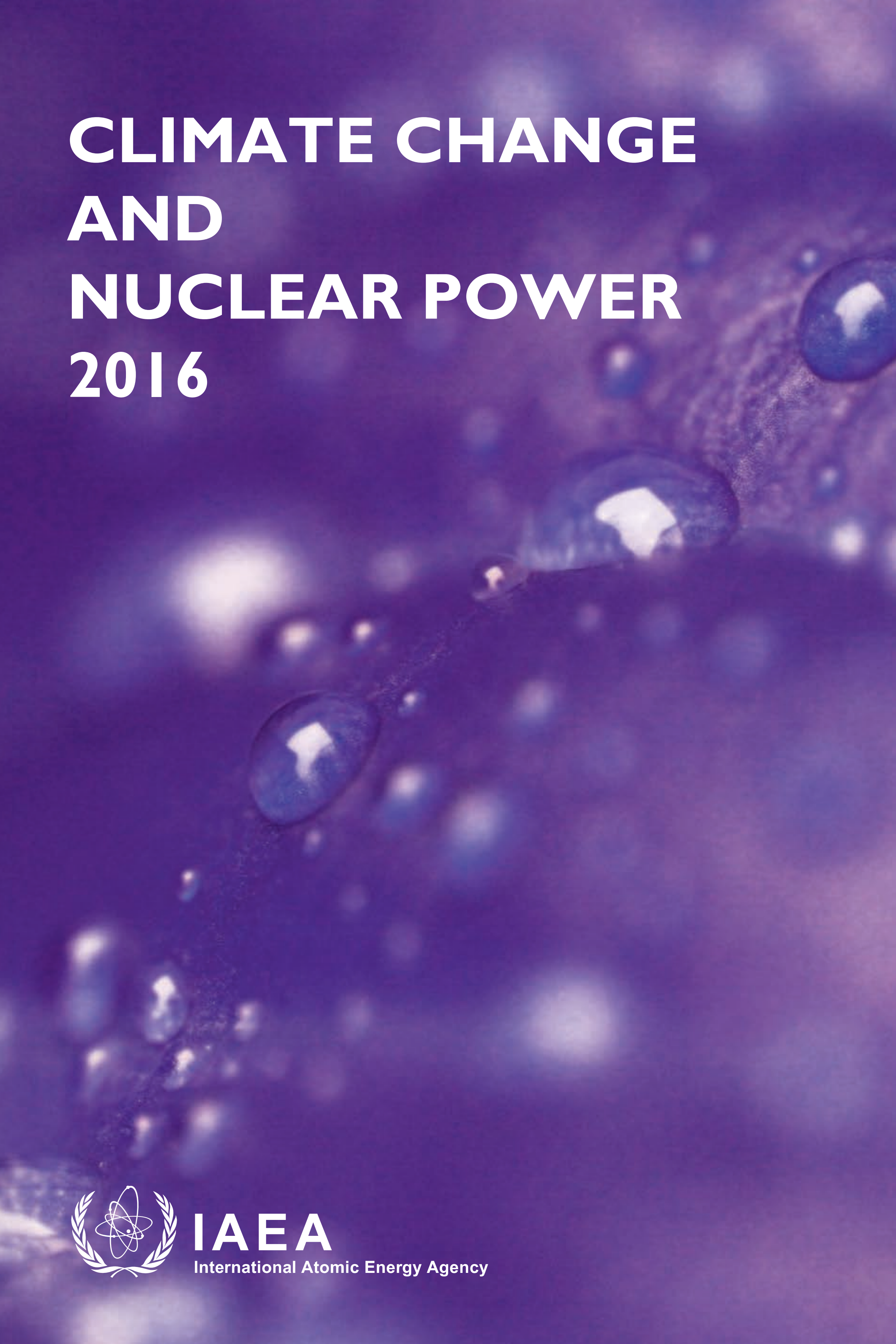
CLIMATE CHANGE AND NUCLEAR POWER 2016



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CLIMATE CHANGE AND NUCLEAR POWER 2016

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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 (GHG) emissions while delivering energy in the increasingly large quantities needed for the socioeconomic well-being of a growing population. Nuclear power plants produce virtually no GHG 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 and at stable and predictable 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 five 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 publication provides a comprehensive review of the potential role of nuclear power in mitigating global climate change and its contribution to other economic, environmental and social sustainability challenges. The report also examines broader issues relevant to the climate change–nuclear energy nexus, such as costs, financing, safety, waste management and non-proliferation. Recent and future trends in the increasing share of renewables in overall electricity generation and its effect on nuclear power are also presented.

This edition substantially revises the 2015 edition. Most sections have been completely rewritten to account for new scientific information, analyses, technical reports and other publications that have become available since the last edition. Sections addressing issues on which the available information has not substantially changed over the past year have been omitted and are summarized in the Appendix. Interested readers are referred to the 2013, 2014 and 2015 editions for more detailed information on the impact of climate change on nuclear power, smart grids, 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.

EDITORIAL NOTE

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SUMMARY

The latest report of the Intergovernmental Panel on Climate Change (IPCC) presents a large volume of new evidence that the climate system of the Earth is changing owing to increasing concentrations of greenhouse gases (GHGs), especially 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 the sea level is rising; features of extreme weather and climate events are changing.

The 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) intends to lessen the distressing impacts of climate change on ecological and socioeconomic systems and to modify current emissions rates to the lowest possible levels by setting an objective of limiting the increase in the global average temperature from pre-industrial levels to significantly less than 2°C. Current policies and investment trends for low carbon technologies fall short of delivering the needed reduction in GHG emissions. Intended Nationally Determined Contributions to GHG emission reduction, communicated by the parties to the UNFCCC before the Paris Agreement, form an important base upon which to build ambitions for mitigation. Power generation from low carbon sources, including nuclear energy, is a critical pillar in meeting the objectives of the UNFCCC.

Energy is a fundamental prerequisite for social and economic development. Mainly driven by large, fast growing, emerging economies, global primary energy demand is projected to increase to nearly 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 the much stronger incentives to decarbonize global energy systems that are reflected in the New Policies Scenario (but which have not yet been implemented), energy related CO_2 emissions are projected to rise by 16% by 2040. By contrast, meeting the 2°C target entails a 41% reduction in total energy related CO_2 emissions and a 70% reduction in power sector emissions. The pace of addressing CO_2 emissions from the energy sector differs in every country, depending on its level of economic development, access to best-in-class technologies, availability of cheap domestic fossil resources and renewable energy potential, access to finance and on the existence of policies and standards already in place or proposed, for instance, in Intended Nationally Determined Contributions.

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, standing at less than 15 grams CO_2-equivalent (g CO_2-eq) per kW·h (kilowatt-hour).

The historical role played by NPPs in the decarbonization of the global electricity mix extends to the future: in the New Policies Scenario, more than 3 Gt CO_2 would be avoided in the power sector in 2040 owing to the expansion of nuclear capacity worldwide (2Gt CO_2 was avoided by nuclear power in 2013). The role of nuclear power is expected to be even larger in scenarios consistent with the 2°C target (more than double current capacity levels by 2050), depending on assumptions about the relative costs and performance of other low carbon technologies. There is also significant scope for innovation in advanced and revolutionary designed reactors as well as in small modular reactors to advance the role of nuclear energy in addressing climate change and sustainable development.

A number of challenges need to be overcome to enable large scale nuclear power generation capacity in a country. Historical experience in the industry has demonstrated that it is possible to succeed, regardless of sociopolitical systems and the stage of economic development that a country may be at. When nuclear investments start to increase, manufacturing and construction capacities expand to meet the need. Financing nuclear power investments would also be feasible given stable government policies, proper regulatory regimes and risk allocation schemes. Once built, nuclear plants usually have very low running costs and tend to earn high margins in most electricity markets.

The scale of nuclear ambition in future updates of Intended Nationally Determined Contributions, which represent a progression towards the objectives of the Paris Agreement, will also affect the timely deployment of nuclear power. In the next couple of years, the rules and modalities of a new market mechanism (established under the Paris Agreement to be used by the parties to contribute to the mitigation of GHG emissions and to support sustainable development), will be determined. It is important that the nuclear power option be kept open under this mechanism for parties that wish to include it and thereby increase their options and the flexibility and cost effectiveness of their climate change mitigation strategies.

The policies supporting the transition to a low carbon economy will only prove effective if implemented jointly with other objectives to maintain a secured supply of energy and meet other sustainable development goals, to avoid potentially inefficient and conflicting outcomes. Nuclear energy can contribute to resolving energy supply concerns. Despite significant decreases in fossil fuel prices in recent years, fears of a return to previous highs and concerns about the security of supply from politically unstable regions are continuous considerations in the energy strategies of many countries. Including nuclear power in the energy supply mix can help alleviate these concerns because ample uranium resources are available from reliable sources throughout the world, and the cost of uranium remains a small fraction of the total cost of nuclear electricity. Besides the reliability and predictability that nuclear power offers in the electricity markets, it also has non-climatic environmental benefits and minimizes the impact on human health as it emits practically no local or regional air pollutants. Among the power generation technologies, it has one of the lowest external costs in terms of damage to human health and the environment that are not accounted for in the price of electricity.

Concerns about nuclear energy relating to radiation risks, waste management, safety 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. Thus, NPPs remain one of the safest industrial sectors for their workers and for the public at large owing to concerted efforts by operators of nuclear facilities and by international organizations such as the IAEA. NPPs incorporate redundant safety systems, and their operation is characterized by industry commitments to safety, international safety coordination, extensive training and stringent qualifications for nuclear workers, and effective responses to accidents. Institutional arrangements are being improved and further technological solutions sought to prevent the diversion of nuclear material for non-peaceful purposes. Spent fuel has been safely stored since nuclear power first generated electricity for public consumption in 1954. Geological and other scientific foundations for the safe disposal of spent nuclear fuel and high level waste are well established. The first repositories are expected to start operation within a decade. Public acceptance, although slowly recovering in some countries, still needs time to rebound to the level of support seen before the Fukushima Daiichi accident. The nuclear sector needs to improve further and to provide adequate responses to these concerns in order to realize its full potential.

Investment in nuclear power is also associated with activities in other sectors in the economy, such as construction, manufacturing and services, as well as with employment creation, and thus it contributes to overall economic growth. Recent experience in countries with developed nuclear power programmes showed that in terms of labour market effects, secondary or ‘ripple’ effects, though indirect, might be much higher than the magnitude of direct employment. A balanced view on benefits and concerns underpins the need to assess the net effects on the society from investments in any energy technologies, including nuclear technology. Subject to a country’s overall economic and social policy objectives, the implementation of the Paris Agreement, together with the 2030 Sustainable Development Agenda, may provide additional incentives for nuclear programme development.

Climate change mitigation is one of the salient reasons for considering nuclear power in future national energy portfolios. Where, when, by how much and under what arrangements nuclear power will contribute to climate change mitigation will depend on local conditions, national priorities and on international arrangements. The final decision to introduce, use, expand or phase out nuclear energy in a national energy portfolio rests with sovereign States.

1. INTRODUCTION

Negotiation of two major agreements — the 2030 Agenda for Sustainable Development [1] and the Paris Agreement [2] on climate change — culminated in 2015. There are obvious linkages between these two landmark agreements, as recognized by the United Nations Secretary-General Ban Ki-moon: "By acting on climate, we advance the Sustainable Development Goals and the 2030 Agenda [for Sustainable Development]" [3]. The Sustainable Development Goals and the resulting development pathways will determine both the magnitude of future emissions of greenhouse gases (GHGs) and the vulnerability of societies to the impact of climate change. The impact of unrestrained climate change can undermine the results of development efforts and can also increase the frequency and intensity of climate related disasters.

The Paris Agreement states that parties aim to reach a global peak of GHG emissions as soon as possible and aim for neutrality of the emissions in the second half of this century to keep the global average temperature increase to well below 2°C, and pursue efforts to limit it to 1.5°C [2]. At the same time, the total supply of energy services — currently the main source of carbon dioxide (CO_2) emissions — needs to expand to meet the rising demand from the world's growing population and economies. Without significant efforts to limit future GHG emissions 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 challenges of climate change and global energy supply. However, low carbon technologies such as renewable sources of energy, nuclear and fossil fuels with carbon capture and sequestration (CCS) will play the principal role because they can provide low carbon electricity to satisfy the increasing demand for modern energy services and because this electricity can also be used in an increasing range of economic activities. Any exemption, limitation, restriction or exclusion of any of these technologies would undermine the economic rationale of cost efficiency and would increase mitigation costs and delay actual emissions reductions.

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 in the dirty fossil fuels of the past [4]. "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 [5].

Nuclear power is already an important contributor to the world's electricity needs. It supplied 11% of global electricity in 2015 [6]. 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, including the high up-front capital costs of building new NPPs, their relatively long construction time and payback period, and the lack of public and political support in several countries. Nonetheless, a growing awareness of benefits (for climate change mitigation, energy security, air pollution, health and economic growth) and understanding of concerns (for waste, safety and proliferation) associated with nuclear energy, might provide more incentives for nuclear programme development when addressing climate change and the United Nations Agenda for Sustainable Development.

This publication explores the possible contribution of nuclear energy to resolving the climate–energy conundrum and to addressing other development and environmental issues.

Section 2 presents climate change and global energy supply challenges and demonstrates the need for nuclear power to resolve them. Section 3 addresses issues pertinent to supplying nuclear power, ranging from timing and requirements for nuclear capacity, its economic competitiveness and financing, and the implications of the Paris Agreement for the scope for innovation in advancing climate action. The latest IAEA projections with regard to global nuclear power capacity expansion are also included. Section 4 is devoted to concerns and benefits associated with nuclear power. It discusses radiation risks, safety, proliferation and waste management, and current efforts to address issues related to these aspects of nuclear power. The potential contribution of nuclear energy to easing supply security concerns and reducing local and regional air pollution problems and human health impact, and its role in supplying low carbon energy for industrial development and economic and employment growth, are discussed. Recent trends in public acceptance in selected countries are also addressed.

2. THE NEED FOR NUCLEAR POWER

2.1. THE CLIMATE CHANGE CHALLENGE

By "holding the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursuing "efforts to limit the temperature increase to 1.5°C above pre-industrial levels", the Paris Agreement, signed in December 2015, marks a major milestone in the fight against climate change [2]. After 20 years of climate negotiations and accumulating scientific evidence, the international community recognized the imperative to reduce the risks and impacts of climate change.

In its Fifth Assessment Report (AR5), the IPCC Working Group I confirmed more confidently than ever before that the climate of the Earth was changing and that "it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century" (i.e. with a 95% to 100% probability) [7]. Over the period 1880–2012, globally averaged surface temperature increased by 0.85°C. The upper layer of the ocean began to be affected by ocean warming, the Greenland and Antarctic ice sheets began to lose mass, glaciers shrunk, and the global mean sea level rose by 0.19 metres between 1901 and 2010.

The latest IPCC scenarios rest on four so-called representative concentration pathways (RCPs) for exploring near and long term climate change implications of different paths of anthropogenic GHG emissions, aerosols and other climate drivers. These projections are based on alternative assumptions about radiative forcing values[1] for the year 2100, relative to the year 1750.

The four RCPs present approximate total radiative forcing values ranging from 2.6 to 8.5 watts per square metre (W/m^2). The RCP2.6 scenario assumes strong GHG mitigation actions resulting from stringent but unspecified climate policies. Radiative forcing along this pathway is expected to peak and decline during the twenty-first century, leading to a low forcing level of 2.6 W/m^2 by 2100, while RCP4.5 depicts radiative forcing stabilizing 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 — converted into corresponding GHG concentrations and emissions — served as inputs to more than 50 global climate models used in the Coupled Model Intercomparison Project Phase 5 (CMIP5), to assess the changes triggered in the climate system globally and regionally [7]. Only the RCP2.6 scenario was found to pave the way for the long term objective stipulated in the Paris Agreement as, 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 (Fig. 1). Relative to the IPCC AR5 reference

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

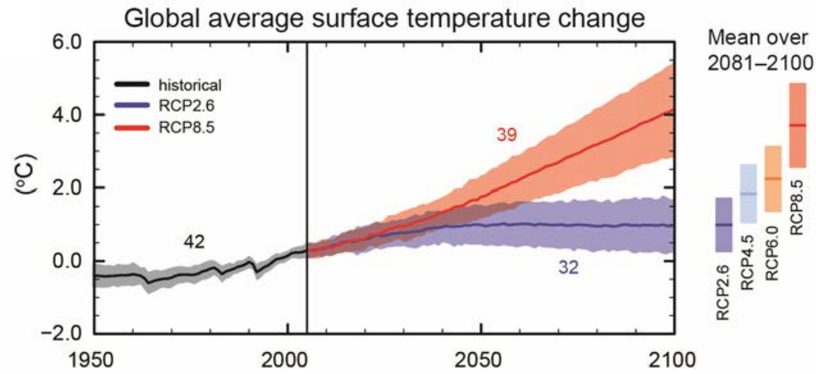

FIG. 1. Change from 1950 to 2100 in global mean surface temperature relative to the 1986–2005 mean values from the CMIP5 concentration driven experiment. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Source: Fig. SPM.7 in Ref. [7]. Note: Labels indicate the number of models used to calculate the multi-model mean; RCP: representative concentration pathway. Reproduced courtesy of IPCC [7].

period (1986–2005), the global surface temperature is expected to rise by 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 projected dynamics of temperature changes for RCP6.0 (approximately corresponding to the continuation of recent trends in GHG emissions) indicate that in the near term (2016–2035), the increase in annual mean temperature is projected to be modest: 0.5°C to 1.5°C in most regions. Over the long term (2081–2100), however, a rather different picture emerges: 2°C to 6°C temperature increases are foreseen in most regions of the world. Even under stringent climate policies (RCP2.6), 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°C–5°C in the continental areas of the already hot tropical regions, and 5°C–7°C in most of the middle and high latitude regions of the Northern Hemisphere.

The contribution of Working Group 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 on small islands owing to storm surges, coastal flooding and sea level rise, and for large urban populations owing to inland flooding in some regions; extreme weather events leading to the 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 owing 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 for vulnerable communities owing to their limited ability to adapt. Without stringent climate action, more than 100 million additional people may fall back into poverty by 2030 [9]. Given the fast increasing GHG emissions in recent decades and the emissions pathways underlying the RCPs, the world faces an enormous mitigation challenge over the coming decades in order to follow RCP2.6. Since 1750, the largest contribution to total radiative forcing has been caused by the increase in the atmospheric concentration of CO_2 [6]. To a large extent, these CO_2 emissions have resulted from fossil fuel burnt in the energy sector. In order to reduce the potentially severe risks of climate change, global GHG emissions and, in particular, CO_2 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.

2.2. THE ENERGY CHALLENGE

The Paris Agreement aims to limit the increase in the global average temperature to well below 2°C above pre-industrial levels.[2] As three quarters of global GHG emissions are energy related, the enforcement of the Agreement would imply a radical transformation of energy production and usage. Current trends in energy markets, investments, technological developments and supporting policy measures, whether enacted or proposed, remain largely insufficient to bring about a timely transition towards a 2°C objective and lower global GHG emissions to about 40 gigatonnes (Gt) in 2030. Estimated aggregate GHG emission levels in 2025 and 2030 resulting from the Intended Nationally Determined Contributions lead to a projected level of 55 Gt in 2030 [2, 10].[3]

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[2] The agreement was deposited at the United Nations in New York and opened for signature for one year on 22 April 2016. The agreement will enter into force after 55 countries that account for at least 55% of global emissions have deposited their instruments of ratification.

[3] The Intended Nationally Determined Contributions submitted to the UNFCCC are not restricted to mitigation measures in the energy sector. These generally include energy, industrial processes and product use, agriculture, land use, land use change and forestry and waste.

Therefore, while these contributions are the appropriate first step towards achieving the long term objectives of the Paris Agreement, the ambition level will have to be progressively revised upwards.

Reversing current trends and paving the way towards a long term temperature target of 2°C requires the global and parallel implementation of three broad mitigation measures in the energy sector:

- Decarbonization of the power sector and substitution of coal and natural gas-fired power generating capacity with low carbon power sources such as nuclear or renewable energy sources or fossil fuel power plants equipped with CCS;
- Across-the-board energy conservation measures to cut down direct fossil fuel consumption in end use and energy transformation sectors;
- Electrification of energy use in all energy end use sectors (i.e. buildings, industry and transport).

The gap between the Paris Agreement and actual trends is illustrated via the global scenarios developed by the IEA for the energy sector [11]. The IEA regularly updates its assessment of 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. Those scenarios are used here to highlight the three key mitigation measures in the energy sector. The central IEA scenario — the New Policies Scenario — takes account of broad policy commitments and plans 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. In the long term, global temperature is set to increase to about 3.6°C and serves as a basis for comparison with a more ambitious scenario — the 450 Scenario — which 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, whether in place or planned.

The New Policies Scenario projects global primary energy use rising at 1%/year between 2013 and 2040, while electricity needs — mainly driven by large, fast growing emerging economies — see the fastest growth of the main energy carriers at 2%/year. The global power generation mix remains largely dominated by fossil fuels, in particular by coal- and gas-fired power plants, which still generate 30% and 23% of total electricity, respectively, in 2040. Globally, the progressive decoupling between economic activity and energy use translates into a moderate slowdown in the growth rate of energy related CO_2 emissions which rise from 31.6 Gt CO_2 in 2013 up to 36.7 Gt CO_2 in 2040. Without any strong incentive to decarbonize power generation globally, emissions in the power sector rise from 13.4 Gt CO_2 to 15.1 Gt CO_2 by 2040. Meeting the 2°C target entails a 70% reduction in power sector emissions by 2040 (Fig. 2). Overall, drastic measures in all sectors lead to a 40% cut in global energy related emissions.

