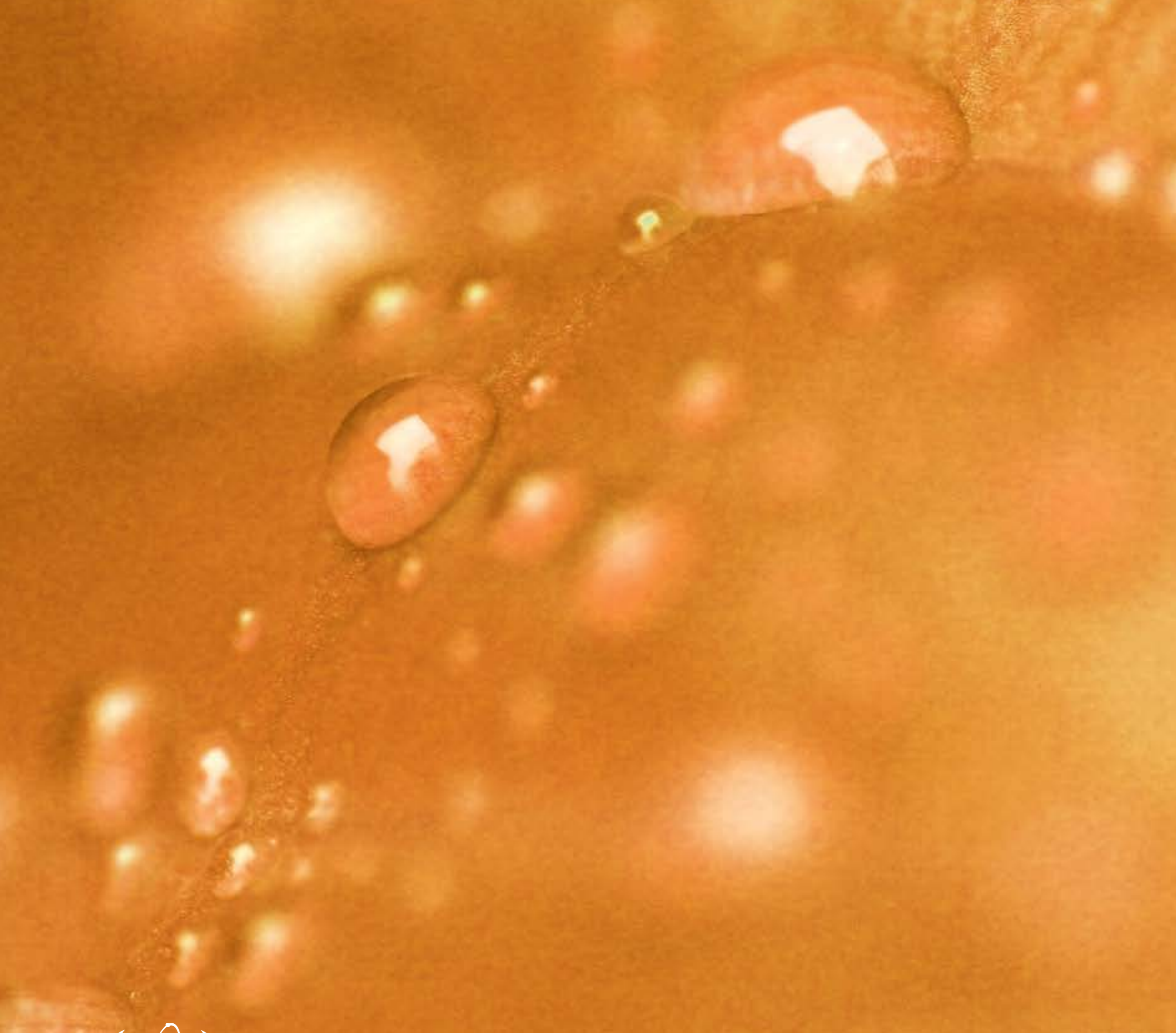
CLIMATE CHANGE AND NUCLEAR POWER 2015



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CLIMATE CHANGE AND NUCLEAR POWER 2015

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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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FOREWORD

Climate change is one of the most important environmental challenges facing the world today. Nuclear power can make a significant contribution 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. Yet, more than four 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 economic, energy 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 electricity generation and distribution technologies and their impacts on nuclear power are also presented.

This edition has been substantially revised relative to the 2014 report. Most sections have been completely rewritten to account for new scientific information, new analyses, and technical reports and other publications that have become available in 2015. Sections addressing issues on which the available information has not substantially changed over 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. Interested readers are referred to the 2013 and 2014 editions for more detailed information on nuclear energy applications beyond the power sector, the thorium option, fast reactors, fusion, competition with shale gas, new developments in small modular reactors and the implications of lifetime extensions. New sections explore emerging issues that will affect the relationship between climate change and nuclear power in the coming decades.

CONTENTS

SUMMARY

The latest report of the Intergovernmental Panel on Climate Change (IPCC) published in 2014 reveals a large volume of new evidence 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. In order to keep the increase in global mean temperature below 2°C relative to pre-industrial levels and thus to avoid distressing impacts of climate change in ecological and socioeconomic systems, 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. The 2°C target is explicitly postulated in the Copenhagen Accord of the United Nations Framework Convention on Climate Change (UNFCCC).

Energy is a fundamental prerequisite for social and economic development. Given the fast growth in the global population and economy, and the need to alleviate energy poverty, especially in developing countries, global primary energy demand is projected to increase to over 18 gigatonnes of oil equivalent (Gtoe) by 2040 according to the New Policies Scenario of the International Energy Agency (IEA) of the Organisation for Economic Co-operation and Development (OECD). Without a major transformation of the global energy system, however, the associated GHG emissions would severely affect the Earth's climate. Even after accounting for announced (but not yet implemented) policy pledges to mitigate climate change, energy related CO_2 emissions are projected to increase from their 2012 level by about 20% by 2040. This is in sharp contrast with the requirements of the Copenhagen Accord. 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 is among the 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 GHG 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. Despite significant decreases in fossil fuel prices in recent years, fears about their return to high levels in the future and concerns about the security of supply from politically unstable regions are fundamental considerations in current energy strategies in many countries. 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. Beyond the climate change benefits, significant environmental advantages arise from replacing fossil power sources with NPPs as they emit practically no local and regional air pollutants. 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, accounting for a carbon cost of US \$30/t CO_2 for fossil technologies, the range of levelized cost of electricity (LCOE) from nuclear power (US \$26–64/megawatt-hour (MW·h)) is below that of coal (US \$65–95/MW·h) and gas (US \$61–133/MW·h) plants at 3% discount rate, while coal and nuclear sources largely overlap between US \$75 and \$100/MW·h (gas turbine costs above US \$100/MW·h, except United States of America (USA) and New Zealand) at a 7% 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 US \$1.40–3.10/MW·h (slightly higher 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 published a major report presenting an authoritative, factual and balanced assessment of the accident and the lessons learned in 2015.

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 within a decade. 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 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 2015 high projection for 2030 is about 9.6% lower than what was projected in 2014 — but did not reverse the upward trends of nuclear power capacities and output. Nuclear capacity is estimated to expand to 385 gigawatt (electrical) (GW(e)) in the low and to 632 GW(e) in the high IAEA projection by 2030 and reach 371 GW(e) in the low and 964 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 the return of 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, use, expand or do away with nuclear energy in the national energy portfolio rests with sovereign States.

1. INTRODUCTION

Negotiations of three major international agreements culminate in 2015. If their conclusion is successful, they will determine pathways and rules of related policies and actions in three areas of key importance for humanity for at least the next decade, and possibly longer. In the field of development, the Millennium Development Goals will be replaced by the post-2015 development agenda and a new set of Sustainable Development Goals to be approved by the United Nations (UN) General Assembly in September. In the climate change arena, the ADP should complete its work and prepare a new legal instrument to be approved at the 21st Conference of the Parties (COP) in December that will supersede the Kyoto Protocol and provide the framework for global climate policy and action after 2020 under the UNFCCC. The Third UN World Conference on Disaster Risk Reduction adopted the Sendai Framework for Disaster Risk Reduction 2015–2030, which will guide action in this area in the future.

There are obvious linkages across these areas: the development goals and the resulting pathways will determine both the future emissions of GHGs and the vulnerability of societies to impacts of climate change. The impacts of unrestrained climate change can undermine the results of development efforts and can also increase the frequency and intensity of climate related disasters. Finally, disasters, especially geological disasters like earthquakes and tsunamis, can eliminate development investments in infrastructures and other assets in a few minutes.

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.

The Copenhagen accord requires Parties to the UNFCCC to control emissions of GHGs so that the increase of global mean temperature will not exceed 2°C relative to pre-industrial levels. The appropriate economic decision making framework is cost efficiency analysis that requires stakeholders to make the necessary reductions of GHG emissions by actors, at locations and in sectors, over time and by using technologies so that the final arrangements minimize the total costs. Any exemption, limitation, restriction or exclusion would increase the mitigation costs, undermine cost efficiency and delay actual emissions reductions.

UN Secretary-General Ban Ki-moon stated that "ending poverty, embracing human dignity and addressing climate change are interlinked. … Climate change and sustainable development, they are the two sides of one coin." He said that the world's governments and businesses need to choose wisely and *invest in low carbon energy*, not the dirty fossil fuels of the past [1]. "Climate change is the biggest environmental challenge of our time," said IAEA Director General Yukiya Amano. He went on to note that nuclear power is one of the lowest-carbon technologies available to generate electricity, and it can play a significant role in mitigating climate change [2]. Nuclear power is already an important contributor to the world's electricity needs. It supplied 11% of global electricity in 2013 [3]. 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 explores the possible contribution of nuclear energy to resolving the climate–energy conundrum and to addressing other development and environmental issues. It is an updated and extended version of the previous edition [4]. 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, the section also discusses recent developments in relevant energy infrastructure and the impacts of climate change on nuclear energy.

2. THE NEED FOR NUCLEAR POWER

2.1. THE CLIMATE CHANGE CHALLENGE

Accumulating scientific evidence prompted the IPCC to make increasingly robust statements about the impacts of human activities on the climate system. In 1996, the Second Assessment Report (AR2) cautiously concluded that “The balance of evidence suggests a discernible human influence on global climate” (Ref. [5], p. 4). About a decade later the Fourth Assessment Report (AR4) made a much stronger statement: “Warming of the climate system is unequivocal… Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations” (Ref. [6], p. 5 and p. 10). In AR5, published in 2014, IPCC Working Group (WG) I 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. [7], 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[1] 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

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

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 [7].

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).

The projected dynamics 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.

Figure 1 shows the projected changes in the annual mean surface air temperature anomalies — or simply: the triggered global warming — relative

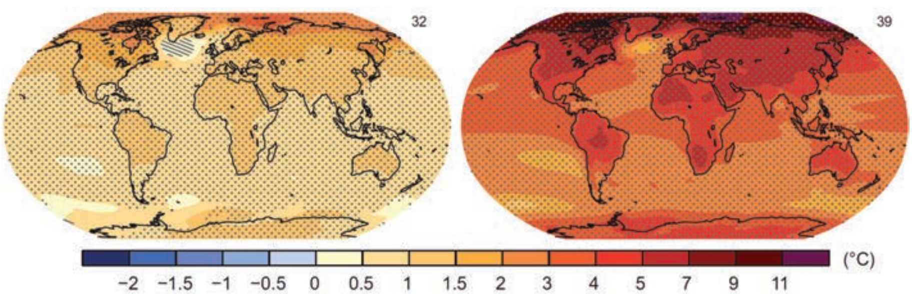

FIG. 1. Annual mean surface air temperature change relative to the 1986–2005 mean values from the CMIP5 concentration driven experiment for the scenarios RCP2.6 (left) and RCP8.5 (right). Source: Figure SPM.8 in Ref. [7]. Note: Numbers in the upper right corners indicate the number of models used to calculate the multi-model mean. RCP — representative concentration pathway. Reproduced courtesy of IPCC [7].

to the 1986–2005 mean values from the CMIP5 concentration driven experiments for the two extreme RCPs. Even under stringent climate policies (RCP2.6), the average surface warming is projected to reach 1.5°C in most terrestrial areas and 2°C in the middle and high latitude regions of the Northern Hemisphere by the end of this century. Fast increasing GHG emissions are projected to lead to mean temperature increases of 4–5°C in continental areas of the already hot tropical regions and 5–7°C in most of the middle and high latitude regions of the Northern Hemisphere.

The contribution of WG II to the IPCC's AR5 [8] 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; and 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" (Ref. [9], p. 1). 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 fast increasing GHG emissions in recent decades and the emissions pathways underlying the RCPs, the world faces an enormous mitigation challenge over the next decades in order to follow RCP2.6. The latest report of the IPCC WG III [10] 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, buildings 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

Access to energy services is widely considered a key prerequisite for sustainable economic growth. The rise of modern industrial civilization and the associated improvements in the standard of living were fostered in large part by replacing human and animal power with energy. This was the driver of early industrialization and it is still at work in developing countries today. Energy access allows use of technological advancements in industry, attracts additional investments in the economy that stimulate employment, increases effective demand, and promotes social and economic development.

Energy is an important part of the answer to the majority of development challenges of the early twenty-first century. Access to sustainable forms of energy leads to immediate and significant savings in labour needed for collecting traditional fuels, thus allowing people in developing countries to spend their time on more productive activities. Use of artificial lighting increases the opportunity for income generating activities after dusk, making the economy more productive and increasing the output from individual agents. The risk of food shortages, still high in some developing nations due to environmental conditions, also decreases as access to electricity allows refrigeration that prolongs the time of storage and reduces food loss.

The same argument is even more applicable for education: as the need for child labour, commonly used for firewood collection, decreases, the time spent on schooling can increase. Children get the opportunity to study beyond daylight hours and use information technologies. Boosting education has exceedingly strong long term effects on national standards of living and economic growth. Additionally, energy is a major contributor to improving access to modern medicine by allowing uninterrupted medical services and refrigeration of medicines, and in other ways. This helps reduce child mortality, improve maternal health and facilitate implementation of vaccination programmes in tropical regions.

Development of human capital is crucial in enabling progress towards modern industrial society. It is also nearly impossible to make significant progress without adequate, affordable and uninterrupted access to energy services. However, despite significant efforts made by the international community and national governments to improve access to modern forms of energy, a significant share of the global population still relies on traditional, polluting and unsustainable energy sources. Moreover, the absolute number of people lacking access to modern energy services is increasing. According to the 2014 estimates of the OECD IEA [11], 2.679 billion people (38% of the global population) relied on traditional biomass for cooking in 2012, an increase of 37 million relative to the 2011 estimate [12]. The number of people without access to electricity is growing as well: from 1.258 billion in 2011 [12] to 1.285 billion in 2012 (18% of the global population) [11].

The problem also involves large regional inequalities: 99.85% of people lacking access to electricity live in developing countries, primarily in sub-Saharan Africa and in developing regions of Asia. The deterioration in the access statistics above is predominantly due to population growth in these regions. Closing the gap between the developed and developing world over the next decades will require major expansion of energy supply in non-OECD countries: out of a world population of 7.22 billion people in February 2015 (according to United States (US) Census Bureau estimates) [13] less than 18% are living in OECD countries [14], yet they consume nearly 40% of global energy [11]. World population will continue growing over the next decades to 9 billion by 2040 [11] and to 9.55 billion by 2050 [15]. Of the additional 2.3 billion people only 0.15 billion will be living in OECD countries. In addition to population growth, the upward pressure on energy demand in developing countries will be driven by rapid urbanization (from 46 to 58% over the period 2011–2035) and fast economic growth. The World Bank projects doubling gross domestic product (GDP) growth rates in developing countries and an acceleration of global economic growth in 2015–2017 [16]. The IEA uses similar assumptions and estimates that 97% of the growth in total primary energy demand in 2012–2040 will occur in non-OECD countries [11].

However, the projected progress in providing energy services for the expanding population in developing regions and allowing them to industrialize will have a major impact on the environment. The magnitude of this impact on climate change will strongly depend on policy measures to be undertaken by the governments of developed and developing countries and their ability to cooperate at the global level over the next decades. The IEA depicts possible sets of policy measures in three scenarios in its World Energy Outlook (WEO) [11] and Energy Technology Perspectives (ETP) [17]. The New Policies Scenario considers policies and measures adopted in 2014 as well as the policy proposals that have not yet been fully developed and implemented, such as the commitments to reduce GHG emissions, efforts promoting renewable energy and energy efficiency, and progress in nuclear energy. Changes in global world primary energy demand and the associated rise of energy related CO_2 emissions projected by this scenario are presented in Fig. 2.

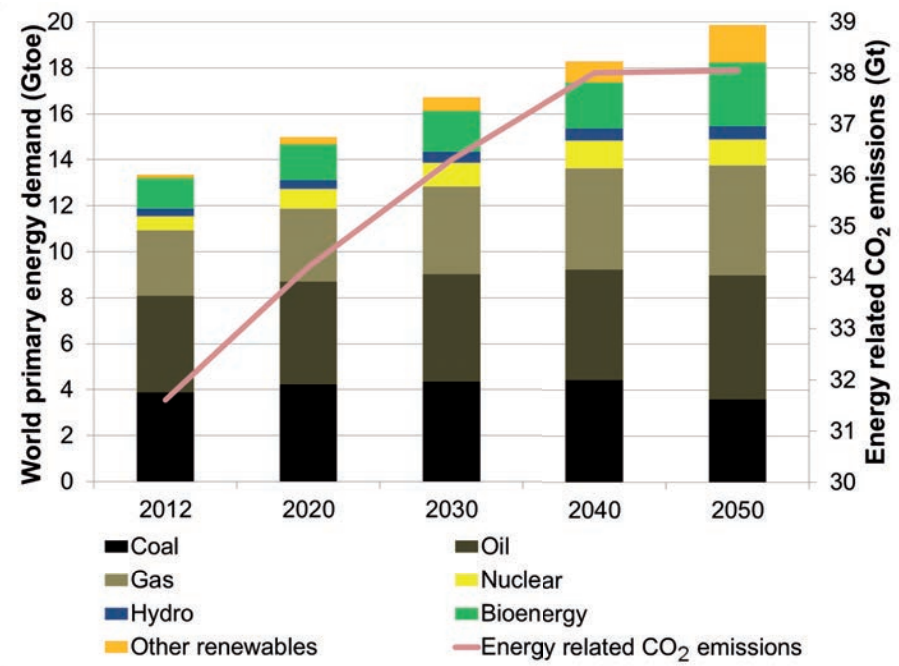

FIG. 2. Global primary energy sources (left axis) and energy related CO_2 emissions (right axis) in the IEA's WEO 2014 New Policies Scenario (up to 2040) [11] and in the ETP 2014 4°C Scenario (4DS) (2050) [17].

Relative to the New Policies Scenario, the Current Policies Scenario includes only policies already implemented in 2014, while the 450 Scenario embraces all necessary measures to limit the average global temperature rise to 2°C. These scenarios draw rather different pictures of the first half of the twenty-first century:

— According to the WEO New Policies Scenario, energy related CO_2 emissions will increase steadily and reach 38 Gt by 2040 (from 31.6 Gt in 2012), levelling off afterwards (according to the ETP 2014 4°C Scenario (4DS)), while in the 450 Scenario CO_2 emissions will peak around 2020 at 32.5 Gt and quickly decline to 19.3 Gt in 2040.

— World primary energy demand is forecast to grow in all scenarios up to 2040 but the projected growth rates differ dramatically. In comparison with the 2012 level (13 361 Mtoe), it is anticipated to increase by 37% (to 18 293 Mtoe) in 2040 in the New Policies Scenario, by 50% (to 20 039 Mtoe) in the Current Policies Scenario and only by 17% (to 15 629 Mtoe) in the 450 Scenario.

— Demand for nuclear energy expands in all WEO 2014 scenarios in the 2012–2040 period: by 88% in the New Policies Scenario, by 57% in the Current Policies Scenario and by 161% in the 450 Scenario. The share of nuclear in world primary energy demand will also increase: from 4.8% in 2012 to 6.6% in the New Policies Scenario, 5% in the Current Policies Scenario and 10.7% in the 450 Scenario by 2040.
— Over the period 2013–2040, nuclear generation capacity is projected to increase from 392 GW(e) to 624 GW(e) in the New Policies Scenario, with the number of countries operating NPPs increasing from 31 to 36. The 450 Scenario projects an even larger increase — up to 862 GW(e) by 2040.
— The share of fossil fuels in the global energy mix varies strongly across the scenarios: it is expected to decrease from 82% in 2012 to 74% in 2040 in the New Policies Scenario, to 80% in the Current Policies Scenario and to 59% in the 450 Scenario.
— The share of non-OECD countries in world primary energy demand is expected to increase from 60% in 2012 to 68–70% in 2040 (depending on the scenario), contributing to narrowing the gap in the level of development between different regions of the globe.

The IEA scenarios present a wide range of possible futures for global energy supply and the related CO_2 emissions. In the absence of additional policies, energy related CO_2 emissions might increase by 45% by 2040 relative to 2012 (Current Policies Scenario), but they could decline by 39% over the same period (450 Scenario) if the required emissions mitigation policies were implemented. It is important to note that the rate of nuclear expansion is highest when the objective of deep decarbonization is pursued.

2.3. NUCLEAR POWER: A LOW CARBON TECHNOLOGY

The double challenge of climate protection and increasing energy demand requires a profound restructuring of the global energy economy. The general direction is clear: the global energy mix needs to change towards environmentally benign technologies with lower GHG emissions.

The techno-economic foundation for steering the global energy transformation is the evaluation of different energy sources and technologies to understand which ones lead to lower GHG emissions and by how much. The final results of such assessments strongly depend on what is included in the underlying calculations. It is misleading to call a technology ‘zero carbon’ based only on consideration of emissions in the operational stage, while the construction of the related infrastructure or manufacturing the equipment can be GHG intensive. Therefore, in order to make an adequate comparison it is crucial to estimate and aggregate GHG emissions from all phases of the life cycle of each energy technology. This approach is called life cycle assessment (LCA). This section focuses on LCAs of power generation technologies.

Properly implemented LCAs include upstream processes (extraction of construction materials, processing, manufacturing and power plant construction), operational processes (power plant operation and maintenance, fuel extraction, processing and transportation, as well as waste management) and downstream processes (dismantling structures, recycling reusable materials and waste disposal). The estimates for each of these phases involve some uncertainty inherent in the method used. Comparing estimates for different energy technologies from many sources makes it possible to check their robustness, determining the overall ranges and the distribution of estimates within the ranges.

This section uses data from two major LCA databases (Ecoinvent [18] and NREL (the United States National Renewable Energy Laboratory) [19]), as well as estimates of the Central Research Institute of Electric Power Industry (CRIEPI) of Japan (which applies a methodology similar to Ecoinvent) [20], environmental product declarations (EPDs) [21] and other estimates published in academic literature. The aggregated results (overall ranges, interquartile ranges and medians) for different electricity technologies are presented in Fig. 3. LCA estimates presented in this section cover all GHG emissions expressed in CO_2-eq and include carbon monoxide (CO), CO_2, methane (CH_4), nitrous oxide (N_2O), trichloroethane (CCl_3CH_3), tetrachloromethane (CCl_4), nitrogen trifluoride (NF_3), halons, chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs).

According to these estimates, the highest GHG emissions are associated with fossil fuels. Coal has the highest median value among all power generation technologies (1025 g CO_2-eq/kW·h in the full range of estimates of 729–1791 g CO_2-eq/kW·h) from all sources. Lignite combustion has higher emissions on average than hard coal (1297 against 1156 g CO_2-eq/kW·h according to Ecoinvent estimates [18]). Gas is the second most important contributor to GHG emissions per unit of electricity produced, with a median estimate of 492 g CO_2-eq/kW·h (overall range is 307–988 g CO_2-eq/kW·h). Carbon dioxide capture and storage (CCS) reduces emissions from fossil technologies. Figure 3 includes combined estimates for coal and gas supplemented with CCS due to the limited number of studies. The median value is 167 g CO_2-eq/kW·h within the overall range of 34–410 g CO_2-eq/kW·h. These results make CCS more of an intermediate option between traditional fossil and renewable technologies in terms of life cycle emissions. Comparing CCS with conventional coal and gas fired power plants is difficult because the first industrial scale coal fired plant with CCS was commissioned late 2014 [11]. This means that all CCS

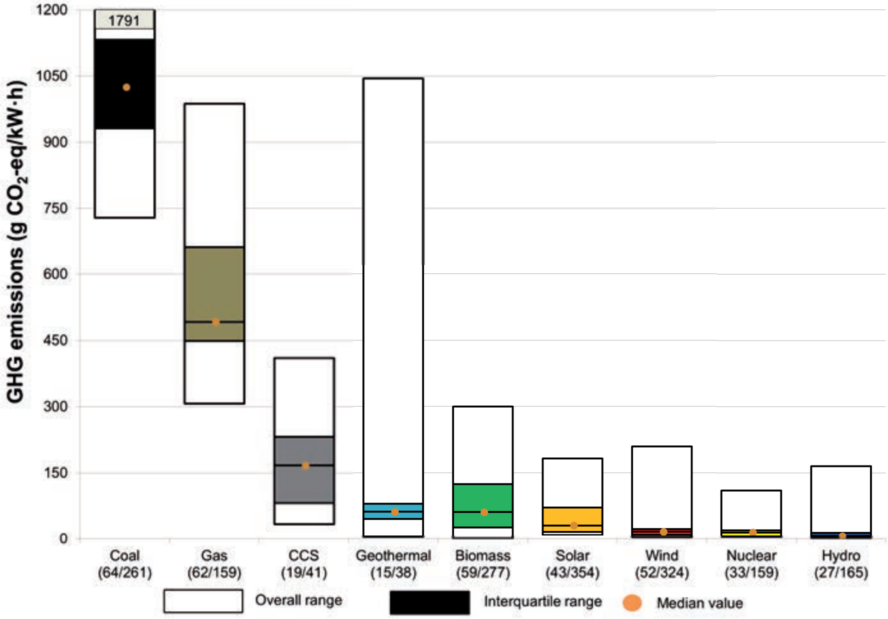

FIG. 3. Life cycle GHG emissions from electricity generation. Data source: IAEA calculations using data from Refs [18–21]. Note: The numbers in parentheses indicate the number of sources/estimates. The interquartile range includes half of the calculations around the median of the overall range. CCS — carbon dioxide capture and storage.

emissions estimates presented in Fig. 3 are based on theoretical calculations and pilot and demonstration projects. This involves a considerable degree of uncertainty when extrapolating to large industrial scale units.

Figure 4 presents life cycle GHG emissions for an extended set of renewable technologies and nuclear power. Their median GHG emissions are lower than those of fossils and CCS by an order of magnitude, making them preferred options in devising the energy mix for coming decades in order to meet global GHG mitigation goals. Geothermal (median value 62 g CO_2-eq/kW·h), biomass (61 g CO_2-eq/kW·h) and solar photovoltaic (PV) (49 g CO_2-eq/kW·h) are estimated to have relatively higher emissions in this group.

There are considerable differences within the types and across generations of technologies within the same technology groups. For example, the first generation of solar cells (crystalline silicon) has on average 50–70% higher GHG emissions than the more advanced second generation (thin film) cells. Thin film technologies, in turn, also differ, with CIGS (Copper Indium Gallium Selenide) panels showing, on average, the highest emissions per unit of electricity produced. CIGS technology is followed by amorphous silicon (a-Si)

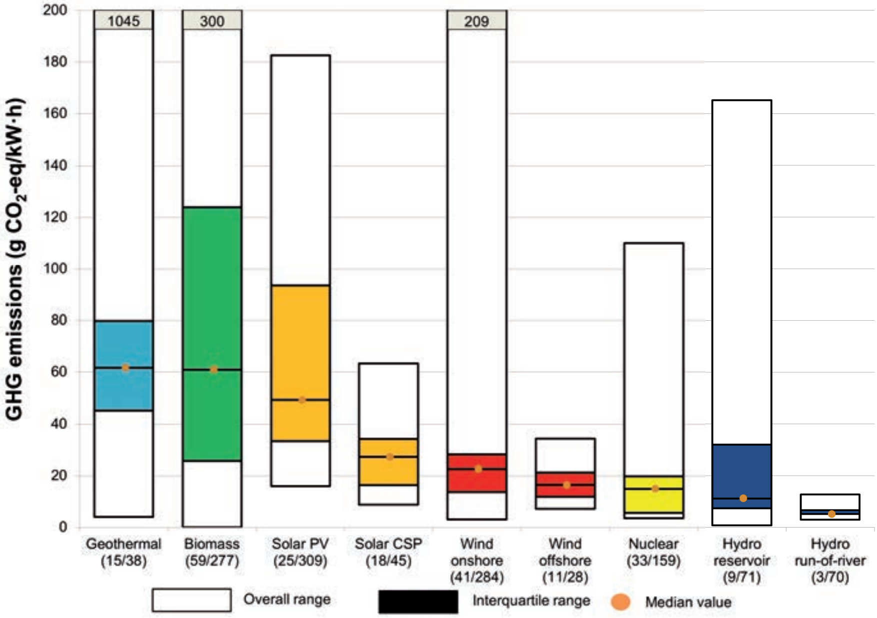

FIG. 4. Life cycle GHG emissions from electricity generation with renewable and nuclear technologies. Data source: IAEA calculations using data from Refs [18–21]. Note: The numbers in parentheses indicate the number of sources/estimates. The interquartile range includes half of the calculations around the median of the overall range. PV — photovoltaic, CSP — concentrated solar power.

and cadmium telluride (CdTe), which have the lowest life cycle emissions among thin film panels. The estimates of NREL [19] for thin film solar PVs are lower than those of Ecoinvent [18]. Within the first generation of solar PVs (crystalline silicon) lower GHG emissions are shown, on average, by monocrystalline silicon panels in comparison with the polycrystalline ones. Such variations make the choice of the most effective mitigation technology less straightforward and require additional investigations into other features of specific technologies considered for deployment. Moreover, GHG emissions per unit of electricity produced by solar PVs strongly depend on the region of deployment, with the best results in South Asia and sub-Saharan Africa (according to Ecoinvent estimates). This adds an important regional dimension to the choice of low carbon electricity sources.

According to state of the art LCAs, concentrated solar power (median value 27.3 g CO_2-eq/kW·h), wind (16.4 g CO_2-eq/kW·h), nuclear (14.9 g CO_2-eq/kW·h) and hydropower (6.6 g CO_2-eq/kW·h) have the lowest GHG emissions among the power generation technologies. Yet emissions vary within these technology groups as well. The analysis of wind power using Ecoinvent estimates [18] shows that larger wind turbines emit more GHGs per kW·h of electricity produced than smaller ones.

Despite the relatively wide ranges of life cycle estimates for some renewables (geothermal, biomass, wind and hydropower), interquartile ranges are rather narrow (except for biomass). This makes the comparison of different energy technologies by their median values an acceptable approach. Analysis of estimates published in the scientific literature clearly puts nuclear among the most climate friendly energy sources, with only hydropower showing superior results.

Long term planning of the use of different types of energy technologies, however, should also consider the prospects for technological progress. Similarly to the drop in GHG emissions from the second generation of solar cells in comparison to the first one, a significant reduction is expected for third generation (organic and plastic) cells compared to current technologies in terms of GHG emissions per unit of energy produced. Life cycle emissions from nuclear power are also anticipated to decrease further. The emissions reductions are expected to result from advancements in uranium enrichment technologies, more efficient use of the uranium fuel and longer operation time of NPPs.

