CLIMATE CHANGE AND NUCLEAR POWER 2018

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

The advantages of nuclear power in terms of climate change are an important reason why many countries intend to introduce nuclear power or to expand existing programmes in the coming decades. 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.

The IAEA has been publishing the Climate Change and Nuclear Power reports since 2008. This edition has been completely revised relative to the latest version published in 2016. It includes many entirely new topics and fully rewritten presentations of earlier themes. The update to the publication is based on the latest scientific information, recent analyses and technical reports, and other publications that have become available during early 2018.

It is hoped it will make a useful contribution to the deliberations of international policy makers participating in the activities of the United Nations Framework Convention on Climate Change and other forums.

EDITORIAL NOTE

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EXECUTIVE SUMMARY

The atmospheric concentration of greenhouse gases (GHGs), especially carbon dioxide (CO_2), and the climate of the Earth has been fluctuating for billions of years, largely driven by orbital, solar and volcanic forcing. Anthropogenic influence on the atmosphere has been accelerating since about 1750. The atmospheric concentration of CO_2 increased from 278 parts per million to over 400 parts per million in 2016, accompanied by rapid increases of methane and nitrous oxide concentrations. These changes are almost entirely due to anthropogenic emissions, hence the concern and the need for action to reverse them. The consequences of elevated GHG concentrations include the warming of the atmosphere and oceans, global mean sea level rise, alterations in the global water cycle and changes in some climate extremes. Human induced contribution to the observed increase of global mean surface temperature between 1951 and 2010 is estimated at 0.5–1.3°C.

The impacts of climate change on natural and human systems in most terrestrial and oceanic areas have become increasingly apparent in recent decades. The geographical ranges, abundances, seasonal activities, interactions and migration patterns of many terrestrial, freshwater and marine species have shifted. Yields of many crops in climatically diverse regions are declining, overwhelming positive impacts in some high latitude regions. Higher heat related and lower cold related mortality has been observed; the distribution of some water-borne disease vectors and illnesses has changed. Sea level rise has caused death, injury, ill health and disrupted livelihoods in low lying coastal zones and small islands, while large urban populations are at risk of inland flooding, jeopardizing human well-being.

The Intergovernmental Panel on Climate Change has prepared four scenarios that assume the stabilization of anthropogenic forcing of the climate system at different levels. Compared with the preindustrial climate (characterized by historical temperature records observed in the 1850–1900 period), the average global surface temperature increase is likely to exceed 1.5°C by the end of this century and warming will continue beyond 2100 for all except the lowest stabilization scenario, which assumes drastic emissions reductions by 2050 and increasing net negative emissions thereafter. The increase in the global mean temperature is projected to exceed 2°C for the three higher scenarios by 2100.

Given the global nature of the climate challenge, the United Nations has become a key actor for coordinating global efforts to address it. The United Nations Framework Convention on Climate Change (which was signed in 1992 and entered into force in 1994) provides the international legal framework for taking action. The Paris Agreement to the Convention (which was adopted in

2015 and entered into force in 2016) aims that the increase in global average temperature should not exceed 2°C relative to preindustrial levels. Its open timeframe and implementation instruments aim to encourage various low carbon energy sources such as nuclear power to contribute to CO_2 emissions reductions. However, their actual contribution will depend on the yet to be defined rules and modalities for these instruments.

The production and use of energy accounts for almost two thirds of total GHG emissions, contributing significantly to climate change. In 2014, the combustion of coal accounted for 45% of total energy related CO_2 emissions, with around one third coming from oil and 20% from natural gas. Three quarters of these emissions arose from electricity generation, manufacturing and road transportation. Between 1990 and 2014, total GHG emissions increased by almost 30%, but emissions from electricity generation almost doubled: during this period, generation from coal more than doubled and generation from natural gas almost tripled. In contrast, electricity generation from low carbon sources, such as nuclear power, hydroelectricity and other renewables, grew by a relatively modest 80% between 1990 and 2014. Reducing emissions from electricity generation will necessitate a larger contribution from these low carbon sources in the future.

Recent projections estimate that primary energy demand will reach 430–900 exajoules (EJ) in 2050, compared with 570 EJ in 2015. Scenarios with strict climate change mitigation foresee primary energy demand in 2050 in the range of 430–650 EJ. In comparison, practically all scenarios project relatively strong growth in electricity demand from 73 EJ in 2015 to 125–157 EJ in 2050, including strict mitigation scenarios that see electricity demand in 2050 between 125 and 143 EJ. The impact on climate change of this increasing demand will depend on the future mix of electricity generation technologies, which differ markedly in terms of carbon intensity (CO_2 emissions per unit of electricity).

As a large scale energy source, nuclear power has a significant potential to contribute to GHG emissions reduction. Nuclear power has avoided a significant amount of CO_2 emissions in recent decades. In the absence of nuclear energy, and assuming that fossil fuel technologies had produced the corresponding amount of electricity according to their historical shares in the electricity mix, CO_2 emissions would have been considerably higher. Over the period 1970–2015, nuclear power avoided around 68 gigatonnes of CO_2 in total, close to the entire actual emissions from the power sector over 2010–2015.

The contribution of nuclear energy to GHG mitigation over the next decades will depend on many factors: the performance of the nuclear industry itself, including technological innovations, economic competitiveness and safety records; developments in the energy sector in general, such as new technologies, their economic performance and resource availability in different countries;

and the broader economic and political agenda affecting national decisions about the use of nuclear power. Political decisions and the role of governments are particularly important. Scenarios devised by various international organizations, the energy industry and non-governmental organizations project nuclear electricity generation in 2050 to be in the range between 0 and nearly 11 petawatt-hours (PW·h), relative to 2.571 PW·h in 2015. Excluding a few extreme outliers, the range is 3–7 PW·h. Relative to the 2016 output of 2.476 PW·h, the 2017 IAEA low projection anticipates a very limited growth (an increase of about 24%) of nuclear power output by 2050, while in the IAEA high projection, nuclear electricity generation is projected to reach 7.041 PW·h in the same year (an increase of about 184%). However, the latest IAEA estimates (as of mid-2018) project significantly lower nuclear capacity for 2050: 26 gigawatt (electrical) lower in the low estimate and 126 gigawatt (electrical) lower in the high estimate. These declining nuclear capacity projections raise serious concerns about the prospects for climate change mitigation. Depending on which technologies fill the gap opened by this lower nuclear capacity, cumulative GHG emissions between 2018 and 2050 could be up to 12 gigatonne CO_2-equivalent higher, compromising efforts to achieve the goals of the Paris Agreement. Alternatively, replacing this nuclear energy capacity entirely with low carbon renewable generation capacity is estimated to increase investment and financing expenditure on renewables by roughly US $ 1 trillion over 2018–2050 and could increase electricity prices and lead to loss of employment.

Total GHG emissions per unit of electricity produced over the entire life cycle of different technologies show their real climate mitigation potentials. Mean life cycle emissions from nuclear power are in the range of 5–20 gram CO_2 per kilowatt-hour, in the same range as hydroelectric and wind power, mainly coming from mining and milling uranium ore and enrichment. They can be further improved by using better technologies for fuel preparation and using reactor designs with longer operation periods and higher efficiency.

Besides the electricity market, the industrial heat market, which currently is almost fully supplied by fossil fuels, could also be supported by nuclear energy. Powering energy intensive processes (electricity and process heat) with nuclear energy can result in significant reductions in the associated GHG emissions. Potential non-electrical applications of nuclear power include seawater desalination, district heating, hydrogen production, oil extraction and other petrochemical applications, and propelling large tankers and container ships. Currently installed and operational desalination plants worldwide are mostly powered by fossil energy sources and emit around 76 megatonne (Mt) CO_2/year. This might almost triple to 218 Mt CO_2/year by 2040. Using nuclear power plants as the energy source for desalination systems could significantly reduce the associated CO_2 emissions.

Although it has a significant potential to contribute to climate change mitigation, nuclear energy also has to cope with a number of challenges, including the debate around radiation exposure, radioactive waste, off-site effects of nuclear accidents and its high capital costs. In this publication, these challenges are examined, followed by a (non-exhaustive) description of innovations by the nuclear industry in developing new fuel and reactor designs.

Radiation exposure to the public from the normal operation of nuclear power plants and the nuclear fuel cycle infrastructure is negligible compared with naturally occurring background radiation. Radiation exposure due to human activities — which, besides nuclear power generation, also include the production and use of radioisotopes for medical and industrial use, and mining and processing of ores and wastes — is subject to strict regulation and control aimed at keeping the radiation exposures within prescribed limits for workers and members of the public. While the devastating earthquake and tsunami in 2011 in Japan caused 20 000 casualties, none were related to the release of radioactive material in the accident at the Fukushima Daiichi nuclear power plant. The levels of radiation exposure from the accident were similar to the global average background levels of radiation and no radiation related health effects are expected among exposed members of the public and their descendants.

The production of energy from NPPs generates spent nuclear fuel and radioactive waste. Spent nuclear fuel can either be considered a resource and therefore reprocessed to extract usable fissile material (uranium and plutonium) and recycled as new fuel (reprocessing activities generate high level waste), or considered waste to be disposed of after some decades of storage. Progress towards opening spent fuel and high level waste disposal facilities is supported by extensive engineering studies and rigorous review by independent regulators. Other possible future developments may reduce the volume and longevity of highly radioactive waste. Research is under way on partitioning and transmutation, which are techniques to convert long lived radioactive elements to shorter half-life species. There is also the possibility of nuclear fuel cycles being fully closed in the future, using fast reactors to continuously recycle and burn all actinides.

Depending on their fuel composition, fast reactor designs can be operated as highly fuel efficient ‘breeders’ or as ‘burners’, feeding on the spent fuel of other reactors. A reduced need for fuel would clearly decrease GHG emissions from the mining and enrichment stage of the nuclear energy life cycle per kilowatt-hour generated. The use of fast reactors would also decrease the radioactivity of the remaining spent nuclear fuel to the level of the original uranium in about 300 years. Another alternative design to address the waste issue is the molten salt reactor.

The IAEA Action Plan on Nuclear Safety initiated after the Fukushima accident involved hardware refurbishments such as making electrical systems and the ultimate heat sink for decay heat more robust, protecting reactor containment systems and spent fuel in storage pools, and reinforcing capabilities for rapidly providing diverse equipment and assistance from on-site or off-site emergency preparedness facilities. The issue of off-site effects from nuclear accidents is being addressed both for existing NPPs and for future, yet to be built plants. For existing reactors, development of innovative fuels with enhanced accident tolerance is under way. They would endure the loss of active cooling in the reactor core for a considerably longer time period than the fuels currently used while maintaining fuel performance during both normal operation and accidents.

When designing reactors for new NPPs, a significant potential for featuring passive and inherent safety characteristics exists. Modular high temperature reactors are conceived on inherent safety principles, including a combination of low power density, high temperature resistant ceramic fuel materials and a long slender reactor core geometry enabling passive heat removal from the core. The decay heat is removed by natural mechanisms and this eliminates the possibility of core melt and large releases of radioactivity to the environment. Another approach to preventing core melt is the concept of liquid reactor fuel that is already in a molten form by design, e.g. a molten fluoride salt containing fissionable material.

Another hurdle for the use of nuclear energy is the high investment costs of NPPs. They are expensive to build compared with coal and gas fired plants. However, fuel, operation and maintenance, decommissioning and waste disposal costs represent only a minor share of their total generating costs. On the basis of the levelized cost of electricity, nuclear power is an economically competitive source of energy compared with other electricity generation technologies, except when low cost fossil fuels such as shale gas are available. If the health and environmental costs of fossil fuels are also considered, nuclear power is even more competitive. Grid level costs of nuclear energy are rather small compared with those of variable renewable energy sources that are non-dispatchable because they depend on weather conditions.

Nuclear power construction and operation generate considerable macroeconomic benefits (measured as the increase in gross output) in addition to generating direct and indirect employment benefits. If the construction phase involves foreign suppliers, these benefits are split between the vendor and the host country. In the vendor country, manufacturing machinery and equipment has the largest share (over 25%) of the total output increase, followed by financial services and the manufacturing of electrical equipment. In the host country, the construction and manufacture of machinery and equipment benefit most, accounting for roughly half of the total output increase. Benefits in a recipient country largely depend on local participation in those parts of the supply chain where national industrial companies can meet the high standards of the nuclear industry in a cost effective way.

As high upfront investment costs can be prohibitive for some potential users, attention has been turning to small, medium sized or modular reactors that take advantage of reduced system size, design standardization, modularization and other advanced construction methods. While existing NPPs have often been designed as a single plant and mostly assembled on the site, small, medium sized or modular reactors could be mostly constructed in dedicated workshops and transported to the site only afterwards. This would also shorten the construction time. When building smaller reactors instead of a few large ones, series production could be applied to offset the disadvantage of the economy of scale. But more importantly, the capital expenditure could be spread over a longer period of time, allowing for the addition of modules as demand grows and while costs are being recovered from the modules already in operation. They would be particularly suited for countries with small power grids, less developed infrastructures and limited financing capabilities. Small, medium sized or modular reactors can be deployed and financed incrementally. Small reactors provide a low carbon alternative to fossil fuel electricity generation and may support non-electrical applications such as seawater desalination and district heating.

Currently operating and future NPPs will need to adapt to changes in climate and weather. For plants to be built, site selection for cooler local climates where possible and different cooling designs could mitigate the decreasing thermal efficiency of generation and decreasing cooling efficiency resulting from higher mean temperatures. For existing plants, adjustments for reusing wastewater, recovering evaporated water, improving wet cooling, installing cooling ponds and dry cooling are examples of possible responses to the cooling water available being reduced in quantity and warmer, caused by higher temperatures and lower mean precipitation that would otherwise lead to reductions in output or even shutdown. Raising dykes and other protective embankments will be crucial to prevent the flooding of low lying coastal sites due to sea level rise. More frequent and more intense extreme weather events will likely exacerbate the impacts of gradual changes in temperature, precipitation and other weather attributes. The increasing frequency of extreme hot temperatures and low climate periods will require enhanced adaptation actions.

1. INTRODUCTION

1.1. BACKGROUND

Anthropogenic climate change is widely seen as the major threat to humans, their natural resources and the environment at large. It has dominated the global environmental policy agenda over the past two decades. Changes in global and regional temperatures, precipitation patterns and other climate attributes are driven by increasing concentrations of greenhouse gases (GHGs) in the atmosphere. Carbon dioxide (CO_2) emitted from burning fossil fuels in the energy sector and other industrial activities is the principal driver of this process. Energy demand is projected to increase significantly in the coming decades, especially in developing countries, where population growth is fastest, where more than 2.5 billion people rely on traditional biomass as their main energy source and approximately 1.1 billion people have no access to electricity. Without considerable efforts to limit future GHG emissions, especially from the energy supply sector, the expected global increase in energy production and use could well trigger changes in climate with huge risks for human societies and the Earth system. All low carbon energy sources and technologies will be required to face the twin challenge of mitigating climate change and meeting global energy needs.

An overwhelming majority of Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have ratified the Paris Agreement and have agreed to make nationally determined contributions (NDCs) to control GHG emissions so that the increase of global mean surface temperature will not exceed 2°C relative to preindustrial levels. Nuclear power can make a significant contribution to achieving the climate change target of the Paris Agreement by reducing GHG emissions. Nuclear power plants (NPPs) produce virtually no GHG emissions or air pollutants during their operation and comparatively very low emissions over their entire life cycle. Moreover, nuclear power fosters energy supply security and industrial development by reliably providing electricity and heat at stable and predictable prices.

1.2. OBJECTIVE

The objective of this publication is to provide an overview of the most important linkages between climate change and nuclear energy.

1.3. SCOPE

This publication summarizes the latest knowledge of anthropogenic climate change, its impacts and efforts to mitigate it. The role of the energy sector in climate change and the possible contribution of nuclear energy to reducing GHG emissions are discussed in detail. Selected issues pertaining to the challenges and development potential of nuclear energy are also presented.

1.4. STRUCTURE

This publication provides a comprehensive review of the potential role of nuclear power in mitigating global climate change. Section 2 briefly describes the greenhouse effect and changes in climate over geohistorical scales, followed by the increasing anthropogenic influence on the climate system through increasing emissions of GHGs, especially CO_2, since the industrial revolution. Increasingly visible impacts of climate change on ecosystems and human societies are also discussed. Largely depending on human emissions of GHGs in the future, a wide range of climate scenarios are plausible, implying possible increases in mean global surface temperature relative to the 1986–2005 period as high as 2.6°C to 4.8°C by the end of this century. The role of the United Nations in managing the climate change challenge is presented in two domains: science and policy. Concerning global climate policy, elements of the Paris Agreement of particular importance for nuclear energy are discussed.

The energy sector has been playing a fundamental role in human induced climate change, as demonstrated in Section 3. While energy and electricity have been key drivers of socioeconomic development in the past and will play a central role in achieving sustainable development goals (SDGs) in the future, the energy system will need to be profoundly transformed in the next decades to become a net zero emitter of GHGs. This involves moving away from burning fossil fuels without capturing and storing CO_2 in geological formations and increasingly relying on low carbon energy sources such as renewables and nuclear power. Section 3 presents direct and indirect GHG emissions from different power generation technologies, together with their other environmental impacts. Because of the large uncertainties about the drivers of energy and electricity demand and the substantial ignorance about the evolution of energy technologies over the next few decades, the scenarios depicting future energy demand and GHG emissions are spread across a very broad range.

Section 4 focuses on the role of nuclear power in alleviating climate change in the past, present and future. The climate mitigation potential of nuclear energy is clearly demonstrated by the fact that between 1970 and 2015 its utilization avoided the emission of about 68 gigatonnes (Gt) CO_2 relative to the volume that would have been emitted if the amount of nuclear electricity had been generated by other technologies. Section 4 demonstrates that nuclear power is a very low carbon energy source on a life cycle basis but its future contribution to GHG mitigation depends on many socioeconomic, technological and especially political factors. This is also valid for its non-electrical applications, of which seawater desalination is discussed in detail.

Although the emissions reductions from the energy sector are far from sufficient to achieve the Paris temperature target, the role of nuclear power as a large scale low carbon energy source is modest; although future scenarios point in a wide variety of directions, the expected growth of nuclear power remains generally limited. Therefore, Section 5 examines existing challenges for nuclear energy such as radioactive waste, off-site effects and high capital costs, and how these are addressed by innovations by the nuclear industry. The section discusses sources and effects of ionizing radiation and how the nuclear industry is improving to reduce their related risks. It is demonstrated that developing accident tolerant fuel and reactors with passive and inherent safety characteristics will further improve the protection of NPPs from accident risks in the future. Costs and economic aspects are considered from three angles: comparing plant level generation costs and grid level system costs of various power generation technologies, macroeconomic effects of nuclear power investments and operation, and the emergence of new reactors implying new types of cost models. Finally, similarly to all other technologies and infrastructure, nuclear energy will also be affected by climate change. The closing part of Section 5 assesses the impacts and adaptation options in NPPs to gradual climate change and shifting patterns of extreme weather events.

The Appendix provides a comprehensive list of topics discussed in earlier editions of this publication issued between 2008 and 2016; all these editions are available on the IAEA web site.

2. THE CLIMATE CHANGE CHALLENGE

The Earth has a natural greenhouse effect due to very small amounts of radiatively active trace gases in the atmosphere (water vapour, CO_2, methane (CH_4) and nitrous oxide (N_2O)) that let the solar radiation reach and warm the Earth's surface, but absorb infrared radiation reflected by the surface and subsequently emit it both upwards to space and downwards back to the surface. This downward emission of radiation further warms the Earth's surface. Without

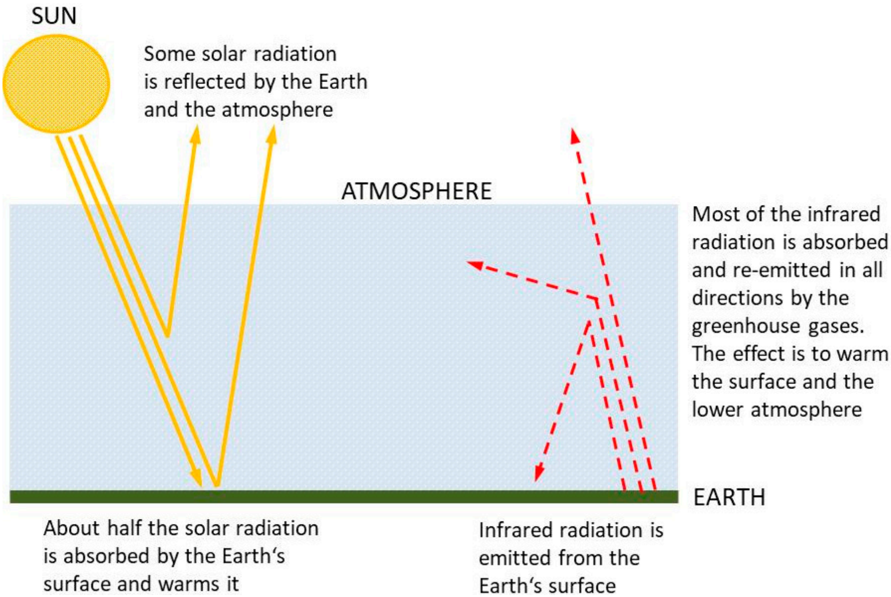

FIG. 1. A simplified diagram of the greenhouse effect. Source: Adapted from Ref. [1].

the greenhouse effect, the Earth would be an icy planet with an average surface temperature of about −18°C. A diagram of the greenhouse effect is presented in Fig. 1.

Emissions from human activities, mainly the burning of fossil fuels and land use change, are substantially increasing the atmospheric concentrations of CO_2, CH_4 and N_2O, thereby enhancing the greenhouse effect and further warming the Earth's surface. Continued anthropogenic emissions of these gases would lead to wide-ranging changes in the climate, imposing possibly severe impacts on human societies and the environment.

2.1. CAUSES AND IMPACTS OF CLIMATE CHANGE

Knowledge about climate and closely related components of the Earth system (e.g. the atmosphere, hydrosphere, cryosphere, geosphere, biosphere) has improved significantly in recent decades. Working Group I of the Intergovernmental Panel on Climate Change (IPCC) regularly evaluates the latest information in these areas with a focus on anthropogenic climate change. Sections 2.1.1 to 2.1.4 draw on the latest findings of Working Group I [2].

2.1.1. The greenhouse effect and past changes in climate

The concentration of radiatively active trace gases (especially CO_2) in the atmosphere and the climate of the Earth have been changing over billions of years, long before humans appeared. Geological records indicate that high atmospheric CO_2 concentrations in several past periods coincided with global mean surface temperatures considerably above the level preceding the industrial revolution. Atmospheric CO_2 concentrations during the Early Eocene (52–48 million years ago) exceeded 1000 parts per million (ppm) and global mean surface temperatures were 9–14°C higher than under preindustrial conditions in the 18th century. Almost 50 million years later, global mean surface temperatures were 1.9–3.6°C above the preindustrial level during the mid-Pliocene (3.3–3.0 million years ago) when atmospheric CO_2 concentrations were between 350 ppm and 450 ppm [2]. Recent reconstructions and simulations of temperatures in the warmest millennia of the last interglacial period (129 000 to 116 000 years ago) indicate that global mean annual surface temperatures were never more than 2°C above the preindustrial level. In contrast, high latitude surface temperatures, averaged over several thousand years, were at least 2°C warmer than the present, which confirms the importance of cryosphere feedbacks (responses from terrestrial and oceanic regions where water is in solid form such as glaciers, ice sheets, sea ice and permafrost). Atmospheric GHG concentrations were close to the preindustrial level during these warm periods [2].

Ice core analyses provide increasingly reliable information about the atmospheric concentrations of GHGs over the past 800 000 years. They show that current concentrations of key GHGs (CO_2, CH_4 and N_2O) exceed the recorded range of concentrations over this long period. Driven by fluctuations in ocean and land carbon storage, atmospheric CO_2 concentrations were as low as 180 ppm during the glacial and as high as 300 ppm during the interglacial periods over this time horizon.

In the absence of human influence, all these changes and fluctuations in the Earth's climate were largely driven by three external forcings: orbital, solar and volcanic. Orbital forcing implies changes in solar radiation driven by fluctuations in the Earth's orbital parameters such as eccentricity (deviation from the perfect circle), longitude of perihelion (the nearest point to the Sun) and axial tilt (the angle between the Earth's rotational axis and its orbital axis) that primarily influence the magnitude and the seasonal and latitudinal distribution of solar energy received at the top of the atmosphere and the durations and intensities of local seasons. Solar forcing denotes changes in the total and the spectral (wavelength dependent) solar irradiance. The former influences the Earth's surface directly, while the latter mostly affects the stratosphere (the second lowest layer of the atmosphere, spanning the region 12–55 km from the Earth's surface) but can also influence circulation in the troposphere (the lowest layer of the atmosphere). Most models attribute changes in total and spectral solar irradiance to magnetic phenomena at the Sun's surface (e.g. sunspots). Finally, volcanic forcing stems from the radiative effects of sulphate aerosols released into the atmosphere by volcanic eruptions. Higher concentrations of aerosols in the atmosphere cool the Earth's surface [2].

2.1.2. Anthropogenic interference with the climate system

The relative importance of natural and anthropogenic forcings and the dynamics of changes in the atmospheric concentration of GHGs, global and hemispheric scale temperatures started changing in the middle of the 18th century. Figure 2 shows variations in the atmospheric concentrations of CO_2, CH_4 and N_2O during the last 11 000 years before the present. During the 7000 year period preceding 1750, atmospheric CO_2 concentrations changed extremely slowly, increasing from 260 ppm to 280 ppm, probably owing to natural causes. There is

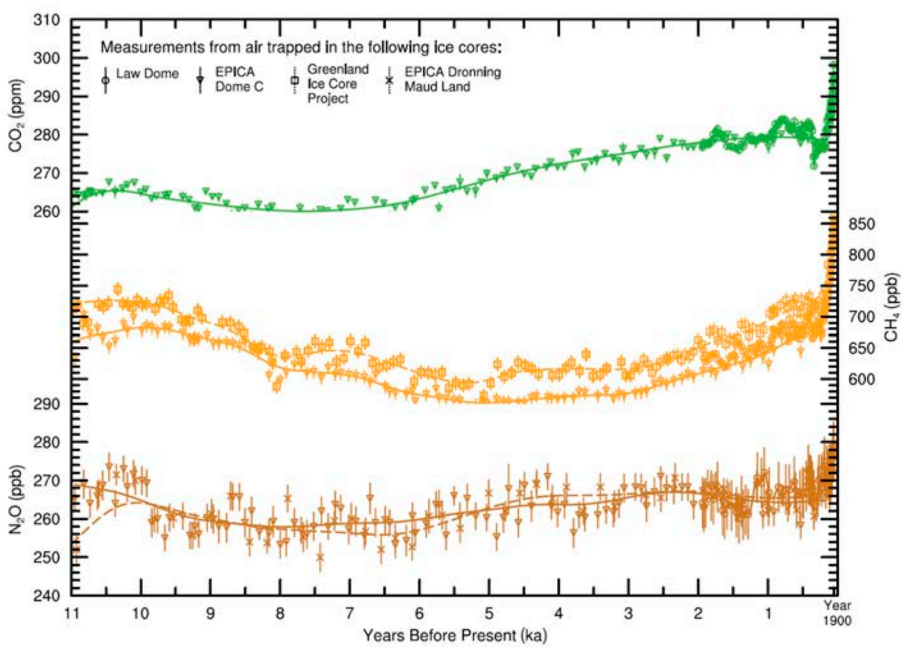

FIG. 2. Variations of CO_2, CH_4 and N_2O during the Holocene. Source: Ref. [2]. Note: CO_2 — carbon dioxide, CH_4 — methane, N_2O — nitrous oxide, ppm — parts per million, ppb — parts per billion, ka — 1000 years, EPICA — European Project for Ice Coring in Antarctica. Reproduced courtesy of the IPCC.

a big difference compared with the increase from 278 ppm in about 1750 to over 400 ppm in 2016 (an increase of almost 44%) due to anthropogenic emissions since the industrial revolution [3]. Similarly, rates of increase in concentrations of other GHGs have also never been as fast as in the past 150 years. Between 1750 and 2011, CH_4 concentration increased from 722 to 1803 parts per billion (150% increase) and N_2O concentration increased from 271 to 324.2 parts per billion (20% increase). It is certain that the current concentrations of these three GHGs are higher than the levels detected over the past 800 000 years. Increases in CO_2 concentrations were very likely caused by emissions from burning fossil fuels and changes in land use.

The most obvious implication of increasing GHG concentrations is the warming of the climate system. Atmospheric scientists consider this unequivocal and maintain that many of the observed changes since the 1950s are unprecedented over timescales from decades to millennia. Globally averaged surface temperature (both land and ocean) increased by 0.85°C between 1880 and 2012. Moreover, the global surface was successively warmer during each of the three decades before 2012 than in any earlier decades since 1850. The period 1983–2012 probably represents the warmest three decades in the last 1400 years [2].

These increasing temperatures have been causing ice sheets to lose mass increasingly quickly: about 147 Gt/year were lost from the Antarctic and about 215 Gt/year from the Greenland ice sheet between 2002 and 2011. Glaciers have been shrinking further, losing about 275 Gt/year in the period 1993–2009. As a result of these processes, along with changes in land water storage and the thermal expansion of the oceans due to warming, the globally averaged sea level rose by about 3.2 mm/year in the period 1993–2010. The warming has also reduced the annual mean extent of the Arctic sea ice by about 3.5–4.1%/decade while the summer sea ice minimum decreased by 9.4–13.6%/decade between 1979 and 2012 [2].

Higher surface temperatures also affect the water cycle, i.e. the continuous movement of water through the climate system, in part because warmer air can accommodate a higher concentration of water vapour. The observed increase of about 3.5% in tropospheric water vapour over the past 40 years is congruent with the observed warming of about 0.5°C over the same period while relative humidity remained nearly unchanged. Past changes in precipitation are much more difficult to measure, therefore their attribution to human drivers is rather uncertain. Uncertainties also plague the role of human factors in changing patterns of climate and weather extremes but increasing evidence seems to support human forcing [2].

In summary, anthropogenic influence in the warming of the atmosphere and oceans, global mean sea level rise, alterations in the global water cycle and changes in some climate extremes has been detected and confirmed by multiple lines of evidence. The dominant cause of the observed warming in the second half of the 20th century was human interference by GHG emissions. The resulting increase in GHG concentrations triggered a warming of about 0.5–1.3°C while other anthropogenic forcings, including the cooling effect of aerosols, contributed between −0.6°C and 0.1°C. In comparison, natural forcings played an almost negligible role, contributing between −0.1°C and 0.1°C, the same as the effect of the natural internal variability of the climate system.

2.1.3. Impacts of anthropogenic climate change

In recent decades, impacts of climate change on natural and human systems in most terrestrial and marine areas have become increasingly apparent. Only a few examples are presented here. In natural ecosystems, the geographical ranges, abundances, seasonal activities, interactions and migration patterns of many terrestrial, freshwater and marine species have shifted. In human systems, a large number of studies have assessed impacts on yields of many crops in climatically diverse regions across all continents and indicate a negative balance: declining yields overwhelm increasing returns that are mainly found in high latitude regions. In comparison with other stressors affecting human health, climate impacts are relatively small and difficult to quantify as yet. Higher heat related and lower cold related mortality have been observed in some regions. Changes in temperature and rainfall have modified the distribution of some water-borne disease vectors and illnesses. Additional risks resulting from climate change and the related sea level rise include death, injury, ill health and disrupted livelihoods in low lying coastal zones and small islands due to storm surges and coastal flooding. Large urban populations in some regions are at risk of inland flooding [4].

