineering projects can lead to lower capital costs [76]. Escalation in overnight costs was far less spectacular in the past in France than in the USA (see above) and the driving forces were somewhat different. In France, the cost increases over time were primarily driven by changes in technology, rising machinery prices and increasing project ownership expenses. Powerful learning effects and regulatory stability are likely to have curbed the cost explosion, though some learning effects were cancelled out by changes in reactor types. The Republic of Korea is likely to enjoy similar favourable conditions as France in depressing explosive overnight cost increases through shorter construction time, reasonably similar reactor designs, a single operator and industrial integration. Finally, China might have foregone some cost-minimizing learning effects by using different reactor types — boiling water, pressurized water and heavy water — though the remarkable speed of construction, standardization of the process and industrial organization offset cost increases. The overnight costs of building an improved Chinese Pressurized Reactor (CPR-1000), a reactor type to which priority was given less than 10 year ago, have likely benefitted from learning effects [75].

Figure 22 [77] presents ranges of the overnight construction costs for six main power generation technologies. The cost of the majority of the reported nuclear projects are in a relatively narrow range (within one standard deviation of

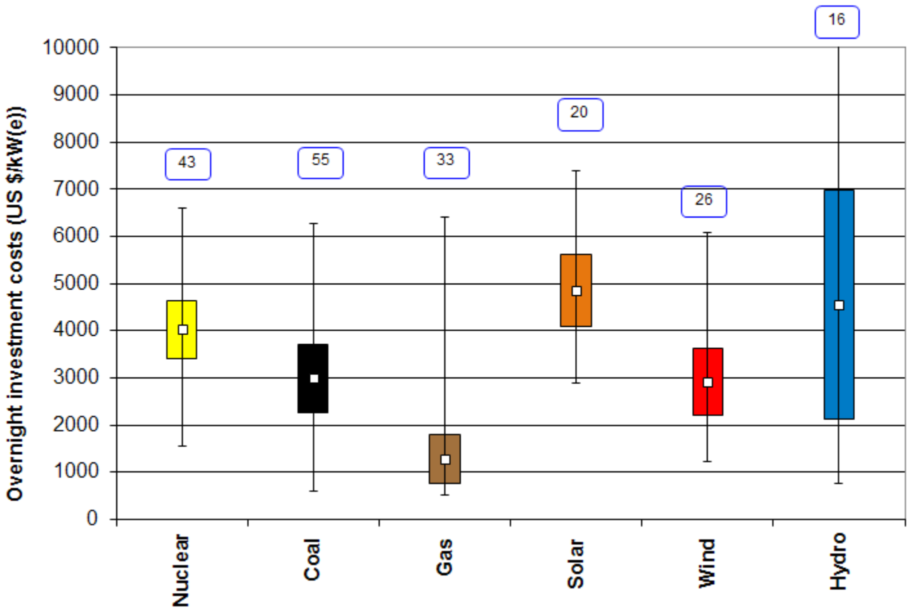

FIG. 22. Overnight investment cost estimates for the main electricity generation technologies. Data source: Ref. [77]. Note: This chart is based on data compiled from sources published between 2010 and 2013.

the mean) compared to renewable power technologies. The variation in estimates reflects the importance of country specific conditions.

3.3. FINANCING NUCLEAR POWER INVESTMENTS

Nuclear power generation projects face particular challenges when it comes to financing. Although nuclear plants enjoy relatively low and stable operating costs, the upfront capital investment costs can be considerable. Figure 23 [78] compares the cost breakdown for a typical NPP with that of a CCGT plant. As well as the costs of physical materials and labour, capital costs include financing costs — often referred to as interest during construction (IDC). Given the lengthy construction periods associated with nuclear projects, these can be substantial. It has been estimated that the IDC of a nuclear project involving a typical profile of spending on plant construction over a seven year period could come to as much as $2.8 billion if financed at an interest rate of 10% [1].

There are two main keys to reducing IDC. First, the amount of IDC can be minimized by shortening the construction period. Second, it can be reduced by obtaining the required financial resources at the lowest possible cost. A key

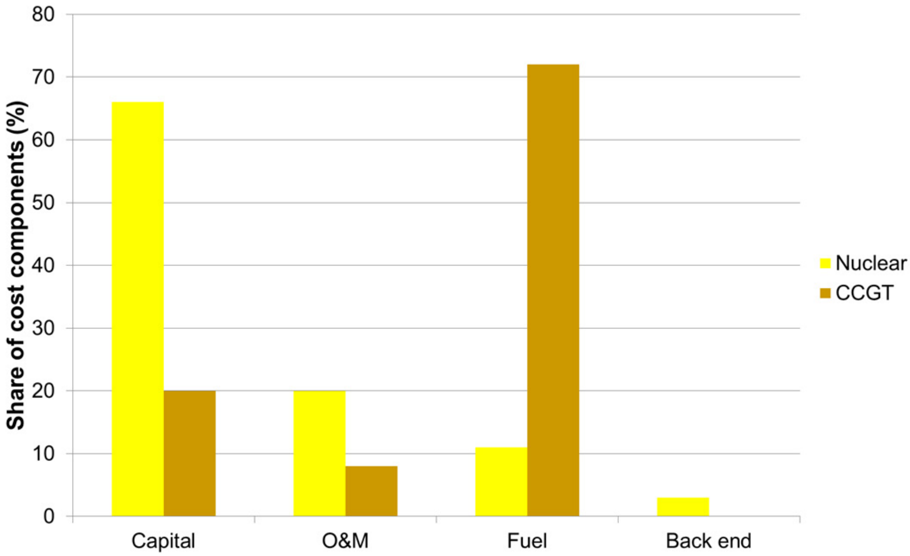

FIG. 23. Cost profile of nuclear versus gas fired generation. Note: O&M — operation and maintenance, CCGT — combined cycle gas turbine. Data source: Department of Trade and Industry [78].

determinant of the cost of capital will be the perceived riskiness of the project — the degree to which potential investors and lenders regard it as possible or even likely that some, or all, of the capital which they commit to the project will not be repaid. In so far as this perceived riskiness can be reduced, the cost of capital can also be reduced. In this context, a number of forms of government support to encourage the development of nuclear energy — involving the government assuming certain types of risk — have begun to emerge.

A fundamental form of government support is support via loan guarantees. An example of a loan guarantee programme is that administered by the United States Department of Energy. Borrowers (sponsors of a qualifying nuclear power project) who qualify for a federal guarantee can finance up to 80% of the project's total construction costs. Guarantees may assure lenders of receiving full repayment of principal and any interest owed on the guaranteed amount — thereby qualifying guarantee recipients for loans from the United States Treasury's Federal Financing Bank — or they may protect the lender against only a portion of potential losses. In February 2014, it was announced that the companies developing the Vogtle 3 and 4 reactors in Georgia would receive up to $8.3 billion in loans to be furnished by the Federal Financing Bank [79].

Similarly, in the UK, the Hinkley Point C project to build two European Pressurized Reactors with a total capacity of over 3200 MW(e) will benefit from the government's UK Guarantees Scheme, which provides a sovereign backed guarantee to help projects access finance. It is expected that UK Treasury guaranteed debt will finance 65% of expected total costs prior to operations, backed by an appropriate security package provided by the investors.

An arguably even more important component of the package of support contemplated by the UK government in the context of Hinkley Point C is the so-called 'contract for difference' (CFD) designed to remove much of the revenue risk typically faced by the owner of a nuclear (or any other kind of) power plant. Under the CFD arrangement, the owners of Hinkley Point C will receive a fixed price (a so-called 'strike price') for the output which it produces. This strike price will be index-linked to the UK consumer price index for the first 35 years of the project's 60 year life, providing a high degree of certainty on the revenues which will be available to pay back lenders' principal and interest, and therefore resulting in a reduced cost of capital for the project.

The UK CFD framework is one example of a more general support arrangement: the host government backed 'power purchase agreement' (PPA). In another example, Turkey plans to implement such an arrangement in the context of the four unit Akkuyu project. The state owned electricity wholesaler TETAŞ will be the counterparty to the owner of the Akkuyu units in a PPA which will target an electricity price of 12.35 cents/kW·h for 70% of the output from units 1 and 2, and 30% from units 3 and 4.

Typically, a PPA backed by the host government will have a number of generic features. First, it will typically offer a guaranteed price, but not a guaranteed return, thereby maintaining pressure to minimize costs. Second, it may offer a 'take or pay' arrangement, under which the power purchasing entity must pay for energy which the owner is not called upon to produce because of insufficient demand. Third, determination of the appropriate strike price will be based on extensive financial modelling designed to ensure that the price offered is just sufficient to provide project developers with sufficient inducement to invest, but does not offer returns which are excessive given the risks the developer will be expected to assume. Fourth, the PPA will typically include one or more forms of contingent price adjustment mechanism such that the strike price is automatically adjusted to reflect unanticipated cost increases which are not due to poor owner-operator performance (e.g. cost increases arising as a result of general wage and price inflation). Fifth and finally, the PPA will often be between the owner and a host government backed counterparty, reflecting the fact that a guarantee on the revenue side is only as good as the guarantor's credit rating.

In addition to the increasing implementation of mechanisms designed to allow host governments to reduce the perceived risks to which potential lenders and investors are exposed, there are a number of other developments in the area of financing which are worthy of note. Perhaps the most significant of these is the growing demand on the part of potential nuclear technology customers for vendors of such technology to take an equity stake in projects. For example, the United Arab Emirates contract provides for 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 [80].

Finally, one measure which has not yet been implemented, but which would assist financing of building new NPPs, would be the uniform application of CO_2 emission penalties (carbon tax or tradable permit system) and green credits.

3.4. TIMELINESS AND CONSTRUCTION CAPACITY

Scenarios exploring the achievement of global GHG mitigation goals consistent with the Copenhagen Accord of the UNFCCC assume a significant increase of the shares of low carbon energy sources in the global energy mix. According to IEA's WEO 2013 estimates, even in the moderate 'New Policies' scenario leading to a long term temperature rise of 4°C, global primary energy demand for nuclear energy will increase by 31% in comparison with 2011 by 2020, and by 66% by 2035 [8]. Total primary energy supply of nuclear energy, according to IEA's ETP 2014, should increase by 72% in 2011–2050 in the New Policies scenario (labelled as 4DS in ETP 2014) [13]. The stringent 450 scenario, limiting global warming to the 2°C target over the long term, assumes that nuclear power will grow by 37% in 2011–2020 and by 126% in 2011–2035. In this case, the total primary energy supply of nuclear energy should increase by 162% in 2011–2050 (according to ETP 2014, where the 450 Scenario is labelled as 2DS).

This raises concerns about the ability of the nuclear and other low carbon technologies to meet the needs of such an ambitious expansion. Over the last decade or so, global demand for nuclear energy has remained largely constant at 676 Mtoe in 2000 and 674 Mtoe in 2011. Since the early 1990s, the nuclear industry has not expanded significantly, but by 2035 it might need to provide new capacities necessary to meet the additional demand of 445 Mtoe (in the New Policies scenario) and 847 Mtoe (in the 450 Scenario) in addition to replacing retired reactors during the same time period [8].

These challenges seem to be less serious if previous experience of the nuclear industry is considered. In 1970, the global reactor fleet consisted of only 82 reactors with a total installed capacity of 16 291 MW(e), growing to 168 reactors (72 860 MW(e) capacity) by 1975 [81] — and to 420 reactors with an overall capacity of 327 670 MW(e) by 1990 [82]. This means that within a twenty year timeframe, the industry was able to increase its capacity five times in terms of the number of reactors in operation, and in terms of net capacity by more than 20 times. In comparison with this, the expected growth of even 126% (450 Scenario of the IEA) during the next quarter of a century does not seem to be enormous (see Fig. 24 [8, 13, 81, 82]). Additionally, the expansion of the nuclear industry in the 1970s and 1980s was achieved when the technology was rather new and users did not have previous experience of fast expansion, while the future progress of the industry will be based on well established knowledge.

