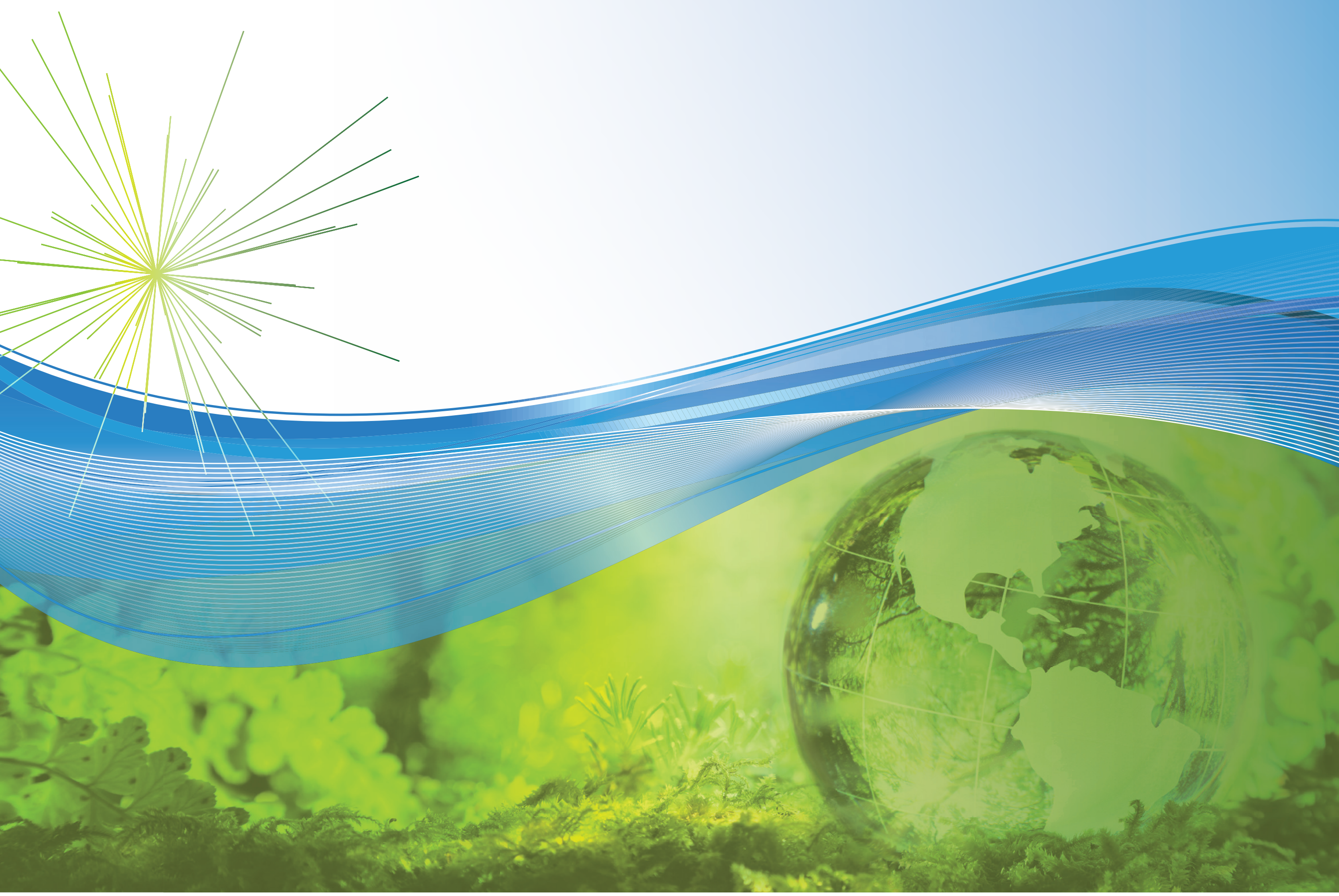
Nuclear Energy: Combating Climate Change



NEA

NUCLEAR ENERGY AGENCY

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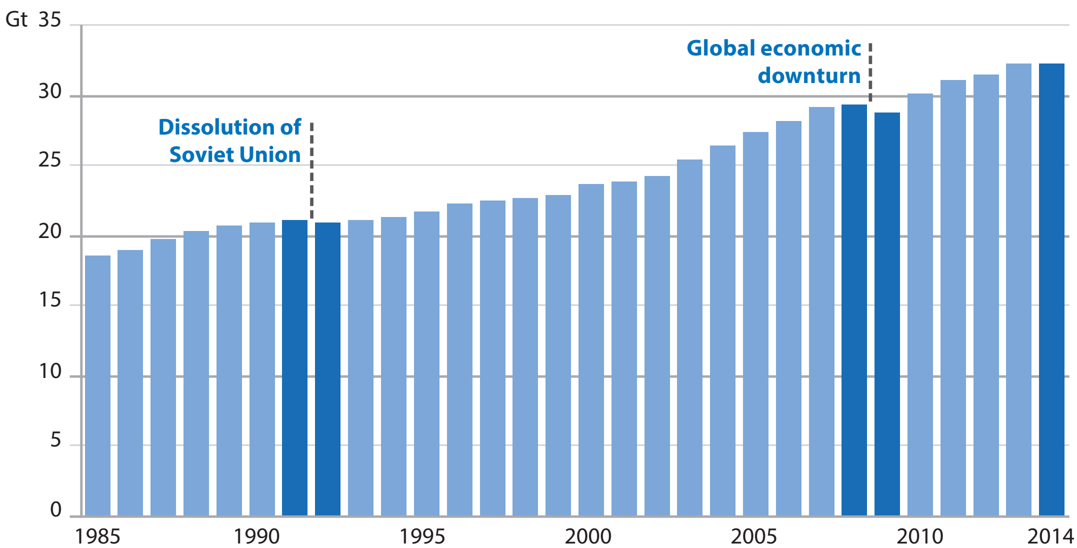
Introduction

The global response to address climate change is a key policy challenge of the 21st century. Many governments around the world have agreed that action should be taken to achieve large cuts in greenhouse gas (GHG) emissions over the coming decades, to adapt to the impacts of climate change and to ensure the necessary financial and technical support for developing countries to take action. They are working towards an international agreement to achieve these goals under the United Nations Framework Convention on Climate Change (UNFCCC), which organises annual Conferences of the Parties (COP). COP 21 will be held in Paris on 30 November to 11 December 2015. There is a growing scientific consensus that global annual GHG emissions will need to be reduced by at least 50% from today's levels by 2050 if the world is to limit the average temperature increase to 2°C by the end of the century in order to avoid the worst consequences of global warming.

Not all anthropogenic greenhouse gas emissions are due to the extraction, transformation and consumption of energy. Sectors such as agriculture and industry also contribute through specific processes. However, **energy use is responsible for about 70% of all GHG emissions,** a share that has remained roughly stable, although absolute emissions have been increasing. The need to cut GHG emissions has therefore become a major driver of energy policy. The main gases emitted by the energy sector are nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2). Of the three, carbon dioxide is by far the most important, contributing over 90% of total energy-related greenhouse gas emissions and about two-thirds of total greenhouse gas emissions.[1] In the energy sector, CO_2 is exclusively generated by fossil fuel combustion. Moving away from the consumption of fossil fuels such as coal, oil and gas towards low-carbon sources such as nuclear, hydro or renewables is therefore a key strategy for reducing climate change and risk.

In the past 30 years, carbon emissions have been steadily rising due to the increased use of all three fossil fuels: coal, oil and gas (see Figure 1) and these now stand at 32 Gigatonnes (Gt). The only periods in history when emissions dipped were during the economic crisis in former Soviet Union countries at the beginning of the 1990s and after the global economic crisis in 2008. It is interesting to note, however, that 2014 was the first year in which global carbon emissions did not increase in the absence of a major economic crisis, although growth in the People's Republic of China has slowed. In 2013, coal contributed 44% of global energy-related CO_2 emissions, oil contributed 35% and gas 20%. The contribution of coal in meeting total global energy demand was 29%, that of oil was 31% and that of gas 21%. The remaining 18% of total energy demand was met by carbon-free sources of energy such as hydropower, renewable energies and nuclear energy (IEA, 2014b).

Figure 1: Energy-related CO_2 emissions since 1985



Source: IEA (2015b).

Gt = Gigatonnes.