Many ecosystems and human systems are vulnerable to climate related extremes such as heat waves, droughts, floods, cyclones and wildfires that are occurring under current climate conditions. These extremes alter ecosystems and lead to damage to and loss of terrestrial, marine and coastal ecosystems, biodiversity, and ecosystem goods, functions and services. Extreme events can also disrupt food production, leading to food insecurity and the breakdown of food systems. Warming, drought, flooding, and precipitation variability and extremes can cause loss of rural livelihoods and income due to insufficient access to drinking and irrigation water, and reduced agricultural productivity and water supply. Climate and weather extremes can also damage infrastructure and settlements, leading to the breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services. All these impacts may increase morbidity and mortality with possibly severe consequences for human well-being. These key risks create particular challenges for the least developed countries and vulnerable communities owing to their limited ability to adapt [4].

It is increasingly obvious that anthropogenic interference with the climate needs to be drastically reduced in order to reduce the potentially severe risks of climate change impacts. The Paris Agreement under the UNFCCC [5] aims to hold the increase in global average temperature well below 2°C relative to preindustrial levels (see Section 2.3). This requires a fast and radical reduction of GHG emissions over the next few decades and removing increasing amounts of GHGs, especially CO_2, from the atmosphere in the second half of this century. Scenarios of plausible futures are summarized in Section 2.1.4.

2.1.4. Scenarios of future greenhouse gas emissions and climate change

Projections of climate change prepared in the last decade or so are mostly based on so-called representative concentration pathways (RCPs) that describe alternative assumptions about selected approximate total radiative forcing values for the year 2100 relative to 1750 [2]. 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. RCPs are scenarios depicting the evolution of emissions and concentrations of the most important GHGs, aerosols, chemically active gases and those related to changes in land use and land cover resulting in specified levels of radiative forcing. The term 'pathway' emphasizes the importance of the trajectory followed over time to reach the indicated end point, while 'representative' indicates that an RCP designates only one of many possible timelines to the specific radiative forcing characteristics. Along the RCP2.6 pathway, radiative forcing peaks at about 3 W/m^2 before the end of this century and then declines. Radiative forcing stabilizes at approximately 4.5 W/m^2 and 6.0 W/m^2 after 2100 in two intermediate pathways. RCP8.5 implies radiative forcing higher than 8.5 W/m^2 by 2100.

The RCPs were extended until 2300 in order to explore the longer term implications of climate change. The extended concentration pathways were designed as hypothetical 'what if' scenarios and involve simple assumptions (e.g. stabilization or steady decline) about GHG and aerosol emissions and concentrations beyond 2100. At the low end of the scenario spectrum, RCP2.6 already entails net negative CO_2 emissions in this century (after around 2060) and assumes the sustained removal of CO_2 from the atmosphere (constant net negative emissions) after 2100, resulting in slowly declining CO_2 concentrations towards 360 ppm by 2300. At the high end, RCP8.5 postulates continued high emissions in the first half of the 22nd century, followed by a linear decline until 2250, when concentrations would stabilize at a very high level. The resulting CO_2 concentrations would be about 2000 ppm, almost seven times the preindustrial level. The two middle RCPs assume a smooth stabilization of concentrations by 2150. Figure 3 shows emissions from fossil fuels calculated by concentrations-driven Earth system models following the four RCP pathways.

The RCPs and the extended pathways were then converted into corresponding GHG concentrations and emissions that served as inputs to more than 50 global climate models used in the Coupled Model Intercomparison Project Phase 5 (CMIP5) to assess the changes they trigger in the climate system globally and regionally [2]. The results of this effort indicate that the global mean surface temperature will increase only modestly in the near term, by 0.3°C to 0.7°C in the period 2016–2035 relative to the 1986–2005 reference period. Looking further into the 21st century, the CMIP5 model simulations project an increasingly steeper rise in global mean surface temperatures for 2081–2100 relative to 1986–2005 resulting from higher RCPs: 0.3°C to 1.7°C (RCP2.6), 1.1°C to 2.6°C (RCP4.5), 1.4°C to 3.1°C (RCP6.0) and 2.6°C to 4.8°C (RCP8.5).

Figure 4 shows changes in annual mean surface air temperatures relative to the 1986–2005 reference period for RCP2.6 and RCP8.5 for the middle and the end of this century as well as for the related extended pathways for the end

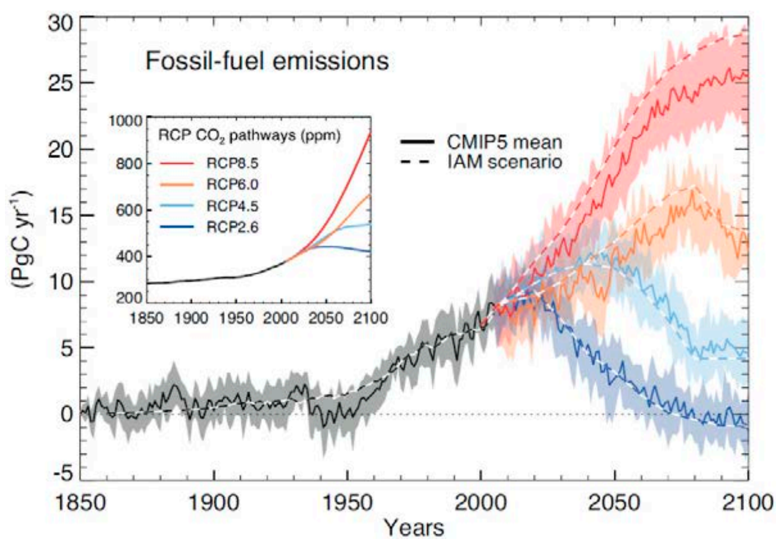

FIG. 3. Historical and future fossil fuel related emissions consistent with the RCP pathways. Source: Ref. [2]. Note: PgC yr^{-1} — petagram carbon per year (1 PgC corresponds to 3.667 Gt CO_2), CMIP5 — Coupled Model Intercomparison Project Phase 5, IAM — integrated assessment model, RCP — representative concentration pathway, CO_2 — carbon dioxide. Reproduced courtesy of the IPCC.

of the next century. Despite strict mitigation efforts in the next three decades in the RCP2.6 scenario, maps in the upper row show considerable warming by 2046–2065, especially in high latitude regions of the northern hemisphere, and slightly declining mean annual temperature by 2081–2100 and beyond (relative to the 2046–2065 temperatures) as GHG removal from the atmosphere reduces concentrations to the level consistent with the 2°C temperature limit by the end of this century. As CO_2 removal continues after 2100, temperatures will also decrease somewhat by the 2181–2200 period.

Compared with the preindustrial level (defined as the temperatures observed in the 1850–1900 period), the global surface temperature increase is likely to exceed 1.5°C by the end of this century and warming will continue beyond 2100 for all RCP scenarios except RCP2.6. The increase in global mean temperature is projected to exceed 2°C for the three higher scenarios by 2100. As shown in Fig. 4, warming is foreseen to proceed more rapidly in the Arctic region than the global mean, and mean warming over land is anticipated to be larger than over the ocean.

As mentioned in Section 2.1.2, atmospheric concentrations of the main GHGs (CO_2, CH_4 and N_2O) already exceed the highest level ever recorded in the past 800 000 years. The climate change projections emerging from the RCP concentration based scenarios for the end of this century depict a rather bleak future for humans, their natural resources and the environment in general. Warned by accumulating scientific evidence in the late 1980s, policy makers also started addressing the issue, as described in Section 2.2.

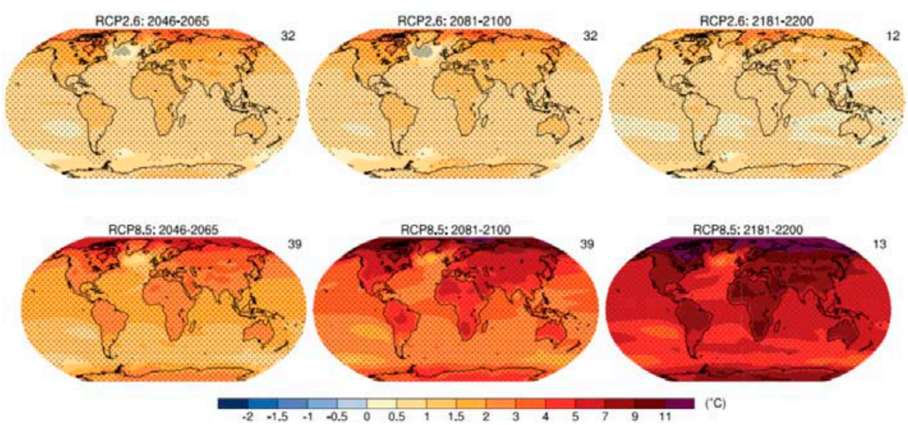

FIG. 4. Changes in average surface air temperatures for two time periods under two RCP scenarios. Source: Ref. [2]. Note: Numbers in the upper right corner of the maps indicate the number of CMIP5 models used. RCP — representative concentration pathway. Reproduced courtesy of the IPCC.

2.2. THE ROLE OF THE UNITED NATIONS

Given the global nature of the problem, the United Nations became a key actor for coordinating global efforts to manage climate change. Since the prevailing climate and changes in the past and future climate affect many facets of natural resources, human societies and economic activities, many United Nations organizations and agencies have included climate change in their work programmes. The broader context is the United Nations resolution Transforming our World: The 2030 Agenda for Sustainable Development [6] adopted in 2015 that aims to end extreme poverty, fight inequalities and protect the planet. The resolution defines 17 SDGs and corresponding targets to resolve pressing development-environment challenges such as access to food, health services, education, clean water and energy. SDG 13 is devoted to climate change and requires countries to "Take urgent action to combat climate change and its impacts" [6]. The SDGs are discussed further in Section 3.1.2. The role of the United Nations is presented in two areas: in science in Section 2.2.1 and in policy in Section 2.2.2.

2.2.1. Climate science in the United Nations

Two United Nations organizations have long had climate change on their agendas. The first is the World Meteorological Organization (WMO). The WMO plays a key role in providing reliable information about climate and weather and their changes and variability. This is indispensable for assessing possible risks for societies and for making decisions about strategies to mitigate negative anthropogenic influence on the climate system (e.g. by reducing GHG emissions), to adapt to changing climate, variability and extremes, and to manage associated risks. Observations and historical records of the atmosphere, oceans and land surface are essential for understanding the Earth's climate. The WMO helps national meteorological and hydrological services; marine, oceanographic and space agencies; and operational and research organizations with observations. It also collaborates with partner organizations on providing guidance based on a shared set of climate monitoring principles. The WMO coordinates the World Climate Research Programme to address key climate science challenges by conducting research related to weather, climate and the atmosphere. The Programme implements large observational and modelling projects and serves as an international forum to support the efforts of climate scientists worldwide to improve knowledge.

The second United Nations entity playing an important role in climate change science is the United Nations Environment Programme (UN Environment). Although its main mandate is to define the global environmental agenda and promote the implementation of the environmental aspects of sustainable development, it also carries out important scientific activities concerning climate change. UN Environment has published annual Emissions Gap Reports (such as Ref. [7]) since 2010, presenting independent scientific assessments of the impacts of national pledges and concrete actions on global GHG emissions (see Section 2.3.2). UN Environment also works jointly with the WMO in the World Adaptation Science Programme which aims to foster the delivery of high quality scientific information on adaptation to countries, international policy makers, the IPCC and other organizations (see Ref. [8]).

The United Nations organization explicitly dedicated to climate change science is the IPCC. It was established in 1988 by the WMO and UN Environment as an intergovernmental and scientific body. Its mandate is to assess scientific, technical and socioeconomic issues to understand anthropogenic climate change, its potential impacts, related vulnerabilities and adaptation options as well as possible actions for mitigation. The mandate of the IPCC does not include undertaking new scientific research but rather preparing regular comprehensive assessments (assessment reports) and occasional reports on issues of particular importance (special reports) by synthesizing the latest knowledge based on peer reviewed scientific and technical literature. The IPCC reports are widely recognized as the principal source of up-to-date scientific information on climate change. They are extensively referred to in international negotiations to support climate policy propositions.

The IAEA is the key organization providing support for countries operating or planning to operate NPPs and helps countries use nuclear science and technology to combat climate change [9]. In monitoring and managing sources of GHG emissions, the IAEA helps scientists use nuclear and isotopic techniques to collect data for identifying the risks and threats to ecosystems and the evolving impact of a warming Earth. To assist in mitigation, the Agency provides assistance to consider nuclear and other technologies to reduce GHG emissions and increase natural carbon sinks by supporting sustainable energy planning, including updates to NDCs under the Paris Agreement; providing guidance on establishing and expanding nuclear power programmes; assisting with the development of low carbon advanced reactor and fuel technology; and identifying new roles for nuclear power to replace high carbon sources. Finally, to assist in adaptation, the IAEA helps experts use nuclear science and technology to improve food security (by developing climate-smart agricultural methods), water availability (sustainable management of freshwater resources) and environmental conditions (protecting ecosystems and countering biodiversity loss) [9].

2.2.2. Climate policy in the United Nations

The starting point for United Nations activities in international climate policy was a resolution of the General Assembly in 1990 that called for the establishment of an International Negotiating Committee to prepare a framework convention. It took less than 18 months to negotiate the UNFCCC, which was signed at the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil, in 1992. The Convention provides a legal framework for stabilizing atmospheric concentrations of GHGs to avoid "dangerous anthropogenic interference with the climate system" [10]. It contains a weak and not legally binding target for developed countries (listed in Annex I to the Convention, comprising members of the Organisation for Economic Co-operation and Development (OECD) (membership as of 1990) plus Belarus, Bulgaria, Croatia, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, the Russian Federation, Slovakia, Slovenia and Ukraine) to stabilize their CO_2 emissions at 1990 levels by 2000.

The Convention entered into force on 21 March 1994. The first Conference of Parties to the UNFCCC (COP 1) was held in Berlin in 1995 and launched the Ad-Hoc Group on the Berlin Mandate to negotiate a protocol or another legal instrument that would set targets and time frames for limiting GHG emissions. At COP 3, held in 1997 in Kyoto, Japan, the Parties agreed to a protocol to the UNFCCC that contains legally binding reduction targets for six key GHGs (CO_2, CH_4, N_2O, sulphur hexafluoride (SF_6), hydrofluorocarbons and perfluorocarbons) for almost all Annex I countries [11]. They made commitments to reduce their collective GHG emissions during 2008–2012 to at least 5.2% below 1990 levels. The Kyoto Protocol also introduced three flexibility mechanisms to help reduce the costs of implementation: emissions trading and joint implementation for countries with quantified emission limitation or reduction commitments (listed in Annex B to the Protocol) and the clean development mechanism between Annex I and non-Annex I countries to jointly support development and climate protection in developing countries. It took another four years and four COPs to agree on the rules of implementation for the Kyoto Protocol at COP 7 in 2001. The Marrakesh Accords [12] practically exclude the use of nuclear power in two of the three flexibility mechanisms: the clean development mechanism and joint implementation. The Kyoto Protocol entered into force in 2005. Since the United States of America did not ratify the Kyoto Protocol, the actual reduction by 2012 was only about 3.8% of the 1990 emissions targets for Annex I countries. This reduction was far outweighed by increases of emissions in the same period in countries not included in Annex I. In the absence of a new, long term agreement, the Kyoto Protocol was amended and a second commitment period (2013–2020) was established in 2012.

While the principle agreed in the Convention that the "Parties should protect the climate system … on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities" ([10], p. 9) is considered to be fair in general, the asymmetry between legally binding mitigation commitments for Annex I countries and very loosely defined desirable efforts for non-Annex I countries has hindered agreement on long term mitigation obligations for a long time. Another impediment has been the top-down approach to international climate policy, involving binding targets and ambitious timetables, to which major States were unwilling to commit themselves [13]. Although COP 13 mandated the Ad Hoc Working Group on Long-term Cooperative Action under the Convention to work on — among other issues — long term mitigation as early as 2007, progress was slow.

The turning point came at COP 15 in Copenhagen during which a bottom-up approach was initiated by inviting countries to provide information on their national mitigation targets and planned actions in the form of intended nationally determined contributions (INDCs). This approach eliminates key drawbacks of the top-down approach and encourages developing countries to also make mitigation commitments according to their national circumstances and abilities. This process culminated at the COP 21 in December 2015 where the Parties accepted the Paris Agreement on climate change.

2.3. THE PARIS AGREEMENT

2.3.1. Key elements and their relevance for nuclear power

The Paris Agreement [5] was widely celebrated as a historic breakthrough in global climate policy because it is the first universal and legally binding global accord to mitigate climate change. (The Kyoto Protocol is also a global and legally binding climate accord but its mitigation provisions apply only for countries listed in Annex I of the UNFCCC.) The mitigation target of the Paris Agreement is specified in Article 2 as

> "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, recognizing that this would significantly reduce the risks and impacts of climate change" (Ref. [5], p. 3).

Much less public and media attention was paid to other components that make the Paris Agreement unique also in the sense that it is truly comprehensive and includes a range of issues on which progressive action will be required to implement environmentally effective, economically efficient and socially just climate protection strategies. Beyond mitigation, these components of the Agreement include adaptation, loss and damage, finance, technology development and transfer, capacity building, and transparency of action and support. In contrast to the closed timeframe of the Kyoto Protocol and its extension, the Paris Agreement is a long term, open ended accord.

The implementation of the Paris Agreement follows the bottom-up approach by committing Parties to communicate their NDCs to the global response to climate change. The NDCs should include planned efforts in each component of the Agreement listed above, except loss and damage. Currently, there are no substantive criteria for NDCs as the Agreement commits countries to declare, report and review but not to achieve pledged outcomes, i.e. it does not establish firm and legally binding commitments in terms of implementation between Parties.

Concerning GHG emissions reductions, Article 4 [5] specifies that each Party shall communicate NDCs that it intends to achieve by pursuing domestic mitigation measures and that successive NDCs should exceed the Party's earlier contributions. Communication of NDCs is linked to the earlier INDC process. Almost all Parties to the UNFCCC submitted INDCs in 2015. For the 176 countries that ratified the Agreement (as of May 2018), their INDCs have turned into NDCs. Parties with an NDC timeframe up to 2025 are requested to communicate a new NDC while Parties whose NDCs cover the period up to 2030 are requested to communicate or update their contributions by 2020. The aggregate progress on mitigation, adaptation and means of implementation will be reviewed every five years in a so-called 'global stocktake' starting in 2023.

In order to foster more ambitious mitigation (and adaptation) commitments and actions, Article 6 of the Paris Agreement defines two mechanisms for 'voluntary cooperation' that are practically market based instruments. Internationally transferred mitigation outcomes (ITMOs) may involve two or more Parties in voluntary cooperation. Parties can use ITMOs subject to several criteria: they should promote sustainable development, ensure environmental integrity and transparency, avoid double counting and apply robust accounting procedures consistent with the forthcoming guidance of the Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement (CMA). Guidance for ITMOs will be developed by the Subsidiary Body for Scientific and Technological Advice for adoption at the CMA. There is no restriction concerning the types of mitigation outcomes to be transferred so ITMOs could involve interconnected GHG pricing mechanisms such as linked regional emissions trading systems.

The other market based mechanism is a somewhat revised version of the clean development mechanism under the Kyoto Protocol. The new Sustainable

Development Mechanism (SDM) has been established to contribute to mitigation and support sustainable development. SDM projects should be based on voluntary participation, ensure additional and quantifiable long term mitigation benefits, involve specific scopes of activities with verified and certified emission reductions and consider experiences from existing mechanisms under the UNFCCC, practically the clean development mechanism. Similarly to ITMOs, the Subsidiary Body for Scientific and Technological Advice is requested to develop the rules, modalities and procedures for the SDM for adoption at the CMA.

Market based mechanisms are particularly important elements of the Paris Agreement because they support its economically efficient implementation but there are many open questions about how to make their governance coherent and how to warrant sustainable development and environmental integrity in their use. A major issue in implementing both ITMOs and the SDM is likely to be ensuring that a reduction is not 'double counted' in both the country of origin and the recipient country. The profound question in the case of the SDM is how offsetting can deliver overall mitigation since offsets will not lead to overall mitigation unless they are cancelled. Another issue is to certify that emissions reductions under the SDM are really additional relative to what would anyway be achieved and that mitigation efforts truly foster sustainable development.

The Paris Agreement also emphasizes "the importance of integrated, holistic and balanced non-market approaches" (Ref. [5], p. 8) in the implementation of NDCs. They should promote mitigation and adaptation, enhance public–private partnership in their implementation and enable coordination across mitigation, adaptation, finance and other elements of the Agreement. These principles, however, do not provide clarity about how to operationalize non-market instruments. Here again, the Subsidiary Body for Scientific and Technological Advice is requested to develop the applicable criteria, rules, modalities and procedures for the non-market approaches for adoption at the CMA.

As a low carbon technology, nuclear energy has been demonstrated to be able to contribute to reducing energy related GHG emissions, which account for around two thirds of total GHG emissions [14]. The IAEA highlighted the potential contribution of nuclear power to achieve the mitigation target specified in the Paris Agreement [15] while also fostering the implementation of several SDGs adopted by the United Nations [16] (see Section 3.1.2). The open time frame of the Paris Agreement has the potential to increase the attractiveness of technologies that involve high upfront investment costs but low operating costs and can deliver low carbon energy and thus GHG mitigation benefits for several decades. These technologies include nuclear energy, hydropower and — albeit with much higher operating costs — CO_2 capture and storage (CCS). The first two are well-proven technologies, although politically controversial in a few countries. Variants of CCS are still under development, prototypes are few and industry scale demonstration projects are plagued by repeated difficulties (see Section 5.2.1). The role of these low carbon technologies in implementing the Paris Agreement will depend on how negotiations about the rules for operationalizing the flexibility instruments proceed and the extent to which the agreed rules allow or exclude the use of specific technologies in voluntary cooperation in climate change mitigation.

In 2017, the International Ministerial Conference on Nuclear Power in the 21st Century concluded that:

> "for many countries, nuclear power is a proven, clean, safe and economical technology that will play an increasingly important role in achieving energy security, reducing the impact of volatile fossil fuel prices and mitigating the effects of climate change and air pollution. For many countries, nuclear power will have an important role to play in achieving the Sustainable Development Goals and meeting the targets in the Paris Agreement. Governments should ensure that their national energy policies support their development and climate goals" (Ref. [17], p. 5).

2.3.2. Prospects for achieving climate change targets

Considering the bottom-up, voluntary nature of mitigation targets and actions in the Paris Agreement and the yet unspecified rules and modalities of its implementation, tangible outcomes are difficult to foresee. A large number of new scenarios and modelling efforts have explored the effects of NDC targets and the feasibility of achieving the main temperature target of the Agreement: a less than 2°C increase in the global mean temperature relative to the preindustrial level, defined as the average of observed temperatures in the period 1850–1900, and the 'auxiliary' target of 1.5°C temperature increase relative to the same reference period. This section summarizes related results of The Emissions Gap Report 2017 released by UN Environment in late 2017 [7] that draws on a number of published scenarios.

The UN Environment report defines various types of scenarios to assess the emissions and temperature change implications of climate policies at the global scale on the one hand, and to depict global emissions paths that must not be exceeded to keep temperature increase below the specified targets on the other. The difference between emissions in the policy scenarios versus in the temperature limit scenarios is called the emission gap.

The UN Environment's Current Policy Scenario estimates emissions trends resulting from currently adopted and implemented policies that are projected to reach 58.9 Gt CO_2-equivalent (CO_2-eq) in 2030. Regarding the Paris Agreement, two NDC scenarios are of particular interest. Unconditional NDC scenarios consider only emissions targets that Parties have pledged to follow without any condition (leading to GHG emissions in 2030 of about 55.2 Gt CO_2-eq) while conditional NDC scenarios also include targets Parties intend to achieve subject to certain conditions such as receiving financial, technological or other support (leading to GHG emissions in 2030 of about 52.8 Gt CO_2-eq).

The two target related pathways include the 1.5°C and the 2°C scenarios. Both assume limited mitigation actions until 2020 and then follow estimated least cost emissions reduction paths from 2020 on that will keep the increase of mean global temperature relative to the preindustrial level by 2100 below 1.5°C with a probability of 50–66% in the first case and below 2°C with a probability of greater than 66% in the second.

The estimated median GHG emission level in 2030 required for the 1.5°C temperature limit is about 36.5 Gt CO_2-eq, 19 Gt CO_2-eq lower than emissions resulting from unconditional NDCs and 16 Gt CO_2-eq below emissions under conditional NDCs. The 2030 median GHG emissions consistent with the 2.0°C temperature target are 41.8 Gt CO_2-eq and the emissions gaps are 13.5 and 11 Gt CO_2-eq for the conditional and unconditional NDCs, respectively. This is a clear indication that the aggregated current mitigation pledges are far from the emissions reductions needed to keep the increase in global mean temperature relative to the preindustrial level below the target of 2°C and far further from the reductions needed to observe the 1.5°C limit specified in the Paris Agreement. Unconditioned pledges imply less than 22% of the reductions needed for the 2°C limit and merely 16.5% of what would be required for the 1.5°C temperature increase relative to the current policies scenario. Even if all prerequisites specified in the conditional scenarios were fulfilled, for which there is no guarantee whatsoever, reductions pledges would barely exceed one third of what would be required for the 2°C target and one fourth of the mitigations needed for the 1.5°C target. Moreover, global GHG emissions are not expected to peak before 2030 in any of the NDC scenarios, whereas least cost pathways compatible with both temperature targets imply that they peak by 2020 at the latest [7].

Another approach to addressing the mitigation challenge under the Paris Agreement is to focus on energy related CO_2 emissions that currently amount to about 60% of total GHG emissions. In this context, it is convenient to frame the mitigation challenge in terms of a CO_2 emissions budget or simply a carbon budget. This budget is defined as the cumulative amount of future CO_2 emissions that would keep the increase in mean global temperature below a specified limit at a specified likelihood. The UN Environment report adopts the latest IPCC (Fifth Assessment Report) estimates of the carbon budget as of 2010 at the level of 1000 Gt CO_2 (uncertainty range 750–1400 Gt CO_2) to keep the 2°C temperature target with more than 66% probability and at about 560 (range 540–580) Gt CO_2 to limit the temperature increase to 1.5°C with a likelihood of 50–66%). Even if current NDCs are fully implemented (including conditional mitigation), about 80% of the carbon budget (750–800 Gt CO_2) will be depleted in the 2011–2030 period for the 2°C target while it will be completely used up well before 2030 for the 1.5°C target. In the absence of more ambitious NDC pledges in their 2020 revision, closing the 2030 emissions gap will be practically impossible. Perhaps the best characterization of the prospects is that the full implementation of current unconditional NDCs and their consistent continuation beyond 2030 is estimated to result in a global mean temperature increase of about 3.2°C (range 2.9–3.4°C) relative to the preindustrial level by 2100. The outcome would only be slightly lower at about 3.0°C if all conditional NDCs were also fully implemented [7].

It is important to note that all these scenarios, temperature related emissions constraints, likelihood estimates and carbon budgets are subject to various geophysical, atmospheric, climate system and socioeconomic uncertainties. However, the magnitudes of the estimated shortfall between targets and pledges raise serious concerns about the prospects for achieving the targets set in the Paris Agreement. They also highlight the need for more ambitious and urgent action.

An important conclusion from the above discussion is that restricting the use of low carbon technologies in voluntary cooperation in the implementation of NDCs or excluding any of them from market based and non-market mechanisms might rather curtail than foster mitigation efforts and thus increase the emission gap. Even in the absence of its exclusion from two of the flexibility mechanisms, nuclear power was unlikely to play any role in implementing the Kyoto Protocol because the implementation time and the period to accrue sufficient amounts of carbon credits to make it a rewarding investment were too short. In the open timeframe of the Paris Agreement, nuclear energy could make a more significant contribution than it does currently to achieving the 2°C target by providing affordable low carbon energy for decades with economic and sustainable development benefits for all participating countries.

Realizing the immense challenge to keep GHG emissions below the limit corresponding to the 2°C target and the virtual impossibility of achieving the 1.5°C mark, the scientific community increasingly explores so-called ‘overshoot’ pathways along which global warming exceeds the specified temperature limit and returns to the target level later as GHGs, especially CO_2, are removed from the atmosphere, thereby reducing their concentrations. As mentioned in Section 2.1.4, RCP2.6 of the IPCC involves increasing amounts of GHG removal beyond 2060. Considering the technological challenges, unfavourable implications (for land use, for example) and the projected costs of CO_2 removal, it seems to be more sensible to avoid emissions in the first place. Moreover, gambling on the success of large scale atmospheric CO_2 removal in the future raises concerns regarding intergenerational equity because it transfers the CO_2 removal burden to future generations together with the more severe implications of a warmer climate. Although nuclear energy could in principle be used to capture CO_2 from the air in the future [18], its main role in the next few decades could be in mitigating emissions to the atmosphere. Figure 5 shows the relative importance of GHG mitigation and CO_2 removal in following the 2°C pathway. It is rather obvious that the less GHG emissions are mitigated in the next few decades, the more CO_2 will need to be removed from the atmosphere in the second half of this century.

Given the magnitude of the mitigation challenge, it is important that decisions on international climate policy give appropriate weight to the substantial mitigation potential of nuclear power to reduce the risks associated with both dangerous climate change and reliance on more costly or speculative mitigation options. Ongoing negotiations defining the rules for the implementation mechanisms of the Paris Agreement can ensure that nuclear power, a proven low carbon technology, can contribute even more to protecting the global climate and support other aspects of sustainable development. The flexibility of the mechanisms in the Paris Agreement can also ensure that the choice of some countries to forgo nuclear power does not necessarily impose the burden of higher mitigation costs on the global community; that is, if designed properly,

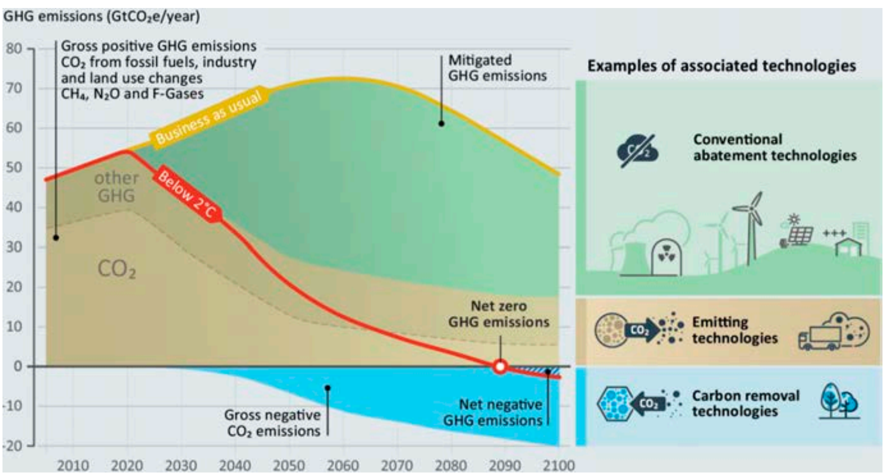

FIG. 5. Greenhouse gas mitigation and carbon dioxide removal in the 21st century to achieve the target of the Paris Agreement. Source: Ref. [7]. Note: GHG — greenhouse gas, $GtCO_2e$/year — gigatonne carbon dioxide equivalent per year, CO_2 — carbon dioxide, CH_4 — methane, N_2O — nitrous oxide, F-Gases — fluorinated gases. Reproduced courtesy of UN Environment.

the mechanisms can create incentives for countries willing to achieve additional abatement with nuclear power (i.e. beyond domestic targets), thereby reducing the need for countries without nuclear power to deploy more costly options, and fostering international cooperation.