Another aspect is that the major share of the increase in energy demand the over next decades is expected in developing nations with limited or no previous experience in building and operating NPPs. Obviously, such states will have to rely substantially on the help and experience of countries with advanced

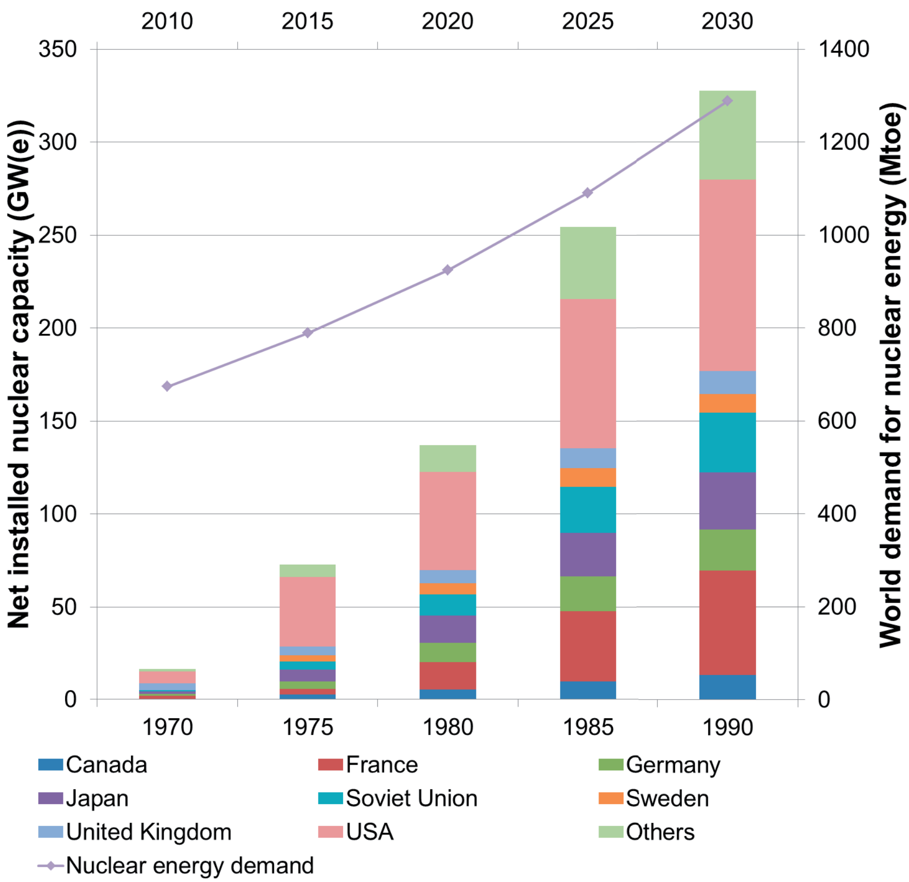

FIG. 24. Net installed capacity of the nuclear industry (GW(e)) in 1970–1990 (left vertical and lower horizontal axis) and projected expansion of world primary energy demand for nuclear energy, according to the IEA 450 Scenario in 2010–2030 (right vertical and upper horizontal axis). Data sources: Refs [8, 13, 81, 82].

programmes. However, countries with advanced nuclear programmes today were not always in this position. They also had to start scaling up their manufacturing industries in the 1970s and 1980s from low levels, quickly expanding the production of sophisticated nuclear manufacturing equipment (reactor vessels, piping, instrumentation and control systems) that require special certification. Production capacities of such equipment in countries with advanced nuclear programmes are likely to expand in response to increasing market opportunities just as they did in the past. The development of national manufacturing facilities, associated with the production of advanced equipment in newcomer countries, will certainly include technology transfer. A recent example is the transfer of the AP1000 technology from the USA to China. This allows recipient countries to gradually catch up with countries operating advanced nuclear industries and to make the necessary growth spurt in this area of industrialization. In general, it is naturally easier to transfer a technology than to develop a new one, so the difficulties associated with this process should not be overestimated.

Country specific examples of nuclear industry development in the 1970s and 1980s demonstrate the opportunities of expanding the nuclear industry at the national level (considering the limited level of internationalization of industry in that era). The USA was able to increase its capacity from 17 reactors with 6347 MW(e) of net installed capacity in 1970 to 68 reactors (52 826 MW(e)) in 1980 and 111 reactors (102 871 MW(e)) in 1990 [81]. Another example of fast nuclear expansion is France, with only 8 reactors in operation in 1970 (1696 MW(e) net installed capacity), but with a fleet of 22 reactors (14 556 MW(e)) in 1980 and 56 reactors (55 998 MW(e)) in 1990, increasing the share of electricity generated in the country from nuclear sources to around 80%. Therefore, there are no specific reasons why developing nations would not be able to follow their example in the next decades, especially as the world economy has become significantly more integrated.

An associated and widely discussed concern is that the construction of NPPs requires a long time, sometimes up to ten years, from the beginning of planning to connection to the grid, so nuclear capacities will become available too late and thus be unable to contribute to achieving global mitigation goals. However, a closer look at other low carbon energy capacities reveals comparable construction periods to those of NPPs for installed capacities of similar order. The IEA Energy Technology Systems Analysis Programme [83] estimates the following typical construction times for the installed capacities specified below:

— 18–96 months for construction of hydro dams with capacity of more than 10 MW(e);
— 42–54 months for supercritical coal power plants with capacity of 600–1100 MW(e);

— 24–30 months for CCGT with capacity of 60–430 MW(e);
— 40–72 months for nuclear power with capacity of 800–1200 MW(e);
— Typical construction times for solar PV and wind power have not yet been provided by the IEA Energy Technology Systems Analysis Program.[1]

The need to expand the nuclear industry quickly is likely to shorten construction times. Current lengthy construction times are partly associated with the limited level of new NPP constructions in recent years that makes each new project unique — even reactors of similar designs can differ as more advanced technological features are developed and introduced over time and there is limited opportunity for learning. In the case of a major expansion of the industry, reactor designs will become standardized, decreasing the construction costs as well as the period of construction (possibly to an average of 42 months).

Expansion of construction capacity will also be favoured by the differences between the market structure of modern economies compared with those in the 1970s. Nuclear energy development over the next few decades will occur in a much more integrated global economy, with increased cooperation between different agents in the market. While in the 1970s and 1980s the components for NPPs came mostly from national producers (usually from integrated suppliers, such as Westinghouse), the industry is now significantly more open and many components are manufactured by several specialized producers around the globe. This should make the industry significantly more adaptive to the requirements of an expanding market. Such international specialization will also favour smaller countries that cannot operate the whole production chain necessary for NPP construction, allowing them to find a specific niche in the market. An important step forward in this direction will be standardization and international certification of various components of the plant, which will additionally decrease average construction time [86].

Another factor that will favour the efforts of industrializing nations with limited previous experience in nuclear energy to expand their construction capacity is the fact that around 30% of the total investment costs of an NPP construction are associated with civil engineering works, for which local producers can be mobilized, similarly to the practice of other large scale private or public construction projects (airports, large railway stations, ports, etc.) [87].

[1] 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 [84], 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 capacity [85]. Shorter and longer construction times for similar generation capacities can be found in projects around the world.

All these factors indicate that, as soon as there is a clear sign of an ambitious global climate change mitigation policy, and investors follow that sign, the nuclear energy sector and its supporting industries will be ready to deliver the necessary volumes of low carbon electricity generation capacities, fostering climate protection efforts globally.

3.5. AVAILABILITY OF URANIUM

A concern heard from time to time about the possibly significant contribution of nuclear power to mitigating climate change is the limited amount of available uranium. It has been suggested that the world will run out of uranium within the next 2–3 decades. This section addresses this concern, also dubbed as ‘peak uranium’.

Two main approaches have been employed in estimating uranium availability. The first is what might be termed the extrapolative/inferential approach, which relies on sampling to arrive at measures of crustal abundance (i.e. average concentration of uranium in the earth’s crust, or portions thereof) and extrapolation to distribute that abundance between different grades or categories. The second approach is the survey based approach, which forms the basis for what is arguably the best known source of uranium resource estimates — the joint IAEA/OECD report on Uranium: Resources, Production and Demand, commonly known as the ‘Red Book’ [30]. Extending the scope of the 2013 edition (Section 4.5 in Ref. [1]), the perspectives provided by both of these approaches are presented here.

Estimates of the composition of the earth’s crust, based on approaches which include large scale sampling of rocks that crop out at the surface, and determining averages in sedimentary rocks or glacial deposits, are the basis for estimates of uranium’s crustal abundance such as:

“There are about 80 trillion tonnes of uranium in the crust of the earth to a depth of 25 km. Uranium, with an average crustal concentration of 2.8 ppm, is much more prevalent than…silver (0.1 ppm) and tungsten (1.4 ppm). It is less common than lead (13 ppm) and copper (55 ppm)…” (Ref. [88], p. 380).

Of course, uranium is not diffused homogeneously through the upper crust, and it is the existence of pockets containing unusually high concentrations (above the average crustal concentration) that has made recovery of the resource economically viable at typical historical prices. In that context, there have been a number of attempts to address the question of how much uranium is present in different concentrations. Three broad approaches are typically employed, moving from an estimate of crustal abundance to an estimate of economically useful resource, namely (a) establishing a relationship between crustal concentration and ore reserves based on regularities observed across several elements; (b) establishing relationships between quantity and quality (tonnage and grade) for a single element; and (c) parameterization of a probability distribution of the element's concentration. These approaches have resulted in a very wide range of estimates for the amount of uranium which is likely to be found in circumstances in which its recovery could be economic in current or future conditions. For example, McKelvey [89] arrives at a range for the world mineable tonnage of uranium of 41×10^5 to 410×10^5 t. Erickson [90] suggests that extractable global resources should approach 0.01% of the amount available in the crust to a depth of 1km. Applying this to the estimated 1.1 trillion t of uranium in the upper kilometre of the earth's crust, we arrive at a figure of 110 million tonnes (Mt) of uranium as the extractable global resource.

Building on the work of Ahrens [91], who noted that the abundance of trace elements in granites could be well represented by a log-normal distribution, Deffeyes and MacGregor [92] seek to establish whether the distribution of uranium in the earth's crust can be approximately fitted by a log-normal curve. In order to test this hypothesis, they estimate the masses of all the various geologic 'units' which contain uranium, and draw on existing literature on average uranium concentrations in those units to rank them in order of decreasing concentration. They find that the resulting histogram, shown in Fig. 25 [93], can indeed be fitted by a log-normal distribution.

A key feature of such a log-normal distribution is that it allows the derivation of a supply elasticity at each ore grade, i.e. the percentage increase in available ore that will result from a percentage decrease in ore grade. This supply elasticity has played a significant role in many resource estimates, such as in the majority of the long term uranium supply models reviewed by Schneider and Sailor [88], and, more recently, the work of Matthews and Driscoll [94]. Over the range of concentrations currently being mined, which is indicative of the increase in recoverable uranium likely to result from reductions in grade which are in immediate prospect, this supply elasticity suggests that a 10-fold decrease in ore grade will result in a 300-fold increase in recoverable uranium.

Given such a projection, it is possible to frame a more meaningful question than the simplistic 'When will we run out of uranium?' Instead we may ask 'How will uranium extraction costs — and hence uranium prices — evolve as lower quality resources are exploited?' The answer, of course, will depend on the extent to which enhancements in extractive technology and productivity over time counteract the tendency for the exploitation of lower grade ores to push up uranium prices. In this context, it is interesting to consider the price trends exhibited by minerals whose exploitation began long before the large scale mining of uranium (which commenced roughly around the early 1950s). Shropshire et al. [95] present evidence on the historic price behaviour of a variety of minerals. Based on data from the United States Geological Survey, this evidence suggests a declining price pattern for several commodities, while increases in long term cost are found only in a few cases. The need to exploit progressively lower grade ores does not appear to lead invariably to increasing prices; the role of technological enhancement in putting downward pressure on commodity prices needs to be borne in mind.