1. Cumulative emissions are thus frequently indicated in CO_2-equivalents although the global warming potential of different gases per unit of mass differs widely.

Figure 2: Global CO_2 emissions by fuel in 2012

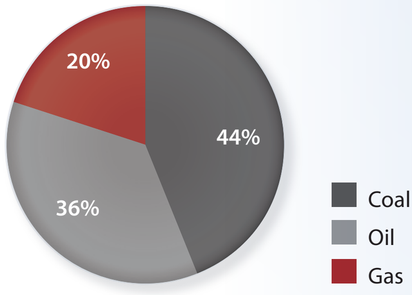
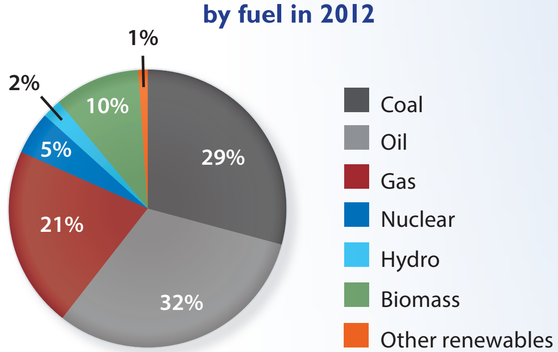


Figure 3: Global energy demand by fuel in 2012



Source: Data from IEA (2015a)

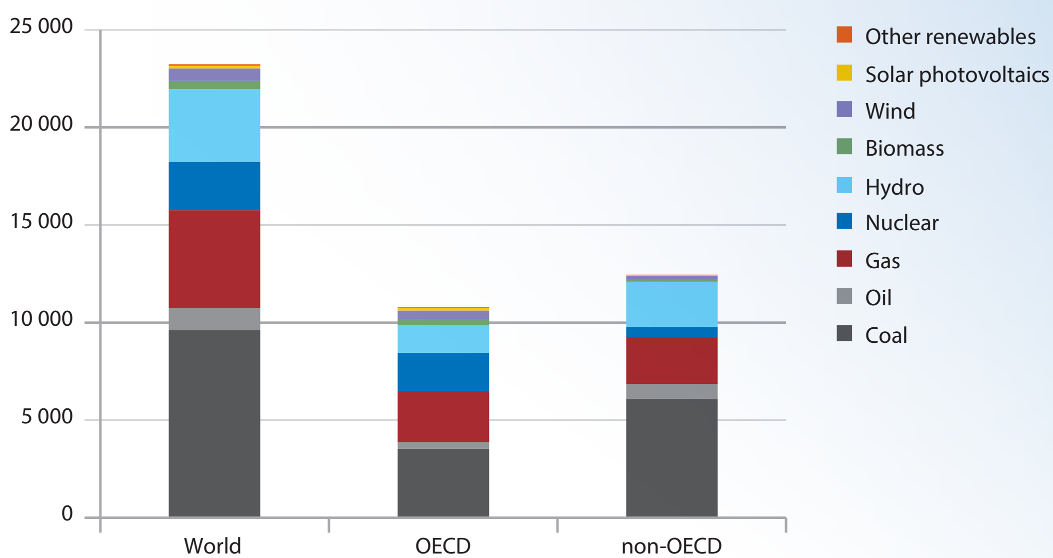
The role of the electricity sector

Electricity plays a particularly important role in this context as the power sector is responsible for over 40% of global carbon emissions (42% in 2013), and this share is rising. While this amounts to slightly less than 30% of total anthropogenic greenhouse gas emissions, the electricity sector is nevertheless the focus of much attention, mainly because it is the one sector where measures to cut GHG emissions have the greatest chance to succeed, at least in the short to medium term. There are three reasons for this. First, the electricity supply system comprises a relatively small number of facilities that are well-known. These facilities are owned and operated by comparatively large organisations and cannot be easily moved. Carbon constraints are thus rather simple to implement, monitor and enforce. While decentralised electricity systems are frequently evoked in an ideal vision of highly developed industrialised countries of the future, the vast bulk of electricity will continue to be provided by large, centralised stations for many years to come.

Second, established low-carbon alternatives for electricity generation do exist. Nuclear energy, hydropower and renewables – in particular onshore wind and solar photovoltaics (PV) – might each have their own challenges but they have been technologically proven and are available for immediate deployment. Third, converting to low-carbon electricity production could initiate a broad wave of electrification, which will help decarbonise other sectors as well. Adopting electric cars powered by low-carbon electricity in transport is the most high-profile example of electricity-driven decarbonisation in other sectors. Switching from biomass to electric stoves for cooking or from fossil-based space heating to electric heating, in particular with heat pumps, are other examples.

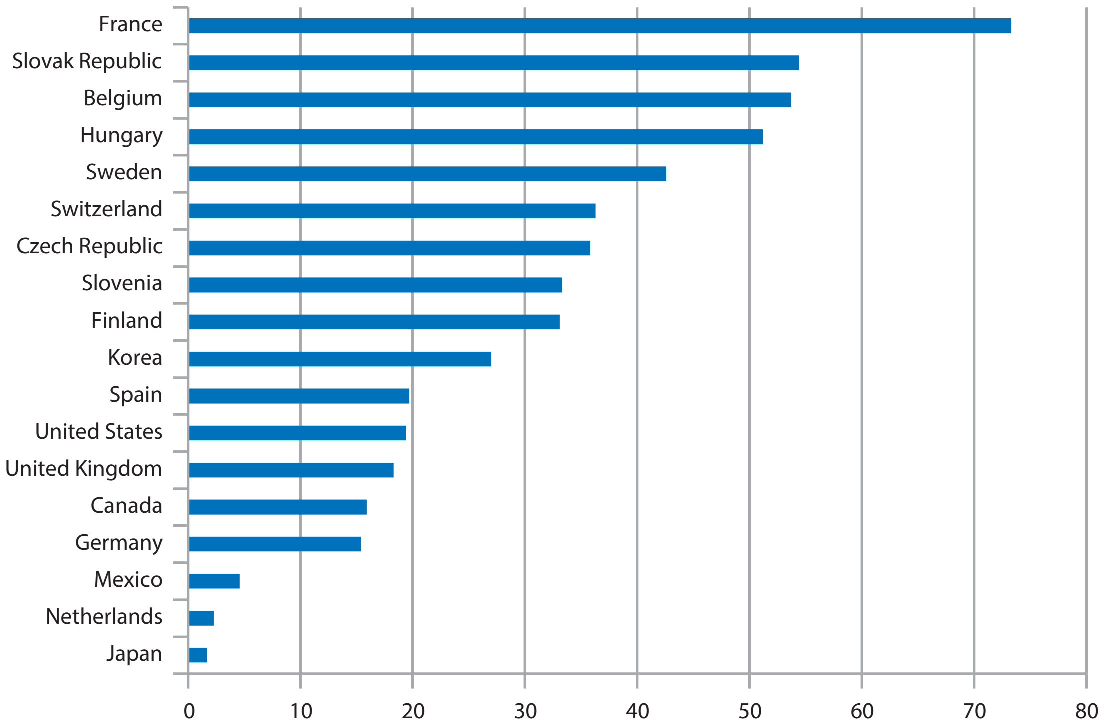
Currently, however, the electricity sector is still far from being low-carbon as it continues to be dominated by coal and gas. In 2013, the share of electricity produced from coal was 41% at the global level, 33% in OECD countries and 49% in non-OECD countries (see Figure 4). Gas produced 22% of global electricity, 26% in OECD countries and 19% in non-OECD countries.

Figure 4: Electricity production by technology (Terawatt hours [TWh] in 2013)



Source: Based on IEA (2015a).

Figure 5: Percentage shares of nuclear in electricity production in 2013



Source: Based on NEA (2014).

The largest low-carbon source of electricity at the world level is hydro power, with a 16% share of electricity production, 13% in OECD countries and 19% in non-OECD countries. Although OECD countries are frequently front-runners in implementing low-carbon solutions, non-OECD countries have a higher production of hydroelectricity in both absolute and relative terms. This highlights the severe constraints experienced in OECD countries and the difficulties involved in further expanding hydroelectric resources. Non-hydro renewable sources (wind, solar PV, biomass, geothermal and marine) contributed 6% to global electricity supply, representing 8% of electricity generation in OECD countries and 3% in non-OECD countries.