3. FOCUSING ON THE ENERGY SECTOR

3.1. THE ROLE OF ENERGY

3.1.1. The role of energy in climate change

The production and use of energy accounts for almost two thirds of total GHG emissions, as shown in Fig. 6, contributing significantly to climate change. Energy related GHG emissions comprise predominantly CO_2 from the combustion of fossil fuels, along with smaller but significant amounts of CH_4, released mainly during the extraction of oil, natural gas and coal, and N_2O formed

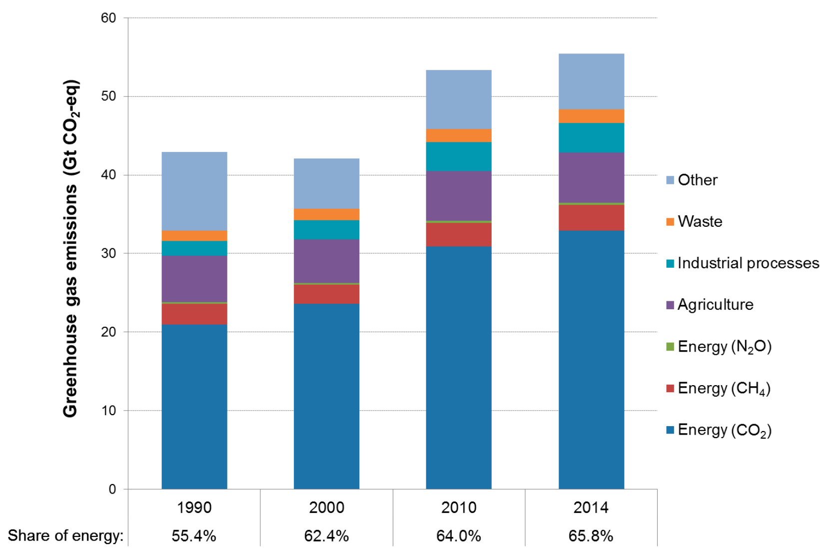

FIG. 6. Global greenhouse gas emissions by major source in 1990–2014 based on 100-year global warming potentials. Data source: Ref. [19]. Note: Gt CO_2-eq — gigatonnes of carbon dioxide equivalent, CH_4 — methane, N_2O — nitrous oxide, CO_2-eq — carbon dioxide equivalent.

during combustion. Other major sources of GHG emissions include agriculture, industrial processes and changes to land use (included in ‘Other’ in Fig. 6). Emissions from most sources have increased since 1990, with the exception of the highly variable emissions from land use change, which declined between 1990 and 2000.

Energy production and use also affects the climate in other ways. Emissions of sulphate aerosols and black and organic carbon from fuel combustion have both positive and negative effects on radiative forcing by directly absorbing or scattering short and long wave radiation, and via their impacts on cloud formation and changes to albedo. Other pollutants from fuel combustion can also react to form tropospheric ozone, which is thought to increase radiative forcing [20].

CO_2 from energy production and use, which represents the largest contributor to climate change, is emitted across a range of sectors and activities, as illustrated in Fig. 7. Electricity generation, manufacturing and road transportation account for around 75% of direct CO_2 emissions, while services, agriculture (included in ‘Other sectors’ in Fig. 7) and the residential sector together contribute only around 10%. These latter three sectors, however, consume around 55% of delivered electricity [21] and thus indirectly account for a significant share of CO_2 emissions from electricity generation. The manufacturing sector consumes

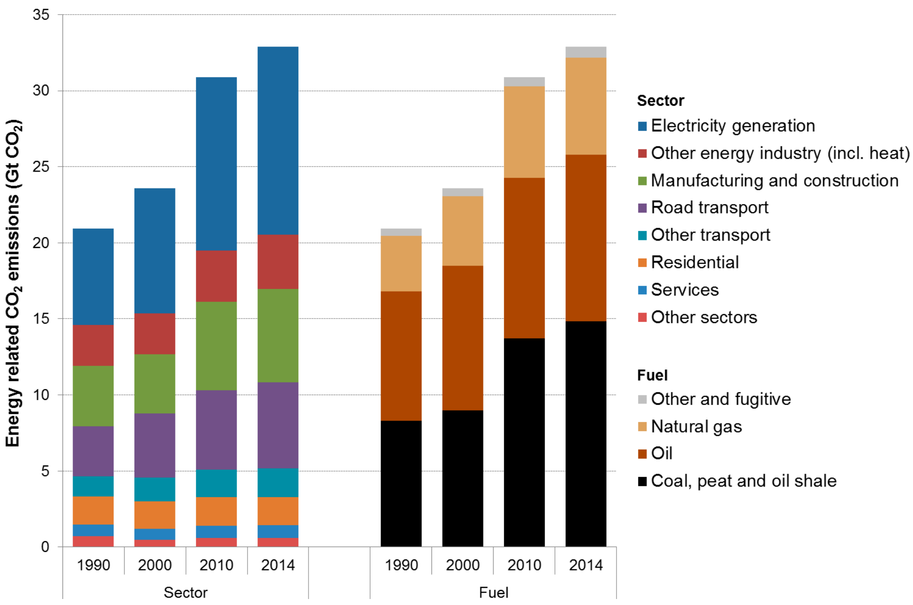

FIG. 7. Global energy related CO_2 emissions by sector and fuel. Data source: Ref. [19]. Note: Gt CO_2 — gigatonnes of carbon dioxide.

most of the remaining electricity and is thus also indirectly responsible for a larger proportion of emissions. Figure 7 also shows the contribution of different fuels to CO_2 emissions from energy production and use. In 2014, around 45% of emissions were produced from the combustion of coal (including peat and oil shale), with around one third from oil and oil products, and 20% from natural gas. The small remainder arises from combustion of non-renewable waste and fugitive releases of CO_2, mainly from venting and flaring in oil and natural gas production.

3.1.2. The role of energy in sustainable development

The sources of energy related CO_2 emissions shown in Fig. 7 illustrate in broad terms the sectors and activities responsible for energy consumption. This energy use, in turn, contributes to social and economic development, including satisfying basic human needs for “food, safe drinking water, sanitation facilities, health, shelter, education and information” [22]. Table 1 illustrates selected linkages between human needs and energy use (and related emissions). These development needs are closely linked to the SDGs adopted by the United Nations [6], as discussed further below.

The scale of energy use and emissions associated with satisfying basic needs and additional demands is substantial. For example, for the provision of food, it is estimated that crop production alone accounts for 4–5% of global final energy consumption, including energy used in fertilizer production, land preparation and crop harvesting. The entire food production chain, including processing, transport and distribution, wholesale and retail trade, and preparation is estimated to consume up to 30% of final energy globally [23], with a commensurate contribution to energy related CO_2 emissions. Similarly, water delivery, transportation and treatment, along with sanitation, are also significant consumers of energy, estimated to account for 4% of global electricity consumption in 2014, and up to 10% in India and the Middle East where energy intensive water desalination is expected to drive increasing demand over the coming decades [24, 25]; see Section 4.4.

While critical for supporting social and economic development, the production and use of energy creates a number of challenges in addition to climate change. For instance, around 7 million premature deaths are attributed to air pollution from the combustion of fossil fuels (especially diesel, coal and kerosene) and biomass [26]. In addition, energy production accounts for around 15% of global water withdrawals, primarily for cooling thermal power plants [24, 25], while biofuel synthesis consumes around 15% of global maize and oil seed production [27] and thus accounts for a significant proportion of agricultural land use.

These linkages between climate, land, energy, water and other aspects of sustainable development mean that integrated approaches are needed when responding to any individual challenge, such as climate change, to both avoid unintended consequences and leverage potential benefits with other goals. To support such integrated resource planning, the IAEA has developed the Climate–Land–Energy–Water assessment framework together with other United Nations agencies and academic partners [28, 29]. This represents one example of how the global development community is responding to the key role of energy in both climate change and broader sustainable development, complementing the major international mitigation initiatives outlined in Section 2.3. This role of energy in development is reflected in a dedicated SDG — SDG 7 — that aims to "ensure access to affordable, reliable, sustainable and modern energy for all" [6]. Achieving SDG 7 can support all the SDGs as illustrated in Fig. 8.

While energy can directly and indirectly support the SDGs, the relationship between energy and climate change (SDG 13) is of utmost importance since it represents a universal threat to all aspects of sustainability. Moreover, since

TABLE 1. SELECTED LINKAGES BETWEEN DEVELOPMENT, ENERGY AND GHG EMISSIONS

Social and economic development needs	Selected links to energy use and emissions, as presented in Fig. 7
Shelter (including heating, cooling, lighting)	Electricity generation, other energy industry (natural gas, liquid petroleum gas, kerosene), manufacturing industries and construction (including minerals, metals, wood products), residential sector, other sectors (forestry)
Food and nutrition	Other sectors (agriculture, fishing), manufacturing (fertilizer production, agricultural machinery, food processing), transportation (distribution), services sector (wholesale and retail trade)
Health and education	Services sector, manufacturing and construction (buildings, including minerals, metals, wood products), electricity generation, energy industry (natural gas)
Clean water and sanitation	Electricity generation (pumping, treatment, desalination), manufacturing and construction (water supply and treatment infrastructure)
Mobility	Road and other transportation, manufacturing industries (vehicles, metals, minerals), energy industry (oil refining), construction (transport infrastructure)
Employment, poverty reduction	All energy uses

1990, emissions from energy production and use have grown faster than total GHG emissions (Table 2). A significant proportion of this growth was driven by emissions from electricity generation, which have almost doubled since 1990 (compared with a 29% increase in total emissions) and now account for

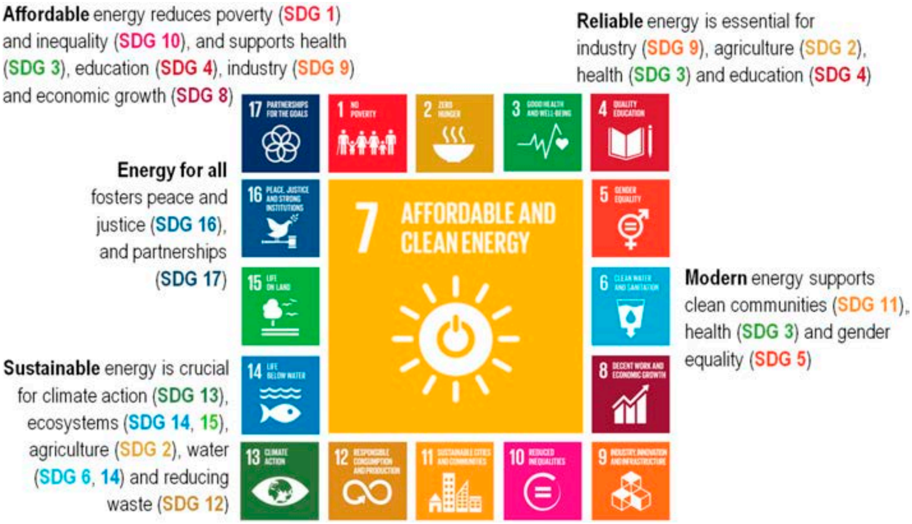

FIG. 8. Ensuring access to affordable, reliable, sustainable and modern energy for all (SDG 7) is central to achieving all 17 SDGs. Source: Ref. [30].

TABLE 2. TRENDS IN GLOBAL GHG EMISSIONS, GHG EMISSIONS FROM ENERGY AND CO_2 EMISSIONS FROM ELECTRICITY
(data source: Ref. [19])

	1990	2000	2010	2014
Global GHG emissions (Gt CO_2-eq)	42.9	42.1	53.4	55.4
% change from 1990	—	*−2.0*	*+24.3*	*+29.2*
Global GHG emissions from energy (Gt CO_2-eq)	23.8	26.2	34.2	36.5
% change from 1990	—	*+10.3*	*+43.6*	*+53.3*
Global CO_2 emissions from electricity (Gt CO_2)	6.3	8.2	11.4	12.3
% change from 1990	—	*+30.4*	*+80.4*	*+95.4*

around one third of energy emissions. This increase in emissions from electricity generation from 1990 to 2014 (6 Gt CO_2) accounted for almost half of the increase in net emissions from all sources (12.5 Gt CO_2-eq), underlining the critical importance of the power sector in any response to climate change.

3.2. ELECTRICITY GENERATION AND CLIMATE CHANGE

3.2.1. Direct and indirect greenhouse gas emission from electricity generation

The rapid growth in emissions from electricity since 1990 has been driven by a substantial increase in generation from fossil fuels, as shown in Fig. 9. Between 1990 and 2014, generation from coal more than doubled and generation from natural gas almost tripled, slightly offset by a decline in generation using oil products. The significance of coal is clearly illustrated in Fig. 9: between 1990 and 2014, coal accounted for 70–75% of direct CO_2 emissions from electricity generation. Compared with the strong growth in generation from coal

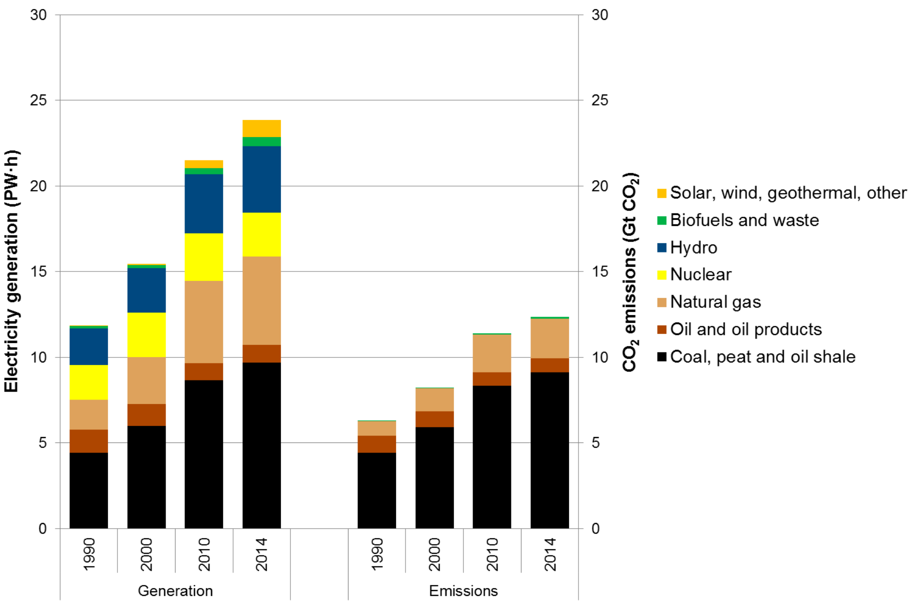

FIG. 9. Global electricity generation and related CO_2 emissions by fuel in 1990–2014. Data sources: Refs [19, 21]. Note: PW·h — petawatt-hour, Gt CO_2 — gigatonnes of carbon dioxide.

and natural gas, generation from electricity sources with negligible direct CO_2 emissions, such as nuclear power, hydroelectricity and other renewables, grew a relatively modest 80% in 1990–2014, despite a 24-fold increase in generation from new renewables (e.g. solar, wind, geothermal). Responding to climate change by reducing emissions from electricity generation will necessitate a larger contribution from these low carbon sources in the future.

In addition to the direct CO_2 emissions from electricity generation shown in Fig. 9, it is also important to consider indirect emissions associated with power plant construction, the manufacturing and transportation of generation equipment, upstream fuel production, processing and transport, waste disposal, and eventual power plant dismantling and site remediation. By taking into account both direct and indirect emissions over this full life cycle — i.e. from 'cradle to grave' — different electricity generation technologies can be compared consistently.

Figure 10 shows that all electricity technologies produce some GHG emissions on a life cycle basis [30]. Nuclear power, along with hydroelectricity and wind power, emits the lowest quantity of GHGs per kW·h of generation, while emissions are substantially higher for fossil technologies, including plants equipped with CCS facilities. It should be noted that the estimates in Fig. 10 generally represent the characteristics of technologies available in the last few years under representative average global conditions, although experience is limited with technologies equipped with CCS and their long term performance is yet to be proven. Life cycle emissions from existing (older) power plants can be higher due to lower efficiency and reliability. This is illustrated by the error bars in Fig. 10, which reflect the performance of a sample of existing plants [31]. In addition, variations from site to site can be substantial depending on the fuel source (e.g. varying CH_4 leakage rates from different natural gas wells or different growing conditions for biomass) and plant location (e.g. variations in transportation requirements, geography and climate for hydroelectricity, and latitude for solar irradiance). For hydroelectricity, for instance, CH_4 emissions from some tropical reservoirs with a large surface area relative to electricity output are estimated to increase life cycle GHG emissions to around 2 kg CO_2-eq/kW·h [32]. For nuclear power, life cycle emissions can vary depending on the nuclear fuel cycle, including the uranium quality and enrichment process (discussed further in Section 4.3) and potential extensions of operating lifetimes, which can spread the emissions from construction and decommissioning over a longer generating period. It should be remembered that:

> "The nuclear fuel cycle includes the 'front end', i.e. preparation of the fuel, the 'service period' in which fuel is used during reactor operation to generate electricity, and the 'back end', i.e. the safe management of spent nuclear fuel including reprocessing and reuse and disposal. If spent fuel is

not reprocessed, the fuel cycle is referred to as an 'open' or 'once-through' fuel cycle; if spent fuel is reprocessed, and partly reused, it is referred to as a 'closed' nuclear fuel cycle" (Ref. [33], p. 5).

While Fig. 10 provides a consistent comparison of emissions per unit of electricity output for different generation options, it is important to recognize that these technologies differ in other ways that can influence their potential to scale and contribute to the overall electricity supply. For example, among the low carbon generation options in Fig. 10, some technologies are dispatchable, i.e. available on demand (including biomass, hydroelectricity, fossil fuel with CCS and nuclear) while others produce less predictable variable output (including wind and solar photovoltaic) and may require dispatchable backup capacity. Realizing a low carbon electricity supply that can match demand 24 hours a day, 365 days

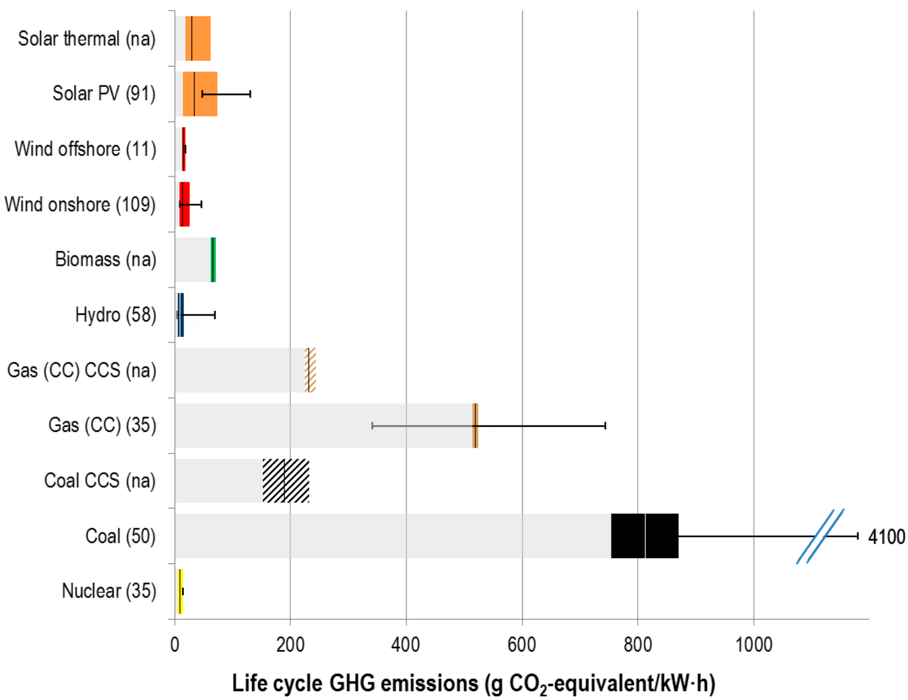

FIG. 10. Life cycle GHG emissions of electricity technologies. Data sources: Refs [30, 31, 34, 35]. Note: Coloured ranges show regional low, average and high estimates for recently (2010) available representative technologies. Error bars indicate variation across a sample of existing power plants (based on the number of plants indicated in parentheses). GHG — greenhouse gas, CC — combined cycle, PV — photovoltaic, CCS — carbon dioxide capture and storage, na – not available (no data).

a year, will almost certainly require a mix of energy sources — depending on resource endowments, demand structure and energy storage options — that will vary across global, regional and local scales.

3.2.2. Additional impacts of low carbon electricity generation technologies

Importantly, like the energy sector more broadly, the production of electricity has additional impacts beyond climate change that should also be considered, including material, land and water requirements, effects on human health and damages to ecosystems. Figure 11 summarizes the life cycle performance of selected electricity generation technologies for six different impact categories based on Ref. [30]. Fossil technologies perform poorly in terms of GHG emissions, as shown in Fig. 10, but also have relatively high impacts on ecosystems, human health and, in the case of coal, land occupation (mainly from mining). The ecosystem damages arise primarily from acidification and eutrophication caused by releases of pollutants from mining, power plant

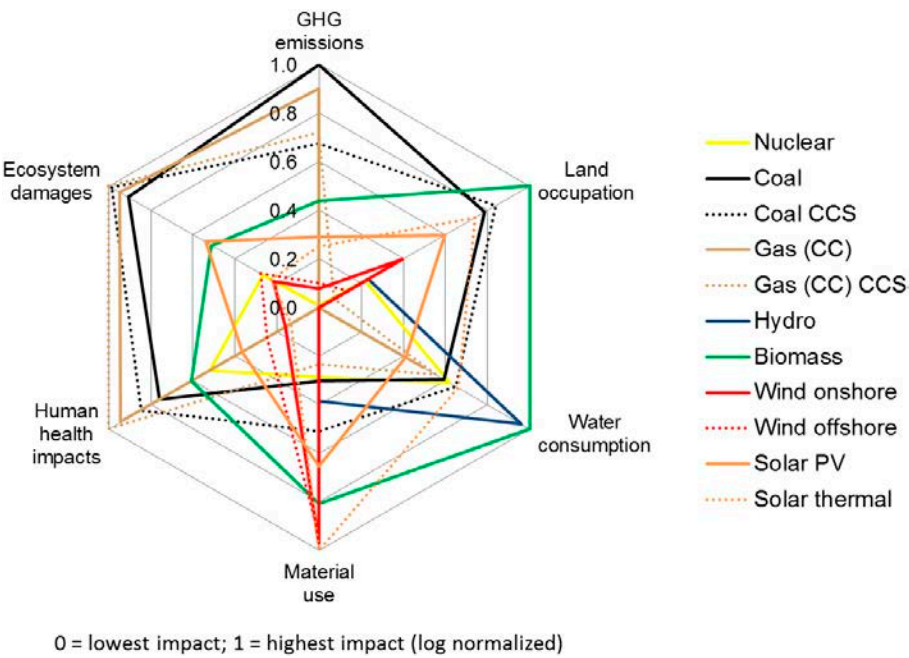

FIG. 11. Summary of life cycle impacts per kW·h for recently (2010) available representative electricity technologies. Data sources: Refs [30, 34–36]. Note: Impacts are log normalized with the lowest impact = 0 and the highest impact = 1. CC — combined cycle, PV — photovoltaic, CCS — carbon dioxide capture and storage, GHG — greenhouse gas.

waste treatment and emissions from combustion. Acidification via the deposition of acid chemicals leads to the impairment of freshwater, fisheries, soils, forests and vegetation; eutrophication caused by increased concentrations of chemical nutrients leads to excessive algal growth and severe impairments to water quality. Health impacts arise largely from toxic releases (such as metal leaching from coal mines) and particulate emissions from combustion. While effective at reducing GHG emissions, the use of CCS tends to worsen performance across all other categories owing to overall reduced power plant efficiency and the use of toxic materials for capture. Among the low carbon technologies, biomass also performs relatively poorly across most impact categories, particularly in terms of land and water use (although these can be highly variable depending on the source of the biomass). On the other hand, hydroelectricity performs well for all categories with the exception of water consumption, noting, however, that the performance of hydropower is highly site dependent, as discussed above in the context of GHG emissions. Other variable renewables also generally perform well, with the exception of the use of structural materials, such as cement and metals (aluminium, copper, iron), and relatively high land requirements for solar technologies. Nuclear power has among the lowest impacts, although water consumption is similar to other thermal generation technologies and health impacts are above those of some renewables. It is important to distinguish between water withdrawn and later returned to its source and water consumed through evaporation, transpiration or incorporation into a product. Thermal plants with once-through cooling withdraw significantly more water than plants employing cooling towers, but consume (evaporate) less. The estimates in Fig. 11 are based on water consumption for plants with evaporative cooling towers.

Figure 11 illustrates that responding to climate change in the electricity sector by switching to low carbon technologies (Fig. 10) can have positive and negative effects on other environmental, health and resource challenges. Accordingly, a comprehensive and integrated approach to technology choice for GHG emissions abatement is needed to avoid unintended consequences for other aspects of sustainable development beyond climate change. However, while the choice of technology is critical, future impacts of the energy sector also depend to a large extent on future demands for energy and electricity.

3.3. FUTURE ENERGY AND ELECTRICITY DEMANDS

Demand for energy and electricity, and in turn, GHG emissions, is driven by a range of demographic, economic, technological and policy factors. Since the early 1970s, increasing population and economic activity have coincided with increasing primary energy demand and energy related CO_2 emissions, as illustrated in Fig. 12. Despite this link, the energy intensity of economic activity has steadily declined by around 1%/year owing to structural factors (e.g. an increasing share of services in the global economy) and technological change leading to improvements in the energy efficiency of appliances, buildings and processes. As a consequence, energy demand and emissions increased at a slower pace than economic output measured in terms of gross domestic product. An

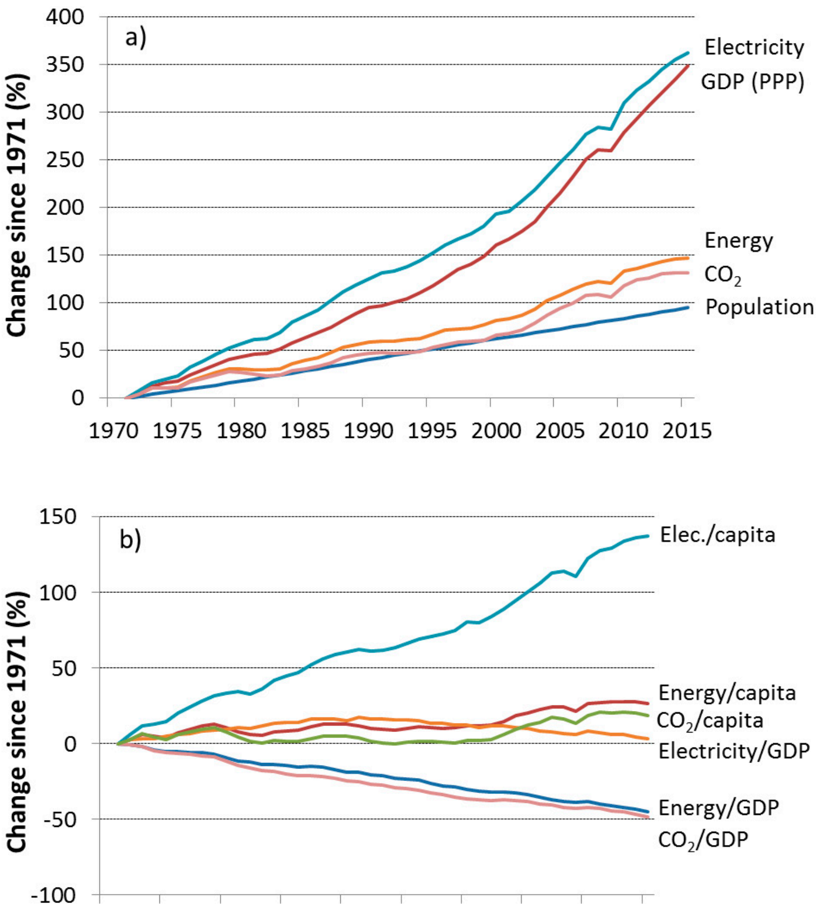

FIG. 12. Historical trends of (a) total and (b) intensity changes in basic global demographic, economic, energy and emissions indicators 1971–2015. Data sources: Refs [19, 21]. Note: 'Electricity' refers to electricity consumption, 'Energy' refers to primary energy supply, 'GDP (PPP)' refers to gross domestic product measured at purchasing power parity (US $\$_{2010}$), '$CO_2$' refers to carbon dioxide emissions from fuel combustion. Elec. — electricity.

exception to this overall decoupling of energy demand and economic activity is evident for electricity generation — electricity use per unit of economic output has remained roughly unchanged, while electricity use per capita has increased substantially since the early 1970s with the increasing electrification of energy demands.

3.3.1. Scenarios of energy and electricity demand

Energy demand in the future will depend on the evolution of key driving forces: population, economy, technology and policy. Recent projections of future energy demand from leading international agencies, non-governmental organizations and industry are presented in Fig. 13. These scenario projections estimate that primary energy demand will reach 430–900 exajoules (EJ) in 2050, compared with 570 EJ in 2015 [21] (Fig. 13(a)). Most studies report primary energy based on the physical energy content of the first energy form downstream in the production process for which multiple energy uses are practical [21]. This means, for example, that the primary energy reported for renewables used for electricity generation such as solar and wind equals the electricity output from these sources, rather than the larger amount of electromagnetic energy of the solar radiation or the kinetic energy of the wind. In scenarios with a strong emphasis on climate change mitigation, primary energy demand in 2050 falls within a lower range of 430–650 EJ, while other scenarios reach 700–900 EJ.

For electricity demand, all but one of the scenarios project an increase from 73 EJ in 2015 to 125–157 EJ in 2050 (Fig. 13(b)), covering a narrower range than future primary energy demand. The one outlier is a scenario in which electricity demand reaches around 200 EJ owing to extensive additional electrification of space heating, transportation and, notably, industrial process heat (this is the 'All disruptions' scenario described by McKinsey Energy Insights [37]). In scenarios emphasizing climate change mitigation (excluding Ref. [37]), electricity demand in 2050 is between 125 and 143 EJ, while other scenarios cover the full 125–157 EJ range. This small difference in future electricity demand between mitigation and other scenarios, and across a wide range of studies produced by organizations with different interests, highlights the broad consensus on the key role of electricity in the future.

For scenario studies presenting a detailed sectoral breakdown, the increase of global electricity demand is driven by increasing demand in buildings (in the residential and services sectors) of 50–125%, industry (30–110%) and transportation (120% to 1700%) as shown in Fig. 14. The wide range of estimates of growth in electricity use in transportation reflects different views on the future of electric mobility.

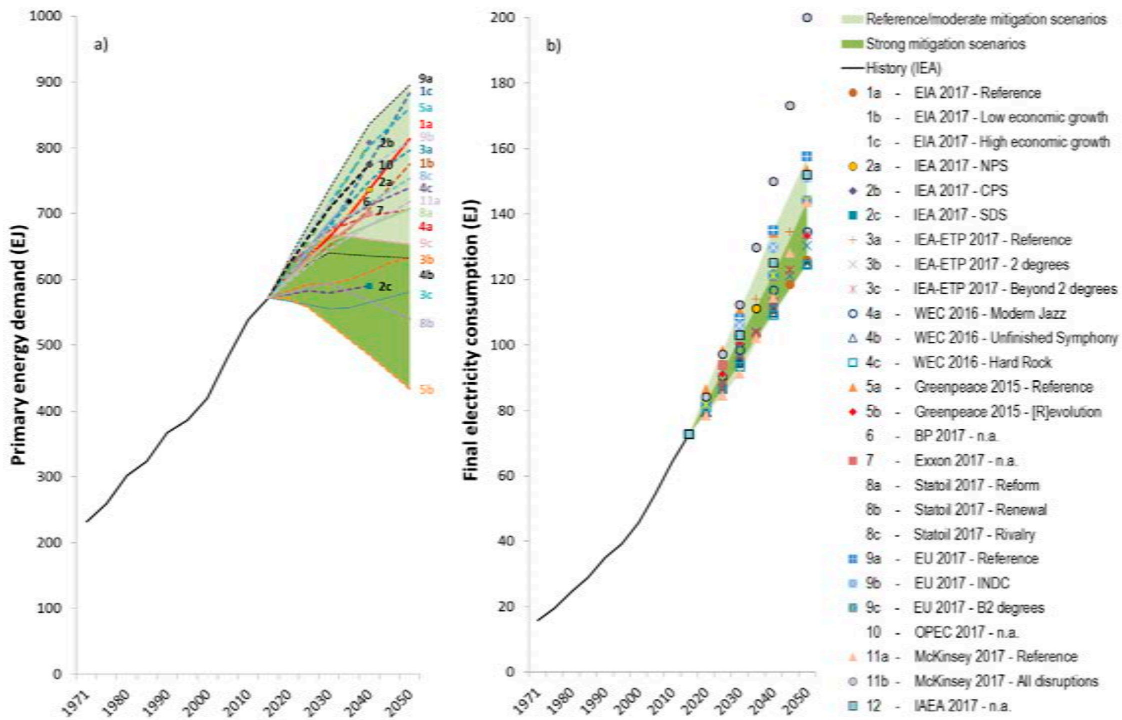

FIG. 13. Recent scenario projections of global (a) energy and (b) electricity demand to 2050. Data sources: Refs [21, 37–49]. Note: EJ — exajoule, IEA — International Energy Agency, EIA — Energy Information Administration, NPS — New Policies Scenario, CPS — Current Policies Scenario, SDS — Sustainable Development Scenario, ETP — Energy Technology Perspectives, WEC — World Energy Council, EU — European Union, INDC — Intended Nationally Determined Contributions scenario, B2 degrees — Beyond 2 Degrees scenario, OPEC — Organization of the Petroleum Exporting Countries, n.a. — not applicable.