At the core of the discussion above is the notion that ore grades which may be uneconomic under current and immediately foreseeable economic and technological conditions may nevertheless become economic in the longer term. An arguably more conservative approach is implicit in the authoritative joint IAEA/OECD report on uranium resources, production and demand [30]. It is reasonable to suppose that respondents to the questions on economically viable resources which feature in the questionnaire underlying this publication base their responses on their assessment of costs which can be attained under current

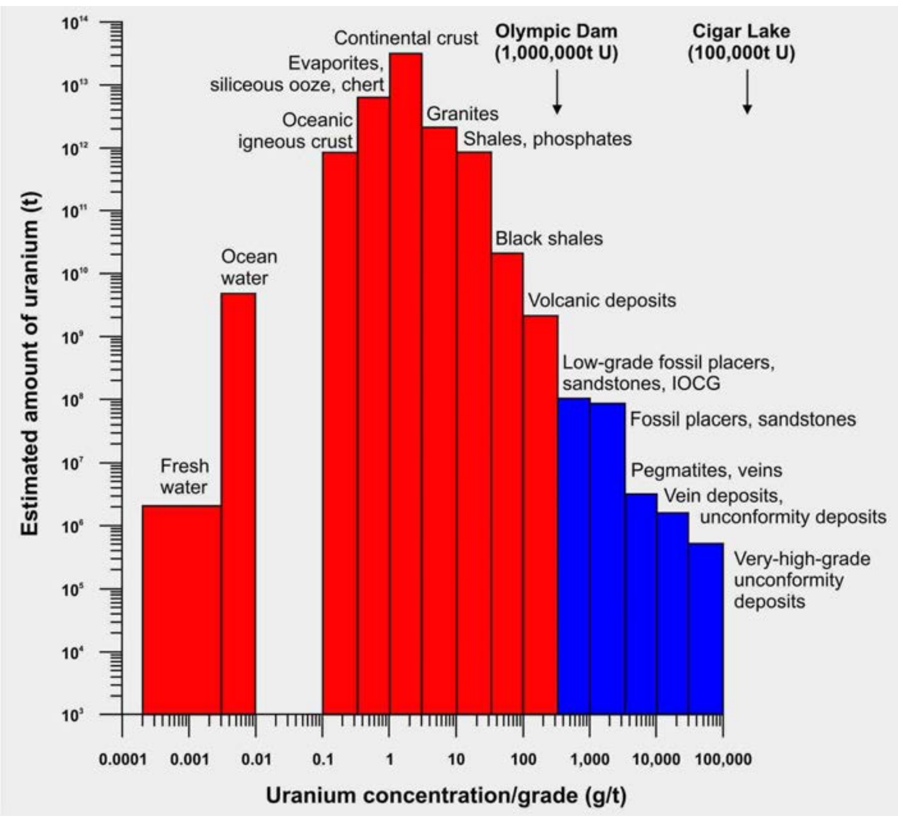

FIG. 25. Uranium distribution in the earth's crust. Data source: Ref. [93]. Note: IOCG: iron oxide copper gold (deposits).

conditions of economic and technological viability and socioenvironmental acceptability. As such, it is to be expected that Red Book estimates of uranium availability will be lower than those described above — as is indeed the case. Nevertheless, the picture of uranium resource availability which emerges from the Red Book is also broadly supportive of the view that uranium resources are sufficient to sustain nuclear power generation in the long run.

The most recent edition of the Red Book estimates the total uranium resource base (counting only "identified resources" — see below) at around 7.6 Mt U. In fact, the Red Book notes that almost 8% more uranium resources have been identified since the last edition was published in 2012. This increase results from re-evaluations of known deposits and increased efforts to extend the productive lives of mines or to expand production capacity at existing mining facilities, particularly in Australia, Canada, China, the Czech Republic, Greenland, Kazakhstan and South Africa, and is equivalent to more than eight years of global supply at 2012 uranium requirements. At the 2012 level of uranium requirements, identified resources are sufficient for over 120 years of supply for the global nuclear power fleet.

The Red Book also provides information on extraction costs, with resources classified into cost ranges: less than \$40/kg U, between \$40 and \$80/kg U, between \$80 and \$130/kg U, and between \$130 and \$260/kg U. Figure 26 shows this cost breakdown. Each column shows the amount of

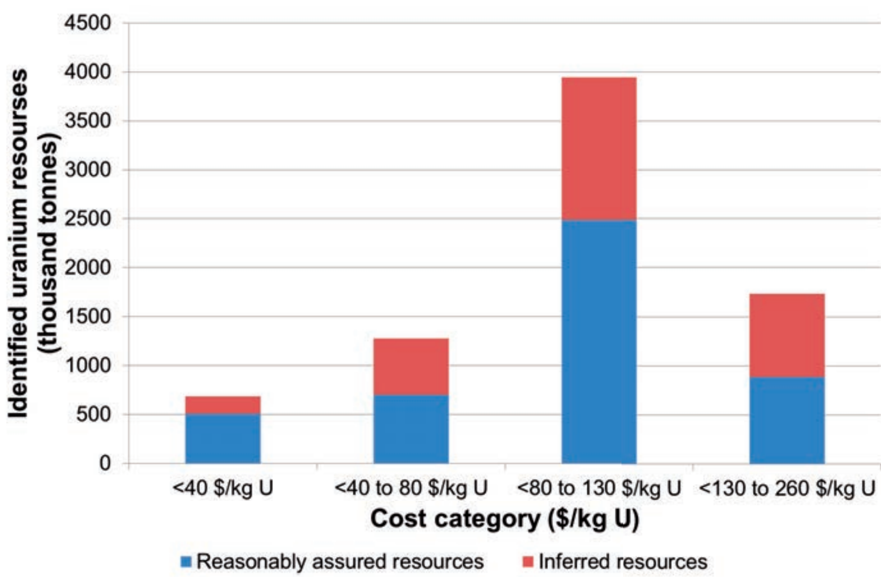

FIG. 26. World identified uranium resources in different cost categories. Source: Ref. [30]

identified resources within each cost category, consisting of uranium deposits for which direct measurements were sufficient to justify pre-feasibility studies, and in some cases even feasibility studies. Within each cost category, the amount of identified resources is further broken down into “reasonably assured resources” and “inferred resources”. For reasonably assured resources, high confidence in estimates of grade and tonnage is generally compatible with mining decision making standards. Inferred resources are not defined with such a high degree of confidence and generally require further direct measurement prior to making a decision to mine.

4. CONCERNS ABOUT NUCLEAR POWER

4.1. 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).

Radiation exposure is measured in sieverts (Sv)[2] 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. 27). 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 [96]. For local populations, the average annual exposure is estimated by UNSCEAR at 25 μSv for uranium 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 oil or gas. Similarly, stack releases from steel production can add 100 μSv to the effective dose for people living in the vicinity [96].

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[2] 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.

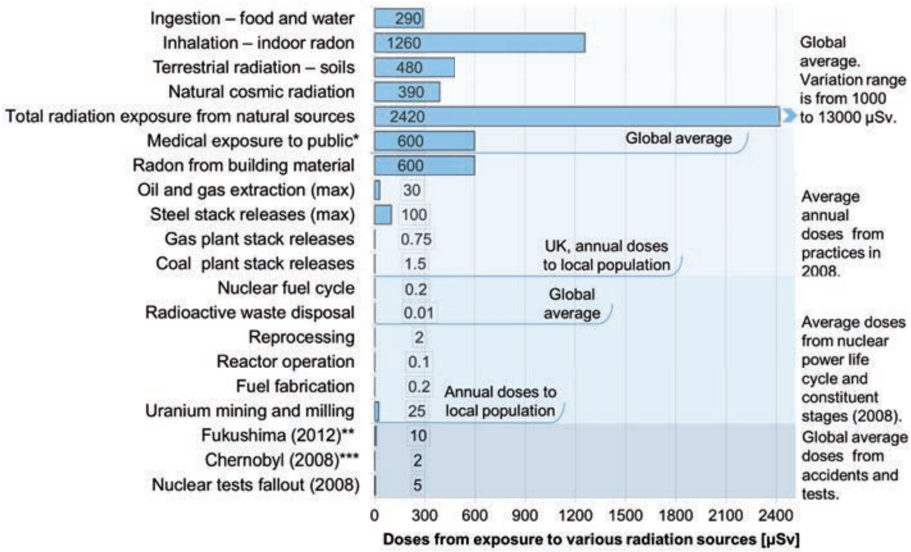


*FIG. 27. Radiation exposure to public in μSv. Data source: Ref. [96]. Note: * Estimate for 2008, corrigendum is being prepared by UNSCEAR. ** 2012, decreasing with time. *** Decreasing from 40 μSv in 1986 for the northern hemisphere.*

Radiation exposure levels of the population around nuclear facilities are significantly lower than naturally occurring radiation exposure levels. Relating such low doses to health effects over large populations and long time periods can be highly uncertain [96]. Nevertheless, calculations of the health impacts of nuclear power from ionizing radiation indicate 2.14×10^{-8} disability adjusted life years[3] (DALYs) per 1 kW·h over the entire life cycle due to ionizing radiation [15, 97]. Therefore, it can be presumed that in 2010, the year preceding the Fukushima accident, nuclear electricity generation in the world gave rise to approximately 59 000 DALYs per year. What is the meaning of this result in the global mortality and morbidity context?

According to the latest statistics of the WHO, the data available for the year 2010 approximate the number of DALYs due to malignant neoplasms (cancers) to be 193 million [97]. In this context, even if uncertainty is ignored, the value calculated above amounts to a negligible contribution of 0.03% of all cancer related DALYs due to the health effects of ionizing radiation from the nuclear power life cycle in 2010. Furthermore, the majority of these

[3] Disability adjusted life years (DALYs) are the sum of years of life lost (YLL) and years of life with disability (YLD).

estimated health effects are associated with the quantity of radon gas emissions from uranium mining and milling [15]. This 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 the 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 Refs [98, 99] for details on radiation from uranium mining.

Comparison between nuclear and fossil fuel power plant operation, or even with other industrial practices (Fig. 27), also indicates the low radiation health risks related to nuclear power. Similar findings were reported by UNSCEAR [98] and the Oak Ridge National Laboratory back in 1978 [100], 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 continue to diminish. On the other hand, radioactive contamination of the environment close to the accident sites of Chernobyl and Fukushima can be severe, covering sizeable areas. However, it should be stressed that the inhabitants of the areas contaminated by the Chernobyl accident received an average effective dose of 9 mSv during the first 20 years of exposure [96], with decreasing increments over the years. Similarly, for the locations within and around the Fukushima prefecture, depending on the deposition, the initial estimated doses among the non-evacuees of all age groups were between 0.1 and 10 mSv for the first year due to external dose from ground deposition and ingestion [101].

The UNSCEAR 2013 report presents lower estimates of the doses received by the non-evacuees in the Fukushima prefecture, citing 4 mSv for adult non-evacuees in the first year and 8 mSv for one year old infants, while the effective dose for the entire lifetime for non-evacuees in the Fukushima prefecture is estimated to be 10 mSv, if no remediation measures are taken [102]. These are average doses and therefore larger doses cannot be ruled out, but so far no radiation related deaths or acute illnesses have been observed. Similar expectations are cited for the non-human marine and terrestrial biota, with exceptions due to local variations restricted to small areas around the release point. The same report estimates the occupational doses for workers who were engaged in the mitigation and other activities at the Fukushima Daiichi NPP and concludes that the average effective dose was 12 mSv over a 19 month period for the 25 000 workers involved. This means that no discernible increase in radiation related health effects are expected either for them or the 2 million Fukushima prefecture residents and their descendants [102].

