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Nuclear energy basics

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Summary. — In the first part of the paper, the basic features of nuclear fission and fusion energy are addressed. In the second part, an overview of energy consumption in the world is presented, which highlights the growing need for electricity from non-CO_2 emitting sources, among which nuclear power is expected to play a role. The perspectives for the future of nuclear energy are then discussed, showing that it develops mostly in emerging countries and the small modular reactors are likely to have an increasing role. The third part is devoted to the question of nuclear waste management and to the non-radioactive environmental impact of nuclear energy in comparison with other sources of energy.

1. – Basics on nuclear fission and fusion

Nuclear energy originates from the release of part of the energy that binds together the constituents of the atomic nucleus. Nuclei are composed of nucleons (neutrons and protons) held together by the strong nuclear force, which overcomes the Coulomb repulsion between the protons. The mass of the nucleus is less than the sum of the masses of its constituents. For a nucleus of mass A with Z protons, the mass is given by

$$M(A,Z) = Zm_p + (A-Z)m_n - B(A,Z), \tag{1}$$

where B is the binding energy.

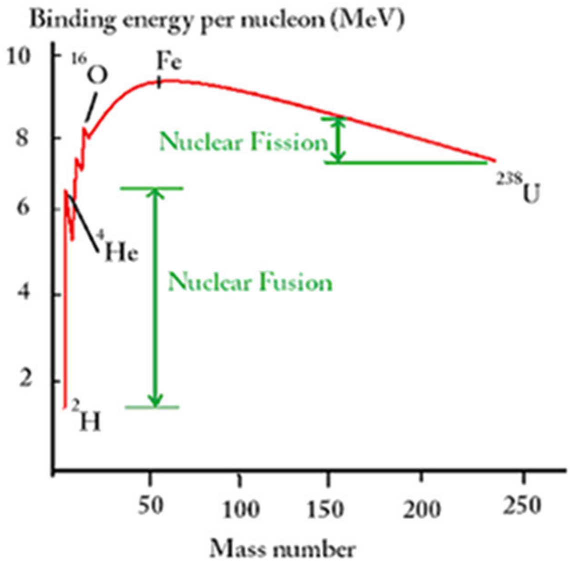

Fig. 1. – Binding energy as a function of the nucleus mass.

Actually, the binding energy per nucleon, B/A, is of the order of several MeV and is maximum around Fe, as can be seen in fig. 1 where it is plotted as a function of the mass of the nucleus. The consequence is that part of this binding energy can be released in nuclear reactions in which the constituents of the initial nuclei are redistributed into different final nuclei. In a reaction between two initial nuclei, A_1 and A_2, leading to A_3 and A_4 in the final state, the energy released, Q, is just the difference between the binding energies:

$$Q = B(A_1) + B(A_2) - B(A_3) - B(A_4). \tag{2}$$

A large amount of energy can be released, in particular in two cases corresponding to the two ends of the curve of fig. 1: either by inducing the splitting of heavy nuclei, such as uranium, into two more or less equal ones with neutrons —this is fission, in which around 1 MeV per nucleon is released, *i.e.* of the order of 200 MeV in total— or by merging two very light nuclei into a larger one — this is fusion, in which several MeV per nucleon are liberated.

1˙1. *Fission.* – Fission reactions can be induced by capture of very slow neutrons on some nuclei such as ^{235}U, which are said to be fissile, producing two fission fragments and 2.4 neutrons in average. The produced neutrons, after slowing down, can initiate further reactions leading to what is called a chain reaction. In a reactor, the chain reaction must be controlled so that it is self-sustained without the risk of diverging. This implies that for each fission reaction, one neutron is used to induce another fission and the remaining neutrons are absorbed or escape from the system. This is criticality.

Natural uranium is composed of 0.7% ^{235}U, 99.3% ^{238}U and traces of ^{234}U. ^{235}U is fissile by neutron capture regardless of the energy of the neutron, but the probability that a reaction can take place decreases with increasing neutron energy. Therefore, it is much easier to ensure the criticality with very slow neutrons, actually neutrons that are in thermal equilibrium with the medium they are interacting with, called thermal neutrons. This implies that the neutrons produced by fission are slowed down in a moderator material. ^{238}U also can fission but only with high-energy neutrons and with a small probability. In a thermal reactor, it has a high probability to absorb neutrons making it difficult to reach criticality with natural uranium. This is why it is necessary to enrich uranium by increasing the proportion of ^{235}U in the fuel. Typically, the enrichment is around 3% in light-water reactors.