2.4. GHG EMISSIONS FROM THE NUCLEAR SECTOR

Similarly to other electricity sources and technologies, nuclear fission is operated in various ways in different types of reactors and related fuel cycles. Life cycle GHG emissions from nuclear energy in general are very low compared to fossil power plants but there is some variation across types and generations of NPPs that might be important in choosing a certain type of reactor for inclusion in a low carbon energy mix. This section takes a closer look at life cycle emissions from the nuclear energy sector.

The overwhelming majority of nuclear reactors in operation around the world (85% as of March 2015) are light water reactors (LWRs) and it is very likely that this high share will remain over the next decades. Unsurprisingly, most LCA studies on nuclear energy compiled in various databases (Ecoinvent [18], NREL [19], CRIEPI [20] and the EPDs [21]) concentrate on LWRs.

According to estimates in the Ecoinvent database, median emissions from LWRs are 15 g CO_2-eq/kW·h, with the overall range of estimates between 14 and 20 g CO_2-eq/kW·h. The range of estimates in Ecoinvent is relatively narrow due to the uniform methodology used. The median value of NREL data is 12 g CO_2-eq/kW·h in a wide range of 4–110 g CO_2-eq/kW·h, although the interquartile range is relatively small at 12–25 g CO_2-eq/kW·h). The reason for this paradox is that NREL aggregates studies using different methodologies, which leads to a significant variation across the estimates. Specifically, the outlying value in the NREL range at the high end (110 g CO_2-eq/kW·h) stems from a hypothetical worst case scenario in one of the reviewed studies. Nevertheless, key parameters in these studies were harmonized, making the comparison more workable. The differences between estimates are associated with variations in measurement techniques and specific assumptions about different steps of the fuel cycle, especially mining, enrichment, and spent fuel reprocessing and treatment.

CRIEPI's analysis of the Japanese nuclear power industry places nuclear energy in the upper part of NREL's interquartile range with a median value of 20 g CO_2-eq/kW·h. In contrast, four reviewed EPDs (Axpo AG Beznau, Vattenfall Forsmark, Vattenfall Ringhals, Sizewell B) are in the lower part of the same range with a median of just over 5 g CO_2-eq/kW·h. This noteworthy difference is caused by differing assumptions about the fuel cycle steps with relatively high emissions. CRIEPI uses a methodology similar to Ecoinvent but the calculations are made for Japan in general, not specific NPPs. The estimates are based on 2009 data and the analysis focuses on LWRs with average thermal efficiency of 33.67%, 1 GW(e) installed capacity, 70% capacity factor and uranium enrichment done abroad (64% by gaseous diffusion and 36% with centrifuges). The assumed lifetime of the NPPs is 40 years.

Longer lifetime, higher share of the less energy intensive centrifuges in the enrichment process and higher capacity factors (by 15 percentage points on average) assumed in EPDs result in significantly lower GHG emissions per unit of electricity produced. Overall, the results obtained from different sources are relatively conformable. They demonstrate the robustness of existing estimates and prove that nuclear power is a low carbon energy source. Region specific analysis of the Ecoinvent data shows that the variations in GHG emissions across LWRs located in different parts of the world are negligible.

LWRs can be further divided into subgroups according to the technology used. The most important subgroups are pressurized water reactors (PWRs) and boiling water reactors (BWRs). The main questions are whether they have significantly different GHG emissions and whether the estimates are as robust across databases as the calculations for the aggregated LWR group. Ecoinvent's estimates for PWRs show an overall range of 13.5–19.8 g CO_2-eq/kW·h, with a median value of 14.9 g CO_2-eq/kW·h, while NREL's data have a much larger range of 3.7–110 g CO_2-eq/kW·h (interquartile range 6.9–33 g CO_2-eq/kW·h), with a median of 12 g CO_2-eq/kW·h. Similar calculations for BWRs show that the overall range of Ecoinvent's estimates is 14.7–17.6 g CO_2-eq/kW·h, with a median of 15.9 g CO_2-eq/kW·h, while NREL's estimates cover the range of 4.6–17 g CO_2-eq/kW·h, with a median of 13 g CO_2-eq/kW·h (see Fig. 5). The main conclusion from these results is that there are no significant

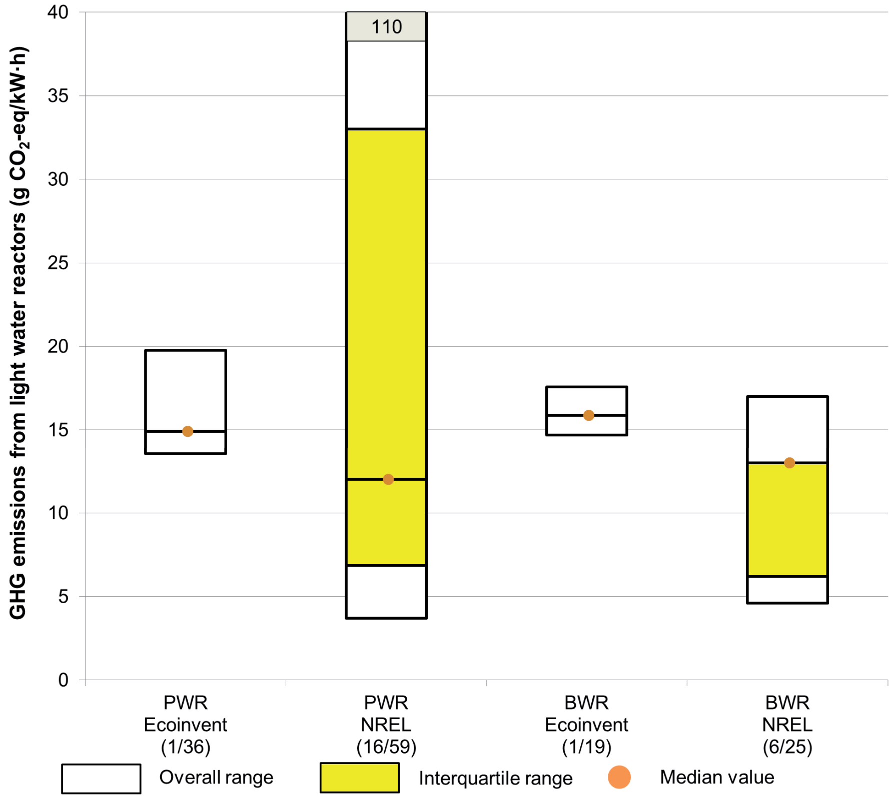

FIG. 5. Life cycle GHG emissions from different types of light water reactors. Data source: IAEA calculations using data from Refs [18] and [19]. Note: The numbers in parentheses indicate the number of sources/estimates. The interquartile range includes half of the calculations around the median of the overall range. PWR — pressurized water reactor, BWR — boiling water reactor, NREL — National Renewable Energy Laboratory.

variations in GHG emissions per unit of energy produced between subgroups of LWR technologies across different databases (as opposed to, for example, the large ranges of estimates for various types of solar PV thin film technologies — see Section 2.3).

In addition to LWR assessments, there are a few studies summarized by NREL on other, less common types of nuclear reactors, such as heavy water reactors (HWRs), gas cooled reactors (GCRs) and fast breeder reactors (FBRs). The estimates on HWRs are in the overall range of 1.7–150 g CO_2-eq/kW·h, with a median of 57 g CO_2-eq/kW·h. This extremely wide range is explained by the nature of the data sources. One of the studies provides 15 estimates with high emissions based on worst case assumptions. This shifts up the high end of the range considerably. Other studies for the same reactor type are in the range of 1.7–19 g CO_2-eq/kW·h. In general, HWRs evade the most GHG intensive steps in the fuel cycle because they do not require enriched uranium for fuel manufacturing.

The number of studies on GCRs and FBRs is limited but they provide a good understanding of the amount of GHG emissions per unit of energy produced. NREL's data about GCRs show a range of 5.1–28 g CO_2-eq/kW·h, with a median value of 6.9 g CO_2-eq/kW·h (see Fig. 6). These relatively low emissions over the life cycle of GCRs are partly due to their higher thermal efficiency, as reactor outlet temperatures can reach 850–900°C. Estimates

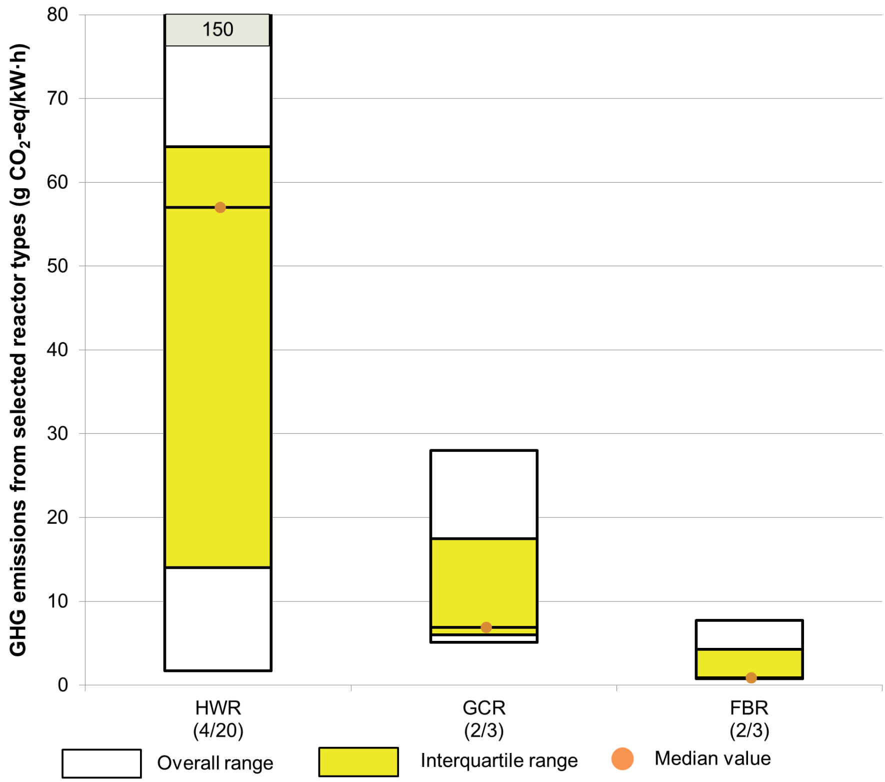

FIG. 6. Life cycle GHG emissions from different types of nuclear reactors. Data source: IAEA calculations using data from Ref. [19]. Note: The numbers in parentheses indicate the number of sources/estimates. The interquartile range includes half of the calculations around the median of the overall range. HWR — heavy water reactor, GCR — gas cooled reactor, FBR — fast breeder reactor.

for FBRs vary in the range of 0.8–7.7 g CO_2-eq/kW·h, and the median value is 0.9 g CO_2-eq/kW·h. FBRs — often seen as the technology of the future for nuclear energy — have extremely low emissions due to their specific fuel cycle attributes that minimize the emissions from mining, milling, enrichment and fuel fabrication. This places them in a more favourable position than hydropower in terms of life cycle GHG emissions.

This in-depth review of LCA results on GHG emissions from different types of nuclear reactors confirms the conclusions based on aggregate nuclear assessments about the very low emissions intensity of nuclear energy. The results are robust across estimates from various data sources for LWRs, the most widely used technology globally. The very low life cycle emissions from the FBR technology are particularly promising because they indicate that, in addition to other benefits associated with closing the nuclear fuel cycle, future reactor fleets with increasing shares of FBRs could make a significant contribution to mitigating climate change.

2.5. CONTRIBUTION TO AVOIDED GHG EMISSIONS

The energy supply of industrial societies has been dominated by fossil fuels since the late 18th century. Up to the late 1960s hydropower was the only low carbon energy source with a significant contribution to the global electricity mix. Driven by various factors, nuclear energy programmes accelerated in many countries from the 1950s on. The oil crisis of 1973 gave an additional impetus to NPP construction. As a result, nuclear energy has been steadily increasing its share in global power generation. These two power sources helped avoid large amounts of GHG emissions even before the emergence of anthropogenic climate change on the global environmental agenda.

This section presents estimates of CO_2 emissions avoided by using low carbon power generation technologies instead of fossil fuels since the 1970s by using data from the IEA [22] and the World Bank [23]. 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 in their absence by increasing 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 explicit policy objective 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 7 shows the historical trends of CO_2 emissions from the global electricity sector and the amounts of emissions avoided by using nuclear energy, hydropower 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 yellow, blue and dark orange segments of the bars show CO_2 emissions avoided by nuclear energy, hydropower and renewables other than hydropower, respectively. Out of the emissions avoided in 2012 due to the use of low these carbon energy sources, 2.96 Gt CO_2 (50.5% of total avoided emissions) was avoided by utilizing hydropower, 1.98 Gt CO_2 (33.9%) was saved by the use of nuclear energy, while other renewables allowed savings of 0.92 Gt CO_2 (15.6%).

Figure 7 reveals that the total amount of CO_2 emissions avoided by the three low carbon energy sources has changed dramatically over the last several decades. Avoided emissions amounted to just over 1.1 Gt CO_2 in 1970, mostly due to hydropower, more than doubled by 1980 to 2.3 Gt CO_2 (109% growth in a decade) and reached 3.9 Gt CO_2 (another 70% increase in ten years) by 1990. This trend continued, albeit at a slower rate, in the following decades when avoided emissions reached an estimated amount of 4.6 Gt CO_2 by 2000 (18% growth) and 5.9 Gt CO_2 in 2012 (28% increase in the period 2000–2012).

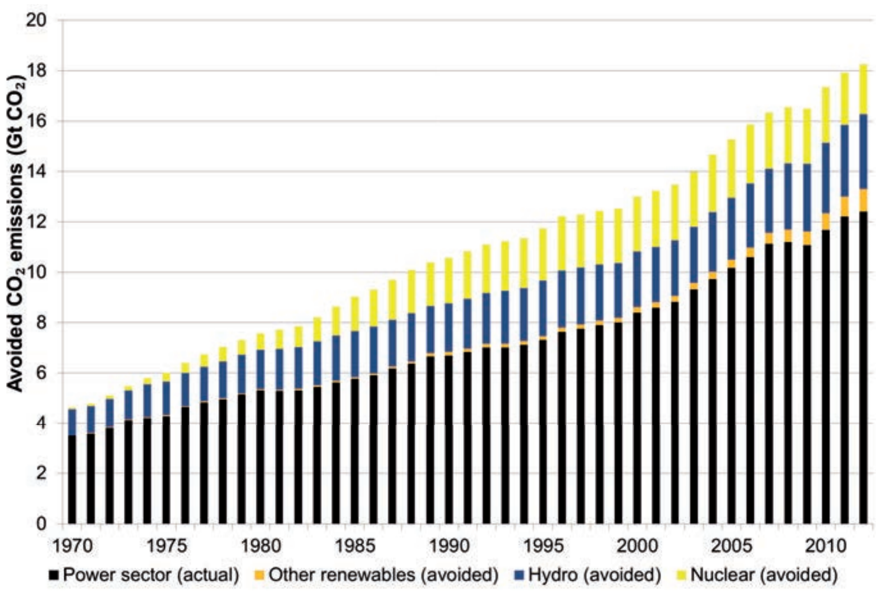

FIG. 7. Global CO_2 emissions from the electricity sector and emissions avoided by using three low carbon generation technologies. Source: IAEA calculations based on data in Ref. [22].

The above numbers indicate that the ratio of avoided to actual power sector emissions fluctuated over time, from 32% in 1970 to 43% in 1980 and peaking at 58% in 1990. After that the ratio decreased: to 55% in 2000 and 47% in 2012. This shows that in the 1970s and 1980s the amount of avoided emissions was growing faster than actual emissions in the power sector due to the fast growth of energy output supplied by low carbon sources, while in the 1990s the trend was reversed. The underlying reasons are diverse: the rapid expansion of nuclear power and the somewhat slower increase of hydropower both decelerated after 1990 while fast growing countries (especially China and India) massively increased their coal based electricity generation in the same time frame.

Over the period 1970–2012, the use of low carbon energy sources made it possible to avoid over 157 Gt CO_2 emissions in total. Hydropower accounted for 53.5% (over 84 Gt CO_2), nuclear contributed 41% (64.5 Gt CO_2) and other renewables saved 5.5% (8.6 Gt CO_2) where the contribution of the latter group was marginal until the late 2000s. Hydropower was the dominant contributor to avoided GHG emissions in the 1970s and 1980s. In the 1990s and 2000s nuclear caught up rapidly and in 2001 and 2002 it saved more CO_2 emissions than hydropower: 2.25 and 2.22 Gt against 2.18 and 2.20 Gt, respectively. This is particularly remarkable considering the fact that in 1970 hydropower saved over 13 times more CO_2 emissions than nuclear. The amount of avoided emissions from hydropower increased by less than three times over the last four decades, compared to a nearly 25-fold increase in the avoided emissions by nuclear.

Figure 8 confirms these global trends by showing shifts in CO_2 intensity of and the shares of non-fossil sources in power generation for selected countries. The estimates of avoided emissions are based on data from the IEA [22] and the World Bank [23]. The latest version of the IEA database includes information on global electricity generation up to and including 2012. Data on the shares of different renewables in electricity generation at country level are from the World Bank's World Development Indicators database [23], in which data about Brazil, the Russian Federation, India and China are not yet available for 2012. For these countries 2011 data are used.

The top scale in Fig. 8 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 or 2012, depending on the availability of data. The bottom scale measures, from right to left, the average amount of CO_2 emitted from generating 1 kW·h of electricity in the same year. The chart demonstrates that countries with the lowest CO_2 intensity (less than 100 g CO_2/kW·h, below 20% of the world average) generate around 80% or more of their electricity from hydropower (Brazil), nuclear (France) or a combination of these two (Sweden and Switzerland). The chart also shows that expanding the share of nuclear power

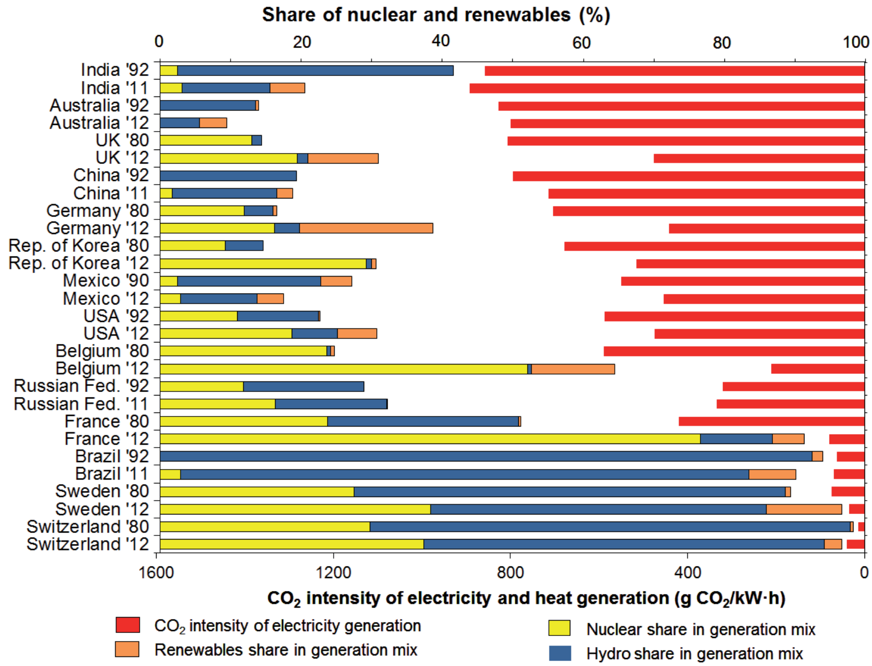

FIG. 8. Carbon dioxide intensity and the shares of non-fossil sources in the electricity sector of selected countries. Data sources: Refs [22, 23].

in the electricity mix contributed to the reduction of CO_2 intensity of the power sector in several countries (e.g. Belgium, Republic of Korea, United Kingdom (UK)) — see the difference between the 1980 and the 2012 bars in Fig. 8. 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 nuclear power 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, the latest data show that the CO_2 intensity of electricity generation in Japan increased from 416 g CO_2/kW·h in 2010 to 548 g CO_2/kW·h in 2012 (by 31.7%) as nuclear power's share of the national generation mix fell from 26% in 2010 to 1.1% in 2012 [23] and was mainly replaced by fossil fuels. In Germany, on the other hand, the 6.3 percentage point reduction of the nuclear share in the generation mix (from 22.6% to 16.3%) between 2010 and 2012 was mainly compensated by renewable sources and did not change the CO_2 emissions intensity much: it was 431 g CO_2/kW·h in 2010 and increased slightly to 441 g CO_2/kW·h in 2012. These trends support the conclusions demonstrated by Fig. 8 that electricity generation can improve its climate protection performance only if changes in the energy mix are made towards or between low carbon sources.

2.6. GHG MITIGATION POTENTIAL ESTIMATED BY THE IPCC

In estimating costs and potentials of mitigation technologies, the AR5 of the IPCC WG III evaluates life cycle GHG emissions of energy technologies, compares them on an LCOE basis and assesses their economic potentials by synthesizing results of global energy economy and integrated assessment models [24]. The assessment involves reviewing more than 1200 emissions scenarios grouped into baseline (absence of climate policy) and mitigation (specified in terms of atmospheric GHG concentration levels in 2100 spanning from 430 to more than 720 ppm CO_2-eq) scenarios. The WG III report highlights the potentially important contributions of nuclear power to mitigation on the basis of its low life cycle GHG emissions and low operating costs but evokes safety, high investment costs, waste management and proliferation concerns as possible constraints to making full use of its mitigation potential.

The integrated models assessed in the WG III report reveal a robust dynamic of increasing electrification across mitigation scenarios: the share of electricity in total final energy consumption increases from 17% in 2010 to over 30% in 2050 (medians) and to over 50% in the higher end of the stringent mitigation scenarios (see figure 7.13 in Ref. [25]). Indeed, climate policies strongly accelerate electrification due to the ample availability of low carbon generation technologies as compared to non-electric energy supply options in the rest of the energy system with limited and/or more costly mitigation options. As a result, high levels of power sector decarbonization are achieved in the majority of stringent mitigation scenarios (reaching low atmospheric GHG concentration levels between 430 and 530 ppm CO_2-eq by 2100). In these scenarios 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 33% in 2010).

Besides the stringency of climate policy, the contribution of low carbon technologies to decarbonizing the power sector is also influenced by the increase of energy demand in the future and competition with other technologies. In stringent mitigation scenarios with high energy demand, nuclear power output is projected to increase by a factor of three to four by 2050 relative to the 2010 production level (see Fig. 9). In such scenarios, a significant increase in the deployment of renewable energy sources such as solar and wind is also projected from their relatively low levels in the mid-2010s. Although optimistic, the projected role of CCS is found to vary to a high degree across the stringent mitigation scenarios due to the profound uncertainties about its future technical and economic performance. Moreover, a significant contribution of CCS to the power sector decarbonization is deemed achievable only in the presence of high carbon prices (US \$100–150/t CO_2). Thus, at lower carbon prices, nuclear and renewable energy sources assume a larger role in decarbonizing the power sector.

The role of nuclear energy in climate change mitigation policies is very sensitive to the way it is represented in the integrated models. Almost half of the models (8 out of 18) used in the Energy Modeling Forum 27 (EMF 27) [26] and assessed in the AR5 of the IPCC WG III restrict the competition of nuclear power with other options by imposing various types of arbitrary constraints on its share, growth, costs or deployment path to reflect concerns about safety, radioactive waste, proliferation and public acceptance. Furthermore, nine of the

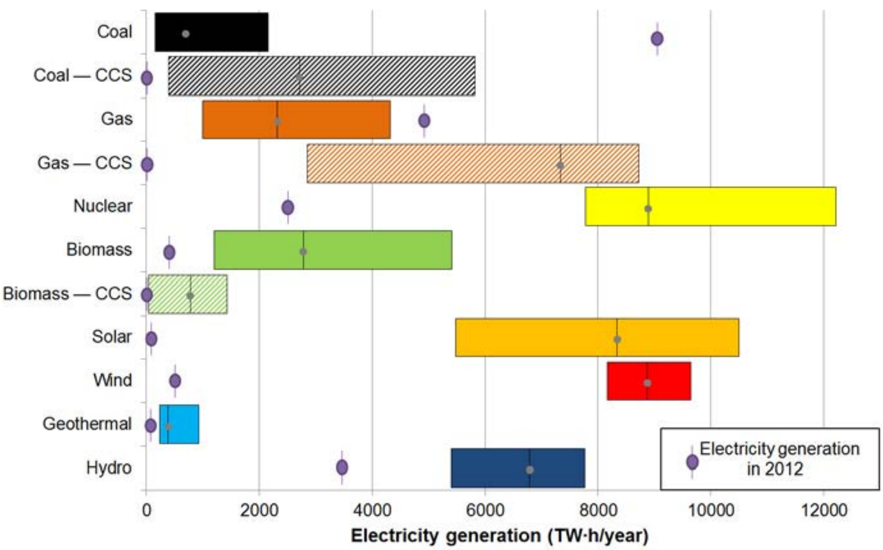

FIG. 9. Deployment of technologies for electricity generation in 2050 in scenarios assuming stringent mitigation (430–530 ppm CO_2-eq GHG concentration in 2100) and high energy demand (increase in final energy demand in 2050 by more than 20% of the demand in 2010). Source: Based on figure 7.11 in Ref. [24]. Note: For each technology the bars represent the 25th to 75th percentile interquartile deployment range, the vertical line with a dot in each bar indicates the median. CCS — carbon dioxide capture and storage.

assessed models have explicit uranium resource constraints, although only few models consider advancements in reactor types (alternatives to LWRs) or in fuel cycle (alternatives to once through) that, in the longer term, will significantly reduce the need for fresh uranium [27]. A more detailed representation of nuclear power in these models would greatly benefit the analysis of its potential role in mitigating GHG emissions.

Based on the EMF 27 study, the report of WG III also discusses the impacts of low carbon technologies on aggregate global economic costs. Figure 10 shows that in the absence or under limited availability of mitigation technologies (such as bioenergy, CCS, their combination (bioenergy with CCS (BECCS)), nuclear, wind and solar), mitigation costs increase substantially. The magnitude of the cost increase depends on the GHG concentration target and the related stringency of mitigation (higher for the 450 than for the 550 ppm CO_2-eq target) as well as on the technology considered. The limited availability or unavailability of CCS and bioenergy leads to the strongest increase in mitigation costs [28] because they are the main options for decarbonizing non-electric energy use. Their

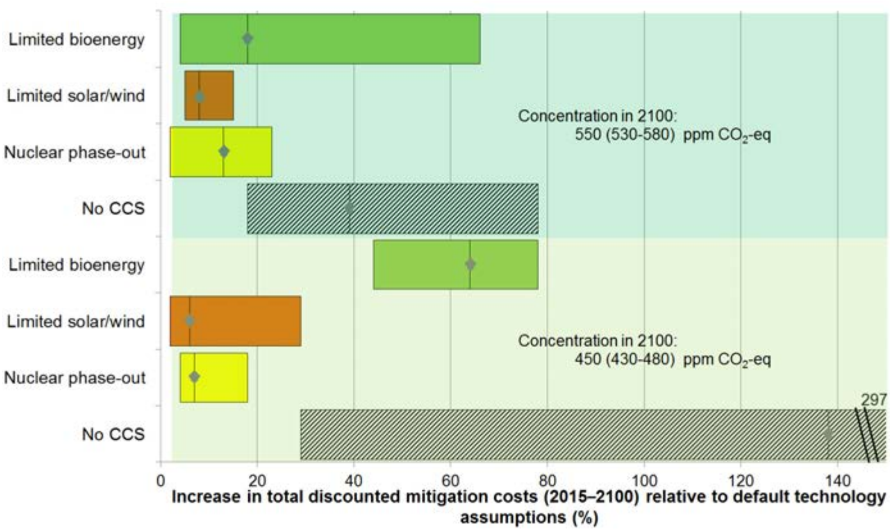

FIG. 10. Increase in global mitigation costs due to limited availability of selected technologies. Source: Based on data in table SPM.2 in Ref. [30]. Note: The bars represent the 16th to 84th percentile range; the vertical line with a dot in each bar indicates the median. No CCS: CCS is excluded in these scenarios; Nuclear phase-out: no addition of nuclear power plants beyond those under construction, operation of existing plants until the end of their lifetime; Limited solar/wind: maximum 20% of global electricity is provided by solar and wind power in any year; Limited bioenergy: maximum 100 exajoules (EJ)/year modern bioenergy supply globally. CCS — carbon dioxide capture and storage.

limited availability or unavailability requires more emissions reductions up to 2050 because negative emissions from BECCS will not be possible in the second half of the century and because higher rates of electrification and/or adoption of hydrogen technologies will be needed in sectors such as transport and industry. In contrast, limited availability of the three truly low carbon electricity generation options — nuclear power, wind and solar — leads to a relatively modest increase in mitigation costs of less than 20% due to the substitutability among numerous alternatives to generate low carbon electricity. However, caution is in order when interpreting these results for at least two reasons:

- In this type of analysis the role of low carbon technologies in providing electric and non-electric energy is one of the major factors explaining the impacts of technology constraints on the mitigation cost. In this sense, the effect of limiting the contribution of nuclear power on the total mitigation cost is not directly comparable to the cost effects of constraining technologies also used beyond power generation such as CCS, which is used in energy supply for transport and industry as well [27].
- In the EMF 27 study, the role of nuclear energy is limited to providing electricity. Although its applications beyond the power sector are well recognised, they are rarely included in modelling exercises. Nuclear energy can be used for hydrogen production to power fuel cells in order to replace contemporary internal combustion engines in transport. Other possible and already existing applications include nuclear desalination and district heating, usually combined with electricity generation [29]. Including these non-electric applications in the models by a more detailed representation of nuclear energy might greatly increase the value of nuclear energy in mitigating emissions.

The WG III report also discusses the delays in implementing climate change mitigation that affect the timing of the deployment of nuclear power and other low carbon technologies. In 2012, the combined contribution of wind, solar, geothermal and bioenergy to global electricity generation was 5%. As of March 2015, only one industrial scale (110 MW(e)) coal power plant with CCS is in operation. In stringent mitigation scenarios, most models project dramatic near term changes (before 2020) in the global energy system with significant increases in renewables and CCS. It is exactly the potential future limitations (e.g. related to system integration issues for renewables and restricted regional storage capacities for CCS [31, 32]) of these low carbon technologies that raise the interest in the expanded use of nuclear energy [27] and in its mitigation potential in some countries. For instance, a study analysing the impacts 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 built [33]. The higher end of this range, explained by the non-availability of CCS technologies, would be unique in history, but is conceivable.

The IPCC AR5 confirms that nuclear power clearly belongs to the set of options to reduce GHG emissions. Nuclear energy can help reduce total mitigation costs. The magnitude of cost reduction depends on the stringency of climate policy, the competition among potentially cost effective low carbon alternatives, nuclear's operational improvements and its applications beyond the power sector. Aside from the economic factors, however, 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.