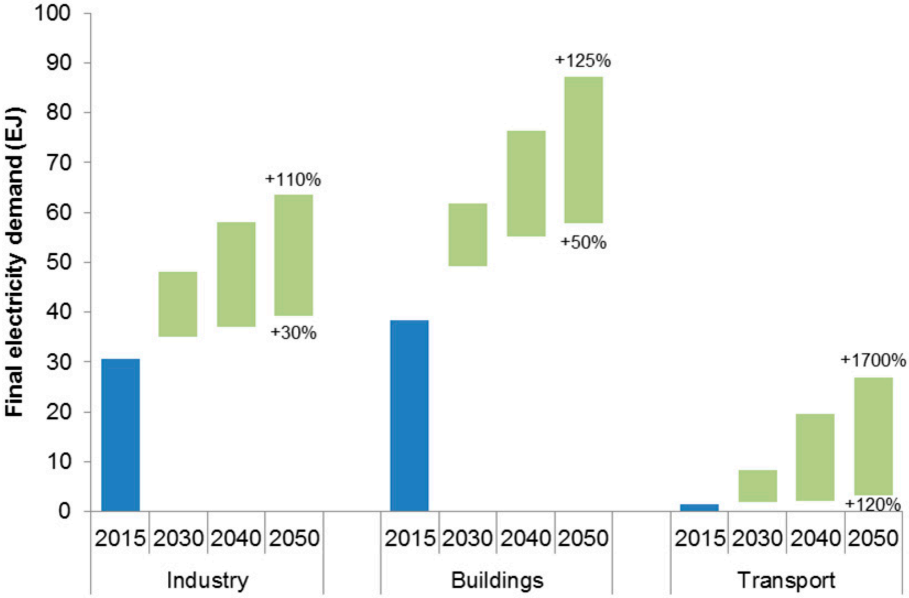

FIG. 14. Scenario ranges of future global electricity demand in industry, buildings and transportation. Data sources: Refs [21, 37–42, 44–49]. Note: EJ — exajoule.

3.3.2. Achieving universal access to electricity

Several of the scenario studies also present a regional breakdown of future electricity demand, with modest growth of 0–50% projected for most regions of the OECD by 2050 compared with a faster increase in developing regions (for example, a two- to threefold increase in China). Electricity demand growth is particularly rapid in Africa (100–450% by 2050) where today many people lack access to modern energy — half the 1.1 billion people worldwide currently without access to electricity live in Africa [50]. While today a large majority of people without access to electricity reside in rural areas, most of the population growth to 2030 will occur in cities, as shown in Fig. 15. Achieving the SDG 7 target of ensuring access for both the currently unserved population and an additional 1.3 billion people globally by 2030 will require a mix of grid, minigrid and off-grid solutions using different generation options [50]. Large scale low carbon generation sources such as nuclear power are well suited to supporting access via the grid, which is likely to be the main solution for providing access to the additional 1.1 billion people expected to be living in urban areas by 2030 (Fig. 15). For more remote minigrid and off-grid access solutions, a mix of small and medium scale generation options will be needed, potentially including

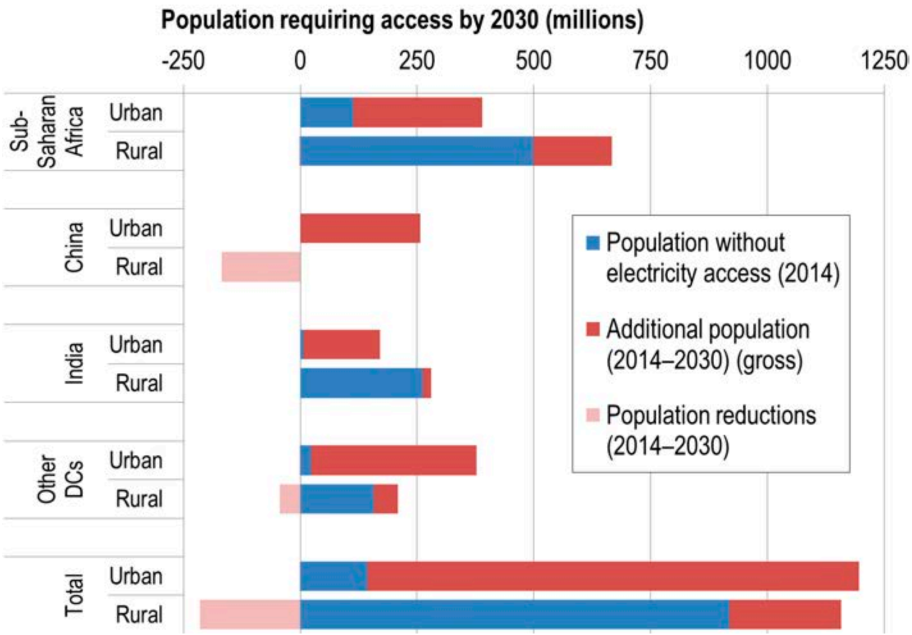

FIG. 15. Population in developing countries requiring access to electricity by 2030. Data sources: Refs [51, 52]. Note: DCs — developing countries.

small, medium sized or modular reactors (SMRs) — see Section 5.4.3 — in some niche applications. Globally, the additional electricity generation needed to support basic access is relatively small, although in Africa achieving universal access to electricity by 2030 is estimated to require the additional generation of 750 terawatt-hours (TW·h) [50], which represents 15–25% of the continent's electricity demand across selected scenarios (3200–4400 TW·h in 2030) [38, 39, 42, 47, 48].

3.3.3. Future energy demands and greenhouse gas emissions

Given the substantial contribution of the energy sector to current and historical GHG emissions, as shown in Section 3.1, the increasing demand for energy and electricity projected for the future has the potential to drive significant growth in emissions. This contrasts with the need to avoid serious climate change by limiting the increase in global temperature to below 2°C (Section 2.3), which will necessitate a large reduction in emissions from the energy sector. The extent of this required reduction is also illustrated by the scenarios of energy and electricity demand summarized in this section. Figure 16 presents global CO_2

emissions from fuel combustion across three groups of scenarios: (1) reference and business as usual scenarios; (2) scenarios with moderate climate change mitigation goals; and (3) scenarios with stringent mitigation goals. The latter group includes scenarios compatible with the 2°C target, which entails reducing direct CO_2 emissions to close to zero soon after 2050. Achieving such a reduction while providing a reliable and affordable energy supply will require the adoption of a combination of low carbon technologies and fuels such as nuclear power and renewables for electricity generation (Section 3.2). Section 4 describes the potential contribution of nuclear power to this mitigation effort in more detail.

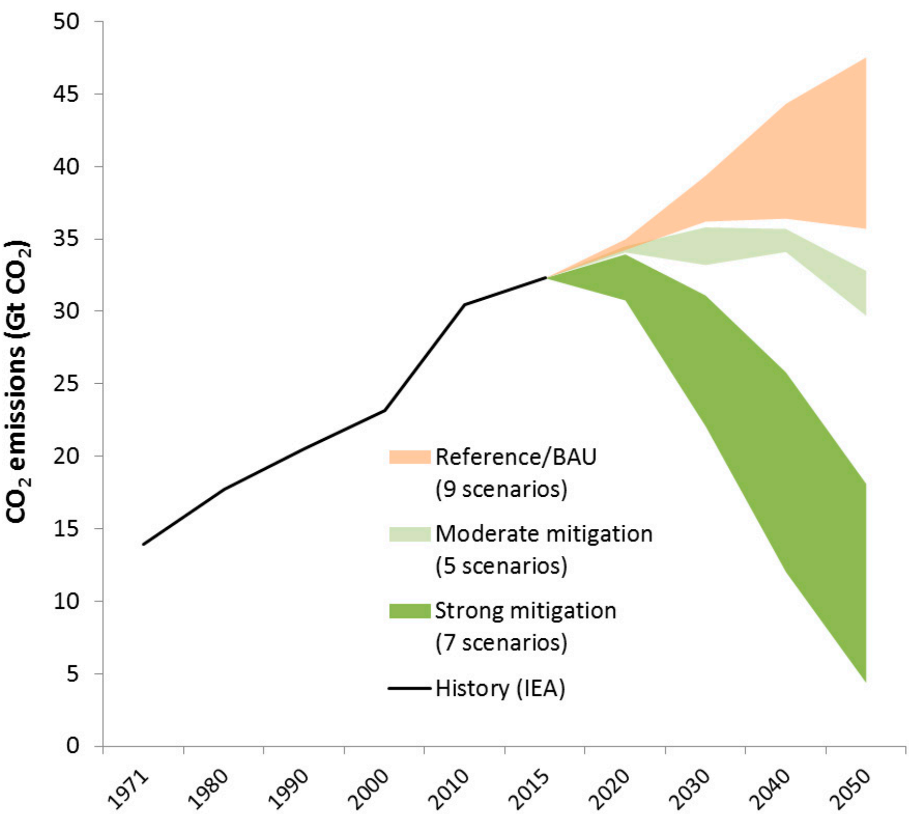

FIG. 16. Scenario projections of global CO_2 emissions from fuel combustion. Data sources: Refs [19, 37–42, 44–47, 49]. Note: Gt CO_2 — gigatonnes of carbon dioxide, BAU — business as usual, IEA — International Energy Agency.

4. THE ROLE OF NUCLEAR POWER IN CLIMATE CHANGE MITIGATION

4.1. GREENHOUSE GAS EMISSIONS AVOIDED IN THE PAST

The global economy has been dominated by fossil energy resources since the rise of the industrial society because of the wide availability of fossil fuels, initially coal and later oil, their high energy density and easy transportability. The possibility to supply energy to emerging industrial centres made fossil fuels an invaluable driver of economic growth. They did not have any viable large scale alternatives until the 1920s–1930s. A direct outcome of this energy development was the gradual rise of CO_2 emissions and the resulting impacts on the Earth's climate (see Section 2.1.2).

The only significant low carbon alternative to fossil fuels until the 1950s was hydropower but its use was limited by the availability of suitable sites, i.e. sites with suitable water resources and topography, and their geographical location. This situation started changing in the second half of the 20th century as new energy technologies became more widely available. They included natural gas among fossil fuels and low carbon options such as nuclear power and, somewhat later, new variable renewable energy (VRE) sources, primarily wind and solar energy.

The addition of non-fossil alternatives to the energy mix was originally driven by multiple non-climatic factors: economic, energy security and environmental concerns, including air pollution caused by burning fossil fuels. Because of this, non-fossil sources were already contributing to reducing CO_2 emissions long before climate change became a central issue on the global environmental agenda. They supplied an increasing part of the energy mix that otherwise would have been provided by fossil fuels. This avoided CO_2 emissions from the mostly coal fired power plants that they replaced. Therefore, even before the start of global action on climate change, non-fossil alternatives were slowing the accumulation of GHGs in the atmosphere.

A related question concerns the actual amount of avoided emissions: how significant was the historical contribution of nuclear energy, hydropower and other renewables to abating GHG emissions in the past? Their estimated contributions to avoided CO_2 emissions between the early 1970s and 2015 are shown in Fig. 17, which is based on data on electricity outputs from different energy sources taken from the World Energy Balances of the International Energy Agency (IEA) [21].

The underlying assumption in Fig. 17 is that the relative share of fossil fuels in the electricity mix would have remained the same if no low carbon electricity sources had been used. For the 1970s and 1980s, this is most likely a conservative assumption owing to the role of energy security in the political agenda of that era as major energy importing countries endeavoured to reduce their dependence on oil imports. Therefore, the share of nuclear energy, hydropower and other renewables would have most likely been supplied by coal, which produces more GHG emissions. This relationship has probably become weaker since the 1990s due to subsequent economic and political developments and the rising role of natural gas.

Another important assumption is that low carbon energy sources were not competing with one another and that therefore their use avoided the average amount of CO_2 emissions from the fossil fuel mix rather than average emissions from all energy sources. This means that if any of the low carbon technologies had dropped out of the energy mix, it would have not been replaced proportionally by the mix of all remaining technologies but by fossil fuels only.

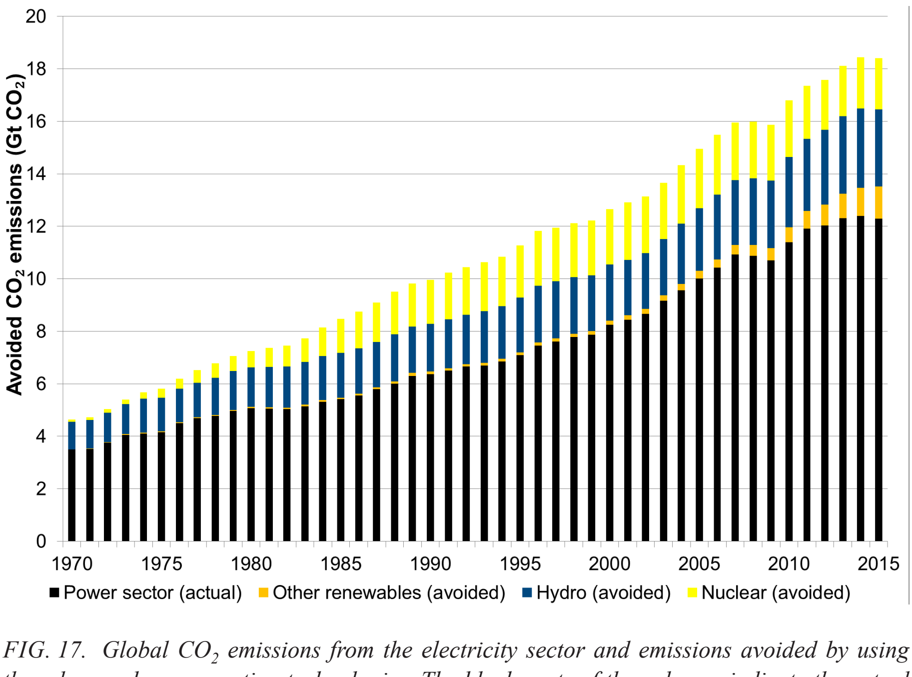

FIG. 17. Global CO_2 emissions from the electricity sector and emissions avoided by using three low carbon generation technologies. The black parts of the columns indicate the actual CO_2 emissions from the global electricity sector in a given year, while the total heights of columns represent the estimated total emissions if fossil fuels alone had been used to supply the same amount of electricity. Coloured sections of the bars represent the emissions avoided by the use of nuclear energy, hydropower and other renewables. Source: IAEA calculations based on data in Ref. [21]. Note: Gt CO_2 — gigatonnes of carbon dioxide.

At the beginning of the surveyed period (1970), the only significant source of avoided CO_2 emissions in electricity generation was hydropower: approximately 1 Gt CO_2 (30% of actual emissions in the power sector). This share remained mostly constant until the late 1990s when it started gradually declining (to 24% in 2015). The role of nuclear energy in avoided emissions was quickly expanding in the 1970s and 1980s: it avoided less than 0.1 Gt CO_2 in 1970, increasing to 0.62 Gt CO_2 by 1980 (an average annual growth rate of 23%), and reached 1.69 Gt CO_2 in 1990 (an average annual growth rate of 10%). By the early 1990s, the amount of avoided emissions from nuclear energy approximately equalled that of hydropower. This remained the case until the mid-2000s when hydropower took the lead again. The amount of avoided emissions from hydropower increased from 2.14 Gt CO_2 in 2000 to 2.95 Gt CO_2 in 2015, while the avoided emissions from nuclear energy remained mostly stagnant in this period, slightly decreasing from 2.12 Gt CO_2 in 2000 to 1.95 Gt CO_2 in 2015. Over the period 1970–2015, nuclear power avoided around 68 Gt CO_2 in total, close to the entire actual emissions from the power sector in 2010–2015. The contribution of hydropower to avoided emissions in 1970–2015 was around 90 Gt CO_2 and that of other renewables around 10 Gt CO_2.

Other renewables (solar, wind, geothermal and biofuels) started making noticeable contributions to avoiding CO_2 emissions after 2000, reaching 0.2 Gt CO_2 in 2003 (2% of actual power sector emissions in that year). This amount increased to 0.57 Gt CO_2 in 2010, demonstrating an average annual growth rate of 14% over the decade, which is comparable to the performance of nuclear energy in the 1980s. Over the subsequent five years, the amount of emissions avoided by renewables more than doubled, reaching 1.21 Gt CO_2 in 2015 (about 62% of the nuclear contribution in that year), which means an average growth rate of 16%/year.

The estimates in Fig. 17 show avoided emissions of CO_2 only, i.e. they do not cover all GHGs. If avoided emissions of CH_4 and other GHGs (e.g. N_2O) are considered, the total amount of abated GHGs is even higher. Although the absolute amounts of other GHG emissions avoided are much lower, their atmospheric impacts are considerable because the global warming potential (GWP) of non-CO_2 GHGs is significantly higher than that of CO_2. Specifically, according to the IPCC Fifth Assessment Report [2], the GWP of CH_4 is 28, i.e. the emission of one unit of CH_4 corresponds to the emission of about 28 units of CO_2 in terms of radiative forcing in the atmosphere. Based on IAEA calculations using data from the Emissions Database for Global Atmospheric Research [53] of CH_4 emissions starting from the 1970s, the amount of CH_4 emissions avoided by nuclear power was 0.008 Gt CO_2-eq in 1971 (i.e. around 8% of the avoided CO_2 emissions), increasing to 0.056 Gt CO_2-eq in 1981 and to 0.16 Gt CO_2-eq in 1991. The amount continued to rise, reached the level of 0.2 Gt CO_2-eq in 2009 and slightly decreased afterwards. The avoided CH_4 emissions by nuclear power in terms of GWP amounted to 8–10% of the avoided CO_2 emissions every year over the period 1971–2014.

In the light of the very limited remaining budget of CO_2 emissions (estimated in the mid-2010s) to keep the increase of the global mean annual temperature below 2°C relative to the preindustrial level as specified in the Paris Agreement [5] (Section 2.3), the importance of GHG emissions avoided in the past by nuclear energy, hydropower and other renewable energy sources is particularly noteworthy. These energy sources are also foreseen to play a key role in the technology components of future mitigation pathways towards the Paris Agreement's target.

4.2. FUTURE CONTRIBUTIONS TO GREENHOUSE GAS MITIGATION

The overview of contributions made by nuclear energy to avoiding GHG emissions in 1970–2015 provided in Section 4.1 shows different stages in the development of the industry. The first stage involved the fast expansion of nuclear energy in the 1970s and thus very high growth rates of avoided GHG emissions. This was followed by a period of stable growth accompanied by a significant contribution to GHG mitigation in the 1980s. The subsequent relatively stable period involved a more or less constant contribution to avoided GHG emissions. The historical lesson is that it is hard if not impossible to adequately predict the future because at each stage of the development process it is tempting to extrapolate existing trends and to project the short and medium term agendas into the long term future. Moreover, the nuclear industry is affected by a multitude of factors and many of them are exogenous, e.g. technological progress in using different energy sources or changes in social choices and preferences affecting the political agenda.

The contribution of nuclear energy to GHG mitigation over the next decades will therefore be determined by different groups of factors. The first group is the performance of the nuclear power industry itself, including stable operational records, implementation of plant life management programmes up to 50–60 years and beyond, reducing the cost of operation of the current fleet, technological innovations, economic competitiveness and safety records. The second group of factors comprises developments in the energy sector in general: emergence of new energy technologies, their relative economic performance and the availability of the necessary resources in different countries. Finally, the broader economic and political agenda will affect the choices of different nations in favour or against nuclear power and other energy sources. The future evolution of all these factors is increasingly less predictable and they affect one another. Therefore, when discussing the possible role of nuclear energy in managing global climate change in the long run, all plausible developments should be considered in projections or scenarios based on consistent sets of assumptions rather than producing predictions. Scenarios remain valid as long as their underlying assumptions are broadly met. Considering past experience from the oil crises in 1973 and 1979 to the current developments in gas markets, major shocks in the energy sector remain unpredictable today and are likely to occur in the long run.

In terms of avoided GHG emissions, the impact of these factors will be twofold: first, the scale of the possible expansion of nuclear power over the next decades, i.e. the question of what will be the magnitude of the nuclear capacity in the future; and second, changes in other energy technologies over time, i.e. the question of which technologies will be replaced by new ones. Specifically, as discussed in Section 4.1, in the 1970s nuclear energy was mostly competing with coal, thus its contribution to avoided CO_2 emissions was among the highest theoretically possible. However, in the future it is likely to compete with a whole range of low carbon energy technologies that would decrease the amount of avoided emissions per megawatt-hour (MW·h) of nuclear electricity. Additionally, technologies for using various energy sources are changing dynamically, which means that their carbon footprint may be decreasing with time. This process will accelerate as the pressure on energy producers to mitigate climate change is likely to progressively increase after the 2015 Paris Agreement [5] entered into force in 2016.

Therefore, when discussing the role of nuclear energy using various projections and scenarios, it is important to see them as images of tomorrow based on knowledge of yesterday and on the goals and policy agendas of today. Figure 18 compiles major projections of the developments in nuclear electricity generation up to 2060.

It is not surprising that different assumptions about future policy choices and technological developments and expectations of the goals to be achieved by the global energy system over the next decades cause the projections of nuclear electricity generation to vary widely, and the range of these projections increases over the scenario horizon. Based on the 26 scenarios reviewed, nuclear electricity generation in 2050 can be in a range between 0 and nearly 11 petawatt-hours (PW·h) relative to 2.571 PW·h in 2015 [21]. However, the extreme values are outliers driven by some aspirational goals. The range of projections is much smaller (3–7 PW·h) if the five outlying scenarios are disregarded — two of which assume the vanishing of nuclear power from the energy mix by the middle of the century (scenarios proposed by Greenpeace [42] and the Energy Watch Group [43]) and three high end cases (over 8 PW·h by 2050): two scenarios

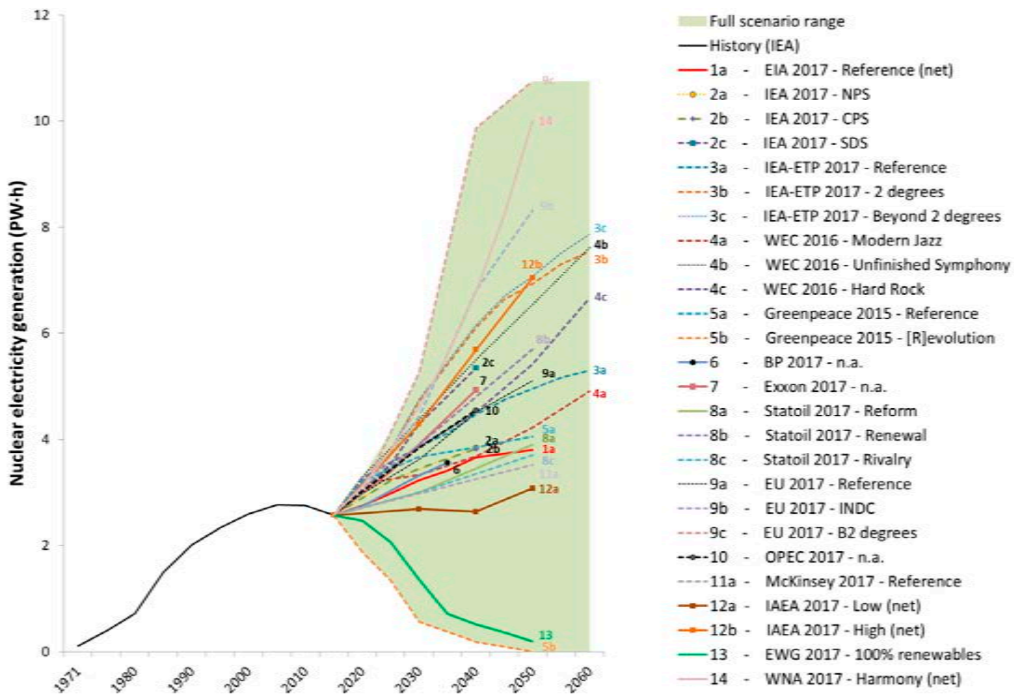

FIG. 18. Scenarios of nuclear electricity generation: historical data (1971–2015) and projections (2015–2060). Data sources: Refs [21, 37–49, 54]. Note: PW·h — petawatt-hour, IEA — International Energy Agency, EIA — Energy Information Administration, NPS — New Policies Scenario, CPS — Current Policies Scenario, SDS — Sustainable Development Scenario, ETP — Energy Technology Perspectives, WEC — World Energy Council, EU — European Union, INDC — Intended Nationally Determined Contributions Scenario, B2 degrees — Beyond 2 Degrees Scenario, EWG — Energy Watch Group, OPEC — Organization of the Petroleum Exporting Countries, WNA — World Nuclear Association, n.a. — not applicable.

proposed by the European Union (B2 degrees and INDC) [47] and one by the World Nuclear Association [54]). The 2017 IAEA low projection assumes only very limited growth of nuclear power by 2050: up to 3.079 PW·h, i.e. an increase of about 20% over 33 years (about 0.5%/year) [48]. According to the 2017 IAEA high projection, nuclear electricity generation will increase to 7.041 PW·h in 2050 (174% growth over 33 years with an average growth of about 3%/year). All other scenarios in Fig. 18 fall between the 2017 IAEA low and high projections in 2050.

Only six scenarios extend their horizons to 2060 and they project nuclear electricity generation in a range between 4.908 PW·h (one of the World Energy Council scenarios [41]) and 7.858 PW·h (the 'Beyond 2 Degrees' scenario in the Energy Technology Perspectives [40] of the IEA). Clearly, all these long term projections have been changing over the last few years and will keep changing in the future, reflecting actual political and economic agendas as well as ongoing events, trends and innovations. The broad general vision of these scenarios is the growing role of nuclear energy over the next four decades and, therefore, an increase of its absolute contribution to climate change mitigation.

Looking at the assumptions and the underlying visions of the future in these scenarios in more detail allows a better understanding of how general priorities and broad political agendas affect the projected role of nuclear energy. Interesting examples include the Reform, Renewal and Rivalry scenarios developed by Statoil for the period up to 2050 as they offer rather distinct images of the future [46]. The Reform Scenario (serving as the reference case) extrapolates current economic trends and policies associated with the Paris Agreement (e.g. NDCs), while the Renewal Scenario is focused specifically on limiting GHG emissions to keep global warming below 2°C (the Paris target). These visions are broadly in line with the New Policies Scenario (NPS) and the Sustainable Development Scenario (SDS) of the IEA (discussed in more detail below) and they postulate climate change mitigation as a major priority. The third Statoil projection, the Rivalry Scenario, considers energy security as the predominant factor in future energy policies owing to an assumption that the nature of international relations will be more confrontational.

In the Renewal Scenario, similarly to the majority of climate friendly scenarios (except those setting the use of renewables as an explicit goal at some point in the future), nuclear energy shows the highest rate of growth among the Statoil scenarios, reaching 5–6 PW·h by 2050 (124% growth relative to 2014). This outcome is probably not surprising. Yet the most interesting conclusion for nuclear energy is that in the Rivalry Scenario, convoluted political trends lead to the prioritization of energy security, thus the role of nuclear energy is nearly the same in 2050 (3.64 PW·h) as in the reference Reform Scenario (3.84 PW·h). The reason is that in this case nuclear energy would likely be seen as one of the pillars of energy security (similarly to the way it was seen in the 1970s and 1980s). In the context of this section, however, the most important insight is that even in less optimistic scenarios for the global economy (lower growth rates, increased protectionism), nuclear power is foreseen to be used to hedge against arising energy security risks due to its other, non-climatic benefits while continuing to serve climate change mitigation goals.

The scenario compilation in this section allows the creation of a broad picture of what could happen in the nuclear industry (i.e. what could be delivered) over the next decades. These projections are an important element of the answer to the question about the future contribution of nuclear energy to GHG mitigation. However, it is not sufficient to understand the absolute amount of contribution without considering what would be replaced by nuclear power in the energy mix, similarly to the analysis in the previous section. In order to understand the contribution of nuclear energy to climate protection, investigation of the trends in the whole energy mix is required.

A possible approach to this analysis is to compare various scenarios and analyse their differences in CO_2 emissions. These differences can be decomposed by their driving factors according to the assumptions in the related scenarios. An example of such assessment is the comparison of two IEA scenarios proposed in the World Energy Outlook 2017 [39]: the NPS and the SDS. The NPS is the central (i.e. reference) scenario in World Energy Outlook 2017, incorporating current energy policies and those announced and likely to be implemented in the future. The SDS is a normative scenario and includes actions needed to achieve the goals of the Paris Agreement, universal energy access and to improve air quality globally. The SDS broadly follows the sustainable development agenda promoted by the United Nations (especially SDG 7, see Section 3.1.2).

The comparison of these scenarios reveals the difference between actions in the ‘business as usual’ case and in the ‘climate change mitigation’ case. The method is to estimate the contribution of various sources, such as low carbon energy technologies and improvements in energy efficiency of the global economy, to the divergence in GHG emissions between the two scenarios over the years. Clearly, changes in the energy system will be steered by additional exogenous driving factors, e.g. population growth rates (which themselves are based on external assumptions) and other exogenous projections. The sources of emissions reductions in the SDS in comparison with the NPS are shown in Fig. 19.

According to the IEA, the key factor in the additional GHG emissions reductions in the SDS over the next decades would be improvements in energy efficiency: 52% of the difference in emissions between the NPS and the SDS in 2025 is expected to be achieved by progress in end use and supply side efficiency. This share will gradually decrease to 40% in 2040. As in its previous projections [55], the IEA expects the share of CCS to start expanding after 2030 but the scale of CCS contribution is expected to be more conservative than in earlier assessments. The role of biofuels is explicitly recognized in these scenarios (separately from VRE sources) with their share in the difference between avoided emissions in the two scenarios remaining around 7% in the period up to 2040. The contribution of VRE sources to the difference between the scenarios remains around 30%.