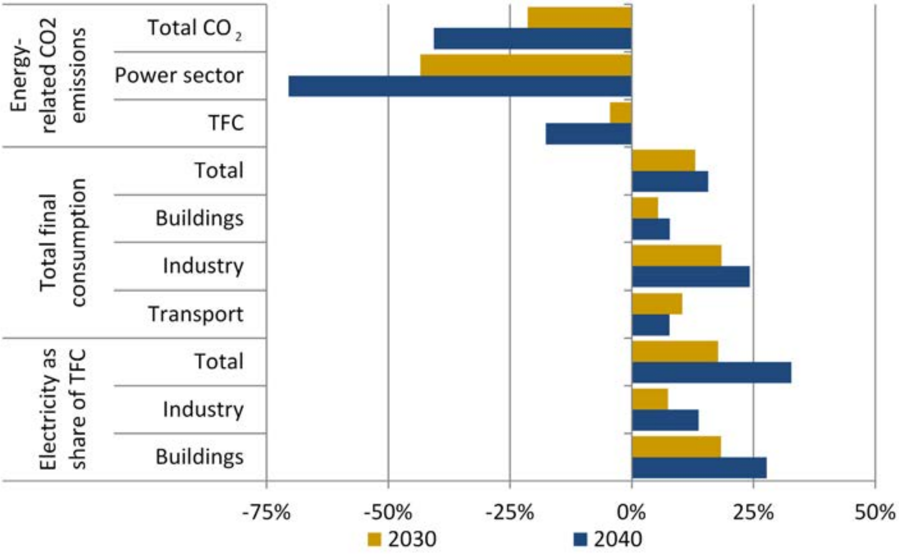

FIG. 2. Projected change in global energy related CO_2 emissions, global total final energy consumption (TFC), and electricity as a share of global TFC relative to 2013 in the IEA's World Energy Outlook 2015 450 Scenario (2°C). Source: Ref. [11].

Incentivizing the large 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 in the long term. About 45% of the total emissions abatement achieved in the 450 Scenario stems from energy efficiency improvements in industrial processes or in the buildings sector. Adopting the most efficient electrical motors, heating and lighting devices, and switching production processes towards more efficient and less carbon intensive natural gas feedstocks in lieu of coal, are among the measures necessary to fully achieve the potential for improvement in industrial efficiency. The buildings sector needs to systematically adopt the best efficiency standards and deploy highly efficient electrical appliances for lighting and space and water heating.

Overall, energy conservation measures in the 450 Scenario lead to a moderate increase in energy demand which, by 2040, is about 16% higher than current levels. The electrification of energy use drives up the share of electricity consumption in final energy use by a third relative to 2013 (see Fig. 2). The pace at which these broad measures to address CO_2 emissions from the energy sector are adopted differs from country to country, depending on their levels of economic development, access to best-in-class technologies, access to finance, and policies and standards (both established or proposed, for instance, in Intended Nationally Determined Contributions). Some of the more economically developed countries, such as the members of the European Union, as well as Japan and the United States of America, are already seeing their energy consumption and associated CO_2 emissions levelling off (Fig. 3). Their energy use and emissions are set to decrease by 10% to 20% in the 450 Scenario. Alternatively, energy use, a key driver for sustained economic growth, continues to rise in fast growing markets such as China and India, even in a stringent climate policy context. However, in line with a 2°C mitigation pathway, appropriate measures to switch away from fossil fuels have the potential to cut CO_2 emissions drastically by 2040, as compared with current levels. Emissions in China, currently the largest CO_2 emitter, decrease by 60% per the 450 Scenario.

Financing the transition to a low carbon economy and redirecting investments away from fossil fuels remain critical aspects of the global energy challenge. Paving the way for the 2°C target notably implies a reversal of current patterns in low carbon investments. In 2013, low carbon investments, comprising investments in energy efficiency and power supply (renewables, nuclear and CCS), reached US $470 billion [12] including US $130 billion dedicated to energy efficiency [13, 14] (Fig. 4).[4]

The year 2015 saw yet another record in renewable power investments, which totalled almost US $330 billion, with China being the main recipient of low carbon projects, receiving double the amount invested in the United States of America [15]. By contrast, globally only US $130 billion was invested in new coal and natural gas power capacity [16].

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[4] Large uncertainties remain with regard to actual efficiency investments.

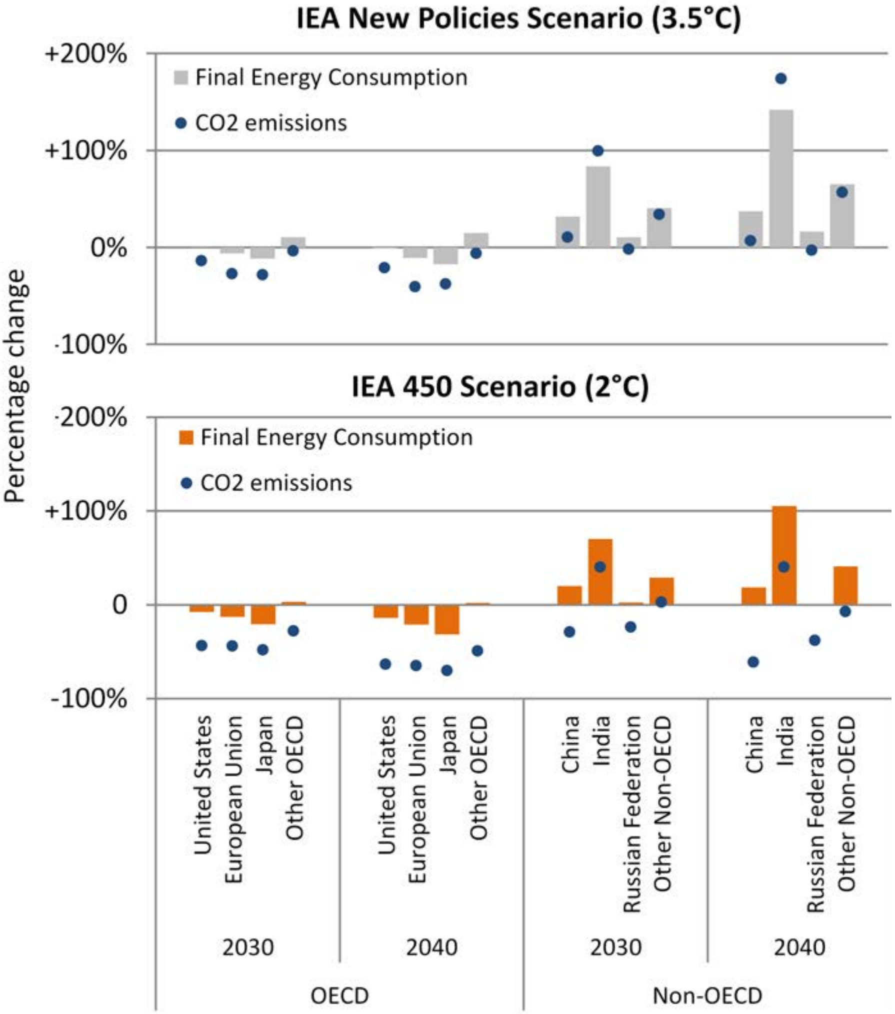

FIG. 3. Change in total final energy consumption and energy related CO_2 emissions by large country groups relative to 2013 in the IEA's World Energy Outlook 2015 New Policies Scenario (top) and 450 Scenario (bottom). Source: Ref. [11].

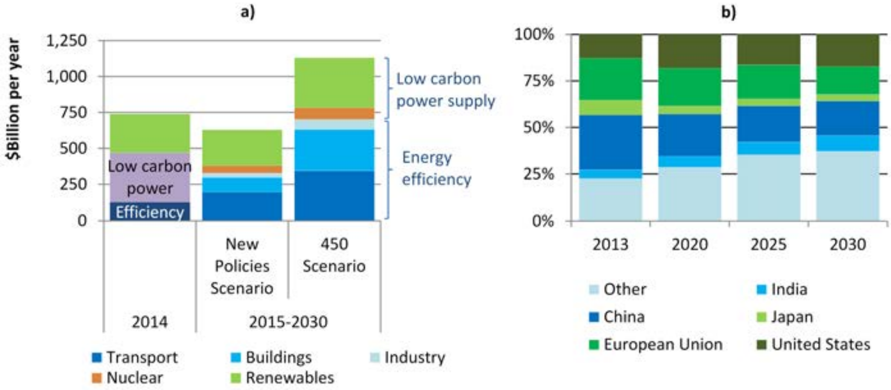

FIG. 4. Global investments in energy efficiency and low carbon power supply: (a) by large country group, (b) in 2013 and corresponding average annual investment to 2030 in the IEA's World Energy Outlook 450 Scenario (2°C). Source: Ref. [12, 13].

By 2030, the transition in line with the 2°C target will require more than doubling low carbon investments (Fig. 4). According to the 450 Scenario, on average, more than US $1100 billion will be invested annually over the period 2015−2030, of which around US $700 billion will be spent on energy efficiency and more than US $400 billion on low carbon power supply, including US $81 billion on NPPs.[5] This investment upgrade also requires the shifting of regional patterns towards less developed countries such as India and South-east Asian or African countries. By comparison, investments over 2015−2030 in the New Policies Scenario are 40% lower than those required in the 450 Scenario.

GHG emissions from the energy sector can be mitigated if strong supporting policy measures are adopted by countries. Some of the measures listed below are addressed in subsequent sections:

- Developing and strengthening national mitigation targets as formulated from Intended Nationally Determined Contributions under the Paris Agreement;
- Putting a price on carbon;

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[5] The Paris Agreement contains an annual US $100 billion provision to support climate change mitigation and adaptation projects in developing countries.

- Reducing risks faced by investors in low carbon technologies by providing clear, long term policy orientations, e.g. contract-for-difference guaranteeing a secured stream of revenues;
- Supporting innovation and technology transfer to enhance the deployment of low carbon technologies;
- Removing subsidies supporting wasteful fossil fuel consumption and production;
- Mitigating upstream methane emitted from extractive sectors;
- Forcing the retirement of inefficient coal power plants;
- Implementing policy incentives which serve the joint purposes of sustainable development.

Policies supporting the transition to a low carbon economy will only prove effective if designed and implemented jointly with other objectives to maintain a secured supply of energy and to meet other sustainable development objectives, to avoid potentially inefficient and conflicting outcomes. The United Nations 2030 Agenda for Sustainable Development identifies universal access to electricity as a key development priority and a prerequisite for sustainable economic growth. Despite recent efforts and improvements, an estimated 1.2 billion people (17% of the global population) continue to live without access to electricity [11]. Given the low levels of individual energy consumption in the least developed countries, providing energy access leads to incremental energy use that affects global emissions only marginally.

2.3. THE NEED FOR A DISPATCHABLE LOW CARBON SOURCE OF ELECTRICTY

Nuclear units have high up-front capital costs and relatively low fuel and operational costs, when compared with fossil fuel generating units. Revenues from electricity generation are maximized at full load operation, when individual NPPs act as price-takers in competitive markets. For these reasons, operating NPPs at baseload is generally considered the most economically advantageous method.

When operated in baseload mode, nuclear power brings multiple benefits to the grid system (e.g. increasing its reliability). While future energy systems will need more flexibility from dispatchable technologies, this will come at a cost. Nuclear power can be part of the solution, and has already demonstrated flexibility in some markets (e.g. in France and Germany).

Increasing the deployment of intermittent renewables puts pressure on conventional dispatchable producers including nuclear or coal- and gas-fired plants to deliver variable amounts of electricity to the grid precisely when needed. Embedded into the interconnecting grid, these technologies are capable of adjusting outputs within a previously agreed range.

Some renewable generation technologies, including hydropower, biomass and geothermal power, are also dispatchable. However, they typically have higher costs (e.g. biomass) and can be limited in supply (e.g. hydropower) or have a limited period of storage (e.g. concentrated solar power) [17]. In contrast, variable renewables such as wind or solar lack this capacity. They are intermittent by nature, delivering electricity when meteorological conditions are met, namely when the wind is blowing and the sun is shining. However, for the grid to be stable and reliable, supply and demand must be matched. The temporal variation of the generation of renewable energy (in this case, wind and solar) therefore requires that dispatchable generation technologies ensure grid stability by varying their output. Given the goal of increasing the penetration of variable renewables to mitigate GHG emissions, electricity grids worldwide would benefit from the increased flexibility offered by nuclear power. It is the sole low carbon source of electricity among the conventional dispatchable technologies.

The following example [18] illustrates nuclear load following in Germany. On 16 June 2013, a sunny and breezy day, wind and solar generating units provided more than 60% of the country's electricity demand — a record. Since priority grid regulations for renewables apply in Germany, wholesale markets accordingly reflected electricity over-supply through negative prices. As a consequence, German NPP owner/operating organizations such as RWE, EON and EnBW were forced to downscale the output. According to data analysed by Bloomberg, RWE's Gundremmingen NPP Units B and C, both boiling water reactors, reduced output for roughly two hours to about 46% rated electrical output, which is more than 700 MW(e), and to about 42% REO, which is nearly 800 MW(e), respectively [15].

With the advanced penetration rate of renewables in future energy systems, higher ramping rates, or deeper and more frequent cycling patterns by dispatchable generating units, including nuclear, will be needed. The latter is likely to occur if no other measures, such as provision of energy storage and more interconnections, are put in place (see below). Production schedules of dispatchable generators can therefore vary more frequently with more deviation from plans. Potential forecast errors and sudden surges in load produced by wind or solar energy when meteorological conditions change unexpectedly will continue to force dispatchable technologies to act with a high degree of uncertainty.

The provision of flexible services might also be needed owing to the low degree of trans-border electricity grid interconnections. In general terms, the latter allows two or more linked electricity grid systems to share power generation resources. A well-developed grid interconnection system with neighbouring countries allows load variation to be kept to minimum levels. For example, German NPPs were capable of largely maintaining high load factors during periods of negative pricing triggered by the integration of renewables, between the first half of 2012 and 2013. Germany’s electricity exports quadrupled roughly over the same period of time [19].

In contrast, a lack of interconnections between neighbouring countries creates a need for dispatchable technologies to adjust output as and when needed. In this regard, dispatchable generators provide services that can, to a certain degree, be viewed as a substitute to trans-border grid interconnections. A recent study commissioned by the IAEA in 2016 revealed that a substantial fraction of demand for flexibility in services in the European Union is driven by exactly this motive, even in the long run up to 2050 [20]. Responding to current and future trends, several existing NPPs have started modifying operating regimes that had initially been optimized for baseload operation. The technical impact of flexibility on the design and operation of NPPs is largely known, and technical solutions have been developed [21]. The recent experience of NPPs in France and Germany has demonstrated the considerable technical capability of reactors to handle load variations. For example, Germany’s 1.4 GW Grohnde nuclear reactor is reported to be capable of ramping up or down by 40 MW per minute [22].

As discussed above, grid flexibility is necessary and inevitable for a variety of reasons. However, NPPs will have to deal with potentially adverse impacts on their costs and revenues. The ability to provide the market with flexible services will come at a cost for NPP operators, in terms of higher initial installation costs or operation and maintenance costs. Additionally, operating at less than full load will also impact fuel costs. Moreover, staff costs may rise, as staff would need to be permanently available to adjust output frequently, in some cases, even unexpectedly. Frequency (rate of change) and intensity (magnitude of change) of flexibility requirements will have a direct impact on future operating costs. It is likely that these additional costs associated with flexible generation at the plant level will not be proportional to the needs of grid flexibility, since several factors — such as age, vintage, design and maintenance activities, among others — will determine the impact in terms of cost additions.

When it comes to the flexible operation of NPPs, cost related impacts as described above have to be separated from revenue related impacts. Any plans to base future energy systems on growing the amount of renewable technologies is likely to cause shrinking of load factors of dispatchable technologies, in comparison with the baseload operation. In the absence of specific market arrangements for flexible services, revenues are likely to decrease.

This adverse impact on revenues via reduction of load factors might be reinforced by price impacts from the electricity markets, as the integration of variable technologies with low or zero short-run marginal cost will result in declining electricity prices as long as the system costs are not internalized. A related issue is those periods when pricing is negative, or shows higher volatility. This decreases profits and makes them less predictable.

Increasing the flexibility of baseload generation will require new regulatory practices to allocate the recovery of the additional capital cost and to compensate for the provision of flexible services in the face of uncertainty in both. These policy options include capacity markets, capacity payments or reliability options to support the availability of flexible capacity.

2.4. NUCLEAR POWER: A LOW CARBON TECHNOLOGY

The total cumulative CO_2 emissions from 1870 to 2014 were around 2015 Gt CO_2. More than two thirds (73%) originated from burning fossil fuels and from cement production. In 2014, CO_2 emissions from these two sources (35.9 Gt CO_2) reached the highest level in human history and were 60% higher than in 1990 (reference year of the Kyoto Protocol [23]). In order to have a 66% chance of keeping the global average temperature below 2°C, the total remaining CO_2 quota from 2014 is 903 Gt CO_2. At current emission rates, this quota will be used up in around 20 years, according to the Global Carbon Project [24]. The essence of the 2015 Paris Agreement is to modify current emission rates to the lowest levels and to essentially decarbonize the global energy sector. Given that global energy demand is expected to rise, the use of energy technologies that emit small amounts of CO_2 per unit of energy service is crucial to meet the needs of populations growing in size and affluence (especially in developing countries and in those that are the least developed). By comparing the GHG emissions of all existing and future energy technologies, this section demonstrates that nuclear power provides energy services with very few GHG emissions and is justifiably considered a low carbon technology.

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. Properly implemented life cycle assessments 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, and 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, determine overall ranges and the distribution of estimates within the ranges.

This section uses data from two major life cycle assessment databases (Ecoinvent, Switzerland [25] and the National Renewable Energy Laboratory (NREL), based in the United States of America [26]), as well as estimates of the Central Research Institute of Electric Power Industry of Japan (which applies a methodology similar to Ecoinvent) [27], environmental product declarations [28] and other estimates published in academic literature. Figure 5 presents life cycle GHG emission estimates, expressed in CO_2-equivalents (CO_2-eq), for different electricity technologies.

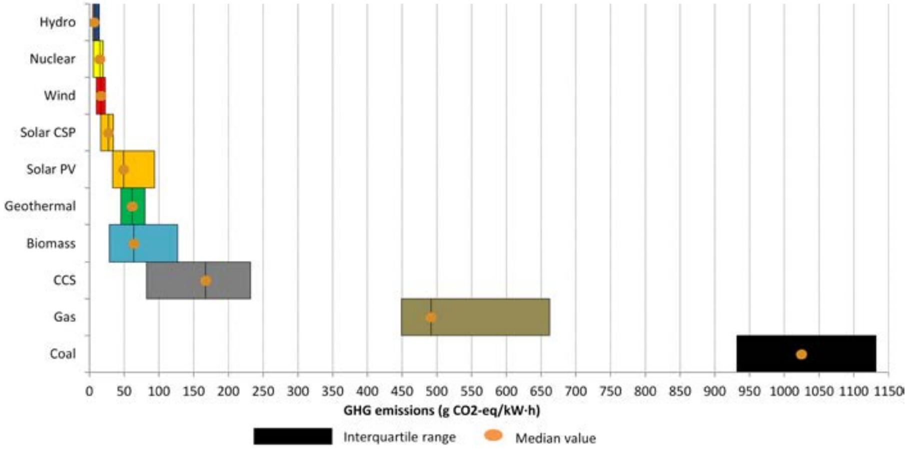

FIG. 5. Life cycle GHG emissions from electricity generation. Data source: IAEA calculations using data from Refs [25–28]. Note: CCS: carbon dioxide capture and storage.

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 interquartile range of estimates of 932–1132 g CO_2-eq/kW·h) from all sources. 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 449–662 g CO_2-eq/kW·h). Carbon dioxide capture and storage reduces emissions from fossil technologies. However, only a limited number of studies estimate life cycle GHG emissions from fossil fuel technologies including CCS. The median value reported is 167 g CO_2-eq/kW·h within the interquartile range of 82–232 g CO_2-eq/kW·h (see Fig. 5). These results place CCS as an intermediate option between traditional fossil and renewable technologies. Assessing the potential advantages of CCS over conventional fossil power plants is difficult because the first industrial scale coal-fired plant with CCS was commissioned in late 2014 [11]. This means that all CCS emissions estimates presented in Fig. 5 are based on theoretical calculations and pilot and demonstration projects. Thus, there is a considerable degree of uncertainty when extrapolating to large industrial scale units.

The remaining set of technologies are the preferred options for devising the energy mix for coming decades, in order to meet global GHG mitigation goals, as they share a median that is lower than those of fossils and CCS by an order of magnitude. Geothermal (median value 62 g CO_2-eq/kW·h), biomass (64 g CO_2-eq/kW·h) and solar photovoltaic (49 g CO_2-eq/kW·h) are estimated to have relatively higher emissions in this group, whereas concentrated solar power (median value 27 g CO_2-eq/kW·h), wind (16 g CO_2-eq/kW·h), nuclear power (15 g CO_2-eq/kW·h) and hydropower (7 g CO_2-eq/kW·h) have the lowest GHG emissions among the power generation technologies.