^{235}U is the only naturally occurring fissile isotope but other isotopes are fissile, such as ^{239}Pu and ^{233}U that can be produced in reactors through the absorption of neutrons by ^{238}U and ^{232}Th, respectively. In both cases, a neutron is first captured, generating a nucleus which then undergoes two subsequent β-decay leading to the long-lived fissile isotope

$$(3) \qquad {}^{238}\mathrm{U}\ (n,\gamma) \longrightarrow {}^{239}\mathrm{U}\ (23\,\mathrm{min}) \xrightarrow{\beta} {}^{239}\mathrm{Np}\ (2.3\,\mathrm{d}) \xrightarrow{\beta} {}^{239}\mathrm{Pu}\ (2.4\ 10^4\,\mathrm{y}),$$

$$(4) \qquad {}^{232}\mathrm{Th}\ (n,\gamma) \longrightarrow {}^{233}\mathrm{Th}\ (22\,\mathrm{min}) \xrightarrow{\beta} {}^{233}\mathrm{Pa}(23\,\mathrm{d}) \xrightarrow{\beta} {}^{233}\mathrm{U}\ (1.6\ 10^5\,\mathrm{y}),$$

^{238}U and ^{232}Th are said to be fertile. In fact, in light-water reactors, up to one third of the fissions come from ^{239}Pu over the lifetime of the fuel. It can be seen from eq. (4) that natural thorium, which is composed only of the ^{232}Th isotope, can also be used as fuel in thermal reactors but it requires either that ^{232}Th is first irradiated in another reactor to provide ^{233}U or that plutonium is added to initiate the process.

It is also possible to burn ^{238}U in fast neutron reactors that use directly the neutrons produced by fission without moderation. This has the advantage that it multiplies the energy that can be extracted from a given mass of natural uranium by a factor of about 100. However, this requires a higher neutron flux in the reactor and the mobilization of a much larger inventory of fissile material, which can be made up of highly enriched uranium, or plutonium.

More details on how a nuclear fission reactor works are given in Ripani's contribution to these proceedings [1].

1˙2. *Fusion.* – As said above and shown by fig. 1, the fusion of light isotopes can produce a huge amount of energy. These reactions are in fact what drives the nucleosynthesis of light elements and are the primary source of energy for stars. This is possible thanks to the gravitational attraction that leads to the formation of a hot and very dense plasma of light isotopes. To replicate this process on earth to produce energy in a controlled way is very difficult and requires the confinement of a very hot and dense plasma of hydrogen isotopes, with a temperature high enough to overcome the Coulomb barrier between the

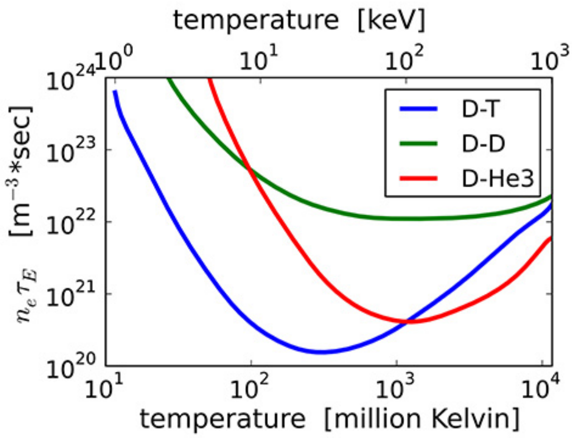

Fig. 2. – Lawson criterion for three possible fusion reactions: *d*-*d*, *d*-*t* and *d*-^{3}He. From [3].

ions, during a sufficient time, and being able to recover the generated energy.