2.7. CONTRIBUTION TO GHG MITIGATION ACCORDING TO THE IEA

The IEA analysis gives emphasis to short and middle term opportunities for action in the energy sector. The IEA policy recommendations are based on several scenarios which differ in their assumptions about the evolution of governmental action to address energy and climate change challenges. The central IEA scenario, the New Policies Scenario, takes account of broad policy commitments and plans that have been announced by countries, on a case-by-case basis, including national pledges to support the deployment of renewable energy, decisions to expand or phase out nuclear power, pledges to reduce GHG emissions and plans to phase out fossil energy subsidies, even if the measures to implement these commitments are yet to be identified or announced.[2] The New Policies Scenario paves the way for a long term increase in global temperature of about 3.5°C (Table 1).

Two alternative policy scenarios depict the impacts of incremental levels of ambition to get closer to the Copenhagen target of less than 2°C increase in global mean temperature [34]. These scenarios hinge on a careful representation of national climate mitigation and adaptation pledges to the UNFCCC ADP, the Intended Nationally Determined Contributions (INDCs), and a few concrete measures. The INDC Scenario is framed by the date of every domestic INDC (e.g. 2025 or 2030).[3] The Bridge Scenario assumes additional measures beyond

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[2] The IEA elaborates another purely illustrative scenario, the Current Policies Scenario, which depicts how global energy markets would evolve without policy intervention from the mid-point of the year of publication.

[3] As the process of making pledges for COP 21 is still evolving, the IEA plans to provide an update of the climate analysis in November 2015 that will incorporate potential revisions or additions to INDCs at that time.

TABLE 1. OVERVIEW OF IEA CLIMATE SCENARIOS *(data sources: Refs [11, 34]).*

		New Policies Scenario	INDC Scenario	Bridge Scenario	450 Scenario
Climate variables					
Indicative long term temperature increase (°C)		+3.6	+3.5	+2.8	+2
CO_2 emissions in 2030 relative to 2013 (%)	Global	+13%	+8%	–4%	–21%
	Power gen.	+7%	+0%	–21%	–47%
World electricity final consumption (Mtoe)	2020	1628	2004	1938	1929
	2030	2466	2432	2240	2220
	2040	2930	n.a.	n.a.	2196
Fuel shares in global power generation (%)	2020	63%	62%	61%	61%
Fossil fuels	2030	58%	56%	50%	43%
	2040	55%	n.a.	n.a.	30%
	2020	12%	12%	12%	12%
Nuclear power	2030	12%	12%	13%	16%
	2040	12%	n.a.	n.a.	18%
	2020	26%	26%	27%	27%
Renewables	2030	30%	32%	37%	41%
	2040	33%	n.a.	n.a.	51%
Cumulative nuclear capacity additions (GW)	2014–2025	157	157	157	182
	2026–2040	222	222	222	323
Nuclear installed capacity (GW)	2025	489	490	490	529
	2030	543	542	542	660
	2040	624	n.a.	n.a.	862

n.a.: not applicable

those of the INDC Scenario to cut energy consumption and related CO_2 emissions further. The proposed measures form a basket of proven policy practices based on existing and commercially viable technologies that can readily be adopted in any country. These measures include:

— Increasing energy efficiency in the industry, buildings and transport sectors;
— Gradual phase-out of fossil fuel subsidies to end users in most regions by 2030;
— Limiting the use and construction of inefficient coal fired power plants;
— Raising investments in renewable energy to US $400 billion in the power sector by 2030;
— Minimizing methane emissions in upstream oil and gas production.[4]

Finally, the 450 Scenario illustrates how the 2°C target can be reached. This scenario builds upon a different approach as it rests on a prescribed time path of GHG emissions and increases the ambition of policies in place or announced.

Global primary energy use rises at 1.1%/year in the New Policies Scenario while electricity needs — mainly pulled by large, fast growing emerging economies — see the fastest growth of the main energy carriers at 2.1%/year. The global power generation mix remains largely dominated by fossil fuels, in particular by coal fired power plants, which still generate 30% of the total electricity in 2040. Global investments in nuclear power expand in this scenario but remain concentrated in just a few regulated markets or in markets where government owned entities build, own and operate plants such as China, France, India and the Russian Federation. Installed nuclear capacity grows by 95 GW(e) within the next decade but two-thirds of the total capacity additions are constructed only after 2025. China alone accounts for almost two thirds of global growth in nuclear capacity in the New Policies Scenario, and overtakes the USA as the largest user of nuclear power around 2030. Despite many new builds, nuclear power accounts for only around 10% of the electricity generation in China at that time. Renewables capacities, predominantly hydropower and wind, benefit from strong government support in China and account for the majority of new generating capacity.

Globally, the progressive decoupling between economic activity and energy use translates into a moderate slowdown in the growth rate of CO_2 emissions (see Fig. 11). Nuclear energy is the second largest source of low carbon electricity generation worldwide after hydropower. According to IEA estimates, global energy related CO_2 emissions would have been 5% higher in 2012 in the absence of nuclear power. The historical role played by NPPs to decarbonize the global electricity mix extends to 2040 in the New Policies Scenario: 6% of energy

[4] The degree of policy implementation is determined so as to leave economic growth unaffected: the cost of mothballing inefficient coal power plants, of enhancing methane emission abatement or adopting energy efficient appliances is offset by the reduction of energy bills for households and private companies that switch to more efficient appliances or electrical equipment.

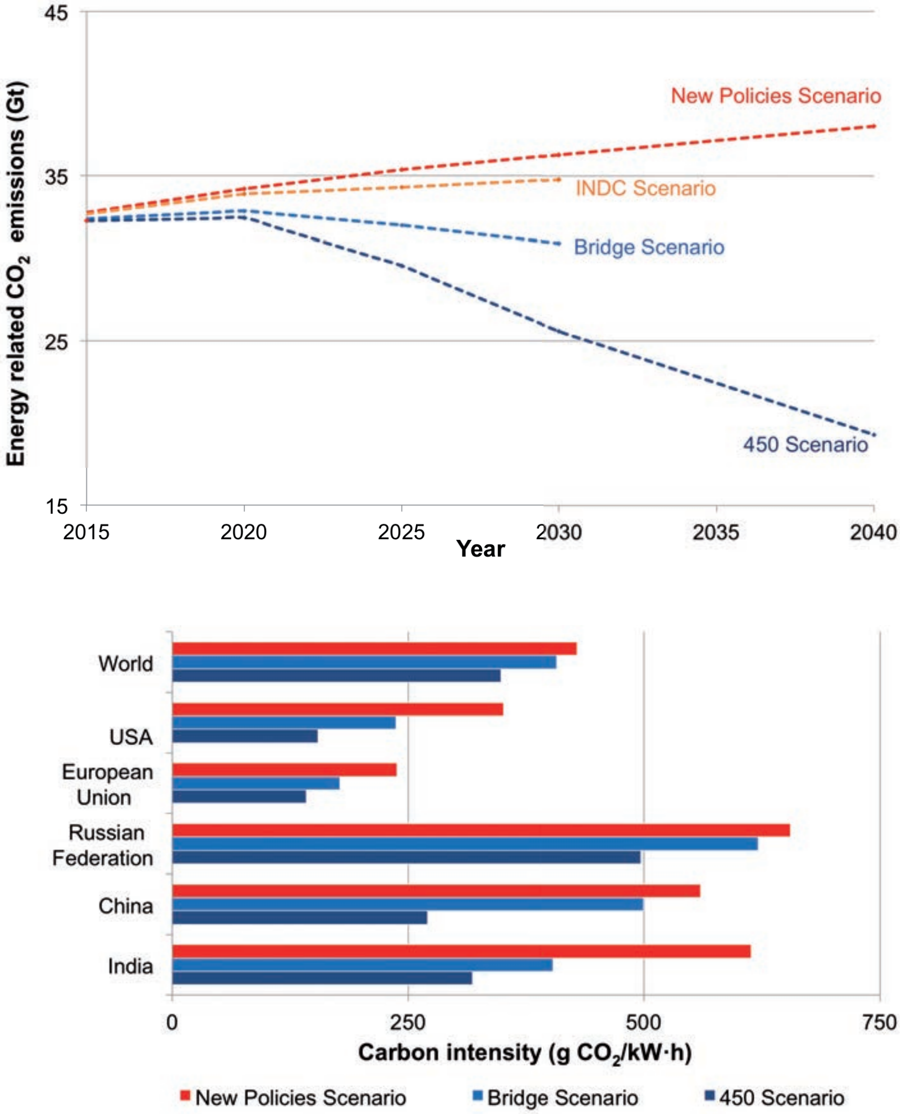

FIG. 11. Global energy related CO_2 emissions (upper panel) and carbon intensity of the power sector for selected countries in 2040 (lower panel). Data sources: Refs [11, 34]. INDC — Intended Nationally Determined Contributions.

related emissions or 14% of power sector emissions are avoided due to the expansion of nuclear capacity worldwide [11].

The INDC Scenario and the Bridge Scenario chiefly rely on enhancing measures to save energy and promote renewable sources, and do not assume further stimulation for nuclear constructions. Without additional support for nuclear development and in the absence of strong CO_2 price signals implemented domestically, no additional nuclear capacity is foreseen relative to those in the New Policies Scenario.

With a view to the public good nature of global climate protection, the national decarbonization goals depicted in the INDC Scenario fall short of sufficiently restraining global GHG emissions. By 2040, global CO_2 emissions remain 8% higher than the emission level in 2013. The rate of increase in demand for energy is declining but non-OECD countries continue to rely on coal usage for power generation. Similarly, the effective implementation of the proposed measures in the Bridge Scenario has a more profound impact by possibly peaking global GHG emissions by around 2020. In this scenario, energy saving measures, particularly those implemented in China, allow for almost half of the additional cuts in GHG emissions relative to the INDC Scenario. Another key difference between the INDC and the Bridge scenarios is the reduction in coal related emissions that helps save 2.5 Gt CO_2 in 2030 because of reduced electricity demand, fostered renewable deployment and improved coal efficiency. With adequate support, there is thus room for deploying nuclear power faster, particularly in countries without nuclear power today. This could complement the environmental benefits of more efficient vehicles as well as efficient electrical appliances for water and space heating in the buildings sector and industries. Nuclear power might be a competitive option in countries relying extensively on expensive coal and natural gas imports, and can moderate the increase in electricity prices faced by households and businesses.

Incentivizing the wide scale adoption of energy efficient equipment and vehicles and tapping their full potential is the prime component of the policy package necessary to limit the increase of global mean temperature to 2°C over the long term. About 45% of the total emissions abatement achieved in the 450 Scenario stems from energy efficiency improvements in industrial processes and the systematic adoption of electrical appliances matching best efficiency standards in the buildings sector. This scenario entails a large reduction of demand for fossil based energy worldwide that reduces fossil fuel prices (to around 20–30% lower relative to those in the New Policies Scenario in 2040). An effective carbon pricing scheme is necessary in the power sector and in industries of major regions to compensate for reduced fossil fuel prices and disincentivize the wasteful use of fossil energy. By 2040, CO_2 prices in the 450 Scenario reach US \$140/t CO_2 in the power sector and industry in OECD countries and US \$125/t CO_2 in China. Decarbonization is only possible via a massive deployment of every emerging low carbon energy source, including electric vehicles and CCS equipped fossil fuel power plants, enabled by technological progress and cost reductions. Strict demand side management of electricity, reducing generation capacity needs, and a switch to low carbon alternatives result in a 44% cut in the carbon intensity of the power sector globally, although there are differences in the required levels of effort across countries. By 2030, carbon intensity of electricity generation in the USA needs to be reduced by almost 60% to catch up with European or Japanese levels of about 150 g CO_2/kW·h, half the global average. It reaches 50 g CO_2/kW·h a decade later. (Carbon intensity here refers to direct emissions only and is thus lower than intensity derived from life cycle emissions.) The required rates of carbon intensity improvement are similar in China or India but the levels remain in the range of 300 g CO_2/kW·h in 2030. The decarbonisation of the power sector in China is fostered only after 2030 and attains American or European levels by 2040. Nuclear power plays a key role in additional climate change mitigation with an acceleration of nuclear constructions by 45% after 2025. In the 450 Scenario, nuclear capacity in 2040 more than doubles to 862 GW(e) relative to the New Policies Scenario. Further nuclear expansion beyond 2040 is needed to achieve full decarbonization of the power sector while meeting ever rising electricity needs [17].

2.8. CONTRIBUTION TO ENERGY SUPPLY SECURITY

Beyond its contribution to reducing GHG emissions, nuclear power can also enhance energy supply security. Energy security is delineated here according to the IEA definition as the uninterrupted availability of energy sources at an affordable price [35]. The energy security benefit of nuclear power stems from its technological characteristics, which are markedly different from those of fossil fuels and intermittent renewables and help nuclear avoid problems of those energy sources to a significant extent.

In comparison with fossil fuels, nuclear power uses incomparably smaller physical amounts of fuel due to the high energy density of its fuel: 1 kg of uranium can produce 50 000 kW·h of electricity, while 1 kg of oil produces about 4 kW·h and 1 kg of coal only 3 kW·h (differences of four orders of magnitude). This entails considerably lower fuel transportation costs for nuclear. For energy security it means that the supplies of uranium are less vulnerable to possible instabilities that may arise in regions along the transport route for supplies. The small amounts of uranium fuel needed for nuclear energy producers allow them to establish national reserves at reasonable costs. 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 [11], while countries operating nuclear power can create fuel reserves covering their needs for a much longer period at a far lower 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 [36]. Good progress is also being made on the establishment of an IAEA Low Enriched Uranium Bank approved by the Agency in December 2010. Such mechanisms to assure supply are expected to provide eligible IAEA Member States with low enriched uranium necessary for fuel fabrication 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. Lower fuel price volatility is an additional benefit of nuclear energy, albeit a relatively small one because uranium and fuel costs amount to only a minor share (about 5–8%) of the price of electricity produced. Therefore, fuel price variations cannot fundamentally change the price of electricity.

Renewable technologies (hydropower, wind, solar) do not face the risk of interruptions in fuel supplies, making them somewhat similar to nuclear power. The difficulty associated with their prospective major expansion in the first half of the twenty-first century forecasted by the IEA [11] is not in making reserves of energy sources but in creating storage for the produced energy. The reason is intermittency: in contrast to the dispatchable technologies powered by fuels (nuclear or fossils) with guaranteed energy output allowing long term planning, some renewables depend on unpredictable variations in natural conditions, such as windiness and insolation. Considering the fact that large scale storage of electricity is not yet affordable, this creates a significant challenge for the stable and reliable functioning of the power grid. In order to close the gap between demand and unstable supply, alternative energy sources are needed. Normally, these are thermal power plants (as the output of NPPs cannot change fast enough to balance the variations in wind or solar outputs), paradoxically increasing the importance of fossils fuels.

It follows that in order to secure the dependability of electricity supply in systems using significant shares of intermittent renewables, such systems will have to include a substantial share of power plants fuelled by coal or gas. This reduces their environmental benefits significantly below the levels estimated by LCAs of various solar and wind technologies (see Section 2.3). Therefore, at the current level of development of energy storage technologies, power systems relying heavily on intermittent renewables will not only be subject to less stable supply but will also face the energy security threats associated with fossil fuels. Moreover, in terms of operational and environmental benefits, such systems are characterized by the inefficiency of fossil fuel power plant operation due to the unpredictable and abrupt changes in their required output. Though their ability to change output quickly makes them preferential options in comparison with nuclear, it leads to an inevitable trade-off in the form of significant N_2O emissions that are hard to control under changing power rate regimes. The magnitude of such environmental penalties is not yet clear but, according to a study of the US National Energy Technology Laboratory (NETL), reductions in N_2O emissions in energy systems with a 20% share of wind or solar PV are only 30–50% of those estimated by ignoring the fossil fuel backup. In the worst case scenarios, emissions of N_2O from such systems can actually increase by 2–4 times [37].

Nuclear power is not subject to these interrelated energy security and environmental trade-offs characterizing fossil fuels and intermittent renewables. Additionally, there is a geopolitical dimension of energy security associated with nuclear energy. Uranium resources are spread across five continents and are available to satisfy the needs of the global economy in abundant quantities. There is little or no likelihood of any uranium producing country or region gaining a monopoly. About 35% of global uranium resources are located in OECD countries. Australia alone holds 23% of global resources, and around one quarter of the resources are located in Eurasia, alongside significant resources in Africa and Latin America (see Fig. 12). Reported uranium production is also dispersed across many countries (see Fig. 13). Owing to the geographical dispersal 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.

The factors determining the energy security of nuclear energy nowadays — globally even distribution of reserves, limited transportation and logistics risks as well as the possibility to keep stockpiles at national and international levels — are likely to remain in place for the foreseeable future. Moreover, the prospective level of energy security associated with nuclear power is likely to increase due to technological advancements, such as the diversification of fuel sources (introduction of thorium on an industrial scale) and the implementation of the closed fuel cycle, which should dramatically decrease the need for fresh uranium [36].

2.9. NON-CLIMATIC ENVIRONMENTAL AND HEALTH BENEFITS

The use of nuclear energy has benefits that go far beyond climate change mitigation. It has a wide range of other environmental and health benefits at local, regional and global scales such as reducing the emissions of air pollutants

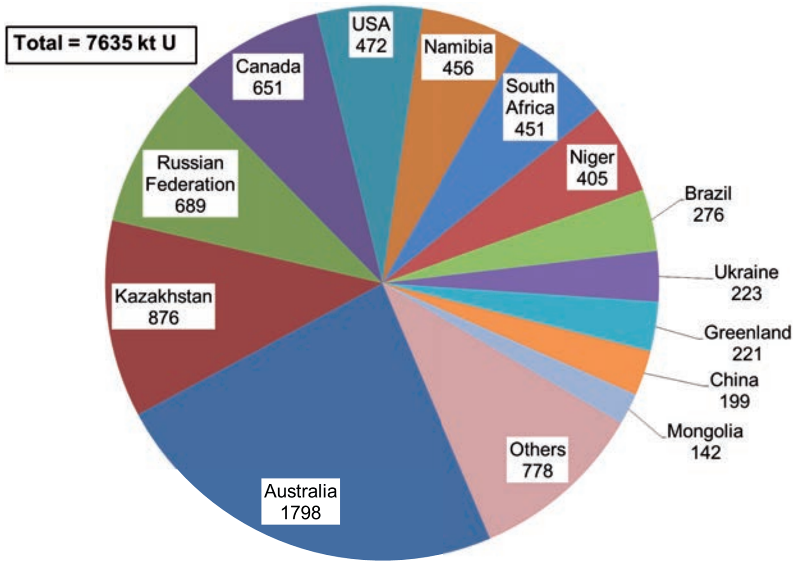

FIG. 12. Reported uranium resources in 2013. Data source: Ref. [38]. Note: The difference between the total given and the sum of the individual values is due to rounding.

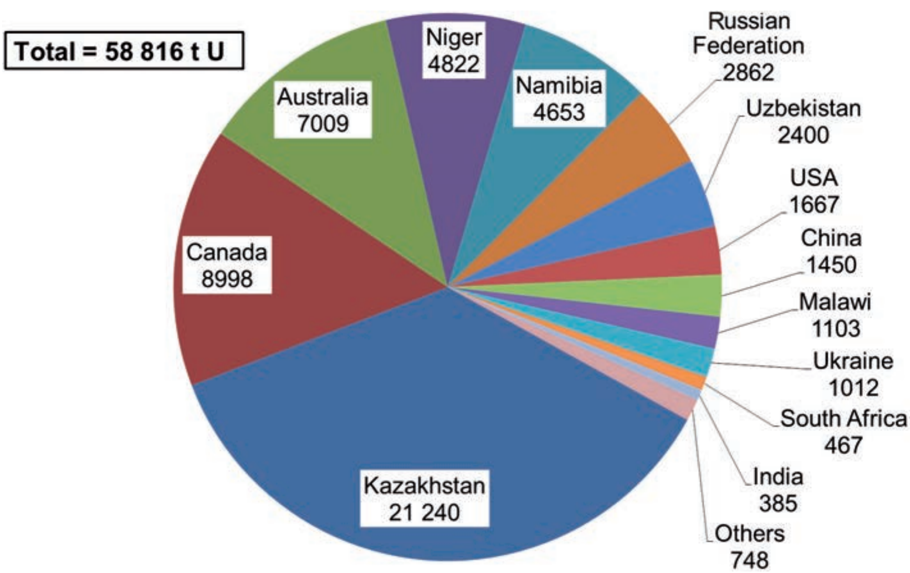

FIG. 13. Reported uranium production in 2013. Data source: Ref. [38]. Note: The difference between the total given and the sum of the individual values is due to rounding.

(see section 2.9 about acidification potentials of emissions from power generation technologies in Ref. [4]) and ozone depleting substances (ODSs), along with the associated negative impacts on human health.

The latest scientific evidence establishes a strong 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 [39]. NPPs emit virtually no air pollutants during their operation, while fossil fuel power plants are among the major contributors to air pollution. According to the latest World Health Organization (WHO) estimates, around 7 million people died as a result of outdoor and indoor air pollution exposure in 2012 — one in eight of total global deaths. The new WHO findings are more than twice as high as previous estimates and confirm that reducing air pollution could save millions of lives [40].

The need to protect human health and the environment against adverse effects resulting from ozone layer depletion was the driving force of establishing the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987. Overexposure to ultraviolet (UV) solar radiation has a range of serious health effects. It leads to more severe sunburn and large increases in skin cancer. According to a recent study, restrictions on emissions of ODSs will prevent up to two million skin cancer cases yearly by 2030 (14% fewer cases per year) [41]. UV radiation is also known to damage the eye’s outer tissues and to cause significant increases in some subtypes of cataracts as well as to cause immunosuppression in humans. Additionally, increased UV radiation harms the growth of crops and damages marine phytoplankton [42].

Electricity generation is responsible for emitting a certain amount of ODSs — i.e. substances with halogen atoms (such as CFCs, HCFCs, halons) — though it is not a major source. ODSs are widely used in fire extinguishers, refrigerators and air conditioners, as well as in solvents for cleaning and many other applications.

Emissions of ODSs in electricity generation stem from certain stages of the life cycle. The Ecoinvent database [18] contains up to date life cycle inventory data about the emissions of ODSs from the power sector. Figure 14 presents ODS emissions from fossil, renewable and nuclear power technologies in μg CFC-11 equivalent per kW·h (μg CFC-11-eq/kW·h) of electricity generated. The chart demonstrates that nuclear power is among the electricity generating technologies with the lowest ozone layer depletion potential.

A key aspect of sustainable development is the depletion of non-renewable natural resources. A commonly used indicator to measure the resource implications of an economic activity is the abiotic resource depletion potential (ARDP). It refers to the depletion of natural — mineral and fossil fuel — resources such as iron ore, coal, crude oil and others. The ARDP is estimated

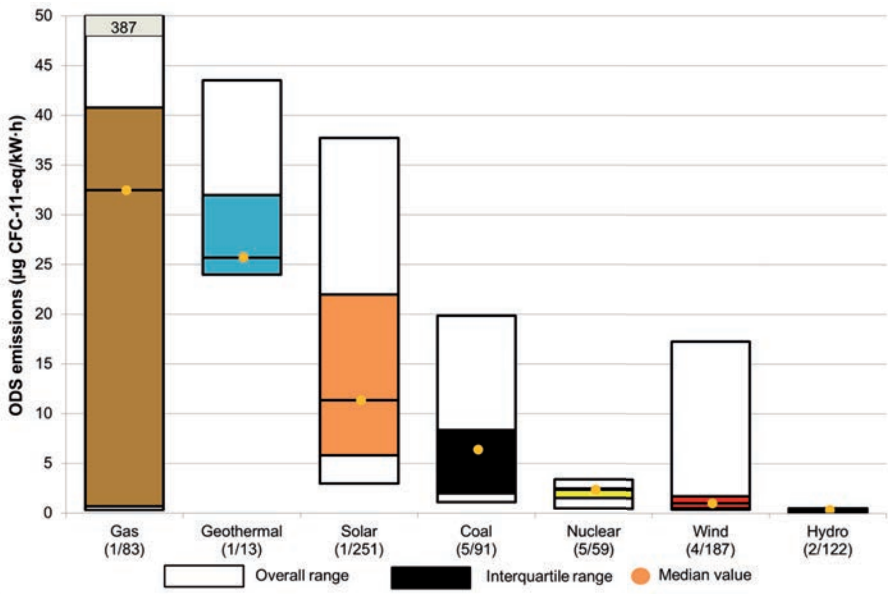

FIG. 14. Life cycle ODS emissions from electricity generation. Data source: IAEA calculations using data from Ref. [18]. Note: The numbers in parentheses indicate the number of sources/ estimates. The interquartile range includes half of the calculations around the median of the overall range. ODS — ozone depleting substance.

for each extraction of minerals and fossil fuels by taking the ratio Production/ (Ultimate Reserve)^2 divided by the ratio Production/(Ultimate Reserve)^2 for a reference resource (antimony) and then multiplying the ratios by the quantity of the resources used and aggregating them. The reference unit for abiotic depletion is kg antimony equivalent (kg Sb-eq). Figure 15 presents the depletion potential of electricity generation technologies in g Sb-eq/kW·h. The indicator refers to the commercially available reserves. Nuclear, wind and hydropower have ARDPs considerably lower than fossil fuels and somewhat lower than other renewables (solar and geothermal).

Using currently available technologies, electricity generation causes costs and benefits for economic agents other than producers and consumers of electricity. These costs stem from a range of environmental impacts of electricity production and distribution but they are not reflected in the price of electricity, hence they are called external costs. The latest analysis of such external costs in the European Union (EU) shows that damages during normal operation (without accidents) occur due to impacts on human health, biodiversity, crop yield losses, material damage and land use [43]. Figure 16 presents the estimated average monetized external costs in the EU in 2025 for a range of electricity generation technologies,

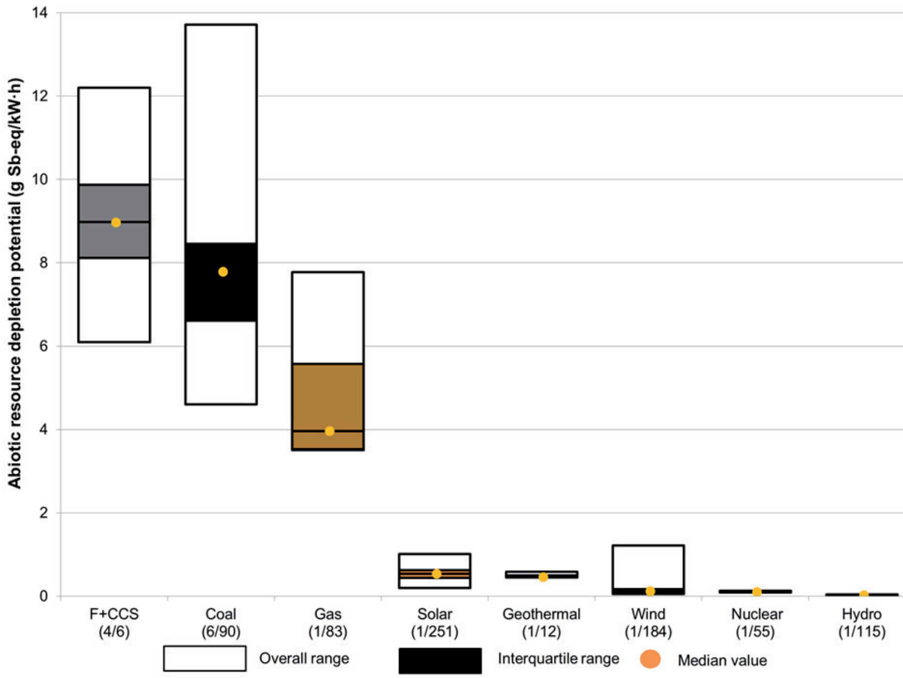

FIG. 15. Life cycle abiotic resource depletion potentials of electricity generation technologies. Data source: IAEA calculations using data from Ref. [18]. Note: The numbers in parentheses indicate the number of sources/estimates. The interquartile range includes half of the calculations around the median of the overall range. F+CCS — fossil with carbon dioxide capture and storage.

from highest (left) to smallest (right). Climate change externalities are excluded. The estimates are in year 2000 Euro cents/kW·h.

A recent study [44] estimates the external costs of wind based electricity augmented by natural gas combined cycle power plants to be higher than those of nuclear, even if the external costs of catastrophic nuclear accidents with impacts similar to those of the Chernobyl and Fukushima accidents are included. The focus of the study is on countries with a well-established safety culture (Canada, EU member states, Japan, Republic of Korea, Taiwan (China) and the USA). Under the central set of assumptions, total external cost of nuclear, related to both normal operation and an accident situation, amount to 0.0079 €/kW·h, while those of nuclear substitutes are estimated at 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.

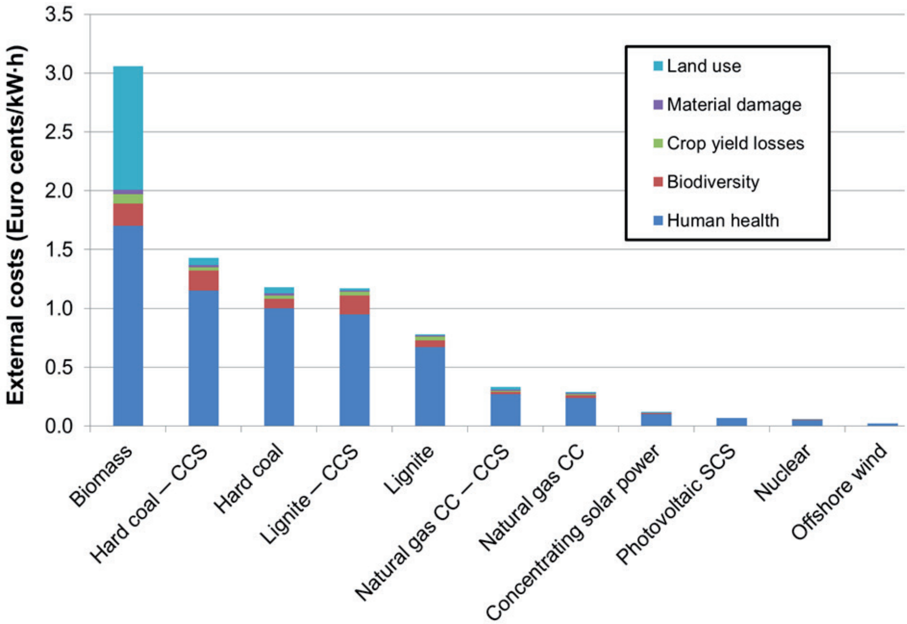

FIG. 16. Estimated average external costs in the EU for selected electricity generation technologies in 2025. Data source: Ref. [43]. Note: CCS — carbon dioxide capture and storage, CC — combined cycle, SCS — single-crystalline silicon.

Economic theory suggests the internalization of externalities as a way to improve socioeconomic welfare. From a normative perspective, possibilities to internalize externalities include imposing a tax on the activity generating a negative externality, or establishing technology standards, tradable emissions permits or other policy instruments. Accounting for external costs and benefits from electricity generation in practice can make a significant difference between private and social costs and thus orient investors' decisions towards environmentally benign technologies.