Finally, nuclear energy produced 11% of global electricity supply in 2013. This corresponds to 18% of electricity supply in OECD countries and slightly more than 4% in non-OECD countries. Nuclear is thus **the largest low-carbon source of electricity in OECD countries.** Its share in non-OECD countries is still low but is expected to rise substantially in coming years. Of course, such global and regional averages do not show the enormous differences at the country level, in particular in the field of nuclear energy.

For instance, France produced almost three-quarters of its electricity with nuclear power. Belgium, Hungary and the Slovak Republic all rely on nuclear energy for more than half of their electricity supply. In the Czech Republic, Finland, Sweden and Switzerland, it constitutes more than a third. In the United States, which has the largest installed fleet with 99 reactors, nuclear power meets roughly 20% of electricity demand. There is thus not a general limit to the share of nuclear electricity at the national level, although the country's electricity demand, grid infrastructure and its interconnection with neighbouring countries will influence the size of the nuclear power plants that can be installed.

Most OECD countries have an important policy objective to progressively decarbonise their electricity sectors by 2050. This transformation will inevitably involve the use of nuclear power in many countries. Yet even then, achieving a deep or even total decarbonisation of the power sector over the next 35 years still presents a formidable challenge. The rate of turnover of existing infrastructure is low, and coal-fired plants that have been built in recent years may well still be in operation in 2050. While OECD countries will need to set an example, they will not be able to solve the global problem of climate change alone. Demand is rapidly increasing in many non-OECD countries, where the introduction of large-scale, low-carbon energy sources such as nuclear power are faced with a different set of challenges and opportunities.

Much hope has been placed in recent years on the production of electricity from renewable energies, in particular from wind and solar PV. While their absolute contribution remains small, their average annual growth rates between 1990 and 2013 have reached around 20%. During the same period, electricity consumption has grown by 3% each year globally, by 1.5% in OECD countries and by almost 5% in non-OECD countries. These impressive figures are the result of both very low initial levels that have amplified growth rates (which have come down somewhat in recent years) as well as of extensive government-sponsored subsidies administered mainly through guaranteed feed-in tariffs.

Producing low-carbon electricity with wind and solar PV also gives rise to problems for the electrical system because of their variability over the day and during the year, and because of their unpredictability. Additional investment into transmission and distribution networks, as well as the increased cost of the residual generation systems that need to guarantee continuous security of supply add "system costs" over and above the plant-level costs of electricity production (see NEA, 2012b for further details). Additional aspects to be considered include declining load factors with increasing capacities and auto-correlation continuing to lead to production when it is least valuable, as well as the growing rarity of the best sites in terms of meteorological conditions. Because of the issue of variability of production, wind and solar PV cannot, in the absence of a breakthrough in cheap and abundant storage, provide round-the-clock electricity supply on their own. Other renewable sources such as biomass, biogas, geothermal or marine resources are too limited to make a significant contribution to low-carbon electricity generation in the coming decades.

Dispatchable low-carbon sources of electricity will thus always be needed. Hydropower resources can no longer be increased significantly in OECD countries, but do constitute an option in a limited number of non-OECD countries. Another possible alternative to produce low-carbon electricity is to capture the CO_2 produced during fossil fuel combustion and to store or dispose of it in suitable geological formations (carbon capture and storage, or CCS). However, as a result of a mix of geological, economic and social acceptance issues, and despite much research to date, only one large industrial-scale CCS demonstration plant exists in the world (Boundary Dam in Canada). In addition, the CCS process decreases energy efficiency as it uses part of the energy generated, and only about 90% of the CO_2 is captured. Furthermore, a large number of geologically suitable and publicly acceptable sites would need to be found to safely store the captured CO_2 if CCS were to be deployed extensively.

The only remaining option for dispatchable low-carbon electricity is nuclear power, which forms a critical element in many decarbonisation strategies of the electricity sector. The following sections explore what the magnitude of the contribution of nuclear power to carbon emissions would need to be in the coming years in order to limit the rise in global temperatures to 2°C, and whether the nuclear industry is up to the task of delivering that contribution.

How CO_2 emissions from the nuclear fuel cycle compare with other energy sources

Unlike the combustion of fossil fuels, the process of nuclear fission does not produce any CO_2 or other GHGs, and thus nuclear power plants do not emit any GHGs directly during operation. However, there are some indirect emissions that can be attributed to nuclear energy, principally due to the use of fossil-based energy sources in the various steps of the nuclear fuel cycle (for example, during uranium mining).

The total life cycle emissions from each electricity generation chain must be assessed to gain an accurate picture. There are many factors that affect these assessments, which can lead to large percentage variations between countries and regions, and over time. However, in general the indirect emissions for each chain are a small fraction of the direct emissions from the combustion of fossil fuels.

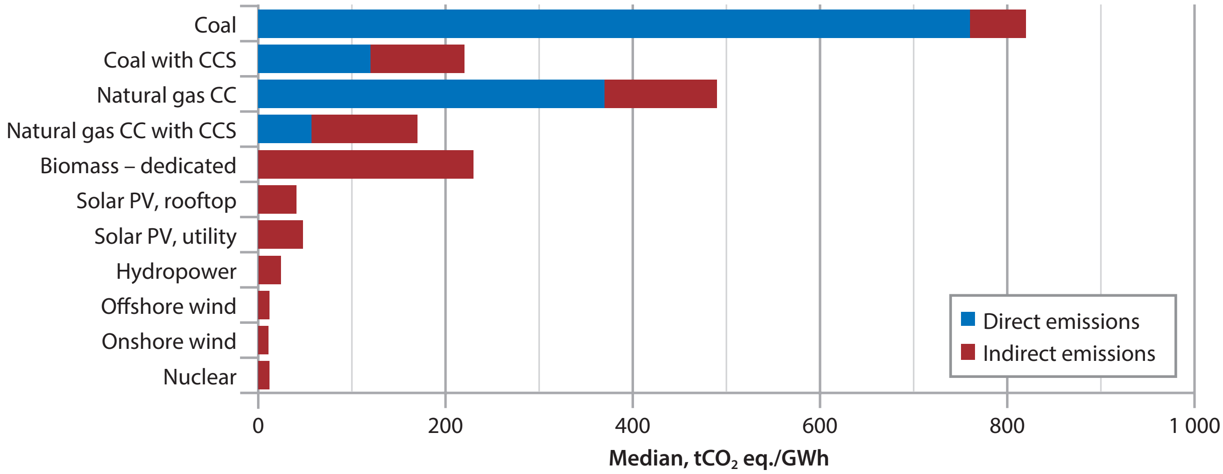
In terms of the indirect emissions from the nuclear fuel cycle, the principal contribution comes from energy used in uranium mining and in uranium enrichment, particularly where this is supplied from coal or oil-based sources. Energy use in these steps varies significantly from case to case; for example, underground conventional mining uses more energy than *in situ* leach mining techniques (where liquid is pumped through boreholes in the ore to extract uranium in solution, avoiding the need for ore extraction).

In the future, different trends may be possible in energy use. If the use of nuclear power expands, lower-grade uranium resources may become economical, leading to somewhat higher energy use. However, low-energy *in situ* mining techniques are also becoming more widespread, and increased uranium exploration can be expected to result in additional higher-grade resources becoming available. In uranium enrichment, the phasing out of the energy-intensive gaseous diffusion plants, replaced by centrifuge plants, has reduced energy use significantly, as well as associated indirect emissions. *The Role of Nuclear Energy in a Low-carbon Energy Future* (NEA, 2012a) provides a comparison of indirect emissions for various nuclear fuel cycles.

Figure 6 compares the GHG emissions per unit of electricity generated from the different full life cycle electricity generation chains averaged across several European countries. It shows that lignite and coal have the highest GHG emissions, with natural gas having the lowest emissions among fossil systems. The indirect emissions of nuclear and renewable energy chains are at least an order of magnitude below the emissions of fossil chains.

Though the issue of CO_2 emissions is directly related to climate change risks, air pollution – principally from fossil fuel combustion – is also a major environmental issue, with more severe and short-term impacts on human health and economic development. As shown

Figure 6: Direct and indirect GHG emissions for different sources of electricity



Note: Lifecycle emissions from dedicated energy crops are relatively high due to the N_2O emissions from agricultural soils. N_2O has a global warming factor that is 298 times that of CO_2 (IPCC [2014], Chapter 11, p. 880).