The reactions that can be considered to produce energy in a fusion reactor are

- Deuterium-deuterium reactions

$$^2\mathrm{H} + {}^2\mathrm{H} \to {}^3\mathrm{He} + n + 3.27\,\mathrm{MeV}, \tag{5}$$
$$^2\mathrm{H} + {}^2\mathrm{H} \to {}^3\mathrm{He} + {}^1\mathrm{H} + 4.03\,\mathrm{MeV}. \tag{6}$$

- Deuterium-tritium reaction

$$^2\mathrm{H} + {}^3\mathrm{H} \to {}^4\mathrm{He} + n + 17.6\,\mathrm{MeV}, \tag{7}$$

  of which 14 MeV are carried out by the neutron.

- Deuterium-^{3}He reaction

$$^2\mathrm{H} + {}^3\mathrm{He} \to {}^4\mathrm{He} + {}^1\mathrm{H} + 18.3\,\mathrm{MeV}, \tag{8}$$

  which is interesting as it does not produce neutrons.

The conditions for a sustained fusion plasma producing more energy than is required for its heating are generally expressed as the Lawson criterion [2] shown in fig. 2 for three different fusion reactions. In the figure T is the temperature, τ_E is the confinement time, n_e, is the ion density.

It can be seen that the most favorable reaction, *i.e.* the one requiring the lowest values of temperature and $n_e\tau_E$ product, is by far the deuterium-tritium reaction, on which current fusion energy projects are based. Deuterium is rather abundant in nature and easy to obtain by separation from ordinary water. On the contrary, tritium is a radioactive isotope, with a half-life of 12 years, which naturally exists only in trace amounts. Therefore, tritium breeding is a key issue for fusion energy economics. Actually, tritium can be produced from lithium which is largely abundant in nature. Natural lithium is composed of 7% of ^{6}Li and 93% of ^{7}Li and tritium can be produced using the reactions

$$^6\mathrm{Li} + n_{\mathrm{slow}} \to {}^4\mathrm{He} + T + 4.8\,\mathrm{MeV}, \tag{9}$$

$$^7\mathrm{Li} + n_{\mathrm{fast}} \to {}^4\mathrm{He} + T + n_{\mathrm{slow}} + 2.5\,\mathrm{MeV}. \tag{10}$$

Most fusion reactor designs involve surrounding the main vessel with a cover made of a lithium-based material. It remains to demonstrate that it is possible to attain tritium self-sufficiency.

Two main technologies are considered to realize the confinement of the hot plasma at a temperature of the order of 10^8 K:

- inertial confinement, using laser beams heating and compressing small fuel pellets, allowing to reach very high densities (10^6 times the air density) but during short characteristic time (10^{-11} s);
- or magnetic confinement, in which a low-density plasma (10^{-5} times the air density) is confined in a vessel, a tore in the case of tokamaks, by a high magnetic field, during a rather long characteristic time (10 s).

More information about fusion energy can be found in the contribution to these proceedings by Ongena [4] and Romanelli [5].

1˙3. *Nuclear energy content compared to fossil fuels.* – As seen above, the energy released in nuclear reactions is of the order of tens of MeV. In the combustion of fossil fuels, it is the chemical energy that is at stake, which is of the order of eVs. We compare below the amount of heat released during the combustion of 1 g of various fuels and the amoun¡t that would correspond to the consumption of a 1000 MWe power plant per day (which can feed around 1 million homes):

- Coal:

  $\mathrm{C} + \mathrm{O}_2 \to \mathrm{CO}_2 + 4\,\mathrm{eV}$;

  energy released by 1 kg of coal: 32 MJ;

  fuel comsumption of a 1000 MWe plant: 6750 ton/day (assuming a 40% efficiency).

- Natural gas (CH4):

  $\mathrm{CH}_4 + \mathrm{O}_2 \to \mathrm{CO}_2 + 2\mathrm{H}_2\mathrm{O} + 8\,\mathrm{eV}$;

  energy released by 1 kg of natural gas: 48 MJ;

  fuel comsumption of a 1000 MWe plant: 3600 ton/day or 64 m^3/s (assuming a 50% efficiency).