4.2. NUCLEAR SAFETY: LEARNING THE LESSONS FROM THE FUKUSHIMA DAIICHI ACCIDENT

The accident at Tokyo Electric Power Company's (TEPCO's) Fukushima Daiichi NPP (the Fukushima Daiichi accident) in March 2011 has been the dominant issue in nuclear safety over the past three years. The accident was an abrupt break in the overall trend towards higher safety of the nuclear industry observed for more than a decade as a result of long term and focused safety policies in Member States. Reactor scram rates provide an indication of success in improving plant safety. The progress in this area is shown in Fig. 28 [103], which illustrates the decrease in the number of unplanned scrams from around 1 per 7000 hours of critical power reactor operation in the early 2000s to 0.6 in the 2010s.

Following the Fukushima Daiichi accident, the IAEA Director General convened the IAEA Ministerial Conference on Nuclear Safety in June 2011 to

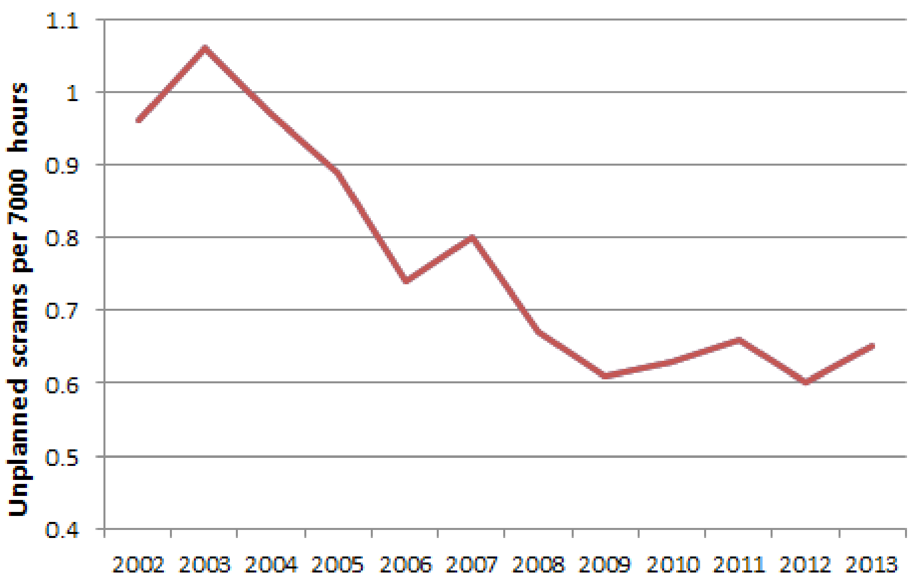


FIG. 28. Total number of unplanned scrams, including both automatic and manual scrams per 7000 h of critical power reactor operation. Data source: Ref. [103].

direct the process of learning and acting upon lessons to strengthen nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. The Conference adopted a Ministerial Declaration on Nuclear Safety, which, inter alia, requested the Director General to prepare a draft Action Plan on Nuclear Safety (the Action Plan). Following the approval of the Board of Governors, the draft Action Plan was endorsed unanimously during the IAEA General Conference in September 2011. The Action Plan [104] comprises 12 main actions and 39 sub-actions in key areas of nuclear safety ranging from safety assessments, IAEA peer reviews, and emergency preparedness and response to international legal framework, capacity building, and research and development.

Since its adoption, the main progress in the implementation of the Action Plan can be summarized as follows ([105–108]):

— The IAEA supported the assessments of safety vulnerabilities of NPPs and strengthened the peer review services in Member States by incorporating the lessons learned to date from the Fukushima Daiichi accident. NPP missions and follow-up missions in the areas of the regulatory framework, operational safety, emergency preparedness and response, and design safety were organized and conducted by the IAEA.
— The IAEA Safety Standards were reviewed and strengthened with a focus on vitally important areas such as the design and construction of NPPs against severe accidents and emergency preparedness and response. An amendment to the Convention on Nuclear Safety (CNS) addressing the design and construction of both existing and new NPPs was recently proposed [107]. As an incentive instrument, the CNS aims to commit participating States and organizations to maintain a high level of nuclear safety by setting international benchmarks.
— Various activities have been implemented to strengthen emergency preparedness and response. An Expert Group was established to provide advice on strategies to strengthen and sustain international preparedness for nuclear and radiological emergencies. As part of the effort, national, regional and interregional training courses and workshops were organized and conducted by the IAEA.
— Progress has been made in improving public information and enhancing transparency and communication during emergency situations. Among the first measures in this area, practical guidance was issued for those responsible for informing the public and the news media and for coordinating all sources of official information in order to ensure the consistency of the message to the public before, during and after a nuclear related emergency.

— The IAEA continued to share lessons learned from the Fukushima Daiichi accident with the nuclear community including through seven International Experts' Meetings (IEMs) and other topical conferences linked with key areas of the Action Plan [108]. Four reports on the first four IEMs were published.

The IAEA began work on a report on the Fukushima Daiichi accident to be finalized by the end of 2014. The report will present an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident as well as lessons learned. Five working groups are covering five key areas: the description and context of the accident, safety assessment, emergency preparedness and response, radiological consequences and post-accident recovery [108]. The report is intended to serve as a key reference document to provide a knowledge base for existing and future generations.

In addition, many actions by regional, national and international bodies were initiated in response to the accident. The European Council requested (in March 2011) the European Nuclear Safety Regulator's Group (ENSREG) to organize stress tests. These comprehensive safety reviews, completed by April 2012, reassessed the safety margins of nuclear facilities with a primary focus on challenges related to conditions experienced at the Fukushima Daiichi NPP, for example, extreme external events and the loss of safety functions, or capabilities to cope with severe accidents. The reviews examined the adequacy of design basis assumptions as well as provisions for beyond design basis events. Although different approaches and methods were used, individual countries reached similar conclusions, achieving consistency in the identification of strengths, weaknesses and possible ways to increase plant robustness across Europe. The peer review process initiated by ENSREG concluded that the necessary modifications and upgrades should be performed without undue delays and to a very high standard [109].

In the USA, the task force of the Nuclear Regulatory Commission (NRC) provided recommendations to enhance reactor safety in July 2011 [110]. These recommendations became the foundation of the NRC's post-Fukushima activities and focused on the clarification of the regulatory framework, the improved efficiency of NRC programmes, increased protection measures and emergency preparedness. The commission approved a three tiered prioritization of the recommendations. The main recommendation requires NPPs in the USA to be designed and built to safely withstand a set of unlikely harmful events such as equipment failure, pipe breaks and severe weather [111].

To determine the causes of the accident and the consequences, and to recommend measures to prevent nuclear accidents in the future, the National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission

(NAIIC) was established in October 2011. In July 2012, the NAIIC released its final report [112] that underlines the necessity of securing a high level of independence and transparency of the nuclear safety regulatory organization and recommends the National Diet to monitor the nuclear regulatory body and to re-examine the crisis management system.

IAEA Director General Yukiya Amano stated that "Fukushima was a wake-up call for all countries with nuclear power and governments have responded with a new focus on nuclear safety" [113]. The accident initiated long term actions and near term measures to ensure the resilience of NPPs to external hazards and to strengthen overall nuclear safety [114]. The IAEA's 2012 Annual report remarked that, "As of the end of 2012, safety performance indicator data on the 437 operating NPPs showed that the operational safety level remains high" [115]. Nonetheless, expectations are growing for older NPPs to meet enhanced safety objectives that are closer to those of recent designs. The Fukushima Daiichi accident demonstrated the importance of employing new safety knowledge throughout the lifetimes of existing NPPs.

4.3. WASTE MANAGEMENT AND DISPOSAL

A long standing public concern about nuclear energy is radioactive waste, which can, if not managed appropriately, 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 storage and final disposal of radioactive waste in terms of scientific understanding and technological development, as well as implementation. Emerging solutions for the long term storage of spent fuel and the ultimate disposal of high level radioactive waste and spent fuel when considered as waste, as well as the fact that solutions already exist for low and intermediate level waste, mean that 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 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, as it helps to reduce both radiation and heat generation prior to waste handling and transfer to the final disposal site. It has been demonstrated over past decades that, as long as active surveillance and maintenance are ensured, the interim storage of radioactive waste can be safe. Moreover, storage is technically feasible and a safe solution for several decades if monitoring, control and care are properly implemented [116, 117].

The disposal of spent nuclear fuel, high level and long lived intermediate level radioactive waste in geological media is a technically viable and safe method for isolating these substances from the hydrosphere, the atmosphere and the biosphere. 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 [120].

In the multibarrier principle, an 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 suitability for containment 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 [121].

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. 29). France is currently preparing a license application for geological disposal in a clay rock host formation.

At the Olkiluoto site in Finland, all vertical shafts of the underground research facility ONKALO had been drilled to the planned depth of about 450 m as of April 2014. Initially, the site will function as an underground rock characterization facility to ensure its suitability. The access tunnel and other underground structures will then 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. The final disposal of spent nuclear fuel is planned to start in 2022 and will continue for about 100 years. In Sweden, in March 2011 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 is expected to start in 2019 and disposal operations are expected to start in the late 2020s. In France, the National Agency

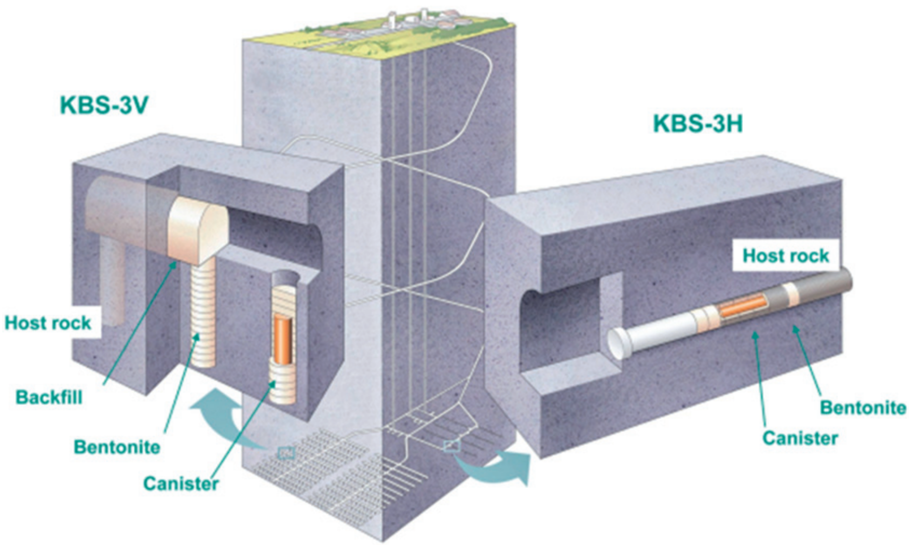


FIG. 29. The KBS-3 disposal concept. (Sources: Refs [122, 123]) (Note: KBS — nuclear fuel safety; H — horizontal; V — vertical.)

for Radioactive Waste Management (Andra) is working on an authorization application to be submitted in two steps: a preliminary application in 2015 and a finalized version in 2017, with the authorization decree expected by 2020. 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 spent fuel emerged as the best solution.

Storage and disposal are complementary and not competing activities, and both are needed to ensure safe and reliable radioactive waste management. The timing and duration of these options depend on many factors. Perpetual storage is not feasible because active controls cannot be guaranteed forever, but there is no urgency for abandoning it on technological or economic grounds. However, ethical reasons and safety considerations require the establishment of final disposal facilities.

4.4. 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 in such a way as to further any military purpose".