CC = combined cycle; CCS = carbon capture and storage; GWh = Gigawatt-hour.

Source: Data from IPCC (2014).

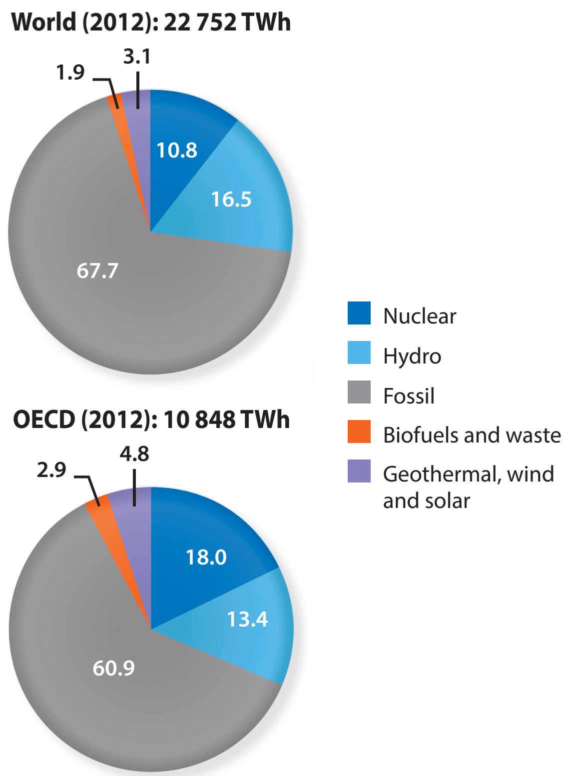
in the box on the following page, GHG emissions and pollution are correlated. In many developing countries with dramatic air pollution problems, the development of nuclear power is driven by the need for clean air technologies rather than for its contribution to the reduction of CO_2 emissions.

The historic and present contribution of nuclear power to reducing carbon emissions

Present nuclear capacity supplied 11% of global electricity production in 2013 and 18% of production in OECD countries (see Figure 7). Its contribution grew rapidly in the 1970s and 1980s, but has since stagnated and even fallen since 1990 as electricity demand growth has outpaced nuclear expansion. Since the Fukushima Daiichi accident, with the subsequent closure of half of Germany's nuclear fleet, and with most of Japan's remaining fleet idle and awaiting authorisation to restart, nuclear generation has decreased globally, dropping to about 10% between 2010 and 2013.[2]

Nuclear power is nevertheless one of the largest sources of low-carbon electricity. Globally, nuclear power avoids each year between 1.2 and 2.4 Gigatonnes (Gt or billion tonnes) of CO_2 emissions per year, assuming this power would otherwise be produced by burning either gas (500 gCO_2/kWh) or coal (1 000 gCO_2/kWh).[3]

Figure 7: Electricity generation by source in 2012, worldwide and for OECD countries



Source: IEA (2014a).

2. In August 2015, a first reactor (Sendai-1) was restarted in Japan and started producing electricity, the first nuclear generation in the country since the shutdown for maintenance and refuelling of Ohi-3 and 4 in September 2013.

3. In its *World Energy Outlook 2014*, the International Energy Agency (IEA) estimates that in 2012, nuclear power worldwide avoided the emissions of 1.7 $GtCO_2$ based on a regional analysis of what generation technology would fill the gap if nuclear power were not present, and that cumulatively since 1971, 56 Gt of CO_2 have been avoided thanks to nuclear power.

Local and regional air pollution and nuclear power

In addition to greenhouse gases that have a global effect on the environment, power generation from fossil fuels also emits pollutants with local and regional air impacts that are of increasing concern, especially in countries with rapid economic and industrial growth, such as China and India. Such air-borne pollution is responsible for high mortality, which the World Health Organization (WHO) estimates at about 7 million deaths annually (www.who.int/mediacentre/news/releases/2014/air-pollution/en/). Power plants are not the only emitters of air pollutants. Industry and transport, as well as indoor sources of pollutants such as fossil fuel cooking apparatus, also contribute greatly to air pollution. The external cost literature focuses on the major groups of air pollutants, which are particulate matter (PM) of varying diameter, sulphur dioxide (SO_2), nitrogen oxide (NO_x) and volatile organic compounds (VOCs). The latter two are precursors for ground-level ozone (O_3). Others include an array of heavy metals and radionuclides. Above certain thresholds, all of them are considered major public health concerns.

The only local air-borne emissions from the generation stage of the nuclear fuel cycle are minor operational radionuclide emissions. The changes in background radiation from these operation emissions are minute. Coal-fired power generation, for instance, releases far more radioactivity (through fly ash emissions) per megawatt-hour (MWh) than nuclear power generation, although the absolute level is very low in this case as well. More significant are the emissions of PM, SO_2, NO_x and heavy metals from all carbon-based power sources, which cause significant damages to public health and ecosystems. When compared to any carbon-based source, air pollutant emissions from nuclear power generation are negligible.

For the nuclear fuel cycle, just as in the case of GHG emissions, most local air pollutant emissions accrue upstream of generation. A majority of these upstream emissions are emitted by the non-nuclear power plants needed to power centrifuge technology for uranium enrichment, involving PM, SO_2, NO_x and volatile organic compounds. These emissions, however, are due to the structure of the electricity system and will decrease as fossil fuel use is reduced. Radon and radioactive dust are emitted into the air during uranium mining, and most of the risk is related to miners. Overall, the damage is minimal. In fact, the very small amounts of air pollutant emissions in the nuclear fuel cycle translate to significantly lower public health concerns than other fuel cycles. Lower local and regional air pollution is a very significant co-benefit to GHG emission abatement resulting from the reduction of fossil fuel use and, in particular, coal use. On the other hand, nuclear power is both a low-carbon source of baseload electricity and a technology associated with clean air.

Life cycle emissions from different power generation sources (mg/kWh)

	Coal		Natural gas		Bioenergy	Nuclear
	Hard coal	Lignite	Combined cycle	Steam turbine		
SO_2	530-7 680	425-27 250	1-324	0-5 830	40-490	11-157
NO_x	540-4 230	790-2 130	100-1 400	340-1 020	290-820	9-240
PM	17-9 780	113-947	18-133	Insufficient data	29-79	0-7

Source: Masanet et al. (2013).

European Commission (1995), *Externe: Externalities of Energy,* Vol. 5, EC, Brussels.

European Environment Agency (2014), *Costs of Air Pollution from European Industrial Facilities 2008-2012,* EEA, Copenhagen.

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IEA (2014), Energy, Climate Change and Environment, OECD/IEA, Paris.

Markandya, A. and P. Wilkinson (2007), "Electricity generation and health", *The Lancet,* Vol. 370, pp. 979-990.

Masanet, E. et al. (2013), "Life-cycle assessment of electric power systems", *Annual Review of Environment and Resources,* Vol. 38, pp. 107-136.

National Research Council (2010), *The Hidden Costs of Energy,* National Research Council of the National Academies of Science, Washington, DC.

Oak Ridge National Laboratory and Resources for the Future (1995), *External Costs and Benefits of Fuel Cycles: A Study by the US Department of Energy and the Commission of the European Communities,* Report 8, ORNL and RFF, Oak Ridge, Tennessee and Washington, DC.

A simple and straightforward assumption to estimate the contribution of nuclear power to global GHG abatement is to substitute nuclear power production with the residual global fuel mix. World electricity generation in 2012 amounted to 22 752 TWh, 2 461 TWh of which was produced by nuclear power and 20 291 TWh by other sources. Global CO_2 emissions from the electricity sector were 13 346 million tCO_2. The average footprint of the total fuel mix without nuclear energy would thus have amounted to 13 346 $MtCO_2$ divided by 20 291 TWh, or 657 gCO_2/kWh. Producing the 2 461 TWh equivalent to nuclear power production by a proportional increase of all other sources would amount to an additional 1.6 Gt of CO_2 or an increase of 12%. In comparison, OECD countries, which host the vast majority of nuclear power plants in operation, emitted 4.8 $GtCO_2$ in 2012 from the electricity sector.[4] Cumulatively, nearly 60 $GtCO_2$ have been avoided globally since 1971, thanks to nuclear power.