Despite the relatively wide ranges of life cycle estimates for some renewables (geothermal, biomass, wind and hydropower), the interquartile ranges are rather narrow (except for biomass). This makes the comparison of different energy technologies by their median values an acceptable approach. Even within the same technology groups, considerable differences exist within the types and across generations of technologies. For example, the first generation of solar cells (crystalline silicon) has 50–70% higher GHG emissions on average than the more advanced second generation (thin film) cells. Thin film technologies, in turn, also differ, with copper indium gallium selenide panels showing, on average, the highest emissions per unit of electricity produced. This technology is followed by amorphous silicon and cadmium telluride, which have the lowest life cycle emissions of all thin film panels.

Estimates by the NREL [26] for thin film solar photovoltaics are lower than those of Ecoinvent [25]. Within the first generation of solar photovoltaic panels (crystalline silicon), on average, monocrystalline silicon panels have lower GHG emissions in comparison with the polycrystalline ones. Such variations make choosing the most effective mitigation technology less straightforward, and other features of specific technologies have to be taken into consideration. Moreover, GHG emissions per unit of electricity produced by solar photovoltaics strongly depend on the region of deployment, with the best results being obtained 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.

An analysis of estimates published in the scientific literature clearly puts nuclear energy among the most climate friendly energy sources. The most important factors influencing future CO_2 levels of nuclear energy involve the nuclear fuel cycle. These include the quantity and ore grade of the fresh uranium needed, the efficiency of the enrichment technology, the fuel enrichment requirements and the carbon intensity of the electricity used in the different process steps in the life cycle (e.g. in the enrichment process) [29]. The use of lower grade uranium ores may become necessary if nuclear power needs to be significantly expanded, making the extraction process more energy and GHG emission intensive. These increases could be mitigated through the use of low energy in situ mining techniques. Additionally, increased demand for uranium could produce higher market prices to incentivize uranium exploration, which historically has led to the emergence of additional higher grade resources. Future revolutionary reactor designs (also known as Generation IV designs) are expected to further decrease life cycle emissions owing to their anticipated higher fuel efficiencies.

In summary, nuclear CO_2 emissions are already among the lowest and future reductions will likely be due to: (i) further improvements in uranium enrichment technologies, shifting from electricity intensive gaseous diffusion to centrifuge or laser technologies that require much less electricity; (ii) an increased share of electricity used for enrichment based on low carbon technologies; (iii) improvements in fuel manufacturing and fuel designs, allowing higher burnup that reduces emissions per unit of electricity in the fuel supply part of the life cycle; and (iv) extended NPP lifetimes from 40 to 60 years, spreading the emissions associated with construction and decommissioning over a longer period, while more electricity (kW·h) is generated. These very low CO_2 and GHG emissions on a life cycle basis make nuclear power an important technology option in climate change mitigation strategies for many countries.

2.5. PAST CONTRIBUTION TO AVOIDED GHG EMISSIONS

Over the last four decades, the growing world economy has relied on abundant fossil fuels to a fairly large extent, with the combined share of coal, gas and oil accounting for around 80% of global energy consumption. Up to the late 1960s, hydropower was the only low carbon energy source to produce electricity. In the early decades of its history, which began in the 1950s, nuclear power was seen as a high tech, abundant, cheap and safe energy source in most countries. Its share in the primary energy supply grew from just 0.5% in 1971 to nearly 7% at the end of the 1990s, before falling to 5% in 2013. Nevertheless, along with hydropower, nuclear power helped to avoid large amounts of GHG emissions even before anthropogenic climate change emerged on the global environmental agenda. In most countries, new renewable generation capacity (wind and solar) recorded a tremendous increase in the last decade, driven by rapid cost reductions and continued public support. As of 2013, these other renewables amounted to 1% of the total global energy supplied.

Figure 6 attempts to quantify the benefits in terms of avoided CO_2 emissions by using low carbon power generation technologies instead of fossil fuels in global electricity generation since the 1970s. The underlying assumption in calculating the amount of avoided emissions is that the electricity generated by hydropower, nuclear energy and renewables would have instead been produced 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 the use of nuclear power because in the historical context of the 1970s, most of the nuclear capacity expansion occurred with the explicit policy objective of reducing dependence on imported oil and gas. Coal would probably have been the predominant non-nuclear alternative at that time. Nonetheless, this approach allows for conservative estimates of avoided GHG emissions.

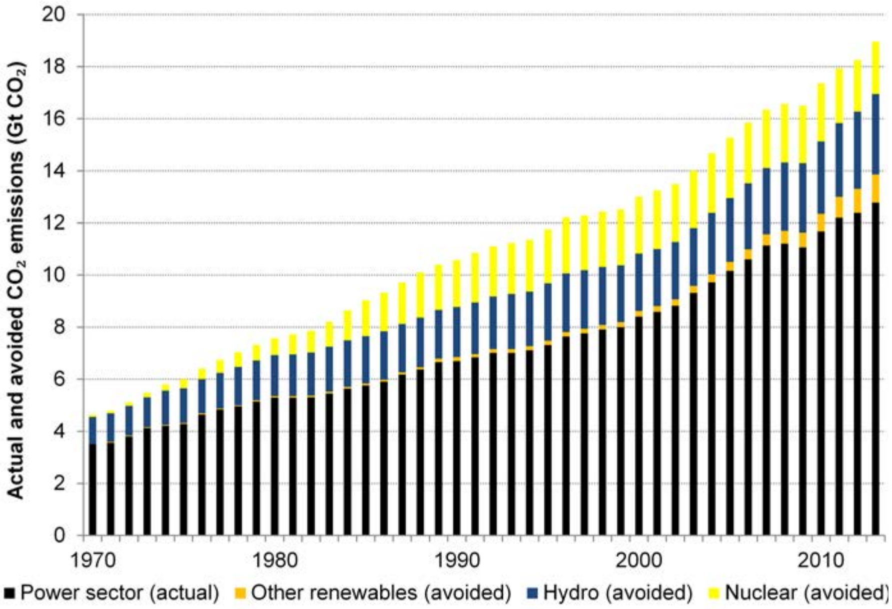

FIG. 6. Global CO_2 emissions from the electricity sector and emissions avoided by using three low carbon generation technologies. Source: IAEA calculations based on CO_2 emissions, power generation and fuel input data in Ref. [30] and emission factors data in Ref. [31].

Figure 6 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 in Fig. 6 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 orange segments of the bars show the CO_2 emissions avoided by nuclear energy, hydropower and renewables other than hydropower, respectively. Over the period 1970–2013, the use of low carbon energy sources made it possible to avoid over 163 Gt of CO_2 emissions in total. Hydropower accounted for 53% (87 Gt CO_2), nuclear power contributed 41% (66 Gt CO_2) and other renewables saved 6% (10 Gt CO_2); the contribution of the latter group was marginal until the late 2000s.

The ratio of avoided to actual power sector emissions reflects the absolute quantities of avoided emissions over time: this ratio fluctuated from 32% in 1970 to 43% in 1980, peaking at 58% in 1990. After that, it decreased: to 55% in 2000 before falling further to 48% in 2013. This shows that in the 1970s and 1980s, the amount of avoided emissions was growing faster than the actual emissions in the power sector owing to the fast growth of energy output supplied by low carbon sources, principally nuclear power, 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 timeframe.

Naturally, the countries that generate most of their electricity from hydropower (Norway: 97%), nuclear (France: 76%) or a combination of these two (Sweden: 49% hydropower and 38% nuclear; Switzerland: 59% hydropower and 38% nuclear) have the lowest CO_2 intensities (less than 100 g CO_2/kW·h as compared with the average of 418 g CO_2/kW·h among the countries of the OECD [32]).

The role of nuclear power in reducing CO_2 intensity will decrease over the coming decades in a few countries that have decided to phase out nuclear energy, but will increase in several other countries that have decided to include nuclear power or augment its share in their electricity generation portfolio. The expansion of the nuclear capacity 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 428 g CO_2/kW·h in 2010 to 569 g CO_2/kW·h in 2013 (by 33%), as nuclear power's share of the national generation mix fell from 25% in 2010 to 1% in 2013 [33] and was mainly replaced by fossil fuels. In Germany, the 6 percentage point reduction of the nuclear share in the generation mix (from 22% to 16%) between 2010 and 2013 was mainly compensated by renewable sources. Nonetheless, there has also been an increase in the share of electricity produced from coal (from 44% in 2010 to 47% in 2013), which led to a slight increase in the intensity of CO_2 emissions in Germany from 439 g CO_2/kW·h in 2010 to 449 g CO_2/kW·h in 2013. These trends support the conclusions that electricity generation can improve its climate protection performance only if changes in the energy mix are made to or between low carbon sources.

2.6. NUCLEAR POWER PROJECTIONS

Each year, the IAEA publishes estimates of energy, electricity and nuclear power trends up to the year 2050 [6]. The annual editions draw on projections prepared by different national and international organizations. As such, the IAEA is regularly involved in the evaluation of information regarding energy, electricity and nuclear power estimates with other organizations. For example, the assumptions for scenario analysis discussed in Sections 2.2 and 2.7 are regularly cross-checked.

The estimates of future nuclear generating capacities are derived by 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 of future energy and electricity demand, and the role of nuclear power, encompass the inherent uncertainties involved in any prognosis. The projections are prepared by assessing the likelihood of each project being implemented in the light of general assumptions made for the low and for the high estimates.

The low and high estimates reflect contrasting, but not extreme, underlying assumptions about factors driving nuclear power deployment. 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 as a worldwide total (see Fig. 7). 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.

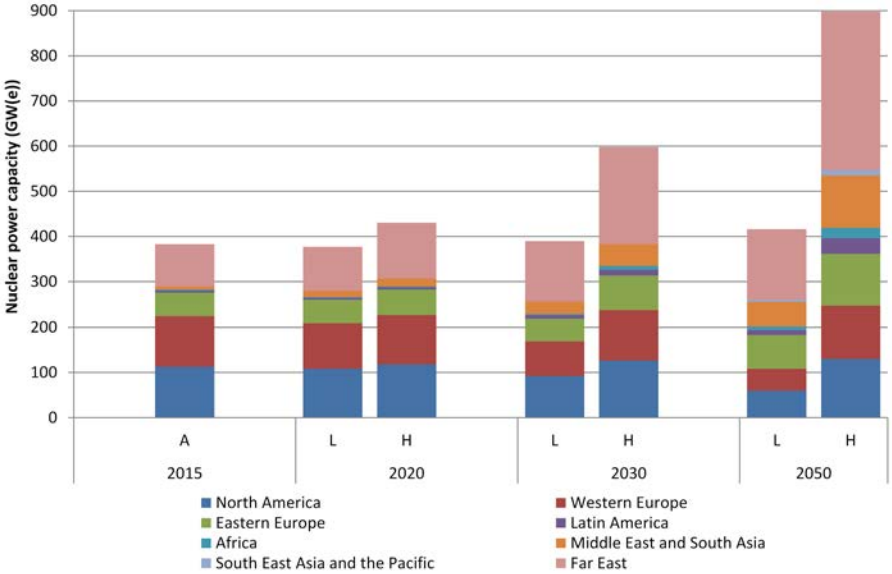

FIG. 7. Prospects for nuclear power in major world regions: estimates of installed nuclear capacity. Data source: IAEA [6].

The low estimate case reflects future expectations, assuming that current market, technology and resource trends will remain unchanged 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 estimate case does not necessarily imply that targets for nuclear power growth in a particular country will be achieved. Policy responses to the accident at the Fukushima Daiichi NPP, as understood in May 2016, are also included in the projections. These assumptions are relaxed in the high estimate case. The high estimate case projections are much more ambitious, but are still plausible and technically feasible (see Section 3.1). The high estimate case assumes that current rates of economic and electricity demand growth, especially in the Far East, will continue. Changes in country policies towards climate change are also included in the high estimate case.

Compared with the 2015 global nuclear capacity for 2030 [6], the 2016 projections are lower by 34 GW(e) in the high estimate case and by 5 GW(e) in the low estimate case. These lower projections reflect the low price of natural gas and the impact of increasing capacities of subsidized intermittent renewable energy sources on electricity prices in the short term. Moreover, the ongoing financial crisis continues to present challenges for capital intensive projects such as nuclear power. In addition to the Fukushima Daiichi accident, heightened safety requirements, deployment of advanced technologies and other factors have increased construction times and costs, contributing to deployment delays. Nevertheless, interest in nuclear power remains strong in some regions, particularly in developing countries. 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.

In the longer run, the underlying fundamentals of population growth and demand for electricity in the developing world, as well as climate change concerns alongside 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 particular, an increase in the share of nuclear energy is foreseen in the future to achieve the objectives of the Paris Agreement as shown in Sections 2.6 and 3.1. Nuclear capacity expansion levels in the IAEA high estimate case are similar to the levels of IEA energy scenarios consistent with the 2°C target (see Fig. 8; see also Section 2.7). Thus, from a climate change mitigation perspective, investment in nuclear power needs to accelerate in order to stay on track with the Paris Agreement objectives and with the pace of the IAEA high estimate case projection.

2.7. FUTURE CONTRIBUTION TO GHG MITIGATION

The diversity of the scenarios in the energy system projections suggest a broad consensus on the increasing role of nuclear power in development pathways compatible with the 2°C target in the short to medium term.

Both the latest fifth assessment report (2014) [35] and the earlier fourth assessment report (2007) of the IPCC Working Group III highlight the potentially important contributions of nuclear power to the mitigation of GHG emissions [36]. For example, across a large number of stringent mitigation scenarios (consistent with the 2°C target) assessed in AR5, nuclear power expands from nearly 5000 TW·h in the lower range (25th percentile) to around 13 000 TW·h in the higher range (75th percentile) in 2050 (from 2410 TW·h in 2014) (see Table 1) [35]. The main variables for this broad mitigation potential are the stringency of climate policy, the level of energy demand growth and competition with other low carbon technologies.

In addition, AR5 brings forward the impact of delays in near term emission mitigation. In stringent mitigation scenarios, most models project dramatic near term changes (already before 2020) in the global energy system, with significant increases in renewables and CCS. It is precisely the potential future limitations (e.g. related to system integration issues for renewables and restricted regional

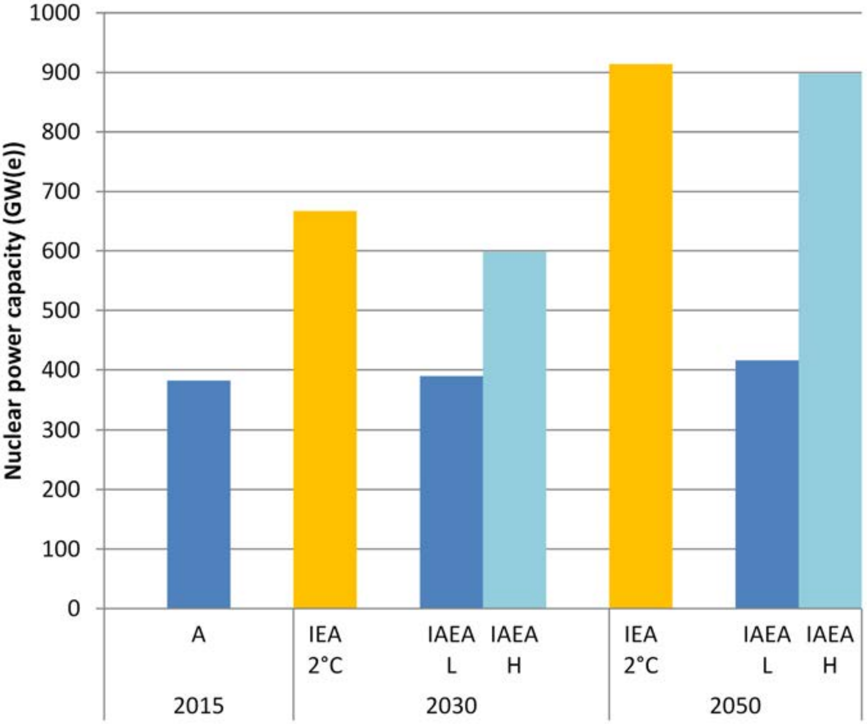

FIG. 8. Prospects for nuclear power worldwide: IAEA Low and High and IEA 2°C Scenario projections of installed nuclear capacity. Data source: IAEA [6, 11, 34]. Note: IEA figures are based on GW(e) gross.

TABLE 1. NUCLEAR POWER GENERATION IN THE LONG TERM, IN SCENARIOS CONSISTENT WITH THE 2°C TARGET [34, 35]

	2014	2050	2050
		IPCC	IEA ETP
Deployment (TW·h)	2410	4 722–13 056	6 802
Rate of change (%/yr)	—	1.9–4.8	2.9

Note: IPCC: Intergovernmental Panel on Climate Change; IEA ETP: International Energy Agency Energy Technology Perspectives. IEA figures are based on TW·h gross.

storage capacities for CCS)[6] of low carbon technologies that raise interest in the expanded use of nuclear energy after 2030. For instance, a study analysing the impact of delays in near term emission mitigation suggests that between 2030 and 2050, anywhere between 29 to 107 new NPPs would need to be built every year [37]. The higher end of this range, explained by the unavailability of CCS technologies, would certainly be unprecedented, but is not inconceivable.

Mid-century prospects for the global energy system are also provided in the IEA Energy Technology Perspectives (ETP) scenarios [34]. Although complementary, the construction of ETP scenarios is different from those in the IEA's World Energy Outlook because of a combination of forecasting to reflect known trends in the near term and backcasting to develop plausible pathways to a desired long term outcome. Scenario 2DS is the main focus of ETP 2015. It lays out the pathway for an energy system compatible with an emission trajectory that has a 50% chance of limiting the average global temperature increase to 2°C. In the 2DS Scenario, electricity generation from nuclear power is projected to increase by a factor of three by 2050. This would amount to an annual average growth rate of almost 3%, as compared with 2014 levels.

How much of the mitigating potential of nuclear energy will be realized depends strongly on domestic policy decisions in the near future and in the following decades. These short and medium term opportunities for action in the energy sector are explored in the scenario analysis up to 2040 presented by the IEA in its World Energy Outlook 2015: the central IEA scenario, known as the New Policies Scenario, and the alternative scenario, known as the 450 Scenario[7] [11]. In the New Policies Scenario, the global power generation mix remains largely dominated by fossil fuels, in particular by coal-fired power plants, which are estimated to still generate 30% of the total electricity in 2040 in this scenario (see Fig. 9). Global investments in nuclear power expand in this scenario but remain concentrated in a relatively small number of markets such as China, India, the Middle East, the Russian Federation, South Africa and the United States of America. Installed nuclear capacity grows in this scenario by 90 GW(e) within the next decade, but almost two thirds of the total capacity

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[6] In contrast to spent nuclear fuel that can be stored safely and inexpensively for decades until a disposal facility becomes operational, immediate disposal of CO_2, which requires infrastructure including capture facilities, transport lines and disposal sites, is necessary for CCS based technologies, thereby imposing a real time constraint. Furthermore, the proximity of future large point sources to potential CO_2 disposal locations is usually not accounted for in the scenario analysis.

[7] 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.

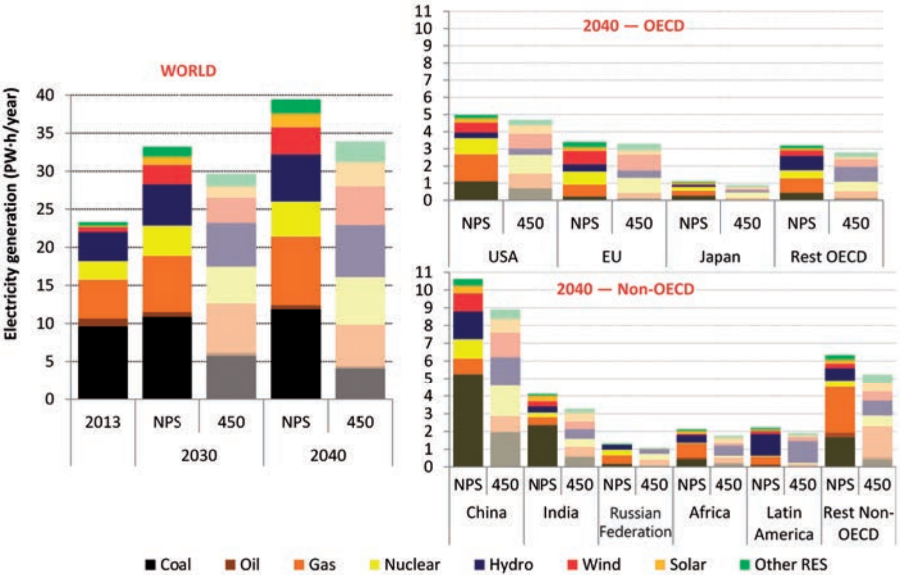

FIG. 9. Power generation mix in the IEA World Energy Outlook scenarios calculated from data in Ref. [11]. Note: NPS: IEA New Policies Scenario; 450: IEA 450 Scenario (2°C), Other RES: other renewable energy sources.

additions are constructed only after 2025. China alone accounts for 58% of global growth in nuclear capacity in the New Policies Scenario, and overtakes the United States of America as the largest user of nuclear power around 2030. The historical role played by NPPs to decarbonize the global electricity mix is more elaborate in the New Policies Scenario: more than 3 Gt CO_2 is expected to be avoided in the power sector in 2040 owing to the expansion of nuclear capacity worldwide.

In the 450 Scenario, the global power generation mix changes fundamentally, reflecting a prescribed time path of GHG emissions consistent with the 2°C target. A large reduction of fossil fuel generated electricity is compensated by significant increases in electricity produced by renewable energy sources, nuclear and fossil fuel plants fitted with CCS (i.e. three quarters of the coal based power is projected to be coming from plants equipped with CCS). Investment in nuclear power generation is around 27% higher in the 450 Scenario and occurs across a larger number of markets compared with the New Policies Scenario. However, according to the IEA, the most distributed investments in the power supply across markets worldwide are based on renewables — accounting for nearly 50% (over US $10 trillion) of the global cumulative power sector investment (around US $22.5 trillion), from 2015 to 2040.