- Nuclear fission (U):

  $^{S23}5\mathrm{U} + n \rightarrow 2$ fission fragments $+ 2.7n + 200\,\mathrm{MeV}$

  energy released by 1 kg of ^{235}U: 8.2 10^4 GJ and by 1 kg of natural uranium in a thermal reactor: 570 GJ;

  fuel comsumption of a 1000 MWe plant: 3 kg/day of ^{235}U or 460 kg/day of natural uranium (assuming a 30% efficiency).

- Nuclear fusion:

  $d + t \rightarrow {}^4\mathrm{He} + n + 17.5\,\mathrm{MeV}$ (of which 80% are carried by neutrons),

  energy released by 1 g of D-T mixture = 3.4 10^5 GJ;

  fuel comsumption of an hypothetic 1000 MWe plant per day: 1.25 kg/day (assuming a 20% efficiency).

2. – Nuclear energy in the world: status and perspectives

2˙1. *Total primary energy and electricity supply*. – At the beginning of the 21st century, the nuclear power industry was expecting a continued growth due to the increase in the world's population, the rapid industrialisation of emerging countries and the growing awareness of the effects of CO_2 emissions. This has not been the case. The Fukushima accident in 2011, which led to the shutdown of Japanese reactors and the decision by some countries to reduce or even abandon nuclear power, had of course an important impact but it was not the only cause. In fact, the decline had begun earlier, partly because of the shale oil "revolution" —the discovery of large oil and gas resources in the US, which provided cheap and easy to produce electricity— and partly because of the economic crisis of 2008. This is reflected in fig. 3, taken from the 2020 BP statistical review of world energy [6], which shows the nuclear energy consumption by region of the world over time. In recent years, however, nuclear power production had begun to grow again, at least before the COVID-19 crisis that led to a general decline in energy consumption.

The question of nuclear energy has to be considered in the context of the global increase in energy demand. This increase is driven by the growth of the world's population, the accelerated development of emerging countries aiming to reach the standard of living of developed countries, and the aspiration of developing countries to improve their living conditions. Figure 4 (left) from [7] presents the total primary energy supply by region over time. It clearly shows that while the energy supply in OECD countries has been stagnating for years, it increases rapidly in middle east, Asia and in particular in China. As regards electricity (see fig. 4 (right)) the global demand increases even faster, and again mainly in non-OECD countries, driven by the needs from industry and residential sector in these countries, and more recently also by the development of smart electronic devices and electric cars. It is quite unlikely that the trend will be reversed in the near future.

If one looks (fig. 5) at the supply of total primary energy (left) and electricity (right) per source, it can be noticed that: i) the vast majority of total primary energy is still

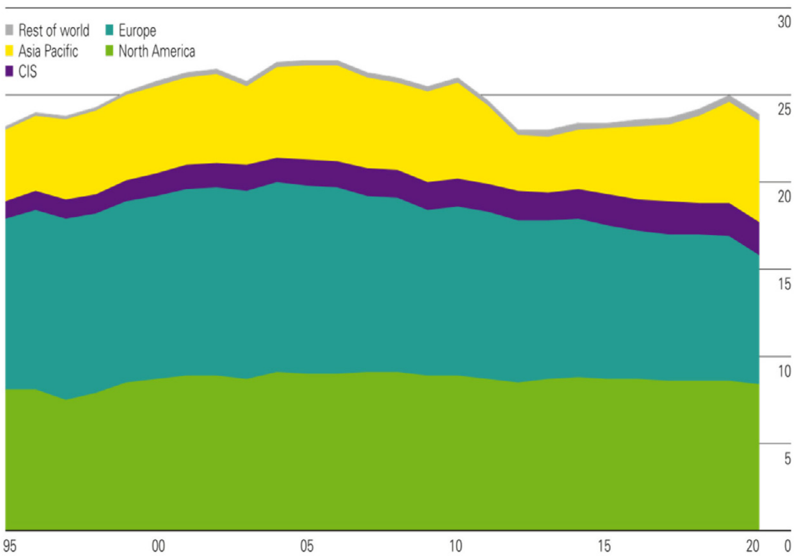

Fig. 3. – Nuclear energy consumption by region. From [6].