Thus, if the present nuclear energy capacity were to be phased out and replaced by remaining technologies in the world's current energy mix, including fossil fuels as well as low-carbon sources such as hydro and other renewables, with an average footprint of 657 gCO_2/kWh, **global annual CO_2 emissions from electricity supply would rise by 12%.** This would make the goal of decarbonising electricity supply an even more challenging and distant prospect. Expanding nuclear power, together with the increased use of hydro and other renewable energies as well as improved energy end-use efficiency, remains crucial for reducing CO_2 emissions.

The future role of nuclear power in a 2°C scenario

Looking to the future, the contribution of nuclear power to limiting global GHG emissions could be even more important than in the past. The recently released IEA/NEA *Technology Roadmap: Nuclear Energy* (IEA/NEA, 2015) takes into account a number of factors that have had a significant impact on the global energy sector since its previous edition in 2010. Many of these factors have not been favourable to nuclear power, including the Fukushima Daiichi accident in March 2011, the global financial and economic crisis, shortcomings in electricity markets and the failure to set up functioning CO_2 markets. The Fukushima Daiichi accident has had a detrimental impact on public opinion and the overall acceptance of nuclear power as a source of energy, causing a few countries to establish policies that will phase out nuclear power. The financial crisis led to the introduction of new financial regulations that have made financing capital-intensive projects such as nuclear new build even more difficult than in the past, while low, long-term interest rates have to some extent improved the competitiveness of nuclear power. Strong policy support for renewable energies such as wind and solar has resulted in a situation of overcapacity and falling wholesale prices in many OECD countries. This has put a break on power generation investments in general. Furthermore, the lack of, or inefficiency of, carbon pricing has penalised investment in capital-intensive low-carbon technologies such as nuclear power, making it even less attractive, while the rapid development of unconventional gas and oil has lessened the urgency of developing new energy technologies in some parts of the world. Cheap shale gas in the United States, for example, has helped to dramatically reduce power sector emissions (as utilities switch from coal to gas) and to lower electricity costs.

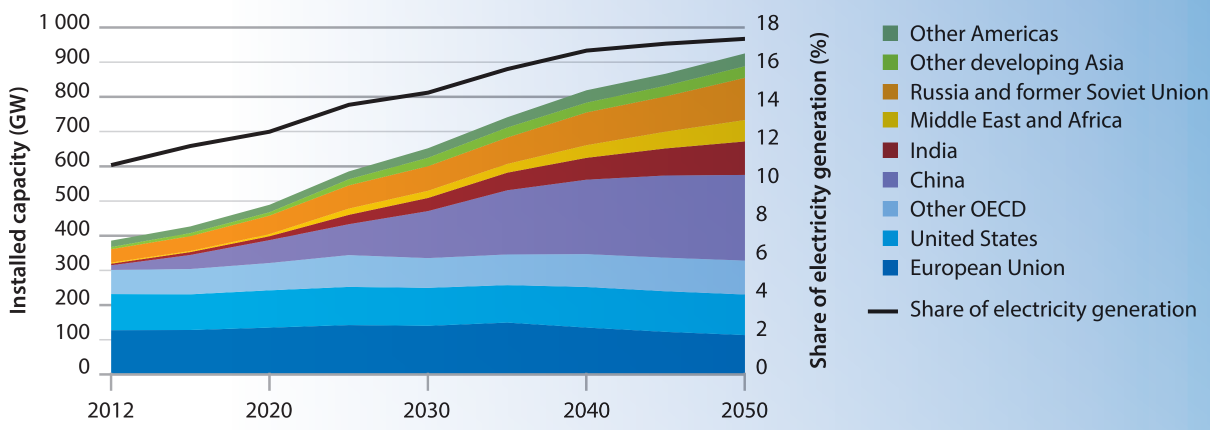
Despite these additional challenges, nuclear energy still remains a proven low-carbon source of baseload electricity, and many countries have reaffirmed the importance of nuclear energy within their countries' energy strategies. It is indeed indispensable in the IEA/NEA long-term vision of a sustainable energy scenario built around the objective of reducing CO_2 emissions in a manner that would limit the increase in global mean temperatures to 2°C. The central vision presented in the 2015 *IEA/NEA Nuclear Roadmap: Nuclear Energy* is based on the IEA's *Energy Technology Perspectives* (ETP) 2015 2°C scenario (2DS) which calls for a virtual decarbonisation of the power sector by 2050. A mix of technologies including nuclear energy, carbon capture and storage, and renewables will be needed to achieve this decarbonisation. In the 2DS, the share of nuclear energy in global electricity production is projected to rise from 11% in 2011 to 17% in 2050 (see Figure 8).

While in these projections, nuclear power is the single largest source of low-carbon electricity, renewables will account for the largest share of production at 65%, with variable renewables supplying 29% of total global electricity production. The high share of variable renewables, which in some countries reaches well over 40%, significantly changes the operating environment of nuclear power and other typical baseload technologies. More flexibility will be required for these latter dispatchable technologies. Operating nuclear power plants in load-following mode is also a possibility and is routinely practised in countries with high shares of nuclear power production, including in France and Belgium, or with high shares of variable renewables, as is the case in Germany. While the power ramping rate of a nuclear power plant is far less than that of a gas-fired peaking plant, it is comparable to or only slightly lower than that of a coal-fired power plant.

Under the 2DS, gross nuclear electricity generating capacity is projected to increase from 390 Gigawatts (GW) today to 930 GW by 2050. The growth in capacity

4. Data from CO_2 *Emissions from Fuel Combustion 2014, and Electricity Information* 2014, IEA, Paris.

Figure 8: Projected nuclear capacity with regional split and share of electricity generation in the IEA *Energy Technology Perspectives* 2015 2°C scenario (2DS)



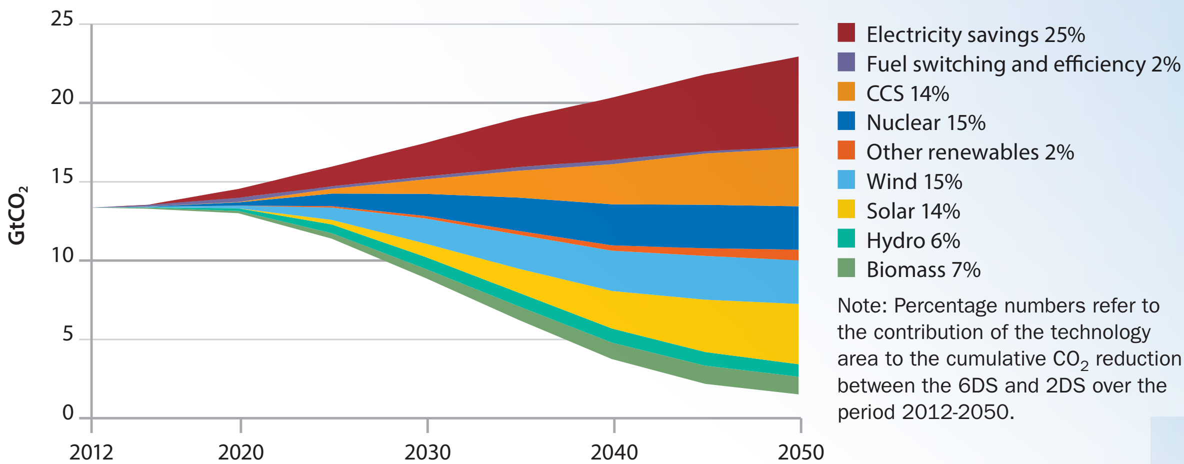
Source: IEA/NEA (2015).

will be essentially driven by non-OECD countries. Currently, OECD countries plus the Russian Federation together account for over 85% of total global capacity. In 2050, these countries combined are forecasted to see only a modest increase in capacity from 350 GW to 400 GW. With a number of countries planning to phase out nuclear and with older plants reaching the end of their operating lifetimes in the next decades, the European Union may see its capacity decline from 2040 onwards, while growth in Russia and Korea is expected to show the largest increase, with capacity in these countries more than doubling by 2050.

Growth in nuclear electricity generating capacity is projected to be primarily led by China, which under the 2DS could surpass the United States by 2030 and, with 250 GW of nuclear, would have more than twice the installed capacity of the United States in 2050. India, which is forecast to be the second fastest growing market for nuclear power, would have about 100 GW of generating capacity in 2050, making it the third largest market for nuclear energy after the United States. Other growth markets for nuclear energy include the Middle East, South Africa and ASEAN countries.