In addition to New Policies and 450 Scenarios, the IEA performed a summary assessment of the energy sector impacts of the Intended Nationally Determined Contributions to GHG emissions reduction communicated to UNFCCC[8] in advance of the Conference of Parties (COP21) in Paris in 2015 [38]. According to this assessment, if these contributions are implemented fully, the growth in energy sector GHG emissions will slow down dramatically, resulting in an increase of around 2.7°C in average global temperature by 2100. This trajectory, however, falls short of limiting the increase to no more than 2°C and corresponds approximately to the middle line between the New Policies and 450 Scenarios. The assessment does not provide details on the power sector generation mix because very few countries distinguish between the energy sector technologies (e.g. nuclear or CCS) or policy options (e.g. fossil fuel subsidy reform or carbon pricing) that are required for a long term transformation of the energy sector. Nevertheless, the assessment provides indicative information on the carbon intensity of electricity generation in 2030 (carbon intensity refers here to direct emissions only and is thus lower than intensity derived from life cycle emissions) (see Table 2). The global carbon intensity of the power sector improves in this scenario — going from 518 g CO_2/kW·h in 2013 to 382 g CO_2/kW·h in 2030 — as the oldest, least efficient and often most polluting fossil fuelled plants are retired and more efficient and lower carbon supply power sources, including nuclear, enter the system.

TABLE 2. CARBON INTENSITY OF ELECTRICITY GENERATION [11, 38]

Indicator		2014	2030		
			NPS	INDC	450
Power sector	CO_2 emissions per unit of electricity (g CO_2/kW·h)	518	427	382	256

Note: NPS: IEA New Policies Scenario; INDC: Intended Nationally Determined Contributions; 450: IEA 450 Scenario (2°C).

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[8] The coverage of Intended Nationally Determined Contributions accounts for around 90% of global economic activity and almost 90% of global energy related GHG emissions in 2015.

The scenario analysis in this section indicates that nuclear power has an important role in decarbonizing the power sector and progressing towards a 2°C target. With adequate support and effective carbon pricing, there is room for faster deployment of nuclear power, particularly in countries without nuclear power. Middle term and further expansion of nuclear power beyond 2040 is needed to achieve full decarbonization of the power sector, while meeting ever rising electricity needs.

3. DELIVERING NUCLEAR POWER

3.1. TIMING AND REQUIREMENTS FOR NUCLEAR DEPLOYMENT

Meeting the 2°C objective defined in the Paris Agreement and implementing the necessary decarbonization of the power supply is a tremendous challenge. This transformation will come at a higher cost if low carbon options, including nuclear energy, are not deployed in a timely manner to their full potential. Many countries thus intend to increase nuclear based electricity generation to contribute to cost effective decarbonization, although this requires a strong political will and coordinated action by the international community and multinational enterprises.

The nuclear capacity needed to meet the stringent climate objectives of the Paris Agreement is estimated to be around 950 GW by 2050 [6, 39], more than double the worldwide capacity of the 441 NPPs, which was 383 GW(e) at the end of 2015 [40]. Supporting such large scale deployment, given the long planning horizons, component long lead times and limited industrial capacities poses a major challenge to the nuclear industry.

The challenge is twofold in terms of unit construction requirements: replacing existing capacity as suggested by the age distribution of the operating fleet (Fig. 10) and ramping up capacity to tap the full mitigation potential of nuclear technologies.

Almost two thirds of the NPPs are more than 30 years old but 60% of this ageing capacity is located in three countries — France, Japan and the United States of America. The majority of existing reactors are having their licences extended by at least 10 years and efforts are being made in some countries (e.g. in the United States of America) to extend operation beyond 60 years. Alternatively, nuclear additions in China account for one third of the total capacity of less than 20 years in age. Replacing ageing capacity without suffering

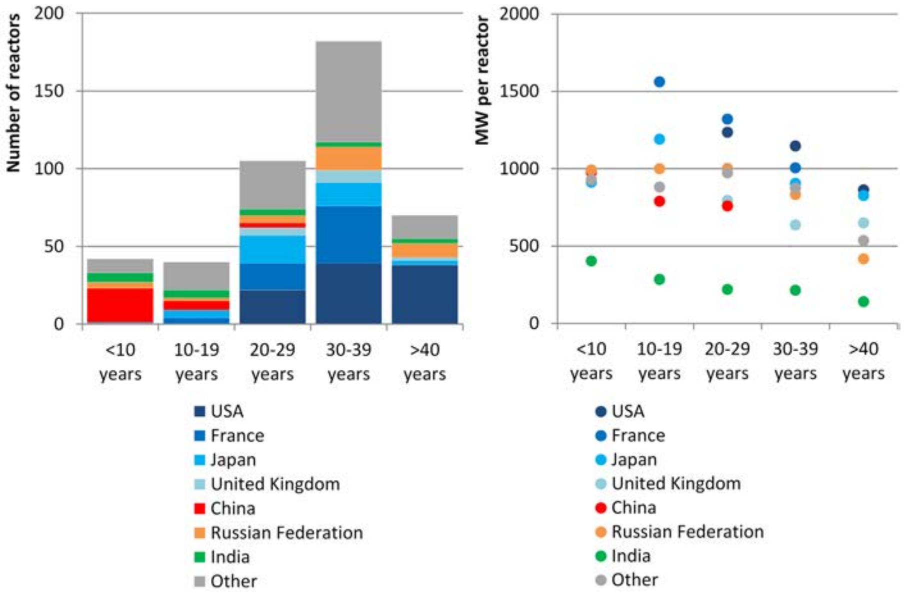

FIG. 10. Age distribution of operating NPPs in 2015 (left panel) and average capacity by age range in 2015 (right panel). Source: Ref. [40].

a break or loss in output is a pressing issue for the countries with the oldest nuclear programmes. Owing to technological improvements and market drivers, the average reactor size has tended to grow in recent decades. The type, size and physical and radiological properties of the nuclear facility, among other factors[9], will impact the decommissioning costs [41].

The timing of new nuclear builds is not only influenced by the replacement of existing capacity but also by the degree of nuclear ambitions in a given country. In the central IEA New Policies Scenario, nuclear developments in China, India, the Russian Federation and in newcomer countries with more limited expansion plans translate into 380 GW of new builds in the next quarter century, equivalent to the existing capacity, on average, 15 GW every year [11].

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[9] Other cost drivers of decommissioning activities are: the extent of decommissioning activities involved in the decommissioning project (inventory of decommissioning activities); the techniques and processes implemented for individual activities (dismantling, decontamination, demolition, waste treatment, disposal, release, legislative aspects, etc.); the personnel involved in decommissioning activities for preparation of decommissioning, management, support activities, surveillance, maintenance and similar activities; the list of collateral costs related to the decommissioning case.

It is worth noting that this scenario falls short of delivering enough low carbon investments into the power sector to meet the 2°C goal. Meanwhile, 150 GW of capacity is retired in the IEA New Policies Scenario which factors in the life extension of numerous plants worldwide. This results in a net installed capacity of 624 GW by 2040.

However, much stronger policy measures are required to drastically cut CO_2 emissions in the power sector, discourage coal or natural gas based power generation and foster nuclear developments. Those developments, albeit challenging, are achievable but imply an extended lifetime of plant operations, and thus a slowdown in retirements, and far more vigorous capacity additions. The pace of nuclear constructions in the IEA 450 Scenario is increased by a factor to both replace retiring capacity and meet ambitious targets. The year 2015 saw a 5.5 GW(e) net increase in capacity installed globally, one of the largest annual increments in the last two decades. By contrast, the projected nuclear deployment in the 450 Scenario consistent with the 2°C objective entails a pace of annual nuclear additions of about 24 GW(e) up until 2050 [39].[10] This pace of construction is close to the peak seen in the early 1980s but would need to be sustained for decades.

The significant experience gained by nuclear industries that was lacking in the 1970s would benefit this new phase of nuclear expansion and would also be supplied by globalized markets. The IEA Energy Technology Systems Analysis Program 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 are realistic for the serial construction of standardized designs. The current lengthy construction times are partly due to unique designs that offer limited learning opportunities for the vendors.

A number of hurdles need to be overcome for a large deployment to materialize. The World Nuclear Association identifies three key challenges: an economic challenge, a quality challenge and a capability challenge [42]. In addition to a broad public consensus, the sheer volume of investments (nuclear investments to 2040 derived from the IEA 450 Scenario amount to US $81 billion per year), or the necessity to avoid construction delays and cost overruns, are

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[10] In the IEA 450 (2DS) Scenario, most growth in nuclear capacity is foreseen in China, whose capacity in 2050 would be more than twice the capacity installed in the USA, followed by India with about 100 GW of installed capacity. Other markets for nuclear deployment include the Middle East, South Africa and South-east Asian countries.

all aspects of a supply chain that needs to work at peak efficiency (Fig. 11).[11] First, this assumes a joint understanding about the safety and security culture that prevails in nuclear installations and quality management (assurance and control) to oversee industrial efficiency and effectiveness. The development and training of a skilled workforce, and of a regulatory body in newcomer countries, building upon existing capabilities and international cooperation and knowhow, is also envisaged through the product realization process.

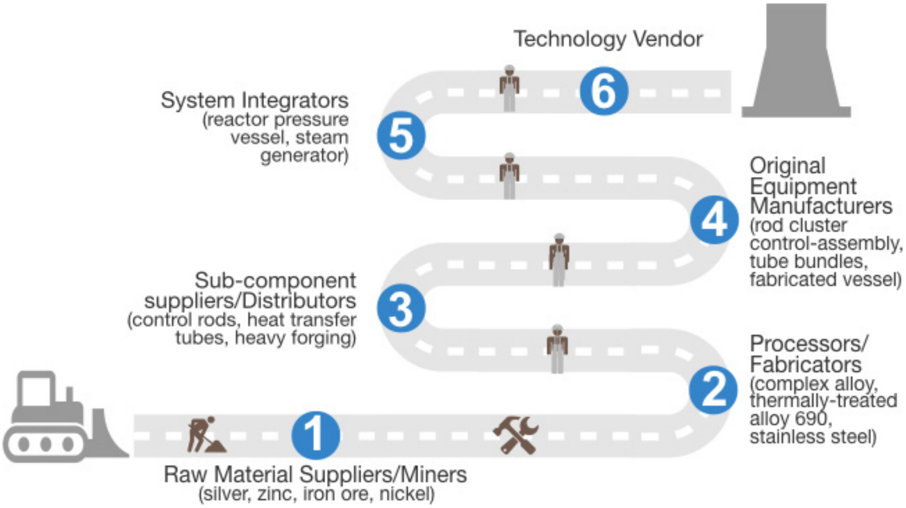

FIG. 11. Nuclear supply chain. Adapted from Ref. [42].

Historical experience in the industry 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. Countries such as the Republic of Korea demonstrate that it is possible to catch up with the forerunners, even with a late start. The prospects for a successful nuclear development

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[11] According to the World Nuclear Association, typical amounts of raw materials, manufactured products and services needed for a Generation III nuclear power plant construction include: 6 000 m^3 of base mat concrete, 61 000 t of steel, 4 000 t of forgings, about 200 pumps, 5000+ valves, 210 km of pipes and 2000+ km of cabling, 50 000+ welding seams, all at the exceptional quality required from nuclear grade components. Performance tested safety related items, other safety significant items with reasonable assurance of performance, multiple engineering services (civil, mechanical, electrical and software) are also required.

programme in a newcomer country will also depend on the strategy of the government and businesses. If implemented efficiently, nuclear development can become a major driver of economic growth and can have a multiplier effect on other sectors of the economy, increasing overall output, enhancing the country's competitiveness with respect to its international counterparts, and creating new jobs, as was observed in the Republic of Korea [43].

3.2. THE ECONOMICS OF NUCLEAR POWER

A power system consists of assets (technologies) with different technical and economic characteristics and these characteristics help determine the respective role of the technologies within the system. In regulated markets, technology selection takes place through a centralized planning process, while in a deregulated market, it is decided in a competitive marketplace. Regardless of market structure, it is generally preferable to have a balanced and diversified portfolio of power generation assets in order to mitigate technical, operational and financial risks. This is true both at the individual company and system level.

Considerations beyond underlying economic forces also help shape electricity systems. A deregulated electricity market is not an unregulated market and policy intervention to ensure system adequacy, reduce carbon emissions or promote certain technologies is a feature of virtually all restructured markets. In regulated markets, too, concerns other than economics and reliability play a part and influence decisions. The role of nuclear power is therefore defined not only by its costs and performance characteristics, but also by how such interventions and concerns affect the relative attractiveness of different technologies.

Two factors in particular shape the challenges for new nuclear power projects: the high share of capital costs in total generation costs, and very large project sizes. This means that the funding required to realize a single project is much higher for nuclear plants than for other technologies (except certain very large hydropower schemes and coal plants). Consequently, investors tend to be wary of the associated risks as the balance sheets of even the largest power companies in the world could be stretched by taking on a project of this size (nuclear power projects can exceed US $10 billion in value) [44, 45]. This is, for instance, illustrated by the concerns over the planned project of Electricité de France (EDF), the Hinkley Point C nuclear power plant in Somerset, United Kingdom [46, 47]. Even if the per unit cost of the electricity produced from nuclear is kept low, the sheer scale of such projects may render them unviable in the absence of Government support. Once built, on the other hand, nuclear plants will usually have very low running costs and tend to earn high margins in most electricity markets. Even with these challenges in mind, the underlying per unit cost of electricity is probably still the most important single metric to assess the relative economics of power generation technologies. The levelized cost of energy (LCOE) is the present value of all costs divided by the present value of all electricity generation over the lifetime of a project. The LCOE therefore represents the average per unit cost of electricity from a facility during its operational life.

The OECD, the IEA and the OECD Nuclear Energy Agency collect and publish such cost estimates for different electricity generating technologies on a regular basis [48–50]. The latest edition includes estimates based on 181 power projects and calculated for three different discount rates. Figure 12 shows the LCOE for 11 different groups of technologies at a discount rate of 3% (real). This can be seen as a 'social' discount rate and represents the rate at which society is deemed willing to defer consumption. It is also of a magnitude similar to that prescribed by many OECD Governments for cost–benefit analysis of government projects and policies [51] and similar to the yield on high quality corporate bonds. Discount rates of 7% (see Fig. 13) and 10 % (see Fig. 14) are closer to market rates in OECD countries and therefore represent the opportunity cost of capital. They are more in line with the cost of capital for the private financing of power projects.

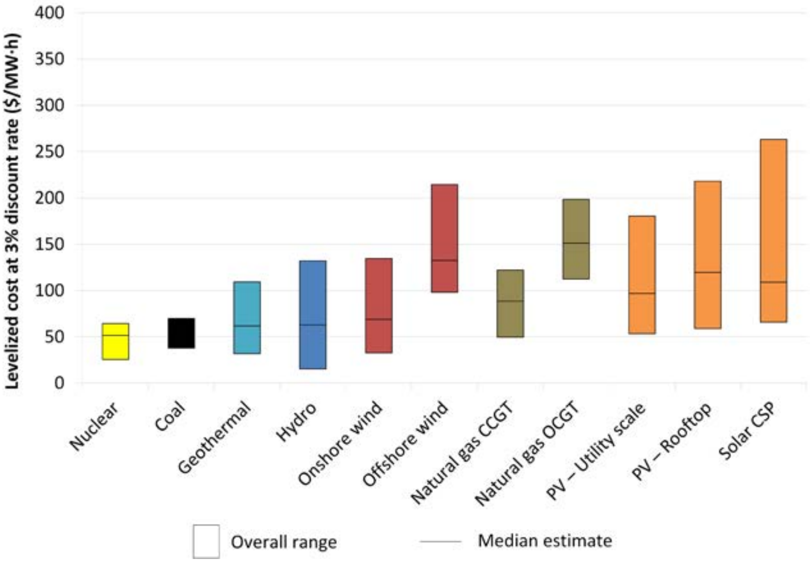

FIG. 12. Ranges of LCOE for new construction at 3% discount rate. Data source: Ref. [48]. Note: CCGT: combined cycle gas turbine; OCGT: open cycle gas turbine; CSP: concentrated solar power.

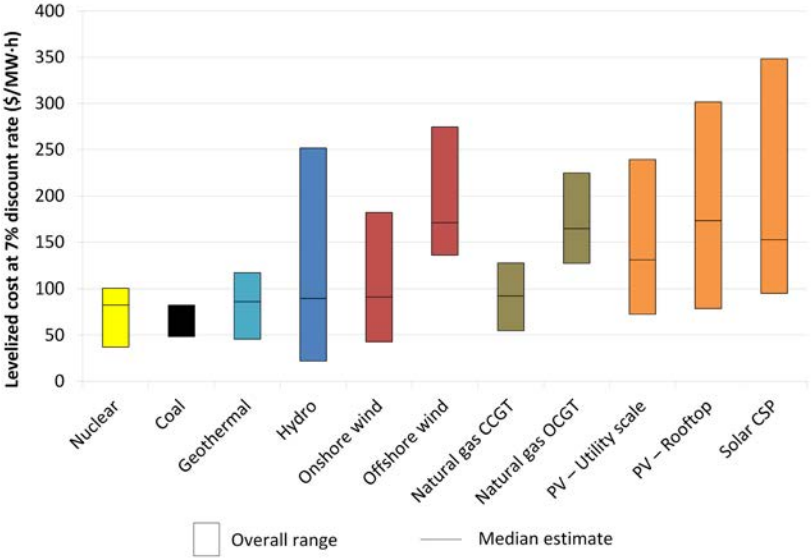

FIG. 13. Ranges of LCOE for new construction at 7% discount rate. Data source: Ref. [48]. Note: CCGT: combined cycle gas turbine; OCGT: open cycle gas turbine; CSP: concentrated solar power.

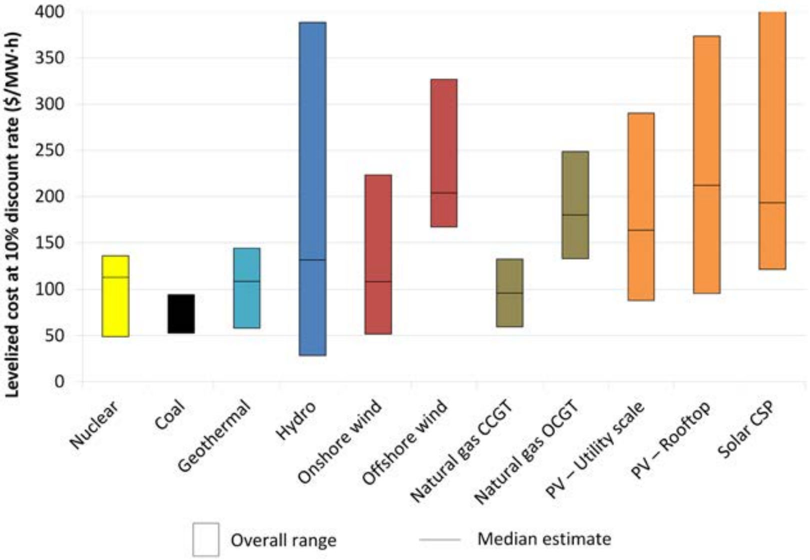

FIG. 14. Ranges of LCOE for new construction at 10% discount rate. Data source: Ref. [48]. Note: CCGT: combined cycle gas turbine; OCGT: open cycle gas turbine, CSP: concentrated solar power.

Figures 12 to 14 depict the lower, middle (median) and upper LCOE estimates from the sample, sorted by technology group. The range in LCOE for different technology groups is driven by variations in assumptions such as factor costs, plant size, fuel costs and plant performance between countries and characteristics of technology subdivisions. For nuclear power and coal, estimates represent plants of similar sizes with some variation in performance and fuel price. The range of estimates is therefore relatively narrow compared with other technology groups, though still considerable in absolute terms. For geothermal and hydro plants, site specific conditions and very large differences in project size are the key drivers behind the broader range of estimates observed for these technologies. In gas-fired generation, the main difference between countries is the fuel price. Wind and solar LCOE variation is determined by economies of scale and differences in achieved capacity factor. This leads to comparatively large ranges of estimates. In addition, differences in factor costs are an important driver for all technologies. At lower discount rates, the LCOE for nuclear compares favourably with other technologies.

While there is significant overlap among technologies, the median cost for nuclear power technology is the lowest among the technologies surveyed. However, at higher discount rates, up-front capital expenditures will make up a greater share of generation costs. Capital intensive technologies such as nuclear and renewables will tend to be more sensitive to discount rates and the ranking of nuclear power relative to other technologies consequently drops with increasing discount rate.

It is important to distinguish between costs and prices. The costs reported here may not be indicative of prices in the markets as cost and price formation are two distinct processes. In particular, the current prevalence of out-of-market payments may drive considerable differences between electricity prices and costs.

Furthermore, these cost estimates include all direct costs normally internalized over the lifetime of a power project, but exclude system integration costs and environmental costs. System integration costs for nuclear power are in the range of US \$1.40 to US \$3.10/MW·h, compared with US \$0.34 to US \$0.56/MW·h for gas, and US \$0.46 to US \$1.34/MW·h for coal, according to a survey of 6 OECD countries [52]. System integration costs tend to be significantly higher for intermittent renewable generators and were found to be in the range of US \$14.82 to US \$82.95/MW·h depending on technology and market share.