Over the course of several decades, the international community has put in place a number of international political and legal mechanisms to help stem the spread of nuclear weapons. They include the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and regional nuclear weapon free zone treaties, export 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, through 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 possible 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 so far.

The widening focus of safeguards implementation, beyond the verification of declared nuclear material at declared facilities to the consideration of the State's nuclear activities and capabilities as a whole, has resulted in improvements 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 information relevant to safeguards about a State from a wide range of sources, primarily information provided by the State itself, and also safeguards activities conducted by the IAEA in the field and at its headquarters, and open sources. 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. When inspecting nuclear installations in the field, safeguards inspectors use specialized equipment to carry out their work. To help detect possibly 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. It 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.

4.5. PUBLIC ACCEPTANCE

Nuclear power has come a long way in terms of technological development from the first NPP, built in 1954, to Generation III+ reactors currently offered by several vendors. Public acceptance of nuclear energy has been fluctuating in many countries in response to minor incidents and large accidents such as those at Three Mile Island (USA), Chernobyl (former Soviet Union) and more recently at Fukushima Daiichi (Japan). Nuclear power is an issue where public acceptance closely follows public opinion and vice versa. “Public acceptance refers to the seeking of collective consensus from the members of society about a certain issue — about a policy, for instance — and it is premised upon their understanding of and support for the issue concerned” [124]. The primary method to assess public acceptance of nuclear power is public opinion polls. Figure 30 summarizes results of national polls conducted by various organizations in Australia, Finland, France, Sweden, UK and USA in the period 2005–2014 in order to gauge how public acceptance of nuclear power has evolved before and after the Fukushima Daiichi accident.

Public acceptance depends on many factors, including geography (distance from NPPs), history (accumulated experience), economics (cost competitiveness with other technologies) and perceived risks (accidents, radioactive waste). In countries operating NPPs, public support for nuclear power tends to be higher and rebounds more quickly after an incident or accident. In the USA, the world’s largest producer of nuclear power, it enjoyed the strongest support in national public opinion polls before the Fukushima Daiichi accident and continues to do so today. In a long series of public opinion surveys conducted regularly since the 1980s, the Nuclear Energy Institute has reported that a large majority

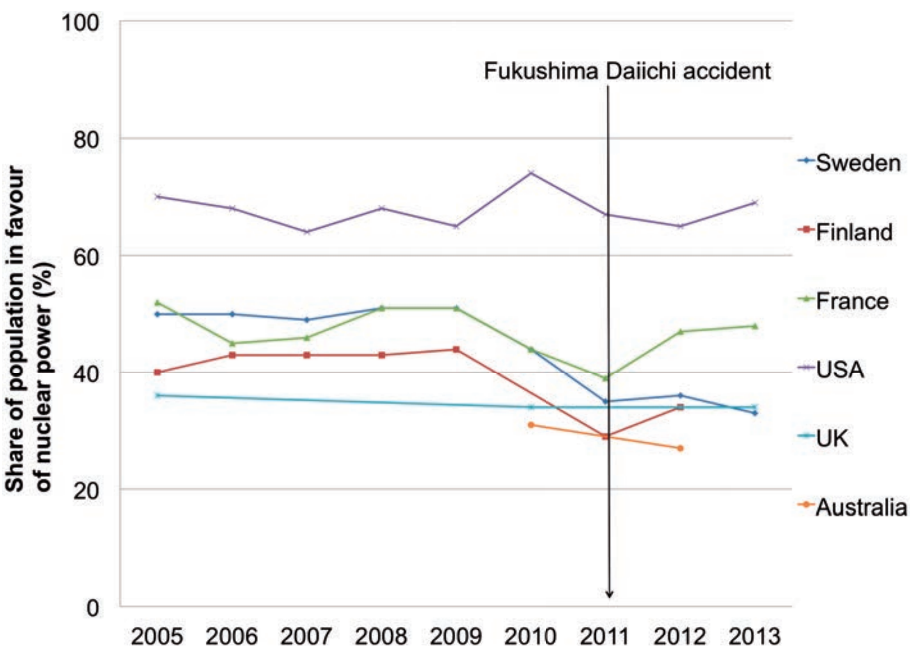


FIG. 30. Public acceptance of nuclear power in selected countries. Data sources: Refs [125–129].

of Americans in 2013 (69%) favour nuclear power [126]. After the Fukushima Daiichi accident, American public opinion had dipped only slightly when sampled a year later, in 2012 (65%). This might be due to the ‘proximity effect’ [130]: public acceptance and distance from an accident site are inversely related. In the case of the USA, this is especially true as public acceptance was marginally affected by the Chernobyl and Fukushima Daiichi accidents, while the effect was much larger after the Three Mile Island Accident in 1979.

Another factor that strongly influences public acceptance of nuclear energy is a country’s accumulated experience with nuclear power. France, the world’s second largest producer of nuclear power, which provides 73.3% of its electricity in 2013, has nearly 54 years of operating experience. Given France’s leadership in the nuclear industry and the high level of expertise of the French nuclear workforce, the majority of the French public believes nuclear power is a national asset that has enabled the country to achieve energy independence. Furthermore, France has historically shown strong public support for nuclear power. Even after the Fukushima Daiichi accident, French public opinion quickly rebounded in favour of nuclear power, increasing from 39% in 2011 to 47% in 2012 [127]. With nearly every French citizen living within 200 km of an NPP, there is a strong familiarity with the technology and respect for the strong safety record of NPPs in France. In the most recent survey in 2013, 48% of respondents supported nuclear power in France, similar to the polling scores that were seen before the Fukushima Daiichi accident. A recent study examined the changes in public acceptance of nuclear energy in 42 countries after the Fukushima Daiichi accident and found that “the proportion of nuclear power generation in a country’s total power supply is positively and significantly associated with public acceptance of nuclear energy after the accident” (Ref. [130], p. 6). Polling data for France confirm this conclusion.

In Northern Europe, the public in both Finland and Sweden continue to support nuclear power despite strong media concerns and Germany’s decision to phase out nuclear energy altogether by 2022. Climate change concerns and a focus on industrial competiveness in Finland have led to a situation where there has been a complete absence of a national debate about a nuclear phase-out. Finland is one of a few European countries currently building an NPP [131]. Just as in other countries in Fig. 30, public support in Finland fell to its lowest level in 2011 (29%), only to recover quickly in the following year (34%) [131]. According to a survey by the Society Opinion Media Institute in Sweden [129], 50% of the Swedish public in 2013 were in favour of phasing out nuclear power. However, 50% is far below the high scores of opposition to nuclear power in Sweden recorded in the 1980s by the same organization in similar surveys. Lastly, a comparative analysis of public opinion about nuclear power in Australia using data from 2010 (31% support) and 2012 (27% support), found that Australians believe nuclear power to be a clean, low carbon option, but also believe the risks associated with it outweigh its benefits [125]. The Fukushima Daiichi accident did not have a significant impact on public opinion regarding nuclear energy in Australia, although support for building NPPs has declined since 2011. In contrast, British public opinion has remained constant in the level of support (34%) for nuclear power before and after the Fukushima Daiichi accident [132].

The Fukushima Daiichi accident has understandably increased opposition to nuclear power in Japan — see Fig. 31 [133–137]. Before the accident, negative opinion was low (2005–2010), but this has changed dramatically since 2011. The latest polls conducted in 2014 by the Asahi Shimbun newspaper [133] and the Japanese Broadcasting Corporation NHK [136] find the highest level of opposition to nuclear power since polling by these organizations began in 1978. Polling data (Fig. 31) from leading Japanese media outlets and the Cabinet Office show a sharp increase in opposition to nuclear power in each of the four quarters of the year following the Fukushima Daiichi accident — a trend confirmed by all polling organizations. Despite strong public opinion against nuclear power, the Japanese Government recently announced its intention to restart some NPPs with improved safety features in seismically tested regions. This decision illustrates that, even taking the disadvantage of public opposition into account, its other advantages, such as reliability, economics and energy, can lead a government to use nuclear power in spite of low public acceptance, as long as the government has assured itself of the safety of its NPPs.

A general caveat about all public opinion polls, including those cited in this section: Individual responses and hence survey outcomes can vary considerably depending on how the questions are formulated. For this and other reasons, their results are not always reliable in terms of data quality [138–141].

5. PROSPECTS FOR NUCLEAR POWER

5.1. NUCLEAR POWER PROJECTIONS

At the end of 2013, there were 434 nuclear power reactors in operation worldwide, with a total capacity of 371.7 GW(e). This represents a decrease of approximately 1.3 GW(e) in total capacity compared to 2012. There were only four new grid connections, while six reactors were officially declared permanently shut down in 2013.

Each year, the IAEA publishes projections of global energy and electricity demand, the world’s nuclear power generating capacity and power generation for

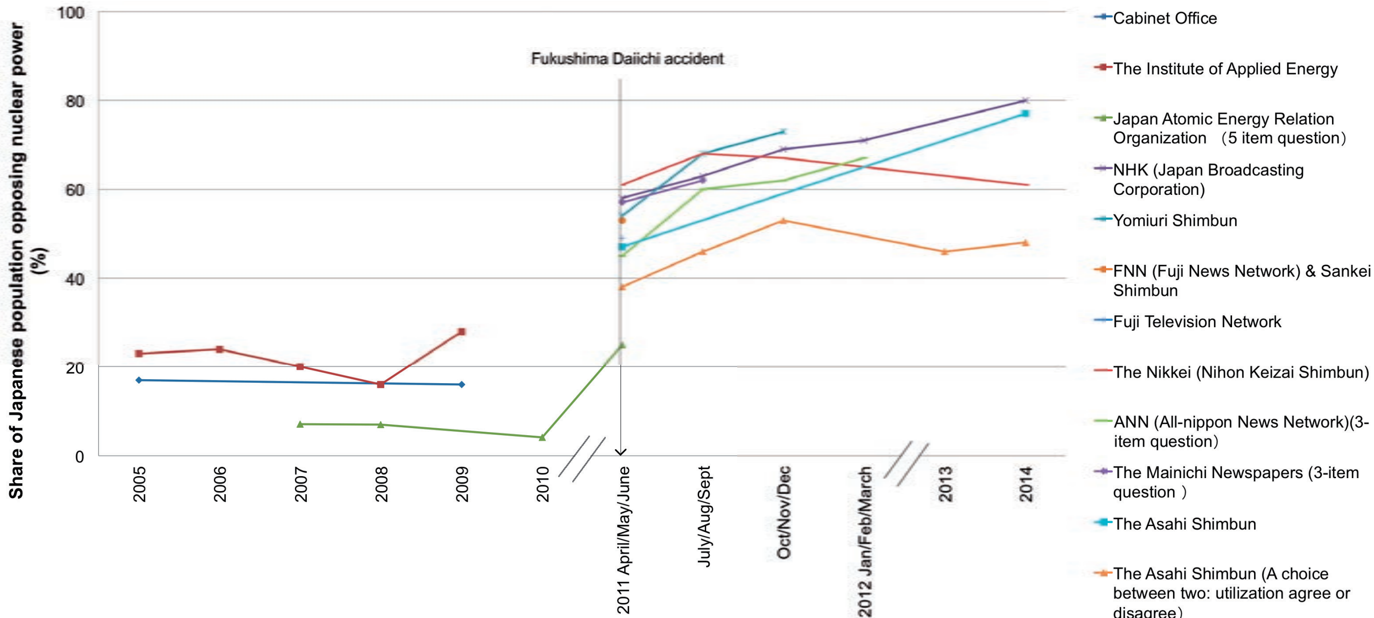


FIG. 31. Public opposition to nuclear power in Japan. Data sources: [133–137].

the forthcoming decades. The projections presented in the 2014 edition [142] 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 assessments. 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 extensions, planned shutdowns and likely construction projects foreseen for the next few decades. The projections are prepared by assessing the likelihood of each project in the light of general assumptions made for the low and the high case, respectively.