Nuclear and renewable (except biomass) power generation have considerably lower external costs than fossil fuels. The nuclear industry has already internalized the bulk of its potential external costs through safety and environmental regulation. Policies to include all external costs of all technologies in electricity prices would allow the economic and environmental benefits of nuclear power 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 IMPACTS OF NUCLEAR ENERGY

Improving economic well-being of citizens is a key priority in most countries. Nuclear power belongs to the energy options that involve large upfront capital costs (see Section 3.3). Yet these investments tend to trickle down to other sectors in the economy such as construction, manufacturing and services, thus generating economic growth and creating new employment. Apart from energy security and climate change mitigation potential, nuclear power can thereby make a significant contribution to a country's economic development.

Empirical evidence about the relationship between nuclear investments and economic growth is emerging, although some conflicting results were reported in the past. An econometric analysis — based on a large dataset including 16 countries for 1980–2005 — has revealed the role of nuclear energy in boosting long term economic growth in the analysed countries [45]. A 1% increase in nuclear energy production and consumption would increase real GDP by 0.32%, according to this study. In comparison, the impact on GDP resulting from investments in real gross fixed capital is significantly lower (0.17% only).

By including more countries and energy technologies in the analysis than previous research, a more recent econometric study confirmed these findings on the nuclear energy–economic growth nexus [46]. Based on panel data covering 17 countries — both developed and developing — over the period from 1990 to 2011, the results lend support for the so-called 'feedback hypothesis' that maintains that energy policies aimed at increasing production and consumption of nuclear energy have a positive impact on economic growth, though at a smaller rate compared to the earlier study. A 1% increase in nuclear consumption would increase GDP by 0.18% on average in all countries investigated. At the country level, positive impacts are reported for Belgium, Finland, Hungary, India, Japan, Spain, Switzerland and the UK, with statistically significant values ranging from 0.17% to 0.43%. In contrast, the feedback hypothesis is not supported by the panel data for investments in renewable technologies. According to the authors, measures to reduce renewable energy consumption are not likely to have an adverse effect on economic growth at the global scale. Notwithstanding, the feedback hypothesis is confirmed for renewables in some countries [46]. Figure 17 presents impacts of the production and consumption of nuclear energy and renewables on GDP growth globally and for 17 countries in the period 1990–2011. The figure also shows the statistical significance of the estimates. The effect is said to be significant if the null hypothesis — i.e. the estimated coefficient is equal to zero — is rejected. Different thresholds (1%, 5% and 10% levels) define the probability at which this hypothesis can be rejected or accepted. The effect is not statistically significant if the null hypothesis is accepted.

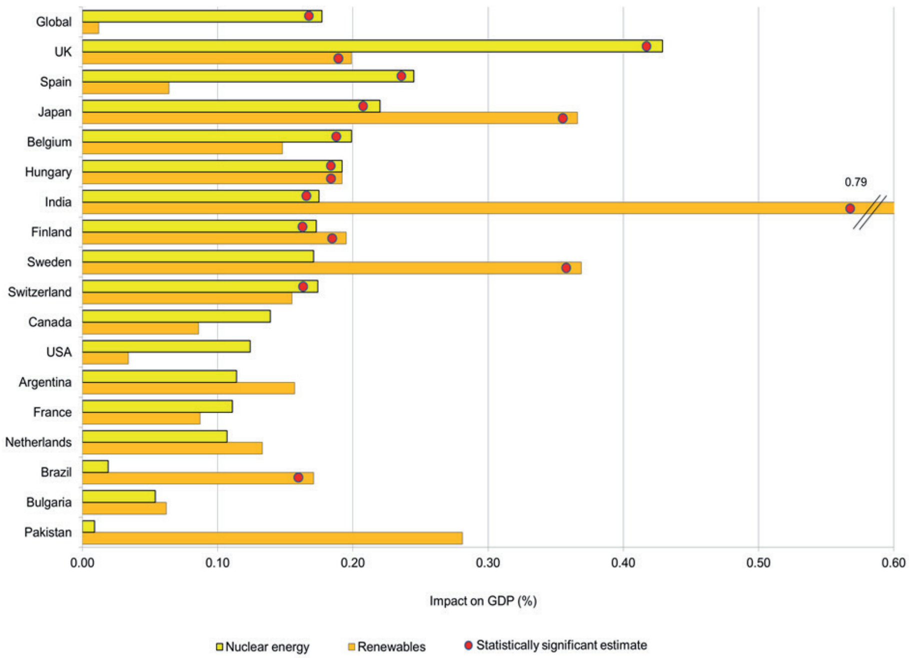

FIG. 17. Increase in GDP triggered by a 1% increase in the production and consumption of nuclear energy and renewables. Source: Based on Ref. [46]. Note: A circle in the bar indicates that the estimate is statistically significant. Statistical significance of the estimates is 10% or higher.

The economic growth associated with nuclear energy investments originates in the constituency and region where the nuclear plant is built and operated. For example, Hinkley Point C — Britain's first new build NPP in nearly 20 years — is expected to give a significant boost to the regional economy of southwest England. Labour market effects are at the core of the impetus for local and regional economic growth. The total number of individuals who will be employed at some time during the construction period is estimated between 20 000 and 25 000. At the peak of construction, likely to commence in 2016, 66% of the 5600 member construction workforce will move into the local area to work [47]. By spending incomes from direct employment, this population will give an additional boost to different sectors of the local economy: private businesses, including wholesale and retail trade, transport, real estate and financial services as well as public services such as administration, education, and health and social services. As a result, investing in the Hinkley Point C project contributes to solving local challenges in very different areas, ranging from demographic change to public transportation [48].

If appropriate macroeconomic conditions are in place, nuclear investments can bring important benefits to a country's economy far beyond the local level. Nuclear investments directly create highly skilled employment in areas related to design, engineering, procurement and consulting services for the reactor, and manufacturing major components, subcomponents, fuel and many other items for other parts of the plant. Most of these businesses are located throughout the country. For example, in the USA, a country with a well developed supply chain infrastructure, for every 100 direct jobs at a nuclear plant, another 726 indirect and induced jobs are created. Almost three quarters of these jobs are generated beyond the local and state levels [49].

Furthermore, the operation of nuclear power has positive implications for electricity and aggregate price stability, leading to a more favourable macroeconomic context for economic growth. The introduction of cap and trade regulation for GHG emissions can amplify the price stabilizing effects of nuclear energy. As a low carbon generation technology, nuclear power reduces the volatility in the price of electricity due to fluctuations in its carbon price component [50].

Despite multiple benefits of nuclear energy for economic development, a clear understanding of risks and challenges is essential in countries embarking on new nuclear power programmes. First of all, with an estimated overnight capital cost of a 1 GW(e) NPP in the range of US $2–6 billion, nuclear power requires a large upfront investment. This is a large amount of money compared to the GDP of many 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 damages 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.

The general conclusion is that the relationship between investments in different energy technologies and general economic performance is rather complex and involves multiple trade-offs. A balanced view on benefits and risks — intrinsic to an economy-wide perspective in economic analysis — underpins the need to assess the net effects on the society from investments in any energy technology. For example, the latest research demonstrates that reducing emissions in the electricity sector by 10% through increased use of renewable electricity is likely to increase the overall (economy-wide) unemployment rate by about 0.1–0.3% in the USA, though some sectors are likely to gain [51]. This example shows that a growing awareness and understanding of wide-ranging

— and sometimes conflicting — economic impacts associated with investments in any energy technology need to guide policymakers towards climate and energy policies consistent with the country's overall economic and social policy objectives.

3. SUPPLYING NUCLEAR POWER

3.1. THE ECONOMICS OF NUCLEAR POWER

The economics of nuclear power needs to be addressed at several levels. First, the direct explicit costs of generating 1 kW·h of electricity levelized across the lifetime of the power plant (LCOE), discussed in this section. Second, the system costs that arise from additional investments and services needed to supply electricity at a particular load and specified level of reliability from different sources (see Section 3.2). Third, 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 2.5). 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 markets 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.

The cost structure of nuclear power is dominated by the investment costs (a feature shared with most renewables). In other words, they are comparatively expensive to build but relatively inexpensive to operate (compared with fossil based power generation technologies). 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, including nuclear power. In Europe, high electricity prices, declining but still relatively high natural gas prices and GHG emission limits under the EU Emissions Trading Scheme (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 nuclear 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 2015, three combined construction permit–operating licences have been issued for five new reactors and six applications for a total of ten reactors were under review [52]. 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.

The OECD IEA and Nuclear Energy Agency (NEA) regularly prepare studies on the projected costs of electricity generation. The latest edition includes a large number of technologies from many countries: 181 power plants in 19 OECD and 3 non-OECD countries. The study presents LCOE calculated on the basis of a common methodology using data supplied by countries and organizations [53].

Figures 18 and 19 present an overview of the LCOE ranges for ten electricity generation technologies in seven major technology groups. The levelized costs are calculated using two discount rates: 3% (Fig. 18) and 7% (Fig. 19). The former is more relevant for government investments while the latter roughly resembles the market rate in deregulated markets, and is hence more adequate for the private sector. Higher discount rates make technologies with large upfront investment costs relatively more expensive.

The LCOE reported by the IEA and NEA includes a harmonized carbon price for fossil technologies at the level of US \$30/t CO_2 emitted. This corresponds to a

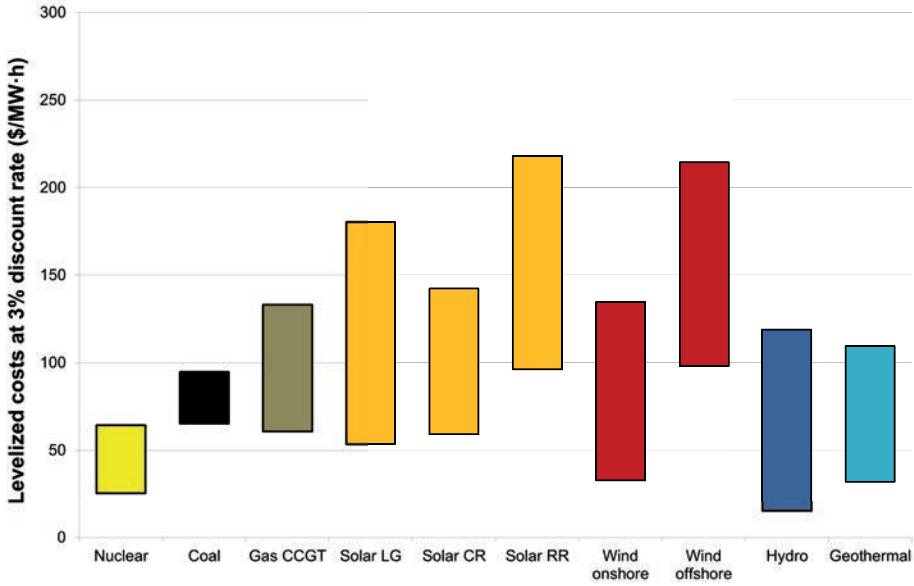

FIG. 18. Ranges of LCOE associated with new construction at 3% discount rate. Data source: Ref. [53]. Note: CCGT — combined cycle gas turbine, LG — large ground-mounted, CR — commercial rooftop, RR — residential rooftop.

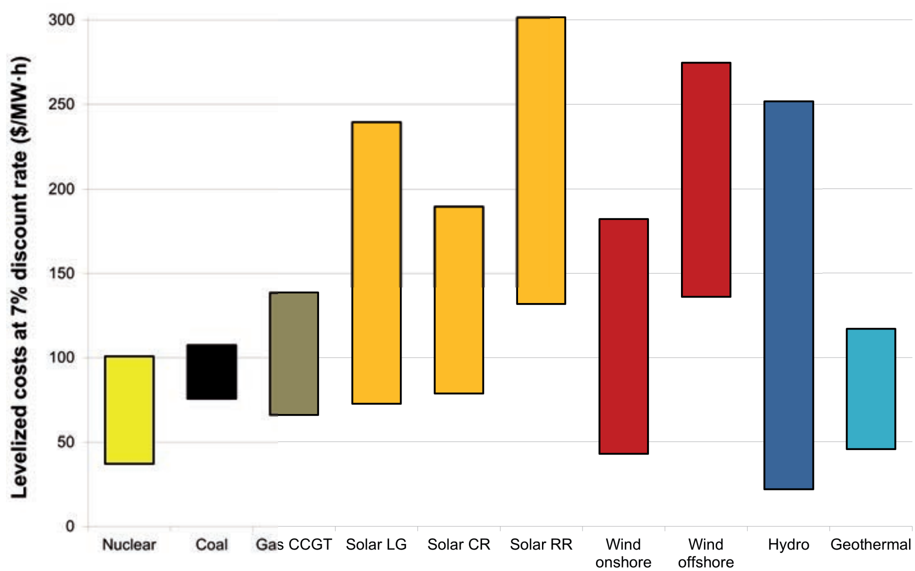

FIG. 19. Ranges of LCOE associated with new construction at 7% discount rate. Data source: Ref. [53]. Note: CCGT — combined cycle gas turbine, LG — large ground-mounted, CR — commercial rooftop, RR — residential rooftop.

carbon cost of US \$10–15/MW·h for combined cycle gas turbines (CCGTs) and US \$20–28/MW·h for coal plants. Ambitious climate policies aspiring to limit the increase of global mean temperature at 2°C involve higher carbon prices, pushing the LCOE bars of fossil technologies higher.

The basic message of the IEA–NEA study is that the LCOE of nuclear power is significantly lower than those of coal and CCGT at 3% discount rate in all OECD countries. Using a discount rate of 7%, the two main baseload generation technologies (coal and nuclear) largely overlap within the US \$75–100 per MW·h range in most OECD countries while CCGT prices are above US \$100/MW·h in all OECD countries except the USA and New Zealand [53]. An important development in recent years is that the LCOE of renewable technologies, in particular solar photovoltaic and onshore wind technologies, has declined significantly, though it still remains above that of baseload technologies in most OECD countries.

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 18 and 19 reflect the full costs of power generation but exclude external costs (disregarded benefits and 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. Despite these limitations, the LCOE figures provide a useful basis for comparing the basic economic characteristics of different generation technologies. They show that nuclear power is on a par with other baseload technologies and still cheaper than most renewable electricity sources.

3.2. SYSTEM COSTS OF POWER GENERATION TECHNOLOGIES

System costs arise from additional investments and services needed to supply electricity at a particular load and specified level of reliability. This means that the costs of electricity production at the power plant are not the final costs. Reliable supply of electricity to customers requires a sophisticated infrastructure based on interconnected national and international grids, balancing variable supply and demand, and ensuring that sufficient operating reserves are available when needed. The system costs discussed in this section are considered at the grid level. The total social costs of electricity additionally include various externalities such as environmental impacts, spillover effects and impacts on energy security (see Section 2.8).

Grid level 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. The factors determining the system costs vary depending on the type of energy sources and technologies used. This may appear to be counterintuitive because electricity produced by any power plant is fed into the grid network and is ultimately supplied to customers, thus making system costs appear to be dependant only on the characteristics of the existing infrastructure.

However, the demand for electricity is not stable but constantly varies depending on the needs of consumers, the time of the day, season of the year and other factors. Therefore, the electric power system as a whole depends on the ability of its components to react to such changes, which, in turn, depends on the type of technologies available. In addition, the supply of electricity from certain energy sources depends on external factors that cannot be predicted in advance (windiness, insolation). All these issues impose additional costs on the electric grid as a whole. Moreover, the increase of these costs for some technologies is not linear because the increase of their shares in the capacity mix affects the reliability of the system in terms of the stability of electricity supply.

All electricity generation technologies involve system costs but for traditional dispatchable technologies (nuclear, hydropower, 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 from US \$0.34 to \$0.56/MW·h for gas, US \$0.46 to \$1.34/MW·h for coal and US \$1.40 to \$3.10/MW·h for nuclear across six OECD countries involved in a study of the OECD NEA [54] (see Fig. 20).

For dispatchable technologies the system costs are associated with the time of reaction to the needs of electricity consumers, specifically, the startup time of the power plant and the maximal rate of change in electricity output per unit of time. The startup time for conventional gas turbines is 10–20 minutes, for coal plants it is 1–10 hours and for NPPs it varies between 2 hours and 2 days [54]. Similarly, the maximal change in electricity output in 30 seconds is 20–30% for conventional gas turbines, 5–10% for coal plants and less than 5% for an NPP. Accordingly, the system costs of nuclear power are slightly higher than those of fossil fuel plants. The clear benefit of dispatchable technologies in terms of system costs is that they remain rather stable as their shares in the capacity mix increase (cf. the system costs of dispatchable technologies for their 10%

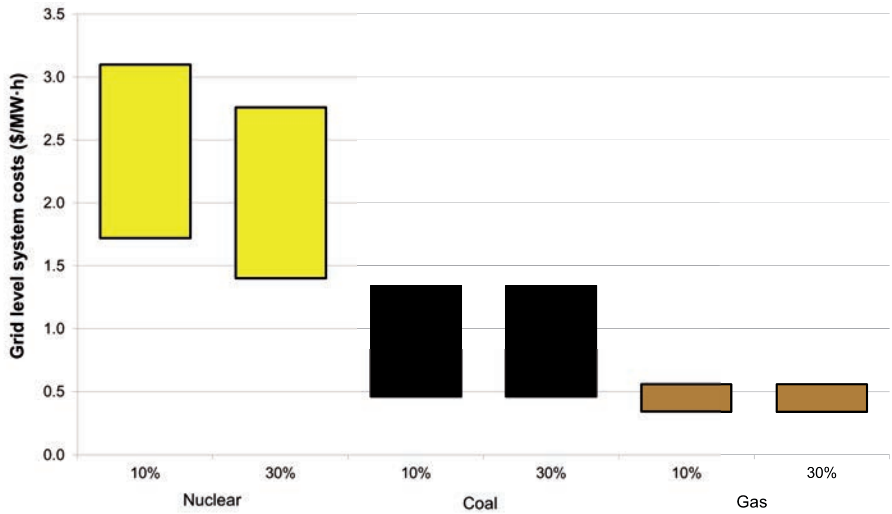

FIG. 20. Grid level system costs of dispatchable technologies. Data source: Ref. [54].

and 30% shares in the total capacity mix in Fig. 20), making their development more predictable.

The system cost implications of intermittent renewable electricity sources are completely different. In a power grid dominated by dispatchable technologies, uncertainties in the system are mostly due to the fluctuation in demand. In contrast, intermittent renewables make the supply rather unpredictable and make the balancing of the system drastically more complicated. This, in turn, requires additional capacities and significantly increases the system costs. Moreover, the increase of their shares in the overall capacity mix makes the supply of electricity increasingly volatile and thus riskier for the economy. Therefore, the grid level system costs of intermittent renewables per MW·h rise as their shares increase. Another factor affecting the system costs is that the change in energy mix cannot be followed by immediate shifts in the whole infrastructural network, which is likely to make the energy system during the period of adjustment more imbalanced and increases the costs even further. Additionally, changes in the use of certain energy sources in the whole energy mix are likely to affect the use of others in order to make the functioning of the system more efficient. For example, in order to balance the intermittency issues it is natural to increase in parallel the use of dispatchable technologies with minimal startup and reaction time. The search for a new equilibrium point for the power system would inevitably require additional time and investments.

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 (Fig. 21). Using the same methodology as for dispatchable technologies, the OECD NEA study estimates total grid level system costs for onshore wind between US $16.3/MW·h (10% share in the USA) and US $43.85/MW·h (30% share in Germany), for offshore wind between US $20.51/MW·h (10% share in the USA) and US $45.39/MW·h (30% share in the UK), and for solar between US $14.82/MW·h (10% share in the USA) and US $82.95/MW·h (30% share in Germany).

The large ranges in Fig. 21 indicate the importance of resource endowments (windiness, insolation), their location and distance to large consumer 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 or by taxpayers if there is some form of government support or cross-subsidy scheme in place. The system costs are partially responsible for the fast growing electricity prices in countries with fast growing shares of variable renewables in the power supply mix.

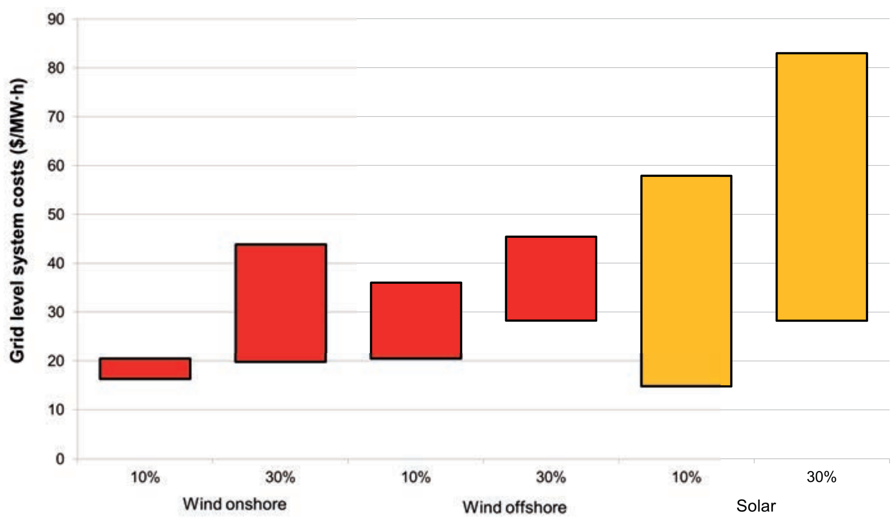

FIG. 21. Grid level system costs of intermittent renewable technologies. Data source: Ref. [54].

3.3. NUCLEAR INVESTMENT COSTS

Nuclear power might become an important technology in the future portfolio of CO_2 emissions reductions. Together with large hydropower plants, it belongs to the energy technologies that involve large investment costs but supply mitigation benefits for half a century or longer at low running costs. NPPs have higher upfront capital cost but relatively low fuel and operational costs when compared with large-scale generating units burning fossil fuels.

Competitiveness of nuclear power depends to a large extent on its capital costs. There are two main indicators measuring the costs of an NPP: the first measures the net total cost of establishing the plant (buildings, equipment, infrastructure) as if it was possible to build it from one day to the next ('overnight cost'); the second measures the total investment costs, including financing costs. For countries considering nuclear programmes, a good understanding of the true investment costs of the project and the annual outlay schedule is particularly important when evaluating the relative competitiveness of technology options to expand generating capacities. The focus of this section is on overnight costs that include pre-construction (owner's costs), construction (engineering, procurement and construction) and contingency costs.

The IEA's Nuclear Energy Roadmap 2015 provides the most recent projections of the overnight costs of an nth of a kind NPP in 2014 dollars [55]. At the lower end of the range, average overnight costs in China are projected to be approximately US $3500/kW(e). The costs in India and the Republic of Korea are reported to be similar. In contrast, overnight costs in the EU at US $5500/kW(e) are at the high end of the range. In the USA, costs are lower than in the EU by about 10%. The substantial cost difference between the EU and USA on the one hand and the Asian countries on the other is partly attributed to the lack of recent experience in building new nuclear plants and to higher labour costs in the EU and USA. Other cost estimates expand the range of uncertainty in nuclear overnight costs even further. In the 2014 update on Nuclear Power in Belarus, the World Nuclear Association quotes overnight costs at US $1960/kW(e) [56].

Academic studies, government reports and general media articles have been consistently documenting the rising costs of nuclear power over the last few decades. In France, for example, overnight construction costs almost doubled between the late 1970s and the early 2000s at constant prices. In the USA, overnight cost increases were even more pronounced over a shorter period of time. Figure 22 presents actual overnight construction costs from the early 1970s to the early 2000s in France and the USA. Data points in the chart are at the level of individual NPPs for the USA and represent pairs of reactors for France. To visualize the differences between the trends, simple linear curves

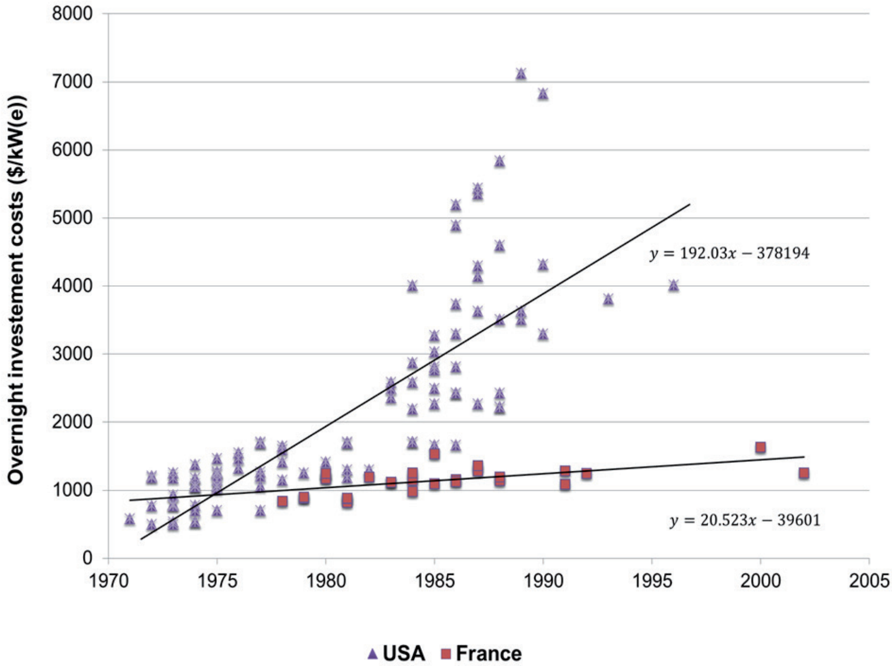

FIG. 22. NPP overnight investment costs in the USA and France in constant 2010 dollars. Source: IAEA calculations based on data from Refs [57] and [58].

have been estimated and fitted over the data points (the estimated functions are displayed in the graph).

What is the explanation for the anomaly of nuclear technology costs following the opposite trend to most other technologies which experience falling costs over time? A study by the University of Chicago identified the following key factors behind rising overnight costs in the USA: increasing technical maturation of the engineering design, improved accounting for the owner's costs, run-up in supply chain pricing and significant premium in fixed or firm price engineering–procurement–construction contracts [59]. According to a study by Lévêque [60], increasing technical maturation of the engineering design is to a large extent a response to stricter safety regulations, by far the strongest driver of the escalating costs observed in the USA.

If the current trend of increasing overnight costs continues, nuclear power may become less competitive in comparison to other energy technologies experiencing cost decreases over time. Nuclear energy needs to become more attractive to investors in order to use its mitigation potential and displace billions of tonnes of CO_2 by 2050. Therefore, it is vital for nuclear power to find ways to reverse the cost escalation trend and remain a competitive energy source.

One of the main challenges in understanding the true nuclear investment costs and drivers behind the cost escalation is related to significant uncertainties and gaps in data. Despite the large number of publications on nuclear cost development in academic journals and media reports, only a limited number of original cost estimates are available. Many studies build their analysis on secondary data, extrapolated from the same original sources, or construct them from available sources. The lack of transparency regarding the cost elements, the year of estimate and data sources impedes comparability of individual cost observations [61].

Problems with the availability and quality of cost data go beyond the pure academic context and are of high policy relevance. A recent example demonstrates how the use of historical data of good quality can refute conclusions based on weak data. In contrast to the conclusions about ‘negative learning by doing’ in the French nuclear programme from a study [62] using cost data extrapolated from different databases and sources, recent econometric studies confirmed the existence of positive learning effects in France based on historical data from the Cour des Comptes, the French Court of Auditors [63]. The latter study finds the cost escalation rate in France to be smaller than previously thought. By using actual costs from the Cour des Comptes, it finds that overnight cost have been rising at the rate of 4.6%/year in the period 1978–2002, while the rate of cost increase is calculated at 5.8%/year by using cost estimates from various sources rather than real data.

Another econometric analysis based on a large set of historical data from France and the USA revealed additional important lessons on how to ease the cost escalation phenomenon. Figure 22 provides an initial suggestion that France was more successful in containing the cost escalation than the USA. Berthélemy and Rangel tested and proved the hypothesis that a lower technological variation in reactor designs together with more vertical integration during the construction phase is a key in suppressing cost escalation [64]. The study shows that standardization in France has contained cost escalation by reducing licensing and construction time, which are among the main drivers of cost escalations. Overnight construction costs also benefit from learning spillovers. However, these spillovers occur only if the plants are built by the same architecture–engineering (A-E) firm. On average, one can expect a 12% reduction in construction costs for the 2nd unit of a reactor model being built by the same A-E firm. In contrast, due to the complexity of nuclear reactors, previous experience gained from the construction of any other type of reactors by the same A-E firm does not translate into cost reduction. Finally, this study also found that, contrary to other energy technologies, innovation does not result in overnight cost decreases.

Similar results were obtained by a joint study of Harvard University (USA) and Fondazione Eni Enrico Mattei (FEEM, Italy) regarding the impacts of additional research spending on nuclear overnight costs [65]. In the survey, 30 US and 30 European nuclear technology specialists were interviewed about the role of government research, development and demonstration (RD&D) spending in shaping the future overnight costs of nuclear technologies. The experts recommended large increases in governmental spending on RD&D for nuclear technology but expected only modest overnight cost decreases for current (Generation III/III+) and future (Generation IV) reactor designs. Doubling RD&D investments into Generation III/III+ is estimated to result in a cost reduction of merely about 1.4% because only incremental improvements in the established set of technologies are possible. Groundbreaking innovations in future technologies leading to fundamental shifts in cost structure are still possible but less likely at the current stage of development, according to the Harvard–FEEM study [65]. Additional RD&D would instead improve performance in safety, waste management and uranium resource utilization. These are very important factors to consider when investing in nuclear energy.

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

3.4. FINANCING NUCLEAR POWER INVESTMENTS

Nuclear energy is characterized by high capital and low operating costs. In addition, construction periods are long (often of the order of 5–7 years), which implies that capital spending is tied up for a long period before revenues start to flow to the project to allow investments to be repaid. As a result of these factors, the cost of electricity generated by an NPP is highly sensitive to the costs of financing.

Over recent years, a number of innovative approaches to financing nuclear energy projects have begun to emerge. A recent publication [67] lists a number of key models.

The government-to-government financing model typically relies on a bilateral loan agreement between a nuclear steam supply system provider's own government and a would-be NPP host government. The broad terms of such arrangements are often set out in a preliminary intergovernmental agreement between the governments concerned. On the positive side, such a model can provide a country embarking on construction of its first NPP with access to a

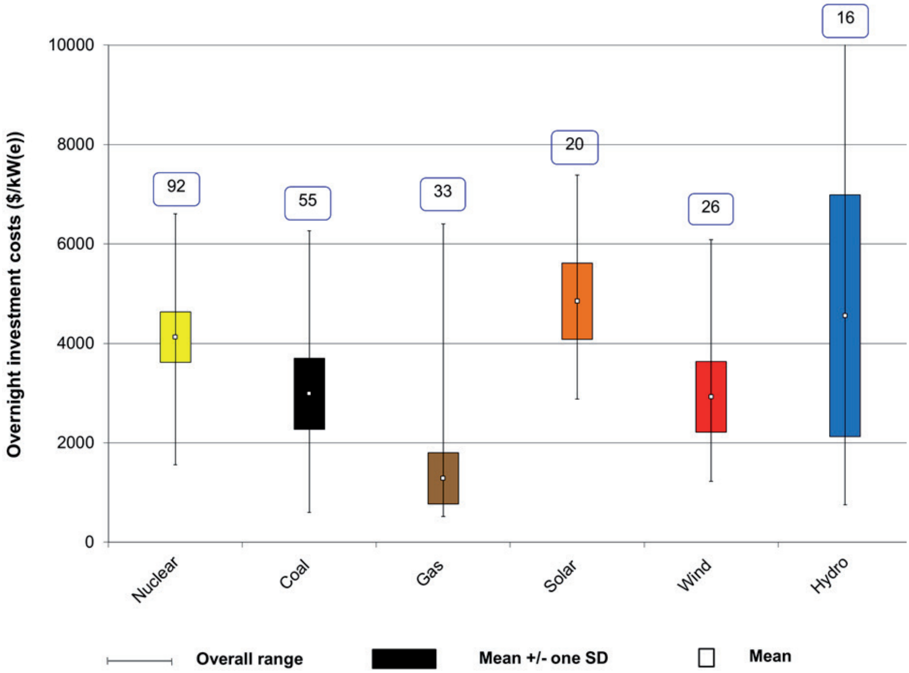

FIG. 23. Overnight investment cost estimates for the main electricity generation technologies. Data source: Ref. [66]. Note: This chart is based on data compiled from sources published between 2010 and 2014. SD — standard deviation.

source of both funding and experience, although this access will be tied to the acquisition of a particular vendor's technology.