The assumed social cost of GHG emissions and other pollutants can be highly contentious and a wide range of estimates exists [53] (see also Section 4.2). As an example, a carbon price of US \$30 per tonne of CO_2 adds US \$9.43/MW·h to US \$16.62/MW·h to the cost of natural gas-fired electricity generation and US \$20.03 to US \$28.88/MW·h to the cost of coal-fired electricity generation [48].

3.3. FINANCING NUCLEAR POWER

Nuclear power projects are highly capital intensive with 70–80% of the total lifetime costs being spent before any power is produced. Since they also require lengthy project development and construction phases, the cost of nuclear power is very sensitive to the cost of capital (see discussion in Section 3.2 and Figs 12, 13 and 14). Securing access to financing at competitive terms is crucial to the economics of these projects.

Nuclear power projects are also very large and are comparable to large scale public works projects (e.g. bridges, tunnels, railways, airports, seaports and wastewater projects) that provide long term public benefits. Combined with high capital intensity, the amount of up-front capital investment required to realize a single project can thus be exceptionally high, much higher than for other electricity generation technologies (except certain very large hydropower schemes and coal plants). The scale and complexity of such projects make them risky propositions and traditional arrangements that are common in other areas of infrastructure development — such as project finance — are unlikely to attract the necessary capital. Corporate balance sheets may also be insufficient to support this level of capital investment, except in the case of very large corporations.

Therefore, access to financing is often a major hurdle to project development. Risks may occur at all stages of the project life cycle, but given the importance of up-front capital costs, risks that can lead to cost overruns and schedule delays during the construction phase are of particular concern. Nuclear projects [54] just like other projects of this scale, are prone to such problems [55]. These risks can be categorized both as potentially high impact and as having high probability of occurrence and therefore may represent major obstacles to project viability. Lower than expected revenues during the operating phase due to poor plant performance or market risks (inadequate demand for an NPP's output or low electricity prices) is another key concern. The key to securing access to financing at favourable terms is effective management of these and other project risks. Lenders will look for assurances that loans will be repaid and will insist that risks are identified and that appropriate strategies to address them are developed. Such strategies may involve, to the extent possible, the reduction or elimination of project risks and the efficient allocation of remaining risks to those stakeholders most able to manage them.

In response to these challenges, a number of innovative approaches to financial arrangements and government support for nuclear power projects have begun to emerge. A recent publication [56] 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. The main benefit of this model is that it can provide a country embarking on the construction of its first NPP with access to a source of both funding and experience. The downside is that this access locks in the acquisition to a particular vendor's technology. India's Kudankulam NPP was partly financed through a bilateral loan agreement between the Indian and the Russian Federation Governments. A loan from the same source is a major component of the financing for the Ostrovets NPP under construction in Belarus.

The loan guarantee framework model provides assurance to lenders that their loans will be repaid by a financially credible entity as guarantor in the event that the project developer fails to repay them. As a result of the reduced risks, the lenders tend to charge lower interest on the loans advanced to a project. In the United States of America, the Department of Energy provided loan guarantees to two of the co-owners of Vogtle 3 and 4 in February 2014 [57]. In the UK, it is planned that the Hinkley Point C NPP project will benefit from a similar guarantee from Infrastructure UK (a part of Her Majesty's Treasury). Several national export credit agencies also facilitate loan guarantees to support the export of their national suppliers' nuclear energy technologies.

Vendor financing comes in various forms, including vendor arranged credit (often involving an export credit agency), vendor provided credit (likely short term) and vendor equity. Vendor equity is typically anticipated to provide a relatively small part of a project's overall financing. The advantage of this source of financing is that it aligns the interest of the vendor to the overall success of the project. However, it also tends to be a relatively expensive source of capital. The French multinational group AREVA was expected to take a 10% equity share in the UK's Hinkley Point C project (before the company was absorbed by EDF) [58]. The Korean Electric Power Corporation is expected to take an 18% share of equity in the Barakah NPP in the United Arab Emirates [59].

Power purchase agreements backed by host governments can provide similar assurances to lenders, by guaranteeing that market risks will not endanger a project's ability to repay its debts and associated interest. The UK's contract for difference mechanism is an example of such a power purchase agreement scheme, and forms a key part of the arrangements (along with the infrastructure and projects guarantee) to support the development of the Hinkley Point C project.

Similar 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 greater willingness to lend to such projects, as well as a likely reduction in borrowing costs. Technology development could also help address financing challenges. Small modular reactors, for instance, would have much smaller initial capital requirements, shorter construction periods and the potential for phased deployment. This may reduce the project scale and risks to levels that make such NPP projects more like other power projects, which would likely improve the prospects for realizing NPPs through more traditional corporate and project financing sources and arrangements.

3.4. PARIS AGREEMENT: WHAT IS THE IMPACT FOR NUCLEAR?

The December 2015 Paris Agreement lays the foundation for meaningful progress to address climate change. It emphasizes the urgency of actions by confirming the target of limiting the global average temperature increases to below 2°C and aspiring to a 1.5°C target. IPCC AR5 and the projections of the IEA acknowledge the role of nuclear in achieving the 2°C target in their scenarios (see Section 2.6). The role of nuclear energy might be even greater, should a more ambitious temperature goal (1.5°C) be adopted. In the post-2020 framework, countries are free to specify technology details in the future updates of their Intended Nationally Determined Contributions under the Paris Agreement. This ‘bottom-up’, flexible regime partly explains the success of the Paris Agreement, in contrast to the ‘top-down’, stringent Kyoto-type regime (and the lessons learned), which could not ensure the participation of all the parties. It remains to be seen whether this bottom-up Intended Nationally Determined Contributions approach will fill the gap between the reality — current trends on GHG emissions and temperature change — and the most stringent 1.5°C target. The action of filling this gap is mainly confined to the national level.

Article 4 of the Paris Agreement states that countries should aim to reach global peaking of GHG emissions as soon as possible and should aim for neutrality of the emissions in the second half of this century, “on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty” [2]. In order to increase the intensity of actions in step with increasing national ambitions, each party is invited to communicate an Intended Nationally Determined Contribution every five years, starting in 2023. In addition, all parties should strive to communicate their mid-century, long term low GHG emission development strategies by 2020. These timely communications, as laid down in the Paris Agreement, highlight the urgency of low carbon transition.

Decarbonization needs to accelerate, which, in the power sector, means reducing electricity generated from coal and increasing the pace of investment in low carbon generation, including in nuclear power. However, the Paris Agreement neither defines energy technologies as low carbon, nor specifies any energy technology [60] (with the exception of the acknowledgement that it makes to the promotion of universal access and sustainable energy in developing countries, in particular in Africa, through the enhanced deployment of renewable energy). Consequently, all technologies, including nuclear, are on the table for implementing countries' Intended Nationally Determined Contributions, as a means of progressing towards the targets of the Paris Agreement. Countries that specifically mention nuclear power as part of their Intended Nationally Determined Contributions to climate change mitigation include Argentina, China, India, Japan, Jordan and Turkey. Other countries that currently use nuclear power (a total of 30) do not exclude the possibility of including nuclear power in the strengthening of their climate actions. Furthermore, another 30 countries that are either considering or planning to include nuclear power in their energy mix are actively working with the IAEA.

Despite the fact that the Paris Agreement does not provide specifics on technologies and leaves this responsibility to the parties, certain aspects of the Agreement could influence the conditions under which low carbon technologies, including nuclear power, can contribute to climate change mitigation after 2020. Three key points have been identified and are discussed here: (a) a new market based mitigation mechanism; (b) domestic policies and carbon pricing; and (c) the relation of nuclear power to Sustainable Development Goals.

(a) A new market based mitigation mechanism

Article 6 of the Paris Agreement establishes a new market based mitigation mechanism that allows parties to pursue cooperative approaches that involve the use of internationally transferred mitigation outcomes to contribute to the reduction of GHG emissions and the support of sustainable development under robust accounting rules and avoiding double counting. This is not the first time that a climate agreement has created a new mechanism. Under the flexible mechanism of the Kyoto Protocol's Clean Development Mechanism, a country with a treaty specified target (i.e. most developed countries) could partly meet that target by investing in a project that lowered GHG emissions in a country without a treaty specified target (i.e. most developing countries).[12] Depending

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[12] Joint Implementation is another mechanism of the Kyoto Protocol. It can be used between countries that both have treaty specified targets.

on the lead time of low carbon technology and the climate commitment period, the monetary benefits received from the emission reduction credits under the Clean Development Mechanism could contribute significantly to the viability of a project [61].

Nuclear power was specifically excluded from the Clean Development Mechanism. These exclusions were part of the Bonn Agreement negotiated at the second session of COP6 in April 2001 and were formalized in the Marrakech Accords at COP7 later that same year, stating that developed countries are to refrain from acquiring credits from nuclear projects under the Clean Development Mechanism. Although few nuclear projects were in prospect for the first commitment period of the Kyoto Protocol (2008–2012), exclusion of any low carbon technology, including nuclear, can only decrease the options, flexibility and cost effectiveness of climate change mitigation.

Some key differences are expected to emerge between the New Market Mechanism and the Clean Development Mechanism. These include the elimination of geographical restrictions (removing the distinction between developed and developing countries), overall reduction of global emissions, rather than offsetting emissions, and expansion of project based offset mechanisms to include policies, activities and programmes. In addition, the Paris Agreement, in contrast to the Kyoto Protocol, provides a long term framework for the transformation of energy systems, thereby providing more certainty and less investment risk for low carbon technologies.

The rules and modalities for the New Market Mechanism will be determined by the technical group under the UNFCCC, once the agreement enters into force. Thus, a discussion on technologies, including nuclear power, could be initiated in parallel with the definition of the rules governing the implementation of this mechanism. It is expected that the New Market Mechanism would initially benefit renewable sources of energy in addressing climate change and energy poverty. Nonetheless, once a country has developed its energy system and infrastructure, it would be in a better position to use nuclear power, should it decide to do so, hence the importance of keeping this option open. Any restriction or exclusion regarding the use of nuclear energy under the New Market Mechanism would likely increase the mitigation costs and undermine international and domestic policies in climate change mitigation and sustainable development.

(b) Domestic policies and carbon pricing

The Paris Agreement also “recognizes the important role of providing incentives for emission reduction activities, including tools such as domestic policies and carbon pricing” [2]. Why is there a need for such incentives? Current policies and investment trends in low carbon technologies fall short of delivering the GHG mitigation below 2°C objective formulated in the Paris Agreement (see Section 2.2).

The issue with all low carbon energy sources, and especially nuclear power, lies in their high capital-to-operations cost ratio. Combined with current low electricity prices and a certain lack of predictable and consistent energy and climate change policies, new builds face barriers in many countries, particularly in countries with abundant cheap fossil fuel supplies. Investments in nuclear capacity today, as well as in other low carbon technologies, principally renewables, are supported by mechanisms such as power purchase agreements that to some extent guarantee long term income security [62] (or by other out-of-market arrangements, such as feed-in tariffs, which are frequently employed to support renewables). These incentives, which may or may not include a subsidy element (i.e. a tariff higher than average costs), are necessary to reduce the investment risk, ensure timely investments in low carbon power generation capacity and avoid the 'lock-in' in fossil fuel intensive assets.

Complementing these incentives with a strong CO_2 price improves the competitiveness of low carbon investments and discourages investments and operations of fossil fuel based power plants. Carbon pricing, which internalizes climate damage, could be introduced in the form of a carbon tax or a cap-and-trade system, such as those introduced in the European Union in 2003, in some provinces of Canada and in some States of the United States of America in 2008, or recently in the Republic of Korea. In order to generate the efficiency gains expected from the carbon market, the carbon pricing mechanism needs to be aligned with other existing national regulations [62].

The key practical issues regarding the incentives mentioned in the Paris Agreement are choosing and designing the policy instruments that are best suited for implementing countries' Intended Nationally Determined Contributions. Alongside this process, energy technologies, including nuclear power, need to be judged on their climate change mitigation merits [63] and within specific national contexts.

(c) Sustainable Development Goals

The Paris Agreement can also contribute to the achievement of the United Nations' Sustainable Development Goals. The agreement "aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty" (Ref. [2] p. 22). The transition to low carbon economies is expected to improve resource efficiency, favour economic transformations, create jobs and stimulate growth.

Despite the consensus on nuclear power as a low carbon technology, there is a lack of research to identify synergies between nuclear power (as well as other energy technologies) and sustainable development [64–68]. According to existing studies and a selection of sustainability indicators, nuclear power compares favourably with its alternatives. Besides its GHG mitigation potential, nuclear power can alleviate reliance on depleting fossil fuels, help to diversify energy mixes, increase the stock of technological and human capital, and reduce impacts on human health, ecosystems and air pollution. Nuclear power can also support greater penetration levels of renewable energy sources than would otherwise be achievable without additional measures (e.g. energy storage and greater interconnections) (see Section 2.3).

The key issues regarding the nexus of sustainable development and nuclear power is the lack of awareness and recognition of these benefits, including the reliability and predictability that nuclear power offers in the electricity markets [69]. The implementation of the Paris Agreement together with the United Nations agenda to address sustainable development and design appropriate policies and measures may provide additional incentives for nuclear programme development.

3.5. ROLE OF NUCLEAR INNOVATION IN CLIMATE CHANGE MITIGATION

An important outcome from COP21 and the Paris Agreement is that innovation is absolutely critical “for an effective, long-term global response to climate change and promoting economic growth and sustainable development” [2]. Innovation, in this context, implies not only the use of new technologies but also creative approaches to implementing actions and regulations, and creating business models. Several conference speakers amplified this message. For example, Ernest Moniz, Secretary of Energy, United States of America, was reported to have particularly insisted on the virtuous circle of increasing innovation, reducing costs and increasing the deployment of low carbon technologies [70].

Fatih Birol, the Executive Director of the IEA, said, “Innovation is at the heart of fighting climate change”, while Maroš Sefčovič, EU vice president, noted that “it will be important for the future to look into how we can streamline and synergise existing efforts to create truly global collaboration in energy technology innovation”.

The clear message is that innovation, together with investment and research in cleaner and sustainable technologies and strategies, rather than continued subsidies for polluting activities, is necessary to bend the carbon emissions curve downward.

A given country's level of research, development and demonstration (RD&D) is seen as a key indicator of its capacity for innovation. Investments in RD&D also attract and stimulate national investments and efforts in innovation [71] including in low carbon technologies. Between 2015 and 2030, more than US $400 billion/year needs to be invested in low carbon power supply, including US $81 billion/year in nuclear (see Section 2.2). The Lima–Paris Action Agenda's[13] focus on innovation is supported by pledges made at COP21 under Mission Innovation [72] including 20 countries seeking to double public investment in RD&D between 2015 and 2020. Investments are needed to support transformational clean energy technologies that can be scaled to the economic and market conditions of a country. These currently amount to about US $10 billion/year. Countries expect that all clean energy technologies, including nuclear[14] and carbon capture, can be driven to expansion and success through innovation.

Private capital investments in clean energy were initiated through the launch of the Breakthrough Energy Coalition [73]. This includes 28 major investors from 10 countries pledging to invest extraordinary levels of private capital in early stage innovations. Investments are guided by a set of principles to catalyse broad business participation in the commercialization and deployment of clean energy technologies worldwide. Current contributors include active supporters of innovative nuclear designs and nuclear energy development, most notably Bill Gates' clean energy investment in TerraPower, an innovative fourth generation reactor design [74].

At the COP21, climate scientists (James Hansen, Tom Wigley, Ken Caldeira and Kerry Emanuel) suggested that only a combined strategy employing all major sustainable clean energy options — including renewables and nuclear power — would suffice to reduce carbon emissions enough to meet climate goals [75]. According to the scientists, innovation is pivotal for the expansion of nuclear power. It is needed in design for constructability, disposability and

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[13] The Lima–Paris Action Agenda is a joint undertaking of the Peruvian and French COP presidencies, the Office of the Secretary-General of the UN and the UNFCCC Secretariat. It aims to strengthen climate action throughout 2015, in Paris in December and well beyond.

[14] The administration of President Barack Obama of the United States of America announced in a Fact Sheet on 6 November 2015 the role that nuclear energy will play in the country's Clean Energy Strategy.

sustainability, as well as in project management and standardization within the nuclear supply chain to strengthen its economic attractiveness. Innovation would make nuclear power more socially accepted and its benefits would be better realized: for the climate, because it is a low carbon technology, to health and the environment because it is non-polluting, and for system costs because it offers power generation with less need for grid enhancements. Additionally, there are enough opportunities for technical innovation for current and future generations of nuclear reactors. These are illustrated in Fig. 15.

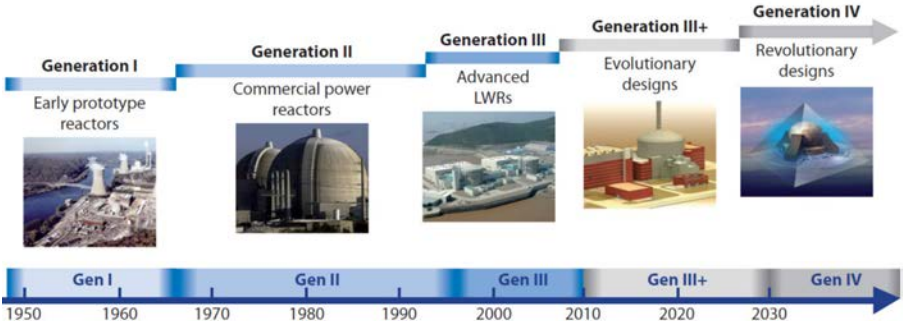

FIG. 15. Generations of nuclear power from 1950–post 2030. Source: Ref. [76] used with permission.

The continued operation of current nuclear technologies is important for achieving short term reductions in GHG emissions from the power sector, given the urgency of climate mitigation. Current commercial power reactors (Generation II) already avoid 2 Gt CO_2/year and innovations can help these reactors to run longer. Advancements are needed for performance upgrades to extend the useful life (long term operation) of existing reactors, and performance and safety upgrades also need to be certified for life extensions. Additionally, concerns about final waste storage, nuclear proliferation risks, cost uncertainties and nuclear safety must be addressed. New builds of advanced reactors (Generation III) and evolutionary reactors (Generation III+) are needed to replace up to 77% of the current reactors retiring by 2050 and to expand nuclear in some markets (for example, in Asia). These new reactors need to overcome barriers to bringing the technology to market including: obtaining financial assistance, access to facilities to conduct necessary RD&D activities, construction of demonstrators and prototypes, and certification and licensing of new nuclear reactor concepts. First-of-a-kind advanced reactors under construction or in early operation need to be optimized through innovation, in order to dramatically reduce licensing and construction costs and to demonstrate their safety capabilities.

Small modular reactors (SMRs) are expected to be deployed with enhanced safety systems [77] in the next 10–20 years. They are envisioned to provide a nuclear low carbon alternative to countries without large power grids, less developed infrastructures and limited financing capabilities. The technology also aims to reduce costs through modularization and factory construction thus reducing construction times. The SMRs are better suited for deployment in remote areas and may additionally support non-electrical applications such as sea water desalination, district heating and heat for low temperature processes such as biomass drying (see section 5.4 in Ref. [78]).

Future revolutionary (Generation IV) reactors can expand nuclear energy over the longer term (2030+). Designs for these reactors include molten salt reactors, supercritical water cooled reactors, very high temperature reactors and fast reactors. The very high temperature reactors may be used in the future to produce hydrogen and support petrochemical and other industrial applications. Fast reactors (e.g. molten salt reactors and accelerator driven systems) could derive significant energy from used fuel to reduce the need for mining and enrichment, which are the most CO_2 intensive steps in the nuclear fuel cycle. Fast reactors specially configured to burn used fuel can substantially reduce the long lived radionuclides in the waste products and the volume of waste requiring deep geological disposal. Current RD&D plans for these systems are contained in the Generation IV technology roadmap [76].

Innovations in the nuclear fuel cycle are also needed to support all generations of nuclear reactors. New fuel designs are needed to support future operating conditions (e.g. load-following), longer fuel cycles and higher burnups [79]. Innovations are needed in the separation and recycling of nuclear materials to fuel future Generation IV fast reactors [80]. Research on thorium could help to extend geological resources for nuclear fuels to meet growing energy demands in regions where uranium is not available [81].

Ultimately, nuclear fusion is the technology at the cutting edge of nuclear RD&D and innovation. Fusion eliminates the production of long lived radioactive waste and the fuel is produced from abundant material such as water, eliminating problems such as energy resource scarcity and nuclear proliferation concerns (see section 6.5 in Ref. [82]).

The priorities for investing in nuclear RD&D need to include the full scope of activity (prototypes and reactors, fuel cycle/waste management and innovative energy systems). Several national and international initiatives have recently been initiated in response to growing energy demands and the global imperative raised at COP21 to address climate change:

- China intends to generate up to 10% of its power from nuclear energy (110 nuclear reactors) as part of a pledge to the international community to reduce carbon emissions and to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030. China stresses the role of innovation, safety and the popularization of its technologies [83].
- The United States of America launched the Gateway for Accelerated Innovation in Nuclear programme in 2016 in response to the Paris Agreement to enhance the deployment of innovative nuclear technology to the market. It will provide the nuclear energy community with access to the technical, regulatory and financial infrastructures necessary to move new or advanced nuclear reactor designs towards commercialization while ensuring the continued safe, reliable, and economic operation of the existing nuclear fleet [84].
- The UK's National Nuclear Laboratory established the Nuclear Innovation and Research Office to provide advice to Government, industry and other bodies on R&D and innovation opportunities in the nuclear sector. According to reports, the

  > "UK would double funding for the Department of Energy and Climate Change's energy innovation programme to £500 million over five years, which will help pay for an ambitious nuclear research programme that will revive the country's nuclear expertise and help turn it into a leader in SMR technology" [85].

