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Nuclear Power—Feature Article

A Chinese–French Study on Nuclear Energy and the Environment

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ABSTRACT

This article focuses on the environmental impact of nuclear energy and addresses the following major environmental issues associated with nuclear power generation: ① controlling the radioactive discharge from nuclear installations under normal operation and evaluating their non-radioactive environmental impact (water withdrawals and non-radioactive discharges); ② long-term management of spent fuel and radioactive waste (radwaste), notably that disposed off in geological repositories; ③ prevention and mitigation of severe nuclear accidents and their radioactive releases and; ④ improving nuclear safety to restrict its environmental impact and to contribute toward the public acceptance of nuclear energy. Nuclear energy, with its very low emissions of green house gases, has a unique capacity to generate massive and on-demand dispatchable amounts of electricity. The annual effective radiation dose delivered to the public surrounding nuclear power plants under normal operation is negligible. Considerable efforts have been made to define sustainable management of high-level long-lived radwaste that is disposed in geological formations. The return of experience from severe nuclear accidents in the past has informed and propelled major improvements in several aspects of nuclear energy production—including reactor design and operational management as well as in the development of accident-management guidelines—and has proved to be highly valuable. The environmental risks in the event of a severe accident have been substantially reduced and protocols have been established to minimize the release of radioactive materials and avoid the large-scale evacuation of people in the event of a severe nuclear accident. Efforts must be continued to improve reactor safety and enhance the transparency of the industry and the authorities that support and control nuclear power to further reduce the environmental impact.

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1. Introduction

1.1. Trends in energy demand

The global demand for primary energy, rising at a rate of 2%–3% per year, has doubled during the last 40 years. In 2021, energy-related emissions of CO_2 reached a record high of 36.6 billion tons [1]. Driven by the growth in world population, economic development in several countries, and improvement in the quality of life, an increase in the energy demand is inevitable. A drastic reduction in greenhouse-gas (GHG) emissions from the energy sector is required to limit climate change. This will require a major transformation of the energy sector with a shift from fossil to carbon-free energies. Electrification will be one of the key enablers of the clean energy transition. Today, the world is in the midst of the first true global energy crisis. Faster clean energy transition will help to moderate the impact of this crisis. One way to deliver massive amounts of electricity, while avoiding fossil-fuel combustion, is to use nuclear energy.

A total of 436 nuclear reactors generated 2653 TWh of electricity in 2021. These reactors provide more than 14% of the electrical power supply in each of the 20 countries where they are operational (Fig. 1) [2]. In the European Union, approximately 25% of the electricity was generated using nuclear energy in 2021 [3]. Nuclear power plants (NPPs) provided approximately 44% of the low-carbon electricity generated in the European Union in 2020. Thus, nuclear energy saves 0.5 billion tons of CO_2 emissions every year in Europe—an amount that would

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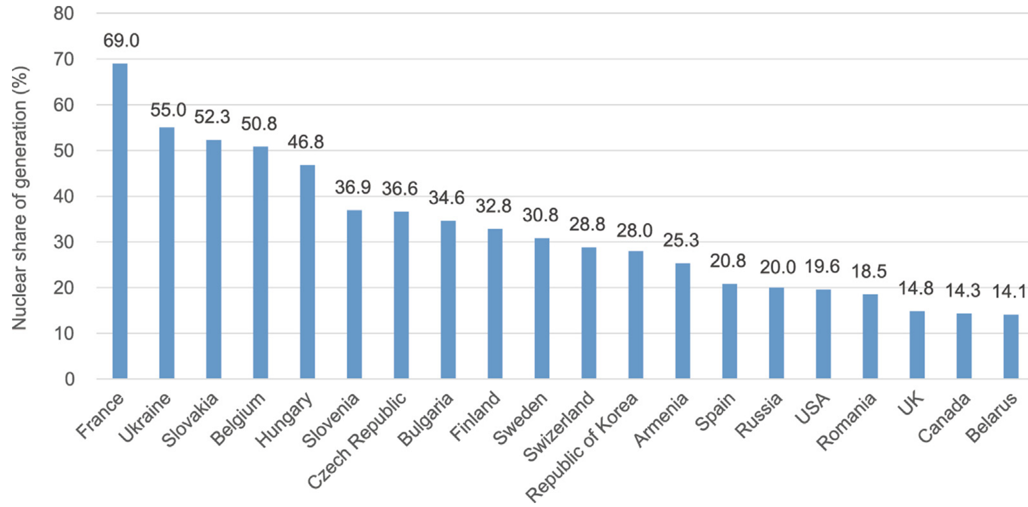

Fig. 1. Countries in which nuclear power accounts for more than one-fifth of the domestic electricity supply (December 2021). Reproduced from Ref. [2] with permission.

otherwise be emitted if the corresponding amount of electricity were produced using fossil fuels. In France, the installed nuclear capacity is 61 GW and nuclear power contributes to 69% of the country's total electricity generation. Under the present European energy crisis, nuclear energy is drawing renewed attention. In February 2022, President Emmanuel Macron announced plans to build six new reactors and to consider the construction of an additional eight reactor units. At the end of December 2022, China's mainland had 55 NPPs with a total installed capacity of 56.99 GW [4]. The outline of "the 14th Five-Year Plan (2021–2025)" clearly states that the installed capacity of nuclear power-in-operation will reach 70 GW in China by 2025 [5]. The medium- and long-term perspective in China is that of a continued increase in electricity demand, a higher proportion of low carbon electricity to reduce fossil energy usage, an accelerated decarbonization of the power supply infrastructure, and the rapid development of clean energy. China's key strategic choice in the long term is to actively develop nuclear power as a pillar of green energy with the premise of safety assurance. The French situation is already in line with this objective and features a nearly decarbonized production of electricity, mainly based on nuclear and non-intermittent renewable hydroelectric power.

1.2. Decarbonization commitment and CO_2 emissions from various energy options

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) put forward a call to stabilize the global concentration of GHGs at a level that would prevent a dangerous change in the climate of the planet [6]. Through the Paris Agreement on Climate Change, which came into effect in 2016, all contracting parties agreed to control the average global temperature rise and keep it well below 2 °C compared with that at pre-industrial levels and pursue efforts to limit temperature rise to 1.5 °C [7]. The report "Net zero by 2050: a roadmap for the global energy sector" published by the International Energy Agency in 2021 pointed out that even if the pledges by the governments were honored fully, they would fall short of what is required to bring global energy-related CO_2 emissions to net zero by 2050. The same report indicated that net-zero commitments would have to be backed by credible actions.

It is generally considered that the proportion of electrical energy will have to be notably increased in the energy mix. This will require the use of more renewable energy sources (wind and solar), which are intermittent or variable, in combination with low carbon dispatchable energy derived from nuclear and hydroelectric plants. In this context, China is planning to raise its nuclear electricity production [8], while France is launching the construction of six new evolutionary power reactor 2 (EPR2) and plans to keep its share of nuclear energy above 50% in the electricity mix.

Nuclear energy clearly constitutes an important option for achieving low GHG-emission levels and complying with climate goals.

Most of the present nuclear energy is based on the fission of uranium atoms. The energy released from the fission of 1 kg of fissionable material contained in nuclear fuel is equivalent to the energy released from the combustion of 2700 tons of standard coal. On a more practical level, this may be illustrated by comparing the amount of fuel that is being used by a typical nuclear reactor to that used by a coal-fired unit, when both are operating at a power of 1 GW over a year. The reactor used 30 tons of a classical nuclear fuel (i.e., 210 tons of natural uranium), whereas the coal unit required 4 Mt of coal. In their full life cycles, annual CO_2 emissions from NPPs, including mining enrichment, fuel fabrication, and reprocessing facilities, account for less than 1% of those resulting from coal-fired power plants, and they are also similar or lower to those associated with the production and integration of wind and solar energy supply chains. Nuclear energy emits no particulates and very low quantities of air pollutants.

1.3. Environmental protection as a requirement of sustainable nuclear energy

In addition to being low in carbon and requiring a relatively limited amount of land, nuclear energy has to be safe and economically competitive. It is also important to examine its environmental impact by considering the operation of NPPs as well as that of nuclear fuel-cycle facilities leading to the release of radioactivity and production of radwaste. It is also necessary to carefully review the specific management of the spent fuel that is periodically discharged from the reactor, its storage, possible reprocessing, and the final disposal of long-lived radwaste.

According to the safety analysis and the environmental impact assessments, the authorized releases from facilities result in radiological and chemotoxic doses to people at levels that are lower than those specified in the regulatory requirements. The national regulations are compliant with International Atomic Energy Agency (IAEA) requirements, but are very often more stringent.

The target is to remain far below the individual effective dose limit of 1 mSv per year to the representative person, as recommended by the International Commission on Radiological Protection (ICRP) [9]. The authorized limits and practical objectives for the release of effluents are becoming lower and more stringent, respectively, as a result of continuous improvements in the operation of nuclear facilities and the treatment of their radioactive material. Most of the reduction is the result of operating with no fuel leakage and therefore a clean primary circuit. For liquids, the process concentrates radioactivity, which can be stored in the form of solid packages. Therefore, less radioactive material is correspondingly released into the environment. These aspects are considered in further detail in the following sections.