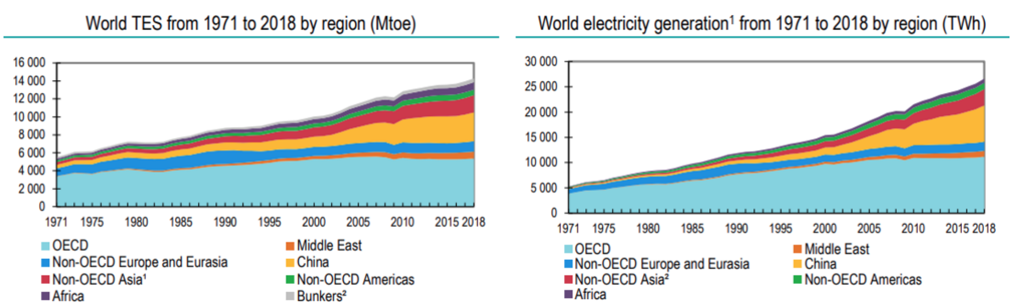

Fig. 4. – Total primary energy (left) and electricity (right) supply by region. From [7].

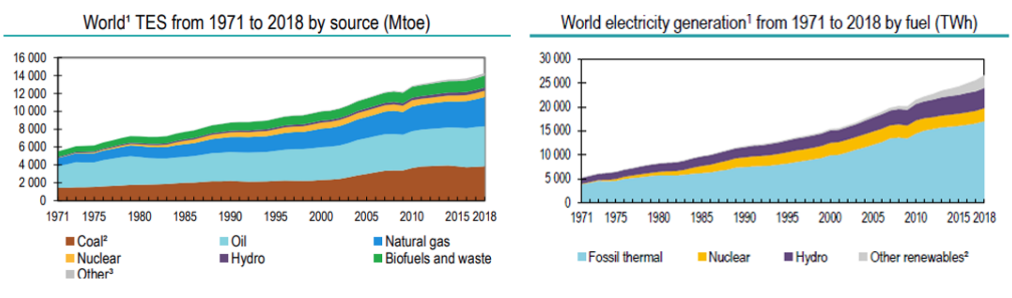

Fig. 5. – Total primary energy (left) and electricity (right) supply by source. From [7].

produced by fossil fuels; ii) the share of nuclear energy in electricity has not been increasing in recent years and remains around 10%; iii) the share of renewable energies, other than hydroelectricity, is rising significantly but is still quite low.

2˙2. CO_2 *emissions.* – It is now well understood that CO_2 emissions contribute to global warming and that we must try to limit them as much as possible. Up to now, although some efforts have been done in Europe and in US, CO_2 emissions continues to grow, especially in emerging and developing countries, as can be seen in fig. 6 as estimated by the Global Carbon Project [8,9], which shows the evolution of the emissions of the 2020 four top emitters and of the rest of the world. This has led, after 2 years of stagnation, to a steady increase since 2017, with the exception of 2020 due to the COVID-19 pandemic.

In order to reduce CO_2 emissions, there are different possible options:

- Reducing the use of fossil fuels, in particular in electricity production and transportation, which is of course the first priority;
- Energy savings and increased energy efficiency need to be amplified, but they are limited and counterbalanced by increasing demand, especially in developing countries;
- Carbon capture and storage should be developed but it is expensive and profitable only if close to the emission site;
- Renewable energies, which are developing rapidly and getting cheaper, but solar and wind energies are intermittent and therefore need to be coupled to backup