- The European Union Horizon 2020 advances nuclear research and training activities through the European Atomic Energy Community's (EURATOM) work programme. The emphasis is on continually improving nuclear safety, security and radiation protection, to contribute to the long term decarbonization of the energy system in a safe, efficient and secure way. The focus is on nuclear fission, including the safety and feasibility of innovative reactors and closed fuel cycle options, radiation protection and nuclear fusion [86].
- The OECD Nuclear Energy Agency launched Nuclear Innovation 2050 to define which technologies are necessary to achieve the nuclear growth needed for the Paris Agreement, and what RD&D is needed versus what is actually being done. A roadmap of RD&D until 2100 will be developed to address the gaps and timelines for five categories: reactors, fuel/fuel cycle, waste/decommissioning, emerging energy systems and cross-cutting issues [87].

There are many opportunities for innovation to advance nuclear energy in addressing climate change. Steps are being actively taken as a result of the Paris Agreement to ensure a continued role for nuclear energy. Although the level of investment in RD&D needs to be increased to meet this challenge, the added cost is justified by continued avoidance of CO_2 emissions with low carbon energy serving increasing rates of electrification throughout the world, and by the extension of nuclear technology beyond the power sector into non-electric applications.

4. BENEFITS OF AND CONCERNS ABOUT NUCLEAR POWER

4.1. ENVIRONMENTAL IMPACTS

In the context of selecting technologies for future energy scenarios, the relative environmental impact of nuclear energy needs to be compared with that of its alternatives. With the primary focus of this publication being climate change, the comparison in terms of life cycle GHG emissions is discussed in Section 2.4. In addition, the environmental effects related to waste and its management are addressed in Section 4.7. Beyond these specific interactions, the primary ways in which nuclear power production affects the environment are through its land use and through the pollutants emitted during its life cycle. In general, a more sustainable energy system includes minimized environmental impacts such as these.

All energy technologies depend upon natural resources to generate electricity. In particular, land use in terms of required land area and plant placement varies considerably among energy production methods, as do the various metrics and methodologies that describe the variety of land uses and impacts on land. By 2050, nearly half of the world's population may reside in urban areas and thus good plant placement is vital to meet growing energy demand [88]. For example, placement close to urban electricity demand centres can reduce resource usage for construction of electricity transmission grids. Additionally, freedom of placement allows power plants to be located where they will have the smallest environmental impact. The output of renewable energy plants depends on their location and they must be placed where they have the highest potential for collecting energy in order to achieve optimum performance. In contrast, the performance of a nuclear power plant is essentially independent of its location. Data collected by the Washington based Nuclear Energy Institute and depicted in Fig. 16 shows that NPPs require a much smaller land area compared with wind and solar technologies. These findings are in line with other scientific studies, which show that nuclear power is a small land user relative to other methods of electricity generation [65]. Nonetheless, there is scope for a more comprehensive comparative assessment of land use requirements for power generation, including properties and conditions of the land required, the nature of land use (exclusive or allowing for multiple use), as well as the duration and reversibility of the transformation (former land use/cover, reclamation times).

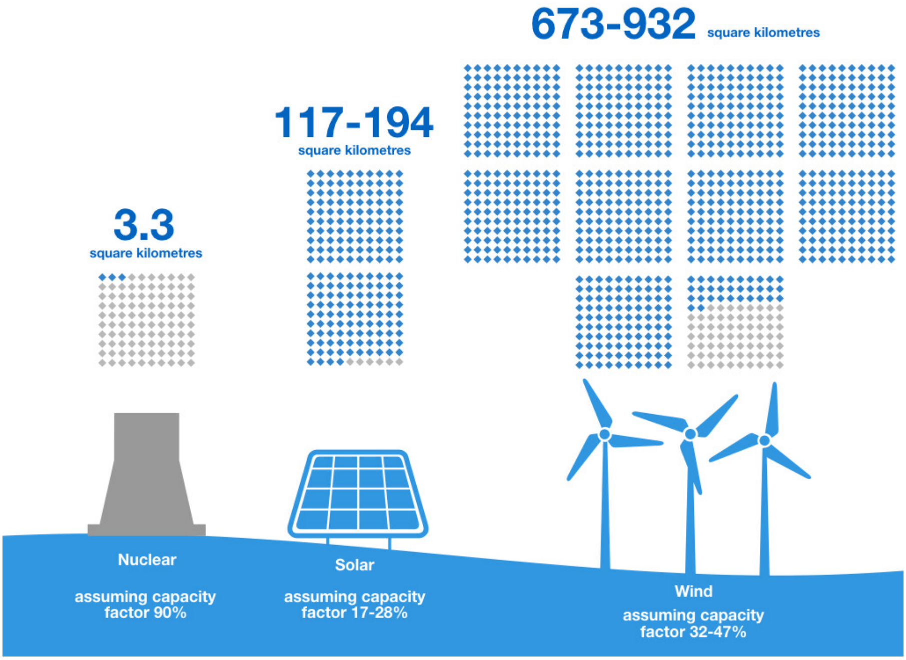

FIG. 16. Land requirement for NPP, wind and solar technologies per 1000 MW of capacity [89].

Energy production is also associated with various pollutants (e.g. sulphur dioxide (SO_2), nitrogen oxides (NO_X), ground level ozone, particulate matter, carbon monoxide (CO) and lead) that can be found in the atmosphere, as well as in streams, rivers, lakes, oceans and soil. Most of the aforementioned are products of the incomplete combustion of fossil and biomass fuels and the presence of non-carbon materials in those fuels. They are also major contributors to smog. In particular, the pollutants SO_2 and NO_X react with oxygen creating ground level ozone, and can be harmful to certain plants [90].

SO_2 and NO_X released as pollutants during the burning of fossil fuels also react with water vapour in the atmosphere, creating acid rain. The primary negative environmental effects of acid rain are its erosion of the surfaces of human-made structures and its effect on aquatic life through water acidification and eutrophication.

Acidification causes stream banks to release dangerous chemicals, killing local fish populations [91]. Effects of this, for example, can be seen in the freshwater fish populations in the Catskill Mountains of New York, United States of America [92]. Several extensive studies have derived and compared the potential of different energy production methods to cause acidification. The figure of merit for acidification (also called acidification potential) is grams of SO_2 equivalent per kilowatt-hour (SO_2-eq/kW·h). Nuclear power, with a median acidification potential of 0.096 SO_2-eq/kW·h, performs similarly to most renewable energy production methods, while producing one tenth of the SO_2-eq of combined cycle gas turbine and geothermal plants and one seventieth of the SO_2-eq of coal plants per kW·h [25].

Eutrophication (i.e. nutrient imbalance) causes oxygen-poor and toxic waters unfit for habitation and consumption by animals and humans [93]. One particular occurrence of eutrophication in Hong Kong, China, in 1998, depleted 90% of the fish stock of local fish farms, causing economic damages worth US \$40 million [94]. Similar to acidification, eutrophication potential is defined as grams of PO_4^{3-} (phosphate ion) equivalent per kilowatt-hour (PO_4^{3-}-eq/kW·h). Nuclear power, with a median eutrophication potential of 0.027 PO_4^{3-}-eq/kW·h, performs similarly to all renewable energy and natural gas-fuelled production methods, while producing one hundredth of the PO_4^{3-}-eq of hard coal and nearly one thousandth of the PO_4^{3-}-eq of lignite coal-fuelled power production methods per kW·h [25].

4.2. HUMAN HEALTH EFFECTS

Independent studies conclude that the health effects from NPP construction and operation are consistently low and are much lower than fossil fuel alternatives and comparable with renewable energy technologies. Study results are comprehensive but do not include health results arising from accidents.

For electricity generated from fossil fuels, adverse health effects from power plant construction and fuel cycles come mainly from particulates, SO_2, NO_X, non-methane volatile organic compounds and ammonia (NH_3). Their principal health effects are respiratory illnesses and fatalities. Power plant construction and the fuel cycle also release GHGs that contribute to climate change. Health effects from climate change include cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis and diarrhoea. They also include the health impacts of increased malnutrition and natural disasters. Additional adverse health effects come from radionuclides released from fossil fuels. These are estimated in terms of fatal cancers, non-fatal cancers and/or hereditary defects. Heavy metals released during mining also have adverse health effects and can cause cancers and poisoning. Renewable energy sources release essentially the same materials. However, almost all releases are associated with the construction and eventual decommissioning of facilities — wind turbines, solar photovoltaics and solar thermal power stations. Biomass is the exception. Unlike wind and solar power, electricity from biomass does involve a fuel cycle, which releases pollutants and GHGs. While nuclear power also releases the same materials, the relative amounts differ. More radionuclides are released, but notably fewer particulates and GHGs.

This section summarizes four studies that compare the health effects of different alternatives. The first three do not include health effects from nuclear accidents; the last one does.

The first is a 2009 study for the European Commission called New Energy Externalities Developments for Sustainability (NEEDS) [53]. It estimates health effects from radionuclides and from air, water and soil pollution for a range of energy technologies. NEEDS converts all the various health effects into external costs expressed in financial terms (euro cents per kilowatt-hour) and calculates the total health effects for each technology. Figure 17 illustrates the results. Since NEEDS focuses on future possibilities, there are two bars for each technology. The striped bar on the left shows health effects for the version of the technology expected to be available in 2025. The solid bar on the right is for the version of the technology expected to be available in 2050.

The second study is a 2008 European Commission study called Cost Assessment of Sustainable Energy Systems (CASES) [95]. In addition to the health effects from radionuclides and from air, water and soil pollution estimated in NEEDS, CASES also includes health effects from climate change. It should be noted that estimates of health effects from climate change are highly uncertain. Unfortunately, it is not possible to compare the estimates from CASES with those of the third study summarized in this section because CASES does not report the health effects from climate change separately, and the two studies use different units to report their results. Figure 18 is based on CASES results.

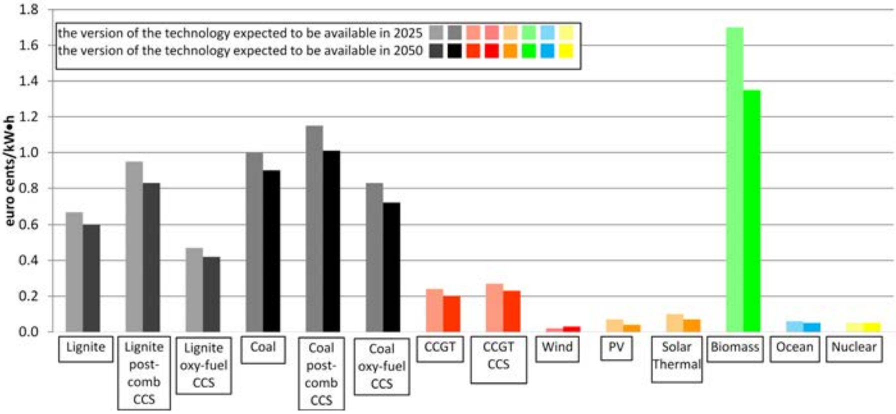

FIG. 17. Results from the NEEDS study [53]. Health effects, measured by their external costs, for 14 technologies as they are expected to perform in 2025 and in 2050. Note: Post-comb: post-combustion; CCS: carbon capture and storage; CCGT: combined cycle gas turbine; PV: photovoltaics.

Comparing CASES and NEEDS, CASES calculates greater adverse health effects for fossil fuel technologies than does NEEDS, most likely because of the inclusion of adverse health effects due to climate change. Another difference is that the findings of CASES show the health effects for most of the technologies increasing with future versions of the technologies. In NEEDS, they decrease. The increase in CASES is largely because its valuations are based on society's 'willingness to pay' to avoid adverse health effects, and as economic growth makes us richer in the future, we will be willing to pay more.

The third is a 2014 study from the Paul Scherrer Institute in Switzerland [96]. In addition to the health effects in the previous studies, it includes effects from ozone depletion, but finds them rather negligible. The study estimates health effects in terms of disability adjusted life-years (DALYs) for technologies expected to be available in 2030. DALYs combine years of life lost due to premature death with years of life spent suffering a disability.

The study used four different evaluation methods. Figure 19 shows results from the 'Hierarchist' variation of a method called ReCiPe [97]. This variation is based on the most common policy principles and is referenced in the standards set by the International Organization for Standardization on life cycle assessments and most frequently used by others [98]. It uses a 100 year timeframe in calculating the health effects of GHG emissions and an infinite timeframe for human, terrestrial, freshwater and marine toxicity. Figure 19 shows the health effects from nuclear power compared with 12 other technologies.

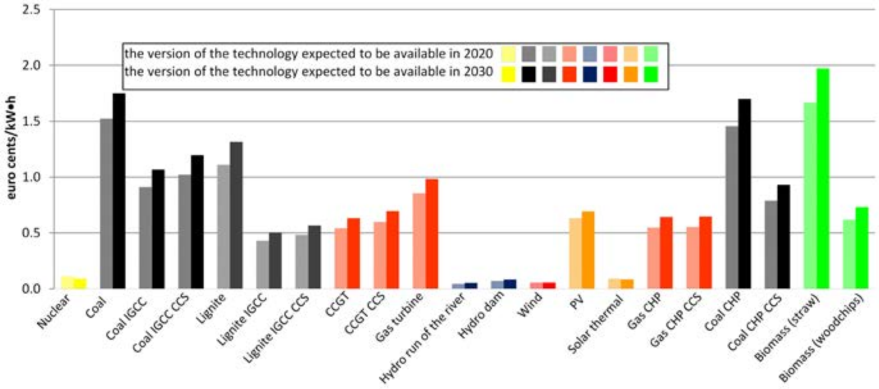

FIG. 18. Results from the CASES study [95]. Health effects, measured by their external costs, associated with 21 technologies. Note: IGCC: integrated gasification combined cycle; CCS: carbon capture and storage; CCGT: combined cycle gas turbine; Hydro: hydropower; PV: photovoltaics; CHP: combined heat and power.

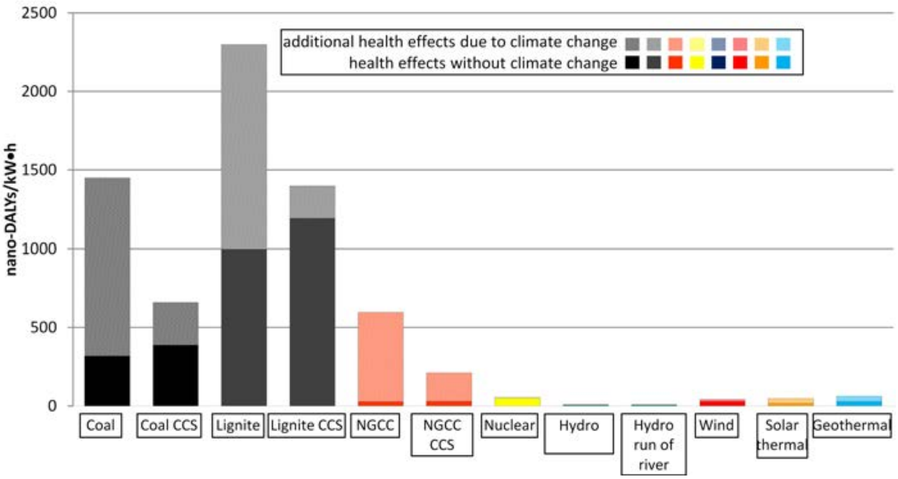

FIG. 19. Adverse health effects for 12 technologies available in 2030 as estimated by the Paul Scherrer Institute [96]. The bottom parts of the bars are estimated health effects other than those from climate change. The top portions are the additional health effects due to climate change. Note: CCS: carbon capture and storage, NGCC: natural gas combined cycle; Hydro: hydropower.

The last study to be summarized presents an itemized calculation of the external costs of nuclear accidents [99]. Its central estimate for the health effects of accidents is €cents 0.02/kW·h. The 95% confidence interval is €0.005–€0.11/ kW·h. The central estimate assumes an accident frequency of once every 25 years, the period between the accidents at the Chernobyl and Fukushima Daiichi NPPs, and it assumes impacts similar to these accidents. The lower bound of the confidence interval assumes an accident every 40 years, and the upper bound, every 15 years. The upper and lower bounds also assume different costs for cancer fatalities and different discount rates. It is generally unwise to compare results across studies because each has its own set of assumptions. With that caveat, however, this central estimate for the health effects of accidents would increase the results in NEEDS and CASES by between 10% and 40%. While that is not insignificant in percentage terms, it is still small in absolute terms.

This final study also compared the external costs of nuclear and wind power. It assumed that power from combined cycle natural gas power plants provides the backup power to cover wind power's intermittency. Although the uncertainty ranges estimated for nuclear and wind power overlap, the central estimate of the total external cost of nuclear power, including accidents, was €cents 0.79/kW·h, while that of wind power was €cents 1.22/kW·h.

4.3. MACROECONOMIC IMPACTS

Nuclear power belongs to the energy options that involve large capital costs up front. Nonetheless, a decision to invest in a nuclear power plant has an impact that goes beyond the project itself and is not captured by a private corporate approach. Apart from energy security and climate change mitigation potential, nuclear power can make a significant contribution to a country's economic development. It can improve the economic well being of citizens.

The economic growth associated with nuclear energy investments originates in the constituency and region where the nuclear plant is built and operated. However, with favourable macroeconomic conditions in place, the benefits to a country's economy go far beyond the plant level.

Nuclear energy investments stimulate other sectors in the economy such as construction, manufacturing and services, thus contributing to economic growth. An econometric analysis — based on a large data set including 16 countries for 1980–2005 — revealed that a 1% increase in nuclear consumption would on average increase a country's gross domestic product (GDP) by 0.32% [100]. However, the impact at the country level might be rather different, depending on the size of the economy, the scope of the NPP programme, industrial participation and a number of other factors.

Labour market effects are known to be at the core of the impetus for local and regional economic growth. They include not only the direct, or initial, employment effects of the economic activity, but also the secondary, or 'ripple', effects that flow from this activity. Recent experience of Member States with developed nuclear power programmes shows that ripple effects might be several times higher than the direct employment numbers. This is also true for nuclear newcomers, according to a study on nuclear energy deployment in Jordan [101]. In the United States of America, a country with a well-developed supply chain infrastructure, another five jobs are created on average for every direct job at a nuclear plant during its operating phase (Fig. 20).

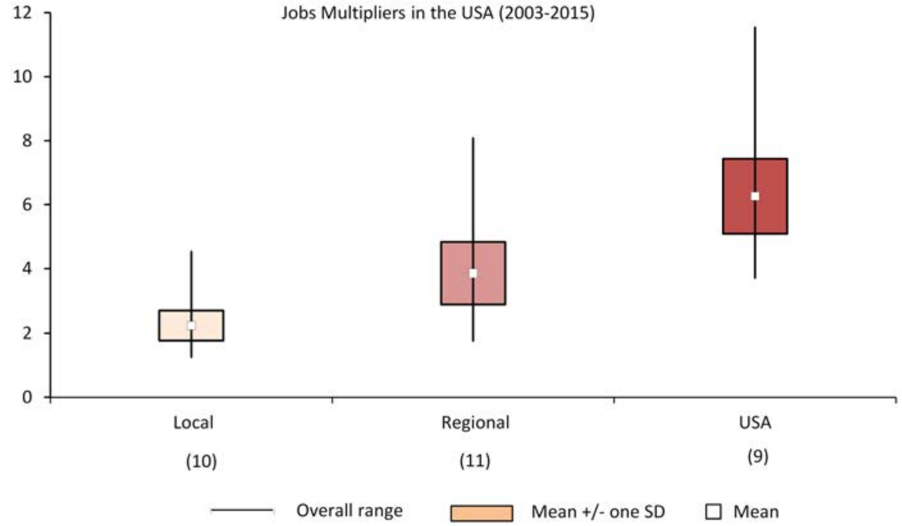

FIG. 20. The total job multiplier includes direct, indirect and induced components. Note: a number in parenthesis indicates the number of observations. Compiled from Refs [102–114].

In NPP construction and operation, two sources create ripple effects. The first source encompasses additional employment generated alongside the supply chain infrastructure (indirect jobs). Nuclear investment creates high skilled employment in areas related to design, engineering, procurement and consulting services for the reactor, manufacturing major components, subcomponents, fuel and many other items. These jobs are typically allocated beyond the local levels (i.e. at the regional and national levels).

The second source includes jobs generated through the spending of wages and salaries of employees on goods and services in private businesses, including wholesale and retail trade, on transport, real estate, financial services and public services such as administration and education (induced jobs). These jobs are primarily located in the local economies.

Figure 20 presents ranges of multiplier effects associated with the operating phase of NPPs in the United States of America. The total job multiplier accounts for both a direct job at the NPP and jobs that are created in addition to every direct job. The multipliers at the national level are the highest, as they include multiplying effects at both the local and the regional level. The majority of job multipliers are in a relatively narrow range (within one standard deviation of the mean). The variations of job multipliers reflect the importance of considering the NPP's specific conditions.

Apart from the potential to create jobs, nuclear power has positive implications for electricity and aggregate price stability leading to an overall more favourable macroeconomic context for economic growth. Also, nuclear power typically provides baseload energy, while generating relatively low system costs in comparison with the intermittent renewables. In addition, being a low carbon generation technology, nuclear power reduces the volatility of electricity prices due to fluctuations in the carbon price component. Thus, nuclear energy can amplify price stabilizing effects in case of the potential introduction of cap-and-trade regulation for GHG emissions [115].