Section 2 discusses environmental consequences during normal operations of NPPs and fuel-cycle facilities. It includes a comparison of various electricity-production systems in terms of GHG and atmospheric-pollutant emissions and then discusses issues related to radioactivity associated with normal operation, water consumption, land use, and material requirements in nuclear plants. Section 3 considers spent fuel and radioactive waste (radwaste) management. It introduces the principles, strategy, and framework that are aimed at preventing the environmental impact of nuclear waste. Basically, this management distinguishes the processing of crude radioactive materials, the resulting various classes of ultimate radwaste, and their disposal. The different impacts in the framework of the open and closed nuclear fuel cycle are considered and the environmental protection measures that are taken at each step of radwaste management are also discussed in this section. Section 4 reviews severe nuclear accidents (Three-Mile Island, Chernobyl, and Fukushima) to underline the lessons learned from these events. It describes the successive upgrading that has been introduced in existing NPPs and improvements that have been included in the new Gen III designs to restrict the environmental impact in case of an accident at a nuclear site boundary. Section 5 considers nuclear safety issues in relation to the environment. It discusses the objectives of nuclear safety, which would restrict the likelihood of a nuclear accident, and prevent and mitigate the consequences.

2. Environmental impact during normal operation of NPPs and fuel-cycle facilities

This section deals with the environmental footprint of nuclear energy, compares the impact of this system of electricity production with other electricity-generation systems, and discusses some trends regarding the reduction of impact resulting from the introduction of new technologies. The present section begins with some general considerations about the necessity of using a life-cycle analysis when one wishes to rate different energy systems in terms of their global environmental impact and, in particular, with respect to GHG emissions.

2.1. Measuring the impact of nuclear energy on the environment

There are two ways of assessing the impact of energy-production systems, depending on time and scale, on the environment. When one examines large potential impacts, such as those affecting the atmosphere and those extending over long periods of time, it is appropriate to use a life cycle analysis (LCA) starting with the construction and ending with the dismantling of the facility (over about a century for a nuclear power plant) to evaluate global impact. LCA accounts for the impacts that have been already recorded and those that are expected. When the impact is limited to and around the sites of the facilities and when the time refers to "daily-life" impact, both immediate and long-term deferred impacts are important; however, only the former can be measured, whereas the latter is obtained from projections relying on detailed modeling in combination with experimental data.

Regarding nuclear energy, the discharge into the environment are either chemical or radioactive or suspected to be so. The chemical discharges have to be carefully dealt with. The following will essentially focus on the radioactive discharges that are more specific to the nuclear industry. They can generally lead to the exposure of human and other living beings to ionizing radiation. To perform these assessments, exposures must always be compared with those to natural sources of radiation (the annual average effective dose to the public from natural background radiation in France, USA, and China is 2.9 [10], 3.1 [11], and 3.1 mSv [12], respectively), or to those used for medical diagnostics. It is worth recalling at this point that exposure to medical imaging diagnostics releases, on average, 0.62 mSv per year, a long-duration flight delivers 0.05 mSv [13], and massive utilization of coal leads to significant exposure to radon both from mining activities and around coal-fired plants [12].

Assessments consider all radionuclides and other elements—both natural and man-made—present in the discharges. The radiological and chemical impact on human beings or non-human species may be estimated using simulations. Nuclear instrumentation can detect and characterize very low levels of radioactivity, with a sensitivity that is better than that of instrumentation used to detect chemotoxicity. The tools for measuring trace amounts of chemotoxic substances in the environment are more complex than those used for measuring radioactivity, which makes the *in situ* acquisition of chemotoxic data difficult.

In France and other countries where nuclear facilities exist, a detailed analysis of all the materials, sources, and waste, existing in the nuclear, industrial, or medical facilities of the country is carried out periodically and a program for managing them on the short- and long-term is implemented. Accordingly, assessments of real or potential radioactive discharges can be carried out.

2.2. Effluents, radiological impacts of nuclear energy, and solutions

In general, the doses estimated on the basis of actual discharges of radioactivity from NPPs in France during normal operation were found to be below the dose levels for natural radioactivity, mentioned previously, by more than three orders of magnitude. The levels determined by monitoring gaseous and liquid effluents during the operations of six pressurized water reactor (PWR) NPPs and one heavy water reactor (HWR) NPP in China were found to be well below the regulatory limits and those from natural exposure. Over the years, the liquid and gaseous radioactive releases have drastically reduced in both China and France.

The estimated radiological impact of the nuclear fuel cycle in France during normal operations is shown in Table 1 [14]. The estimated received doses were again quite low—from two to four orders of magnitude below the annual dose obtained from natural radioactivity.

Gaseous and liquid effluent levels monitored during the operation of six PWR NPPs and one HWR NPP in China are displayed in Fig. 2 [15]; it shows the average emission of various type of effluents during 2011–2013 for these seven plants. The maximum discharges were effectively regulated and controlled and, in all cases, were well below the regulatory limits and the levels of exposure from natural sources of radiation. The normalized collective dose to the public from effluents of NPPs in China during 2011–2013 was estimated to be 6.4×10^{-2} man·Sv·(GW·a)$^{-1}$ [15].

The effluents from the nuclear fuel cycle in China are well controlled and documented. Fig. 3 [15] shows the effluent emissions from the nuclear fuel cycle in China during 2011–2013.

Table 1
Radiological impact of nuclear fuel cycle plants since 2015. These were calculated on the basis of actual discharges from the installations and for the most exposed reference groups [14].

Nuclear fuel cycle plants	Distance to site (km)	Estimation of received doses per year (mSv)					
		2015	2016	2017	2018	2019	2020
Andra/CSA	1.7	2×10^{-6}	2×10^{-6}	2×10^{-6}	3×10^{-7}	3×10^{-7}	4×10^{-7}
Andra's Manche repository	2.5	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}	2×10^{-4}
Framatome Romans	0.2	3×10^{-4}	3×10^{-4}	2×10^{-5}	2×10^{-5}	3×10^{-5}	1×10^{-5}
Orano Cycle/La Hague	2.8	2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}	1×10^{-2}
Orano/Tricastin	1.2	3×10^{-4}	2×10^{-4}	2×10^{-4}	9×10^{-5}	8×10^{-5}	4×10^{-5}

CSA: Centre de Stockage de l'Aube, low level–short lived waste repository.

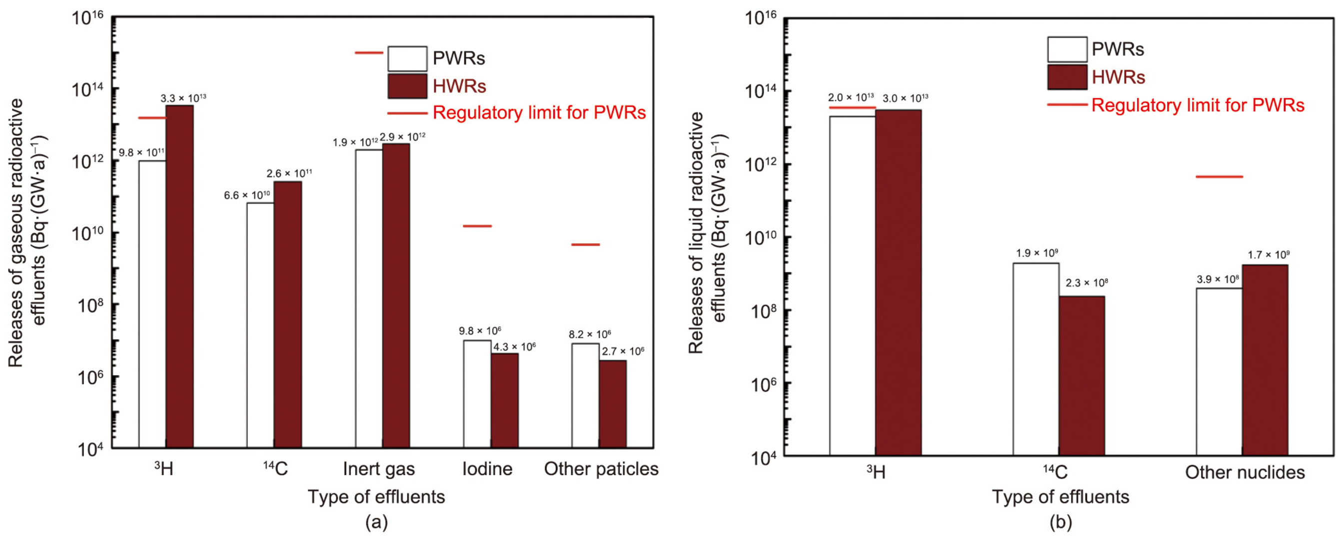

Fig. 2. The average emission of effluents from NPPs in China (2011–2013). Reproduced from Ref. [15] with permission.