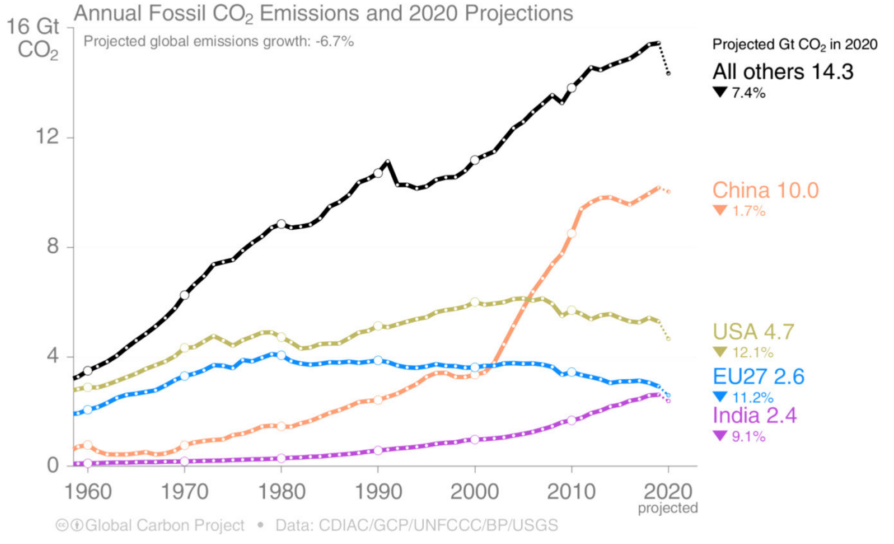

Fig. 6. – CO_2 emissions of the top 4 emitters. From [8].

resources, as far as possible CO_2 free, capable of responding to changes in their availability. Battery storage technology, up to now, has not reached a sufficient maturity and may face a problem in rare-earth element supply;

- Nuclear energy, which suffers from the rejection of a part of public opinion due to the fear of an accident and the question of waste.

It is clear that there is no single solution that can solve the problem. Instead, a combination of all these options will be needed to significantly reduce CO_2 emissions and thereby tackle global warming.

2˙3. *The IEA net zero by 2050 scenario.* – This is precisely the conclusion of the International Energy Agency that has recently issued a report proposing a scenario for reducing the CO_2 emission down to zero by 2050 (NZE) [10]. It is stated that this would require a further rapid deployment of available technologies as well as a widespread use of technologies that are not on the market yet. In the NZE scenario, among the various hypotheses, the share of fossil fuel is reduced to about 20%, the electric car sales is assumed to be multiplied by 18, and an annual average reduction of 2.2% in energy intensity, *i.e.* energy use per unit of GDP is used.

One of the results of the NZE study is that the share of electricity in the total energy supply must increase drastically. The evolution of the distribution of total primary energy and electricity between the different sources of supply by 2050 is presented in fig. 7 and fig. 8, respectively.

The share of nuclear energy in the electricity supply will still represent only about 10%. However, because of the increase of the electricity demand, nuclear power capacity has to be at least doubled. It is advocated that this could be done differently in advanced economies and in emerging and developing countries. In the first case, the nuclear power capacity could be increased by extending the lifetime of existing reactors and building 4.5 GW per year of new reactors from 2021 to 2035, with an increasing emphasis on small modular reactors. In emerging and developing economies, the fleet of reactors would have to be multiplied by 4 by 2050, which would represents two thirds of the new nuclear power capacity, mainly in the form of large-scale reactors.

2˙4. *Perspectives.* – The previous section shows that, after years of decline, the prospects for nuclear power are quite favorable. This is confirmed by the fact that the number of reactors under construction or planned is increasing again. New countries are joining the group of nuclear nations, such as Poland and the Czech Republic in Europe and Turkey, and other countries are planning to join, notably in Africa and the Middle East. To date, 56 reactors are under construction, including 16 in China, 6 in Russia and 7 in India, and 152 reactors are planned, including 43 in China, 25 in Russia and 14 in India, as can be seen in fig. 9 taken from [11], demonstrating the growing importance of Asia in the nuclear domain.

Most of the reactors currently in operation are based on light water technology and belong to the so-called Generation II, while the newly built reactors or those under con-