The loan guarantee framework provides assurance to lenders that their loans will be repaid by having a financially credible entity stand behind the NPP project developer in the sense that the guarantor will repay the loans if the project developer is unable to do so. As a result of the reduced risks, the lenders tend to charge lower interest on the loans advanced to a project. In the USA, the Department of Energy provided loan guarantees to two of the co-owners of Vogtle 3 and 4 in February 2014 [68]. In the UK, the Hinkley Point C NPP project will benefit from a similar guarantee from Infrastructure UK (a part of HM Treasury). Several national export credit agencies also facilitate loan guarantees to support the export of their national suppliers' nuclear energy technologies.

Power purchase agreements (PPAs) backed by host governments can provide similar assurance to lenders — in this case by guaranteeing that market risks (inadequate demand for an NPP's output or low electricity prices) will not endanger a project's ability to repay its debts and associated interest. The UK's contract for difference (CFD) mechanism is an example of such a PPA scheme, and forms a key part of the arrangements (along with the Infrastructure UK guarantee) to support the development of the Hinkley Point C project. Similarly to loan guarantees, the reduction of (one type of) risk to the economic performance of a nuclear energy project can be expected to result in more willingness to lend to such projects, as well as a likely reduction in borrowing costs.

Vendor financing comes in various forms, including vendor arranged credit (often involving an export credit agency), vendor provided credit (likely short term) and — a relatively recent development — vendor equity. Vendor equity is typically anticipated to provide a relatively small and expensive part of a project's overall financing. The advantage is that the vendor is fully incentivized or vested in the overall project's success.

Figure 24 provides a framework to illustrate the role of some of these models in increasing the financeability of NPP projects as well as the importance of the more general contractual framework within which a nuclear project can be developed.

On the left of Fig. 24 are just three examples of the many commercial contractors typically engaged with an NPP project developer who may become the owner and operator (OO) at a later stage. The difference between the revenue

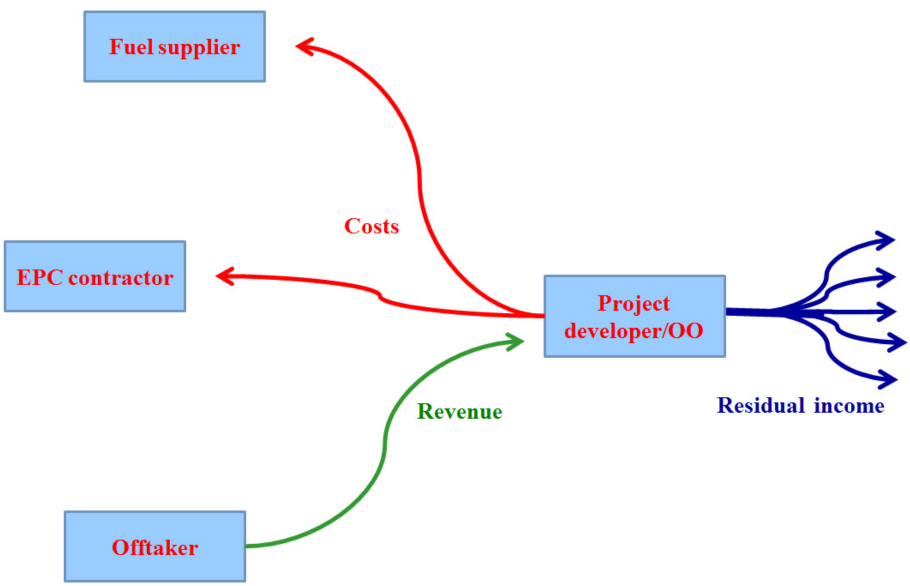

FIG. 24. Financing scheme of nuclear power projects. Note: EPC — engineering, procurement and construction; OO — owner and operator.

received by a project developer/OO from its offtaker and the costs it will incur in paying its engineering, procurement and construction (EPC) contractor and fuel supplier represents the residual income available to pay financial stakeholders (lenders and equity investors). Given that the costs shown include payments to an EPC contractor and that such payments will typically occur during the construction phase, Fig. 24 is perhaps best regarded as showing revenues, payments and residual income which will arise over the course of a project's entire lifetime. It is important to recognize that the residual income will in general be risky. In fact, it will inherit its risk characteristics from the framework of contracts between the project developer/OO and the counterparties shown on the left of the figure. Insofar as the risks inherent in these contracts can be assigned to its commercial counterparties, the project developer/OO will ensure a more stable flow of residual income available to pay its various financial stakeholders.

Arrangements to mitigate market risks in the PPA/CFD framework — as discussed above — will reduce the volatility of this residual income. Loan guarantees can be viewed as transferring some of the project risks left by the final commercial contracts with the project developer/OO to a third party (e.g. the US Department of Energy or the UK Treasury — and ultimately US or UK taxpayers). This will further reduce the volatility of the residual income available to pay financial stakeholders. In both cases, reduced volatility will be reflected in an increased willingness to finance NPP projects which benefit from such arrangements at lower cost. Given the sensitivity of nuclear generating costs to the cost of financing, the benefits to electricity consumers can be substantial. Lower financing costs also improve the overall competitiveness of nuclear power among the low carbon technologies and this improves its prospects to play an important role in climate change mitigation.

3.5. TIMELINESS AND CONSTRUCTION CAPACITY

In deliberations about climate change mitigation strategies, opinions are expressed from time to time about the inability of nuclear power to make a significant contribution owing to the long planning and construction time and limited industrial capacities. This section takes a closer look at these concerns.

The need for a fast transformation of the global energy mix towards low carbon energy sources raises questions about the feasibility of the implementation. Over the next few decades, renewables are projected to expand faster than ever before in history and significant shares of this growth will occur in developing countries with limited experience in large scale transformation of national energy systems. The ability of national economies, the international community and multinational enterprises to meet this challenge will be crucial for the development prospects of the global community. Nuclear power is expected to be part of this challenge while also facing some industry specific issues.

According to the IEA WEO 2014 [11], the demand for nuclear energy will increase from 642 Mtoe in 2012 to 845 Mtoe in 2020 (according to the New Policies Scenario), showing an average annual growth rate of 3.5%. Average growth rate in the 2020–2040 period in this scenario is projected to slow down to 1.8%/year, which will still result in an increase of 43% (to 1210 Mtoe) over this period. Moreover, the climate friendly vision of the future presented in the 450 Scenario assumes that demand for nuclear will grow by 3.4% annually in the 2020–2040 period (95% increase, reaching 1677 Mtoe). The analysis of the development prospects for the global energy system until the middle of the century provided in the IEA ETP 2014 [17] shows the growth of total demand for nuclear power by 72% in the period 2011–2050, according to the 4DS (broadly corresponding to the New Policies Scenario in WEO) and by 162% during the same period in the 2°C Scenario (2DS) (a broad analogue of the 450 Scenario in WEO).

These growth rates are far below those projected for wind and solar, which are anticipated to expand by 6.5 times in the New Policies Scenario (from 142 to 918 Mtoe) and by 10.8 times (up to 1526 Mtoe) in the 450 Scenario by 2040. Nevertheless, the projected expansion of nuclear power is still remarkable, especially when considering the retirement in this period of the bulk of the current nuclear fleet mostly built in the 1970s. In the New Policies Scenario [11], the capacity of nuclear power expands from 392 GW(e) to 624 GW(e) between 2013 and 2040, but approximately 150 GW(e) of current capacity will be retired and needs to be replaced during this period, putting additional pressure on the industry. Considering the fact that the nuclear sector did not experience major expansions in the 1990s and 2000s, these projections inevitably raise questions about the ability of the related construction and manufacturing industries to extend their capacities to satisfy increasing global demand. The reason for this is that the construction of new NPPs requires specialized manufacturing capacities (e.g. for heavy forging and advanced components) that can be supplied only by specially certified companies. These capacities, however, can be established in a reasonably short timeframe if a major increase in demand for them is expected. An additional factor favouring an expansion is that in a more globalized market newcomers will be able to use equipment produced in different parts of the world. This, in turn, will stimulate additional specialization of component producers, allowing them to harness the benefits of economies of scale.

One response to the expansion question is offered by the history of the previous phase of massive expansion of the nuclear industry. In 1970, the global reactor fleet consisted of only 82 reactors with a total installed capacity of 16 291 MW(e). This grew to 168 reactors (72 860 MW(e) capacity) by 1975 [69] and to 420 reactors with an overall capacity of 327 670 MW(e) by 1990 [70]. This means that in 20 years the reactor fleet expanded five fold and installed capacity was multiplied by 20. These are much faster growth rates than those projected for the next decades by the IEA in its scenarios, including the most ambitious mitigation cases — the 2DS and the 450 Scenario — with the largest nuclear increases (see Fig. 25). Moreover, the new phase of nuclear expansion will take place in a rather different context: the relevant industries have already accumulated significant experience that they lacked in the 1970s, and operate under significantly more globalized market conditions.

One possible challenge might be that a certain share of the nuclear power expansion is projected to occur in developing countries with limited

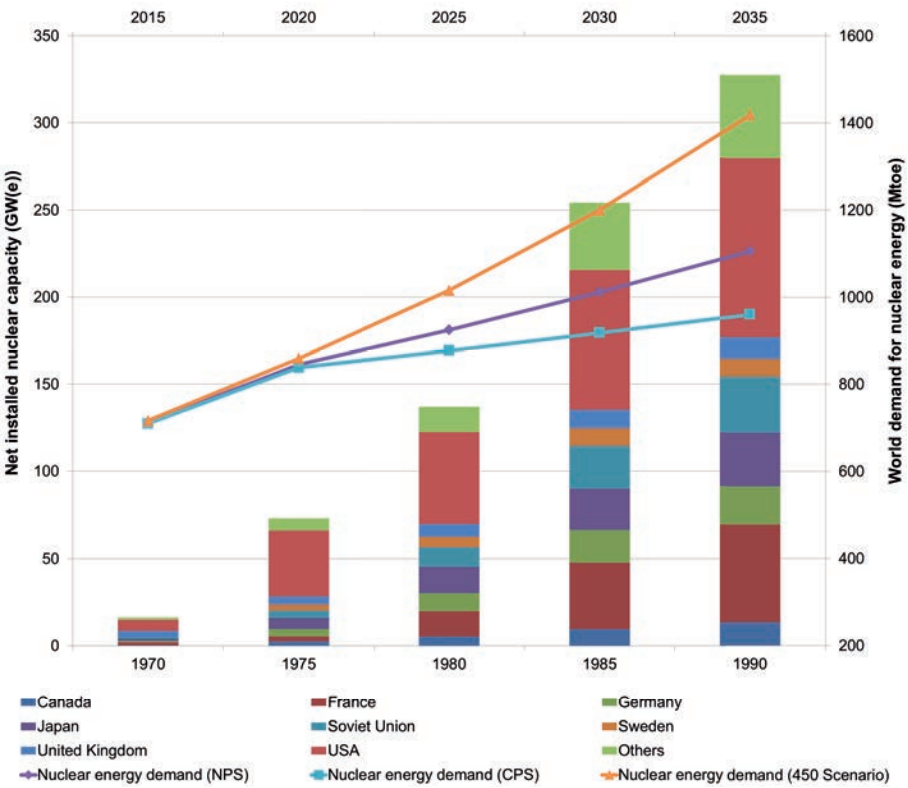

FIG. 25. Net installed capacity of the nuclear industry (GW(e)) in 1970–1990 (bars, left vertical and lower horizontal axes) and projected expansion of world demand for nuclear energy, according to the IEA NPS, CPS and 450 Scenarios in 2015–2035 (lines, right vertical and upper horizontal axes). Data sources: Refs [11, 17, 69, 70]. Note: NPS — New Policies Scenario; CPS — Current Policies Scenario.

experience in building and operating NPPs. One should also consider, however, that the number of newcomers will be limited and the bulk of new builds will be in countries with well established national nuclear industries (China, India, Russian Federation). In newcomer countries, the development of national nuclear programmes will most likely be implemented through cooperation with countries with advanced nuclear construction and manufacturing capacities, and multinational enterprises utilizing their experience obtained over decades of operation. The prospects for the nuclear industry will also depend on the strategy of the government and businesses in a newcomer country: to what extent is the nuclear project perceived as an opportunity to progress faster towards a more advanced stage of technological development and to improve the competitiveness of the national economy in international markets. If implemented efficiently, nuclear development can become a major driver of economic growth with multiplicative effect on other sectors of the economy, increasing overall output and creating new jobs, as was observed in the Republic of Korea [71].

Some countries with advanced nuclear industries today were themselves not so long ago in a position similar to that of today's newcomers and managed to promote their national nuclear programmes. Countries like the Republic of Korea demonstrate the prospects for catching up with the forerunners. Historical experience in the industry also demonstrates the possibility of success in countries with different sociopolitical systems and at different stages of economic development, thus demonstrating the possibility for developing countries to make their national programmes a success. Additionally, the new phase of nuclear expansion is likely to benefit from more open and decentralized markets with equipment produced by several specialized enterprises. Enhanced international cooperation will also have a positive technological spillover, allowing newcomers to develop their national programmes faster.

The projected growth of nuclear energy in the IEA's New Policies Scenario will require the construction of 12 GW(e) capacity per year on average until 2020 [11]. New capacity additions should increase to 15 GW(e) in 2020–2040. Such a growth is easily achievable, as it is two or three times lower than the peak growth rates in the 1980s. In addition, capacity additions will be split across a larger number of countries in comparison with the 1970s and 1980s. Even if some newcomer countries will have limited ability to steer the construction of their NPPs and outsource it to multinational enterprises, it is likely that local companies will be involved in numerous civil engineering tasks (comprising up to 30% of the total investment costs) and other activities, thus decreasing the pressure on foreign corporations and allowing them to use their construction capacities simultaneously in other countries.

A related concern about nuclear energy is the length of time required for construction of a new NPP, as it can take up to ten years from planning to final connection to the grid. Some argue that this makes nuclear power unsuitable for mitigating climate change in comparison with renewables because urgent mitigation needs require fast deployment of low carbon energy sources. However, the appropriate context is not to compare an NPP with a single solar panel of a single household or a few windmills, but rather with industry scale facilities. Planning, construction and integration into existing grid systems normally take a long time. Planning and grid integration strongly depend on the national regulations and the level of development of the existing energy system. Typical construction times for different types of power plants are illustrated by the following examples:

— 18–96 months for hydropower plants with capacity over 10 MW [72];
— 48 months for the proposed 150 MW Moree solar PV plant in Australia [73];
— 60 months for the proposed Caledon wind park with 243 MW installed capacity in South Africa [74].

The IEA Energy Technology Systems Analysis Programme estimates a construction time of 40–72 months for NPPs of 800–1200 MW(e) capacity, which is in line with some large scale renewable energy projects. Such construction times might be expected in the case of serial construction of standardized designs. The current long construction times are partly due to unique designs with limited learning opportunities for the vendors.

3.6. AVAILABILITY OF URANIUM

A question which often arises in evaluating the potential contribution of nuclear energy to climate change mitigation is whether sufficient uranium exists to fuel future reactors at a cost which will allow them to be competitive with other generation technologies. A widely recognized resource for answering this question for the short to medium term is the joint IAEA/OECD report on Uranium: Resources, Production and Demand, commonly referred to as the 'Red Book'. This statistical resource draws on a survey which is sent to the Member States of the IAEA. The latest edition provides information and analyses from 45 countries [38].

Figure 26 shows the evolution of estimates for 'identified [uranium] resources' over successive (2011 and 2014) editions of the Red Book. These identified resources consist of uranium deposits delineated by sufficient direct measurement to conduct pre-feasibility and sometimes feasibility studies; they can be further broken down into 'reasonably assured resources' and 'inferred resources'. For the former, high confidence in estimates of grade and tonnage

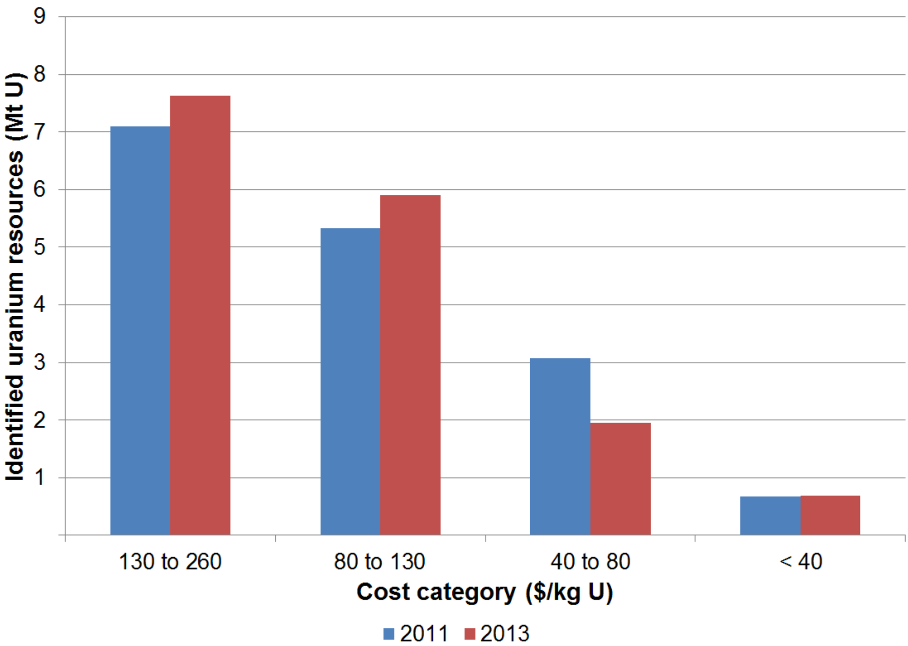

FIG. 26. Evolution of estimates of uranium resources in different cost categories. Source: Ref. [38]. Note: Years indicate the reference times of the surveys. Mt U — million tonnes of uranium.

is generally compatible with mining decision making standards. The latter are not defined with such a high degree of confidence and generally require further direct measurement prior to making a decision to mine. The numbers presented for total identified resources show an increase between the 2011 and 2014 editions, to a total of 7.6 million tonnes of uranium (Mt U). This would be sufficient to meet demand for over 120 years, considering 2012 uranium requirements of 61 600 tonnes. It should be noted that the bounds of these cost bands are defined in terms of current year prices and exchange rates. However, the movement in the value of the US dollar between the dates at which identified resources were inventoried for these two editions was of the order of just 1 percentage point.

A broader estimate of potentially available uranium would include all identified resources plus prognosticated and speculative resources to come up with a total of about 15.3 Mt U as the conventional resource base — a figure which does not include secondary sources or unconventional resources (e.g. uranium from phosphate rocks). This higher number would increase the projected longevity of the uranium resource, though significant exploration and development, motivated by significantly increased demand and prices, would be required to move these prognosticated and speculative resources into more definitive categories.

A notable feature of Fig. 26 is the shift in the distribution of identified resources away from the lower cost categories between the 2011 and 2014 editions of the Red Book. The notion that the focus of the process of identifying and exploiting uranium resources will shift over time from higher grade to lower grade deposits is consistent with this feature of the Red Book survey data and with the view that the cost of uranium will increase over time. However, it is important to recognize that ore grade is only one determinant of the cost of uranium. Warren and De Simone [75] argue that productivity growth and learning can significantly mitigate any tendency of uranium costs to increase as poorer quality ore reserves are exploited. They explore the potential for increased efficiency in uranium extraction to counter the tendency towards increased cost arising from decreasing ore quality. They suggest that such efficiency increases will at least moderate any tendency towards increased uranium cost, and that in fact — with some relatively conservative assumptions on productivity growth and learning — uranium costs can be expected to decline similarly to costs of other commodities, which have been observed to be decreasing over the long run. The work of Warren and De Simone builds on a model of uranium availability and concentration in the earth's crust first developed by Deffeyes and MacGregor [76]. Insofar as this model is derived from geological considerations, it may be regarded as less subject to survey respondents' natural tendency to ignore potential sources of uranium whose recovery is economically infeasible under current technological and economic conditions. Consequently, it provides a more long term perspective which is complementary to the Red Book's short to medium term perspective.

In terms of the impact of uranium cost on the overall competitiveness of nuclear generated electricity, it is important to recognize that the cost of uranium itself makes up a relatively small part of the total cost of generation. D'Haeseleer [77] presents figures based on (i) the fraction (15–50%) of natural uranium cost as a part of the portion of the LCOE arising from fuel cycle costs; and (ii) the fraction (7–16%) of the LCOE made up by fuel cycle costs. Based on these numbers, d'Haeseleer concludes that the contribution of the cost of natural uranium may range from as little as 1% of the overall LCOE to as much as 8%.

In general, the literature supports the view that possible shortages of uranium — and their reflection in increased uranium cost — should not be regarded as an obstacle to nuclear energy's making a significant contribution to the reduction of GHG emissions. The discussion above addresses the potential for supply shortages and consequent cost increases as one (economic) dimension of the security of supply. The risk of supply interruption due to geopolitical and other local causes (such as closure of significant supply routes) is another dimension of supply security discussed in Section 2.8.

4. CONCERNS ABOUT NUCLEAR POWER

4.1. RADIATION RISKS

While ionizing radiation is a ubiquitous part of the natural environment, it is probably the single most important topic for nuclear power. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was established by the General Assembly of the UN; its mandate in the UN system is to assess and report levels and effects of exposure to ionizing radiation to the public and to workers from natural and human-made sources. Governments and organizations throughout the world rely on the Committee's estimates as the scientific basis for evaluating radiation risk.

Radiation exposure is measured in sieverts (Sv). UNSCEAR's assessments have repeatedly reported that nuclear power is a minute source of ionizing radiation for the public (see Fig. 27). In order to establish a baseline, radiation exposures from natural sources have been estimated. While the global average annual effective dose from natural radiation sources is estimated to be 2400 μSv, the range of typical doses spans from 1000 to 13 000 μSv/year [78]. For comparison, the worldwide average of annual effective doses to the public from NPP operation is on the order of 0.1 μSv [78]. For local populations, the most important source of radiation at 25 μSv/year comes from uranium mining and milling operations, whereas uranium enrichment and fuel fabrication are estimated to contribute only 0.2 μSv/year, respectively (within 100 km of the site). In contrast, oil and gas extraction alone can expose the local population to a maximum effective dose of 30 μSv/year [78]. Coal fired power plants involve an exposure of 1.5 μSv/year. The radionuclides ^{210}Pb and ^{210}Po contained in the feedstock used to produce steel in blast furnaces are discharged into the atmosphere via the stack. These stack releases can add up to a maximum of 100 μSv/year to the effective dose for individuals living in the industrial area surrounding the plant [78]. The conclusion is that the radiation exposure levels of populations around nuclear facilities are significantly lower than naturally occurring background radiation.

Furthermore, the majority of the estimated health effects are associated with the exposure to radon gas emissions from uranium mining and milling [18]. This is consistent with the UNSCEAR calculation premises on exposure for local populations, but seems rather conservative given the fact that: (a) radon has

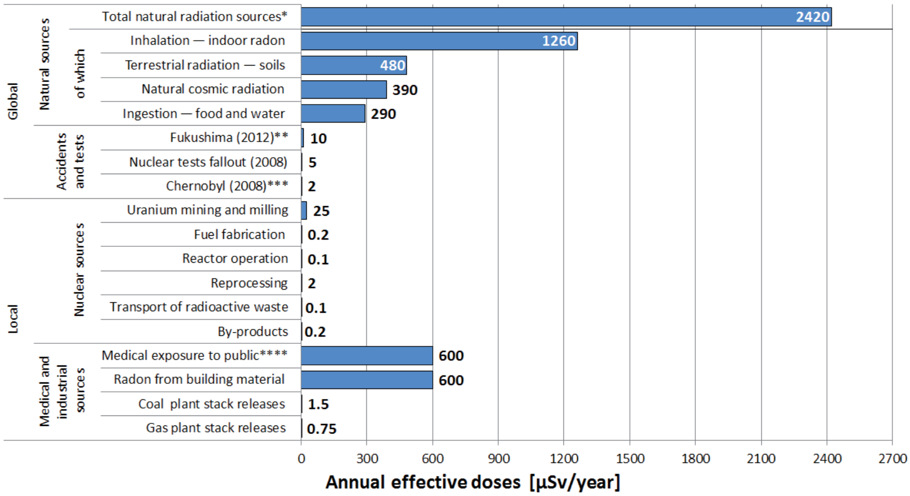

*FIG. 27. Annual effective doses to the public from exposure to selected radiation sources. Data source: Ref. [78]. Note: * Typical individual doses range from 1000 to 13 000 µSv. ** 2012 global average, decreasing over time. *** Decreasing from 40 µSv in 1986 for the northern hemisphere. **** Estimate for 2008, corrigendum is being prepared by UNSCEAR.*

a short half-life, 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 reduce radon inhalation, minimizing occupational health risks; and (d) uranium mines and mills are usually far from populated areas. See also Refs [79] and [80] for details on radiation from uranium mining.

When compared to fossil fuel power plant operation or other industrial practices (Fig. 27), nuclear power creates relatively low radiation health risks. UNSCEAR and the Oak Ridge National Laboratory reported similar findings in 1978 [81], showing that individuals living next to a coal power plant receive higher effective dose than those living in the vicinity of an NPP. Contrary to the perception of most people, the present level of the global average effective doses to the public from major nuclear accidents and military tests are very low owing to the decay and dispersion of radionuclides. As the decay of radionuclides continues, doses to the public continue to diminish. Nonetheless, radioactive contamination of the environment close to the accident sites of Chernobyl and Fukushima Daiichi can be severe and affect sizeable areas. The registry data for recovery operation workers in Chernobyl show that the average recorded doses decreased from year to year, from about 170 000 µSv in 1986, to 130 000 µSv in 1987, 30 000 µSv in 1988 and 15 000 µSv in 1989 [82], with decreasing declines over the years. Similarly, at locations within a 20–30 km radius from the Fukushima Daiichi NPP site, depending on the deposition, the initial estimated doses to non-evacuees of all age groups are estimated to be between 10 000 and 50 000 μSv [83]. The dominant pathway in these locations is estimated to be external dose from ground deposits but there are also contributions from other exposure pathways. In these locations, only the first four months of exposure from external dose have been included as it has been assumed that relocation would have occurred at that time.

According to the 2013 UNSCEAR report, the lower estimates of the doses received by non-evacuees in the Fukushima prefecture averaged 4000 μSv for adults and 8000 μSv for one year old infants in the first year. UNSCEAR estimates average lifetime effective doses on the order of 10 000 μSv for adults in Fukushima prefecture (assuming no remediation measures were taken) [84]. These are average doses and therefore larger doses occurred as well. However, the doses were well below levels that could cause deterministic radiation effects (including radiation fatalities or acute radiation syndrome). 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 mitigation and other activities at the Fukushima Daiichi NPP and concludes that the average effective dose was 12 000 μSv over a 19 month period for the 25 000 workers involved. The UNSCEAR report concludes that no discernible increase in radiation related health effects is expected either for them or for the 2 million Fukushima prefecture residents and their descendants [84].

The effects of radiation exposure during childhood as compared to adulthood are a complex matter. After half a century of research on the effects of ionizing radiation on children, the commonly held notion that children might be two to three times more susceptible is confirmed for some health effects. However, this is clearly not always the case. In fact, for a few effects (e.g. lung cancer), children are more resistant than adults [85]. Health effects and risks depend on a number of physical factors. Regarding external radiation exposure, children have less shielding due to smaller body diameter. Thus, for a given external exposure the dose will be higher for infants and children than for adults. While clear instances for increased risks in children compared to adults (e.g. leukaemia, breast and brain cancer) do exist, there appears to be no difference in risk for other tumour types (e.g. bladder cancer) [85]. At present, there are no statistically sufficient projections of lifetime risk for specific tumour types at young ages. Published models assuming that after radiation exposure the same increased relative risk of carcinogenesis in children as in adults applies to nearly all tumour types are overly broad generalizations without clear scientific support. Furthermore, for many of these health effects, there are significant variations in magnitude during the span from infancy through childhood and into adolescence. Thus, in a discussion of the effects of childhood radiation exposure, generalizations are best avoided and attention should be directed towards the specifics of the exposure, age at exposure, absorbed dose to certain tissues, age at the time of the assessment and the particular effects of interest [85].

In conclusion, radiation exposure to the public from normal operation of NPPs and nuclear fuel cycle infrastructure is negligible (27–28 μSv/year) compared to that from natural (2400 μSv/year) and other anthropogenic sources (600 μSv/year), where individual doses depend primarily on medical treatment, occupational exposure and proximity to test or accident sites [78]. Immediate radiation exposure resulting from the Fukushima accident may have been considerably higher (10 000 μSv/year) in the vicinity of the power plant, but the contribution to global exposure is negligible. These values are much smaller than those observed in high background radiation areas, where adverse health effects cannot be observed, such as the Afra hot springs in Jordan reaching up to 158 000 μSv/year, Ramsar in the Islamic Republic of Iran reaching 132 000 μSv/year, parts of the coastal belt in Kerala in India reaching 45 000 μSv/year, Guarapari beach in Brazil reaching up to 10 000 μSv/year, or Yangjiang County in China reaching 6400 μSv/year [84, 86–89] (see Fig. 28). However, when radiation doses of the two largest accidents (Chernobyl

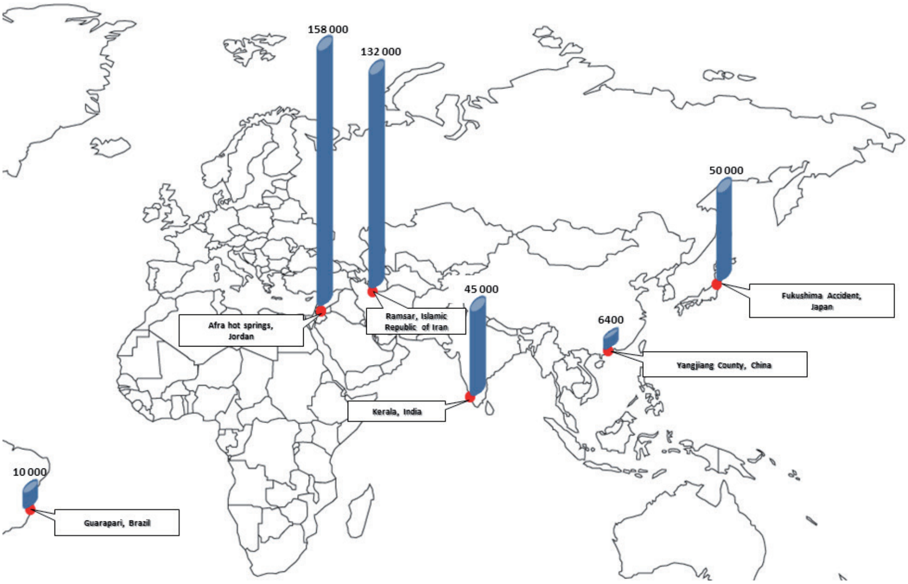

FIG. 28. Annual effective doses in high radiation areas and in the vicinity of the Fukushima accident. Data source: Refs [84–89]. Note: All doses are expressed in μSv.

and Fukushima) are considered on a global scale, the exposure levels sink to insignificant amounts.