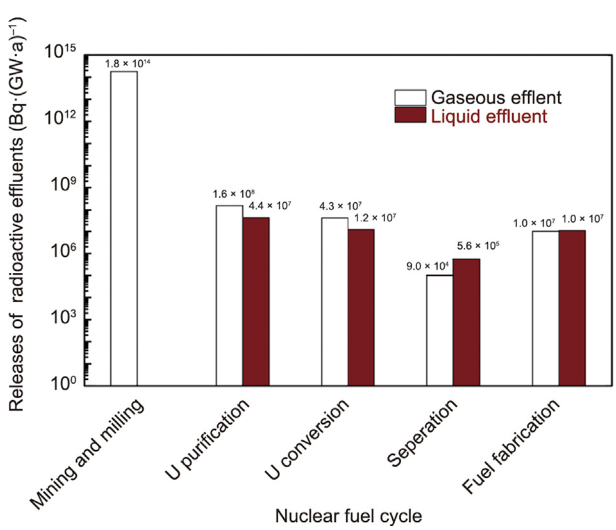

Fig. 3. Average emission of effluents from the nuclear fuel cycle in China (2011–2013). Reproduced from Ref. [15] with permission. U: uranium.

Monitoring the radioactivity in the environment is the main concern of all operators and the safety and environmental authorities in all nuclear countries. In France, radioactivity monitoring is implemented through three remote surveillance networks, whereas the Chinese surveillance system consists of a multi-level environmental radiation monitoring network for the continuous detection of environmental radiation levels during the operation of nuclear facilities.

In European and American countries, epidemiological investigations have been performed near nuclear facilities since the 1950s. However, the results of these investigations showed no significant differences in cancer mortality and childhood leukemia incidence near the sites of nuclear facilities and those in far-away reference areas [16,17].

Around 770 000 consignments of radioactive packages are transported each year in France. This represents approximately 980 000 packages of radioactive substances, or just a small percent of the total number of dangerous goods packages transported each year in France. Most of them concern non-nuclear industries and the medical sector. The bulk of these transportations handles very low sources and waste. Only 12% are related to new and spent fuel and low, intermediate, or high-level radioactive short-lived waste from the nuclear industry. Among the different transportation options (rail, maritime, road, or air), the choice is made based on the characteristics of radioactive materials and the requirements of transportation [14].

In France, local commissions for public information and interaction with stakeholders (CLI) are set up for the most hazardous facilities classified as important for environmental protection (ICPE). Fifty-three CLIs exist in France, including thirty-eight in the neighborhood of nuclear sites. China has established a public communication system featuring central-supervising, government-leading, enterprise-acting, and society-participating to promote popularization of science, public participation, information publicity, public-opinion response, and integrative development.

2.3. Environmental impact of nuclear energy compared with that from other sources of electricity

The environmental impact of power generation depends upon the underlying technologies. In the context of climate change, it is important to consider GHG emissions associated with different technologies. Fig. 4 [18] shows that CO_2 emissions from fossil fuel-fired electrical power plants are one to almost two orders of magnitude higher per kilowatt hour than those produced from nuclear, wind, solar, and hydro-electric plants.

The contribution of nuclear energy to GHG emissions (around 20 $kg{\cdot}(MW{\cdot}h)^{-1}$) is 40 and 4 times lower than that from coal-fired power plants and photovoltaic electricity farms, respectively. The values shown in Fig. 4 show that the $gCO_2{\cdot}(kW{\cdot}h)^{-1}$ from nuclear energy is very low, and therefore it stands out as a low carbon energy source. In addition, nuclear energy also generates very low levels of SO_x and NO_x compared to those from fossil-fueled electrical power plants.

Next, it is interesting to examine the direct land used by the different technologies. For nuclear power plants, it is relatively low as can be seen from Table 2 [19,20] gathering the footprints relating to the various energy systems on an area per megawatt basis. LCA indicates that nuclear power requires a lesser amount of land. The comparison would be even more favorable to nuclear power if it were carried out in terms $m^2{\cdot}(MW{\cdot}h)^{-1}$ because the load factors of the different energy sources are notably different. The typical load factor of onshore wind energy in France is approximately 23% and that of solar photovoltaics (PV) does not exceed 13%. The comparison should also take into account the necessity to compensate for the variability inherent to wind and solar energies, which requires additional production or storage capacities and consequently additional land use.

Nuclear power is a favorable option in terms of land occupation and the preservation of biodiversity as it reduces land artificialization.

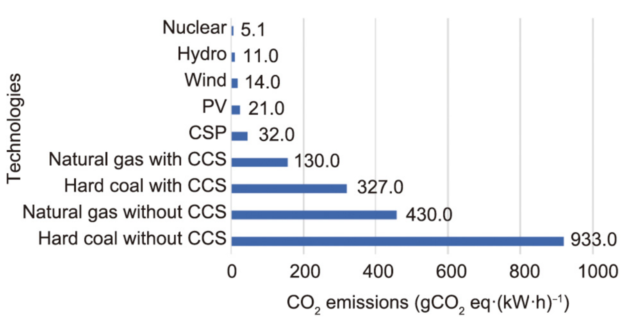

Fig. 4. Life cycle CO_2 equivalent (from selected electricity supply technologies). Arranged by increasing median $(gCO_2eq{\cdot}(kW{\cdot}h)^{-1}$, one $gCO_2eq{\cdot}(kW{\cdot}h)^{-1}$ is the equivalent of emitting one gram of CO_2 per kilowatt hour $(gCO_2{\cdot}(kW{\cdot}h)^{-1}))$ values. Reproduced from Ref. [18] with permission. CCS: carbon capture and storage; CSP: concentrated solar power, PV: solar photovoltaic.

The figures proposed for hydro-electric power seem to be high; however, power generation, in several cases, is one of the various purposes of a dam (water is also stored for irrigation, domestic and industrial uses, shipping, and flood protection). The land use is owing to the extent of the reservoir where one is needed. Regarding energy supply, the purpose of the reservoir is not only the delivery of power but also the flexible storage of electricity, which is an important asset for increasing the capacity of the electrical network in response to demand.

The direct land use from NPPs is quite low. Thus, nuclear power is a favorable option with regard to land use and, consequently, to preserve biodiversity, which is undermined by land occupation and artificialization.

It is interesting to compare amounts of materials used by the different technologies. This may be done in terms of $kg{\cdot}MW^{-1}$, given the mass of material per installed MW (Fig. 5 [21]) and in a second stage in terms of $tons{\cdot}(TW{\cdot}h)^{-1}$, which corresponds to the amount of material per electrical energy produced on an LCA basis (Fig. 6). The utilization of materials by the various energy sources is represented graphically in Fig. 7.

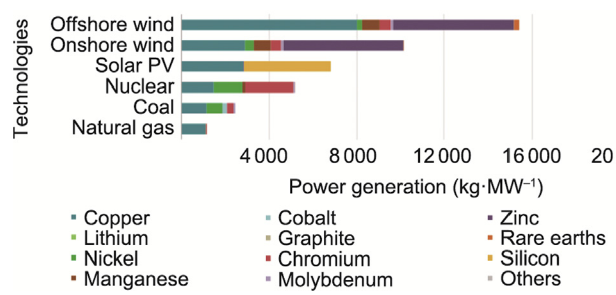

Fig. 5. Material required (fuel excluded) for various technologies, expressed in terms of mass of material per unit installed power in MW. Reproduced from Ref. [21] with permission.

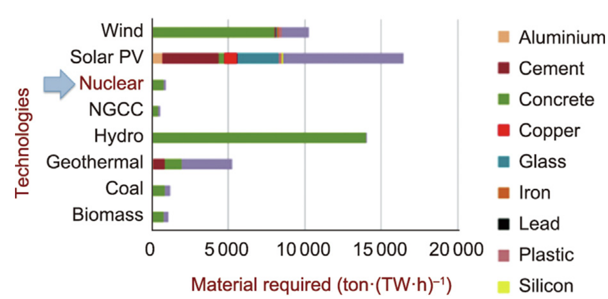

Fig. 6. Material required (fuel excluded) for various technologies quoted in terms of $tons{\cdot}(TW{\cdot}h)^{-1}$. Reproduced from Ref. [20] with permission. NGCC: natural gas combined cycle.

Table 2
Land use intensity per MW of installed power [19,20].

Energy technology	Installed power ($m^2{\cdot}MW^{-1}$)	System boundary/energy resource extraction area plus power plant site
Hydropower/reservoir	20 000–10 000 000	Site of reservoir and generators.
Solar PV	10 000–60 000	Site of PV system, which includes the area for solar energy collection. PV systems on pre-existing structures have essentially no net increase in land use.
Solar thermal	12 000–50 000	Site for concentrating solar thermal system, which includes the area for solar energy collection.
Wind	2 600–1 000 000	Low-end value is for the site only, which includes the physical footprint of the turbines and access roads. The high-end value includes the land area between turbines, which is typically available for farming or ranching.
Nuclear	6 700–13 800	Low estimate is site only. High estimate includes transmission lines, water supply, and rail lines, but does not include land used to mine, process, or dispose off the waste.