The contribution of nuclear energy to differences in emissions reductions between the NPS and the SDS is expected to be 0.3 Gt CO_2 in 2025, 0.7 Gt CO_2 in 2030, 0.9 Gt CO_2 in 2035 and 1 Gt CO_2 in 2040. This makes the share of its contribution, varying in the range of 5.7–7.5% of emissions reductions across the scenarios, comparable to that of biofuels. In comparison with the estimates of historically avoided emissions by nuclear power (presented in Section 4.1), the additional 1 Gt CO_2/year in the 2030s is about half of what has been annually avoided by the technology in the 2010s. However, this is an additional 1 Gt in comparison with the NPS, which assumes a steady growth of nuclear power output (to 3.844 PW·h in 2040, i.e. by 49% over the next 25 years), although at a

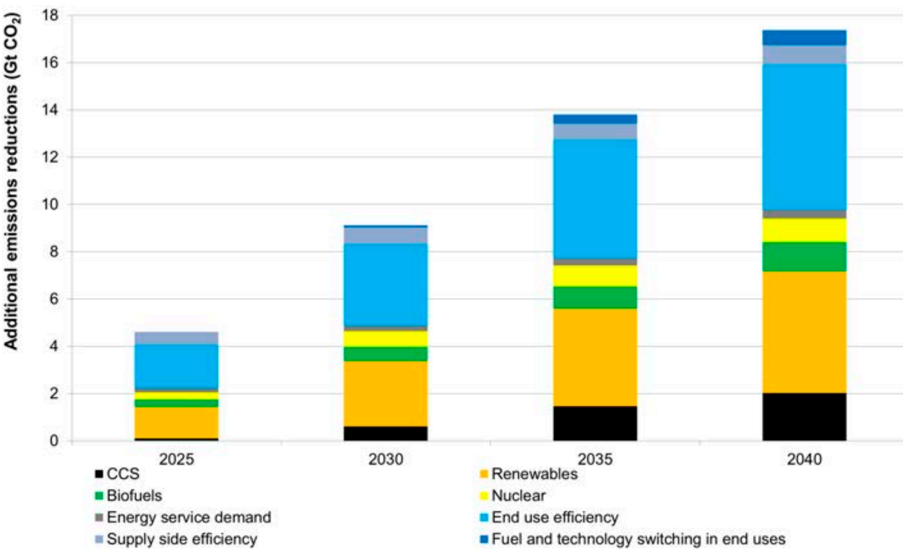

FIG. 19. Additional global CO_2 emissions reductions by technologies in 2025–2040 achieved through policies potentially needed to implement the United Nations sustainable development agenda (World Energy Outlook 2017 Sustainable Development Scenario) relative to those relying on policies implemented and planned as of mid-2017 (World Energy Outlook 2017 New Policies Scenario). Data source: Ref. [39]. Note: Gt CO_2 — gigatonnes of carbon dioxide, CCS — carbon dioxide capture and storage.

slower pace than in the SDS: 5.345 PW·h in 2040 (108% growth). This means that the total contribution of nuclear energy is projected to increase significantly even in the more conservative scenario, although relative gains from each replaced unit of electricity production will decrease owing to changes in the overall energy mix and the improving carbon footprint of other energy technologies over time.

The projections for nuclear energy in all IEA World Energy Outlook 2017 scenarios are rather conservative and, as can be seen in Fig. 18, are far from the extremes of the full scenario range on both sides. In its climate friendly scenarios (the 2 Degrees and the Beyond 2 Degrees cases), the IEA's Energy Technology Perspectives 2017 publication [40] projects the expansion of nuclear energy at much higher rates over the next decades (up to 2060). This means that, in the view of the IEA, the contribution of nuclear power to climate change mitigation is expected to increase over the longer term.

The approach followed by the IEA in its climate friendly scenarios is based on the idea that in order to achieve the global climate change mitigation goals, all available mechanisms and instruments should be used, i.e. emissions reductions within the framework of the Paris Agreement should be prioritized above any other possible considerations. In practical terms, this means that all technologies currently available at an industrial scale will be used in full to keep global temperature rise well below 2°C relative to the preindustrial base period (the 1850–1900 climate), including low carbon energy sources (nuclear and renewables) and energy efficiency improvements. This approach is used in the majority of the scenarios presented in Fig. 18 and, in general, results in the increase of nuclear and renewable energy generation, at least in absolute terms. Typically, the relative share of low carbon energy sources in the global energy mix is also expected to increase over the next decades. The differences are mostly due to the assumptions about how fast low carbon energy sources will be able to expand and how much global energy demand will grow. Also, these projections do not include any assumptions about breakthrough technological innovations that could change the energy system in the future.

However, the above approach is rational only if the fundamental assumption about the prioritization of climate change mitigation holds. In scenarios where some other assumption becomes predominant, future developments will change accordingly. Specifically, if the primary goal is to switch to renewables, as in, for example, the Greenpeace Revolution Scenario [42] or the Energy Watch Group's 100% renewables scenario [43], the role of nuclear power is dramatically less important because in such scenarios smart grids and electricity storage are expected to make very significant progress. Scenarios prioritizing energy security (discussed above in the example of the Statoil Rivalry Scenario) [46] would be yet another vision of a possible future in which the share of nuclear energy is likely to remain high and expanding, and the contribution of renewables to the global energy mix to remain limited. In this case, fossil fuels will remain the dominant resource in the global energy and economy over the 21st century. This means that a high nuclear scenario is not always a low fossil (and therefore also a low carbon) scenario.

It is clearly possible to construct alternative scenarios with other priorities and assumptions that would depict very different energy futures. Specifically, the options discussed above can be divided into three conceptual groups with a view to the role of low carbon energy sources: (i) expansion of both nuclear and renewables, (ii) expansion of renewables only, (iii) expansion of nuclear energy. It is possible to construct scenarios in which, for example, there will be no major expansion of renewables, but nor will their role be taken over by nuclear power. However, of the 26 scenarios presented in Fig. 18, 24 expect expansion of nuclear energy by the middle of the century, though the magnitude of the expansion varies in a very broad range.

The contribution of nuclear energy to avoiding CO_2 emissions in the near term will be accomplished by NPPs currently in operation, under construction and in preparation. The first components of the near term contribution lie in the lifetime extension of operating plants. In the USA, this has already been practised since 2000 and about 90% of the US plants have already renewed their licences once, extending their operation to 60 years [56]. The reason so far has mostly been energy supply rather than climate protection. Plants are usually licensed for an operational period of 40 years, which can be extended to 60 years after an extensive safety evaluation. Outside the USA, different licensing periods apply but extension is possible in most countries.

Concerning new builds, the first plants of a new generation of large evolutionary water cooled reactors have recently started operation or are just about to do so. They are all large power plants (e.g. AP1000, EPR, APR1400, VVER1200), with power levels in the range of 1100 to 1600 megawatts (electrical) (MW(e)), designed by vendor companies from various countries in Europe, Asia and the Americas. In addition to countries that have been using nuclear energy for years or decades, a number of countries have started construction of their first NPPs in the past few years, including Bangladesh, Belarus, Turkey and the United Arab Emirates.

Although nuclear power capacity is being added in this way, a considerable number of NPPs are retiring globally, both for market reasons and lifetime reasons. Market reasons mean that the current electricity market and regulation schemes (especially subsidies) where the plant is operating are unfavourable to such an extent that the plant can no longer recover its costs from its revenues, and is forced to shut down. Lifetime reasons mean that the plant has already been operating for a very long time, therefore it would need safety refurbishments requiring an investment that is not expected to be earned back. CO_2 emissions might be more difficult and expensive to abate if the current NPP fleet starts down a steep retirements slope and new generation reactors do not replace and add sufficient capacities to maintain or grow the market share of nuclear power. Early fleet retirements will only make the impacts worse. Significant nuclear losses may wipe out the recent gains of renewables very quickly, partly eliminating the progress from the mitigation policy. If sufficient subsidies are extended to grow renewables to compensate for accelerating nuclear capacity losses, then the grid instabilities from renewables' fraction growth will very soon require either more subsidies for mass storage technology developments or more fossil plant backup or rapid transitions to smart grid, to stabilize the grid. Those subsidies will likely be greater than those that would be required to properly maintain and increase the nuclear fleet.

The 2018 edition of the IAEA nuclear power capacity projections [57] indicates that, compared with the estimates published in 2017 [48], the new assessments are lower rather than higher, meaning that nuclear power would contribute less to climate change mitigation than foreseen in 2017. Quantitatively this means that, relative to the nuclear capacity projections of 2017 (discussed above), the new estimates are 7 GW(e) lower for 2030 and 26 GW(e) lower for 2050 in the low estimates, and 43 GW(e) and 126 GW(e) lower for 2030 and 2050, respectively, in the high estimates. For reference, the 2017 low estimates were 345 GW(e) for 2030 and 382 GW(e) for 2050, while the high estimates reached 554 GW(e) for 2030 and 874 GW(e) for 2050. As there is a general agreement that electricity demand will increase steeply during the coming decades (see Fig. 13) and the trend of CO_2 emissions is not yet going down, declining nuclear energy projections raise serious concerns about the prospects for climate change mitigation. Low carbon sources are not only expected to replace fossil fuel fired generation capacities, but will also need to satisfy the additional rise in electricity demand. One reason for this rise in demand is that many countries around the world are currently in a phase of economic development in which an increasing share of total energy demand needs to be supplied by electricity. All low carbon sources will be needed to satisfy this demand, none can be left out, and policies should be developed and deployed to enable the proper contribution of all energy technologies.

The scenarios described above illustrate the magnitude of uncertainties regarding the future contribution of nuclear power to global energy supply. To resolve some of these uncertainties, the IAEA works with regional experts to produce projections of nuclear power each year that incorporate the latest information and account for changes in policy and market conditions over the preceding year. The 2018 IAEA high estimate for nuclear generation capacity in 2050 has been revised from the 874 GW(e) projected in 2017 to 748 GW(e) (see Fig. 20). The trend of successively revising estimates downwards in

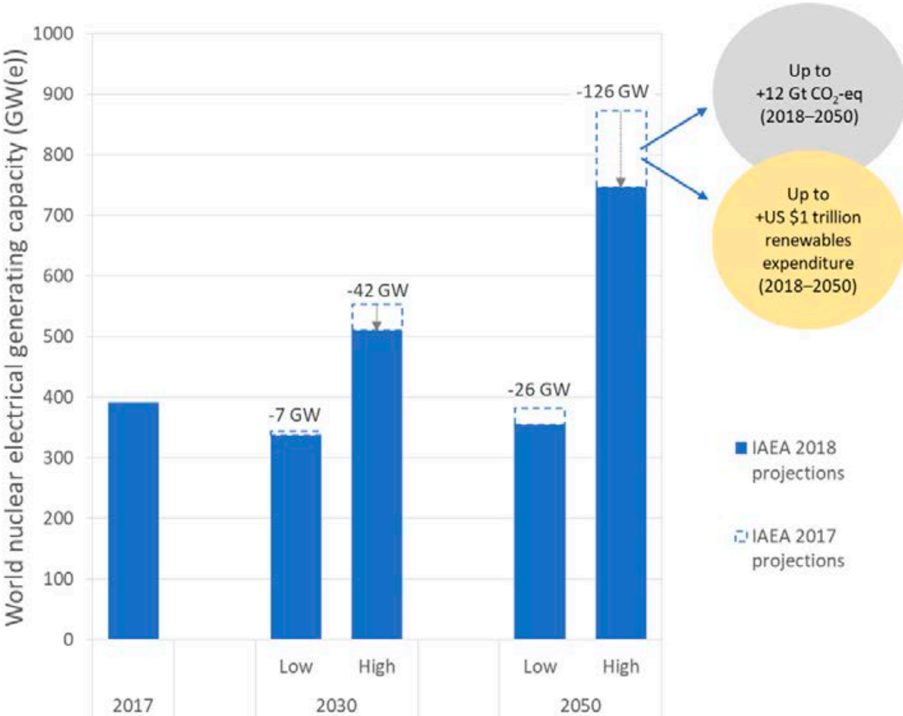

FIG. 20. Comparison of recent IAEA projections of future nuclear generation capacity. Data sources: Refs [39, 48, 57]. Note: GE(e) — gigawatt (electric), Gt CO_2-eq — gigatonnes of carbon dioxide equivalent.

subsequent projections has been continuing for several years, as can be seen from Fig. 21.

The reduction in generation capacity of 126 GW(e) between the two latest projections has implications for GHG emissions, the deployment of alternative low carbon options, investment and infrastructure requirements and energy system performance. For instance, depending on which technologies fill the gap opened by this lower nuclear capacity, cumulative GHG emissions (see Section 3.2) over 2018–2050 could be up to 12 Gt CO_2-eq higher, compromising efforts to achieve the goals of the Paris Agreement. Alternatively, entirely replacing this nuclear energy capacity with low carbon renewable generation capacity is estimated to increase investment and financing expenditure on renewables by roughly US $ 1 trillion over 2018–2050. Additional economic effects could be an increase of electricity prices and a loss of employment [58] that can be significant on a local or regional level.

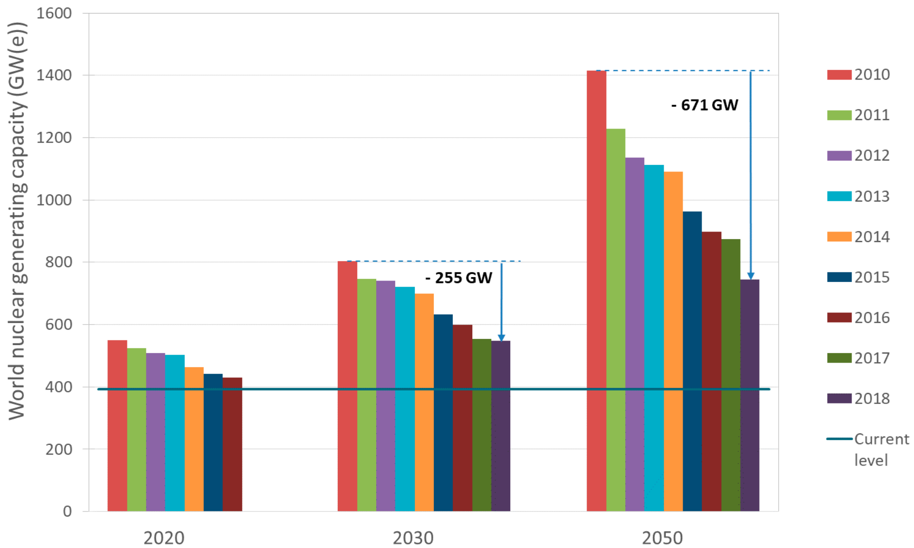

FIG. 21. IAEA high projections of future nuclear generation capacity from 2011 to 2018. Data sources: Refs [48, 57]. Note: GE(e) — gigawatt (electric).

4.3. GREENHOUSE GAS EMISSIONS FROM NUCLEAR POWER

The analysis of GHG emissions from nuclear power presented in this section covers the whole life cycle of the technology. This approach is important because nuclear energy and many renewable energy technologies are often erroneously considered 'zero carbon' electricity sources as NPPs, wind turbines and solar panels themselves do not emit GHGs. However, this is applicable only for the operational stage of their life cycles, as the construction of the necessary infrastructure, equipment manufacturing and fuel production, decommissioning and spent nuclear fuel management involve a certain amount of GHG emissions.

This section presents recent assessments of GHG emissions from the upstream, operational and downstream stages of the life cycle. For nuclear power, the upstream stage includes the preparation of the nuclear fuel (also called the front end of the nuclear fuel cycle, specifically mining, milling, conversion, enrichment and fuel rod fabrication) as well as activities associated with the construction of NPPs (material extraction and processing, parts manufacturing, facility construction). Analysis of the nuclear fuel cycle is crucial for making an adequate estimate of its climate change mitigation potential. According to the estimates provided in the Environmental Product Declarations (EPDs) for the Axpo AG Beznau, Vattenfall Forsmark, Vattenfall Ringhals and Sizewell B NPPs [59], mining, milling and enrichment are responsible for over

50% of the life cycle GHG emissions from these plants. The downstream stage of the fuel cycle (also discussed in Section 5.2.1) includes temporary, long term and permanent waste storage as well as facility decommissioning and the associated disposal and recycling activities.

GHG emissions in life cycle assessments include not only CO_2 but also CO, CH_4, N_2O, trichloroethane, carbon tetrachloride, nitrogen trifluoride, halons, chlorofluorocarbons, hydrochlorofluorocarbons and hydrofluorocarbons, all converted to CO_2 equivalents based on their GWP (similarly to the case of CH_4 in Section 4.1). The objective is to create a comprehensive and adequate estimate of the climate impacts of different energy technologies and to allow a better comparison of them. It is important to note that in the past few years enrichment technology has been completely transferred from gaseous diffusion to the much more energy efficient ultra-centrifuge technology, whereas many life cycle studies still take diffusion technology into account.

This section focuses on light water reactors (LWRs), the most widely used technology in the nuclear industry (see Fig. 22). Data are based on the Ecoinvent database version 3.3 [31], information from different studies collected and harmonized by the United States National Renewable Energy Laboratory (NREL) [60], estimates by the Central Research Institute of Electric Power Industry (CRIEPI) in Japan [61], the EPDs mentioned above [59], a UN Environment study encompassing nine estimates for major global regions [34] and a related study [35].

Figure 22 shows life cycle GHG emissions in terms of CO_2-eq/kW·h of electricity produced. The major observation from the graph is that when a standardized methodology is used, GHG emissions from nuclear energy vary in a very limited range, as can be seen from the estimates made by Ecoinvent, CRIEPI and the EPDs. Ecoinvent (Version 3.3) provides a synthesis of data for 35 NPPs with a median emission of 12 g CO_2-eq/kW·h. The overall range is 11–14 g CO_2-eq/kW·h. By using a similar methodology, CRIEPI [61] obtained a median value of 20 g CO_2-eq/kW·h in the range of 19–22 g CO_2-eq/kW·h for the Japanese nuclear industry. Based on estimates from the 2000s, this result is comparable with the estimates in earlier versions of Ecoinvent (e.g. Version 3.1 released in 2013 [62]).

The estimates by NREL reveal a very wide range from 4 g CO_2-eq/kW·h up to 110 g CO_2-eq/kW·h with a median value of 12 g CO_2-eq/kW·h. The reason is that NREL compiles studies based on very different assumptions (in this case 27 studies with 99 estimates for different NPPs). These studies were harmonized according to GWP, operating lifetime, capacity factor, thermal efficiency and system boundaries. However, the very different methodologies used in the original studies still produced a broad variation in the final results. The interquartile range, i.e. the middle half of the results, is 12–25 g CO_2-eq/kW·h. Significantly higher results are rare outliers with a maximum value of 110 g CO_2-eq/kW·h describing the hypothetical worst case scenario. The estimates made by UN Environment [34, 35] for nine global regions show a variation between 4 CO_2-eq/kW·h and 14 g CO_2-eq/kW·h with an average

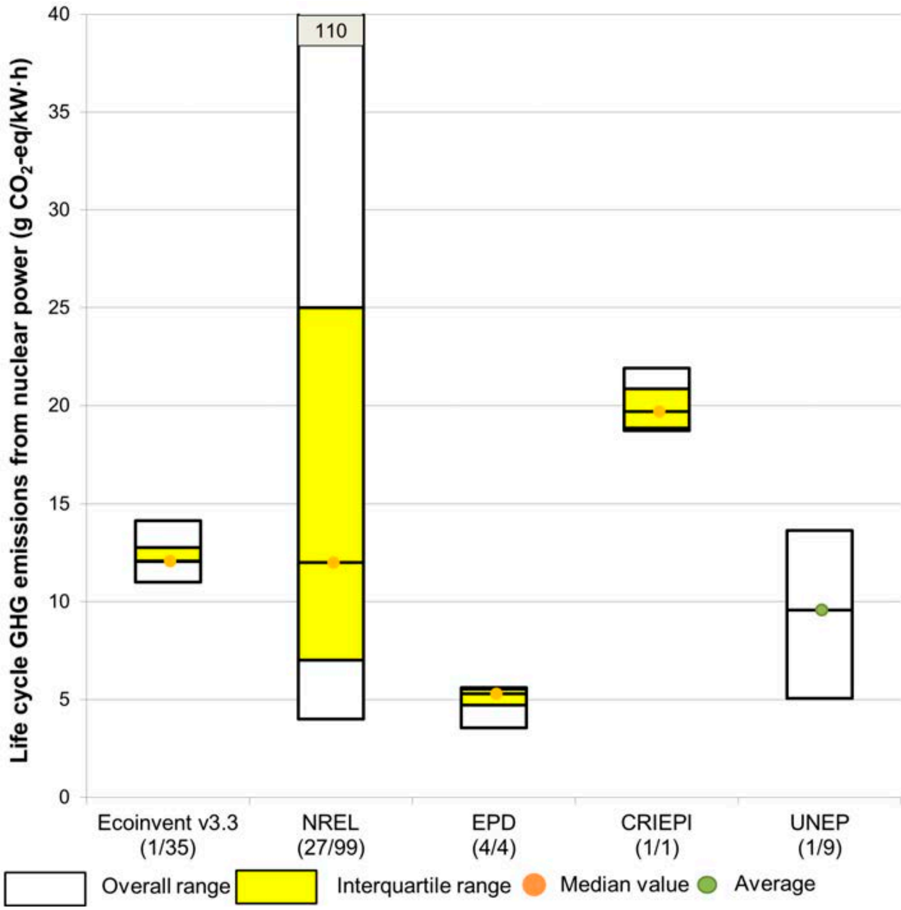

FIG. 22. Life cycle GHG emissions from nuclear electricity generation. Data source: IAEA calculations using data from Ecoinvent [31], NREL [60], CRIEPI [61], EPDs [59] and UN Environment [34, 35]. Note: The numbers in parentheses indicate the number of sources/estimates. The interquartile range includes half of the calculations around the median of the overall range. The average rather than the median of the range is shown in the case of the UN Environment study because its results show estimates for global regions and not for individual NPPs. g CO_2-eq/kW·h — gram carbon dioxide equivalent per kilowatt-hour, NREL — National Renewable Energy Laboratory, EPD — Environmental Product Declaration, CRIEPI — Central Research Institute of Electric Power Industry, UNEP — United Nations Environment Programme.

value of 9.5 g CO_2-eq/kW·h. This is lower than the estimates by Ecoinvent and CRIEPI because UN Environment was focusing on the most recent technologies and reactor designs.

The EPDs demonstrate significantly lower estimates with a very narrow range of variation: 3.5–5.5 g CO_2-eq/kW·h. This is a very interesting result because the assessments were conducted by different organizations for different NPPs. This means that a standard methodology can obtain robust estimates and also that assumptions play a major role in the final results. Life cycle studies typically assume that spent fuel is placed in interim storage and not in final disposal facilities.

Additionally, comparing assumptions used in various standardized methodologies provides insights about the major drivers of GHG emissions from nuclear energy. Specifically, CRIEPI uses the following assumptions about NPPs: 33.67% average thermal efficiency, 70% capacity factor, uranium enrichment carried out abroad with the following split of technologies: 64% by gaseous diffusion and 36% by centrifuges. Additional assumptions include 1 gigawatt (electrical) (GW(e)) installed capacity and a 40 year NPP lifetime. Assumptions and results of EPDs for four NPPs and the nuclear power industry in Japan are summarized in Table 3.

Consequently, the most important factors affecting the performance of nuclear power in terms of life cycle GHG emissions are the differences in load factor (it is on average 15 percentage points higher in EPDs than in other studies) and the length of the NPP's operation. Since NPPs do not emit GHGs during their operation (except negligible amounts from testing diesel generators), the above results are not unexpected. However, the comparison also shows a significant impact of the enrichment technologies used in the fuel cycle. The currently completed shift from gaseous diffusion towards centrifuges results in significant decreases in life cycle emissions.

Nuclear power has one of the lowest levels of GHG emissions per unit of electricity produced and it continues to improve and, similarly to other technologies, has the potential to further lower its carbon footprint. The major areas for further improvements in the short term are improved practices of operation and maintenance (O&M), reduction of outage durations, extension of the operational period up to 60 years and beyond, advancements in the development of nuclear fuel with improved materials and slightly higher enrichment and therefore higher burnup, and the use of reactor designs with longer planned periods of operation. In the longer term, significant improvement in fuel utilization could be reached with alternative nuclear technologies ('fast' reactors) as described in Section 5.2.2.

TABLE 3. ASSUMPTIONS ABOUT NUCLEAR POWER PLANT PERFORMANCE AFFECTING LIFE CYCLE GHG EMISSIONS
(data source: Ref. [59])

	Axpo AG Beznau EPD (2010)	Vattenfall Forsmark EPD (2010)	Vattenfall Ringhals EPD (2010)	Sizewell B EPD (2008)	CRIEPI (2009)
Load factor (%)	86.7	82.5	78.1	89.6	70
Thermal efficiency (%)	32.3	34.3	32.8	34.7	33.67
NPP operation (years)	50	50	50	40	40
Uranium enrichment	Mix of fuel: supplies from Russian Federation (stockpiles, enrichment facilities), and reprocessing (MOX fuel)	15.5% with gaseous diffusion and 84.5% with centrifuge	15.5% with gaseous diffusion and 84.5% with centrifuge	100% centrifuge	64% with gaseous diffusion and 36% with centrifuge
Installed capacity (MW(e))	730	3 units: 1 × 1010 1 × 1120 1 × 1190	4 units: 1 × 865 1 × 900 1 × 1070 1 × 1120	1188	1000
Life cycle GHG emissions (g CO_2-eq/kW·h)	3.54	5.1	5.6	5.5	18.7–21.9

4.4. NON-ELECTRICAL POTENTIAL

Powering energy intensive processes with nuclear energy can potentially result in a dramatic reduction in the associated GHG emissions. Many of these systems consume both electricity and process heat, which can also be provided by NPPs. The current generation of NPPs can provide heat up to (about) 300°C. In the longer term, reactor designs under development, such as the high temperature gas cooled reactor, can be used to power high temperature applications. Potential non-electric applications of nuclear power include seawater desalination, district heating, hydrogen production, oil extraction and other petrochemical applications, fuelling large tankers and container ships as well as space applications. NPPs can cogenerate electricity and process heat for a number of applications (Fig. 23).

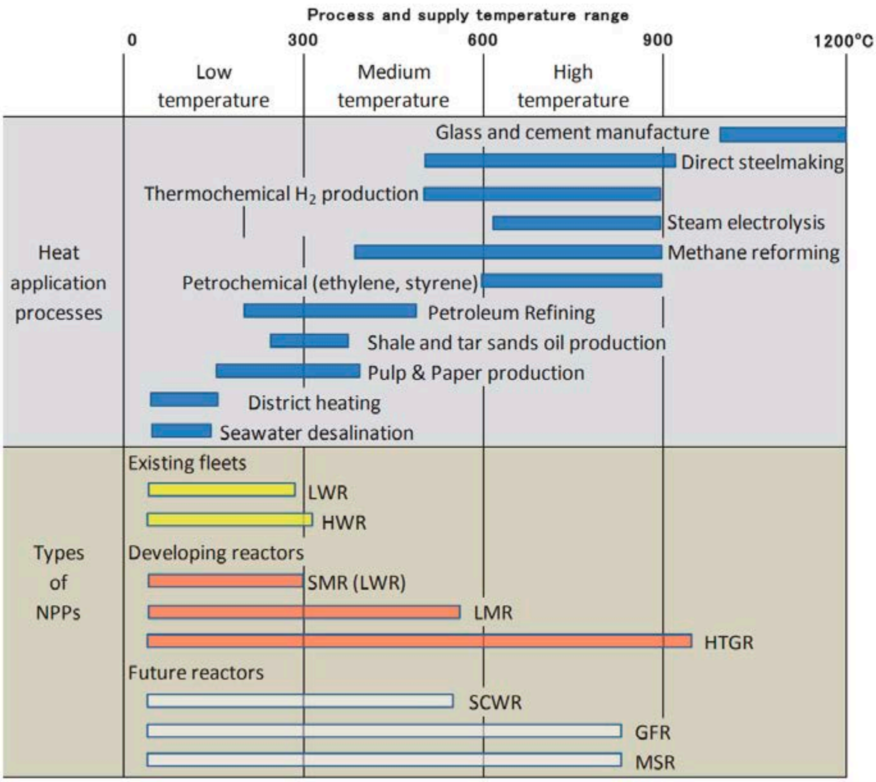

FIG. 23. Temperature ranges of heat application processes and types of NPPs. Source: Ref. [63]. Note: H_2 — hydrogen, NPP — nuclear power plant, LWR — light water reactor, HWR — heavy water reactor, SMR — small, medium sized or modular reactor, LMR — liquid metal reactor, HTGR — high temperature gas reactor, SCWR — supercritical water reactor, GFR — gas cooled fast reactor, MSR — molten salt reactor.

Since the 1950s, nuclear power has been used as an energy source for seawater desalination (in Aktau, Kazakhstan), district heating (in Beznau, Switzerland, and elsewhere), icebreakers and cargo ships (e.g. the Savannah and Otto Hahn merchant ships) as well as space exploration (NASA's Curiosity is powered by a plutonium energy source). Low fossil fuel prices, combined with increased regulation, disincentivized further development of these applications. This section focuses on seawater desalination to address the pressing need for potable water in certain regions of the world. More nuclear power process heat applications are presented in other IAEA reports [63, 64].

The idea of using nuclear energy to desalinate sea water is not new. Launched 60 years ago, the US submarine Nautilus — the world's first nuclear-powered submarine — relied on a nuclear-powered desalination system for producing drinking water on board. The nuclear powered desalination plant in Aktau, Kazakhstan, produced up to 120 000 cubic metres (m^3) per day of drinkable water from the Caspian Sea for about 30 years (1967–1997). Today, nuclear desalination is used by a number of countries, including India and Pakistan, to provide fresh water for growing populations and for irrigation. Commercial uses are also being considered in Europe, the Middle East and South America.

Throughout the world, many highly populated regions face frequent and prolonged droughts. According to the United Nations Development Programme [65], water scarcity already affects more than 40% of the world's population, an alarming figure that is projected to increase with the rise of global temperatures as a result of climate change. By 2050, it is projected that at least one in four people will be affected by recurring water shortages. Water crises were rated as one of the three greatest risks of harm to people and economies in the next decade by the World Economic Forum, alongside climate change and mass migration [66].

Desalination is the main technology used to alleviate water scarcity, with almost 100 million m^3/day of global cumulative contracted capacity in 2017 [67]. Most of this capacity (about two thirds) is based on reverse osmosis (Fig. 24 [68]). The remaining capacity entails mainly thermal desalination: multi-effect evaporation and multistage flash processes, mostly in the Middle East. In this region, desalination systems are often coupled to power generation units to form integrated water and power plants in which steam is supplied to thermal desalination processes by the power conversion system. Desalination units located at the power plant site may use existing seawater intake infrastructure and pretreatment systems, in addition to low grade heat, resulting in improved economics. Membrane based systems can potentially benefit from the availability of low grade heat. The influence of temperature and permeate recovery on energy consumption of reverse osmosis was investigated

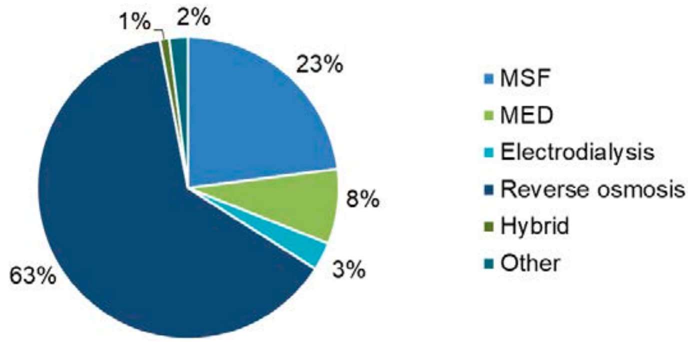

FIG. 24. Contribution of desalination technologies to the world's desalted water production in 2013. Data source: Ref. [68]. Note: MSF — multistage flash, MED — multi-effect evaporation.

by Agashichev and Lootahb in 2002 [69]. They demonstrated that a limited rise of the feedwater temperature causes the specific energy consumption of reverse osmosis to decrease, confirming conclusions reached earlier by Humphries and Sweeney [70]. An analysis of the influence of temperature on the degree of concentration polarization and transmembrane flux demonstrated the existence of an optimal temperature range — 29°C to 31°C — maximizing the specific permeability of reverse osmosis membranes. Thermal and reverse osmosis technologies can be combined to form optimized hybrid systems, which are less sensitive to the quality of sea water compared with stand-alone reverse osmosis plants. Hybrid systems can produce desalinated water for a variety of end uses, including ultrapure make-up water for a nearby power plant.