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

During the last four years, discussions on NPP safety focused largely on identifying and applying the lessons to be learned from the March 2011 accident at the Fukushima Daiichi NPP. Since then, many actions and initiatives aimed at strengthening nuclear safety have been taken at the national, regional and international levels [90].

At the national level, prompt action was taken by NPP operators and national regulators to undertake comprehensive safety reassessments or 'stress tests'. The aim of these reassessments was to evaluate the design and safety aspects of NPP robustness to protect against extreme events and to identify and implement any necessary improvements. As a result, safety margins for beyond design basis events have been re-evaluated and arrangements for managing severe accidents have been reviewed. The measures taken to implement the results of the national assessments have included hardware improvements at NPPs, such as the provision of additional mobile diesel generators and mobile pumps. In addition, measures are being introduced to mitigate the impact of severe accidents through protecting the containment by filtered venting, passive autocatalytic recombiners and containment water sprays.

Some countries conducted their safety reassessments within a regional framework, such as the European Nuclear Safety Regulators Group (ENSREG) and the Ibero-American Forum of Radiological and Nuclear Regulatory Agencies (FORO) stress tests, which also included a subsequent peer review. Despite varying emphases and the use of different terminology, the safety reassessments carried out in different countries have largely converged on the same conclusions. In addition, the similarities in the implementation of appropriate measures based on the findings of these tests indicate that significant safety issues have not been overlooked and a high level of commonality was achieved in the safety improvements.

At the international level, an important contribution to strengthening nuclear safety was made by the IAEA. A Ministerial Conference on Nuclear Safety was convened in June 2011, to direct the process of learning and acting upon lessons following the Fukushima Daiichi accident in order to strengthen nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. The Conference adopted a Ministerial Declaration which requested, inter alia, that the IAEA Director General prepare an Action

Plan on Nuclear Safety (the Action Plan). The Action Plan was presented to the 2011 General Conference and was unanimously endorsed by Member States.

The Action Plan [91] comprises 12 main actions relating to key areas of nuclear safety including: the IAEA safety standards and the IAEA peer reviews, emergency preparedness and response, infrastructure development and capacity building, regulatory effectiveness and research and development.

Significant progress continues to be made in several key areas of the Action Plan, which has contributed to the strengthening of the global nuclear safety framework. This progress is described in three annual reports [92–94].

Highlights from the activities undertaken in the framework of the Action Plan during 2014–2015 include the following areas:

— Significant progress has been made in reviewing the IAEA safety standards, which continue to be widely applied by regulators, operators and the nuclear industry in general. The review has focused on important areas such as design and operation of NPPs, protection of NPPs against severe accidents, and emergency preparedness and response;
— The IAEA continued to review the effectiveness of its peer review services and introduce enhancement by incorporating the lessons learned from the Fukushima Daiichi accident and from discussions on the needs of Member States. Requests for these services have continued to increase, with more than 20 missions registered during 2014–2015. The IAEA continues to make available on its web site updated information on Member State activities regarding the IAEA peer reviews, including those peer reviews that have already been carried out and those that are planned for the future;
— Upon request from Japan, the IAEA continued to assess progress achieved in the Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 through international peer review missions. The third mission conducted early in 2015 highlighted the on-site improvements that have been achieved through the completion of several important tasks including the removal of fuel from Unit 4 [95];
— The efforts to strengthen international emergency preparedness and response continue. The IAEA encouraged Member States to register their assistance capabilities in the IAEA Response and Assistance Network (RANET). The process to review the capabilities registered under RANET has been elaborated and expanded to include performance and participation in exercises, provision of assistance and the conduct of review missions.

The Action Plan also mandated the IAEA to organize International Experts Meetings (IEMs) to analyse all relevant technical aspects and establish the lessons learned from the Fukushima Daiichi accident. Between March 2012 and February 2015, the IAEA organized eight IEMs and has so far published six associated reports to communicate and disseminate the lessons worldwide. The reports consider the following topics: reactor and spent fuel safety [96], transparency and communication [97], protection against extreme earthquakes and tsunamis [98], decommissioning and remediation [99], human and organizational factors [100], and radiation protection [101]. Three additional reports are being prepared on severe accident management, research and development effectiveness, and assessment and prognosis in response to a nuclear or radiological emergency.

As part of the ongoing international effort to further strengthen nuclear safety, a Diplomatic Conference was held in Vienna in February 2015 where the Vienna Declaration on Nuclear Safety was adopted by the Contracting Parties to the Convention on Nuclear Safety (CNS) [102]. The Declaration contains a series of principles for the implementation of the objective of the CNS aimed at preventing accidents and mitigating the radiological consequences should an accident occur.

The IAEA Report on the Fukushima Daiichi Nuclear Power Plant Accident was published in September 2015 [103]. The report is an authoritative, factual and balanced assessment addressing the causes and consequences of the accident as well as the lessons learned. It is intended to serve as a key technical reference document on the accident for years to come. Five working groups composed of approximately 180 internationally recognized experts from 42 Member States and several international bodies worked on the preparation of the report. It provides a description of the accident and its context and addresses nuclear safety and emergency preparedness and response issues, the consequences of the accident and post-accident recovery.

Nevertheless, while learning the lessons arising from the Fukushima Daiichi accident remains important, IAEA Director General Yukiya Amano stated that it is time to start considering a broader approach to strengthening nuclear safety: “to look at safety aspects of other important issues including decommissioning old facilities, extending the operating life of existing NPPs, disposing of high level radioactive waste, and developing innovative technologies such as fast reactors and new small and medium sized reactors” [104].

As a result of all the above actions, nuclear safety is improving throughout the world. Operational safety at NPPs remains high and improves steadily, as shown by the safety performance indicator presented in Fig. 29. The number of unplanned shutdowns (‘scrams’) per 7000 hours (approximately one year) of operation is commonly used as an indication of success in improving plant safety. In 2014, this indicator was below 0.5/7000 hours for the first time in at least a decade.

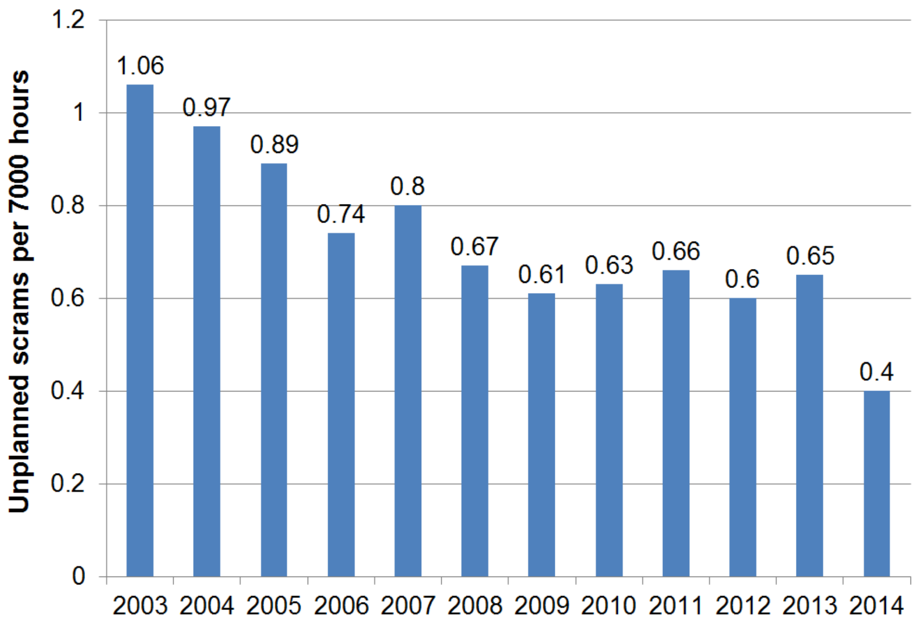

FIG. 29. Total number of unplanned scrams, including both automatic and manual scrams per 7000 h of critical power reactor operation. Data source: Ref. [105].

4.3. WASTE MANAGEMENT AND DISPOSAL

Opponents of using nuclear power as part of the climate change mitigation strategy argue that the nuclear industry cannot deal with the radioactive waste it produces and thus creates another severe environmental risk. These arguments exploit long standing public concerns about radioactive waste, which can, if not managed appropriately, create hazards for humans and the environment lasting for centuries — or millennia. Over the past three decades, major advances have been made towards the safe storage and final disposal of spent fuel and 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 repositories 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 a nuclear reactor, the formation of new radionuclides causes the fuel to become highly radioactive. As the depleting fuel reduces the efficiency of the reaction, it needs to be removed. The first step involves a temporary storage phase to reduce both the radiation and heat output of the highly reactive materials prior to waste handling and transfer to the final disposal site. Radioactive waste undergoes a number of predisposal management steps to transform it into a safe, stable and manageable form suitable for transport, storage and disposal. The pre-treatment involves decontamination techniques to reduce the volume of waste and conditioning to encapsulate the waste in cement, bitumen or glass to slow any release of radionuclides [106]. It has been demonstrated over the past decades that interim storage of spent fuel and high level radioactive waste is a technically feasible and safe solution for several decades if monitoring, control and care are properly implemented [107, 108].

Deep geological disposal has emerged as the ultimate solution for isolating high level waste and spent fuel from humans and the environment. Considering the long time spans involved, the OECD NEA Radioactive Waste Management Committee suggests a geological system that provides a unique level and duration of protection for spent fuel and high level radioactive waste. The safety is based on the IAEA safety standards and the recommendation of the International Commission on Radiological Protection [109]. The principles of geological disposal are well understood, and the disposal sites are designed to be passively safe [110, 111].

The long term safety is based on the multibarrier concept in which the synergy of several engineered and natural barriers prevent the transport of radionuclides produced in radioactive waste repositories from chemical and biochemical reactions as well as radioactive decay via different pathways (e.g. groundwater, migration of gas, etc.) [112]. The engineered barriers are a high technology solution proposed in advanced programmes and contribute significantly to the overall costs of a geological disposal facility [109]. They comprise a solid waste matrix and various containers and backfills to immobilize the waste inside the repository. The natural barrier (the geosphere) is composed of a rock and groundwater system isolating the repository and the engineered barrier system from the biosphere. The host rock is part of the natural barrier in which the repository is located. Following geological assessments, locations are selected in a tectonically stable environment at depths of several hundred meters, where 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, possibly longer. After a suitable geological formation is chosen and the repository is constructed, the engineered structures containing the waste are placed there [113]. Figure 30 shows the design of a deep disposal facility.

The site characterization and selection for deep geological repositories have been under way since the 1970s and disposal programmes for spent fuel and high level waste are well advanced in several countries, such as Finland and Sweden, where licensing is close to completion and the general principles and

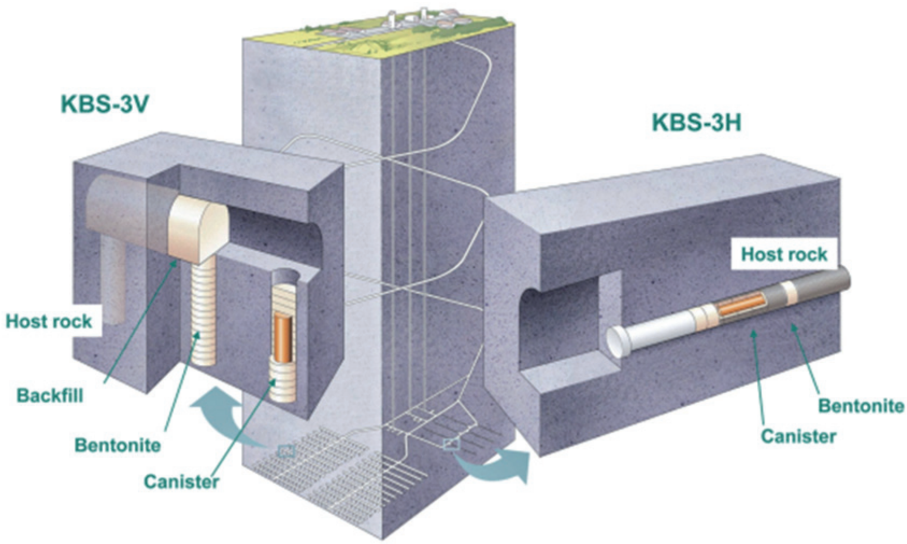

FIG. 30. The KBS-3 disposal concept. Sources: Refs [114, 115]. Note: KBS — nuclear fuel safety; H — horizontal; V — vertical. Reproduced courtesy of SKB [115].

designs are similar. Likewise, France is currently preparing a licence application for geological disposal in a clay rock host formation. As of 2014, 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. 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 in 2020. The final disposal of spent nuclear fuel is planned to start in 2022 and will continue until 2120.

The Swedish Nuclear Fuel and Waste Management Company (SKB) submitted its application for a final spent fuel repository to be located in Östhammar in March 2011. With construction work planned to start in 2019, disposal operations could begin in the late 2020s. The National Radioactive Waste Management Agency (ANDRA) in France 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, technical, political and public participation) required for the characterization, licensing, selection and construction of disposal sites.

Based on the multidecadal investigations and research programmes concerning the disposal of radioactive waste in many countries, other areas of research dealing with climate change could benefit greatly from the knowledge and expertise accumulated [113]. The geological disposal of CO_2, a technology currently being considered to reduce emissions from fossil fuel combustion into the atmosphere, could benefit significantly from the experience gained in exploring radioactive waste disposal. These include, inter alia, dealing with various types of uncertainty, systemic methodologies for transparent audit and assessment processes, as well as modelling long term system evolution using information from natural systems [116]. While there are some fundamental differences between the two waste products, there are many issues facing the disposal of both CO_2 and radioactive waste, including legal issues like the ownership of the underground space and liability for the disposal sites, transparency, public information, public acceptance and possible compensation, and ethical considerations like intergenerational equity [117].

To foster the adequate management of spent fuel and radioactive waste, the IAEA publishes basic principles about nuclear energy systems, including human, technical, management and economic aspects. The framework defines the appropriate institutional, funding and legal structures for the long term management of spent fuel and radioactive waste storage, reprocessing and disposal facilities. With a view to the continuous progress of nuclear technologies, the basic principles require spent fuel and high level waste to be retrievable from deep geological sites for future reprocessing or recycling to extend the fuel resource base [118]. All in all, given present solutions to manage and dispose of radioactive waste ranging from low to high level waste as well as spent fuel, the 'waste problem' should not prevent nuclear power from contributing to climate change mitigation.

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 concept under which all this work takes place is the so-called State level concept.

The IAEA collects and processes information relevant to safeguards about a State from a wide range of sources: information provided by the State itself; safeguards activities conducted by the IAEA in the field and at its headquarters; and 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 may 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 energy is an important component of the current global energy mix and a feasible option for countries looking to reduce GHG emissions. Some countries use nuclear energy to meet significant proportions of their domestic electricity demand (France (75%), Sweden (38%), USA (19%)) with the extra benefit of energy security and less dependence on fossil fuels. Public opinion about nuclear energy tends to fluctuate and is affected by many factors. This section presents the changes in public opinion about nuclear power in recent years in selected countries based on public opinion polls. It is important to note that the results of polls vary considerably depending on how the questions are framed and arranged, thus invariably they are just indicative and should not be considered definitive. Different polling organizations use different sample sizes and this can also influence data quality and reliability.

According to Lühiste et al. [119], past research has shown that accidents such as those at Three Mile Island and Chernobyl can reduce public acceptance of nuclear energy but this is not a universal trend for all countries. For example, after the Chernobyl accident, public opinion about nuclear power in the Netherlands, France and Belgium was recorded to be more pro-nuclear in 1987 than ever before [120]. Moreover, 18 new reactors became operational in Western Europe after the Chernobyl accident despite Italy closing all of its nuclear reactors and Denmark banning the construction of NPPs. Likewise, the USA did not reduce its nuclear energy production after the Three Mile Island accident but rather the opposite happened: nuclear generated electricity tripled between 1979 and 2007.

The accident at the Fukushima Daiichi NPP in Japan in 2011 has prompted some countries (e.g. Germany, Switzerland and Belgium) to phase out nuclear energy under pressure from domestic public opinion. At the same time, for many other countries it remains an important component of the energy mix as a relatively clean source for energy, especially for meeting GHG emissions reductions targets in the next decade. Figure 31 presents changes in public opinion in selected countries with NPPs currently in operation. The most recent survey in March 2015 of a long standing public opinion tracking programme — in existence for over 32 years and commissioned by the Nuclear Energy Institute — found that more than two thirds (68%) of US citizens support nuclear energy [121]. In Spain, public opinion in favour of nuclear energy has recovered to pre-Fukushima levels though it has remained lower than the EU-28 average [122]. This pattern of low

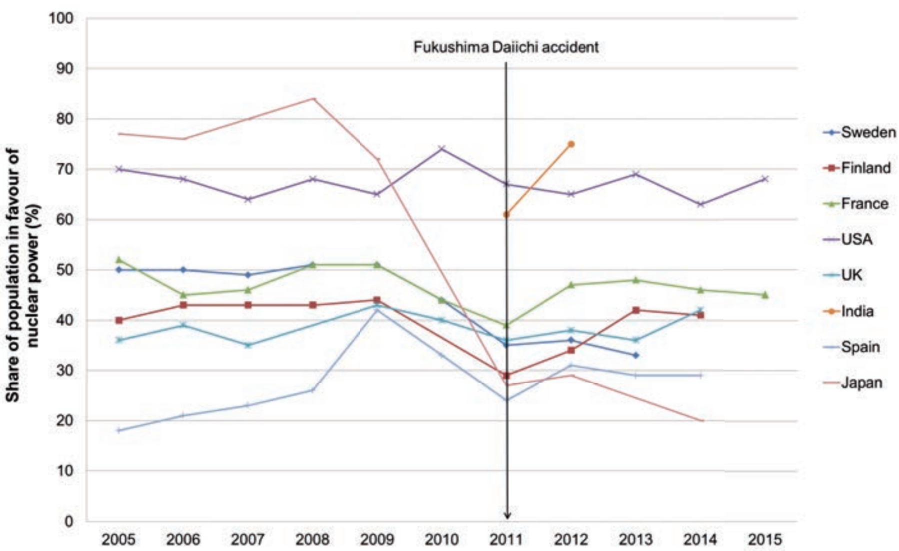

FIG. 31. Public opinion about nuclear power in countries with operating NPPs. Data sources: Refs [120–137].

public support (seen also in Romania in the last Eurobarometer study [123]) for a country with operational NPPs could be attributed to the relatively low level of public awareness of the importance of nuclear power in domestic energy production. Two successive global polls done by Ipsos MORI right after the Fukushima accident in 2011 and a follow-up global poll in 2012 found a 28% increase in public support for nuclear energy in India where domestic public opinion views nuclear energy as a long term viable option [124, 125].

According to the IAEA's projections [138] (see also Section 5.1), the majority of new NPPs will be built in China, India, the Russian Federation and the Republic of Korea. Many other countries aspire to add nuclear power to their electricity supply portfolio. These 'newcomer' countries either never have had a civilian nuclear energy programme or currently are not operating any reactors but want to seize the potential of nuclear energy. Seven countries have moved forward in actively developing nuclear programmes and two countries (Belarus and the United Arab Emirates (UAE)) have already started constructing their first NPPs [139]. IAEA Members States considering embarking on a nuclear energy programme find comprehensive guidance on how to develop a safe, secure and sustainable infrastructure for nuclear power in the IAEA publication Milestones in the Development of National Infrastructure for Nuclear Power [140].

Figure 32 presents recent data about public opinion in nuclear newcomer countries for the period 2009–2014. Apart from Poland and the Islamic Republic of Iran, public opinion in all other newcomer countries bounced back shortly after the Fukushima Daiichi accident. In Poland, a poll conducted by the Polish Institute of International Affairs (PISM) in August 2014 (see Refs [141, 142]) found 64% support, out of which 57% of the respondents cited energy independence as the main reason for their support followed by economic benefits and employment opportunities as additional reasons. Polls conducted by Gallup, the University of Maryland and the Rand Corporation show a decline in public support in the Islamic Republic of Iran from 87% in December 2009 to 68% in 2013 after the region's first civilian NPP was built at Bushehr in 2011 (see Refs [143–145]). The polls were conducted by phone and involved both rural and urban areas. The slide in support could be due to the Fukushima accident and the ongoing international economic sanctions that are crippling the Iranian economy. In the UAE, public opinion polls carried out by the market research company TNS found high public support for the first NPP being built at Barakah [146]. This enthusiasm can be attributed to the strong public engagement and information campaign spearheaded by the national government after the dip in public support in 2011 to 66% after the Fukushima accident [147].

In summary, four years after the Fukushima Daiichi accident which raised public concerns about nuclear energy worldwide, public acceptance seems to be on a rebound according to the polls in most countries already operating

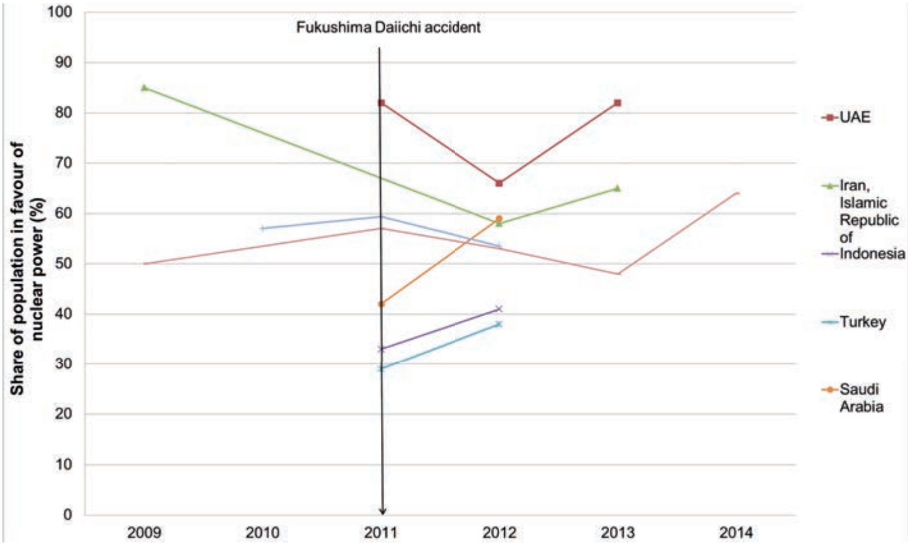

FIG. 32. Public support for nuclear power in newcomer countries. Data sources: Refs [141–149].

NPPs as well as in newcomer countries. Energy independence and tackling climate change are seen as the key advantages according to the public opinion polls. Despite delays in implementation in some countries and the abandonment of nuclear energy in others, the current trends in public acceptance indicate a promising future for nuclear energy in this century.

5. PROSPECTS FOR NUCLEAR POWER

5.1. NUCLEAR POWER PROJECTIONS

At the end of 2014, there were 438 nuclear power reactors in operation worldwide, with a total capacity of 376 GW(e). This represents an increase of approximately 5 GW(e) in total capacity compared to 2013. There were five new grid connections, while only one reactor was officially declared permanently shut down in 2014.

Each year, the IAEA publishes projections of global energy and electricity demand, the world’s nuclear power generating capacity and power generation for the forthcoming decades. The projections presented in the 2015 edition [150] draw on two major sources as background information:

- — National projections submitted by countries for a recent OECD/NEA study;
- — 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 33 and 34). 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 2015, 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 (see Section 3.5). 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.

Over the short term, the low price of natural gas and increasing capacities of subsidized renewable energy sources are expected to affect nuclear growth prospects in some regions of the developed world. These low natural gas prices

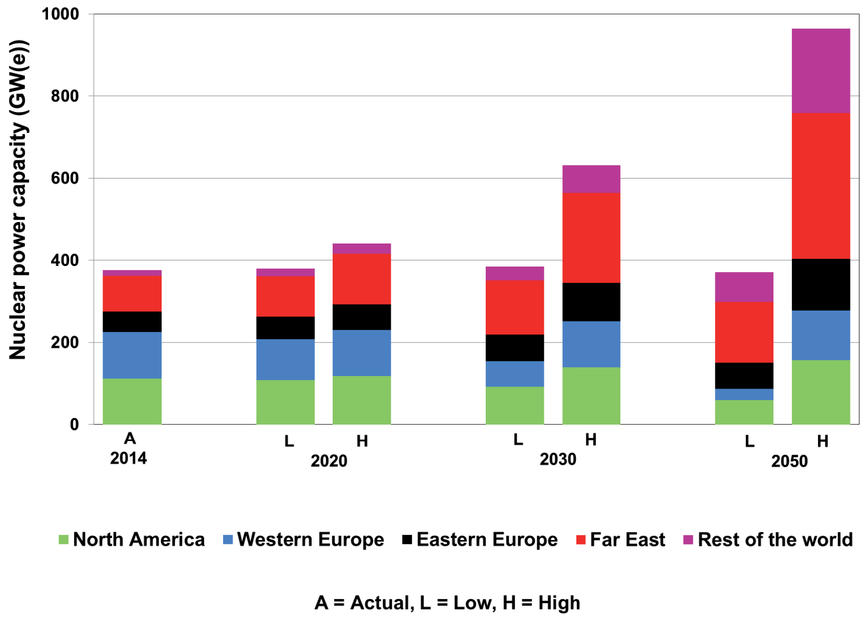

FIG. 33. Prospects for nuclear power in major world regions: estimates of installed nuclear capacity. Data source: IAEA [150].

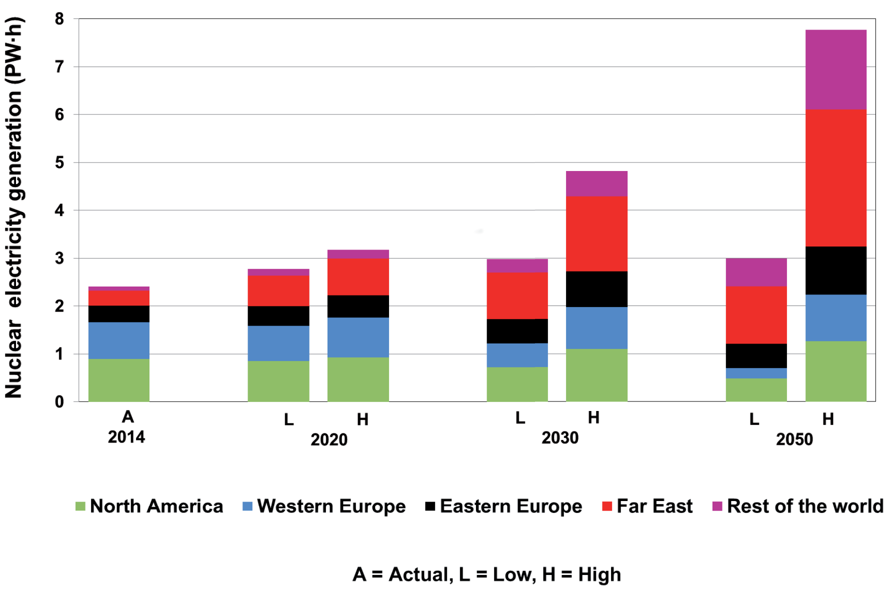

FIG. 34. Prospects for nuclear power in major world regions: estimates of nuclear electricity generation. Data source: IAEA [150].

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.

In recent years, 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 2014 global nuclear capacity projections for 2030 [3], the 2015 projections are lower by approximately 67 GW(e) in the high case and by 15 GW(e) in the low case.[5] These lower projections reflect national responses to the Fukushima Daiichi accident and factors noted above. 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. It should be noted, however, that even the high projection is far below the nuclear capacity projected by IEA in the 2DS that would be required to limit the increase of the global mean temperature to 2°C above pre-industrial level.

5.2. SMART GRIDS AND NUCLEAR POWER

The term ‘smart grid’ refers to the increased use of communications and information technology throughout the electricity value chain from power plants through the transmission and distribution infrastructure all the way into the homes

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[5] 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).

and businesses of final users. A smart grid is thus a system where the components (e.g. meters, voltage sensors, fault detectors, energy consuming devices, etc.) are able to both send and receive information. The aim is to increase the flow of information and thereby provide system operators and consumers with more and better data to support their decisions in real time. Smart grid development involves technological challenges like distributed generation, which allows bidirectional energy flows. Current grids are designed for one directional flow but the increase of the share of intermittent renewable capacities in the grid will require the capability of reversing flows.

For power companies, utilities and transmission system operators, smart grid technologies provide more information and ultimately better knowledge about the state and operation of their system as events unfold and two-way communication allows for a greater degree of automation. Distribution automation technology, for example, can be used to optimize voltage and reactive power levels and facilitate efficiency measures, such as conservation voltage reduction. The experience of utilities shows that average energy savings from such measures have been 2.2% on average so far [151], somewhat lower than the potential estimated at around 3% [152]. Deployment of smart meters can also reduce metering costs, with savings in the range of 13–77% for recent programmes in the USA [153].

Smart grid technology can make systems more reliable as well. Information about interruptions or voltage fluctuations in remote locations can instantly find its way to control centres and systems can react automatically and take remediating actions. In a survey of projects for deployment of automated feeder switches, for example, it was found that the frequency of outages was reduced by 11–49% and both outage duration and the number of affected customers were also reduced [154].

A key component of smart grid development is the installation of smart meters — electricity meters that keep a running tab not only on total electricity consumption, but also when electricity is used. This makes it possible to differentiate prices based on the time of day. Since the cost of delivering electricity (and in competitive markets the wholesale price) can vary significantly during the course of a day, this should improve market efficiency by providing more accurate price signals to consumers. So while smart grid technologies can deliver important benefits to the electricity supply industry, the biggest potential for transformative change is conceivably on the demand side. The transaction costs of active participation in power markets could be reduced dramatically, opening up the opportunity for consumers to become active market participants individually or through an intermediary. This would mark a departure from the traditional industry structure where producers deliver electricity to customers who are largely passive market participants buying electricity at a fixed price.

The role of the utilities has been to deliver power to the customers when they want it, and they have had to match their production schedule to the consumption habits of their customers. However, if consumers are provided with the ability to better adapt their demand patterns as well as an incentive to do so (e.g. real time or 'time of use' pricing), this could radically change the functioning of the electricity market. It could pave the way for a more dynamic and decentralized marketplace with a larger number of participants. This should strengthen the market power of consumers and improve market efficiency. Simulations of a competitive electricity market estimate welfare gains from real time pricing equivalent to 2.5–11% of total electricity bills compared to flat rate pricing [155].