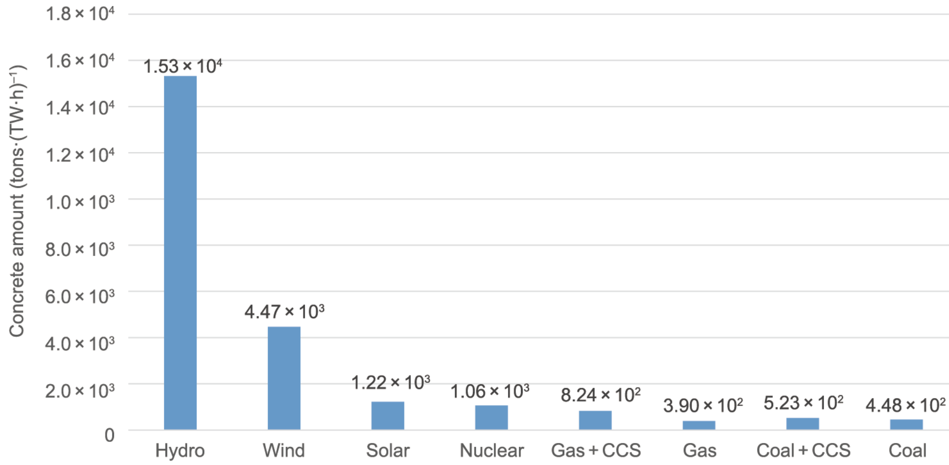

Fig. 7. Amount of concrete (tons·(TW·h)$^{-1}$) deduced from a life-cycle analysis. Reproduced from Ref. [22] with permission.

Fig. 5 indicates that nuclear plants require more material per megawatt, in particular for their civil engineering, than natural gas and coal thermal plants. However, nuclear plants use less material than solar PV and onshore and offshore wind turbines. The values quoted in this figure need to be complemented by those shown in Fig. 6, which refers the amounts of material per unit of energy produced over the lifetime of a particular plant. This chart (Fig. 6) takes into account the load factor which is relatively low for solar PV and higher for wind turbines (in France, the load factor is approximately 0.13 for solar PV, 0.23 for onshore wind, and 0.35–0.40 for offshore wind). The data appearing in Fig. 6 have to be updated, but the estimates given in this figure will not change much. They are included here because they provide a better indication of the respective merits of the various technologies in producing energy.

According to Fig. 6, onshore wind farms require relatively more concrete per terawatt hour than NPPs because of their relatively lower load factor. Offshore wind farms laid on the subsea ground require much more cement, aggregate, and rockfill for the construction of the foundation on the subsea floor if a gravity basement is selected. The present experience of floating offshore wind farms is too brief to produce a sound figure for the required anchorage foundations. However, the volume of aggregate and rockfill will be far lower than that for masts laid on the subsea ground.

The solar PV farms as well as concentrated solar energy farms require steel and concrete. In both cases, there are slabs of reinforced concrete and steel supports. The low concentration of power associated with a low load factor give rise to a relatively high demand of material per terawatt hour delivered. It should be mentioned that the maintenance of PV and wind farms has not been considered here.

The utilization of concrete in hydro-electric power plants and by other energy sources is reflected in Fig. 7. The material demand for hydro power is about 1.53×10^4 tons·(TW·h)$^{-1}$ [22]. In fact, the estimates for hydro power are not very relevant for the reasons mentioned above, because the need for aggregate and cement depends upon the availability of rock and aggregate close to the dam site. Many large dams are embankment dams because these are the cheapest option. However, the volume of concrete used in embankment dams is significantly dependent upon the size of the maximum flood and the installed power.

The relatively short service life of both solar and wind technologies is also reflected in Fig. 7, where the amount of concrete is measured with respect to the total amount of energy generated during the whole life of the plant. Dismantling and reconstruction are or will be relatively frequent and the recycling of at least part of the materials is an open question.

2.4. New technology perspectives

Electricity and heat generation are responsible for over 40% of the global CO_2 emissions from fuel combustion, with coal-fired plants emitting over 70% of the associated emissions (from 1971 to 2020 for over 203 countries and 42 regions) [23]. It is of paramount importance to drastically limit and, if possible, replace fossil energy used in these sectors.

Two main routes can be considered to reduce carbon emissions from burnt fuels: carbon capture and storage (CCS), and direct generation of carbon-free electricity. CCS faces three challenges: reducing costs, improving public acceptance, and developing storage capacities. Presently, only 42.5 Mt·a^{-1} of CO_2 is stored in the world, (i.e., more than one hundredth of what would be needed in 2050 [24]). The possibility of CO_2 storage on the scale required has not been demonstrated. Carbon storage can only reduce CO_2 emissions but will not be enough to achieve carbon neutrality. On the other hand, leading technologies being considered to generate carbon-free electricity are wind and solar power, but they share the same limits of intermittency. From this article, it can be concluded that only hydro—for which available sites are scarce—and nuclear power have the potential to generate dispatchable, carbon-free electricity.

3. Spent fuel and radwaste management

A specificity of the nuclear industry is that it uses fuel that does not disappear when "burned." The nuclear industry cannot manage waste in the same way as the fossil-fuel industry, i.e., in the form of GHG emissions into the atmosphere on one hand and accumulation of solid residue deposits on the other. Fission and other nuclear processes inside the nuclear fuel produce short- or long-lived radionuclides, (i.e., radioactive isotopes). The chemical properties of these radionuclides differ drastically. The nuclear fuel radioactivity increases—from a few kBq·cm^{-3} (fresh fuel) to 10^{10} and 10^{11} Bq·cm^{-3}—when it is downloaded from reactors (spent fuel). Management of radwaste is then a part of the nuclear fuel cycle and this task is implemented in industrial channels operated in all nuclear countries. A great majority of the radwaste (the less radioactive and more abundant) is finally disposed off in surface/sub-surface repositories; the remainder (the more radioactive and less abundant) is kept in storage pending the launching of deep geological repositories. Despite the high level of care taken in such operations, the sorting out of radioactive matter from spent fuel and the mere handling of radioactive material leads to the immediate release of a few radionuclides into the environment. In a long-term future (from centuries up to thousands of centuries), one may expect the return of some radionuclides to the biosphere from the disposed-off radwaste in the geosphere. However, safety measures must be undertaken today to keep the radiological impact within the normal variations of natural sources of radiation, irrespective of geography and timescale.

This section focuses on the environmental impact associated with the management of radwaste.

3.1. Principles, strategies, and framework of radwaste management to prevent environmental impact

The first basic management principle of radwaste is inter-generational equity, i.e., our generation should not leave the burden of our technical decisions to future generations. Our environment is the common property of all generations. Leaving a clean environment to the next generations is a major duty of the present one, particularly with respect to restraining the addition of man-made radioactivity to the natural radioactivity. The second is the inter-generational right of access to information so that each generation remains informed about the practices of radwaste management at national and international levels. To restrain the release of radionuclides into the environment, operators have to implement the best available technologies (BATs) for radwaste management in all nuclear facilities to minimize radwaste production.

The global strategy defining radwaste management is to ① maximize in-reactor burning of radioactive materials, ② concentrate and confine radionuclides and toxics and, ③ finally, dispose off the ultimate radwaste in repositories. These engineered infrastructures are designed to isolate radwaste from the biosphere in such a way that the time of return of radionuclides to the living world would be as far-off as possible in terms of centuries or thousands of centuries.

The frameworks of radwaste management are defined at the international level mainly by the Joint Convention (IAEA, INFCIRC/546, December 24, 1997) on the safety of spent-fuel and radioactive-waste management and the basic safety standards applicable to ionization, radiation, protection, and safety of radiation sources (IAEA Safety Standards Series, No. GSR Part 3, 2014), which are taken into account by all countries.

3.2. Specific characteristics and classification of radwaste

Nuclear countries have adapted the classification of nuclear radwaste to their national industrial channels, and the ensuing management practices of radwaste categories may differ to some extent, but there are several commonalities. The traditional denominations used are as follows: very low-level waste (VLLW), low-level long-lived waste (LLW-LL), low and intermediate-level short-lived waste (LILW-SL), intermediate-level long-lived waste (ILW-LL), and high-level long-lived waste (HLW). The type of highest activity radwaste (ILW-LL and HLW) depends on the decision made by nuclear countries with regard to the management of spent fuel.

Nuclear energy produces much smaller amounts of waste per megawatt hour compared with fossil energies. This is linked to the energy density of nuclear fuel, which is thousands of times higher than that of fossil fuels, depending upon the burn-up of the nuclear fuel and on the reactor type. The main environmental impact that one can expect from radwaste management is linked to public exposure to ionizing radiation and to modifications of the quality of aquatic and terrestrial ecosystems, possibly leading to a loss of biodiversity. The doses (external and internal) obtained after the release of gases or liquids containing radioactive or toxic substances are estimated according to tested methods and the results are submitted for international scrutiny (Round Robin tests). It is less easy to quantify the impact of radioactivity and toxics on ecosystems because data on the non-human biosphere are still lacking. Usually, human beings are more sensitive to radiation hazards compared to other species. Non-human species would be suitably protected when human beings are adequately protected against radiation.