Seawater desalination is an energy intensive process. The lowest energy consumption — and the closest to the theoretical minimum set by the laws of thermodynamics (1.06 kW·h/m^3) [71] — is achieved by reverse osmosis processes equipped with energy recovery devices; the energy requirement of seawater reverse osmosis using electricity ranges between 2.7 and 7 kW·h/m^3 [68]. Thermal desalination processes consume heat in addition to electricity. Heat consumption varies between 40–65 kW·h/m^3 for multi-effect evaporation and 55–80 kW·h/m^3 for multistage flash [72]. The electricity needed for pumping in multistage flash processes varies between 2.5 and 5 kW·h/m^3 [73]. The specific electricity consumption of multi-effect evaporation technologies is below 2.5 kW·h/m^3 [68].

According to the IEA's World Energy Outlook 2016 [74], 4% of the global electricity consumption in 2014 was used to extract, distribute and treat water and wastewater, along with 50 Mt oil equivalent of thermal energy. Over the period up to 2040, the amount of energy used in the water sector is projected to more than double. By 2040, 16% of the electricity generated in the Middle East region is expected to be exclusively used for water supply.

Currently installed and operational desalination plants worldwide are mostly powered by fossil energy sources and emit around 76 Mt CO_2/year, according to the Global Clean Water Desalination Alliance [75]. If no action is taken, the Alliance expects these emissions to grow at least to around 218 Mt CO_2/year by 2040. Using NPPs as the energy source for desalination systems can significantly reduce the associated CO_2 emissions.

5. NUCLEAR POWER CHALLENGES AND DEVELOPMENT POTENTIAL

5.1. RADIATION RISKS

5.1.1. Sources, effects and risks of ionizing radiation

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 considers, by appropriate weighting factors, the impacts of different types of radiation and their effects on different parts of the body.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has been assessing and reporting the levels and effects of exposure to ionizing radiation from various sources since its establishment in 1959. The reports of the Committee provide the scientific basis for evaluating radiation risks and for establishing protective measures. The 2016 UNSCEAR report on sources, effects and risks of ionizing radiation describes the results of the most recent assessment of the levels of radiation exposure associated with different technologies of electricity generation: nuclear fuel cycle, coal cycle, combustion of natural gas, oil and biofuels, and geothermal, wind and solar power. This section presents the main conclusions of the report [76].

For members of the public, annual exposure to radiation resulting from generating electricity is small and typically much less than 1% of the corresponding average natural background exposure. The radiation exposure of workers in electricity related industries exceeds that of the public because of the mining activities that precede any form of electricity generation. Coal miners receive the largest collective dose of radiation through enhanced exposure to naturally occurring radionuclides. Such exposure has been declining over the years owing to better mining conditions.

Activities related to the coal cycle contributed more than half of the total radiation dose to the global public from electricity generation. The contribution from the nuclear fuel cycle represents less than one fifth of that of the coal cycle. These results should be seen from the perspective of the share of each technology in worldwide electricity production. In 2010, the baseline year for the assessment, 40% of the world’s energy was produced by the coal cycle compared with 13% by nuclear.

On the basis of a unit of electricity generated, radiation exposure associated with coal and nuclear power are about the same in the short term. Over longer periods, such as hundreds of years, an accumulation of very small doses from long lived radionuclides results in larger collective doses from the nuclear fuel cycle. Table 4 shows the collective dose to the global public and the related normalized collective dose. Unless otherwise specified, the collective doses indicate the local and regional components. The UNSCEAR estimates collective doses to populations on a local, regional and global scale, based on a methodology that considers the following distance bands: 0–100 km (local component of collective dose), 100–500 km, 500–1000 km and 1000–1500 km. The results for 100–1500 km are summed to constitute the regional component of collective dose. Table 4 also shows the shares of electricity generating technologies in total world electricity generation in 2010 and the discharges of ^{222}Rn (an isotope of radon, a naturally occurring radioactive noble gas) normalized to electricity generation in 2010. It is important to note that projections of any health effects using collective doses in the table are not recommended by UNSCEAR. All estimates in the table are calculated based on best estimates; site and location specific collective doses are not presented.

The highest occupational exposure related to building power plants (per unit of electricity generation capacity) is associated with solar energy plants, followed by wind energy plants. These technologies require, in fact, large quantities of rare earth metals, and the extraction of vast volumes of very low grade minerals exposes workers to radiation during the extensive mining operations. Mining, milling and processing of metal ores contribute to occupational exposure because of the presence of natural radionuclides [77, 78]. The collective dose from occupational exposures during the mining of metals is presented in an UNSCEAR report [77]. Recent data (2012) on the radiation exposure of miners of rare earth metals in China is reported in Ref. [79]. Table 5 shows the occupational collective effective doses, normalized to energy production, received during the construction of various electricity generating technologies [76]. Occupational exposures depend on the amounts of steel and metals used for construction but

TABLE 4. COLLECTIVE DOSE TO THE WORLDWIDE PUBLIC AND ASSOCIATED NORMALIZED COLLECTIVE DOSE IN 2010 INTEGRATED TO 100 YEARS
(data source: Ref. [76])

Electricity generating technology	Collective dose (man Sv[a])	Normalized collective dose (man Sv/GW·a[b])	Share in total world electricity generation (%)	Normalized ^{222}Rn discharges (TBq/GW·a[c])
NUCLEAR FUEL CYCLE				
Nuclear, total from mining and milling, power plants and reprocessing, excluding global component	130	0.43	13	Uranium mining: 66 Milling: 3 Operational mill tailings: 3 Mill tailings[d]: 10
Adding global component[e] integrated to:				
100 years	910	3.0	—	—
500 years	1700	5.5	—	—
10 000 years	7600	25	—	—
COAL CYCLE				
Coal, older coal plants	1400	1.4	40	Coal mining: 2.8 Power plants: 0.07 Ash[d]: 1.8
Coal, modern coal plants	670	0.7		

TABLE 4. COLLECTIVE DOSE TO THE WORLDWIDE PUBLIC AND ASSOCIATED NORMALIZED COLLECTIVE DOSE IN 2010 INTEGRATED TO 100 YEARS (cont.)
(data source: Ref. [76])

Electricity generating technology	Collective dose (man Sv[a])	Normalized collective dose (man Sv/GW·a[b])	Share in total world electricity generation (%)	Normalized ^{222}Rn discharges (TBq/GW·a[c])
OTHERS				
Natural gas	55	0.10	22	0.75
Oil	0.03	0.0003	4.6	0.002
Geothermal (low-density population — default population)	5–160	1–20	0.3	150

Note: Cells with dashes indicate that the collective dose was not estimated. Doses in this table are evaluated based on the UNSCEAR revised methodology for estimating public exposures due to radioactive discharges.

[a] Sv: sievert.

[b] Sv/GW·a: sievert/gigawatt-year.

[c] TBq/GW·a: terabecquerel/gigawatt-year.

[d] The values of the normalized ^{222}Rn discharges (TBq/GW·a) for uranium mine mill tailings (‘Mill tailings’) and for coal ash deposits (‘Ash’) were multiplied by 100 to account for radon emanating for 100 years from these surfaces. The value for coal ash deposits was also multiplied by a factor of 0.6 because only 60% of the ashes produced are deposited.

[e] ‘Global component’ refers to the collective dose due to globally circulating radionuclides (^{3}H, ^{14}C, ^{85}Kr and ^{129}I).

also on the plants' capacity factors and lifetimes (a higher capacity factor and longer lifetime imply a lower collective dose per unit of generated electricity).

The collective dose to the global population from the accident at the Fukushima Daiichi nuclear power plant and the Chernobyl accident (Table 6) is two orders of magnitude higher than that from one year's normal operation of an NPP with its fuel cycle facilities.

TABLE 5. COLLECTIVE EFFECTIVE DOSE NORMALIZED TO UNIT OF ELECTRICITY GENERATION FOR CONSTRUCTION OF ELECTRICITY GENERATING PLANTS OR DEVICES
(data source: Ref. [76])

Electricity generating technology	Normalized occupational collective dose due to mining and processing of ores needed for construction (man Sv/GW a[a])
Nuclear	0.02
Coal	0.01
Natural gas	0.01
Solar photovoltaic	0.8
Wind	0.1
Biomass	0.01

[a] Sv/GW·a: sievert/gigawatt-year

TABLE 6. ESTIMATES OF THE COLLECTIVE EFFECTIVE DOSES FROM THE FUKUSHIMA DAIICHI AND CHERNOBYL ACCIDENTS
(data source: Ref. [76])

Accident	Collective effective dose (thousand man Sv)		
	Over the first year	Over ten years	Up to 80 years of age[a]
Fukushima Daiichi	18	36	48
Chernobyl Reactor 4	—	—	400

Note: — indicates that the collective dose was not estimated.

[a] Summing the dose to all exposed individuals integrated from their age at the time of the accident until they reach 80 years of age.

The Committee also assessed the biological effects of radiation from two internal emitters: tritium and uranium. Internal emitters are radionuclides that have been deposited in body organs and tissues via either inhalation or food. Once in the body, they continue to deliver doses of radiation internally. Doses to organs from these emitters are generally estimated by models that use either environmental or human measurements. The UNSCEAR 2016 report [76] concluded that there is no clear demonstration of a causal association between cancer risks and radiological exposure to these internal emitters.

In conclusion, radiation exposure to the public from the normal operation of NPPs and nuclear fuel cycle infrastructure is negligible compared with naturally occurring background radiation, especially radon emanating from soil and buildings. Radiation exposures due to human activities — mining and processing of ores and wastes, nuclear power generation, production and use of radioisotopes, etc. — are subject to strict regulation and control aimed at keeping radiation exposures within the prescribed limits for workers and members of the public.

5.1.2. Radiological lessons learned from the Fukushima Daiichi accident

Since the Fukushima Daiichi accident, one of the foremost concerns for the people of Japan has been the possible health consequences that might arise from the release of radioactive material from the damaged reactors. This concern has been especially important for those in the regions surrounding the Fukushima Daiichi NPP who have been directly affected by evacuation, and for workers at the plant who were present at the time of the accident and who have been participating in emergency and remedial actions.

In 2015, the IAEA published a report by its Director General and five Technical Volumes on the accident at the Fukushima Daiichi nuclear power plant [80]. This publication provides a description of the accident, its causes, the evolution of events and the consequences, based on the evaluation of data and information from a large number of sources. The fourth technical volume, entitled 'Radiological Consequences', presents a review of post-accident studies — including earlier international assessments by the World Health Organization [81] and UNSCEAR [82] — focused in particular on possible radiation induced health effects and psychological consequences to individuals resulting from the accident. Technical Volume 4 ([83], pp 167–168) reports the following observations and lessons learned:

"— **The risks of radiation exposure and the attribution of health effects to radiation need to be clearly presented to stakeholders, making it unambiguous that any increases in the occurrence of health effects**

in populations are not attributable to exposure to radiation, if levels of exposure are similar to the global average background levels of radiation. In the case of the Fukushima Daiichi accident, doses to members of the public were low and comparable with typical global average background doses. There is a need to clearly inform the public, particularly the people affected, that no discernible increased incidence of radiation related health effects is expected among exposed members of the public and their descendants as a result of the accident. An understanding of radiation and its possible health effects is important for all those involved in an emergency, in particular for physicians, nurses, radiation technologists and medical first responders. This needs to be ensured through appropriate education and training of medical professionals in the topics of radioactivity, radiation and health effects associated with radiation exposure.

— **After a nuclear accident, health surveys are very important and useful, but should not be interpreted as epidemiological studies. The results of such health surveys are intended to provide information to support medical assistance to the affected population.** The Fukushima Health Management Survey provides valuable health information for the local community, helping to ensure that any health effects are detected quickly, and that appropriate actions are taken to protect the health of the population. The overall results of health checks may provide important information, but they should not be misinterpreted as the results of an epidemiological assessment.

— **There is a need for radiological protection guidance to address the psychological consequences to members of the affected populations in the aftermath of radiological accidents. A Task Group of the ICRP has recommended that "strategies for mitigating the serious psychological consequences arising from radiological accidents be sought… [[84]]".** Psychological conditions have been reported as a consequence of the accident. This has been a repeated issue in the aftermath of accidents involving radiation exposure. In spite of its importance, these consequences have not been recognized in international recommendations and standards on radiological protection.

— **Factual information on radiation effects needs to be communicated in an understandable and timely manner to individuals in affected areas in order to enhance their understanding of protection strategies, alleviate their concerns and support their own protection initiatives.** Arrangements at the national and local level need to be put in place to share information in an understandable manner with the public who may be affected by accidents with radiological consequences. The arrangements need to allow for person to person dialogue, so that individuals can seek clarifications and express their concerns. These arrangements will require the concerted efforts of the relevant authorities, experts and professionals in supporting and advising the affected individuals and communities. Sharing information is important when conveying decisions to protect these individuals, including the support of their own initiatives."

A recent study by the Fukushima Medical University School of Medicine [85] confirmed that, considering the severity of the accident, the direct health effects of radiation were relatively well controlled not only among emergency workers but also among residents. The study also highlighted serious health issues unrelated to radiation such as deaths during evacuation, collapse of the radiation emergency medical system, increased mortality among displaced elderly people and public healthcare issues among Fukushima residents.

5.2. SPENT NUCLEAR FUEL AND RADIOACTIVE WASTE

5.2.1. Spent fuel and radioactive waste management

The production of energy by NPPs generates spent nuclear fuel and radioactive waste. Spent nuclear fuel can either be considered a resource and is therefore reprocessed to extract usable fissile material (uranium and plutonium) and recycled as new fuel (reprocessing activities generate high level waste), or considered waste to be disposed of after some decades of storage.

Storing spent nuclear fuel consists of holding it in a facility that provides for its containment, with the intention of retrieval. Although storing spent fuel is de facto an interim measure, the term 'interim storage' is widely used to refer to an intermediate step before spent fuel is either reprocessed or disposed of. Countries such as China, France, India, Japan, the Russian Federation and the United Kingdom reprocess and recycle their spent nuclear fuel, which results in vitrified high level waste (HLW) to be disposed of. Other countries, such as Canada, Finland, Germany, Sweden and the USA, consider their spent nuclear fuel waste to be disposed of. Hence, irrespective of the strategic option selected, a geological disposal facility will eventually be required for the disposal of spent nuclear fuel and/or HLW arising from reprocessing.

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, in an engineered pool at the reactor site. The capacity of such pools differs between reactors. If additional storage capacity is needed, 'away from reactor' facilities are built based on either wet or dry technologies (vaults or casks) [86]. Both are mature technologies and a range of storage facilities have been safely deployed and are in use worldwide. Operational experience on the safe storage of spent nuclear fuel has been gathered for more than 50 years under wet conditions and for more than 30 years under dry conditions. There are currently 151 away from reactor storage facilities of which about 80% are under dry conditions. The majority of these have been deployed over the last 25 years [87].

Dry storage is also used for the HLW generated by reprocessing plants. This liquid HLW is vitrified in a glass matrix. 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 fuel and HLW issued from reprocessing, there are two other categories of radioactive waste that are worthy of note: low level waste (LLW) and intermediate level waste (ILW) [88]. LLW and ILW make up 97–98% of the total waste volume produced by an NPP, but they constitute only 8% of the 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 must be isolated from the environment for up to a few hundred years, until they decay to reach background (natural) levels. LLW is typically stored on-site until its radioactivity has decayed to a level that enables it to be disposed of, often in engineered near surface facilities. ILW does not generate significant heat either, but requires a greater degree of containment and isolation than LLW, owing to its higher radioactivity. ILW requires shielding during storage and transport, and is typically disposed of in underground mined vaults or chambers with specifically designed engineered barriers to contain and isolate the waste.

Disposal facilities for LLW and ILW are already in operation or under construction around the world. These include near surface engineered facilities for LLW in China, the Czech Republic, France, India, the Islamic Republic of Iran, Japan, Poland, Slovakia, Spain, the UK and the USA, among others. Construction of a new LLW near surface repository in Bulgaria began in August 2017. In addition, engineered facilities for LLW and ILW sited in geological formations (at varying depths) are in operation in Finland, Germany, Hungary, the Republic of Korea, Sweden and the USA.

Further disposal facilities for LLW and ILW are at different licensing stages in Belgium, Canada, Lithuania, Romania and Slovenia. The Konrad Repository for LLW and ILW in Germany is under construction and scheduled to begin accepting waste in 2027. Figure 25 shows a waste transportation tunnel under construction at the Konrad Repository.

Based on the outcome of a collaborative project undertaken by the IAEA, the OECD Nuclear Energy Agency (NEA) and the European Commission, the IAEA recently provided a global overview of the status of radioactive waste and spent fuel management concerning inventories, programmes, current practices, technologies and trends. It includes an analysis of national arrangements and programmes for radioactive waste and spent fuel management, an overview of current waste and spent fuel inventories and estimates of future amounts. International and national trends in these areas are also addressed [89].

For the final disposal of spent fuel and HLW, the most common strategy is to plan to use deep geological formations. Progress towards opening spent fuel and HLW disposal facilities is supported by extensive engineering studies and rigorous review by independent regulators. Finland and Sweden have made the greatest advances in this field. In November 2015, the authorities in Finland granted Posiva, an organization with expertise in nuclear waste management, a construction licence for Finland's spent fuel and HLW disposal facility in Olkiluoto [90]. In March 2011, the Swedish Nuclear Fuel and Waste Management Company (SKB) applied for a construction licence for Sweden's

FIG. 25. Waste transportation tunnel under construction at the Konrad Repository in Salzgitter, Germany. Reproduced courtesy of the Bundesgesellschaft für Endlagerung mbH.

disposal facility at Forsmark [91]. In January 2018, the Swedish Radiation Safety Authority issued an affirmative recommendation for the construction of the repository. The Swedish Environmental Court identified that additional information is needed prior to construction authorization. Both the Finnish and Swedish facilities are intended to start operation in the 2020s.

Figure 26 shows Sweden's disposal plans (Finland's are similar). After 30–40 years of storage in cooling ponds, spent fuel will be encapsulated in cast iron containers that are in turn contained within a corrosion resistant copper encasement. These will be placed surrounded by bentonite clay in specially designed disposal holes installed from tunnels at a depth of 500 m within 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. Once all the waste has been disposed of, the access tunnels 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 during their operating lifetimes.

Some countries' long term plans for managing highly radioactive waste keep the possibility open to retrieve spent fuel to allow its future recycling rather than committing it to permanent disposal. Other possible future developments may reduce the volume and longevity of highly radioactive waste. Research is under way on partitioning and transmutation, which are techniques to convert long lived radioactive elements to shorter half-life species. There is also the

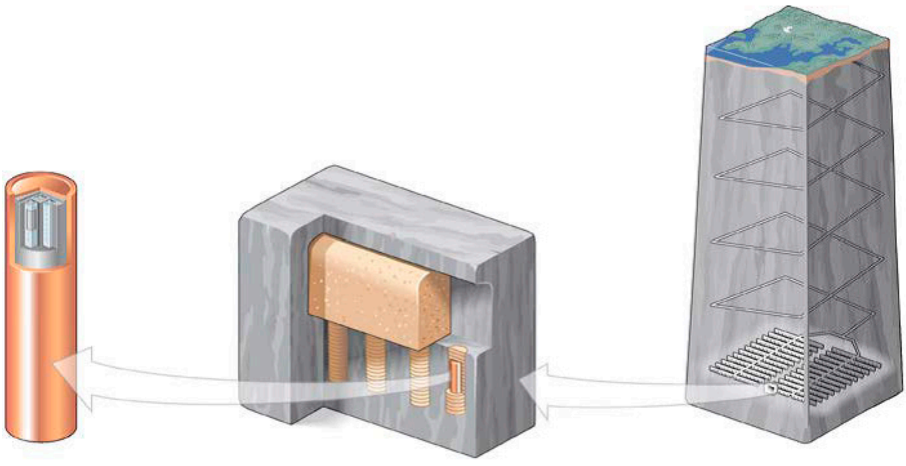

FIG. 26. Three barriers to prevent radionuclides in spent fuel from reaching the ground surface in the planned final repository in Sweden. Source: Ref. [92]. Reproduced courtesy of the Swedish Nuclear Fuel and Waste Management Company (SKB).

possibility of fully closed nuclear fuel cycles in the future, using fast reactors to continuously recycle and burn all actinides. This would reduce by a factor of about 200 the amount of transuranic elements to eventually be disposed of (plutonium, americium, curium and neptunium) and which constitute the bulk of long lived radiotoxicity [16].

In contrast to nuclear energy, fossil fuel technologies still release various gaseous wastes, especially CO_2, into the atmosphere. Efforts to move away from this strategy to reduce their impacts on the climate include CCS. It relies on technologies to capture CO_2 before, during or after burning coal or gas and to store it in underground geological formations. This would significantly reduce GHG emissions from burning fossil fuels (though not to the level of truly low carbon technologies). The most common criticism of CCS is obviously the issue of possible leakages from disposal sites that could result in releasing CO_2 into the atmosphere.

Additionally, despite the initial enthusiasm regarding the possible contribution of CCS to climate change mitigation efforts, the technology has been showing rather mixed results at industrial scales up to now. CCS projects currently under way are facing significant delays and cost overruns. Specifically, the Kemper power plant in the USA was expected to become the flagship gas fired power plant using CCS technology. The start of its operations was originally scheduled for 2014. However, after significant construction delays and cost overruns made it the most expensive power plant in history (per unit of generating capacity), the idea of using CCS was completely abandoned in June 2017 [39]. Currently, the Kemper power plant is expected to operate as a regular gas fired power plant. It is, therefore, not surprising that projections increasingly postpone the expansion of the CCS technology into the more distant future. In the latest edition of the IEA World Energy Outlook [39], even the most climate friendly SDS projects that the share of fossil fuel plants equipped with CCS will account for only 3% of world primary energy demand in 2030. The World Energy Outlook 2017 [39] estimates the contribution of CCS to CO_2 emissions abatement in 2035 — measured as the difference between emissions in the SDS and the NPS — to be less than 11%, while in the World Energy Outlook 2012 [93], this estimate was 17%.

5.2.2. Development of reactors reducing radioactive waste

The traditional approach to handling radioactive waste produced by the nuclear industry (discussed in Section 5.2.1) is the result of the historical development of mainstream reactor technologies. Reactor designs currently in operation produce some amount of spent nuclear fuel that should be safely reprocessed and stored. The challenge is to do this in the most efficient way. The question is, however, whether this solution is the only possible one, and how to change the status quo in a way that the waste burden as a trade-off for the benefits of nuclear energy (contribution to GHG mitigation, energy security) would be minimized.

With the reactor types currently in operation, the amount of radioactive waste is unlikely to change in any significant way. However, similarly to how life cycle emissions of nuclear energy can be decreased by technological advancements (less energy and carbon intensive enrichment technologies, longer operating lifetimes), the amount of radioactive waste could also be reduced by introducing new reactor designs.

One option is the fast breeder reactor. The term 'fast' in this case means that in reactors of this type, fast neutrons are used for sustaining the fission reaction. This is the major difference from conventional LWRs, where thermal (slowed down) neutrons are used. Fast breeder reactors employ a technology that allows the production of more fissile material than they use, i.e. the ratio of final fissile content to the initial content is over 1. The technical explanation for this outcome is that nuclear fuel consists of different types of isotopes, and only a minor share of them fission readily. In fast breeders, certain isotopes of uranium that do not fission at low neutron energy can either fission or are transformed into plutonium isotopes that fission and can be used as nuclear fuel. This way, multiple use of the fuel should theoretically allow the transformation of all non-fissionable isotopes of uranium into fissile plutonium. This could potentially allow the extraction of nearly the full energy content of the nuclear fuel, in contrast to contemporary LWRs that utilize only a few per cent of the potential energy in the fuel that then becomes spent fuel and has to be managed as radioactive waste. Less need for fuel would clearly decrease GHG emissions from the mining and enrichment stage of the nuclear energy life cycle.

An additional potential benefit of fast neutron systems in terms of waste reduction is the possibility to destroy (burn) transuranic elements contained in spent fuel. These elements are heavier than uranium and they are produced by nuclear reactions when fuel is used in contemporary reactors. They are a special issue in spent nuclear fuel management because these isotopes have very long half-lives and therefore remain a health hazard for a long time. Therefore, if they were removed from spent fuel and effectively destroyed, a major share of long term radioactivity associated with nuclear waste would be eliminated. In this case, the radioactivity of the remaining spent nuclear fuel would already fall to the level of the uranium ore it originates from after 300 years.

Since the previous review of fast reactor technology presented in Climate Change and Nuclear Power 2014 [94], the major progress achieved has been the commissioning of the Prototype Fast Breeder Reactor in India and the operation of the BN-800 reactor at the Beloyarsk NPP in the Russian Federation (see Fig. 27). (BN stands for ‘fast, sodium cooled’ in Russian.) This is a more advanced version of the earlier BN-600 design, in operation since 1980. The BN-800 reactor was connected to the grid in December 2015 and its industrial utilization started in November 2016. However, it is still a prototypical design seen as a step towards the industrial scale innovative BN-1200 design. Another example of progress in fast breeder technology is the above mentioned Prototype Fast Breeder Reactor currently under commissioning in India. Its planned capacity is about 500 MW(e) and it builds on the experience from the 40 MW(e) Fast Breeder Test Reactor, in operation since 1985. Additionally, in China, an experimental 20 MW(e) fast reactor has been operating since 2010. Much earlier, from the 1950s until the 1990s, fast reactors have been operating in Europe and the USA. The driver for their development in that era was the expectation of the possible shortage of available uranium fuel for the industry. However, as a result of subsequent discoveries of uranium resources around the globe and nuclear capacities growing at a much slower rate than previously estimated, an adequate supply of uranium ore and reliable fuel supply to the market weakened the incentives for further development of fast breeder reactor technology.

Challenges for further progress in this area are associated with the economics of the prospective fast reactor designs, production of special types

FIG. 27. Fast reactor BN-800 at the Beloyarsk nuclear power plant, Russian Federation. Reproduced courtesy of Rosenergoatom.

of fuel for fast neutron reactors (e.g. mixed fuel that contains mixtures of uranium and plutonium fissile material) and reprocessing spent fuel for further use in breeder reactors. Industrial implementation of the advanced reprocessing technologies is necessary for establishing a closed nuclear fuel cycle that would allow the extraction of nearly all energy from the fuel.

Another prospective option to reduce the amount of radioactive waste is the molten salt reactor (MSR). This type of reactor can operate in either the fast or the thermal neutron spectrum and their major difference from the current light water designs is that they will use liquid fuel instead of the usual solid fuel (see Section 5.3.3). The fissile fuel in MSRs can be dissolved in a mixture of molten salts (liquid fuel MSR design) that will be a significant shift from the approach used in modern designs because fuel rods will not be needed. Initially, however, solid fuel options (ceramic fuel in the form of pebbles, prisms or plates) are also likely to be used.

MSRs could make a significant contribution to resolving the issue of radioactive waste. Many variations in fission product and actinide management can be implemented, depending on the design. Specifically, fission products in liquid fuel MSRs could be constantly removed (especially in thermal spectrum designs) and this would allow significantly higher burnup rates of the fuel. Also, the transuranic elements (actinides) can be fully utilized because they can remain in the reactor until they either fission themselves or are converted into other elements that would fission. In practical terms, MSRs could burn actinides and significantly reduce the long term radioactivity of nuclear waste as in the case of traditional fast reactors. If long lived transuranic elements were removed from spent nuclear fuel, radioactive waste would need to be isolated for only hundreds of years, rather than tens of thousands of years, as in the case of fuel used in current reactors. This will clearly have significant implications for the approaches to radioactive waste management discussed in Section 5.2.1 concerning the long term safety of permanent disposal and the intermediate storage and reprocessing of spent nuclear fuel.

Currently, the most vigorous progress on MSRs is being made in China where two projects are being implemented simultaneously: a solid fuel and a liquid fuel design. An MSR is also under development at Terrestrial Energy of Canada: the Integral Molten Salt Reactor (IMSR400), a 185 MW(e) design. The company intends to initiate its first design review with the Canadian Nuclear Safety Commission in 2019. As MSRs mostly have a significantly smaller capacity and need a significantly smaller amount of water per unit of energy produced, the idea is to locate them in regions with limited water resources. Existing experience in the field of MSRs is based on the Molten-Salt Reactor Experiment undertaken in the USA in the 1960s, which demonstrated at an experimental scale the general viability of the technological concept. Currently, the MSR concept is seen as one of the options for advanced reactor designs, and research is being pursued in many countries, including efforts by startup companies, specifically, in Canada, Japan, the Russian Federation, the UK, the USA and the European Union.

Yet another amendment in the fuel cycle and, correspondingly, in radioactive waste management could be made by introducing thorium as a nuclear fuel. Reactors of modern designs use uranium as a fuel but it is not the only possible fuel source. Thorium is not a fissile material itself but after absorption of neutrons it transmutes into a fissile isotope of uranium [95].

Given the characteristics of thorium, it is expected to be a good fuel option for MSRs. Current progress in this area is associated with the research efforts undertaken in China where a programme of thorium breeding MSRs was launched in 2011. Thorium is also included in India's strategy for nuclear industry development owing to its abundance in the country.

The thorium fuel cycle is expected to produce smaller amounts of radioactive waste that would also contain fewer transuranic elements (actinides). Similarly to fast reactors and MSRs, reactors operating on thorium would, therefore, contribute to solving the problem of long lived waste. The major challenge for introducing thorium in the fuel cycle is the absence of the fuel supply chain and, therefore, the associated economic uncertainty. Additionally, though thorium is significantly more abundant in nature than uranium [96], the industry does not face challenges in uranium supply and this limits the incentives for developing an industrial supply chain in this area.

The technologies discussed in this section could contribute to a significantly more efficient use of nuclear fuel, and therefore a reduction of the amount of radioactive waste produced per unit of energy.

5.3. OFF-SITE EFFECTS

5.3.1. Safety lessons from the Fukushima Daiichi accident and other accidents

Most industrial activities have operational impacts on the environment by releasing substances, noise or bad smells. These impacts partly affect the premises (sites) of the company and partly cross the fence of the site and become off-site impacts.

At some level of probability, most industries may cause large off-site effects in case of accidents. There is a non-zero likelihood that some of them, such as chemical plants and nuclear facilities, may set off disastrous accidents with significant off-site effects. Notorious cases on the chemical side include the

Bhopal toxic gas disaster in India in 1984 and the Jilin chemical plant explosions in China in 2005. The death toll of the Bhopal disaster [97] was at least 4000 and about 500 000 people were exposed to toxic gases. The Jilin explosions killed six people, injured dozens and caused the evacuation of tens of thousands of residents.

Nuclear accidents include the Three Mile Island accident in the USA in 1979, the Chernobyl accident in the former Soviet Union in 1986 and the Fukushima Daiichi accident in Japan in 2011. In all three accidents, the nuclear reactors were destroyed. In the Three Mile Island accident, the reactor core melted because decay heat removal ceased after internal mechanical causes led to cooling system failures. Decay heat is generated constantly by the radioactive decay process of fission products in the reactor core. Its generation proceeds also when the fission chain reaction has been stopped. Directly after shutting down the fission process, the decay power is still 6% of the nominal reactor thermal power capacity, diminishing to 1.5% after one hour, 0.4% after a day and 0.2% after a week. Although the off-site release of radioactive material was minimal, it caused a great panic and 140 000 people voluntarily evacuated a 32 km radius around the plant within days [98]. Lessons learned by the nuclear industry include control room design and severe accident management [99].

The accident at Reactor Number 4 of the Chernobyl NPP also involved meltdowns, and molten fuel was later found several floors below the reactor. A lot of technical efforts were spent to prevent the potential penetration of corium to groundwaters. But the main issue was that the reactor exploded because the reactor design could not prevent the nuclear fission reaction running out of control. The Chernobyl reactor type was a special one, constructed only in the then Soviet Union, hence the technical lessons for plant designers were limited although the importance of safety features by design was highlighted. One of the main lessons was that operators should strictly follow safety standards and regulations. Operators at Chernobyl made a series of very serious violations and mistakes. However, the accident encouraged national authorities to harmonize their rules and standards on emergency preparedness. The World Association of Nuclear Operators 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 promote a safety culture in NPPs around the world.