Exactly how smart grid deployment will affect nuclear power operation and investment is difficult to predict. It will heavily depend on local conditions and need to be evaluated against the national power market situation as well as the regulatory and institutional environment. It should benefit producers in general by improving asset utilization and operational efficiency, but the increased market power for consumers is likely to reduce margins and transfer wealth from producers to consumers. However, such shifts may prove to be transient as producers scale back investments in response to the lower margins [156].

Smart grid deployment could also lead to a shift among different asset types and a restructuring of generation portfolios. It would make it easier to accommodate variable sources, such as wind and solar, as lack of dispatchability and ability to load-follow would be less of an impediment to deployment of these technologies. NPPs could also benefit as flatter load curves would be suitable for the high steady load operation normally typical of these plants because a larger share of total electricity demand could be met through baseload operation. Since NPPs generally have low variable operating cost, they are high in the dispatch order and would rarely have to curtail operations in most markets. Conversely, plants lower in the dispatch order with higher running costs, such as mid-merit and peaking plants, would most likely see reduced operating time. Peak demand would be lower and the need for peak capacity would be reduced, limiting the role of such generators. Furthermore, in the past, ramping flexibility and ancillary services had to be provided by generators. If a range of participants on the demand side can enter the market and provide flexibility and other services then the need for (and value of) providing these on the supply side should drop (along with total costs). This will in particular be detrimental to the viability of assets like peaking plants that generate a large share of their revenues from generating electricity at times of high demand and from selling ancillary services. It follows that widespread adoption of smart grid technologies may improve the competitiveness of nuclear against conventional fossil generators, while it may reduce its competitiveness relative to variable renewable generators. Extreme scenarios of a smart grid and distributed generation revolution implying dismantlement of the traditional utility model represent visions of the future that are not conducive to nuclear power investments for which large balance sheets and secure revenue streams are normally required. However, such scenarios are most likely in competitive market environments that are not the main markets for new NPPs in the first place.

How extensive the smart grid revolution will be is highly uncertain and will depend on technology, development, policy, regulation and a host of other factors. Concerns over cyberattacks and invasion of privacy could hold back developments. Smart grid is already a major industry though and, according to estimates, investment in energy smart technologies, such as smart meters, distribution automation and storage, totalled US $16.8 billion in 2014, up by 8% from 2013 [157]. China is the biggest market for smart grid technologies and by the end of 2013 there were approximately 250 million smart meters installed in the country [158]. The costs of smart grid developments are significant, but the benefits could be higher. A fully functional smart grid serving all 145 million electricity customers in the USA is estimated to cost US $338–476 billion over a 20 year period with net benefits of US $1.294–2.028 trillion [159]. The nuclear industry is well advised to explore the risks and opportunities arising from such a development.

5.3. COMPARING EMISSIONS FROM FOSSIL PLANTS WITH CCS AND NUCLEAR POWER

CCS technology became a widely discussed element of the energy policy discourse in the 2000s. CCS is often seen as a possible response to the climate change challenge to secure the continued use of fossil fuels. CCS prevents venting CO_2 into the atmosphere by capturing it in the combustion process and transporting it to a suitable and safe storage site for long term storage. Currently, the most promising solution is deep geological formations that guarantee safe holding of CO_2 for a prolonged period of time. Some previously discussed options such as deep ocean storage [160] are not considered anymore due to their possible environmental risks.

Optimistic expectation about CCS peaked in the 2000s. According to the IPCC Special report on CCS [160], 15–55% (220–2200 Gt CO_2) of cumulative global mitigation efforts was projected to be associated with CCS by 2100. These expectations were bolstered when a pilot CCS project was launched at the Schwarze Pumpe power station (Germany) in 2008. The IEA projected in its 2010 WEO that by 2035 power generation from coal plants equipped with CCS would exceed that using conventional technology [161]. Since that time, however, practical difficulties have significantly lowered the expectations. In the 2014

WEO, significant capacity additions in CCS technology are expected only in the rather strict mitigation case envisioned in the 450 Scenario, and only after the 2020s [11]. In all other scenarios, CCS is projected to play only a marginal role in electricity generation. Specifically, in the intermediate 4DS presented in the ETP 2014 [17], coal based generation capacity without CCS is expected to be 1774 GW(e) by 2050, while coal with CCS is expected to be only 98 GW(e). The gap is even larger for natural gas: in the same scenario, total gas fired capacity is projected to reach 3184 GW(e) by 2050, out of which only 6 GW(e) will be equipped with CCS.

In October 2014, the first industrial scale coal plant with CCS was launched in Canada (the Saskpower Boundary Dam project) [162], demonstrating some commercial prospects for the technology. The project involved a refurbished 110 MW(e) power plant with the addition of a CCS system using post-combustion capture technology. The first new power plant using CCS technology is expected to be the Mississippi Power Kemper County plant in the USA [163]. This 582 MW(e) facility, however, faces significant construction delays: in WEO 2014 [11] it was projected to become operational in early 2015, but in late 2014 it was announced that it would not be completed before mid-2016.

Prospects for the large scale use of CCS are still debated but it is important to assess its possible contribution to GHG emissions reductions. Existing abatement estimates for CCS are largely hypothetical as the first industrial scale equipment is currently being deployed. Estimates presented in this section (from Ecoinvent, NREL and the majority of other sources) show not only CO_2 but all GHG emissions expressed in CO_2-eq. Normally they include atmospheric impacts of CO, CO_2, CH_4, N_2O, CCl_3CH_3, CCl_4, NF_3, halons, CFCs, HCFCs and HFCs, and cover the emissions over the entire life cycle.

The estimates for coal fired power plants presented in Fig. 35 demonstrate significant decreases in GHG emissions, by a factor of 6–7, in comparison with hard coal or lignite plants without CCS. The median value of emissions from CCS is estimated at 186 g CO_2-eq/kW·h (with the overall range of estimates being 39–410 g CO_2-eq/kW·h), while the median values for hard coal and lignite are 1156 and 1297 g CO_2-eq/kW·h, respectively. Gas fired plants equipped with CCS are estimated to reduce GHG emissions by a factor of 4–6 (see Fig. 36). On average, conventional gas plants are assessed to emit between 599 g CO_2-eq/kW·h (median value according to the NREL harmonized estimates) and 683 g CO_2-eq/kW·h (according to Ecoinvent). The range for more advanced combined cycle power plants is between 424 g CO_2-eq/kW·h (median value according to Ecoinvent) and 449 g CO_2-eq/kW·h (NREL estimates). When CCS is added to gas fired plants, emissions are expected to be in the range of 34–245 g CO_2-eq/kW·h with a median value of 129 g CO_2-eq/kW·h.

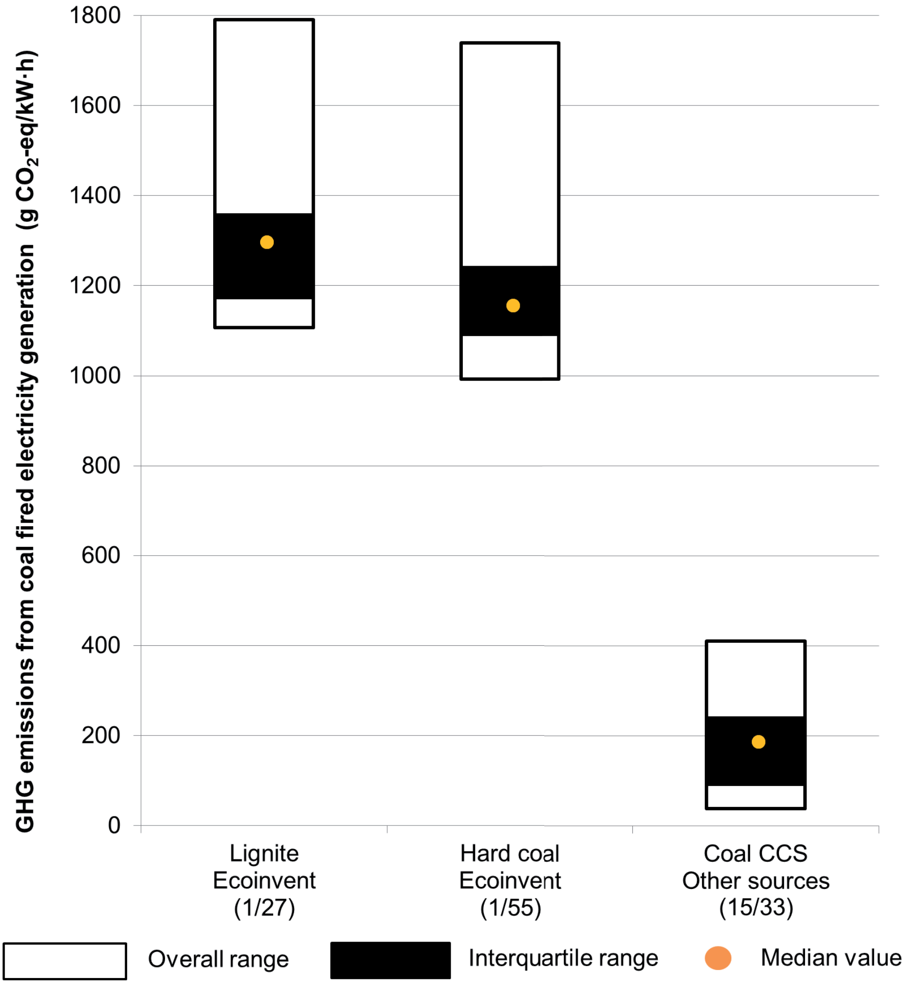

FIG. 35. Life cycle GHG emissions from coal based technologies. Data source: IAEA calculations using data from Ecoinvent [18], NREL [19] and IAEA [164]. Note: The numbers in parentheses indicate the number of sources/estimates. The interquartile range includes half of the calculations around the median of the overall range. CCS — carbon dioxide capture and storage.

The emissions ranges presented in Figs 35 and 36 are still far from those of renewables and nuclear power (with emissions estimates in the range of 3.5–110 g CO_2-eq/kW·h and median value 14.9 g CO_2-eq/kW·h) (see Section 2.3). Therefore, CCS can only be a partial solution, an intermediary technology to be used during the transition towards a truly low carbon economy. The costs are still hard to predict considering its current semi-experimental status. The

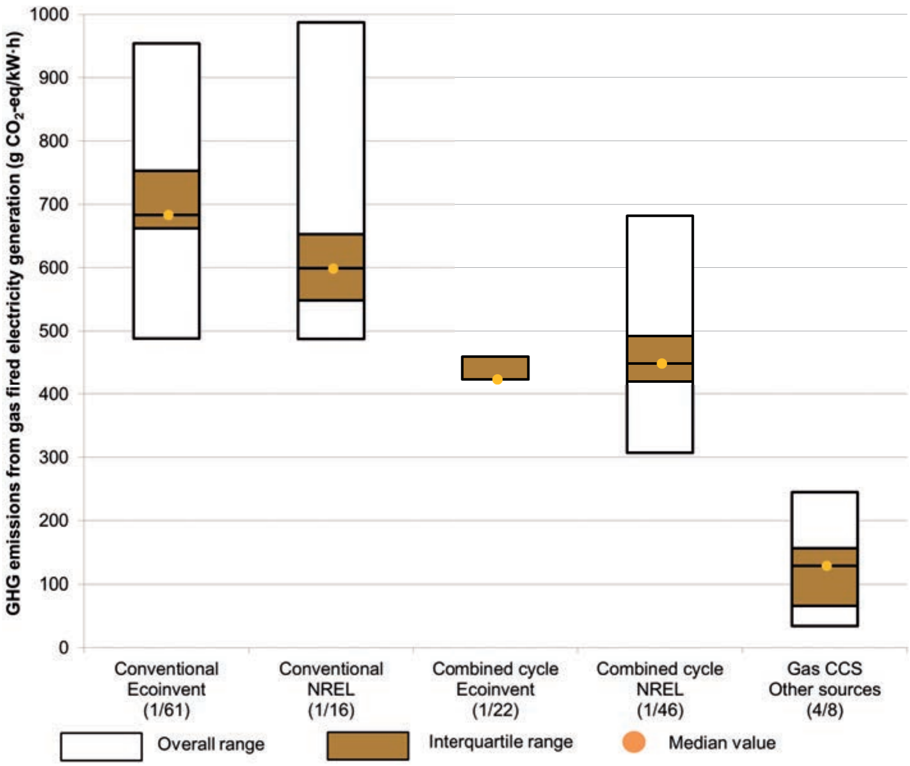

FIG. 36. Life cycle GHG emissions from gas based technologies. Data source: IAEA calculations using data from Ecoinvent [18], NREL [19] and IAEA [164]. Note: The numbers in parentheses indicate the number of sources/estimates. The interquartile range includes half of the calculations around the median of the overall range. CCS — carbon dioxide capture and storage.

cost of the refurbishment and the full integration with CO_2 capture technology of the 110 MW Boundary Dam coal fired plant was Canadian $1.4 billion. The construction costs of the Kemper Project are continuously increasing as its completion is delayed, prospectively making it one of the most expensive power plants in terms of the cost per unit of generation capacity ($/kW(e)). Moreover, CCS significantly reduces the resource efficiency of the plants because a considerable share of the electricity generated is used for operating the capture equipment and this increases the amount of fuel per kW·h of net power output by up to 40% [160]. This makes the future of construction of new coal generation capacities with CCS somewhat uncertain and raises the question of switching directly to genuinely low carbon technologies (renewables and nuclear).

Nonetheless, the use of CCS will be meaningful for reducing emissions from the power system based on intermittent renewable sources (see Section 2.8). Such systems will need significant backup capacities and spinning reserves due to the unpredictable variations of wind and solar output; CCS can reduce the carbon intensity of the combined system, especially if existing power plants are refurbished with CCS equipment (like the Saskpower Boundary Dam project). In this respect, the plants based on fossil fuels with CCS are likely to serve as backup capacity. However, their capability to change their output fast enough to balance the variations in the grid is yet unproven. In this case, CCS plants are not in a direct competition with nuclear power due to their much higher life cycle GHG emissions but they have the potential to contribute to the reliability of electricity supply systems including high shares of intermittent renewables. Nevertheless, siting CO_2 storage locations remains challenging.

5.4. IMPACTS OF CLIMATE CHANGE ON NUCLEAR ENERGY

Anthropogenic climate change is projected to increase the global mean temperature and precipitation and affect most other attributes of the Earth's climate, albeit with considerable regional variations. These changes will also modify the frequency, intensity, duration, timing and spatial extent of extreme events and might trigger considerable impacts for the nuclear energy sector. Changes in climate and extreme weather events will modify hydrological conditions everywhere. The amount of water resources, their interannual and seasonal variation, flood and drought conditions, magnitudes and frequency will change. Combined with projected increases in the demand for water in most sectors (agriculture, industry, households), these changes will pose major challenges for water management [165]. Water is a key external resource for NPPs due to their special features such as the need to preserve the physical protection and security of the power plant and ensure the operation of the diverse, independent and redundant safety systems. Most importantly, there is a need for long term core cooling and for reliable electric grid connection.

The nuclear energy sector will be affected by climate change and extreme weather events in many ways. Higher mean ambient air temperatures will reduce the efficiency of thermal conversion, leading to less output from the same capacity. Higher air and water temperatures will reduce cooling efficiency, increasing the demand for water diversion for cooling purposes. Lower precipitation will decrease the amount and increase the temperature of water available for cooling. Greater windiness would increase and lower windiness would decrease cooling performance while the former may also increase evaporation from the cooling facilities. Increased insolation in general would warm exposed surfaces. Finally, in coastal regions gradual sea level rise may increasingly affect power plants located at low elevation. The impacts of these relatively slow and gradual changes in climate attributes will produce some minor effects for which it is easy to prepare.

In contrast, extreme weather events are causing problems to NPP operators under the current climate regime and it is expected that the impacts of more frequent and more intense events will increase the related challenges and potential damages. Warm spells with very high temperature conditions lasting longer will exacerbate the decline of conversion efficiency and increase the cooling challenge. Longer and more intense drought conditions will add to these problems. At the other end of the spectrum, extreme precipitation events can lead to floods, inundating emergency equipment, spent fuel storage and other sensitive installations.

Various combinations of extreme events may intensify the above problems. For example, the combination of extreme high temperature and extreme low precipitation conditions can lead to acute cooling problems. These conditions also favour bush and forest fires in the area surrounding NPPs, inhibiting access to the site for personnel and supplies. If wind brings smoke and soot to the plant site, they can damage instrumentation, switchyards, transformers and other sensitive equipment. Lightning can also damage instrumentation and control as well as the switchyard and other parts of the electric equipment.

Extreme wind events can cause structural damage, blow debris against buildings or deposit it in sensitive areas. The loading parameters of interest here are wind strength, gustiness and persistence. Increased force on buildings can cause structural damage to large structures, or collapse of cooling towers, chimneys and high cranes. The group effect of neighbouring large structures can lead to turbulence and jets, increasing the wind force. Extreme wind can also swing electric cables and trigger flashover, and cause damage to the switchyard. Moreover, pressure differentials can create false signals to the instrumentation and affect ventilation systems.

Other combinations may also lead to severe consequences. Extreme rain with simultaneous strong wind can increase the flood risk. Wind combined with low precipitation and/or high temperature may lead to sand storms in some regions whereby dust and sand can damage the exposed surfaces and deteriorate or inhibit functioning of equipment.

All these impacts will affect the operation of existing NPPs and the design, siting and operation of future NPPs. The major challenge will be associated with water and cooling. In the past ten years, reactors in several countries had to be shut down or operated at reduced capacities due to restricted availability of cooling water. Various technologies are used at NPPs for cooling purposes, depending on the local climatic and hydrological conditions. They will need to be enhanced and further developed in response to changing mean climatic attributes and extreme weather events.

What were the major effects of weather events on the operation of NPPs in recent years? The IAEA collects data from its Member States about the operation and performance of NPPs in the Power Reactor Information System (PRIS) [105]. Outages are classified according to a large variety of internal technical (e.g. plant equipment failure) and operational (e.g. inspection, maintenance or repair combined with refuelling) as well as external technical (e.g. grid failure or grid unavailability), environmental (e.g. flood) and other causes. The category 'environmental conditions' includes all events and conditions in the natural environment that lead to operation at reduced capacity or temporary shutdown. Some environmental causes are geological (earthquake, tsunami) but most of them are weather related, such as the lack of cooling water due to dry weather, cooling water temperature above regulatory limits, lightning, flood, storm, etc.

Figure 37 shows the distribution of outages due to eight weather related causes between 2004 and 2013. More than two thirds of the outage events were due to warm cooling water in this eight year period. Interestingly — although not surprisingly if one considers the location of many nuclear plants in the temperate zones — cooling water that was too cold was the second most common cause, responsible for more than a fourth of the outages.

Figure 38 shows annual outage data. A decade is far too short to analyse linkages between weather and outage trends. Nevertheless, it is worth noting that

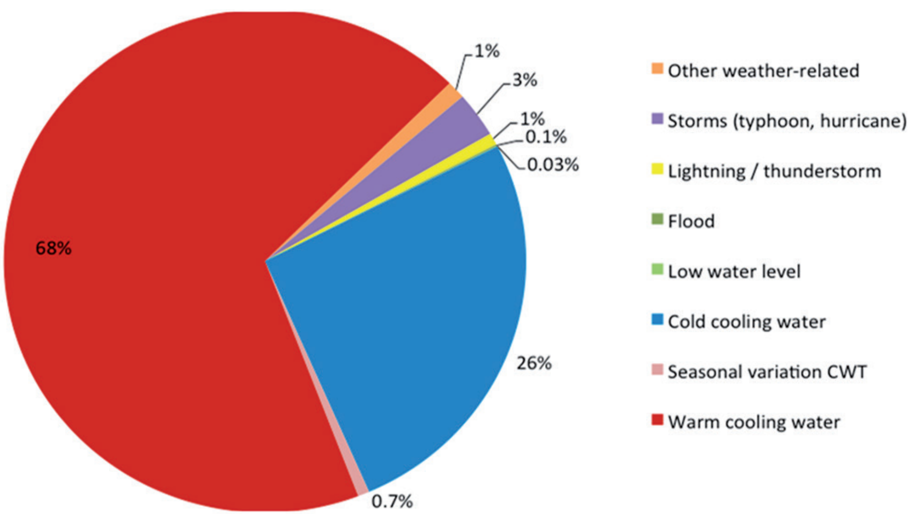

FIG. 37. Distribution of outage events due to weather related causes in 2004–2013. Data source: Ref. [105]. Note: CWT — cooling water temperature.

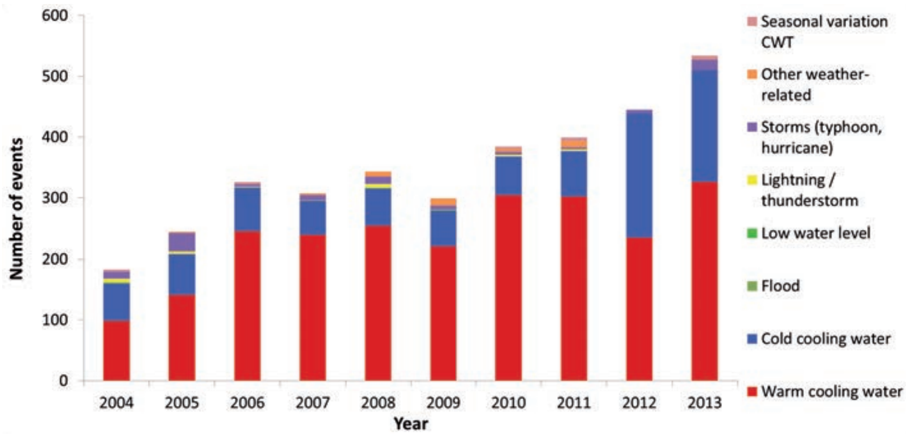

FIG. 38. Number of outage events due to weather related causes in 2004–2013. Data source: Ref. [105]. Note: CWT — cooling water temperature.

between 2004 and 2013, numbers of outage events due to most other weather related causes changed only slightly while the number of outages due to warm and cold cooling water has significantly increased, although some fluctuation can be observed.

As noted above, high ambient water temperatures diminish the cooling capacity of NPPs. In many countries and regions, warm water discharge may not be allowed legally when water temperatures are already high. The result is forced shutdown. In the summer of 2003, France lost 5.3 TW·h of electricity from 17 nuclear plants worth about 300 million euros, although the regulator granted waivers to discharge water above the prescribed temperature limit in several cases. The loss was only about 1% of the total annual electricity production that year but it happened at a very bad time of extreme peak loads mostly due to air conditioning. Three years later in 2006, the French regulator had to grant waivers again for hot water discharge while in Germany thermal power plants had to reduce their operation by the equivalent of 1741 MW(e) capacity in total [166].

In general, every 24 hours a 1 GW(e) NPP is shut down, the cost to the owner (in terms of lost income) is about \$1.2 million (assuming an electricity price of \$50/MW·h). Beyond these direct costs to the owner, outages leading to wider blackouts can impose substantial indirect costs. The extent to which these indirect costs should be taken into account by power plant operators when they make decisions on investments that would make their operation less vulnerable to extreme weather events depends on the electricity market regulation scheme and the delivery obligation rules.

Figures 37 and 38 show that NPPs are exposed and vulnerable to various types of extreme weather events under the current climate regime, especially to extremely hot periods that can significantly increase the temperature of water bodies used for cooling (rivers, lakes). At the same time, the industry has demonstrated resilience and capacity to adapt to changing conditions.

Changes in climate and extreme weather events in the future will raise new challenges, including the design and implementation of adaptation measures for existing NPPs to make them less vulnerable and more resilient to changing extreme weather events. The first question is always safety: what enhanced safety measures are necessary to withstand more frequent and more intense extreme weather events and keep safety at the prescribed level specified by the applicable safety standards and regulations. The next questions concern the related costs and whether those safety improvements and other adaptation measures are worth making with a view to the expected gains in terms of uninterrupted operation and income generation during the rest of the economic life of the power plant.

Decisions are somewhat easier for new builds. The design bases in related areas will be changed in response to projected degrees of climate change and shifts in extreme weather events. This will also include various safety standards and guides. Criteria for site selection for new builds will also have to consider projected climate change in the region. Finally, major components can be chosen and developed according to the climatic conditions projected to prevail at the selected site for the next 60–80 years. The IAEA prepares and publishes periodically revised safety standards and other documents to enhance the capacity of its Member States to design, build and operate NPPs to the highest level of safety to endure the impacts of global climate change in the coming decades.

Over the longer term, the nuclear sector can reduce its vulnerability to high temperature extremes and cooling water problems by developing and installing dry cooling equipment. Moreover, future nuclear technologies will be more efficient, produce less waste heat and thus will require less cooling water.

Appendix

SHORT SUMMARIES OF 2013 AND 2014 SECTIONS OMITTED FROM THIS EDITION

This Appendix presents short summaries of sections in the 2013 [167] and 2014 [4] editions of this publication 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 and 2014 editions for details.

Sections in the 2014 edition

A.1. POWERING ENERGY INTENSIVE INDUSTRIES

An estimated 36% of the world's CO_2 emissions are attributed to manufacturing industries, yet the associated energy requirements are dominated by a few key industries. These energy intensive industries comprise the chemical and petrochemical, iron and steel, cement, pulp and paper, and aluminium branches. As industry consumed 42.6% of world electricity in 2011, major reductions in CO_2 emissions from electricity generation could be achieved by substituting fossil based power generation with nuclear energy and other low carbon energy sources as well as within some of the production processes themselves.

The chemical and petrochemical industry requires large amounts of hydrocarbon feedstock, thus greatly limiting the possibility to decrease fuel consumption. In the iron and steel industry, 30% of global steel production uses electric arc furnaces, where CO_2 emissions could be reduced by increasing the share of nuclear energy. Cement manufacturing requires the mixing of ingredients under intense heat, resulting in very energy intense 'wet' processes in which slurry water needs to be evaporated. To achieve a reduction in CO_2 emissions, increased electrification of production processes would be necessary to facilitate the substitution of fossil fuels by low carbon energy sources. The paper and pulp industry meets almost half of its energy needs from biomass, part of which is a by-product of the industry itself. Nonetheless, electricity constitutes a major component of energy demand in paper and pulp production. Consequently, a decrease in related GHG emissions using low carbon technologies in power generation is possible. The aluminium industry's dominant production process (Hall–Héroult reduction) requires a constant source of power traditionally provided by hydroelectricity. However, with limited opportunities to further expand hydropower capacity in developed countries, nuclear energy could satisfy this particular demand.

A.2. FINANCING COSTS OF NUCLEAR POWER INVESTMENTS

The viability of nuclear energy projects and hence their potential contribution to climate change mitigation crucially depends on the ability of investors to raise large volumes of capital. Financing costs constitute a major portion of the total investment costs. They are heavily influenced by the duration of construction and the interest rate. This can be shown by comparing the relative amounts of interest during construction (IDC) incurred by two projects of identical value ($5.75 billion) in terms of overnight costs (costs of materials, equipment, labour, etc.), but which differ in terms of project duration and the rate of interest paid on financing. The total amounts of IDC incurred by these two projects was almost $2.8 billion if a 7 year construction duration and 10% rate of interest was assumed, versus $1 billion if a 5 year duration at a 5% rate of interest was assumed. The two main ways in which IDC can be decreased include reducing the duration of the construction period and obtaining the required financial resources at the lowest possible interest rate.

A.3. LIFETIME EXTENSIONS

The bulk of the global fleet of nuclear power reactors were constructed in the 1970s and 1980s and many are operating near or even beyond their initially anticipated technical lifetimes (e.g. 30 or 40 years). Several IAEA Member States have therefore given high priority to licensing their NPPs to longer term operation past these original time frames. The engineering specialty dedicated to managing the ageing of NPPs is often referred to as plant life management. It involves systematic analysis of the ageing of structures, systems and components and it is 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 aim is to ensure safe, long term supply of electricity in the most economically competitive way.

Extending the operating life of existing NPPs is often cost competitive compared to building new capacity. As long as safety can be ensured, long term operation will therefore usually be preferable. Unless all of the power capacity replacing retired NPPs is carbon free, lifetime extension will also reduce carbon emissions. The carbon reduction benefit of extending operating licences in the USA, for instance, has been approximately 540 g CO_2/kW·h of electricity generated by NPPs with extended licences.

A.4. 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, operation and maintenance, and any new capital expenses. If these criteria are not met, the plant is likely to be closed. While wholesale electricity prices in most markets have remained high enough to keep profit margins adequate to support investment in the extension of the operating life of nuclear power stations, 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 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 amounts of additional natural gas accessible at a low cost, bringing down natural gas prices and consequently also electricity prices. The lower prices have been a contributing factor to recent NPP retirements such as the Kewaunee and Vermont Yankee plants.

Although the replacement of the incumbent generation by lower cost competitors in itself is not a reason for concern, closing down NPPs early is likely to lead to increases in GHG emissions. A straight substitution of gas for nuclear power would lead to an increase in emission intensity of around 390–430 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 by the IEA 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.

A.5. SMALL MODULAR REACTORS

Today's global energy market is in the midst of a paradigm shift, from a model dominated by large centralized power plants owned by large utilities to distributed energy generation facilities — smaller residential, commercial and industrial power generation systems. Small modular reactors (SMRs) with less than 300 MW(e) capacity could serve an important role in energy security as well as provide the flexibility to integrate with small and regional transmission and distribution systems with less developed infrastructures. SMRs would also allow many countries without large power grids to gain the advantage of using low carbon nuclear as part of their climate change mitigation strategy.

Currently there are more than 45 SMR designs under development for different applications. In 2015, four reactors in the SMR category are under construction in Argentina (CAREM 25), the Russian Federation (KLT-40S and RITM-200 for floating nuclear power units) and China (HTR-PM with gas cooled reactor technology). These SMR designs are scheduled to be in operation by 2018. The projected timelines of readiness for deployment of other near term SMR designs (e.g. ACP100, SMART, NuScale) generally range from 2025 to 2030.

The IAEA is currently developing a technology roadmap for SMR deployment. The objective is to provide Member States with the planning foundation to ensure the availability of near term deployable SMRs as option to enhance energy supply security in the time frame of 2025–2030. The roadmap will help the Member States avoid unforeseen barriers to deployment and align investments with development needs. The IAEA is also developing SMR deployment indicators to provide Member States with a decision support system for adopting and deploying SMRs. The study defines indicators that assess the potential suitability for using SMRs in categories relating to finance and economy, technology, infrastructure, government policy, and energy and carbon reduction.

Sections in the 2013 edition

A.6. 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 because 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 replacement 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.7. 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 would be reduced in the long run and most of the radiotoxic elements produced in the fuel cycle could 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 LWRs, allowing the extension of the current sources available. Its future expansion will mostly depend on the growth of energy demand.

A.8. FAST REACTORS: BREEDING THE FUTURE

The introduction of 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 LWRs. 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. In addition, 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.9. 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 characterize 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 burned 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.

REFERENCES

[1] CARRINGTON, D., Ban Ki-moon urges governments to invest in low carbon energy, Guardian (3 Jun. 2015), http://www.theguardian.com/environment/2015/jun/02/ban-ki-moon-urges-governments-invest-low-carbon-energy

[2] GASPAR, M., Role of Nuclear Power Key in Combating Climate Change, IAEA Director General Says, IAEA (27 May 2015), https://www.iaea.org/newscenter/news/role-nuclear-power-key-combating-climate-change-iaea-director-general-says

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, 2014 edn, Reference Data Series No. 1, IAEA, Vienna (2014).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Climate Change and Nuclear Power 2014, IAEA, Vienna (2014).