Regarding the environmental impact, a distinction between short-lived and long-lived waste is crucial. Indeed, the former is generally disposed off in surface/sub-surface facilities and its environmental impact can logically be of direct concern to our generation. Long-lived waste is disposed-off in deep geological repositories, down to several hundred meters, and its expected environmental impact is seen as possibly occurring in the far future. Notwithstanding, both strategies are subjects of careful investigation. An additional distinction considers the origin of radionuclides present in radwaste: natural (uranium, thorium, and their daughters) or man-made (actinides, fission products, and tritium). Radwaste containing only uranium originates from the front-end nuclear cycle. Radwaste linked to the back-end of the nuclear cycle contains, in addition, several other radionuclides.

3.3. Processing and discharge of radwaste

The risk from radwaste management to the environment is lowest when the amount of crude radwaste to be processed is the lowest. The minimization of the radwaste quantities starts by sorting out the radioactive substances produced in all facilities. It allows the elimination of the radwaste that is characterized by a radioactivity that is at the detection limit or under the clearance level, if they exist. The next step is the packaging of radwaste to reduce the dispersion of radionuclides in transport operations and storage. There are several packaging techniques for finding the economic optimum between any immediate environmental impact due to packaging and storage and delayed environmental impact due to geological disposal. In all cases, BATs are usually implemented.

Nearly all countries have clearance levels or detection limits for radwaste, which lead to the de-categorization of potential radwaste in non-radioactive material. Such releases of materials for public uses can result in a substantial reduction of the most-abundant VLLW. They concern the concepts of exemption and of clearance of radioactive materials. The first concept relies on the definition of activity concentration ($Bq{\cdot}g^{-1}$ or $Bq{\cdot}cm^{-2}$ or total activity) for designed limited quantities of matter (1 ton for instance), below which no control is necessary to assure radiological protection; this is because their radiological impact is negligible when, for instance, recycled materials are used. The second concept also relies on the consideration of the activity concentration ($Bq{\cdot}g^{-1}$ or $Bq{\cdot}cm^{-2}$ or total activity) less than, or equal to, those for exemption for possible re-use of any materials decontaminated or not. Universal clearance levels are such that for any pessimistic scenario the radiological impact is less than 0.01 $mSv{\cdot}a^{-1}$ (recommended dose by IAEA- RS-G-1.7 and Directive 96/29 (Euraiom)). Such low doses would not have any impact on the environment.

The other way to minimize radwaste quantities is the recycling of LLW such as metallic materials. They can be melted in such a way that the processes lead to their decontamination. Melting is the only process that leads to homogenization of the radioactivity of the material used for recycling, later facilitating their monitoring. It seems impossible to reduce the quantities of other radwaste produced along the fuel cycle by recycling.

Gaseous or liquid releases to the environment are the main sources of immediate environmental impact, as already indicated. In waste management, it is the question of the effluents associated with the packaging of primary waste. Gaseous discharges are decontaminated by filtration and/or by washing with appropriate aqueous solutions, if necessary. This leads to solid secondary waste and decontaminated gases, which are released into the atmosphere according to regulatory requirements. The liquid effluents originating from the processes implemented in nuclear facilities are treated locally to produce decontaminated liquid solutions, which are released into the environment in compliance with the authorizations.

3.4. Disposal of radwaste

For radwaste with low or very-low activity (less than 10^2 $Bq{\cdot}g^{-1}$), even containing trace amounts of long-lived radionuclides (such as uranium), the landfill disposal concept (on surface or sub-surface) is generally adopted by most nuclear countries around the world. In general, there are large quantities of such radwaste. IAEA recommends surface/sub-surface management by trenching. France will have to dispose off more than 2.0×10^9 m^3 of VLLW, which exceeds the capacity of the present sub-surface repository by a factor of 4 to 5 [25]. A major part of VLLW will come from the decommissioning of nuclear reactors and facilities. There are four operational landfill facilities for VLLW disposal in China. Around 10 000 m^3 of VLLW has been disposed off so far [26].

Short-lived radwaste (10^2–10^6 $Bq{\cdot}g^{-1}$) mainly originates from NPP operations. Some contain very small amounts of long-lived radionuclides. Packages of short-lived radwaste are in general disposed off in specifically engineered surface/subsurface facilities. The depth of sub-surface facilities could be of several tens of meters. Packages take the form of steel or concrete drums or large containers, sealed or not. Safety and environmental authorities define the radiological capacity, and the capacity for each radionuclide or toxic material, which can be accepted up to the closure of the repository. The capacity limitations consider the perspective that they could return to a greenfield status after several hundred years when short-lived radionuclides will have disappeared, but not the long-lived ones. France will have to dispose off approximately 1.5×10^9–2×10^9 m^3 LILW-SL originating from the present nuclear fleet [25]. This type of waste, which corresponds to low-level waste in China, can be disposed off in near-surface disposal facilities [27].

The LLW-LL (10–10^5 $Bq{\cdot}g^{-1}$) cannot be accepted in repositories for LILW-SL or LLW because it contains some radionuclides such as ^{36}Cl or ^{14}C, which are difficult to confine by engineered or natural barriers and are present in quantities that are too large to be disposed off in deep geological repositories. If a sub-surface disposal is considered, the site has to be selected according to the requirement of confining these radionuclides for a very long time. Therefore, the depth of disposal must be sufficient to guarantee a well-functioning natural barrier of adequate thickness. The total amount of LLW-LL expected from the present nuclear fleet is around 190 000 m^3 in France. The agency Andra continues to characterize a potential site in clay. In China, the radwaste (10–10^5 $Bq{\cdot}g^{-1}$) containing long-lived radionuclides at lower levels of activity concentration than the upper limit of LLW belong to LLW and the waste containing long-lived radionuclide at higher levels of activity than the upper limit of LLW would be categorized as "intermediate-level radioactive waste".

According to nuclear and geological experts, the isolation of ILW-LL (10^6–10^9 $Bq{\cdot}g^{-1}$) and HLW (10^9 $Bq{\cdot}g^{-1}$ and more) from the environment and confinement of radionuclides can be assured in deep geological formations combined with multiple engineered barriers. The basic reason for choosing geological disposal for this radwaste comes from sociological considerations regarding the stability of society, which cannot be assured for more than a few centuries. There are several concepts for deep repositories depending upon the geological rock formations chosen as sites, for instance clay or granite. Up to now, only Finland has drilled shafts in granite to establish an underground spent nuclear fuel repository (Onkalo) down to approximately 450 m. In France, over-packed nuclear glasses will be deposited in horizontal tunnels and over-packages of ILW-LL will be deposited in large cavities excavated in the (vertical) center of an extended horizontal 130 m-thick clay layer (Callovo-Oxfordian clay). Ten other nuclear countries have been in a more-or-less active preparation stage for several decades to find a site for disposal of nuclear waste. Implementation of geological repositories spans long periods of time owing to the extensive processes of site characterization, analysis, and final selection, involving large-scale scientific studies, as well as political and public participation in the decision-making process. International organizations (European Union, Organization for Economic Co-operation and Development-Nuclear Energy Agency (OECD-NEA), and IAEA) have set up joint international research projects in this regard.

According to the present fuel-cycle strategy, it is expected that approximately 72 000 m^3 of ILW-LL and 12 000 m^3 of HLW will need to be placed in the repository. This radwaste is in storage pending the commissioning of Cigeo in France [25]. As specified in the current radwaste classification system in China, the "intermediate level waste" is defined as waste that will be disposed off in intermediate depth facilities. There are plans to develop an underground research laboratory (URL) and a geological repository by approximately 2020 and 2050, respectively [28].

Large quantities of uranium radwaste from uranium mining consist of tailings and waste residues from ore processing (to get the yellow cake) and additional technological waste. This radwaste contains uranium and all its non-volatile daughters as well as other chemicals (^{226}Ra is the only one present in a sizable amount). In France, uranium mining was operational for 50 years at 250 sites producing 80 000 tons of uranium from 52 million tons of ores; this has now been discontinued. Eighty sites for uranium mining have been constructed in China and approximately thirty of them have been decommissioned. Mining radwaste accounts for 34 million tons of excavated rocks, including tailings and 11 million tons of mining residues [26].

3.5. Open/closed nuclear fuel cycle

Environmental impact owing to waste management is linked to the radionuclides released from reactors and facility operations (including mining) and the quantities of radwaste produced. These indicators enable comparisons between nuclear fuel cycles. The estimates from the French Commissariat à l'Energie Atomique (CEA) for open fuel cycle (OFC) and closed fuel cycle (CFC) with single recycling of plutonium actually operated in France are as follows. Reprocessing in CFC releases noticeable quantities of noble radioactive gases and tritium (5.50×10^{11} $Bq{\cdot}(TW{\cdot}h)^{-1}$) into the atmosphere as well as some slightly radioactive liquids into the sea (2.24×10^{10} $Bq{\cdot}(TW{\cdot}h)^{-1}$), but without significant radiological impact. The production of LLW and LILW-SL does not differ significantly for the two fuel cycles; however, a CFC produces four times more ILW-LL than OFC (1.18 versus 0.32 $m^3{\cdot}(TW{\cdot}h)^{-1}$, respectively) and it is the reverse for HLW (0.36 versus 1.17 $m^3{\cdot}(TW{\cdot}h)^{-1}$, respectively) [29,30].