The projections of future energy and electricity demand, and the role of nuclear power in the low and high estimates, encompass the inherent uncertainties involved in any prognosis. The low and high estimates reflect contrasting, but not extreme, underlying assumptions about factors driving nuclear power deployment (see Figs 32 and 33). 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 that there will be few additional changes in laws, policies and regulations affecting nuclear power. This case is explicitly designed to produce a 'conservative but plausible' set of projections. Moreover, the low case does not necessarily imply that targets for nuclear power growth in a particular country will be achieved. Policy responses to the Fukushima accident, as understood in May 2014, are also included in the projections.

These assumptions are relaxed in the high case. The high case projections are much more ambitious, but still plausible and technically feasible. The high case assumes that current rates of economic and electricity demand growth, especially in the Far East, will continue. Changes in country policies toward climate change are also included in the high case.

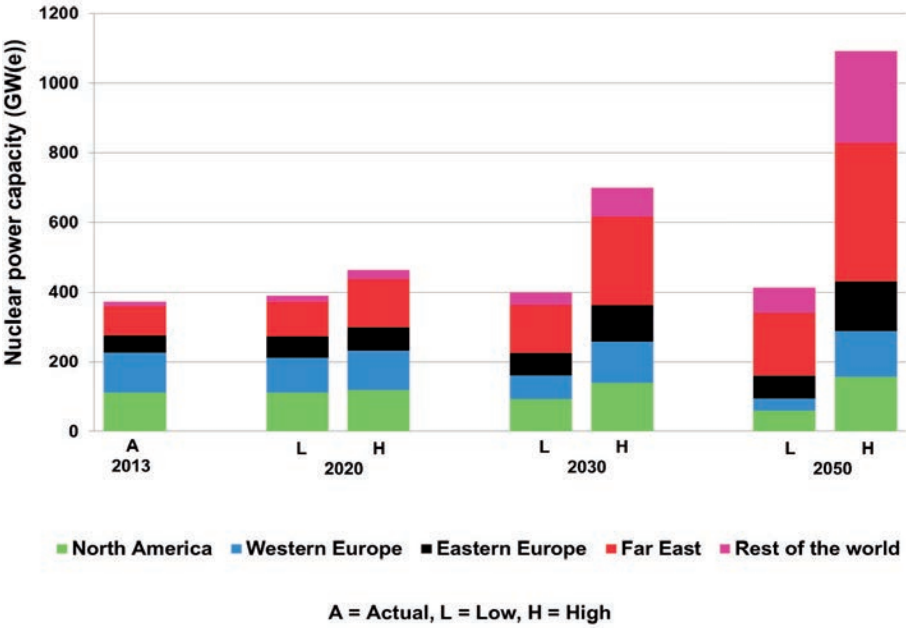


FIG. 32. Prospects for nuclear power in major world regions: estimates of installed nuclear capacity. Data source: IAEA [142].

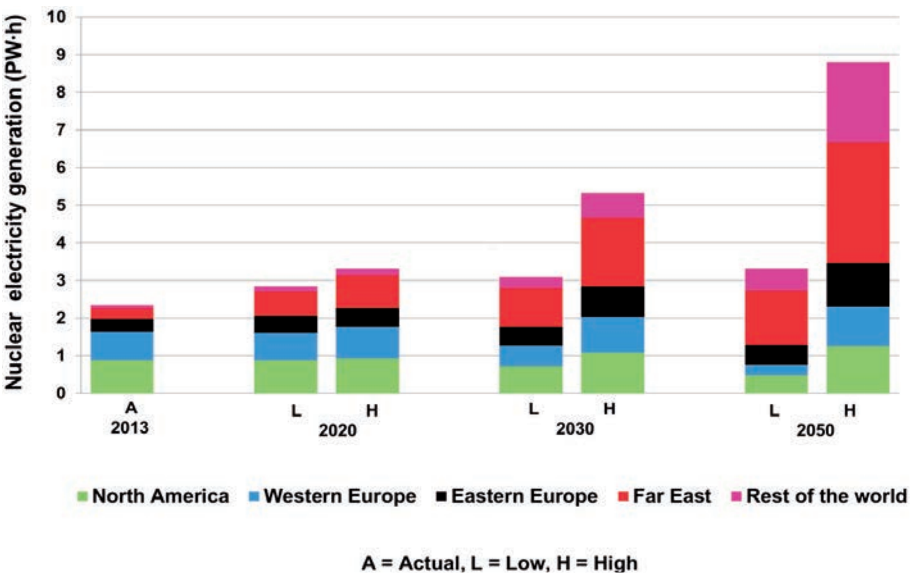


FIG. 33. Prospects for nuclear power in major world regions: estimates of nuclear electricity generation. Data source: IAEA [142].

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 IAEA 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.

In the last year, most countries 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 2013 global nuclear capacity projections for 2030 [143], the 2014 projections are lower by approximately 23 GW(e) in the high case and by 34 GW(e) in the low case.[4] These reduced projections reflect national responses to the Fukushima Daiichi accident and factors noted above. The decline of the projected capacities in 2014 relative to those in 2013 is slightly greater than the decline between the 2012 and 2013 projections. Effects of the Fukushima Daiichi accident include earlier than anticipated reactor retirements, delayed or possibly cancelled new builds and increased costs owing to changing regulatory requirements in the high projection. 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.

[4] The projections consist of both available capacity (currently supplying electricity to the grid) and installed nominal capacity (available, but not currently supplying electricity to the grid).

5.2. LIFETIME EXTENSIONS

Many IAEA Member States have given high priority to licensing their NPPs to operate longer than the originally anticipated timeframe (e.g. 30 or 40 years). As of December 2013, of 434 NPPs operating in IAEA Member States, approximately 80% had been in service 20 years or more. The task of managing plant ageing is assigned in most Member States to an engineering speciality called Plant Life Management (PLiM) which applies a systematic analysis methodology to the ageing of System Structure Components (SSCs). PLiM can be defined as the integration of ageing and economic planning for maintaining a high level of safety and optimal plant performance by successfully dealing with ageing issues, maintenance prioritization, periodic safety reviews, education and training.

The importance of PLiM in facilitating the technical and economic goals of long term operation (LTO) is thus presented in terms of the requirement to ensure the safe, long term supply of electricity in the economically most competitive way. The NPP should maintain an acceptable level of performance and enable a maximum return on investment while maintaining or increasing safety. This implies three main requirements that need to be continually reviewed while efforts are made to improve them:

- To maximize the annual generation of power;
- To minimize operational costs;
- To assess the potential additional costs necessary to ensure continued safe and profitable operation.

Economic feasibility is an essential criterion for LTO. It means that the costs of operating an NPP over the long term should be compared with the costs of equivalent replacement power such as conventional electricity generation (fossil, hydro or renewables), power imports and contracts with independent power producers. Alternative power generation options may raise additional issues (e.g. GHG mitigation benefits, external costs, environmentalist opposition, public acceptance). The preliminary economic analysis should include a review of the operation and maintenance costs during the extended operation period, the costs to upgrade the plant hardware (including the refurbishment and replacement of major components) and software, fuel costs, income during the extended operation period, amortization of investment, etc. Detailed economic analysis can only be achieved when all cost elements (e.g. refurbishment, upgrading and replacement) associated with PLiM and LTO are known or best estimates are available. Costs of radioactive waste management, conditioning, storage and final disposal must also be included in the business case argumentation and analyses.

Most nuclear reactors in the USA were originally granted operating licences of approximately 40 years. These licences can be extended for up to 20 years, provided a renewal is granted by the NRC. At the end of 2013, there were a total of 100 reactors in operation, of which 26 were operating beyond the end of their original licence. From the date of expiry of their original licences to the end of 2013, these reactors had produced approximately 262 TW·h of electricity. If these plants had been retired at the end of their original licence, this electricity would have had to be produced from different sources and CO_2 emissions would have been higher. Assuming replacement power with a CO_2 emission intensity equal to the average national emission intensity over that period (540 g CO_2/kW·h), the cumulative avoided emissions from operating licence renewals can be estimated at 141 Mt CO_2.

Of the remaining 74 reactors, 37 had received their licence renewals by the end of 2013, while 27 had either submitted a renewal request or had a number of years left of their original licensed operating period. If all reactors currently in operation receive a 20 year extension of their licence and stay in service until the end of that extension period, the expected production from these reactors would total 14 600 to 15 600 TW·h between the end of 2013 and the end of 2050. The uncertainty band is tied to the achieved load factor, which is assumed to remain at the recent average of 91% for the higher end of the range and gradually deteriorate to 80% by 2050 for the lower. The estimate incorporates the announced retirement of the Vermont Yankee reactor, but ignores the potential for capacity uprates. Assuming the CO_2 emission intensity of the replacement power is between 260 g CO_2/kW·h, as estimated by the US Energy Information Administration in its scenarios for accelerated nuclear retirements [144], and 480 g CO_2/kW·h, the average emission intensity over the entire projection period from the baseline scenario [144], the total cumulative emissions avoided would be in the range of 3800–7500 Mt CO_2. If a second 20 year extension is granted for these reactors, bringing the total operating life to approximately 80 years, the additional power generation would total 7200–8100 TW·h in the period to 2050. Following the same methodology as above, the total cumulative avoided emissions would be between 1900 and 3900 Mt CO_2 for a second round of licence renewals for all reactors. The generation from nuclear power under these different scenarios for lifetime extensions is depicted in Fig. 34.

5.3. SHALE GAS COMPETITION

Decisions regarding lifetime extension and retirement of NPPs ultimately hinge on the economic prospects of continued operation. In the long run, the expected revenues from the sale of electricity must be sufficient to cover fuel,

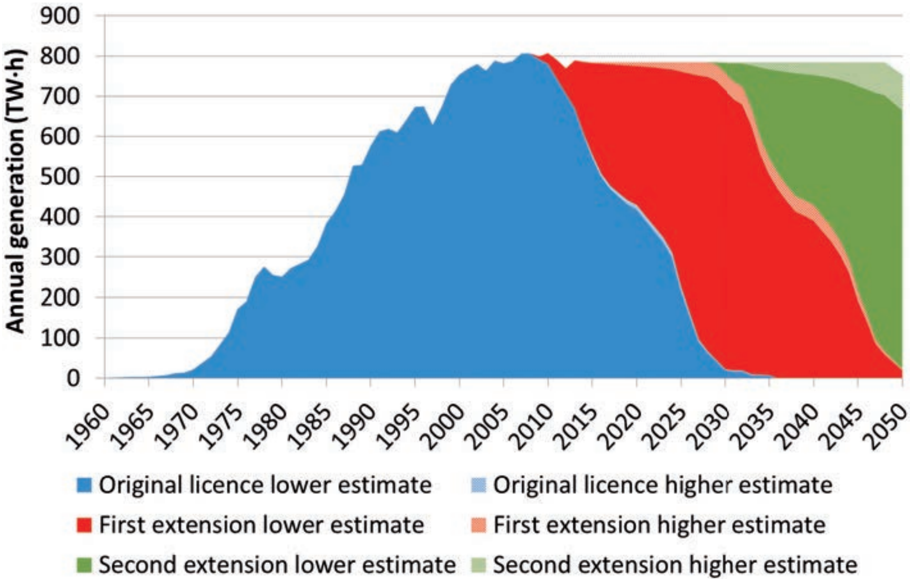


FIG. 34. Historical and projected nuclear electricity generation from the USA's current nuclear fleet under different assumptions for lifetime extensions.

operation and maintenance, and any new capital expenses (such as safety upgrades or replacement of structures and components), and to provide owners with an acceptable return on their investments and assets. If these criteria are not met, the plant is likely to be closed.