[5] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Climate Change 1995: The Science of Climate Change, Contribution of WGI to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge (1996).

[6] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Climate Change 2007: The Physical Science Basis, Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge (2007).

[7] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Climate Change 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge (2013).

[8] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Climate Change 2014: Impacts, Adaptation, and Vulnerability, Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge (2014).

[9] UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, Report of the Conference of the Parties on its Fifteenth Session, held in Copenhagen from 7 to 19 December 2009, FCCC/CP/2009/11/Add.1, UNFCCC, Bonn (2010).

[10] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Climate Change 2014, Mitigation of Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge (2014).

[11] OECD INTERNATIONAL ENERGY AGENCY, World Energy Outlook 2014, OECD/IEA, Paris (2014).

[12] OECD INTERNATIONAL ENERGY AGENCY, World Energy Outlook 2013, OECD/IEA, Paris (2013).

[13] UNITED STATES CENSUS BUREAU, U.S. and World Population Clock, International Data Base (2015),
http://www.census.gov/popclock/

[14] ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, OECD Factbook 2014: Economic, Environmental and Social Statistics, OECD, Paris (2014).

[15] UNITED NATIONS, World Population Prospects: The 2012 Revision, UN, New York (2012),
http://esa.un.org/unpd/wpp/index.htm

[16] WORLD BANK, Global Economic Prospects, World Bank, Washington, DC (2015),
http://www.worldbank.org/en/publication/global-economic-prospects/data

[17] OECD INTERNATIONAL ENERGY AGENCY, Energy Technology Perspectives 2014: Harnessing Electricity's Potential, OECD/IEA, Paris (2014).

[18] CENTRE FOR LIFE CYCLE INVENTORIES, Ecoinvent Database Version 3 (2015),
http://www.ecoinvent.org/database/

[19] NATIONAL RENEWABLE ENERGY LABORATORY, Life Cycle Assessments of Energy Technologies (2015),
http://www.nrel.gov/analysis/sustain_lca_about.html

[20] IMAMURA, E., NAGANO, K., Evaluation of Life Cycle CO_2 Emissions of Power Generation Technologies, CRIEPI, Tokyo (2010) (in Japanese).

[21] THE INTERNATIONAL EPD SYSTEM, General Programme Instructions for the International EPD System 2.01, Stockholm (2013).

[22] OECD INTERNATIONAL ENERGY AGENCY, IEA World Energy Statistics and Balances, IEA, Paris (2015),
http://dx.doi.org/10.1787/data-00512-en

[23] WORLD BANK, World Development Indicators, World Bank, Washington, DC (2015),
http://data.worldbank.org/indicator/EG.ELC.NUCL.ZS

[24] BRUCKNER, T., et al., "Energy Systems", Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (EDENHOFER, O., et al., Eds), Cambridge University Press, Cambridge and New York (2014) 511–597.

[25] CLARKE, L., et al., "Assessing Transformation Pathways", Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (EDENHOFER, O., et al., Eds), Cambridge University Press, Cambridge and New York (2014) 413–510.

[26] WEYANT, J., et al., The EMF 27 Study on Global Technology and Climate Policy Strategies, Special Issue, Clim. Chang. **123** (2014) 345–783.

[27] KIM, S.H., et al., Nuclear energy response in the EMF 27 study, Clim. Chang. **123** (2014) 443–460.

[28] KREY, V., et al., Getting from here to there – Energy technology transformation pathways in the EMF 27 scenarios, Clim. Chang. **123** (2014) 369–382.

[29] INTERNATIONAL ATOMIC ENERGY AGENCY, Advances in Nuclear Power Process Heat Applications, IAEA-TECDOC-1682, IAEA, Vienna (2012).

[30] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Climate Change 2014: Synthesis Report, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (PACHAURI, R.K., MEYER, L.A., Eds), IPCC, Geneva (2015).

[31] LUDERER, G., et al., The role of renewable energy in climate stabilization: Results from the EMF 27 scenarios, Clim. Chang. **123** (2014) 427–441.

[32] KOELBL, B.S., et al., Uncertainty in Carbon Capture and Storage (CCS) deployment projections: A cross-model comparison exercise, Clim. Chang. **123** (2014) 461–476.

[33] EOM, J., et al., The impact of near-term climate policy choices on technology and emission transition pathways, Technol. Forecast. Soc. Chang. **90** (Part A) (2015) 73–88.

[34] OECD INTERNATIONAL ENERGY AGENCY, Special Report on Energy and Climate Change, OECD/IEA, Paris (2015).

[35] OECD INTERNATIONAL ENERGY AGENCY, Energy Security, IEA, Paris (2015), http://www.iea.org/topics/energysecurity/

[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Technology Review 2014, IAEA, Vienna (2014).

[37] NATIONAL ENERGY TECHNOLOGY LABORATORY, Thermal Plant Emissions Due to Intermittent Renewable Power Integration, NETL, Morgantown, WV (2010), http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/DOE-NETL-404-102909-ThermPlantduetoIntermittentRenewPowerIntegration.pdf

[38] OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2014: Resources, Production and Demand, OECD Publishing, Paris (2014).

[39] WORLD HEALTH ORGANIZATION, Air Quality and Health, Fact Sheet No. 313, WHO, Geneva (2014), http://www.who.int/mediacentre/factsheets/fs313/en/

[40] WORLD HEALTH ORGANIZATION, 7 million premature deaths annually linked to air pollution, News Release, WHO, Geneva (2014), http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/

[41] VAN DIJK, A., et al., Skin cancer risks avoided by the Montreal Protocol — Worldwide modeling integrating coupled climate-chemistry models with a risk model for UV, Photochem. and Photobiol. **89** (2013) 234–246.

[42] UNITED NATIONS ENVIRONMENT PROGRAMME, How the Montreal Protocol Protects Health, OzonAction Fact Sheet, UNEP Division of Technology, Industry and Economics, Paris (2014), http://www.unep.org/ozonaction/Portals/105/documents/events/MOP26/Fact%20Sheet%20How%20the%20MP%20protects%20Health%20Nov%2020.pdf

[43] NEW ENERGY EXTERNALITIES DEVELOPMENTS FOR SUSTAINABILITY (NEEDS), External Costs from Emerging Electricity Generation Technologies, Deliverable No. 6.1, RS1a, Project No. 502687 (2009), http://www.needs-project.org/docs/RS1a%20D6_1%20External%20costs%20of%20reference%20technologies%2024032009.pdf

[44] RABL, A., RABL, V.A., External costs of nuclear: Greater or less than the alternatives? Energy Policy **57** (2013) 575–584.

[45] APERGIS, N., PAYNE, J.E., A panel study of nuclear energy consumption and economic growth, Energy Econ. **32** (2010) 545–549.

[46] OMRI, A., CHAIBI, A., Nuclear Energy, Renewable Energy, and Economic Growth in Developed and Developing Countries: A Modelling Analysis from Simultaneous-equation Models, Working Paper 2014-188, IPAG Business School, Paris (2014), http://www.ipag.fr/wp-content/uploads/recherche/WP/IPAG_WP_2014_188.pdf

[47] EDF ENERGY, Hinkley Point C, Development Consent Order Application, Accommodation Strategy, Other Documents, Doc Ref 8.13 (2011), http://infrastructure.planningportal.gov.uk/wp-content/ipc/uploads/projects/EN010001/2.%20Post-Submission/Application%20Documents/Other%20Documents/8.13%20Accomodation%20Strategy/8.13%20Accomodation%20Strategy.pdf

[48] EDF ENERGY, Hinkley Point C, Pre-Application Consultation, Stage 2, Environmental Appraisal, Volume 2, Chapter 8 on Socio-Economics (2010), http://hinkleypoint.edfenergyconsultation.info/Preferred_Proposal_Documents/Environmental%20Appraisal/Volume_2/Environmental%20Appraisal-%20Volume%202%20MAIN%20MENU.pdf

[49] NUCLEAR ENERGY INSTITUTE, Nuclear Energy's Economic Benefits — Current and Future, NEI, Washington, DC (2014).

[50] MARI, C., Hedging electricity price volatility using nuclear power, Appl. Energy **113** (2014) 615–621.

[51] RIVERS, N., Renewable energy and unemployment: A general equilibrium analysis, Resour. Energy Econ. **35** (2013) 467–485.

[52] UNITED STATES NUCLEAR REGULATORY COMMISSION, Combined License Applications for New Reactors (2015), http://www.nrc.gov/reactors/new-reactors/col.html

[53] OECD INTERNATIONAL ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, Projected Costs of Generating Electricity: 2015 Edition, OECD Publishing, Paris (2015).

[54] OECD NUCLEAR ENERGY AGENCY, Nuclear Energy and Renewables: System Effects in Low-Carbon Electricity Systems, OECD Publishing, Paris (2012).

[55] OECD NUCLEAR ENERGY AGENCY, OECD INTERNATIONAL ENEGY AGENCY, Technology Roadmap – Nuclear Energy: 2015 Edition, OECD Publishing, Paris (2015).

[56] WORLD NUCLEAR ASSOCIATION, Nuclear Power in Belarus, WNA, London (2014), http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Belarus/

[57] COUR DES COMPTES, The Costs of the Nuclear Power Sector, Thematic Public Report, Cour des Comptes, Paris (2012).
[58] KOOMEY, J., HULTMAN, N.E., A Reactor-Level Analysis of Busbar Costs for US Nuclear Plants, 1970–2005, Electronic Annex for a Reactor-Level Analysis of Busbar Costs for U.S. Nuclear Plants: Documentation of Data and Methods, Energy Policy **35** (2007) 5630–5642.
[59] ROSNER, R., GOLDBERG, S., HEZIR, J.S., DAVIS, E.M., Analysis of GW-Scale Overnight Capital Costs, University of Chicago, Energy Policy Institute at Chicago, Chicago, IL (2011).
[60] LÉVÊQUE, F., Estimating the Cost of Nuclear Power: Benchmarks and Uncertainties, Working Paper 13-ME-01, Interdisciplinary Institute for Innovation/CERNA, MINES ParisTech, Paris (2013).
[61] WORLD NUCLEAR ASSOCIATION, The Economics of Nuclear Power, Information Papers, WNA, London (2008),
http://www.world-nuclear.org/uploadedfiles/org/info/pdf/economicsnp.pdf
[62] GRUBLER, A., The Costs of the French Nuclear Scale-Up: A Case of Negative Learning by Doing, Energy Policy **38** (2010) 5174–5188.
[63] RANGEL, L.E., LÉVÊQUE, F., Revisiting the Nuclear Power Construction Costs Escalation Curse, IAEE Energy Forum, International Association for Energy Economics, Cleveland, OH (2013),
http://www.iaee.org/documents/2013EnergyForum3qtr.pdf
[64] BERTHÉLEMY, M., RANGEL, L.E., Nuclear Reactors' Construction Costs: The Role of Lead-Time, Standardization and Technological Progress, WP 14-ME-01, CERNA, MINES ParisTech, Paris (2013).
[65] ANADÓN, L.D., BOSETTI, V., BUNN, M., CATENACCI, M., LEE, A., Expert Judgments about RD&D and the Future of Nuclear Energy, Environ. Sci. Technol. **46** (2012) 11497−11504.
[66] INTERNATIONAL ATOMIC ENERGY AGENCY, Investment Cost Data Collection, unpublished data.
[67] INTERNATIONAL FRAMEWORK FOR NUCLEAR ENERGY COOPERATION, Financing Nuclear Power Projects: New and Emerging Models (2014),
http://www.ifnec.org/Portals/0/Docs/Seoul%20Korea-Oct-2014/IFNEC%20
Finance%20Report%202014.pdf
[68] NUCLEAR ENERGY INSTITUTE, Loan Guarantee Finalized for Vogtle 3 & 4 (2014),
http://www.nei.org/News-Media/Media-Room/Media-Briefings/
Loan-Guarantee-Finalized-for-Vogtle-3-4
[69] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power Reactors in the World, 2006 edn, Reference Data Series No. 2, IAEA, Vienna (2006).
[70] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Power Reactors in the World, 2012 edn, Reference Data Series No. 2, IAEA, Vienna (2012).
[71] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Technology and Economic Development in the Republic of Korea, IAEA, Vienna (2009).

[72] OECD INTERNATIONAL ENERGY AGENCY, Energy Technology System Analysis Programme (2014),
http://www.iea-etsap.org/web/Supply.asp

[73] BP SOLAR, Proposed Solar Power Station Near Moree, NSW, Environmental Impact Assessment Report (2011),
http://www.moreesolarfarm.com.au/pdf/Environmental_Assessment_Report.pdf

[74] CALEDON WIND, Environmental Impact Assessment for the Proposed Caledon Wind Farm, Western Cape Province (2012),
http://projects.gibb.co.za/Portals/3/projects/201201%20Caledon/Caledon%20Final%20EIA%20Report_13Feb2012_Final.pdf

[75] WARREN, P., DE SIMONE, G., Fuelling the future? Energy Policy **74** (2014) S5–S15.

[76] DEFFEYES, K.S., MacGREGOR, I.D., Uranium Distribution in Mined Deposits and in the Earth's Crust, Princeton University, Princeton, NJ (1978).

[77] D'HAESELEER, W.D., Synthesis on the Economics of Nuclear Energy, Study for the European Commission, DG Energy, Final Report, European Commission, Brussels (2013).

[78] UNITED NATIONS, Sources and Effects of Ionizing Radiation (2008 Report to the General Assembly with Scientific Annexes), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Vol. I, UN, New York (2010).

[79] UNITED NATIONS, Sources and Effects of Ionizing Radiation (1993 Report to the General Assembly with Scientific Annexes), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (1993).

[80] CANADIAN NUCLEAR SAFETY COMMISSION, Radon and Health INFO-0813, CNSC, Ottawa (2011).

[81] McBRIDE, J.P., et al., Radiological impact of airborne effluents of coal and nuclear plants, Sci. **202** (1978) 1045.

[82] UNITED NATIONS, Exposures and effects of the Chernobyl Accident, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2000).

[83] WORLD HEALTH ORGANIZATION, Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, WHO, Geneva (2012).

[84] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation (2013 Report to the General Assembly with Scientific Annexes), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Vol. I, UN, New York (2014).

[85] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation (2013 Report to the General Assembly with Scientific Annexes), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Vol. II, UN, New York (2014).

[86] GHIASSI-NEJAD, M., et al., Very high background radiation areas of Ramsar, Iran: Preliminary biological studies, Health Phys. **82** (2002) 87.

[87] HENDRY, J.H., et al., Human exposure to high natural background radiation: What can it teach us about radiation risks? J. Radiol. Prot. **29** 2A (2009) A29–A42.

[88] ANJOS, R.M., et al., Radioecology teaching: Evaluation of the background radiation levels from areas with high concentrations of radionuclides in soil, Eur. J. Physics **25** (2004) 133.

[89] AJLOUNI, A.W., et al., Radiation doses due to natural radioactivity in the Afra hot springs, Jordan, Int. J. Low Radiat. **7** (2010) 48.

[90] OECD NUCLEAR ENERGY AGENCY, Actions taken by regulatory bodies and international organisations following the Fukushima Daiichi nuclear accident, OECD NEA, OECD Publishing, Paris (2014), http://www.oecd-nea.org/nsd/fukushima

[91] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Action Plan on Nuclear Safety, IAEA, Vienna (2011), https://www.iaea.org/sites/default/files/actionplanns.pdf

[92] INTERNATIONAL ATOMIC ENERGY AGENCY, Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GOV/INF/2012/11-GC(56)/INF/5, IAEA, Vienna (2012), http://www.iaea.org/About/Policy/GC/GC56/GC56InfDocuments/English/gc56inf-5_en.pdf

[93] INTERNATIONAL ATOMIC ENERGY AGENCY, Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GOV/INF/2013/8-GC(57)/INF/5, IAEA, Vienna (2013), http://www.iaea.org/About/Policy/GC/GC57/GC57InfDocuments/English/gc57inf-5_en.pdf

[94] INTERNATIONAL ATOMIC ENERGY AGENCY, Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GOV/INF/2014/15-GC(58)/INF/7, IAEA, Vienna (2014), https://www.iaea.org//About/Policy/GC/GC58/GC58InfDocuments/English/gc58inf-7_en.pdf

[95] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO'S Fukushima Daiichi Nuclear Power Station Units 1–4 (Third Mission), Tokyo and Fukushima Prefecture, Japan, 9–17 February 2013, IAEA, Vienna (2015), https://www.iaea.org/sites/default/files/missionreport170215.pdf

[96] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2012), https://www.iaea.org/sites/default/files/spentfuelsafety190312.pdf

[97] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Enhancing Transparency and Communication Effectiveness in the Event of a Nuclear or Radiological Emergency, IAEA, Vienna (2012), https://www.iaea.org/sites/default/files/enhancetransparency180612.pdf

[98] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2012), https://www.iaea.org/sites/default/files/protection040912.pdf

[99] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Decommissioning and Remediation after a Nuclear Accident, IAEA, Vienna (2013), https://www.iaea.org/sites/default/files/decommissioning0913.pdf
[100] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2014), https://www.iaea.org/sites/default/files/humanfactors0914.pdf
[101] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Radiation Protection after the Fukushima Daiichi Accident: Promoting Confidence and Understanding, IAEA, Vienna (2014), https://www.iaea.org/sites/default/files/radprotection0914.pdf
[102] INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna Declaration on Nuclear Safety, IAEA, Vienna (2015), https://www.iaea.org/sites/default/files/cns_viennadeclaration090215.pdf
[103] INTERNATIONAL ATOMIC ENERGY AGENCY, The Fukushima Daiichi Accident, 6 vols, IAEA, Vienna (2015).
[104] AMANO, Y., Statement to Fifty-Eighth Regular Session of IAEA General Conference 2014, Vienna (2014), https://www.iaea.org/newscenter/statements/statement-fifty-eighth-regular-session-iaea-general-conference-2014
[105] INTERNATIONAL ATOMIC ENERGY AGENCY, Power Reactor Information System, PRIS database (2015), http://www.iaea.org/pris
[106] INTERNATIONAL ATOMIC ENERGY AGENCY, Radioactive Waste: Meeting the Challenge, IAEA Bulletin, 55-3, IAEA, Vienna (2014).
[107] INTERNATIONAL ATOMIC ENERGY AGENCY, Storage of Radioactive Waste, IAEA Safety Standards Series No. WS-G-6.1, IAEA, Vienna (2006).
[108] INTERNATIONAL ATOMIC ENERGY AGENCY, Policies and Strategies for Radioactive Waste Management, IAEA Nuclear Energy Series No. NW-G-1.1, IAEA, Vienna (2009).
[109] INTERNATIONAL ATOMIC ENERGY AGENCY, Options for Management of Spent Fuel and Radioactive Waste for Countries Developing New Nuclear Power Programmes, IAEA Nuclear Energy Series No. NW-T-1.24, IAEA, Vienna (2013).
[110] CHAPMAN, N., MCCOMBIE, C. (Eds), Principles and Standards for the Disposal of Long-lived Radioactive Wastes, Waste Management Series No. 3, Pergamon Press, Amsterdam (2003).
[111] ALEXANDER, W.R., McKINLEY, L.E. (Eds), Deep Geological Disposal of Radioactive Waste, Radioactivity in the Environment Series No. 9, Elsevier, Amsterdam (2007).
[112] INTERNATIONAL ATOMIC ENERGY AGENCY, Disposal Approaches for Long Lived Low and Intermediate Level Radioactive Waste, IAEA Nuclear Energy Series No. NW-T-1.20, IAEA, Vienna (2009).

[113] BACHU, S., McEWEN, T., “Geological media and factors for the long-term emplacement and isolation of CO_2 and radioactive waste”, Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment (TOTH, F.L., Ed.), Springer, Dordrecht (2011) 23–79.
[114] VÄHÄNEN, M., Finnish Industry Research Programme for the Disposal of Nuclear Waste (2007),
http://www.stuk.fi/julkaisut_maaraykset/alara/alara_3_2007/fi_FI/alara_3_2007/_files/12222632510025106/default/vahanen_presentation.pdf
[115] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, SKB Swedish Nuclear Fuel and Waste Management Company, SKB (2009),
http://www.skb.se/default__24417.aspx
[116] MAUL, P.R., et al., Performance assessments for the geological storage of carbon dioxide: Learning from the radioactive waste disposal experience, Int. J. Greenh. Gas Control **1.4**, 444 (2007).
[117] TOTH, F.L., “Comparing the geological disposal of carbon dioxide and radioactive waste: Introduction and overview”, Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment (TOTH, F.L., Ed.), Springer, Dordrecht (2011) 1–20.
[118] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Fuel Cycle Objectives, IAEA Nuclear Energy Series No. NF-O, IAEA, Vienna (2013).
[119] LÜHISTE, M., MORALES, L., BISCHOF, D., BERNARDI, L., The Effects of the Fukushima Disaster on Nuclear Energy Debate and Policy: A Comparative Examination (2014),
http://paperroom.ipsa.org/app/webroot/papers/paper_35660.pdf
[120] KOOPMANS, R., DUYVENDAK, J.W., The political construction of the nuclear energy issue and its impact on the mobilization of anti-nuclear movements in Western Europe, Soc. Probl. **42** (1995) 235.
[121] BISCONTI RESEARCH, US nuclear support increasing, World Nuclear News (2015),
http://www.world-nuclear-news.org/NP-US-nuclear-support-increasing-2403158.html
[122] FORO NUCLEAR, Results and Nuclear Prospects (2014),
http://aspes.securezone.net/indexPop.jsp?id=3942/6193/25652&startPage=1&lng=es#3942/6193/256521es
[123] EUROBAROMETER, Special Eurobarometer 364 (2011),
http://ec.europa.eu/public_opinion/archives/ebs/ebs_364_en.pdf
[124] IPSOS MORI, Global Citizen Reaction to the Fukushima Nuclear Plant Disaster (2011),
https://www.ipsos-mori.com/Assets/Docs/Polls/ipsos-global-advisor-nuclear-power-june-2011.pdf
[125] KNIGHT, R., Monitoring Communication Impact: Tools and Public Perceptions of Nuclear Energy (2011),
https://www.iaea.org/NuclearPower/Downloadable/Meetings/2012/2012-10-09-10-11-TM-NPE/IpsosMori-Knight.pdf

[126] LITMANEN, T., Finnish Exceptionalism: Drivers of Nuclear New Build (2013), http://casepyhajoki.info/wp-content/uploads/2013/08/Tapio-Litmanen_Finnish-Exceptionalism_CasePyhajoki_010813
[127] ASAHI SHIMBUN, Nuclear Energy Poll (2014), http://mansfieldfdn.org/program/research-education-and-communication/asian-opinion-poll-database/listofpolls/2014-polls/asahi-shimbun-regular-public-opinion-poll-022814
[128] KITADA, A., Public opinion on nuclear power generation measured in continuous polls changes after Fukushima Daiichi nuclear power plant accident over the past 30 years, Trans. At. Energy Soc. Jpn. J. **12** (2013) 177–196.
[129] DEPARTMENT OF INTERNATIONAL AFFAIRS, JAIF, Trend of Public Opinions on Nuclear Energy after Fukushima Accident (March 11) in Japan (2011), http://www.jaif.or.jp/english/news_images/pdf/ENGNEWS02_1312778417P
[130] TORRES, I., Survey says 80% of Japanese don't want nuclear plants anymore, Jpn. Dly. Press (10 Mar. 2014), http://japandailypress.com/survey-says-80-of-japanese-dont-want-nuclear-plants-anymore-1045537
[131] KAMEDA, M., National or not, nuclear issue ranks high with Tokyo voters, Jpn. Times (2014), http://www.japantimes.co.jp/news/2014/02/03/national/politics-diplomacy/national-or-not-nuclear-issue-ranks-high-with-tokyo-voters
[132] KIDD, S.W., Nuclear power — Economics and public acceptance, Energy Strategy Rev. **1** (2013) 277, http://www.sciencedirect.com/science/article/pii/S2211467X13000394
[133] KOTLER, M.L., HILLMAN, I.T., Japanese nuclear energy policy and public opinion. Japanese Energy Security and Changing Global Markets: An Analysis of North-East Asian Energy Cooperation and Japan's Evolving Leadership Role in the Region, Baker Institute Policy Report 13, Houston, TX (2000).
[134] HOLMBERG, S., Swedish Opinion on Nuclear Power 1986–2013, SOM Institute, Gothenburg (2014).
[135] POORTINGA, W., AOYAGI, M., PIDGEON, N.F., Public perceptions of climate change and energy futures before and after the Fukushima accident: A comparison between Britain and Japan, Energy Policy **62** (2013) 1204–1211.
[136] LITZLER, J.-B., Pourquoi les particuliers ont moins confiance dans les énergies renouvelables, Le Figaro (22 Jan. 2015), http://immobilier.lefigaro.fr/article/pourquoi-les-particuliers-ont-moins-confiance-dans-les-energies-renouvelables_b871c3fa-a158-11e4-afe6-da40cd099cb4
[137] IPSOS MORI, Nuclear Energy Update Poll (2014), https://www.ipsos-mori.com/researchpublications/researcharchive/3284/British-public-split-on-nuclear-power.aspx
[138] INTERNATIONAL ATOMIC ENERGY AGENCY, International Status and Prospects for Nuclear Power 2014, GOV/INF/2014/13-GC(58)/INF/6, IAEA, Vienna (2014), http://www.iaea.org/About/Policy/GC/GC58/GC58InfDocuments/English/gc58inf-6_en.pdf

[139] WORLD NUCLEAR ASSOCIATION, Emerging Nuclear Energy Countries (2015), http://www.world-nuclear.org/info/Country-Profiles/Others/Emerging-Nuclear-Energy-Countries

[140] INTERNATIONAL ATOMIC ENERGY AGENCY, Milestones in the Development of a National Infrastructure for Nuclear Power, IAEA Nuclear Energy Series No. NG-G-3.1 (Rev. 1), IAEA, Vienna (2015).

[141] KUBACKI, Z., Polish Nuclear Power Programme: Current Status and Prospects (2014), http://www.iaea.org/NuclearPower/Downloadable/Meetings/2014/2014-02-04-02-07-TM-INIG/Presentations/31_B2_G4_Poland_Kubacki.pdf

[142] WORLD NUCLEAR NEWS, Polish public supports nuclear plan (26 Aug. 2014), http://www.world-nuclear-news.org/NP-Polish-public-supports-nuclear-plan-2608147.html

[143] ELSON, S.B., NADER, A., What Do Iranians Think? A Survey of Attitudes on the United States, the Nuclear Program, and the Economy, Rand Corporation (2011), http://www.rand.org/content/dam/rand/pubs/technical_reports/2011/RAND_TR910.pdf

[144] YOUNIS, M., Iranians Feel Bite of Sanctions, Blame U.S., Not Own Leaders, Gallup (2013), http://www.gallup.com/poll/160358/iranians-feel-bite-sanctions-blame-not-own-leaders.aspx

[145] ABDO, G., Iranians support their nuclear program, Newsday (26 Oct. 2012), http://www.newsday.com/opinion/oped/iranians-support-their-nuclear-program-geneive-abdo-1.4156752

[146] EMIRATES NUCLEAR ENERGY CORPORATION, UAE poll shows continued support for peaceful nuclear energy program (2011), http://www.enec.gov.ae/media-centre/news/content/uae-poll-shows-continued-support-for-peaceful-nuclear-energy-program

[147] AWAD, M., Public support for nuclear energy in UAE rises, The National (19 Mar. 2013), http://www.thenational.ae/news/uae-news/public-support-for-nuclear-energy-in-uae-rises

[148] SHAVEL, S., MARTISCHENKOVA, E., The Dynamics of Public Opinion on Nuclear Power Development in the Republic of Belarus (2013), http://elib.bsu.by/handle/123456789/97881

[149] HURSA, M.N., Dynamics of Public Opinion on NPP Construction in Belarus, Institute of Sociology of NAS of Belarus (2011), http://socio.bas-net.by/Library/Publ_files/_aes_hurs.pdf

[150] INTERNATIONAL ATOMIC ENERGY AGENCY, Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, 2015 edn, Reference Data Series No.1, IAEA, Vienna (2015).

[151] UNITED STATES DEPARTMENT OF ENERGY, Drivers and Barriers for the Application of Conservation Voltage Reduction Practices by Electric Utilities, Draft report, DOE, Washington, DC (2014).

[152] SCHNEIDER, K.P., FULLER, J., TUFFNER, F., SINGH, R., Evaluation of Conservation Voltage Reduction (CVR) on a National Level, Pacific Northwest National Laboratory, Richland, WA (2010).
[153] UNITED STATES DEPARTMENT OF ENERGY, Smart Grid Investment Grant Program Progress Report II, DOE, Washington, DC (2013).
[154] UNITED STATES DEPARTMENT OF ENERGY, 2014 Smart Grid System Report, Washington, DC (2014).
[155] BORENSTEIN, S., The long-run efficiency of real-time electricity pricing, Energy J. **26** 3 (2005) 93–116.
[156] RUFF, L.E., Demand response: Reality versus "resource", Electricity J. **15** 10 (2002) 10–23.
[157] BLOOMBERG NEW ENERGY FINANCE, Rebound in Clean Energy Investment in 2014 Beats Expectations, Press release, BNEF (9 Jan. 2015), http://about.bnef.com/press-releases/rebound-clean-energy-investment-2014-beats-expectations/
[158] BLOOMBERG NEW ENERGY FINANCE, China Out-Spends the US for First Time in $15bn Smart Grid Market, Press release, BNEF (18 Feb. 2014), http://about.bnef.com/press-releases/china-out-spends-the-us-for-first-time-in-15bn-smart-grid-market/
[159] ELECTRIC POWER RESEARCH INSTITUTE, Estimating the Costs and Benefits of the Smart Grid: A Preliminary Estimate of the Investment Requirements and the Resultant Benefits of a Fully Functioning Smart Grid, Report 1022519, EPRI, Palo Alto, CA (2011).
[160] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, Carbon Dioxide Capture and Storage, Cambridge University Press, New York (2005).
[161] OECD INTERNATIONAL ENERGY AGENCY, World Energy Outlook 2010, OECD/IEA, Paris (2010).
[162] SASKPOWER, Saskpower CCS Boundary Dam Carbon Capture Project (2014), http://saskpowerccs.com/ccs-projects/boundary-dam-carbon-capture-project/7913%20CSS%20Factsheet-Boundary%20Dam-newtense.pdf
[163] MISSISSIPPI POWER, Kemper County Energy Facility (2015), http://www.mississippipower.com/pdf/generaloverview.pdf
[164] INTERNATIONAL ATOMIC ENERGY AGENCY, Greenhouse Gas Emissions Data Collection, unpublished data.
[165] TOTH, F.L., Linkages between climate change, water and nuclear energy, Indian J. Power River Val. Dev. **51** (2014) 117.
[166] WILLIAMS, E., TOTH, F.L., Nuclear Power: Impacts of Climate Change and Extreme Weather. IAEA, Climate change impacts on the energy sector, Working material, pp. 1–17. CD release, IAEA, Vienna (2013).
[167] INTERNATIONAL ATOMIC ENERGY AGENCY, Climate Change and Nuclear Power 2013, IAEA, Vienna (2013).

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