At the Fukushima Daiichi NPP, there was evidence of partial nuclear meltdowns (or partial core melt) in Units 1, 2 and 3 due to the lack of afterheat removal when the Great East Japan Earthquake and Tsunami struck Japan in March 2011. Cooling systems ceased functioning owing to the lack of electricity supply as electrical grid connections were disrupted and emergency diesel generators, located in the building basement, were inundated by the tsunami. The two principal lessons learned from the accident were that (i) 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 (ii) Japan failed to adequately plan for two sets of 'common cause failures', i.e. the loss of electric power and tsunami flooding, both of which disabled multiple safety systems at one blow [80]. After the accident, a worldwide IAEA Action Plan on Nuclear Safety (the 'Action Plan') [100] was adopted in September 2011 and is being implemented by the IAEA. An important outcome is the Report by the Director General and five Technical Volumes on the Fukushima Daiichi accident [80]. Status updates are still being published on the IAEA web site, including reports by the Japanese Government to the IAEA on topics such as discharge records, seawater monitoring results and progress related to recovery operations, about once every month. In addition, many other actions have taken place at the national, regional and international level, resulting in hardware related refurbishments, including [101]:

— Making electrical systems more robust;
— Making the ultimate heat sink for decay heat more robust;
— Protecting reactor containment systems;
— Protecting spent fuel in storage pools;
— Reinforcing capabilities for rapidly providing diverse equipment and assistance from on-site or off-site emergency preparedness facilities.

It was possible to carry out these refurbishments with existing technology and they did not require the development of new components. However, the fundamental issue of afterheat removal failure and subsequent fuel overheating can also be addressed by innovative fuel and reactor designs. Sections 5.3.2 and 5.3.3 briefly describe these avenues of progress in nuclear technology.

5.3.2. Accident tolerant fuel

The second consequence of the lack of cooling in the Fukushima Daiichi reactors was visible explosions, suspected to be caused by hydrogen gas, in Units 1 and 3. A suspected explosion in Unit 2 may have damaged the primary containment. Hydrogen was formed because the fuel cladding material reacted with the cooling water (in this case with steam), forming hydrogen gas. At low temperature, this reaction (cladding oxidation) is relatively slow. At high temperature, however, the reaction becomes highly exothermic, resulting in temperature escalation and the acceleration of oxidation kinetics. At a normal operating temperature (approximately 300°C), the reaction does not occur but above 1200°C it does. Hydrogen was also formed during the Three Mile Island accident and a small explosion occurred but the containment building remained intact.

In order to address this vulnerability to severe accidents involving the loss of coolant and steam interaction with cladding, there is renewed interest in alternative fuel designs that would be more resistant to cladding oxidation, resulting in temperature escalation and hydrogen production. Such innovative fuel designs will need to be compatible with existing fuel and reactor systems if they are to be utilized in the current reactor fleet and in current new build designs [102].

Innovative fuels with enhanced accident tolerance would endure the loss of active cooling in the reactor core for a considerably longer time period than the fuels currently used while maintaining fuel performance during both normal operation and accidents. For LWRs, they incorporate a change in fuel cladding material (various zirconium alloys (zircaloys)) and sometimes also in the fuel itself (uranium dioxide). For the cladding material, two main classes of material can be identified, metallic and ceramic. As the current LWR cladding material is also metallic (zircalloy), novel metallic materials can probably be developed in a shorter time period. Examples include chromium coatings on traditional cladding, iron-chromium-aluminium and chromium-molybdenum claddings. Figure 28 presents one possible design for illustrative purposes. The ceramic claddings would be mainly based on silicon carbide because of a number of advantages,

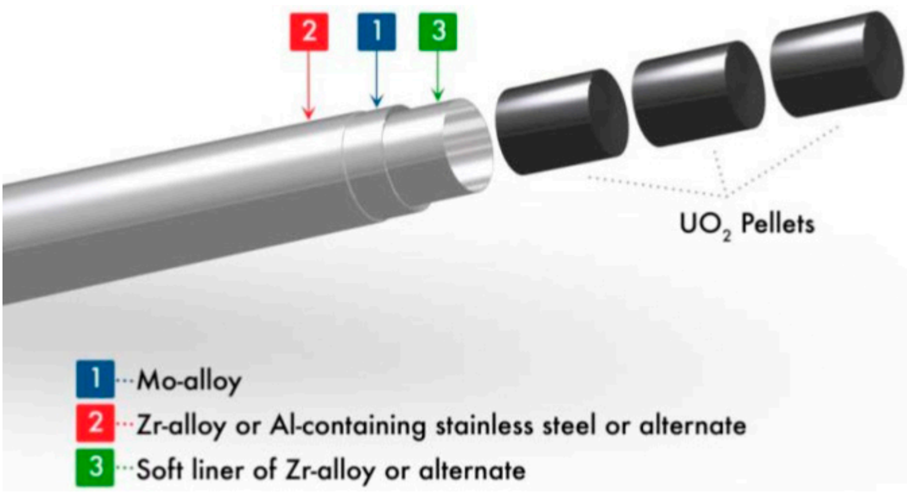

FIG. 28. Diagram of coated molybdenum cladding for enhancing accident tolerance. Source: Ref. [102]. Note: UO_2 — uranium dioxide, Mo — molybdenum, Zr — zirconium, Al — aluminium.

including greater resistance to oxidation even at higher temperatures [102], but it would take longer until they can be deployed in NPPs. The development process includes thermomechanical and chemical interaction testing, irradiation testing and computational modelling. After lead test rod trials start in 2019 and trials of lead test assemblies for the new fuels (of the short term designs) in commercial reactors follow a few years later, commercial deployment may be possible after the mid-2020s [103].

5.3.3. Development of reactors with passive and inherent safety characteristics

After the Three Mile Island accident, research started independently in Germany and in the USA on reactor designs that would not require permanent afterheat removal. This means that the fuel would stay intact even if the coolant was partially or fully lost.

In the early days of nuclear power development, alternative reactor designs with different materials were developed for applications other than electricity generation. One design was the high temperature reactor technology developed to operate at higher temperatures for heat applications and to achieve greater efficiency. In these reactors, the inert noble gas helium is used as a coolant instead of water. In addition, high temperature resistant ceramic fuel elements containing the fissionable material in small coated particles build the reactor core instead of metal alloy clad fuel rods (Fig. 29).

On this basis, the modular high temperature reactor was conceived on inherent safety principles, including a combination of low power density, high temperature resistant ceramic fuel materials and a long slender reactor core

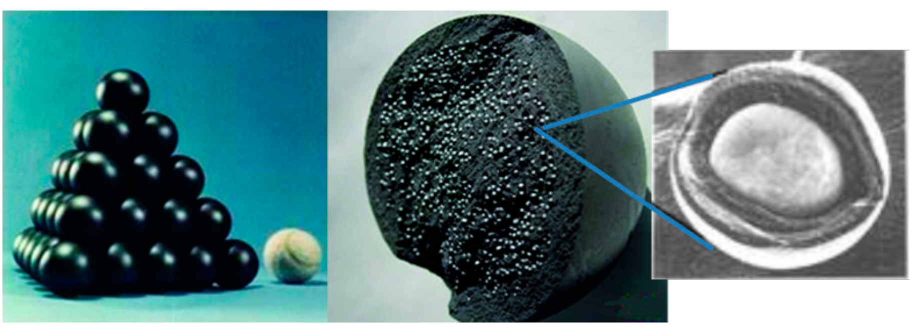

FIG. 29. Coated particle fuel in spherical fuel element form in the German design. On the right, an opened coated particle can be seen: a uranium kernel of 0.5 mm in diameter coated with carbon and ceramic layers. One pebble contains about 10 000 such particles.

geometry enabling passive heat removal from the core. The decay heat is passively removed from the core under any designed accident conditions by natural mechanisms such as heat conduction or heat radiation, and thus the maximum fuel temperature is kept below 1620°C. High quality ceramic coated particle fuel has been tested and shown to retain the vast majority of fission products at very high temperatures, even if the fuel is kept at these high temperatures for a long time. Only a very small volume of fuel will approach this temperature limit and failed coated particles cannot lead to additional failures or a reduction of heat removal. This eliminates the possibility of core melt and large releases of radioactivity into the environment.

Another feature of the modular high temperature reactor design is the long time period of accident progression owing to the substantial heat capacity of the fuel elements and the graphite internal structures. It requires days for the fuel elements to reach the temperature limit at which the coolant is completely lost. The reactor uses helium as coolant, an inert gas that has no phase changes, no heat transfer limits and insignificant neutronic interactions. The reactor has been designed in such a way that in case of a coolant loss, it will shift to a safe shutdown state by itself, forced by the laws of physics only. This has been demonstrated in test reactors in China and Germany.

Compared with current reactor technologies, the unit power level is small: about 100 MW(e) per reactor. Commercial reactors of any size can then be built by using more reactor modules. Different fuel geometries have been developed for modular high temperature reactors, including tennis ball like spheres (Fig. 29), also called pebbles. In a pebble bed reactor, on-line refuelling takes place continuously, ensuring that no more fuel is in the reactor than the amount immediately needed. A commercial demonstration plant is currently under construction in China. It is a high temperature reactor pebble bed module (HTR-PM), due for completion in 2018.

Another approach to preventing core melt is the concept of liquid reactor fuel that is already in a molten form by design, e.g. a molten fluoride salt containing the fissionable material. This is a highly stable and inert liquid with high intrinsic radionuclide retention and an extremely high boiling point. Favourable coolant properties allow operation at very low pressure, reducing the risk of leaks and failures. Operating at low pressure and without water or steam in the reactor, both physically and chemically stored energy is eliminated from the reactor system, thus removing the main potential drivers for radioactivity release from such a plant. The concept is based on experimental reactors designed by a laboratory in the USA in the early days of nuclear power (see also Section 5.2.2).

Liquid fuels further reduce the costs of fuel manufacturing and impose no limit on the potential burnup (as is the case with solid fuels). Small amounts of fuel salt are simply added when required and fuel utilization can be increased by up to 80%, compared with about 4% in current reactors. Resources are not only used more effectively but the volume of high level radioactive waste is also reduced. Nuclear fission products are chemically removed from the fuel salt, separated to remove waste from the long lived products that can be recycled, then purified before final disposal.

The design approach of both the modular and the liquid fuel reactors is to ensure safety without the need for any operator action, availability of electricity or dependence on externally powered systems, valves or pumps. Any nuclear reactor design should comply with three fundamental safety requirements: control of reactivity (nuclear fission chain reaction), afterheat removal and containment of radioactive material. These safety functions are assured by the inherent characteristics of both reactor designs:

— Excess reactivity in both core designs is limited because fuel is added during operation instead of refuelling only once a year or even less frequently. Reactivity insertion events only lead to a stable reactor condition at a slightly higher temperature.
— Heat removal is achieved through inherent heat sinks to absorb transient and decay heat in the short term and by heat losses for long term cooling.
— The containment of radioactive materials relies on heat resistant ceramic coated particles in high temperature reactors and on fluoride salts that bind radioactive fission products in MSRs.

Both reactor systems described above work at significantly higher fluid temperatures (600–750ºC) than current water cooled reactors (320ºC). This leads to more efficient electricity generation (more efficient conversion of heat into electricity) (up by 20 percentage points) that conserves resources, reduces wastes and fosters potential access to heat and cogeneration markets. Detailed information on these advanced reactor designs are presented in an IAEA publication on Advances in Small Modular Reactor Technology Developments [104].

5.4. COSTS AND ECONOMICS

5.4.1. Energy source cost comparison, system costs and the value of dispatchability

Nuclear power projects and programmes are characterized by large capital investments, vast complexity and long lasting macroeconomic and environmental impacts. Capital costs are, in fact, the biggest contributor to the lifetime unit cost of nuclear electricity, which is not the case for fossil fuel plants. Estimating the costs attached to such ‘megaprojects’ is a crucial step for technology and policy assessments, and a key input to many important studies such as feasibility, investability and bankability studies of nuclear projects and programmes as well as macroeconomic and environmental impact assessments. A good understanding of power generation costs is also important for developing optimized energy mixes and designing efficient energy policies. This section discusses nuclear power costs and how they compare with those of other energy sources. The focus is on both plant level (busbar) and grid level (system) costs.

Building an NPP requires thousands of workers, vast amounts of steel and concrete, and a variety of components, equipment and systems that need to be manufactured, tested, inspected and assembled. The construction time of an NPP is usually defined as the duration between pouring the first concrete and connecting the plant to the grid. Seven years is a typical duration for NPP construction [105] but shorter construction times are also achievable; the two advanced boiling water reactor units at the Kashiwazaki-Kariwa NPP in Japan took only four years to build. The IAEA Power Reactor Information System [106] has more detailed information about construction durations.

Capital expenditures generally include the costs of site preparation, construction and commissioning of the NPP. Figure 30 illustrates a typical NPP capital expenditure breakdown structure [107]. Operating expenditures encompass the costs of fuel, O&M and a provision for funding the costs of decommissioning the plant and treating and disposing of used fuel and wastes. In estimating power generating costs, it is important to consider how capital and operating expenditures are distributed over the economic lifetime of the project from the pre-development phase through construction and operation to retirement, decontamination, dismantling and the disposal of radioactive waste. Each phase has its specific time horizon and cash flow profile.

Power generation costs are usually expressed in monetary units per unit of electricity (e.g. US \$/MW·h) to allow a consistent comparison of different energy technologies. All expenditures incurred over the lifetime of a given plant are divided by the total amount of electricity generated during that period, with both figures discounted to the base year by using a discount rate that also reflects the risks associated with the project (Fig. 31). The result is referred to as the levelized cost of electricity (LCOE), and its calculation is based on the discounted cash flow method. The scope of the LCOE is usually limited to the plant (or busbar) costs and does not include grid level (or system) costs and externalities beyond those included in environmental taxes and charges accounted for in the expenditures. However, the LCOE model presented in this section explicitly accounts for CO_2 emissions by calculating the carbon costs per unit of electricity generated and including them in the total levelized electricity costs.

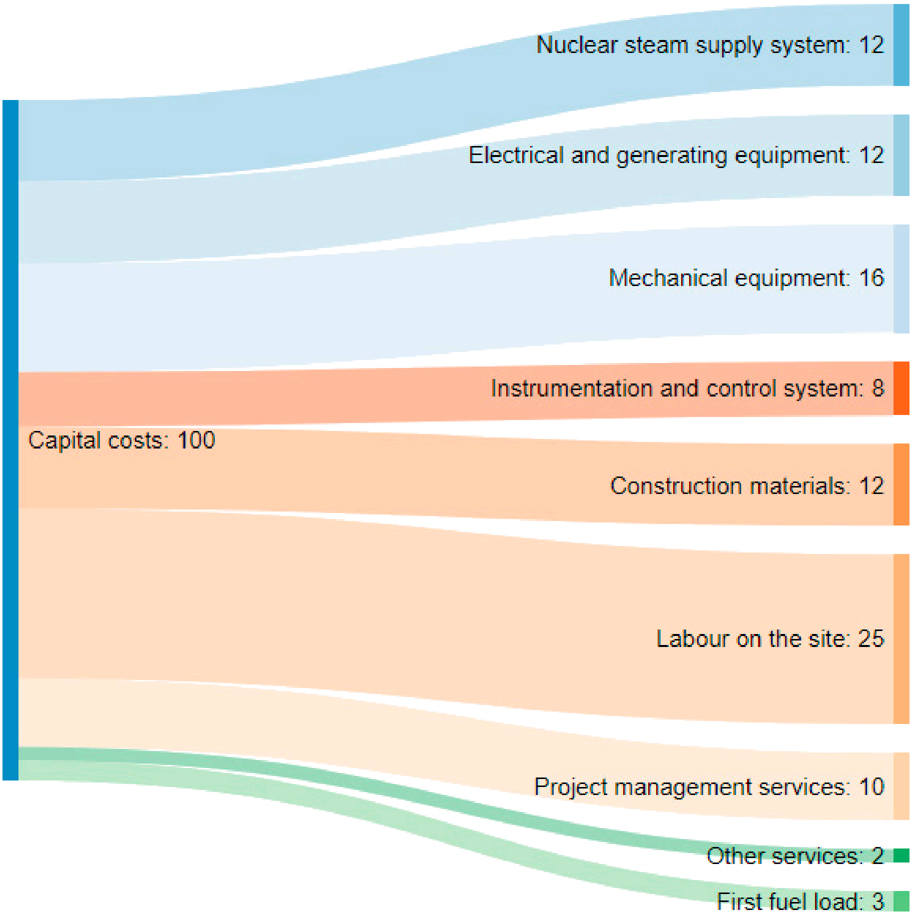

FIG. 30. Typical NPP capital expenditure breakdown structure. Data source: Ref. [107]. Note: Numbers indicate portions of the total capital costs in per cent.

The IEA and the OECD NEA have been publishing cost estimates for different power generation technologies on a regular basis. The 2015 edition of Projected Costs of Generating Electricity [105] evaluated the LCOE for 181 power projects — fossil fuel, nuclear and renewable technologies — in 22 countries based on three types of inputs:

— The amount of electricity (MW·h) generated in a year, which depends on an assumed average availability or utilization rate for each technology.
— Annual expenses during the three key phases: construction, operation and end-of-life, assumed to be constant over the lifetime of the plant.

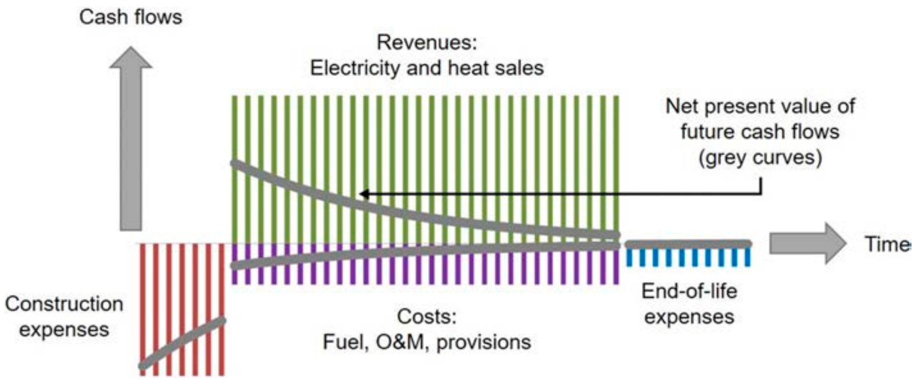

FIG. 31. Discounting future cash flows over the lifetime of an NPP. Note: O&M — operation and maintenance.

— A discount rate used for converting future revenues and costs into present value. (Traditionally, the discount rate is adjusted for risk, project by project, phase by phase (construction, operation and end-of-life).) The IEA and OECD NEA [105] report applies the same constant rate for all technologies and all periods.

Figure 32 illustrates the main results of this study for three dispatchable technologies: nuclear, coal and natural gas. The output from dispatchable technologies can be varied to follow demand while the operation of non-dispatchable technologies depends on the availability of intermittent resources. The chart shows various cost components and the resulting LCOE. The first two vertical lines to the right of the bar 'Technology' represent the investment costs per MW·h of electricity generated for two discount rates: 3% (the social cost of capital) and 7% (the market rate in deregulated or restructured markets). The next three vertical lines indicate recurring costs: fuel, O&M and carbon costs, also per MW·h of electricity generated. Finally, the last two vertical lines show the LCOE at 3% and 7% discount rates, respectively.

The investment costs of NPPs are higher than those of coal or gas fired plants because they use special materials, incorporate sophisticated safety features and backup control equipment, and have a longer construction time. Construction and startup delays increase financial charges and interests during construction. The latter can represent as much as 30% of the total investment costs for nuclear energy [108] and this cost element is very sensitive to the discount rate. The operating costs of NPPs — fuel, O&M and carbon costs per MW·h of electricity generated — are lower than those of almost all fossil fuel competitors, with a very low risk of operating cost inflation. The LCOE from nuclear energy is largely driven by capital expenditure and the applicable discount rate. At 3% discount rate, nuclear power is cheaper than other dispatchable technologies while at 7% it is still cheaper than natural gas and comparable with coal. Table 7 summarizes the main results of the IEA-OECD NEA report [105] for OECD countries.

Recent studies, including some by the IEA and OECD NEA, call into question the relevance of the LCOE metric because it aggregates costs into one number, blurs the distinction between capital and operating costs, and hides the importance of interest rates. Moreover, LCOE does not capture system costs and the value of dispatchability. In an electrical system, power plants interact with one another physically and economically. Interactions result in system effects that can cause instability in electricity networks and jeopardize supply security. These interactions are becoming increasingly important with the introduction of VRE technologies. Plants using VRE sources are built in areas with favourable meteorological conditions, often far from urban and industrial load centres.

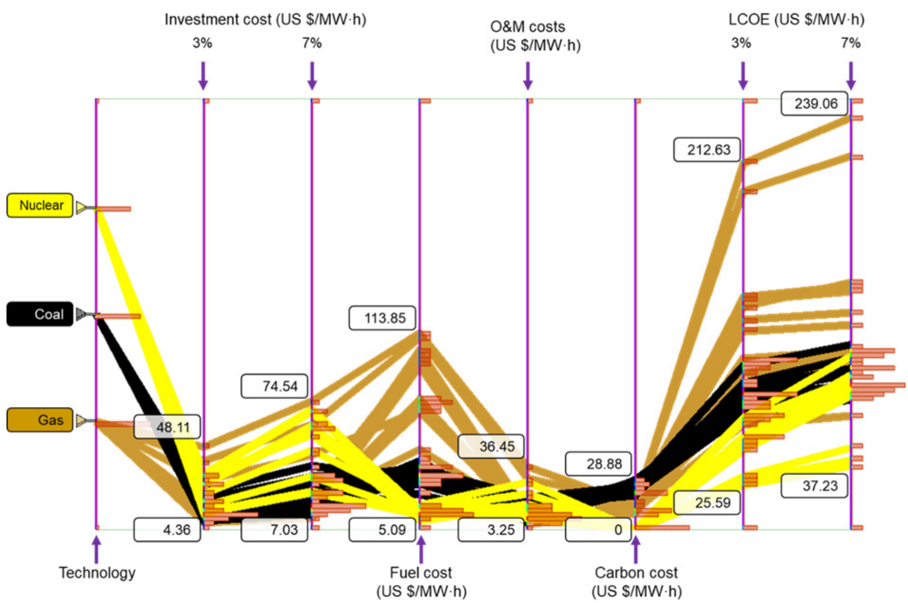

FIG. 32. Cost comparison of electricity technologies. Data source: Ref. [105]. Note: The chart shows various cost components and the resulting levelized cost of electricity. Each colour is associated with a particular technology. The vertical lines use the same units (US $/MW·h) and have a different scale. Numerical values indicate lower and upper limits for each dimension. Investment costs include overnight costs (with contingency) as well as the implied interests during construction.

TABLE 7. COST COMPARISON FOR SELECTED OECD COUNTRIES
(*data source: Ref. [105]*)

Technology	LCOE[a] at 3% (US $/MW·h[b])		LCOE[a] at 7% (US $/MW·h[b])		LCOE[a] at 10% (US $/MW·h[b])	
	Min.	Max.	Min.	Max.	Min.	Max.
Natural gas fired plants	61 USA	133 Japan	66 USA	138 Japan	71 USA	143 Japan
Coal plants	66 Germany	95 Japan	76 Germany	107 Japan	83 Germany	119 Japan
Nuclear power plants	29 Rep. of Korea	64 UK	40 Rep. of Korea	101 UK	51 Rep. of Korea	136 UK
Solar PV[c] technologies (residential)	96 Portugal	218 Japan	132 Portugal	293 France	162 Portugal	374 Portugal
Solar PV[c] technologies (commercial)	69 Austria	142 Belgium	98 Austria	190 Belgium	121 Portugal	230 Belgium
Solar PV[c] technologies (large, ground mounted)	54 USA	181 Japan	80 USA	239 Japan	103 USA	290 Japan
Onshore wind	33 USA	135 Japan	43 USA	182 Japan	52 USA	223 Japan
Offshore wind	98 Denmark	214 Rep. of Korea	136 Denmark	275 Rep. of Korea	167 USA	327 Rep. of Korea

[a] LCOE: levelized cost of electricity
[b] US $/MW·h: US $/megawatt-hour
[c] PV: photovoltaic

Their output is variable and uncertain. Consequently, dispatchable generation technologies (mainly fossil fuel and nuclear energy) need to be maintained to ensure supply security. Dispatchable technologies have more value to a system than less flexible units, and this is not captured by their plant level costs. The value of a technology to the grid could be measured by the levelized avoided cost of electricity metric [109]. This value (benefit) would certainly exceed the LCOE for dispatchable technologies, making them economically more attractive to build. Unlike the LCOE, calculation of the levelized avoided cost of electricity requires modelling and simulating the operation of projects considered and evaluated for inclusion in a regional power system [110].

The integration of VRE sources into existing power grids profoundly affects the operation and economics of electricity systems and incurs three types of additional costs: grid connection and upgrading costs, short term balancing costs and long term costs for maintaining backup capacities. These costs are technology and country specific and strongly depend on the penetration level of VRE sources. According to the OECD NEA [111], system costs for dispatchable technologies are below 3 US \$/MW·h compared with (up to) 40 US \$/MW·h for onshore wind, 45 US \$/MW·h for offshore wind and 80 US \$/MW·h for solar energy. The latest study of the OECD NEA confirms that the grid level system costs of dispatchable technologies decline slightly as the shares of VRE generation increase from 10% to 30% while those of VRE technologies increase by 35–40% for wind and 60–65% for photovoltaic under the same conditions [112]. Since electricity generated from VRE sources is dispatched first in most grid regulation schemes, their increasing shares reduce the load factors and thus the profitability of dispatchable technologies in the short term. The consequence in the long run might be that high fixed cost technologies such as nuclear power will face increasing difficulties in financing new investments in electricity markets where prices are low and volatile.

In conclusion, on the basis of the LCOE, nuclear power is an economically competitive source of energy compared with other electricity generation technologies. NPPs are expensive to build compared with coal and gas fired plants. However, fuel, O&M, decommissioning and waste disposal costs represent only a minor proportion of their total generating costs (measured by the LCOE metric). Nuclear power is cost competitive with other forms of electricity generation, except in cases where low cost fossil fuels such as shale gas are available. If the health and environmental costs of fossil fuels are also considered, nuclear power is even more competitive. Grid level costs of nuclear energy, similarly to those of other dispatchable technologies, are rather modest compared with those of VRE sources.

5.4.2. Macroeconomic impacts

According to the latest Word Bank estimates, 767 million people were living below the poverty line in 2013, which is set globally at US $ 1.90/day per person. By this standard, roughly 11% of the global population is considered to be poor. Despite a steady decline since the 1990s, the global poverty rate today remains unacceptably high [113]. This explains why the United Nations SDGs symbolically list poverty eradiation as Goal 1. The creation of stable and well paid jobs can tackle the root causes of poverty but the challenge is real. According to the International Labour Organization, global unemployment levels are high and increasing, for example, in 2017 by roughly 6% or by almost 3.5 million people compared with 2016 levels [114].

The decision to invest in an NPP has employment impacts that go far beyond the project itself. Investments in nuclear energy can bolster a country's economic, educational and technical development and create conditions that allow people to have skilled jobs while not harming the climate. Jobs created by an NPP project include employees who work at a construction site while it is being built. After its completion, jobs are created when the plant starts its operation. These jobs are permanent and highly skilled. For example, at an average NPP in the USA, salaries are more than 30% higher than in the area located close to it [115]. Both types of employment are mostly direct jobs.

Additional employment opportunities comprise jobs generated alongside the supply chain in highly skilled employment areas related to the design, engineering and procurement of the reactor and many other components (indirect jobs). In addition, new jobs are created in wholesale and retail trade, transport and real estate services, financial and public services such as administration and education (induced jobs). Jobs in the latter category are typically generated in close proximity to a construction site or a newly built NPP because this is where employees typically spend a large fraction of their salaries. Recent experience in IAEA Member States shows that the number of indirect and induced jobs can be several times higher than direct employment [116–118].

When starting a nuclear power programme or expanding existing capacities, some countries take the decision to engage with foreign suppliers. Reasons for a joint project are multiple but perhaps the most common causes are of a technological and financial nature as nuclear power involves tremendous technological know-how and large upfront capital costs. In joint projects, the associated macroeconomic benefits, including the job creation potential, are split between two or more countries: a vendor country or countries suppling nuclear technology and the host country where the NPP is constructed and operated.

The distribution of macroeconomic benefits between participating countries is determined by a variety of factors and varies over time. Calculations show that for a supplier country the largest benefits are likely to occur during the construction phase. During this time, major reactor components are manufactured and shipped to the country where the NPP is being built. In contrast, the recipient country is more likely to benefit during the operational phase. One of the major drivers of this distribution is linked to the creation of induced jobs in close proximity to an NPP [119].

Figures 33 and 34 illustrate, based on real project data, the distribution of macroeconomic benefits for both the supplier and the recipient country, respectively, for one year during the construction phase. Illustrative calculations are for the year of the construction when the largest part of the investment is made. Macroeconomic benefits are measured as gross output increases at the sectoral level in both countries in 2013 US $. Increases in production outputs imply that sectoral employment would also increase. In relative terms, those increases in the recipient country might be rather substantial, particularly if the related sectors are labour intensive.

During the construction phase, a nuclear energy investment generates economic growth in the vendor country because it owns a large part of the supply chain infrastructure related to designing and engineering the reactor, manufacturing major subcomponents, delivering fuel and many other items. According to Fig. 33, manufacturing machinery and equipment is the sector with the largest output increase by far, about one quarter of the total output increase. It is followed by financial services and the manufacturing of electrical equipment.

In the country where the NPP is built, two sectors benefit most: construction and the manufacturing of machinery and equipment. As shown in Fig. 34, they account for almost half of the total output increase in the given year. Benefits in a recipient country largely depend on local participation in those parts of the supply chain where national industrial companies can cost effectively meet the high standards of the nuclear industry [120]. Countries opting for nuclear power typically aspire to increase local participation, which is likely to translate into a greater number of jobs created throughout the economy and several other macroeconomic benefits.

Beyond job creation and increased industrialization, nuclear investments have a number of other benefits, such as creating a reliable electricity supply and economy-wide price stability. However, a balanced view requires weighing potential macroeconomic benefits against macroeconomic risks. A country's gross domestic product and foreign currency reserves should be sufficiently large to be able to deal with potential construction cost increases, maintain the required infrastructure and cover liabilities in case of an accident.

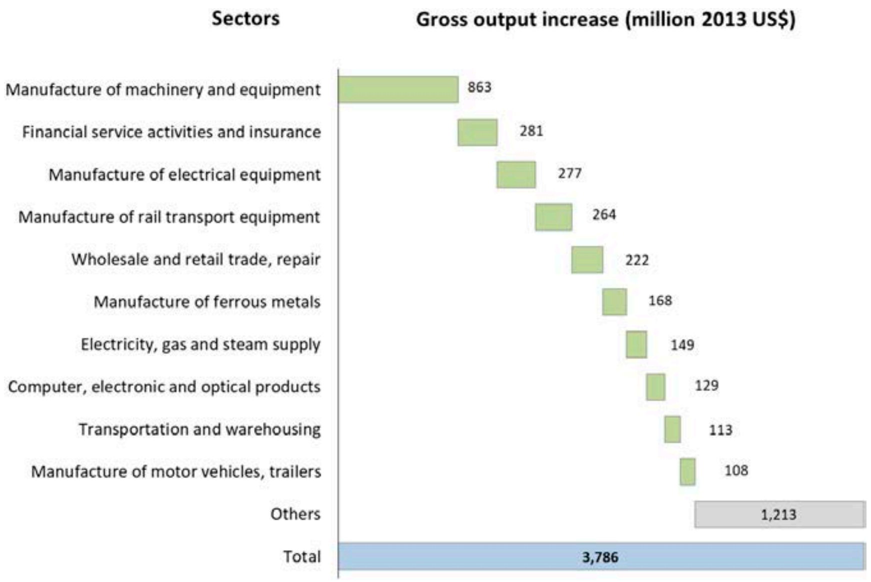

FIG. 33. Sectoral gross output increases in the country supplying nuclear technology. Source: Ref. [119].