In most markets, wholesale prices have remained high enough to keep profit margins sufficient to support investment in the extension of the operating life of nuclear power stations. However, changing circumstances can alter the outlook drastically. Changes in governance and regulation (e.g. market liberalization), policy (e.g. government support for competing technologies such as renewables or nuclear phase out programmes), or technological change (e.g. shale gas or smart grids) will impact the economics of, and decisions regarding, continued operation.

Perhaps the most prominent recent example of such a large scale transitional shift in energy markets is the emergence of shale gas in the USA. Technological advances in horizontal drilling and hydraulic fracturing have made vast additional amounts of natural gas accessible at a low extraction cost. The growth in shale gas production has dramatically changed the prospects for the use of natural gas in power generation, as the prices paid by electricity producers have dropped from a high of 8.55 $/GJ in 2008 to 4.15 $/GJ in 2013. During this period, the share of natural gas in electricity generation increased from 21% to 27%, replacing coal in particular. Because natural gas is often the marginal producer,

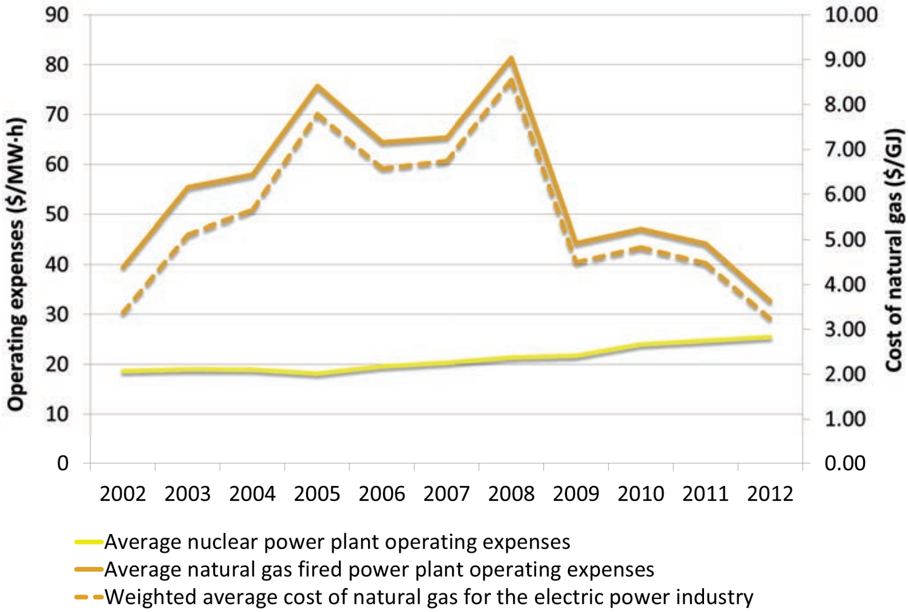


FIG. 35. Average power plant operating expenses for an average nuclear and natural gas fired power plant in the USA (left axis) compared with average cost of natural gas for the power industry (right axis). Data source: Ref. [147].

this has also heavily impacted electricity prices. The average locational marginal price for PJM, the largest independent system operator in the USA, dropped from 66.40 $/MW·h in 2008 to 38.66 $/MW·h in 2013 [145, 146]. In some areas of the country, the average annual wholesale prices have dropped below 30 $/MW·h.

With operating expenses of nuclear power in the USA averaging 25.48 $/MW·h [147], margins are severely squeezed at some plants (see Fig. 35) and have led to concerns that the low gas prices could be making a growing number of US NPPs uneconomical [148, 149]. Since 2012, five reactors have been shut down, or had their shutdown announced. In two of these cases, low electricity prices were cited as a contributing factor to the decision. Dominion said in its press release that failure to realize economies of scale and "projected low wholesale electricity prices in the region" were the main reasons behind the decision to close the Kewaunee plant [150]. Entergy similarly blamed "sustained low power prices, high cost structure" for the reduced profitability of its Vermont Yankee plant and the decision to close the plant rather than invest in required safety upgrades [151].

Although the replacement of the incumbent generation by lower cost competitors is not in itself a reason for concern, closing down NPPs early is likely to lead to increases in GHG emissions. The power will have to be replaced by generation from some other source and unless this replacement power is also low carbon, the net effect will be an increase in overall carbon emissions. In its 2014 Annual Energy Outlook [144], the US Energy Information Administration (EIA) explored scenarios for accelerated power plant retirements. When determining the impact of early nuclear retirement, the EIA found that closing an additional 35 GW(e) of nuclear capacity by 2040, over and above closures in the reference case, increased annual CO_2 emission by 81 Mt (approximately a 4% increase in overall emission and 5% increase in the emission intensity of power generation) and cumulative emissions by 442 Mt. This corresponds to an increase in CO_2 emissions equivalent to 0.26 kg for every kW·h hour of reduction in nuclear generation. In a less detailed assessment, the Center for Climate and Energy Solutions has estimated that without nuclear power, cumulative emissions of CO_2 from the US power sector between 2012 and 2025 would be 4–6 billion tonnes higher [149].

North America is the only region where large scale production of shale gas has started so far, but the global resources are vast. The extent of the resource is highly uncertain as many formations are un- or under-explored, but an assessment of 137 shale formations worldwide, undertaken for the EIA, arrives at an estimate of 207 trillion m^3 of technically recoverable resources [152]. Some of this potential is located in regions that have limited conventional gas reserves and low production rates and there is therefore a possibility of significant market transformation in many regions. The recent technological progress and increases in unconventional gas production have left the IEA to ponder the prospects for a "Golden Age of Gas" [153, 154] and project a growing role for natural gas in energy supply over the coming decades [8].

However, a range of factors unique to North America, such as private mineral rights, availability of drilling rigs and existing pipeline infrastructure, have made the recent boom possible, and it is not clear if this experience can be replicated elsewhere. Too little is currently known of the prospects for development of shale gas in the rest of the world to say much about the impacts on the economics of nuclear power and plant life extensions with any confidence, other than to say that this and other market disruptions will always pose a risk to nuclear power and other incumbents in the market. The retirement of nuclear power reactors prior to the expiry of their operating licenses is almost certain to lead to an increase in carbon emissions. A straight substitution of gas for nuclear power would lead to an increase in emission intensity of around 390 to 430 g CO_2/kW·h. Alternatively, it could be assumed that the emission intensity of the replacement power equals that of the average emission intensity of electricity production globally. In 2011, this was 450 g CO_2/kW·h and it is projected to be in the range of 280–350 g CO_2/kW·h by 2035 without stringent climate policy, although it may decline to as low as 100 g/kW·h depending on policy and market developments [8].

5.4. 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 large power range is feasible for expanding countries with a large power grid, but less feasible for many countries to be able 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. Over the next 10–20 years, the deployment of advanced small and medium sized nuclear power reactors (SMRs) is envisioned to fill the gap. The IAEA defines small reactors as reactors with an electrical output of less than 300 MW(e) and medium sized reactors with outputs up to 700 MW(e). However, the current and future focus is on addressing the development and deployment of small modular reactors, defined as modern reactors with a power output of less than 300 MW(e) built in the factory and shipped to the site as modules by rails, trucks or ships. Some of the designs are to be deployed as multiple module plants.

SMRs are designed 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 costs, SMRs will offer better financing options (i.e. better affordability for developing countries). SMRs are also 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 into improved thermal efficiency and a better return on capital investment.

SMRs could be used to replace retiring coal plants because of their similarity in size in the range of 50–300 MW(e). In the USA, 60 GW of capacity are estimated to be retired by 2020, according to the IEA reference case from the Annual Energy Outlook report [144]. Retiring coal plants in Europe may be replaced by low carbon technologies, including SMRs, in countries receptive to nuclear energy, in order to reduce GHG emissions and air pollution.

Advanced SMRs, particularly 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:

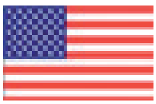
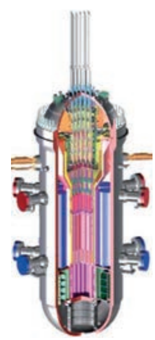
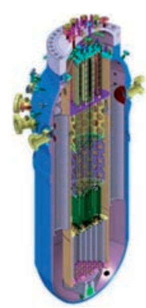
- Argentina is now constructing the CAREM-25 prototype reactor, with the first concrete pour in November 2013.
- In China, two modules of gas cooled reactors, called HTR-PM, are under construction for domestic use. China is also developing several integral Pressurized Water Reactor (PWR) type SMRs for near term deployment, including the ACP-100, which will be constructed by 2018.
- France has been developing the Flexblue, a 160 MW(e) capsule to be seabed moored 60–100 m deep at a range of 5–15 km from the coast, with offshore and local control rooms.
- In India, the Prototype Fast Breeder Reactor is ready for commissioning and startup test. The AHWR300-LEU is at final design stage and is being prepared for construction.
- In Japan, the 4S, a 10 MW(e) sodium cooled fast reactor, was proposed for design certification with the United States NRC for remote applications in Alaska and newcomer countries.
- The Republic of Korea issued design approval for SMART (100 MW(e)) in July 2012; the reactor is intended for cogeneration of power production and non-electric application.
- In the Russian Federation, construction of two KLT-40s floating NPPs is near completion. The bismuth cooled SVBR-100 and lead-cooled BREST-300 will deploy by 2018. Conceptual design work began on SHELF, a seabed based reactor.
- In the USA, six modular and integral PWR type SMRs are under development, called mPower, NuScale, W-SMR, SMR-160, GTMHR and EM2. The Department of Energy (DOE) sponsors cost sharing programmes aimed at accelerating commercialization. In December 2013, NuScale was selected as the winner in the second round of applications for DOE funding to support accelerated development and licensing.

Many newcomer countries have expressed interest in SMRs, but the lack of commercial availability is a limiting factor on adoption. Many countries prefer that the SMR technology be first deployed in the country of origin to minimize licensing and performance risks. They have also requested that technology developers, nuclear regulatory authorities and operating organizations primarily responsible for reactor safety incorporate the lessons learned from the Fukushima Daiichi accident into existing plants as well as into advanced nuclear new builds, including SMRs. In conclusion, as a result of all these, SMRs might become important future constituents of the technology portfolio to mitigate global climate change.

Table 2 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 [155, 156].

The smaller footprint of SMR plants also offers flexibility in different 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). SMRs can work in synergy with other renewable energy sources,

TABLE 2. EXAMPLES OF SMR DESIGNS

Technology developers and SMR designs	Main technical features	Reactor diagram
 United States of America NuScale (advanced SMR)	• 45 MW(e) integral iPWR; • Light water coolant and moderator, natural circulation; • 24 month fuel cycle; • Fuel enrichment below <4.95%; • Passive safety features; • 60 year design life; • Received DOE's funding subsidy for design review with the NRC, expected to start mid-2016; • 12 module deployment scheme.	
 Republic of Korea SMART (System Integrated Modular Advanced Reactor)	• 100 MW(e) integral iPWR; • Light water coolant and moderator, forced circulation; • 36 month fuel cycle; • UO_2 fuel; • Active and passive safety features; • 60 year design life; • First iPWR, received design certification in July 2012; • Single module.	
 Argentina CAREM-25 (Modified concept)	• 27 MW(e) PWR integral iPWR; • Light water coolant, natural circulation; • Fuel enrichment 3.1%; • Passive safety systems; • 60 year design life; • Under construction, with 2016 deployment target; • Single module.	

such as wind and solar, which are 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 owing to either environmental concerns or obsolescence.

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 (because of an 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) [157, 158].