3.6. New technologies

If electricity was produced by Gen IV fast neutron reactors, such as a sodium fast reactor (SFR), this would lead to a drastic reduction of releases and waste production owing to the elimination of all the operations of the front-end cycle. An SFR fleet at equilibrium can be operated using its own spent fuel and additional depleted uranium and has the possibility to burn minor actinides. Theoretically, the multi-recycling of plutonium and uranium and minor actinide transmutation, which require additional steps in spent-fuel reprocessing, would allow the shortening of the length of time for hazards from HLW from several hundreds of thousands of years to only hundreds of years. In France, the feasibility of such an extraction of minor actinides has been demonstrated at the pilot level on a kilogram scale. The extension to the industrial scale would become possible if and when Gen-IV fast reactors come to maturity. It has been shown that transmutation of minor actinides produced by an SFR fleet is only possible if all the SFRs of the fleet are able to transmute actinides. A fleet of fast reactors would essentially burn depleted uranium, circumventing the front-end of the fuel cycle—in particular uranium ore mining—thereby further reducing the environmental footprint of nuclear energy systems. Table 3 [30] provides a comparison based on an LCA of the French nuclear-installed base.

Implementation of recycling substantially reduces the volume of high-level waste, which determines the size of geological repositories required for accommodating its high residual thermal power. With recycling, the repository volume and surface are divided by a factor greater than two.

Regarding the environment, the higher is the amount of radioactive matter submitted to chemical processes, the greater is the risk of radionuclide release.

Another method for the transmutation of minor actinides is under investigation and uses an accelerator-driven-system (ADS) that couples a reactor and an accelerator. In ADS, criticality of the reactor can be achieved by the addition of an external source of neutrons, generated by spallation with an external beam of accelerated protons. High flux of neutrons allows the transmutation of long-lived minor actinides into short-lived fission products. However, technical challenges faced by these technologies are significant both in physics and chemistry fields. The most advanced project is the Myrrha in Belgium. During the last ten years, France has developed an ambitious research program that will be ready to launch the first commercial SFR in the frame of Gen-IV around 2040; however, this target has now been abandoned. The ambition of China is to have its first commercial SFR by 2035 and to deploy large-scale construction around 2050. An ADS project has also been initiated in China.

The assessment of the radiological and chemical impact on people is the responsibility of the radiation- and health-protection authorities. These assessments are based on reliable scientific data and on tested models of irradiation and incorporation of radionuclides. However, research and development (R&D) continues to reduce uncertainties on the data and to improve the models and this effort needs to be maintained. Estimates of ionizing radiation impact on ecosystems are less well supported, and the R&D effort on this subject needs to be increased. In terms of society, it is important that the proven or potential impact of radioactive waste management on the environment be brought to the public's attention in a transparent manner.

4. Severe nuclear accidents

The peaceful use of nuclear energy initiated in the 1950s has led to its large-scale development and nuclear power has become one of the main sources of electricity. More than 50 years of normal operation of commercial nuclear reactors indicates that their radiation impact is extremely low; in fact, much lower than the natural background radiation level. However, the three severe accidents that marked this period have had a major impact on the development of nuclear energy and on the world view of nuclear generation of electricity. It is important to review these accidents, summarize the return of experience, and examine the design improvements and measures taken by the nuclear industry to reduce the severe-accident frequency and limit any post-accident consequences.

4.1. Review of three severe NPP accidents

Three severe NPP accidents have had a notable impact on the nuclear industry worldwide. These accidents took place at the Three-Mile Island (TMI) NPP in USA in 1979, at the Chernobyl NPP in the former Soviet Union in 1986, and at the Fukushima Daiichi NPP in Japan in 2011. It is important to review these nuclear accidents at this stage, and to summarize the lessons learnt and improvements made by the nuclear industry thereafter.

The TMI NPP employed PWRs developed at an early stage in USA. The cause of the accident was equipment failure, inadequate interpretation of the state of the system by the operators, and the subsequent inappropriate decisions. As a result, the reactor core melted, and a substantial amount of fission products was released into the containment. Fortunately, the containment maintained its integrity and confined a major part of radioactive substances produced in the accident, resulting in a limited release to the environment. The maximum dose to the surrounding public was ten times less than the doses from the annual natural background. No casualties were recorded and there was no mid-or long-term impact to the environment [31].

The Chernobyl accident was primarily due to the unstable characteristics of the reactor core of the Russian reactor (high power channel-type reactor (RBMK) graphite moderated, water boiling cooled) under certain conditions, flaws in the management of the NPP operation, and an insufficient nuclear safety culture [32]. A prompt criticality induced a sharp power increase, which in turn led to an unconfined explosion of the reactor and sizable radioactive releases into the atmosphere. Large areas of Europe were affected to some degree by the Chernobyl releases. Much of the release comprised radionuclides with short half-lives; long-lived radionuclides were released in smaller amounts [33]. One hundred and thirty-four emergency workers suffered an acute radiation syndrome, of whom 28 died from radiation. Among the recovery operation workers who were exposed to moderate doses, there is some evidence of a detectable increase in the risk of leukemia and cataract. The occurrence of thyroid cancer among those exposed during childhood or adolescence increased significantly due to the drinking of milk contaminated with radioactive iodine during the early stage of the accident [34–36].

Table 3
Comparison of three fuel cycle options [30].

Fuel cycle	CO_2 emissions $(g\cdot(kW\cdot h)^{-1})$	SO_x emissions $(g\cdot(MW\cdot h)^{-1})$	NO_x emissions $(g\cdot(MW\cdot h)^{-1})$	Land use $(m^2\cdot(GW\cdot h)^{-1})$	Liquid chemical effluents $(kg\cdot(GW\cdot h)^{-1})$	Gaseous radioactive release $(MBq\cdot(kW\cdot h)^{-1})$	Liquid radioactive release $(kBq\cdot(kW\cdot h)^{-1})$	HLW $(m^3\cdot(TW\cdot h)^{-1})$
OTC	5.45	18.73	29.01	222.6	333.92	0.80	2.80	1.17
TTC	5.29	16.28	25.30	211.0	287.53	1.22	27.20	0.36
SFR	2.33	0.59	3.83	50.2	12.60	0.53	3.56	0.30

OTC: once through fuel cycle; TTC: twice through fuel cycle; SFR: Gen-IV fast neutrons reactors fuel cycle; HLW: high level waste.

The Fukushima Daiichi NPP adopted a boiling water reactor type of the earliest commercial reactor technology developed in USA. The triggering event of the Fukushima Daiichi accident was a super earthquake and the subsequent tsunami with an amplitude that by far exceeded the design standard. Severe damage caused by the magnitude nine earthquake and subsequent tsunami to the infrastructure such as transportation and power systems in the surrounding areas deferred the recovery of offsite power for nine days after the earthquake; a time period that far exceeded the design consideration. The lack of tightness of diesel generator rooms and the flooding of their air intakes ended up with a station blackout and failure to evacuate residual heat from the three operating units and the spent fuel storage pools caused core melting, hydrogen generation, and accumulation leading to an explosion and the release of radioactive material into the environment. Lack of prevention and mitigation measures in case of severe accidents in NPP design can have serious consequences [37,38].

4.2. Improvements to make nuclear energy free of environmental impact in case of accident

Taking into account the lessons learned from the above accidents, the nuclear industry has implemented several important technical improvements to Gen-II PWR NPPs for those under operation and those under construction. At the same time, the concept of the Gen-III PWR NPPs was developed based on the requirements of improving safety, availability, and reliability of NPPs, to practically eliminate large radioactive releases after severe accidents.

Comprehensive protection and mitigation measures for severe accidents contribute to a higher level of safety in Gen-III reactors. Gen-III PWRs are equipped with advanced large containment vessels capable of resisting external hazards such as earthquakes, tornadoes, aggressions by fires and explosions induced by humans, as well as accidental or intentional crashes by large commercial aircraft. These vessels are also able to withstand harsh internal conditions such as augmented temperature, increased pressure, and radiation after accidents, and maintain their integrity, thus avoiding radioactive release into the environment. Nuclear power industries in France and China have both developed their own Gen-III PWR technology, which have materialized in the EPR and the HPR1000. The first EPRs are already connected to the grid, whereas the first HPR1000 project is progressing well. In addition, the nuclear industry in China has made specific technical improvements to the safety of its “inland nuclear power plants.”

To improve the safety of NPPs, especially for PWRs, the nuclear industry has actively developed new technologies, such as the new generation of accident tolerant fuel (ATF) or the in-vessel retention after a severe accident.