Despite the multiple benefits of nuclear energy for economic development, a clear understanding of risks and challenges is essential for countries embarking on new nuclear power programmes. Ideally, a country's GDP should be large enough to allow sufficient savings to cover the investment and costs associated with establishing and maintaining the necessary physical and institutional infrastructure, and to cover the liability for potential environmental and health damage if an accident occurred.

The macroeconomic context also largely determines the profitability of an NPP as it governs debt and interest payments, variable labour costs and many other relevant factors. Recent economic research showed that a country's macroeconomic conditions may impact the profitability of an NPP, depending on the duration of construction. Based on an extensive data set covering the period from 1950 to 2013, a study from the University of Munich demonstrates that countries that have strong economic conditions to begin with (as measured by per capita income) are capable of realizing nuclear projects faster. The authors also found that higher oil prices during the construction period tend to speed up the construction process [116]. However, a significant number of other factors influence the construction period. Among others, technological variations in reactor designs tend to increase construction time. In fact, the standardization of reactor design is at the heart of cost containment, as it reduces construction time, as demonstrated in France [117].

A growing awareness and understanding of the wide-ranging economic impact associated with investments in any energy technology, including nuclear power, are needed to guide policy makers towards climate and energy policies consistent with the country's overall economic and social policy objectives. A balanced view on benefits and risks underpins the need to assess the net effect on society from investments in any energy technologies, including nuclear.

4.4. CONTRIBUTION TO ENERGY SUPPLY SECURITY

Concerns about energy supply security were important to the nuclear expansion programmes of France, Japan and other countries at the time of the 1970s oil crises. Energy security still remains an important motivation driving expansion today.

The IEA defines energy security as "the uninterrupted availability of energy sources at an affordable price" [118]. This section discusses these two elements of energy security.

Factors that contribute to the uninterrupted availability of nuclear power include: diversity of countries that have uranium resources and ability to process the uranium into fuel feedstock (yellowcake), ease of transport, ease of storing several years' worth of fuel (compared with coal or natural gas) and dependability of baseload electricity from nuclear power (compared with intermittent sources of renewable energy).

Table 3 shows the international distribution of uranium resources and production in 2014. Both resources and production are spread across a range of countries that are diverse and stable. Thus, sudden disruptions in one or more of the countries that supply uranium are unlikely, and if they were to occur, it would be unlikely they would seriously disrupt the overall global uranium supply. The diversity of the countries in Table 3 also reduces the risk of any uranium producing country or region gaining a monopoly.

TABLE 3: REPORTED URANIUM RESOURCES AND PRODUCTION IN 2014
Based on Ref. [119]

Country	Resources (kt U)	Country	Production (t U)
Australia	1798	Australia	7009
Kazakhstan	876	Kazakhstan	21240
Russian Federation	689	Russian Federation	2862
Canada	651	Canada	8998
USA	472	USA	1667
Namibia	456	Namibia	4653
South Africa	451	South Africa	467
Ukraine	223	Ukraine	1012
China	199	China	1450
Niger	405	Niger	4822
Others	1417	Others	4636

Uranium is also easier to transport than fossil fuels. It is transported as a solid so, unlike natural gas, it needs neither expensive conversion facilities (for ocean transport) nor pipelines that can be difficult to route and are inflexible once built (for land transport). It also has a much higher energy density than fossil fuels, so much less of it needs to be transported. One kilogram of uranium can produce 50 000 kW·h of electricity. This is about four orders of magnitude higher than oil (1 kg produces 4 kW·h) and coal (1 kg produces 3 kW·h).

It is easier to build up strategic fuel reserves of uranium than of fossil fuels, since uranium has a higher energy density, and therefore small volumes of uranium fuel can provide reserve fuel for years. In practice, the trend over time has been to move away from strategic reserves towards supply security based on a diverse well-functioning market for uranium and fuel supply services. However, the option of relatively low cost strategic reserves remains available for countries that find it important.

Finally, NPPs provide constant baseload power with high capacity factors (e.g. 91.8% in 2014 in the United States of America [120]), unlike the intermittent power from wind and solar plants. Because large scale electricity storage is not yet affordable, systems using significant shares of intermittent renewables have to include substantial backup power, usually from plants fuelled by coal or natural gas. To the extent that the coal or natural gas used are imported, they may provide less energy security than nuclear power for the reasons noted above.

In recent years, several mechanisms have been created to add assurance to the international supply of low enriched uranium (LEU) used to make nuclear fuel. In 2010, the Russian Federation created a reserve of 120 tonnes of LEU at the International Uranium Enrichment Centre in Angarsk. Its availability is at the discretion of the IAEA's Director General for a "Member State experiencing a disruption in the supply of LEU that is not related to technical or commercial considerations" [121].

In 2011, the United States of America created the American Assured Fuel Supply [122] which is approximately 230 t of LEU that the US Department of Energy holds "in reserve to address disruptions in the nuclear fuel supply of foreign recipients that have good nonproliferation credentials." Also in 2011, the IAEA introduced a Nuclear Fuel Assurance mechanism allowing it to enter into agreements with interested Member States whereby the Supplier State:

> "(of LEU) undertakes not to interrupt the supply of enrichment services and LEU to the Recipient State, without any additional demands beyond compliance with the international obligations and published export licensing standards of the Supplier State" [123].

Finally, an IAEA Low Enriched Uranium Bank was approved by the IAEA in December 2010 to serve as a last resort for a Member State

> "that is experiencing a supply disruption of LEU to a nuclear power plant due to exceptional circumstances impacting availability and/or transfer and is unable to secure LEU from the commercial market, State-to-State arrangements, or by any other such means" [124].

The IAEA is currently setting up the bank at the Ulba Metallurgical Plant in Kazakhstan.

Affordability is another core element of energy security. For nuclear power, fuel costs are a smaller part of the overall cost of generating electricity as compared with power generated by fossil fuels. Thus, any increase in the cost of uranium would have less of an impact on the cost of nuclear generated electricity than an increase in fossil fuel prices would have on electricity generated from fossil fuels. For example, the cost of uranium is only 7–10% of the total cost of nuclear generated electricity. A doubling in the price of uranium would therefore only increase the total cost of nuclear power by 7–10%. In contrast, for combined cycle gas turbines, the cost of the natural gas is about 70% of the total cost of electricity, so a doubling of natural gas prices would correspondingly increase the cost of electricity by 70% [66].

In addition, the cost of electricity from NPPs is immune to new or increased restrictions on GHG emissions. New or increased carbon taxes, permit fees or emission penalties would increase the cost of electricity generated from coal and natural gas power plants, but not the cost of electricity from NPPs or renewable sources, as they essentially do not emit GHGs while generating electricity.

Thus, in situations where nuclear power is a good investment because of, among other reasons, its low and affordable levelized cost of electricity (see Section 3.2) relative to alternatives, it should remain affordable in the face of any changes in uranium costs or carbon prices.

In the future, nuclear power’s advantages in terms of energy security could further increase if thorium-fuelled reactors were introduced (thereby expanding the resource base) or if a closed fuel cycle were introduced (thereby dramatically decreasing the need for uranium mining) [81].

4.5. RADIATION RISKS

Public uncertainty about the radiation risk from nuclear power generation exists owing to a lack of awareness about ionizing radiation and its relation to energy production. Humans are exposed to ionizing radiation as a part of their daily lives. For example, we receive some radiation exposure from the soil under our homes (in the form of radon and thoron gas), from cosmic radiation when we fly, from medical tests and procedures and even from natural sources in foods we eat. This section discusses three principal topics: the health effects of radiation dose; the radiation dose received historically by humans from natural and artificial sources; and the radiation dose received from the Fukushima Daiichi and Chernobyl nuclear accidents.

Ionizing radiation can damage the human body at the cellular level when it ionizes the atoms that make up living cells. The amount of cumulative ionizing radiation damage done to the human body is called the effective dose, which is measured in sieverts (Sv). Effective dose takes into account, by appropriate weighting factors, the impacts of different types of radiation and their effects on different parts of the body. If the human body is exposed to a very large amount of radiation in a short period (<24 hrs and >1 Sv), then the exposed person may begin to show symptoms of acute radiation syndrome [125].[15] Additionally, a statistically significant relationship between high doses of radiation (>100 mSv) and different types of cancer risks and hereditary effects has been derived from epidemiological studies; these studies primarily use survivors of the twin atomic bomb explosions in Japan as subjects [126]. As for low doses of radiation (<100 mSv), statistical limitations make health effects practically impossible to study. However, to enable the creation of conservative radiation protection guidelines, the International Commission on Radiological Protection (ICRP) has established the commonly used linear no-threshold model with the assumption that health effects from radiation are present at low doses [126]. Nonetheless, the determination of health effects from low doses of radiation is a continued topic of study, with some scientists hypothesizing that there may even be no health effects at all [127].

Natural and human-made sources of ionizing radiation can be found in many places in the environment and doses to humans from these radiation sources can vary significantly. A dedicated Committee of the United Nations — the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) — provides up-to-date information on sources of environmental exposure of humans to ionizing radiation. Table 4, which draws significantly from information provided by UNSCEAR, presents a comprehensive compilation of radiation doses to humans from significant sources.

It is important to note that the radiation doses listed in Table 4 are cross-population averages, and that many different factors can affect an individual's annual radiation dose, such as occupation, geographical location and specific prior health procedures.

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[15] The effects of acute radiation syndrome are survivable at doses of 1–6 Sv. However, at higher doses, death is almost certain without immediate intensive care.

TABLE 4. ANNUAL EFFECTIVE DOSES TO THE PUBLIC FROM EXPOSURE TO SELECTED IONIZING RADIATION SOURCES [128, 129]

			Average (mSv/yr)	Range (mSv/yr)
Global				
	Natural			
		Inhalation	1.26	0.2–10
		Terrestrial	0.48	0.3–1
		Cosmic and cosmogenic	0.39	0.3–1
		Ingestion	0.29	0.2–1
		Total	2.4	1–13
	Accidents and tests			
		Chernobyl accident (in 2008)	0.002	n.a.
		Fukushima Daiichi accident (in 2011)	0.01	
		Atmospheric nuclear tests (in 2008)	0.005	
Local				
	Nuclear power			
		Uranium mining and milling	0.025	n.a.
		Fuel fabrication	0.0002	
		Reactor operation	0.0001	
		Reprocessing	0.002	
		Transport of radioactive waste	0.0001	
		By-products	0.0002	
		Chernobyl accident	See Table 5	
		Fukushima Daiichi accident	See Table 6	
	Medical and industrial sources			
		Medical procedures	0.6	n.a.
		Coal plant stack releases	0.0015	
		Gas plant stack releases	0.00075	
		Oil and gas extraction	0.03	

Humans have also been exposed to ionizing radiation at the regional level by several nuclear accidents. The most significant health effects from radiation after the Chernobyl accident were local, having been experienced primarily by the plant staff and emergency workers. Among this group, there were 134 cases of acute radiation syndrome, which proved fatal for 28 people. The remaining group of 106 people continues to experience health effects from radiation induced skin injuries and cataracts [128]. In addition, large doses of radiation were received by recovery workers and members of the public (see Table 5), which led to an increased incidence of cancer. For example, up to 2005, in Belarus, the Russian Federation and Ukraine, more than 6000 cases of thyroid cancer (15 proving fatal) were diagnosed among those who were children and adolescents at the time of the accident [128]. More cases can be expected during the next decades, though it is difficult to quantify the long term magnitude [130].

TABLE 5. SUMMARY OF DOSES RECEIVED BY VARIOUS POPULATION GROUPS AFFECTED BY THE CHERNOBYL ACCIDENT [128]

	Number of people	Average effective dose, 1986–2005 (mSv)
Recovery operation workers	530 000	117
Evacuees	115 000	31
Inhabitants of the contaminated areas of Belarus, the Russian Federation, and Ukraine	6 400 000	9
Inhabitants of Belarus, the Russian Federation and Ukraine	98 000 000	1.3
Inhabitants of the rest of Europe (excluding countries mentioned above)	500 000 000	0.3

For occupants of the surrounding area of the accident at the Fukushima Daiichi NPP, doses received from radiation were much lower than from the accident at Chernobyl (see Table 6). This is evidenced by the fact that no occurrences of acute radiation syndrome have been observed among recovery workers or the public [131]. The highest doses received during the accident at the Fukushima Daiichi NPP were received by the approximately 25 000 recovery workers, 0.7% of whom (173 people) received over 100 mSv. Unfortunately, because of this high radiation dose, the possibility of two to three additional cancers can be inferred to occur in this group during their lifetime [132].

TABLE 6. SUMMARY OF DOSES RECEIVED BY VARIOUS POPULATION GROUPS AFFECTED BY THE FUKUSHIMA DAIICHI ACCIDENT [131]

	Size	Average effective dose (mSv)
Recovery operation workers	25 000	12
Evacuees (<20 km radius + ‘deliberate evacuation area’)	88 000	<10
Remaining residents of Fukushima Prefecture (lifetime dose)	2 000 000	<10
Populations outside Japan	Unknown	0.01

Overall, health effects from radiation dose can vary in magnitude and type, depending upon the dose amount and the period over which it was received. The radiation dose that needs to be received for a health effect to be observable is quite large. This is particularly notable when compared with the radiation dose received by the public from everyday nuclear power generation. Though it most likely bears no health risk at all, the primary source of radiation exposure for the general population is the natural environment and medical sources.

4.6. NUCLEAR SAFETY AND PROLIFERATION

In over 16 000 cumulative reactor-years of commercial nuclear power operation in 33 countries and over 60 years of operating experience, 2 major accidents have occurred. NPPs are subject to stringent safety regulations and are overseen by independent regulatory bodies. They incorporate redundant safety systems and their operation is characterized by industry commitments to safety, international safety coordination, extensive training and stringent qualifications for nuclear workers, and effective responses to accidents. While accidents can happen, a commercial nuclear power reactor cannot explode like a nuclear bomb.

Since the inception of nuclear power in 1954, there have been two accidents that were assigned the highest category, Level 7, on the International Nuclear and Radiological Event (INIS) Scale. These are the Chernobyl accident in 1986 and the Fukushima Daiichi accident in 2011. The Chernobyl accident was caused by serious design flaws coupled with grave mistakes made by the operator. It was a catastrophic accident that cost lives and caused widespread suffering. However, it also brought about major changes, including the founding of a 'safety culture' of constant improvement, thorough analysis of experience and sharing of best practices. The World Association of Nuclear Operators (WANO) was created in the wake of Chernobyl, as was the IAEA's International Nuclear Safety Advisory Group, both of which have helped to spread best practices, tighten safety standards and infuse a safety culture in NPPs around the world. The post-Chernobyl global exchange process also includes:

- Regular meetings of the IAEA–OECD/Nuclear Energy Agency Incident Reporting System, where recent incidents are discussed and analysed in detail;
- The 1994 Convention on Nuclear Safety, which brings countries together to report on how they are living up to their safety obligations and to critique each other's reports;
- Peer reviews by the IAEA, WANO, the Institute of Nuclear Power Operations and the Japan Nuclear Safety Institute that help NPP operators, regulatory agencies, emergency responders and others to compare themselves with the best performers around the world and identify ways to improve.

The changes following the Chernobyl accident are largely responsible for the safety improvement that followed in the two decades after the accident. Figure 21 shows a substantial decrease in the frequency of automatic scrams[16] between 1990 and 2000. Improvements have continued since 2000, but at a slower rate (see also Fig. 21(b)). Note that Fig. 21(a) shows the frequency of unplanned automatic scrams whereas Fig. 21(b) is more comprehensive in terms of safety performance as it includes both automatic and manual scrams. However, the IAEA data in Fig. 21(b) only go back to 2003. Therefore, the WANO data in Fig. 21(a) were included to highlight the significant improvement that took place immediately after Chernobyl.

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[16] Scrams are an important safety feature of a nuclear plant. In the event of an imbalance in operations, the NPPs are designed to shut down automatically, i.e. automatically scram, well before any safety margins are exceeded. This feature is comparable to the role of a fuse or circuit breaker in a house to protect the wiring system.

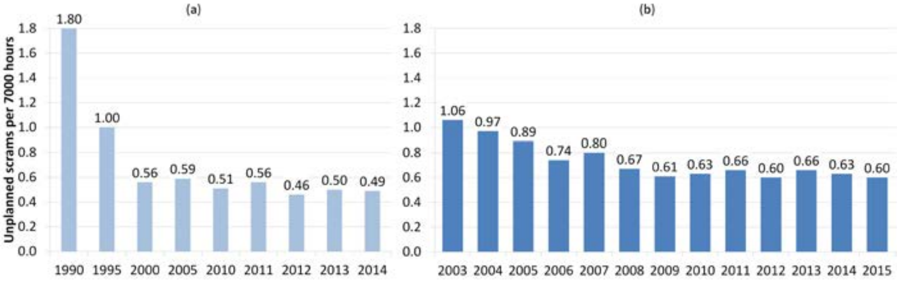

FIG. 21. Unplanned scrams for every 7000 hours of reactor operation[17]*: (a) automatic, (b) automatic and manual. Sources: Refs [40, 133].*

More recently, changes have also come in the wake of the Fukushima Daiichi accident. Like Chernobyl, it was a terrible catastrophic accident that caused substantial grief and suffering. But unlike Chernobyl, it has not yet caused any deaths. No early radiation related deaths or acute diseases have been observed among workers or members of the public that could be directly attributed to the accident [134]. In addition, UNSCEAR has concluded that "no discernible increased incidence of radiation-related health effects are expected among exposed members of the public and their descendants" [135].

The two principal lessons learned from the accident were that Japan's regulatory body underestimated the tsunami risk by giving too much weight to historical records and not enough to up-to-date geological analyses, and that Japan failed to adequately plan for two sets of 'common-cause failures', i.e. the loss of electric power and the tsunami flooding, both of which knocked out multiple safety systems in one blow [134]. After the accident, a worldwide IAEA Action Plan on Nuclear Safety (the Action Plan) [136] was adopted in September 2011 and is being implemented by the IAEA. Many other actions at the national, regional and international level have been taken place, which have [137]:

— Re-examined external hazards;
— Made electrical systems more robust;
— Made the ultimate heat sink for decay heat more robust;
— Protected reactor containment systems;
— Protected spent fuel in storage pools;

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[17] 7000 hours is a common industry standard representing the number of hours that a typical plant is critical in a year.

- Reinforced capabilities for rapidly providing diverse equipment and assistance from on-site or off-site emergency preparedness facilities;
- Reinforced the safety culture at nuclear plants, including human and organizational factors in decision making during emergencies;
- Continued safety research.

Nuclear power should be safe and used solely for peaceful purposes. Over several decades, the international community has established political and legal mechanisms to stem the spread of nuclear weapons. These mechanisms include the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), regional nuclear-weapon-free-zone treaties, export control arrangements, nuclear security measures and the safeguards system of the IAEA. The purpose of the safeguards system is to provide credible assurances that nuclear material and other specified items are not being diverted from peaceful nuclear activities and, by increasing the likelihood of early detection, to deter proliferation.

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. Over 180 States have safeguards agreements with the IAEA.

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 focusing only on the nuclear material and facilities declared by States. It showed the importance of detecting possible undeclared nuclear material and activities. This led to the model Additional Protocol, which provides the IAEA with broader access to information and locations. Over 120 States now have an Additional Protocol in force.

The IAEA analyses information not only from facility inspections, but also from State reports and open sources. It manages the IAEA Safeguards Analytical Laboratories in Austria to analyse environmental samples collected in the field. It constantly monitors innovative technologies to improve efficiency and effectiveness and contributes to international efforts to make future nuclear technologies more proliferation resistant.

4.7. WASTE MANAGEMENT AND DISPOSAL

Spent fuel has been safely stored since nuclear power first generated electricity for public consumption in 1954. There are no major technical obstacles to extended storage. Thus, every country with spent fuel has time to store it until recycling technology is technically and economically viable, or to complete its disposal plans and choose its sites at its own politically appropriate pace.

It is important to note that spent fuel has significant remaining fuel value that can be recycled. It is often referred to as used nuclear fuel. Further, the fuel rods containing the material look nothing like the popular images in mass media of radioactive marked waste in 55-gallon barrels.

When it is removed from the reactor, spent nuclear fuel is highly radioactive, and generates heat as well as radiation. It is initially stored under water, which provides both cooling and radiation shielding. The initial storage period lasts a minimum of nine months to allow both the heat and radiation levels to decay sufficiently. In most cases, spent fuel is stored in these on-site pools for several years, and sometimes up to tens of years, depending on the storage capacities of the pools.

In China, France, India, the Russian Federation and the UK, spent nuclear fuel is reprocessed (another term for recycling) to extract usable material (uranium and plutonium) for new fuel. Japan is currently commissioning a commercial reprocessing plant at Rokkasho, and other countries may choose to reprocess spent fuel in the future. The reprocessing may take place at a reprocessing facility co-located with the reactor or the fuel may be transported to a reprocessing facility located elsewhere and stored in buffer storage pools or dry storage before being fed into the process. Modern reprocessing plants have large buffer storage capacities.

In some countries, spent fuel is simply considered high level waste (HLW) and is stored pending disposal. It is stored in the original reactor storage pools or is transported to separate away-from-reactor fuel storage facilities. Despite the name, these facilities may be either on the reactor site or at other dedicated sites. There are currently 147 away-from-reactor spent fuel storage facilities operating in 27 countries [138].