In terms of contributing to the reduction of CO_2 emissions, an IEA analysis (2015a) shows that in order to steer the global power sector from a "business-as-usual" 6DS to a 2DS, nuclear power would have to contribute 15% of CO_2 reductions annually to 2050 (see Figure 9). With its current large base of generation, nuclear power would therefore provide the largest individual contribution of any single technology to emission-free energy.

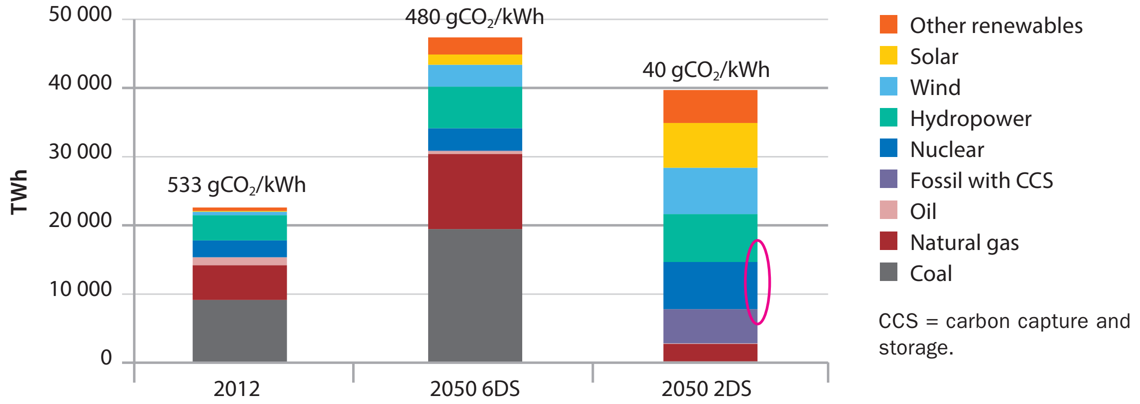
Figure 9: Emissions reductions required in the power sector by 2050 to move from the 6°C scenario (6DS) to the 2DS



Note: Percentage numbers refer to the contribution of the technology area to the cumulative CO_2 reduction between the 6DS and 2DS over the period 2012-2050.

Source: IEA (2015c).

Figure 10: Shares of different technologies in global electricity production until 2050 in the 2DS



Source: IEA/NEA (2015).

Figure 10 shows how the contribution of nuclear power to emission reductions would play out in terms of total global electricity production under the 2DS. Nuclear energy would represent the single most important low-carbon electricity generating technology by 2050. In summary, according to the 2DS projections by the IEA:

- **cumulatively, up to 2050, nuclear power would enable the highest CO_2 emission savings in comparison to other technologies;**
- **in 2050, nuclear power would represent the largest source of low-carbon electricity.**

This emphasises the importance of nuclear energy in the decarbonisation of the world's energy system. But these projections are only those of an ambitious scenario. In the absence of strong carbon pricing policies, with the current rate of construction of nuclear power plants, and the economics of long-term operation of the existing fleet challenged in many countries, by either low wholesale prices driven by subsidised renewables or by cheap fossil fuel alternatives, **nuclear power is not on track to fulfil its potential as one of the main decarbonising technologies.**

Although the stable operating costs of nuclear power make it an attractive solution for long-term competitive power supply, financing such capital-intensive investments remains a challenge, and the IEA/NEA *Technology Roadmap: Nuclear Energy* reviews the most recent options that are being considered. In terms of technology evolutions, the roadmap covers changes made in the aftermath of the Fukushima Daiichi accident to improve the safety of current reactors, and the latest evolutions in newer designs, including small modular reactors based on light water reactor technology. More long-term developments such as generation IV reactors and non-electric applications are also addressed in the roadmap, though their contribution to the overall decarbonisation of the energy system is not anticipated to be significant by 2050.

Can nuclear power be expanded rapidly enough to make a full contribution to combating climate change?

Nuclear power technology has been developing continuously over more than 50 years, and the latest designs for nuclear plants – generation III plants – incorporate the experience gained over these decades in terms of safety, fuel performance and efficiency. While further technological development can be expected, **nuclear power is already a mature technology. The barriers to its more rapid deployment are essentially political, social and financial, rather than technical.**

Before significant nuclear power expansion can begin in any country, clear and sustained policy support from governments is needed, as part of an overall strategy to address the challenges of providing secure and affordable energy supplies while protecting the environment, both in terms of GHG emissions and air pollution. In recent years, a number of governments have reassessed their approach to nuclear energy and now view it as an important part of their energy strategy, while others continue to believe that nuclear should not be part of their energy supply mix.

The 2°C scenario presented in the previous section projects more than a doubling of the current nuclear capacity of 390 GW today to 930 GW by 2050. This would require annual grid connection rates of over 12 GW in the present decade, rising to well above 20 GW in the following decade. However, current grid connection rates are far below these targets, with annual rates between 3 and 5 GW per year since 2010. A comparison with the major expansion of nuclear power in the 1970s and 1980s indicates that, given strong policy support, nuclear power could expand in a sufficiently rapid manner. During the 1970s, nuclear reactor construction projects typically reached 30 per year, peaking even at above 40. This was translated later to annual grid connection rates from 15 and 30 GW between 1980 and 1987, much higher rates than today's. At the beginning of the 1980s, there were 180 reactors under construction in the world, compared to fewer than 70 today. Although these were smaller than many current designs, the technology was also less well developed at that time. In addition, relatively few countries were involved in that expansion, and overall global industrial capacity was much smaller.

The two most important challenges of building a new nuclear power plant today are assembling the conditions for successful financing and managing a highly complex construction process. Because of their high fixed costs, nuclear power plants fare better with stable long-term prices. High fixed costs of investment are common to all low-carbon technologies such as nuclear power, but also hydropower, wind or solar PV. In markets with price risk, nuclear power is at a competitive disadvantage with fossil fuel-based technologies such as gas or coal, even though it scores as well or better on traditional measures of competitiveness such as average levelised costs of electricity (LCOE).

While a robust carbon price would certainly be helpful to decarbonise electricity systems, measures ensuring price stability such as long-term contracts, regulated tariffs, feed-in tariffs (FITs) or contracts for difference (CfD) remain important for all low-carbon generating projects including nuclear power. All successful projects rely on long-term financing. However, for the time being such long-term financing is still based on individual, ad hoc measures rather than on a general investment framework capable of spurring nuclear power growth on a broader basis. This would include a rethink of electricity market design. There are no technology-neutral electricity market designs. The competitiveness of nuclear power will be very different in liberalised electricity markets than in regulated markets.

In construction, where the emergence of a competitive, global supply chain is not yet ensured, the convergence of nuclear engineering codes and quality standards remains a key step to promote both competition and public confidence. In parallel, a number of smaller technological and managerial improvements keep the industry moving forward.

During a time of major technological, structural and geographical shifts, it is important that the global nuclear industry maintains a dynamic of continuous technological, logistical and managerial improvement. There is good reason to be optimistic that given sufficiently stable framework conditions, the nuclear industry will be able to deliver on its contribution to combating climate change and reducing global greenhouse gas emissions.