After the Fukushima Daiichi accident, self-inspection was actively carried out by all NPP operators in China, as well as in western countries. According to the requirements from the regulatory agencies, several technical improvements have been implemented, including increased resistance to external flooding, improvements in the emergency core cooling system and related equipment, and the implementation of ① emergency control centers, ② transportable back-up power supplies, ③ spent fuel pool monitoring, ④ hydrogen monitoring and control, ⑤ radiation environment monitoring and emergency response, and ⑥ means to respond to external natural hazards.

In recent years, the development of small modular reactors (SMRs) has made great progress. Current projects covering a range of powers and at various stages of design and implementation include CAREM25 (Argentina), KLT-40S (Russia), Nuscale (USA), ACP100 (China), and Nuward (France). SMRs tend to enhance safety features through inherent and passive systems and offer better economic affordability. Some SMR designs have lower power densities and capacities to deliver heat and most of the proposed concepts make use of the potential for below-ground or even underwater locations for enhanced protection from natural hazards and ill-intentioned attacks [39].

4.3. Insights obtained from severe accidents in the past

Among the three severe nuclear accidents to date, those in Chernobyl and Fukushima had serious consequences.

As already indicated, the Chernobyl accident was caused by flaws in design and repeated violations of safety procedures by operators, which left the reactor out of control. This gave rise to prompt criticality, which resulted in the reactor explosion due to sharp power increase. After the accident, the nuclear industry abandoned core design concepts with positive feedback. The inherent safety of the reactors was also improved.

The Fukushima nuclear accident was the first NPP accident in history that was induced by an external disaster, (i.e., a high-amplitude earthquake plus an accompanying tsunami). It was also the second nuclear accident in human history after the Chernobyl nuclear accident that was rated as level seven on the international nuclear event scale (INES) scale. After the Fukushima accident, China carried out an extensive safety analysis on the coastal NPPs’ resistance to earthquakes and tsunamis. Coastal conditions in China differ from those prevailing in Japan, both in terms of earthquake-magnitude levels and high-amplitude tsunamis. This is also the case for France where such extreme natural disasters have never occurred for thousands of years. Several causes that made the Fukushima nuclear accident so severe have also been eliminated.

Today, the designs of new reactors around the world have been significantly improved giving rise to Gen-III NPPs. Furthermore, with the accumulation of operating experience, the management ability of nuclear units has been effectively improved, so that even in the worst situation, the risk of radioactive-material release into the environment is decreased to an extremely low level. In parallel, safety authorities have published guidelines for emergencies in case of accidents as well as for remediation. Regulations were also moved to reinforce the obligation of operators to apply these guidelines.

In addition to large commercial reactors, a considerable research effort has been made on other new reactors, and some of them have entered the construction stage. In October 2021, the State Council of China issued the "Action Plan for Carbon Peak by 2030," which set the goal to actively promote advanced reactor-demonstration projects, such as high-temperature gas cooled reactors (HTRs), fast neutron reactors (FNRs), SMRs, and offshore floating reactors, for carrying out demonstrations of the comprehensive utilization of nuclear energy. During the research and development (R&D) and design of new reactor types, more attention will be paid to the implementation of passive and inherent safety systems. In addition, during the siting selection process of nuclear engineering projects, screening and analysis will also be carried out in accordance with IAEA and China’s nuclear safety regulations, including seismic evaluation, water resources, meteorological conditions, and other factors, to ensure that the site conditions meet the nuclear safety requirements.

In conclusion, accidents such as the Chernobyl and Fukushima nuclear accidents that caused large radioactive releases are now unlikely in China and France given the reactor design, the low probability of natural disasters, the enhanced safety measures, and emergency response capacities that have been implemented.

5. Nuclear safety and the environment

The fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation. This is primarily achieved by controlling the radiation exposure of workers and the release of radioactive material to the environment during normal operation of NPPs and fuel-cycle facilities. The smaller the release of radioactive substances from nuclear facilities, the smaller their impact on the environment. Releases are continuously monitored and controlled and their consequences on the environment are well below the level of natural radiation as indicated in Section 2. Furthermore, they are kept as low as reasonably achievable, and records show that releases have been steadily reduced over time to reach an asymptote at an extremely small fraction of authorizations granted by safety and environmental agencies. Long-term deferred release of radioactivity from radwaste disposed off in geological formations is also expected to lead to radiological exposition; however, these releases are expected to be much smaller than natural radioactivity as discussed in Section 3. This section addresses the two other objectives of nuclear safety—restricting the likelihood of nuclear accidents and mitigating the consequences of such accidents should they occur.

5.1. Safety of NPPs and their environmental impact

Historically, the safety analysis of NPPs was based on the identification of a design basis accident (DBA). Probabilistic assessments were reported in 1975 and 1990 [40,41] and, unfortunately, severe historical accidents owing to core melt provided evidence that DBAs did not encompass all situations that must be considered for nuclear safety.

The quantitative safety goals of NPPs have been assigned after the TMI NPP accident, such as the two ''one thousandth'' rule for the relative risks of immediate death due to a reactor accident and cancer death owing to the operation of the NPP. However, both the Chernobyl and the Fukushima Daiichi NPP accidents showed that nuclear safety should not only consider the lethal consequences of nuclear accidents, but also the environmental impact that could require evacuation and relocation of population. Therefore, new safety objectives, including the consideration of severe accidents, have now been formalized in the regulations of several countries. After the Fukushima Daiichi NPP accident, the European Union promoted the performance of ''stress tests'' for all European sites, the results of which were made available publicly. All French reactors are presently being upgraded as part of a large retrofit program (Grand Carénage) to meet the requirements applied to Gen-III reactors as closely as possible. The Chinese government has made provisions to enhance nuclear safety to prevent large releases of radioactive substances in case of a severe accident.

It is advisable to ''practically eliminate'' (according to WENRA wording) any scenario that induces large or early releases to drastically limit the residual risk, by increasing safety margins, adopting supplementary safety measures, and strengthening the ''defence in depth'' strategy. Design and setup of supplementary measures should be based on the principle that nuclear safety needs be as high as reasonably achievable and ensure that such measures will not induce negative effects. To this end, various factors including the probability and consequences of the residual risks should be comprehensively taken into consideration, and the adverse effects on response functions dedicated to normal operation, anticipated operational occurrences (AOOs), DBAs, and design extension conditions (DECs) should be prevented.

The risk-informed defense-in-depth system (RDIDS) is illustrated in Table 4 [42,43]. RDIDS employs engineered safety features, additional safety features, and supplementary safety features.

Special considerations should be given to new threats such as terrorism and also cyber-attacks because digitalization of the nuclear industry has progressed quite rapidly at all stages. Operators should appoint a chief security officer (CSO) and set up a dedicated group, under the responsibility of the CSO, to develop and implement a digital security policy at all levels of its organization [44].

Terrorism is not specific to nuclear facilities; nevertheless, its consequences would be quite serious, unfortunately. In principle, the same defense-in-depth strategy applies to this specific hazard. A national agency should be assigned the responsibility of identifying the safety threats to be considered; the operator should build prevention and mitigation measures to cope with them in cooperation with the forces in charge of national security (police and army).

5.2. Siting NPPs

NPP siting should not only take into account power demand and plant layout, but also consider the suitability of the site in all its aspects, namely, ① safety, ② environmental protection, and ③ emergency preparedness as provided for by the international consensus on elementary requirements for siting of nuclear facilities. Furthermore, issues such as the transportation infrastructure for shipping large equipment to the site, the local economy, and public acceptance also need to be considered in choosing a site, although these issues are not safety related.

There is no difference in safety requirements for NPPs between inland and coastal sites, but factors that may be considered (such as typhoons, tsunamis, or dam collapse) may vary. Abundant research has been carried out in China, resulting in the formulation of four principles for dealing with the management of large amount of radioactive wastewater after accidents, (i.e., the radioactive wastewater can be ''stored,'' ''blocked,'' ''treated,'' and ''isolated''). Similar research and development has been carried out in France, resulting in solutions adapted to each site and facility,

Table 4
Risk-informed defense-in-depth system [42,43].

Level of RDIDS	Objective	Basic measures	Conditions of NPP
Level 1	Prevention of abnormal operation and failures	Conservative design, and high-quality construction and operation	Normal operation
Level 2	Control of abnormal operation and detection of failures	Control, restriction, and protection of systems and monitoring facilities	AOOs
Level 3	To restrict accidents within design basis	Engineered safety features and accident response procedures	DBAs (to assume a single postulated initial event)
Level 4	To control severe conditions, including prevention of severe accidents (4a) and mitigation of consequences (4b)	Additional safety features and accident management	DECs, including multi-failures (4a) and severe accidents (4b)
Level 5	Engineering rescue under extreme conditions; mitigation of consequences of radioactive releases	Supplementary safety features, guidelines for management of extensive damage condition, and off-site emergency response	Residual risks

4a: design extension condition without core damage; 4b: design extension condition with core damage.

which are regularly reviewed. Exchanges between the French and Chinese institutes in charge of these matters should be encouraged.