There are two storage technologies: wet storage in pools or dry storage in vaults or casks [139]. Both are mature technologies based upon decades of operating experience. The advantages of dry storage are that it is modular, which spreads capital investments over time, and that its simpler passive cooling systems reduce operation and maintenance costs. Dry storage facilities use a variety of configurations including modular vaults, silos and casks. Most operating commercial away-from-reactor spent fuel storage facilities are dry storage at reactor sites.

Dry storage is also used for the HLW generated by reprocessing plants. The liquid HLW from reprocessing is first solidified, most often by vitrification or calcination. For vitrification, the waste products are melted together with glass material to incorporate them into the glass structure. The melted mixture is poured into stainless steel containers and cooled to a solid. The containers are welded shut, decontaminated to remove possible surface contamination and stored.

In addition to spent nuclear fuel and HLW from reprocessing, there are two other categories of radioactive waste that require special management: low level waste (LLW) and intermediate level waste (ILW)[18] [140]. LLW and ILW make up 97–98% of the total waste volume produced by a nuclear power plant, but they constitute only 8% of total waste radioactivity. LLW includes contaminated clothing, protective shoe covers, floor sweepings, mops, filters and tools. ILW includes reactor water treatment residues and filters used for purifying the reactor's cooling water. The radioactivity of LLW and ILW ranges from just above natural background level to higher levels for components removed from inside the reactor vessel.

LLW does not generate heat. It mostly contains radionuclides with short half-lives. These have to be isolated from the environment for up to a few hundred years to reach background (natural) levels. LLW is typically stored on-site until its radioactivity has decayed so that it can be disposed of in engineered near surface facilities. ILW also does not generate significant heat, but needs a greater degree of containment and isolation than LLW owing to its higher radioactivity and possibly higher proportion of long lived radionuclides. It requires shielding during storage and transport.

For HLW, the most common strategy is planned disposal in deep geological formations. Progress towards opening HLW disposal facilities has been slow, and none is yet in operation. Finland and Sweden have made the greatest advances in this field. In November 2015, Finland granted Posiva, an expert organization in nuclear waste management, a construction licence for Finland's HLW disposal facility in Olkiluoto [141]. In March 2011, the Swedish Nuclear Fuel and Waste Management Company applied for a construction licence for Sweden's disposal facility at Forsmark [142]. Both facilities are intended to start operation in the 2020s.

Figure 22 shows Sweden's disposal plans (Finland's are similar). After 30–40 years in cooling ponds, spent fuel will be encapsulated in cast iron inside 5 m welded copper canisters. These will be packed in bentonite clay in holes in tunnels 500 m deep in the bedrock. The bentonite clay isolates the canisters from trace amounts of water and other substances in the bedrock. The bedrock is 2 billion years old and is very stable.

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[18] ILW does not apply to the USA, where waste is classified as either LLW (A, B, C or greater than Class C), HLW or defence transuranic waste.

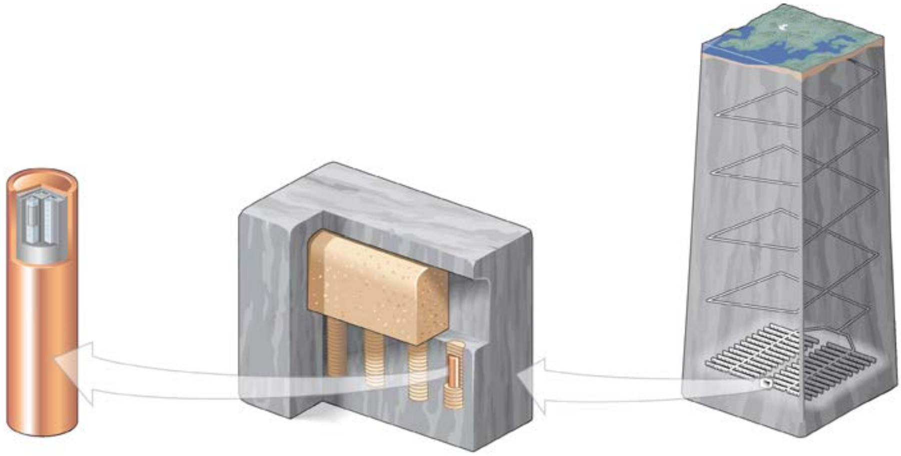

FIG. 22. Three barriers to prevent the radionuclides in the spent fuel from reaching the ground surface in the planned final repository in Sweden. Source: Ref. [143], used with permission.

When all the tunnels are full, they will also be filled with bentonite clay, and the facility will be sealed. There are over 65 km of tunnels, enough to dispose of all the spent fuel that Sweden's current reactors will produce in their operating lifetimes.

Some countries' HLW plans consider the retrieving of spent fuel to allow the possibility of recycling it in the future rather than committing it to permanent disposal. Other possible future developments may reduce the volume and longevity of HLW. Research is under way on partitioning and transmutation, which are techniques to convert long lived radioactive waste components to shorter half-life species. There is also the possibility of fully closed nuclear fuel cycles in the future that use fast reactors to continuously recycle all actinides until they fission. This would reduce by a factor of about 200 the amount of transuranic elements for final disposal (plutonium, americium, curium and neptunium), which constitute the bulk of long lived radiotoxicity in HLW [67].

In contrast to HLW, disposal facilities for LLW and ILW are already in operation or under construction around the world. These include near surface engineered facilities for LLW (e.g. in China, the Czech Republic, France, India, the Islamic Republic of Iran, Japan, Poland, Slovakia, Spain and the UK) and engineered facilities for LLW and ILW sited in geological formations at a varying range of depths (e.g. in Finland, Germany, Hungary, the Republic of Korea, Sweden and the United States of America). Further disposal facilities for LLW and ILW are at different licensing stages in Belgium, Bulgaria, Canada, Germany, Lithuania, Romania and Slovenia. Figure 23 shows the LLW disposal site at Japan's reprocessing facility at Rokkasho.

FIG. 23. The LLW disposal site at Japan's reprocessing facility at Rokkasho.

4.8. PUBLIC ACCEPTANCE

Public opinion remains a central component of the future contribution of nuclear power to climate change mitigation. This section presents data from public opinion polls on nuclear power in several countries. Results from polls can vary considerably depending on how questions are framed and arranged, and need to be considered as indicative rather than definitive. Different polling organizations use different sample sizes, which can also influence data quality and reliability.

Several public opinion polls [144–161] were taken to gauge global attitudes towards nuclear power. The accident at the Fukushima Daiichi NPP in Japan in 2011 resulted in an almost universal decline in public support for nuclear power. This is especially true in Japan where favourable public opinion dropped from 70% in 2010 to 22% in the most recent national survey by the Asahi Shimbun (a national newspaper) [144].

Figure 24 presents public opinion polls from 2005−2015 in eight countries with operating NPPs. In the United States of America, a 2015 survey of long standing public opinion commissioned by the Nuclear Energy Institute found that 64% of the respondents were in support of nuclear power. Public support was found to be particularly strong in the Midwest and Southern states where five reactors are under construction. However, another long running 2016 Gallup survey in the United States of America communicated lower support levels of 44%. Gallup's latest finding also deviates from the trend revealed in its annual survey over the last 10 years, which showed that a majority was in support of nuclear power, with a peak of 62% in 2010 just before the Fukushima Daiichi NPP accident. As there has been no accident since 2011, Gallup suggests that the shift in public attitude may be due to the fact that energy prices and perceived abundance of energy sources are the most relevant factors in attitudes towards nuclear power, rather than continued safety concerns prompted by nuclear incidents [145].

Similarly, the UK Department of Energy & Climate Change, in its Public Attitudes Tracker (July 2015), found diminishing support for nuclear power (36%) in the UK since the survey started in March 2012 [146]. In contrast, a national poll conducted in Sweden in November 2015 by Novus Group International in cooperation with Swedish Energy found no change in support for nuclear power (34%) in the last two years [147]. In addition, nearly seven out of ten Swedes polled in the latest survey supported the use of operational nuclear reactors to produce electricity. In neighbouring Finland, where nearly 30% of electricity comes from nuclear power, public support is beginning to return to pre-2011 levels. A 2014 survey commissioned by Finnish Energy Industries (Energiateollisuus) found 41% support for nuclear power compared with 48% in 2010 before the accident at the Fukushima Daiichi NPP [148]. This small rebound in support for nuclear energy in Finland could be because two important pillars of energy reliability and energy independence — both key advantages of nuclear power — shape Finland's energy choices.

Public opinion polls on nuclear power usually include multiple questions including some related to socioeconomic characteristics such as gender, in order to understand its relation to nuclear power support or opposition. Between 2005–2015, a gender gap of around 10% in the United States of America has remained constant between men and women where men (74%) on average are more favourable towards nuclear power than women (63%). The Nuclear Energy Institute survey has been running since 1983 and the gender gap was even larger at 20% in 1983 (Men: 63%, Women: 43%) in terms of support for nuclear power [162]. Not only has the gender gap reduced considerably between 1983 and 2015, but also the attitudes of both men and women have become more favourable towards nuclear power. A similar poll in Sweden conducted by

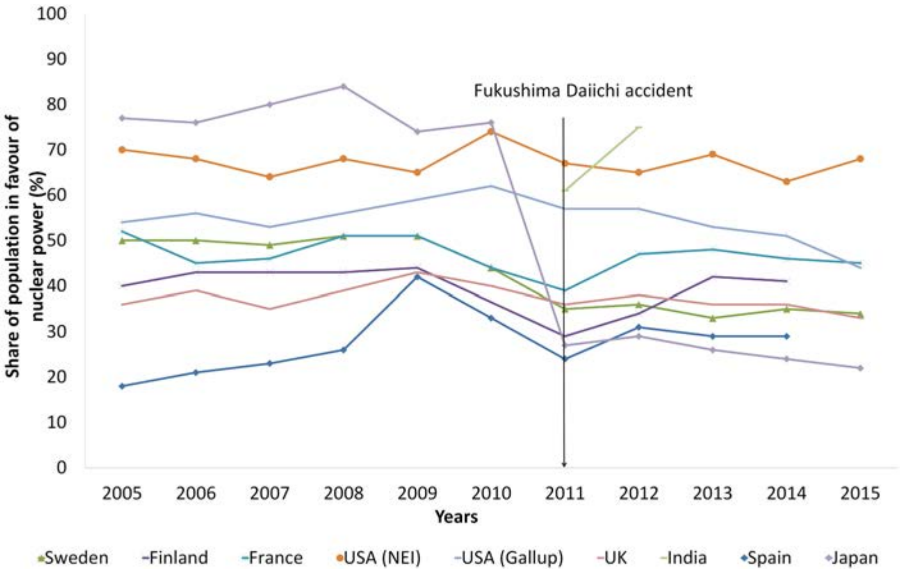

FIG. 24. Public opinion about nuclear energy in countries with operating NPPs [149–161].

Novus Group International in cooperation with Swedish Energy found the gender gap between men and women in favouring nuclear power to be nearly constant between 2010 and 2015. Bisconti Research also pointed out that "more than 50% of women either somewhat support or somewhat oppose increasing nuclear power generation", as a sign that most women are undecided about nuclear energy [162]. Better information is correlated with greater support for nuclear power [163], therefore a broader information campaign discussing the benefits of nuclear power is expected to reduce the gender gap even further.

In summary, five years after the accident at the Fukushima Daiichi NPP raised public concerns about nuclear power globally, public opinion still needs more time to rebound to the level of support in 2010. A closer look at socioeconomic determinants, for instance, gender, highlights the importance of public campaigns on the merits of nuclear power.

Appendix

SUMMARIES OF SECTIONS FROM THE 2013, 2014 AND 2015 EDITIONS OMITTED FROM THIS EDITION

This Appendix presents summaries of sections in the 2013, 2014 and 2015 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, 2014 and 2015 editions for details.

1.1. SECTIONS IN THE 2015 EDITION

1.1.1. 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, albeit consistently low, present some variation across types of NPPs.

The overwhelming majority of nuclear reactors in operation around the world (85% as of March 2015) are light water reactors, and it is very likely that this high share will remain over the next decades. Unsurprisingly, most life cycle assessment studies on nuclear energy compiled in various databases concentrate on the two primary subgroups of light water reactors (LWRs): pressurized water reactors and boiling water reactors. Data from one database compiled by the NREL on life cycle assessment studies of pressurized water reactors show a range of calculated emissions from 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. For boiling water reactors, the same database shows a range of emissions from 4.6–17 g CO_2-eq/kW·h, with a median of 13 g CO_2-eq/kW·h. The differences between estimates found by different studies 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. Further region-specific analysis shows that the variations in GHG emissions across light water reactors located in different parts of the world are negligible.

In addition to light water reactor assessments, there are a few studies on other, less common types of nuclear reactors, such as heavy water reactors, gas cooled reactors and fast breeder reactors. These studies calculate similar or lower GHG emissions than light water reactors. In general, heavy water reactors evade the most GHG intensive steps in the fuel cycle, because they do not require enriched uranium for fuel manufacturing. The relatively low emissions over the life cycle of gas cooled reactors are partly due to their higher thermal efficiency, as reactor outlet temperatures can reach 850–900°C. Fast breeder reactors are estimated to have extremely low emissions owing to their specific fuel cycle attributes that minimize the emissions from mining, milling, enrichment and fuel fabrication.

1.1.2. 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. These costs are not captured by a private corporate approach at the plant or fleet level. Grid system costs include investments required to expand and augment transmission capacities and distribution grids on the one hand, and short term balancing and long term adequacy costs to ensure the stability and reliability of electricity supply on the other.

All electricity generation technologies involve system costs but for traditional dispatchable technologies (nuclear, hydropower, coal and 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 US $0.56/MW·h for gas, US $0.46 to US $1.34/MW·h for coal and US $1.40 to US $3.10/MW·h for nuclear, according to a recent OECD/Nuclear Energy Agency report.

The grid connection costs of intermittent renewables 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. The above mentioned OECD/Nuclear Energy Agency study estimates total grid level system costs for onshore wind to be between US $16.3/MW·h (10% share in the United States of America) 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 United States of America) and US $82.95/MW·h (30% share in Germany).

System costs are typically borne 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 increasing electricity prices in countries with fast growing shares of variable renewables in their power supply mix.

1.1.3. Nuclear investment costs

In the future portfolio of CO_2 emissions reductions, nuclear power can play a major role as it supplies mitigation benefits at low running costs. However, in order to displace billions of tonnes of CO_2 by 2050, nuclear energy needs to become more attractive to investors. Nuclear power projects are highly capital intensive. This is why its competitiveness is very sensitive to the cost of capital and strongly depends on the length of project development and construction phases.

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. At the lower end of the range, average overnight costs in China are projected to be approximately US \$3500/kW(e). In contrast, overnight costs in the European Union at US \$5500/kW(e) are at the high end of the range. In the United States of America, costs are lower by about 10%.

Academic studies, government reports and general media articles have been consistently documenting the rising investment costs of nuclear power over the last few decades. A study by the University of Chicago identified the following key factors behind rising overnight costs in the United States of America: 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.

It is vital for nuclear power to find ways to reverse the cost escalation trend. For example, a study based on a large set of historical data from France and the United States of America revealed that a lower technological variation in reactor designs together with a more vertical integration during the construction phase is key in suppressing the cost escalation. Standardization in France has been shown to contain cost escalation by reducing the licensing and construction times that are among the main drivers of cost escalations.

1.1.4. 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 and businesses of final users. A smart grid is thus a system where the components (e.g. meters, voltage sensors, fault detectors and energy consuming devices) 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.

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 on when electricity is used. This could pave the way for real time pricing of electricity for end users who, with the increased opportunity to manage consumption, would have both the incentive and the means to become more active market participants. Such developments could have a transformative impact on power markets and have the potential to profoundly impact the electricity business.

Exactly how smart grid deployment will affect nuclear power operation and investment is difficult to predict. It will depend heavily on local conditions and needs 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 may end up reducing margins for producers and may transfer wealth from producers to consumers.

1.1.5. Comparing emissions from fossil plants with CCS and nuclear power

CCS prevents the venting of 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 the use of deep geological formations that guarantee safe holding of CO_2 for a prolonged period. Optimistic expectation about CCS peaked in the 2000s; since that time, however, practical difficulties have significantly lowered expectations. In the 2014 World Energy Outlook, 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. In all other scenarios, CCS is projected to play only a marginal role in electricity generation.

In comparison with traditional coal-fired power plants, estimates for plants using CCS demonstrate significant decreases in GHG emissions. A compilation of several estimates shows a reduction in emissions by a factor of 6–7, with the median value of emissions estimated at 186 g CO_2-eq/kW·h (with the overall range of estimates being 39–410 g CO_2-eq/kW·h). Additionally, gas-fired plants equipped with CCS are estimated to reduce GHG emissions by a factor of 4–6. The emissions ranges are still far from those of renewables and nuclear power, whose emissions estimates range from 3.5 CO_2-eq/kW·h to 110 g CO_2-eq/kW·h with a median value of 14.9 g CO_2-eq/kW·h).

Costs are also an issue with CCS. Similarly to NPPs, plants with CCS have large capital costs, which can quickly compound if construction is delayed. Additionally, CCS significantly reduces the resource efficiency of the power plants (owing to the power requirement of capture equipment), thus increasing fuel usage by up to 40%. Nonetheless, the use of CCS may be meaningful for backup capacities and spinning reserves, and for reducing emissions from power systems largely relying on intermittent renewable sources.

1.1.6. Impact of climate change on nuclear energy

Climate change is projected to increase global mean temperature and affect most other attributes of the Earth's climate. It will also modify the frequency, intensity, duration and spatial extent of heat waves, droughts, storms and other extreme weather events (EWEs). These changes might have a considerable impact on the energy sector, including nuclear. For example, higher temperatures will reduce the efficiency of thermal conversion and will also reduce cooling efficiency. Lower precipitation will decrease the amount and increase the temperature of cooling water. In coastal regions, a gradual rise in sea level may increasingly affect power plants located at a low elevation. However, the impact of these relatively slow and gradual changes in climate attributes will produce some minor effects, for which it is easy to prepare. In contrast, EWEs are far more problematic for NPP operators under the current climate regime, and it is expected that the impact of more frequent and intense events will increase the related challenges. Long lasting spells of very high temperature will exacerbate the decline of conversion efficiency and increase the cooling challenge. Longer and more intense drought conditions will add to these problems. The major challenge will be associated with water and cooling.

New challenges are therefore raised, including the design and implementation of adaptation measures for existing NPPs. Safety is the first aspect to consider, followed by the related costs of the adaptation measures, and whether these are worth it in terms of expected gains during the rest of the economic life of the power plant. Decisions are somewhat easier for new builds. The design bases for future reactors will be changed in response to projected degrees of climate change and shifts in EWEs. 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.

1.2. SECTIONS IN THE 2014 EDITION

1.2.1. 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 are 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, in which 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, the 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.

1.2.2. 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 incurred by two projects of identical value (US $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 interest during construction incurred by these two projects was almost US $2.8 billion if a 7 year construction duration and 10% rate of interest was assumed, versus US $1 billion if a 5 year duration at a 5% rate of interest was assumed. The two main ways in which interest during construction can be decreased include reducing the duration of the construction period and obtaining the required financial resources at the lowest possible interest rate.

1.2.3. Lifetime extensions

The bulk of the global fleet of nuclear power reactors was constructed in the 1970s and 1980s and many of these reactors are operating close to the end of 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 for longer term operation past these original timeframes. 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 to maintain a high level of safety and optimal plant performance by successfully dealing with ageing issues, prioritizing maintenance, periodically reviewing safety, and by providing education and training. The aim is to ensure a safe, long term supply of electricity in the most economically competitive way.

Extending the operating life of existing NPPs is often cost competitive compared with building new capacity. Therefore, as long as safety can be ensured, long term operation will 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 United States of America, for instance, has been approximately 540 g CO_2/kW·h of electricity generated by NPPs with extended licences.

1.2.4. 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 that profit margins remain 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 United States of America. 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.

1.2.5. 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 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), China (HTR-PM with gas cooled reactor technology) and the Russian Federation (KLT-40S and RITM-200 for floating nuclear power units). These SMR designs are scheduled to be in operation by 2018. Other near term SMR designs (e.g. ACP100, SMART, NuScale) will be ready for deployment between 2025 and 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 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.

1.3. SECTIONS IN THE 2013 EDITION

1.3.1. Nuclear energy applications beyond the power sector

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

1.3.2. 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 owing 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 with 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.

1.3.3. Fast reactors: Breeding the future

The introduction of fast breeder reactors (FBRs) may have a revolutionary impact on the future of nuclear energy and enhance its contribution to climate change mitigation efforts. The adoption of FBRs has the potential to enhance the use of natural resources and make the nuclear industry self-sustainable. In fact, FBRs allow the extraction of over 50 times more energy per kg of uranium and have a very efficient neutron economy compared with 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 burnup the most toxic minor radioactive elements, decreasing the amount of radioactive waste. The plutonium stockpile produced is also reduced compared with conventional reactors.

The major limitations of FBRs are their high capital costs and the limited technical experience in 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.

1.3.4. 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, since the plasma used in the reactor is burnt under specific conditions, and any significant deviation from these conditions will result in the halting of the reactor operation, meaning that the possibility of any power plant disaster can be excluded. Fusion also has beneficial energy security implications. In the fusion process, the fuel used is produced from abundant material such as water, thus eliminating problems such as energy resource scarcity and the concerns emerging from uneven resource distribution, thereby making international energy policy more collaborative and predictable. Finally, the specific design of fusion based reactors makes it impossible to produce the material used for nuclear weapons.

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