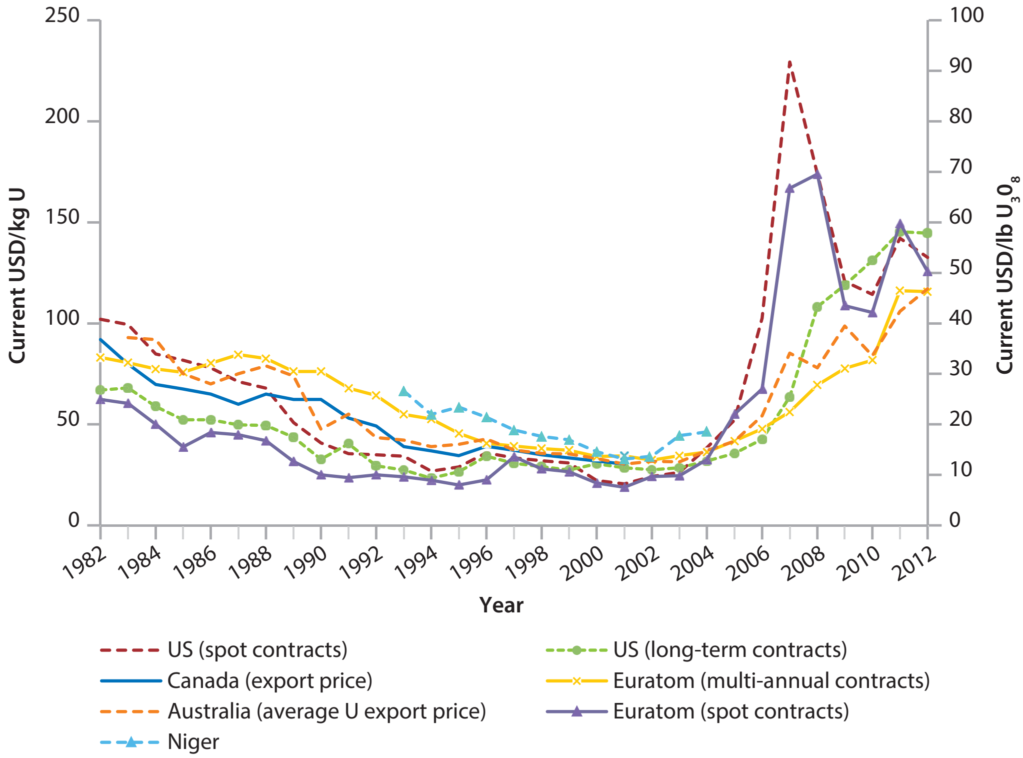
Will uranium supplies be adequate?

A major expansion of nuclear power would require a commensurate increase in nuclear fuel cycle capacities. Nuclear power has a relatively complex fuel cycle, involving uranium mining as well as several industrial processes to prepare the finished fuel assemblies, which, for most reactor types, consist of pellets of enriched uranium dioxide encased in a lattice of metallic tubes. Expanding the use of nuclear power will require increased uranium production, as well as the associated uranium enrichment capacities. Given sufficient time, both production and enrichment should increase to levels that would allow for the fuelling of a deployment of nuclear power plants as ambitious as that projected in the 2DS of the IEA/NEA *Nuclear Roadmap: Nuclear Energy*.

Uranium mining has been affected by a prolonged period of low prices, which lasted throughout the 1990s and only ended in 2003. Reasons for these lower prices included lower than expected nuclear power expansion and past overproduction with the market entry of large stocks of previously mined uranium held by utilities and governments, including former military stocks released through nuclear disarmament following the end of the Cold War. In 2003, uranium prices began to increase, eventually rising to levels not seen since the 1980s, then rising more rapidly through 2005 and 2006 with spot prices reaching a peak through 2007 and 2008, then falling off rapidly (see Figure 11). The Fukushima Daiichi accident precipitated an initially rapid decline in prices that has continued more gradually through to the end of 2013 as reactors were shut down in Germany and gradually laid-up in Japan when the new nuclear safety regime was established. Projects to increase uranium production, implemented before the accident, resulted in increasing production even as demand weakened and the market became saturated with supply, putting further downward pressure on prices through to the end of 2013.

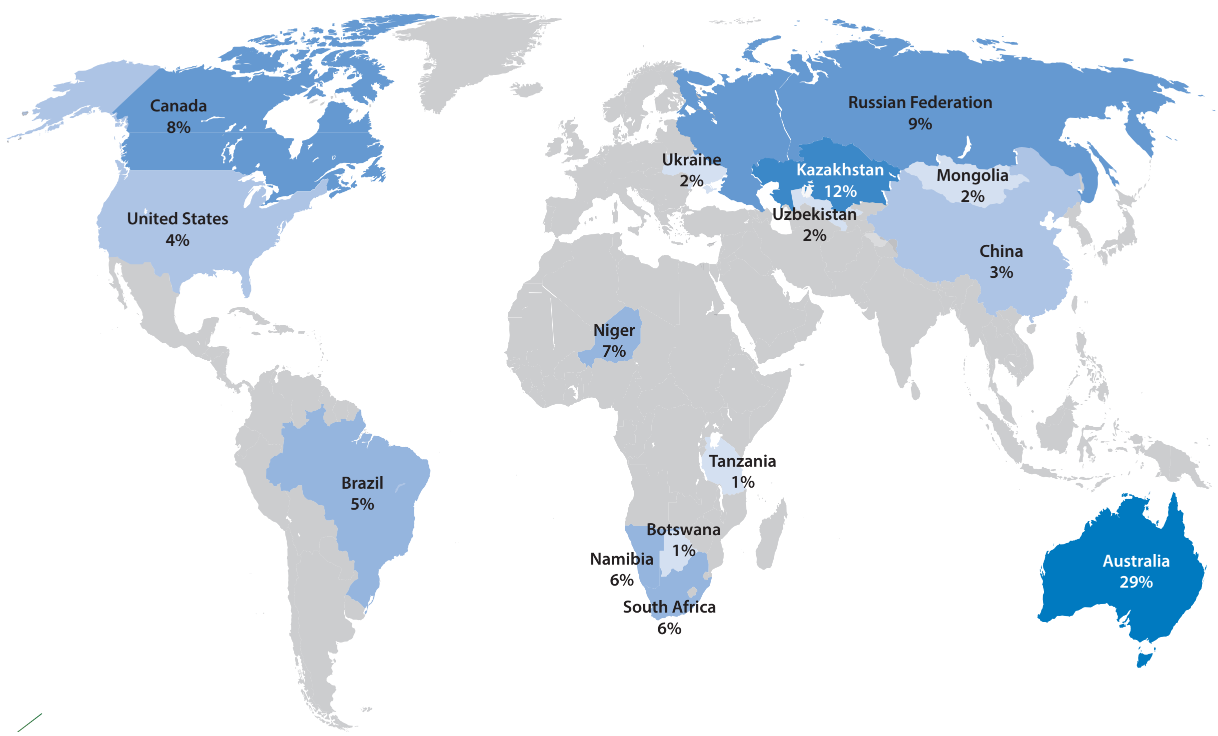
According to the 2014 edition of *Uranium: Resources, Production and Demand* (the "Red Book") (NEA/IAEA, 2014), annual uranium production in 2013 was balanced with annual requirements for the first time since the early 1990s, due to both an increase in production and decreased requirements linked to a great extent to post-Fukushima permanent or temporary shutdowns. Total identified resources at a cost of less than USD 130 per kg of uranium have increased by almost 11% since 2011. Today, there is more than 100 years of supply at current rates of consumption, though investments in mines will continue to be needed. Current identified resources are also sufficient to meet higher growth in nuclear generation. In its high case, the Red Book projects 680 GW in 2035, which is close to the 720 GW projected in the IEA's 2DS for the same period.

Figure 11: Uranium prices, 1982-2012



Source: NEA/IAEA (2014).

Figure 12: The global distribution of uranium resources at production costs of less than 130 USD per kg



Source: NEA/IAEA (2014).

Even if today over 90% of the world's uranium output is produced by only eight countries, resources are widespread around the world (see Figure 12). Furthermore, the nature of the nuclear fuel cycle means that nuclear power plants are not dependent on continuous deliveries of large quantities of fuel. Nuclear fuel is a very concentrated energy source and is easy to stockpile, which explains why many governments view nuclear power as an important component of their strategy to increase the security of their energy supplies.

In the longer run, nuclear fuel also offers important possibilities for recycling, since with current water-cooled reactors, only a small fraction of the uranium is usually consumed in the reactor. This could vastly increase the energy potential of existing uranium stocks and known resources, from a few hundred to several thousand years of nuclear fuel demand. It could also greatly reduce the radiotoxicity of the resulting high-level waste (HLW). Present recycling techniques use sensitive technologies, and are unlikely to expand significantly in the short to medium term. However, the expansion of recycling in the longer term could be facilitated by further technological development of recycling technologies, and the deployment of fast neutron reactors, one of the generation IV reactor technologies currently being developed. Such deployment of advanced technologies would have important implications for the long-term sustainability of nuclear energy, as it could multiply by between 30 to 60 times, and perhaps more, the amount of energy extracted from each tonne of uranium, thereby making available uranium resources sufficient to power fast neutron reactors for several thousands of years.

Safety, radioactive waste management and non-proliferation

Low-level and short-lived intermediate-level wastes account for the largest volumes of radioactive waste, although they only contain a small proportion of its total radioactivity. Technologies for the disposal of such waste are well developed and most countries with major nuclear programmes operate facilities for their disposal or are at an advanced stage in developing them. Governments should continue to work with the nuclear industry to ensure the safe management and disposal of nuclear waste.