After the accident at the Fukushima Daiichi NPP, the development of nuclear power in China encountered some challenges, especially for inland NPPs. Owing to the shortage of "good" coastal sites, some "not so good" coastal sites (especially with higher earthquake risks) have been reassessed and considered as appropriate for Gen-III NPPs. Building NPPs in regions with higher seismic risks requires special attention from each party and an in-depth analysis, inclusion of augmented safety margins, to allow for conservative decisions that are compatible with the required safety level.

In France, the suitability of sites is reviewed every ten years, before granting authorization to continue the operation for the next ten years. For several sites, (such as Cadarache and Fessenheim), the seismic design criteria were increased during the lifetime of the facilities; however, it could be proven that these designs had sufficient margins to cope with these increased requirements without impairing safety.

5.3. Responsibility for safety and role of the government

The prime responsibility for safety must rest with the person or organization responsible for the facilities and activities that give rise to radiation risks [45]. On a legal standpoint, this person is the nuclear licensee, sometimes called "the owner/operator," who maintains full responsibility for controlling safety. He shall have enough technological and financial resources for ensuring this role.

The IAEA has rightly reminded that the prime responsibility of the nuclear operator is to achieve nuclear safety. It would be helpful if, in connection with the World Association of Nuclear Operators (WANO), it makes basic recommendations on the best practices to be implemented by operators to fully take charge of their duties.

The role of the government is to protect people and the environment. It has to establish a legal and governmental framework for safety, including an independent regulatory body. In turn, the regulatory body must grant construction and operating licenses in accordance with nuclear regulations. To check compliance with the license, the regulator performs supervision and inspections on the operator/licensee. However, these supervisions and inspections do not take away the full responsibility of the operator in assuring nuclear safety, whatever the controls of the regulators are.

To implement these principles, China promulgated the "Nuclear Safety Law of the People's Republic of China," which was enacted on January 1, 2018. China has legally stipulated the legal responsibilities, obligations, and rights of all parties responsible for nuclear safety. In France, these principles are included in the "Environmental Cod" (articles L591-1 and following) and consequential decrees.

5.4. Nuclear safety and public understanding

Owing to the complexity of nuclear power and external consequences of large accidents such as the accident at the Fukushima Daiichi NPP, the public is still haunted by "nuclear panic," which raises doubts about the peaceful use of nuclear power. The not-in-my-back-yard (NIMBY) syndrome has reached an acute level for nuclear power and there is an escalating resistance and opposition to NPP projects. Public acceptance has become a bottleneck and hinders the development of nuclear power, whatever its capacity to generate massive amounts of electricity or its merits with respect to cost and CO_2 emissions. There is a long way to go for better communicating with the public on nuclear safety.

Improving nuclear safety, to better prevent and mitigate the consequences of severe accidents, is a prerequisite for the further acceptance of nuclear energy. However, it is also important that the public is aware of and understands these improvements. It is an important part of healthy nuclear development to improve public communication and raise public confidence in nuclear energy. Good public communication requires effective and transparent information, active public involvement, and a permanent dialogue with local authorities and the public. Better education for the public in technical matters—starting with educators at all levels and as early as elementary school—should be a target of the educational systems.

Nuclear regulatory agencies have an important role to play in their handling of an open and transparent supervision and management of nuclear safety, and in establishing a public communication mechanism comprising "central government supervision, local authorities' leadership, enterprise implementation and public participation." It is not the role of nuclear regulatory agencies to promote nuclear energy; but it would be worth explaining to the public how they play their role and how they conclude with confidence that a nuclear license can be granted. Governmental websites, as information disclosure platforms, should be improved to release relevant documents such as reports on environmental impact of nuclear projects, results of national radiation monitoring, and information on project licensing. Public opinions should be widely listened to and engaged in the process of policy formulation and in the environmental evaluation of nuclear projects.

In general, there is no problem in public acceptance of the existing NPP-site expansion, probably because the local public (including local authorities) is fairly acquainted with nuclear energy and its benefits in promoting local economic and social development, while feeling no safety risk from nuclear power on the neighboring communities. Public acceptance of new NPP sites, however, may be more challenging as they have to be accepted without previous local experience.

6. Conclusions

Under normal operation, the impact of nuclear energy on people and the environment is well documented and measurements of the activity concentration of radionuclides in the environment are now easy to do. This allows independent monitoring of such installations. The radioactivity levels of the releases are regulated in all nuclear countries according to safety rules for radiation protection and environmental protection. The actual releases only reach a small percent of the authorized levels, and are, in terms of radiological impact, well below the impact of natural sources of radiations. Thus, it is concluded that the radiological impact of NPPs and associated nuclear facilities under normal operation is negligible or quite limited.

Protection of the environment is being considered at each step of radwaste management and in particular in the:

- Isolation/confinement in packages.
- Storage and disposal in near-surface or deep-geological facilities adapted to each type of radwaste.

Solutions rely on best-available engineering technologies and are supported by continuous R&D on the behavior of radionuclides/toxics in engineered barriers and in the geosphere undertaken in the framework of a large international cooperation.

Monitoring is carried out during all operations from production of radwaste to its final disposal in repositories, where radwaste packages are isolated from the biosphere. The background level is permanently monitored around these facilities. Feedback from these operations shows that operational releases are less than those expected initially and authorized by safety and environmental authorities when the facilities were licensed. After closure of the repositories, monitoring will be continued during an appropriate test period; then, safety will change from active to passive.

One aspect that is still not settled is that of the long-term effects of low or very low dose rate exposures. There is no consensus within the scientific and nuclear communities, even though a large majority of epidemiological studies around the world converge to demonstrate that these exposures are not harmful.

One major issue considered in this article pertains to the environmental impact of severe accidents that have marked the history of nuclear energy development. On the one hand, the accidents ranked at level 7 on INES (Chernobyl and Fukushima) have had a large impact on the environment and have reduced public confidence in the nuclear energy generation system. On the other hand, the return of experience has led to important improvements in several aspects of nuclear energy production, including reactor design and operational management. It has also proved valuable in the development of management guidelines in case of a severe nuclear accident.

The environmental risks in the event of a severe accident that might occur in the future have been substantially reduced. The NPPs, which are operating or under construction are endowed with prevention and mitigation measures that will limit the impact of such an accident, if it occurs. These are meant to drastically reduce the area affected, thereby limiting pollution and avoiding the need for a long-term and large-scale evacuation of people.

Comprehensive prevention and mitigation measures for severe accidents contribute to a higher safety level of Gen-III reactors, which are equipped with additional systems to prevent core melt to escape the main building, and large containment buildings capable of resisting external hazards and maintaining their integrity in case of severe accidents, thus avoiding radioactive releases into the environment.

The return of experience has led to the upgrading of existing NPPs and has promoted design improvements of new reactors together with the safety guidelines now implemented by NPP operators. It drastically reduces the probability of the occurrence of a nuclear accident such as Chernobyl and Fukushima. In case of such an accident, radioactive material releases would be minimized and would not require large-scale or long-term evacuations of people. It is believed that a global assessment by IAEA or WANO could demonstrate that a high level of upgrading has been implemented globally for operating NPPs.

Considering that safety management is essential for environmental protection, this article underlines that:

- The risk-oriented defense-in-depth system constitutes an improved and more complete safety methodology than the previous ones. It comprises five levels of dispositions that significantly reduce the residual risks and probability of a severe accident and this, in turn, has an important influence on the environment.
- NPP siting should not only take into account power demand and plant layout, but must also consider the suitability of the site from a safety perspective in all its aspects, namely, site safety, environmental protection, and emergency preparedness, as provided for by the international consensus on elementary requirements for the siting of nuclear facilities.
- Safety authorities play a major role in the dynamics of safety improvement and its control but the full responsibility rests on nuclear operators. Both should be engaged in a positive dialogue to ensure the highest level of environmental protection.

In summary, this article is aimed at providing a balanced assessment of the impact of nuclear energy on the environment. On the one hand nuclear energy has positive effects in providing energy with a very limited level of GHG emissions, without emissions of air pollutants or solid nano- or micro-particles that characterize energy systems that use fossil fuels. This is an essential asset in the current situation where climate change induced by human activities has become one of the most difficult challenges facing humankind and where air pollution has become a major problem in several countries. On the other hand, nuclear power raises local and more global environmental issues that pertain to radwaste management and to the multiple consequences of severe accidents. Considerable efforts have been devoted to defining a sustainable management protocol for high-level radioactive waste leading to its final disposal in geological formations. Lessons learnt from the three main severe accidents have served to improve nuclear reactor design, reduce the probability of occurrence of the release of radioactivity, and ensure that the consequences to the environment remain limited if one such accident occurs.

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Compliance with ethical guidelines

Xiangeng Zhao, Qizhen Ye, Sébastien Candel, Dominique Vignon, and Robert Guillaumont declare that they have no conflict of interest and no financial conflicts to disclose.

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