5.5. VULNERABILITY OF NUCLEAR ENERGY TO CLIMATE CHANGE

The global energy system will face a double challenge over the coming decades: it will be transformed by climate change mitigation requirements and related policies, and adaptation to impacts of emerging changes in climate and weather will be crucial for a secure and reliable energy supply [159]. Energy services, infrastructure and resources, as well as seasonal demand, will be increasingly affected by changing trends, increasing variability, greater extremes and large interannual variations in climate parameters in some regions. Gradual climate change (GCC), extreme weather events (EWEs) and combinations of the two will put additional pressure on the nuclear sector in all stages of the energy supply chain, ranging from the extraction and transport of primary energy resources, through conversion into secondary energy forms, to their distribution for end use as final energy.

The extraction of uranium will be mostly affected by EWEs. The extent of the vulnerability of uranium mining will depend on the mining method. Open cast mining might be particularly affected by high precipitation extremes and related floods and erosion. These can increase the amount of trace elements leached from the overburden and thus their environmental impacts on water bodies. Temperature extremes, especially extreme cold, might also encumber extraction.

The transport of uranium and nuclear fuel will be affected by GCC only modestly. In regions with declining mean annual precipitation levels, ship and barge transport in rivers will be affected by declining water levels. Port and dock facilities, as well as coastal roads and rail tracks, will need to be amended to gradually rising mean sea level to avoid or at least reduce damage caused by flooding. Increasing frequency and intensity of EWEs will bring more severe and potentially costly impacts for the transport sector. For instance, an air temperature of above 43–45 °C leads to increasing deformities of rail tracks and derailment, to softening of road surfaces in general, and rutting and bleeding of asphalt surfaces.

NPPs operate under diverse climatic conditions and are well adapted to prevailing weather conditions. However, they might face new challenges as a result of climate change and will need to respond with hard (design or structural methods) or soft (operating procedures) measures, especially those with remaining economic lifetimes of 30 years or more. Rising mean temperatures will generally decrease the efficiency of thermal conversion as well as increase the mean temperature of water used for cooling. Diminishing mean precipitation will reduce the volume and increase the temperature of cooling water. These trends may lead to operation at reduced capacity and even temporary shutdown of power plants. Adaptation possibilities include relatively simple and low cost options such as exploiting non-traditional water sources. More drastic and expensive measures include installing dry cooling towers, heat pipe exchangers and regenerative cooling. Planning and designing the construction of new facilities, taking into account the effects of GCC, and selecting the pertinent cost efficient cooling technology, are easier and less costly than refurbishing existing power plants, especially those towards the end of their economic lifetime. Many NPPs are located in low-lying coastal areas and require the construction of barriers to protect against flooding from any rise in sea level, taking into account the impacts of changing patterns of coastal storms. That site selection for new plants should take sea level rise into account is the obvious solution.

Most EWEs tend to exacerbate the impacts of gradual changes in the related climate attribute on NPPs. The increasing frequency of extreme hot temperatures and low precipitation periods aggravate the impacts of already warmer conditions: reduced thermal and cooling efficiency, overheated buildings and water availability problems. Cooling of buildings, especially those housing key instrumentation and control equipment, is crucial for NPPs. On the positive side, lower frequency of extreme cold/frost events will cause less corrosion. Cooling water discharge will be limited if temperatures are too hot for water quality regulations. High temperature extremes increase the need for adaptation measures beyond those intended to mitigate impacts under GCC. As a secondary impact, heat can foster the rapid growth of biological material that can clog cooling water intake, leading to reduced generation or shutdown. Indirect biological impacts are simple to manage by increasing the maintenance of screens to ensure that biological matter does not clog water intake systems.

Local high precipitation events can cause floods directly at the site of power plants, damaging buildings, equipment, and downstream fuel cycle components such as spent nuclear fuel storage. Adaptation options include hard measures, such as flood protection by dams, embankments, flood control reservoirs, ponds, channels, drainage improvement, rerouting and isolation of water pipes, while soft measures comprise zoning and restricting activities in flood prone areas. Lightning can short-circuit or create false signals in instrumentation, and short-circuit onsite grid connection, backup diesel connection and controls at NPP sites. Exposure would be reduced by ensuring that circuits are insulated and grounded; key circuits are buried underground, and diesel generator controls are shielded. Extreme wind and storms (tornadoes and other rare events) can damage buildings, cooling towers and storage tanks. Upgrading construction standards can reduce the risk of structural damage.

An indirect combined impact is that drought may trigger wildfires, from which smoke blown to power plants may damage sensitive equipment and hinder access for critical personnel, supply deliveries and emergency response workers. Storm surges, superimposed on sea level rise, increase the flood risk for all facilities in low-lying coastal areas.

Considering the relatively slow rate of projected changes in generic climate attributes and extreme event patterns, there will be ample time to undertake investments in physical infrastructure and to initiate and implement changes in operational procedures and practices to reduce their impacts in NPPs and other components of the nuclear supply chain. Retrofitting existing infrastructure to cope with the impacts of a changing climate may be expensive. Probably the least-cost adaptation strategy would be accounting for projected regional climate change when drawing up siting regulations and relevant elements of the design basis, as well as construction standards.

Appendix

SHORT SUMMARIES OF 2013 SECTIONS OMITTED FROM THIS EDITION

This Appendix presents short summaries of sections in the 2013 edition of this publication [1] that are relevant to the climate change–nuclear power nexus, but where rates of changes in the related fields do not warrant annual updates. Interested readers are referred to the 2013 edition for details.

A.1. NUCLEAR ENERGY APPLICATIONS BEYOND THE POWER SECTOR

Nuclear energy has potential applications beyond electricity generation. These can range from desalination and hydropower production to district heating, oil extraction, fuelling of large tanker and container ships as well as space applications.

Desalination technologies are extremely important since many countries face water shortage challenges and have to start looking for alternative ways of providing water. Existing experience with nuclear reactors allows fast and large scale implementation of nuclear desalination techniques, which provide a viable and climate friendly alternative to conventional fossil fuel based desalination plants.

Hydrogen production from nuclear energy can replace current internal combustion engines with hydrogen fuel cells, allowing the gradual substitution of oil by hydrogen with near zero pollutant emissions.

Nuclear energy is 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 prospects for this technology were demonstrated in the last expedition to Mars by the Curiosity rover.

A.2. CONSTRUCTION CAPACITY EXPANSION

The expansion of the nuclear energy sector, and consequently its climate change mitigation potential, have been questioned because of rising concerns about both the adequacy of current construction capacity and the lack of a well trained and specialized labour force. However, the internationalization of the modern nuclear industry and previous developments in the sector in the 1970s and 1980s demonstrate that expansion in construction capacity at a relatively fast pace is feasible, should demand for nuclear energy increase in the next decades.

Indeed, the manufacturing of major power plant components by companies around the globe means there is a high level of technology transfer between different countries. The transmission of technical knowledge and equipment, the standardization of facilities design and more increased migration of the workforce in an international market will enable the expansion of current nuclear energy capacity. This has already been taking place in the past few years, especially in east Asia.

Regarding the availability of skilled workers, it must be recalled that during the rapid development of the nuclear industry, the sector also lacked the necessary labour force, yet it was able to quickly train staff. Moreover, some workers with no previous experience in nuclear construction will be able to adapt existing knowledge and skills acquired through work on other large industrial projects such as conventional power plants, refineries and chemical plants. The enhancement of international cooperation, both in terms of manufacturing and in the formation of a skilled labour force, will be an essential tool to support construction capacity expansion.

A.3. TIMELINESS OF SUPPLY

The contribution of nuclear power to climate change mitigation is often challenged on the grounds that licensing and building an NPP is a lengthy process, making it unsuitable for tackling the urgent issue of GHG emissions from the electricity sector, which need to be reduced rapidly. NPPs actually have construction times comparable to other low carbon power generating options, and they can deliver higher amounts of low carbon electricity after completion — in most cases, much higher. The IEA Energy Technology Systems Analysis Programme estimates that it takes 18–96 months for the construction of hydroelectric dams with a capacity of more than 10 MW(e), and 40–72 months for nuclear power with a capacity of 800–1200 MW(e).

The main constraint on a fast transition to a low carbon power sector is actually not the construction time of new facilities, but the commissioning time of new grid assets, which can be problematic for all types of low carbon electricity generation technologies. The main shortcomings related to grid integration stem from the incorporation of renewable energy sources.

Considering the various time frames and limitations concerning the deployment of large electricity generation capacities, regardless of which low carbon energy technologies are used, there is no a priori reason to exclude nuclear energy from a climate change mitigation portfolio.

A.4. THE THORIUM OPTION

Despite the relative abundance of uranium and the industrial experience with the uranium fuel cycle, concerns around proliferation and radioactive waste disposal, combined with the expansion of the nuclear industry due to the growth in global energy demand and climate change mitigation needs, will drive the search for alternatives to uranium. The most realistic and feasible one is thorium.

There is higher availability of thorium compared to uranium (three times higher), making it an attractive option for those countries that do not have sufficient uranium reserves, and enabling it to play a stabilizing role in the market for nuclear fuels. Thorium also possesses important safety and non-proliferation properties. In fact, because of the specific characteristics of the thorium cycle and the presence of highly radioactive elements, the regulation of the plutonium stockpile would be much easier, and self-protection incentives would complicate attempts to violate international security regimes. Furthermore, the toxicity of nuclear waste is reduced in the long run and most of the radiotoxic elements produced in the fuel cycle can be recycled. Finally, the thorium based fuel cycle is more economically competitive than the uranium one, being 20% cheaper. However, the production of thorium fuel is more complicated.

There are no technical constraints on the development of thorium based nuclear energy. This fuel can be used in existing light water reactors, allowing the extension of the current sources available. Its future expansion will mostly depend on the growth of energy demand.

A.5. FAST REACTORS: BREEDING THE FUTURE

The introduction of fast breeder reactors (FBRs) may have a revolutionary impact on the future of nuclear energy and enhance its contribution to climate change mitigation efforts. The adoption of FBRs has the potential to enhance the use of natural resources and make the nuclear industry self-sustainable. In fact, FBRs allow the extraction of over 50 times more energy per kg of uranium and have a very efficient neutron economy compared to conventional light water reactors. This means that the use of FBRs can extend the duration of uranium reserves as well as drastically reduce the need for mining and enrichment, which are the most energy intensive — and potentially the most CO_2 intensive — steps in the once-through fuel cycle. Besides, future FBRs are expected to use recycled fuel from existing reactors. Another advantage of this technology is that future FBRs are expected to burn up the most toxic minor radioactive elements, decreasing the amount of radioactive waste. The plutonium stockpile produced is also reduced compared to conventional reactors.

The major limitations of FBRs are the high capital costs and limited technical experience for their construction. However, the attractiveness of FBRs, which lies in their potential to decrease waste production — which is not only costly but is also a matter of great public concern — might lead to a decision in favour of this type of reactor even before it becomes economically competitive.

A.6. IGNITING THE FUSION SUN

When it comes to long term options for climate change mitigation, nuclear fusion is the technology at the cutting edge of current research efforts. Fusion is free from the weaknesses that characterise fission, the nuclear reaction used to produce energy in conventional reactors. The result of the nuclear fusion process is benign helium, in contrast with the heavy radioactive isotopes in spent nuclear fuels from existing reactors. The use of fusion based reactors increases safety standards; since the plasma used in the reactor is burnt under specific conditions, and any significant deviation from these conditions will result in the halting of the reactor operation, meaning that the possibility of any power plant disaster can be excluded. Fusion also has beneficial energy security implications. In the fusion process, the fuel used is produced from abundant material such as water, thus eliminating problems such as energy resource scarcity and the concerns emerging from uneven resource distribution, thereby making international energy policy more collaborative and predictable. Finally, the specific design of fusion based reactors makes it impossible to produce the material used for nuclear weapons.

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IAEA
International Atomic Energy Agency

For more information, please contact:
Planning and Economic Studies Section
Department of Nuclear Energy
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Tel: +43-1-2600-22776
Fax: +43-1-2600-29598
Email: Official.Mail@iaea.org

Web: www.iaea.org/OurWork/ST/NE/Pess/