Most of the radioactivity generated by nuclear power plant operation is concentrated in the smaller volumes of HLW, which comprise spent nuclear fuel and waste from recycling, for countries that have chosen that strategy. There is, in fact, no immediate requirement to dispose of such materials as they can be safely and easily stored in existing facilities for many years. Nevertheless, countries with existing nuclear programmes are developing longer-term plans for the final disposal of waste, and there is an international consensus that deep geological disposal of HLW is the most technically feasible and safe solution. Although no facilities for final disposal of such waste are yet in operation, some countries are moving ahead to license, construct and operate deep geological repositories (DGRs). Finland and Sweden will have DGRs in operation in the early 2020s and France after 2025.

The safety performance of nuclear power plants and other civil nuclear facilities in OECD countries is generally excellent, certainly by comparison with other energy cycles. Reactors of the latest designs have enhanced safety features and systems, including increased levels of "passive" safety and systems to prevent and mitigate severe accidents. Following the Fukushima Daiichi accident in Japan in March 2011, safety requirements were enhanced for all nuclear operators and hazard re-evaluations or "stress tests" were carried out for all operating nuclear power plants, as well as for reactors under construction. Improvements in areas such as seismic resistance, emergency power supply and decay heat removal systems were recommended in many cases and are in the process of being implemented by operators.

A major expansion of nuclear power would mean nuclear power plants being built in countries without previous experience in nuclear regulation. It is essential therefore that these newcomer countries develop appropriate legal and institutional frameworks, including a strong and independent regulatory system. The International Atomic Energy Agency (IAEA) is engaging with many such countries to develop their institutional capabilities in this regard.

At the same time, it is important to point out that materials or technologies developed for civil use in electricity production could potentially be diverted for military purposes. The IAEA safeguards system and Treaty on the Non-Proliferation of Nuclear Weapons (commonly known as the Non-Proliferation Treaty or NPT) have served well in helping to prevent a diversion of civil nuclear materials and technologies. However, a major expansion of nuclear power, involving many more countries, is likely to require a strengthening of the non-proliferation regime and its implementation. A balance needs to be found between achieving non-proliferation goals and providing adequate supply assurances to countries relying on nuclear power.

Nuclear energy and adaptation to climate change

There is increasing concern that if GHG emissions cannot be reduced quickly enough, climate change will occur on a scale such that ecosystems, economies and industry will be significantly affected. The IEA, for instance, has repeatedly warned that the "door is closing" on the possibility of maintaining global warming under 2°C. Increased use of renewable technologies (wind, solar and hydro) is at the same time likely to make electricity production and distribution systems more dependent on climatic conditions. However, thermal power plants, such as fossil fuel and nuclear power plants, will also be affected by the reduction of water availability and the increased likelihood of heat waves, both of which would have an impact on the cooling capabilities of the plants and on their power output.

Different regions and countries will not be affected by climate change in the same way. Some countries will benefit, others will be negatively affected in terms of electricity production, generation costs and security of supply. According to the latest Intergovernmental Panel on Climate Change report (IPCC, 2014), **the world is ill-prepared for risks from a changing climate.** This includes the energy sector. The IPCC makes the case that these risks can be partly mitigated through adaptation measures.

Given the long operating lives of nuclear power reactors – 60 years for generation III designs – the possible impact of climate change on the operation and safety of these plants needs to be studied and addressed at design and siting stages to limit costly adaptation measures during operation. A study carried out by the NEA provides an assessment of the potential vulnerability of nuclear power plants to climate change (NEA, forthcoming). The availability of water for cooling will certainly become one of the major criteria for siting new nuclear plants. Existing reactors, on the other hand, may require more significant investments to deal with variations in climatic and hydrological conditions that exceed initial design values at the sites where they are located, especially if long-term operation is under consideration. In addition, more severe environmental and regulatory constraints are also being implemented in many countries. This in turn may impose operational limitations on the use of thermoelectric plants and add considerable costs to power plant retrofits, which will ultimately have an impact on the electricity generation cost of such plants.

Climate change projections such as those of the IPCC see increased frequencies of intense heat waves and droughts in some regions. In addition to the impact on water quality and availability, climate change may also lead to extreme climatic events that can undermine the operation of nuclear power plants, for instance, floods, frazil ice and forest fires. Severe storms may be another matter of concern, as they undermine the integrity of the transmission network or contribute to the flooding and transport of debris, challenging the operation of the cooling systems and leading in some cases to the shutdown of the nuclear power plant.

According to the IPCC, floods are expected to occur with greater frequency and severity, as a result of the increased intensity of precipitation events, greater storm wind speeds and rising sea levels. Reactors located on shorelines of oceans and large lakes are more vulnerable to this type of event.

There are different ways in which the resilience of nuclear power plants can be improved in the face of climate change. Protection against extreme floods can be achieved through elevated dykes and water tight access ports into buildings, or rooms housing safety equipment. Technological improvements can be made to existing plants, through minor engineering changes or retrofits of cooling systems. Lowering the water intake at the source, for example, can decrease the temperature sensitivity of the cooling water in the case of a heat wave. Changing the cooling system from a once-through cooling system to a closed-cycle or hybrid system is another possible improvement, and represents a more ambitious retrofit effort.

To guarantee the safety functions of nuclear plants' cooling systems and ensure that threshold temperatures are not reached in the buildings, more efficient heat exchangers or equipment able to operate at higher temperatures than the initial design, and more powerful air conditioning units, can also be installed.

Constructing a new nuclear power plant offers more possibilities to effectively address the issue of cooling water availability, at the stage of design and siting. Because nuclear power plants situated along the coasts are less vulnerable to temperature-related phenomena (though they can be more vulnerable to flooding), coastal sites should be preferred over river sites, if the country has access to the sea. Otherwise, use of closed-cycle cooling reduces the water intake, though not the overall water consumption as a fraction is evaporated. Use of non-traditional water resources, for example municipal water, reclaimed water, brackish water or mine water, can be considered for cooling thermoelectric plants.

Nuclear power plants are thus to some extent as vulnerable to changes in the climate as are other thermoelectric plants, but adaptation measures and innovations in the design can help improve the resilience of these plants.

Conclusions

Global electricity demand is expected to increase strongly over the coming decades, even assuming much improved end-use efficiency. Meeting this demand while drastically reducing CO_2 emissions from the electricity sector will be a major challenge.

Given that the once-significant expectations placed on carbon capture and storage are rapidly diminishing, and given that hydropower resources are in limited supply**, there are essentially only two options to decarbonise an ever increasing electricity sector: nuclear power and renewable energy sources such as wind and solar PV. Of these two options, only nuclear provides firmly dispatchable baseload electricity,** since the variability of wind and solar PV requires flexible back-up that is frequently provided by carbon-intensive peak-load plants. The declining marginal value of electricity production and the security of electricity supply are additional issues that must be taken into account.

Nuclear power plants do, however, face challenges due to their large up-front capital costs, complex project management requirements and difficulties in siting. As technologies with high fixed costs, both nuclear power and renewables must respond to the challenge of acquiring long-term financing, since investments in capital-intensive low-carbon technologies are unlikely to be forthcoming in liberalised wholesale markets. In order to substantially decarbonise the electricity systems of OECD countries, policymakers must understand the similarities, differences and complementarities between nuclear and renewables in the design of future low-carbon electricity systems. The value of dispatchable low-carbon technologies, such as hydro and nuclear, for the safe and reliable functioning of electricity systems must also be recognised.

Should the decarbonisation of electricity sectors in the wake of COP 21 become a reality, nuclear power might well be the single most important source of electricity by 2050, thanks mainly to the contribution of non-OECD countries. COP 21 offers the opportunity to include nuclear energy firmly in future flexibility mechanisms such as the Clean Development Mechanism (CDM), or a potential successor in the post-2020 period, thus enabling nuclear's full potential to reduce climate-change inducing greenhouse gas emissions. To achieve this objective, however, it is important to understand the current and potential contribution of nuclear power in reducing future greenhouse gas emissions, as well as the appropriate measures that governments can take to address outstanding social, institutional and financial issues so as to ensure the necessary expansion of nuclear generating capacity that will make the 2° scenario a reality.

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