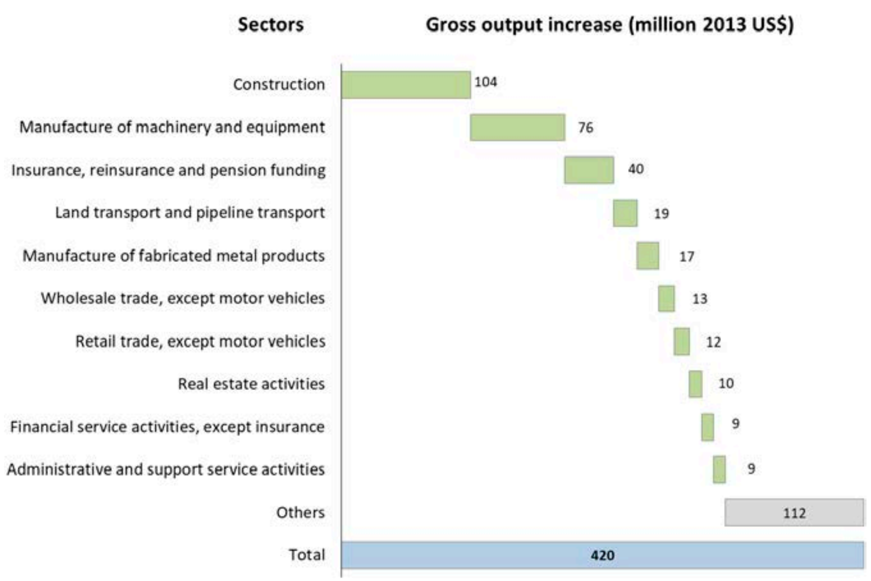

FIG. 34. Sectoral gross output increases in the country where the nuclear power plant is built. Source: Ref. [119].

5.4.3. Development of reactors with alternative cost models

An important element of the UNFCCC COP 21 and the Paris Agreement asserts that innovation is critical "for an effective, long term global response to climate change and promoting economic growth and sustainable development" ([5], p. 15).

One challenge for nuclear power is its high capital costs that sometimes make it prohibitive for use in some parts of the world. Illustrative cost structures for various power generation technologies are presented in Fig. 35.

Innovative reactor designs with smaller capacity are addressing this issue. Many reactors that were initially built were small (the world's first nuclear power plant that generated electricity for commercial use was a small reactor (5 MW) built in the Soviet Union in 1954), but with evolving technology and increasing demand, GW scale NPPs were developed, taking advantage of economies of scale as larger reactors have smaller unit costs (US \$/MW of installed capacity or US \$/MW·h of generated electricity). As costs and delivery delays mount at large new nuclear power projects around the world, attention is turning again to smaller alternatives, the so-called SMRs. SMRs are defined as small, medium sized or modular reactors. They are designed to take full advantage of reduced system size, design standardization, modularization and other advanced

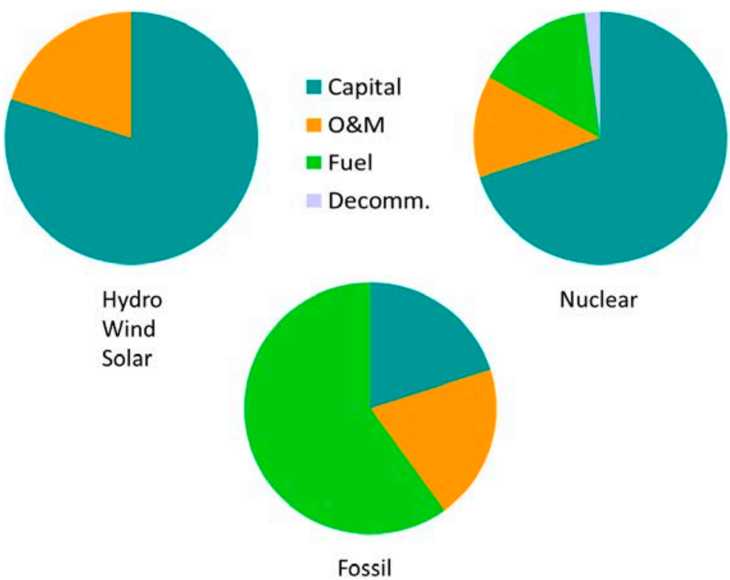

FIG. 35. Illustrative cost structures for power generation technologies. Note: O&M — operation and maintenance, Decomm. — decommissioning.

construction methods. Modularization is a construction technique that consists of moving activities from the reactor construction site to a different location, which can be a factory (an off-site location) or an assembly area (an on-site location). Typically, small transportable modules are manufactured in factories and then assembled at the on-site assembly area into bigger modules. These modules are moved to the construction site and then integrated to complete the nuclear islands and the power conversion system. These concepts have still to be proven but show favourable SMR potential in engineering and marketing studies.

Small reactors would be suited for countries without large power grids, less developed infrastructures and limited financing capabilities. SMRs can be deployed and financed incrementally to closely match demand for electricity and/or process heat, hydrogen production or seawater desalination. Cogeneration, i.e. the simultaneous production of electricity and heat, results in significantly improved energetic efficiencies and additional income, leading to better returns on investments. Some SMR designs may also serve niche markets, for example 'burning' radioactive waste. Most of the SMR designs have high potential for operation in load following mode, continuously adjusting power output to match demand in electricity or as backup dispatchable generation systems. (Modularity enables SMRs to divert a variable part of the core thermal power to external heat consuming processes — district heating, for example — and convert the rest into electricity.) In small isolated grids or in grids with high shares of VRE sources, SMRs would offer a wide range of 'system' services beyond baseload electricity.

The SMR designs currently under development are based on different reactor technologies: water cooled reactors, high temperature gas cooled reactors, liquid metal, sodium and gas cooled reactors with fast neutron spectrum, and MSRs. Three industrial demonstration SMRs are in an advanced stage of construction: in Argentina (CAREM, an integral pressurized water reactor), in China (HTR-PM, a high temperature gas cooled reactor) and in the Russian Federation (KLT40S, a floating power unit). They are scheduled to start operation between 2019 and 2021. Other SMR designs are also being prepared for near term deployment. Table 8 lists selected SMR designs under development as of May 2018 for near term deployment, and applicable technologies along with the output capacity, reactor type and information about the design institute [104].

Interest in SMR designs is driven by the very high costs and long duration of GW scale NPP construction projects. These costs and delays are directly related to the size and complexity of such megaprojects. The term 'megaprojects' refers to large, complex and long term infrastructure projects, involving a large number of stakeholders entering the project at different stages with different roles and responsibilities. Poor project structuring and risk management — including interface risk management — often lead to cost overruns and project delivery delays. The Channel Tunnel, the Cologne–Frankfurt high-speed rail link in

TABLE 8. STATUS OF DEPLOYMENT OF SELECTED SMALL, MEDIUM SIZED OR MODULAR REACTOR DESIGNS AND TECHNOLOGIES
(updated from Ref. [104])

Design	Output (MW)	Type	Designers	Country	Status
KLT-40S	70	Floating NPP[a]	OKBM Afrikantov	Russian Federation	Advanced stage of construction
HTR-PM	210	HTGR[b]	INET, Tsinghua University	China	Advanced stage of construction
CAREM	30	PWR[c]	CNEA	Argentina	Advanced stage of construction
4S	10	LMFR[d]	Toshiba Corporation	Japan	Detailed design stages
SVBR-100	100	LMFR[d]	JSC AKME Engineering	Russian Federation	Detailed design stages
ACP100	100	PWR[c]	CNNC	China	Detailed design stages
SMART	100	PWR[c]	KAERI	Republic of Korea	Received a Standard Design Approval in 2012
NuScale	50 × 12	PWR[c]	NuScale Power	USA	Undertaking a Design Certification Review

[a] NPP: nuclear power plant
[b] HTGR: high temperature gas cooled reactor
[c] PWR: pressurized water reactor
[d] LMFR: liquid metal cooled fast reactor

Note: The liquid metal cooled fast reactor is subject of an intense research, development and demonstration effort aimed at, in particular, developing and qualifying advanced material (see Section 5.3.3 on advanced reactor concepts). This technology is significantly less proven than LWRs and much effort is still needed to develop a consistent supply chain and set up a licensing procedure.

Germany and the Kuala Lumpur Airport in Malaysia were all delivered over budget and with significant delays. In NPP construction, a small size combined with modular construction can potentially result in smaller upfront investments due to the smaller scale, faster construction and shorter payback period.

Two major factors drive the costs of SMRs: power scaling (as a power plant gets larger in size, it gets progressively cheaper to add additional capacity) and learning. The effect of scale on construction costs is expected to be small. The predicted savings from increases in size would be offset either by extended construction duration or the additional safety enhancements required for larger reactors [121]. Learning is measured by the rate of cost reduction for every cumulative doubling of production. High learning rates could be achieved by design standardization (minimal design changes during and between builds), regulatory stability, in-factory fabrication, testing and inspection, sustained demand for nuclear systems and components over time, and ongoing orders for the nuclear supply chain. (A rule of thumb derived by the shipbuilding industry indicates that the labour time of carrying out a task at the construction site will be approximately eight times longer than the time of carrying out the same task in the factory [122].) In March 2015, the UK Government commissioned an independent techno-economic assessment of SMRs to help inform policy decisions. According to the SMR cost reduction study led by Ernst & Young [123]:

- The LCOE for the first SMR will be 30% higher than for an nth-of-a-kind large reactor.
- By manufacturing ten units per year, SMRs could achieve LCOE parity with large reactors at 5 GW(e) total deployment.
- SMRs would have a construction time of 36–48 months.
- The use of advanced manufacturing techniques and processes (methods such as building information modelling), and a strategic decision to install multiple reactors at a single site, would result in an additional 20% saving in capital expenditures.
- The specific O&M cost is expected to be higher for SMRs than for large reactors owing to the staffing levels required to meet safety regulations. Higher operating costs could be offset by higher operational efficiencies.

SMRs can potentially compete with larger reactors on capital costs and also in terms of plant level (LCOE) and system level costs if built in sufficient numbers, according to a standard design, in a controlled, efficient and productive factory environment where nuclear systems and component are fabricated, tested and inspected by the regulator before being transported to and assembled at the construction site. A well-structured regulatory framework will enable shorter construction times and thus lower interests during construction without compromising safety.

In conclusion, SMRs provide a low carbon alternative to fossil fuel powered electricity generation systems in countries with small power grids and limited financing capabilities. They may additionally support non-electrical applications such as seawater desalination and district heating. Around 50 SMR designs are currently being developed for near term deployment and three are being constructed. Much work is yet to be accomplished by reactor designers, national authorities, including nuclear regulators and electric utilities to address various technical, safety and regulatory issues. The supply chain to support the mass production of components for SMRs cannot mature without government involvement. Government support is also crucial for designing and constructing first-of-a-kind SMRs, which have higher upfront capital investment and longer construction periods than standardized nth-of-a-kind power plants.

5.5. ADAPTATION OF NUCLEAR ENERGY TO CLIMATE CHANGE

Fossil fuel technologies are the main drivers of global warming while nuclear and renewable energy sources can contribute to reducing GHG emissions but all energy technologies will be affected by climate change. This section draws on an IAEA publication currently in preparation [124] that presents a systematic overview of impacts on the energy sector and options to reduce vulnerability to such effects and possibilities to adapt to them.

The most important aspects of gradual climate change (GCC) (persistent changes in the mean and/or the variability of climate properties over an extended period, typically a few decades) relevant for nuclear energy and considered here include slow changes in mean temperature, precipitation, windiness and sea level. The second type of climate impacts are the shifts in incidences of extreme weather events (EWEs) (defined as a value of weather or climate variables close to the upper or lower end of the observed range) [125] that are most relevant for nuclear energy including changing patterns (frequency, intensity, duration, timing and/or spatial extent) of extreme high and low temperature and precipitation, extreme high winds, storms (tropical and extratropical cyclones, hurricanes, typhoons, tornadoes) and storm surges, lightning, and forest and wildfires (see also Ref. [126]).

For all climate trends and EWEs, it is important to distinguish direct impacts (those affecting nuclear facilities or infrastructure directly) and indirect impacts (caused by climate or weather phenomena affecting other components of the energy system or the environment at large that impose impacts on nuclear energy). For example, lightning could damage the instrumentation of an NPP directly. In contrast, a snowstorm disrupting power transmission lines and forcing an otherwise intact NPP to shut down for safety reasons (station blackout) is an indirect effect. The distinction between direct and indirect impacts is important for assessing and implementing options to reduce the exposure and increase the adaptive capacity in affected components of the nuclear energy sector and to make its operation safer and its energy supply more secure. In this section, focus is on the power generation phase of the nuclear energy cycle. A few selected impacts and related adaptation options are presented first for GCC, followed by a similar assessment for EWEs.

5.5.1. Gradual climate change

NPPs are operated under diverse climatic conditions from cold temperate to warm tropical regions and are well adapted to prevailing weather conditions. However, they might face new challenges and will need to respond by hard (design or structural methods) or soft (operating procedures) measures as a result of climate change. Higher mean ambient temperatures reduce the thermal efficiency of all thermoelectric plants, including that of NPPs. As discussed in Section 2.1.4, IPCC scenarios project global mean surface temperature increases between 0.3˚C (low end of the lowest scenario) and 4.8˚C (high end of the highest scenario) by 2100. Near term increases are expected to be in the range of 0.3–0.7˚C in the period 2016–2035 [2].

According to recent estimates, with every increase of 1°C in monthly ambient temperature, NPP generation output declines by 0.7% at low temperatures (around 0°C) and by 2.3% at high temperatures (around 20°C) [127]. Net economic losses to operators will depend on their locations and the selling price of electricity.

Other than siting new plants in areas expected to have lower than average temperature increases, which may not be an option for many countries, no choices are available to avoid reductions in thermal efficiency due to higher temperatures. Furthermore, even if siting in a cooler area were an option, ambient temperature would be only one of dozens of factors that affect siting, many of which would have greater influence on the final siting decision them temperature. Other options include adopting different, more efficient cooling systems.

Climate change will also alter precipitation patterns in most regions. The impacts of gradually increasing mean annual precipitation would be positive because larger amounts of water would be available for cooling. However, significantly higher precipitation can lead to flooding that can have serious implications (see Section 5.5.2).

In contrast, decreasing annual precipitation would lead to long term reductions in water levels in rivers and lakes that provide cooling water for existing NPPs and this could cause serious problems. In areas where long term rainfall patterns will reduce water availability, NPPs must compete with many other vital uses of scarce water. In unfavourable circumstances, generation may need to be curtailed or even halted if water levels are too low. Adaptation options to avoid such events include establishing possibilities for reusing wastewater and recovering evaporated water in recirculating systems. Adding new cooling ponds or increasing the capacity of existing cooling ponds could also help. Improving wet cooling and installing dry cooling are further options.

Higher average wind speeds brought on by the changing climate can have some impact on NPPs. More persistent wind and fog can, over time, carry additional salt spray to plants near the coasts. Salt deposited on exposed cables and metal parts will lead to faster corrosion and, potentially, to short circuits if the deposits are not cleaned regularly. For plants in dry areas, higher average winds can build up more dust and dirt that can cause problems with mechanical devices, electronic circuit boards and other sensitive parts. For both salt and dust, increased preventive maintenance, appropriate shielding and seals are effective solutions.

Although sea level rise has not yet affected any NPPs, it threatens to be one of the most economically damaging climate change events. Any flooding can be problematic for an NPP, but sea level rise in combination with coastal storms could lead to site inundation. Raising dykes and other protective embankments are technically simple and economically affordable adaptation options. Table 9 summarizes the most important impacts of GCC on nuclear energy together with the related adaptation options.

5.5.2. Extreme weather events

NPPs are built to withstand EWEs that are possible based on past experience, typically the worst expected event, not always natural hazards, at the plant site over a 50 or 100 year period or much longer (e.g. 500 year floods) [128, 129]. However, as the climate changes, past events are becoming an increasingly inappropriate basis on which to predict the severity of future events. Existing NPPs may become vulnerable to EWEs, and the siting and design of future NPPs need to account for changing climatic conditions. NPPs are exposed to an additional level of vulnerability beyond those that other types of generating plants face. Various types of EWEs can affect critical safety systems and can increase risks to human health and the environment, making adaptation more than an economic calculus for their owners. Licensing requirements may need to be adapted over time. Ensuring that external events do not lead to safety system failures is the highest priority for adaptation to EWEs.

TABLE 9. IMPACTS OF GRADUAL CLIMATE CHANGE AND ADAPTATION OPTIONS IN NUCLEAR ENERGY

Impacts	Potential vulnerabilities	Examples of adaptation options
Higher mean temperatures	Decreasing thermal efficiency and decreasing cooling efficiency	Select site with cooler local climates where possible and use different cooling designs
Lower mean precipitation	Less and warmer cooling water leading to potential reductions in output or even shutdown	Reuse wastewater, recover evaporated water in recirculating systems, construct cooling ponds, improve wet cooling, install dry cooling
Increased windiness near coasts and dry areas	Salt sprays from sea can lead to long term corrosion and short-circuit exposed electrical equipment and dust and sand carried by wind can lead to equipment malfunction	Increase frequency of preventive maintenance, shield and weather seal critical equipment
Sea level rise	Flooding of low lying coastal sites	Raise dykes and other protective embankments

An NPP is one of the most complex electricity generating technologies, requiring a large number of systems to operate safely and properly. Key components vulnerable to EWEs include those systems needed to ensure access to the electrical grid system, water cooling, electronic control and monitoring, physical plant access, structural integrity and ventilation.

Access to water for the cooling system is as important as the electricity needed to pump it. Long term climate change can lead to more extreme cold in winter and extreme heat in summer. Hot weather can facilitate algal blooms or rampant growth of seaweed and other plant materials that can also block cooling water intake. If cooling water is too hot because of high ambient temperatures, cooling capacity can diminish and safety can be jeopardized. If discharging used cooling water into a river or lake would raise the temperature above the limit allowed by heat pollution standards, an NPP must reduce its operation level or shut down altogether until ambient temperatures decline. Long term droughts can lead to water rationing that would limit water intake for cooling with the same implications for operation.

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

Under extreme cold conditions, ice can block the cooling water intake system, reducing the flow of cooling water to unsafe levels. Freezing pipes can lead to the internal flooding of critical areas and ice can also damage the grid system. Routeing heated water from the cooling system to the inlet area and insulating critical piping are simple engineering adaptation options.

Local high precipitation events can cause floods directly at the site of power plants, damaging buildings, equipment and downstream fuel cycle components such as spent fuel storage, e.g. on-site dry casks (Fig. 36). Floods upstream in the river basin may carry large amounts of debris and items accumulated on the river bank that would require precautionary measures to protect cooling water intake. Adaptation options include hard measures such as flood protection by dams, embankments, flood control reservoirs, ponds, channels, drainage improvement, rerouting and isolation of water pipes, while soft measures comprise zoning and restricting activities in flood prone areas.

Structures and building related systems such as ventilation must also withstand EWEs. The integrity of the reactor containment vessel and surrounding structures is critical to ensure safety, as is the integrity of structures protecting spent fuel and radioactive waste storage. Buildings that house diesel generators, control equipment and so on must also be able to withstand high winds, projectiles driven by high winds, floods, and heavy loads due to rain or snow. Extreme pressure differentials accompanied by high winds, as well as smoke and ash, can impair ventilation systems, without which personnel would be unable to continue to remain in affected buildings.

Extreme winds and storms (tornadoes and other rare events) can damage buildings, cooling towers and storage tanks. High winds and lightning (see below) have always been a threat to NPPs and the threat will rise as these EWEs become more intense as a result of climate change. Generally speaking, critical safety systems are well protected by reinforced structures designed to withstand extreme winds. Typically, the greatest threat from winds is their ability to disrupt power from the grid system, either off-site or in the NPP's internal power connections. Without connection to the grid system for any length of time, an NPP's reactors must sometimes be tripped to stop generating electricity. However, the NPP's safety systems must continue to operate and need power to do so. Diesel generators fill this gap. Upgrading construction standards can reduce the risk of structural damage.

Storm surges, superimposed on sea level rise, increase the flood risk for all facilities in low lying coastal areas. Many impacts and adaptation options are similar to those presented for extreme precipitation and the resulting floods.

Electronic control and monitoring systems consist of sensitive electronic equipment and kilometres of cables and sensors, all of which can be damaged by lightning strikes or corroded by moisture, dust, sand and salt. Climate change can increase the intensity of storms that result in lightning strikes [130] as well as bolster the underlying causes of corrosion [131] that can lead to short-circuiting. Although the probability that multiple systems fail simultaneously is low, the threat is there and must be considered. Lightning could short-circuit or create false signals in instrumentation and can also short-circuit on-site power connections, backup diesel connection and controls at NPP sites. Exposure would be reduced by ensuring that circuits are insulated and grounded, key circuits are buried underground and diesel generator controls are shielded.

FIG. 36. Floods around the Krško Nuclear Power Plant in Slovenia in 1990. Reproduced courtesy of the Slovenian Nuclear Safety Administration.

Landslides and forest fires and wildfires (possibly started by lightning) are, in and of themselves, not EWEs but they can be triggered by extreme weather. Climate change can intensify storms and rainfall patterns leading to landslides and it can also intensify drought, creating the conditions for a wildfire. NPP siting takes into consideration the potential for increased probability of landslides and forest and wildfires, so there is little direct threat from these events. However, such events can disrupt transmission lines connecting an NPP with the grid system. They both can also disrupt emergency access to and away from an NPP. Nearby landslides and fires can potentially inhibit NPP personnel from entering or exiting the plant. Another indirect combined impact is smoke blown from wildfires to NPPs that may damage sensitive equipment and hinder access for critical personnel, supply deliveries and emergency response workers. The most important impacts of EWEs on NPPs are summarized in Table 10.

Risk analysis of EWEs were part of the European Nuclear Safety Regulators Group's post-Fukushima-Daiichi-accident stress tests on European NPPs [132]. Similar tests or detailed inspections and engineering assessments of NPPs were implemented in other regions as well (e.g. Ref. [133]). In the European stress test, 140 NPPs in 17 countries (15 European Union member states plus Switzerland and Ukraine) were assessed. The final report recommends four main areas of safety improvement: (i) the standardized extension of safety margins beyond the design basis, (ii) carrying out another periodic safety review in 2021, (iii) starting containment integrity protections now, and (iv) improved defences against natural hazards. By implementing the resulting action plan, nuclear operators will considerably reduce their vulnerability to GCC and EWEs in the coming decades.

In summary, the most significant impacts of GCC on NPPs are the degradation of thermal efficiency and the volume and temperature of water in adjacent water bodies affecting cooling water availability. A range of alternative cooling options are already available or are increasingly being considered to deal with water deficiency, ranging from reusing wastewater and recovering evaporated water [134] to installing dry cooling [135, 136].

The implications of EWEs for NPPs can be severe due to the nature of the technology. Reliable interconnection (on-site electric power and instrumentation connections) of intact key components (reactor vessel, cooling equipment, control instruments, backup generators) are indispensable for the safe operation and/or shutdown of a nuclear reactor. A reliable connection to the grid system for power to run cooling systems and control instruments in emergency situations is another crucial item. Several EWEs can damage critical components or disrupt their interconnections. Preventive and protective measures include technical and engineering solutions (circuit insulation, shielding, flood protection) and adjusting operation to extreme conditions (reduced capacity, shutdown).

TABLE 10. IMPACTS OF EXTREME WEATHER EVENTS AND ADAPTATION OPTIONS IN NUCLEAR ENERGY

Impacts	Potential vulnerabilities	Examples of adaptation options
Extreme heat	Heat can limit water discharge if temperatures are too high for water quality regulations, which can in turn reduce generation or force a shutdown; heat can further reduce the effectiveness of cooling; heat can foster the rapid growth of biological material that can clog cooling water intake, leading to reduced generation or shutdown.	Reduce generation to avoid raising stream temperatures from discharged water above regulation; switch from once-through cooling to recirculating to reduce temperature of discharged water; switch from wet cooling to dry cooling; increase maintenance of screens to ensure that biological matter does not clog the water intake system.
Extreme cold	Ice can clog water cooling systems, leading to reduced generation or automatic shutdown; ice can inhibit plant access; freezing pipes can lead to internal flooding; ice can damage the grid system.	Route heated water from cooling system to inlet area; insulate critical piping.
Precipitation	Excessive rain can cause floods, extreme heavy snow can collapse unreinforced structures; heavy rain and snow can inhibit plant access by critical personnel and supply deliveries. Floods can carry debris that can block cooling water intake.	Ban construction in flood prone areas; provide flood protection by dam, reservoir and drainage improvement; protect water intake areas.
Drought	Low water levels can force plants to reduce generation output or shut down.	Implement alternative cooling options: reuse wastewater, recover evaporated water in recirculating systems; switch to dry cooling.
High winds	Wind generated projectiles can damage buildings and backup generators; can knock out grid system interconnection.	Install projectile shields. Establish sufficient emergency generation capacities.

TABLE 10. IMPACTS OF EXTREME WEATHER EVENTS AND ADAPTATION OPTIONS IN NUCLEAR ENERGY (cont.)

Impacts	Potential vulnerabilities	Examples of adaptation options
Floods or sea level rises	Coastal plants can become vulnerable to storm surges as sea levels rise and storms become more intense; inland plants may become vulnerable to river floods, both of which can force an automatic shutdown but can also damage critical safety systems and grid system interconnections, and threaten spent fuel storage.	Consider flood risks in site selection for new plants; build earthworks to minimize risk of flooding; upgrade flood resistant doors; raise elevation of backup diesel generators.
Lightning	Can short-circuit or create false signals in instrumentation; can short-circuit on-site power connection and backup diesel connections and controls.	Ensure that circuits are insulated and grounded; bury key circuits underground; shield diesel generators controls.
Forest- and wildfire	Can disrupt plant access by critical personnel, supply deliveries and emergency responders.	Develop emergency access and response plans in case of nearby wildfires.

It is important to note, however, that the nuclear industry has ample experience in adapting its plants and operations to changing environmental conditions as well as in accounting for climatic and other environmental factors in site selection for and construction of new NPPs. As shown in this section, the options for adaptation are of a technical or procedural nature that can be accommodated at moderate costs during planned maintenance outages. There is no indication that costly adaptations measures such as fundamental refurbishing or major construction work would be required in the next few decades that would render the currently operating fleet of NPPs uneconomical.

Appendix

CLIMATE CHANGE AND NUCLEAR POWER: LIST OF TOPICS IN EDITIONS PUBLISHED BETWEEN 2008 AND 2016

TABLE 11. LIST OF TOPICS ADDRESSED IN EARLIER EDITIONS OF CLIMATE CHANGE AND NUCLEAR POWER

Topic	2008	2009	2011	2012	2013	2014	2015	2016
Foreword			X	X	X	X	X	X
Summary / Main messages		X	X	X	X	X	X	X
Introduction	X	X	X	X	X	X	X	X
Need for nuclear power								
The global energy challenge	X	X	X	X	X	X	X	X
The climate change challenge	X	X	X	X	X	X	X	X
Need for dispatchable low carbon source of electricity								X
Nuclear power is a low carbon technology	X	X	X	X	X	X	X	X
GHG[a] emissions from the nuclear sector — reactor types							X	
Contribution to avoided GHG emissions in the past	X	X	X	X	X	X	X	X
Future contribution to GHG mitigation								X
Nuclear has GHG reduction potential	X	X	X	X	X	X	X	

TABLE 11. LIST OF TOPICS ADDRESSED IN EARLIER EDITIONS OF CLIMATE CHANGE AND NUCLEAR POWER (cont.)

Topic	2008	2009	2011	2012	2013	2014	2015	2016
Contribution of nuclear energy to GHG mitigation	X	X			X	X	X	
Contribution to resolving other energy supply concerns	X	X	X	X	X	X	X	X
Nuclear energy applications beyond the power sector	X	X	X	X	X			
Nuclear power has non-climatic environmental benefits	X	X	X	X	X	X	X	
Macroeconomic benefits					X	X	X	
Powering energy intensive industries						X		
Supplying and delivering nuclear power								
Timing and requirements for nuclear deployment								X
Economics of nuclear power	X	X	X	X	X	X	X	X
Systems costs of power generation technologies							X	
Nuclear investment costs	X	X	X	X	X	X	X	
Financing nuclear power investments	X	X	X	X	X	X	X	X
Construction capacity for nuclear power	X	X	X	X	X			
Sufficient uranium to fuel increasing nuclear power	X	X	X	X	X	X	X	
Timeliness of supply					X	X	X	

TABLE 11. LIST OF TOPICS ADDRESSED IN EARLIER EDITIONS OF CLIMATE CHANGE AND NUCLEAR POWER (cont.)

Topic	2008	2009	2011	2012	2013	2014	2015	2016
Paris Agreement: What is the impact on nuclear energy								X
Role of nuclear innovation in climate change mitigation								X
Concerns about and benefits of nuclear power								
Radiation risks and their broader context	X	X	X	X	X	X	X	X
Nuclear plant safety and, from 2011 onwards, lessons from the Fukushima Daiichi accident	X	X	X	X	X	X	X	X
Waste management and disposal solutions	X	X	X	X	X	X	X	X
Proliferation concerns	X	X	X	X	X	X	X	
Public acceptance	X	X			X	X	X	X
Environmental impacts: land, acidification, eutrophication								X
Human health effects								X
Prospects for nuclear power								
Electricity and nuclear power projections by the IAEA	X	X	X	X	X	X	X	X
Smart grids and nuclear power							X	

TABLE 11. LIST OF TOPICS ADDRESSED IN EARLIER EDITIONS OF CLIMATE CHANGE AND NUCLEAR POWER (cont.)

Topic	2008	2009	2011	2012	2013	2014	2015	2016
Small modular reactors					X	X		
Fast reactors			X	X	X			
The thorium option					X			
Nuclear fusion			X		X			
Lifetime extensions						X		
Shale gas competition						X		
Vulnerability of nuclear energy to climate change						X	X	
Comparing emissions from fossil with CCS[b] and nuclear power							X	
Main messages	X							
References	X	X	X	X	X	X	X	X
Appendix: Short summaries of sections omitted						X	X	X
Annex: National perspectives on climate change and nuclear energy	X	X						

Note: Topics indicate thematic contents, not verbatim titles; X indicates the topic was included in the edition in the given year.

[a] GHG: greenhouse gas.

[b] CCS: carbon dioxide capture and storage.

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LIST OF ABBREVIATIONS

CCS	carbon dioxide capture and storage
CMA	Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2-eq	carbon dioxide equivalent
COP	Conference of Parties
EPD	environmental product declaration
EWE	extreme weather event
GCC	gradual climate change
GHG	greenhouse gas
GWP	global warming potential
HLW	high level waste
HTR-PM	high temperature reactor pebble bed module
ILW	intermediate level waste
INDC	intended nationally determined contribution
ITMO	internationally transferred mitigation outcome
LCOE	levelized cost of electricity
LLW	low level waste
LWR	light water reactor
MSR	molten salt reactor
NDC	nationally determined contribution
NPP	nuclear power plant
NPS	New Policies Scenario
O&M	operation and maintenance
RCP	representative concentration pathway
SDG	Sustainable Development Goal
SDM	Sustainable Development Mechanism
SDS	Sustainable Development Scenario
SMR	small, medium sized or modular reactors
VRE	variable renewable energy

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