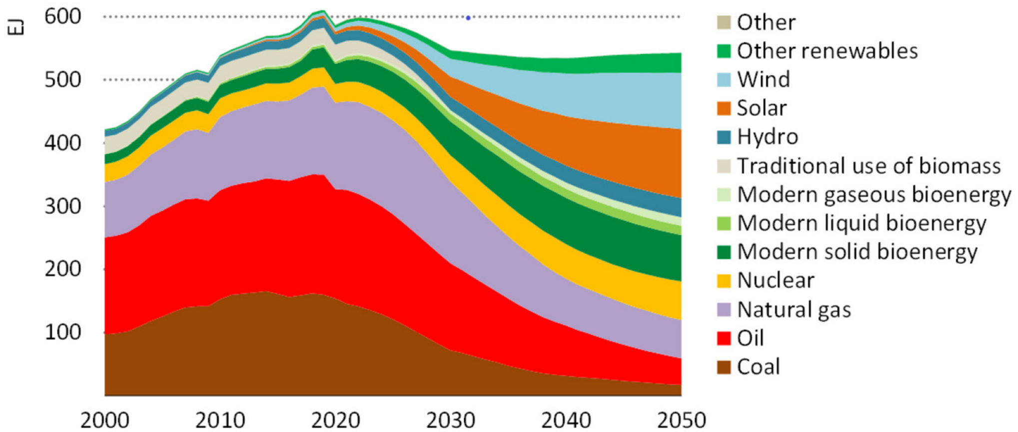

Fig. 7. – Evolution of the total energy supply by source in the IEA Net Zero Emission scenario up to 2050. From [10].

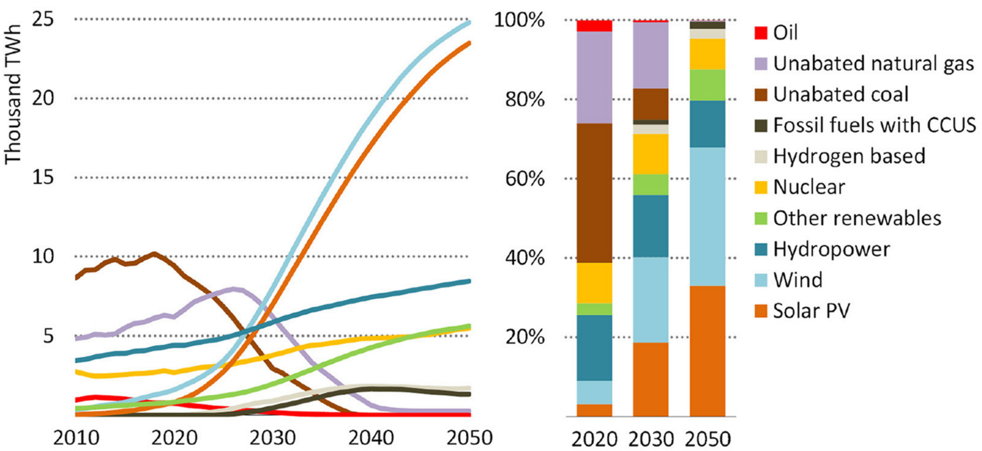

Fig. 8. – Evolution of the electricity supply by source in the IEA Net Zero Emission scenario up to 2050. From [10].

struction belong to Generation III, which is essentially an evolution of the Generation-II technology towards greater safety and competitiveness. There is however an important effort in the world to study more innovative designs, mainly driven by the Generation-IV International Forum [12], established in 2000, which brings together 13 countries, as well as Euratom —representing the 27 European Union members— to co-ordinate research and development on these systems. The goal is to design systems that would satisfy the following criteria: i) sustainable energy generation and effective fuel utilization; ii) long-term availability, iii) minimization and management of their nuclear waste; iv) economical competitiveness; v) high level of safety and reliability; vi) Proliferation-

COUNTRY	NUCLEAR ELECTRICITY GENERATION 2020		REACTORS OPERABLE June 2021		REACTORS UNDER CONSTRUCTION June 2021		REACTORS PLANNED June 2021		REACTORS PROPOSED June 2021	
	TWh	% e	No.	MWe net	No.	MWe gross	No.	MWe gross	No.	MWe gross
Argentina	10.0	7.5	3	1641	1	29	1	1150	2	1350
Armenia	2.6	34.5	1	415	0	0	0	0	1	1060
Bangladesh	0	0	0	0	2	2400	0	0	2	2400
Belarus	0.3	1.0	1	1110	1	1194	0	0	2	2400
Belgium	32.8	39.1	7	5942	0	0	0	0	0	0
Brazil †	13.2	2.1	2	1884	1	1405	0	0	4	4000
Bulgaria	15.9	40.8	2	2006	0	0	1	1000	2	2000
Canada	92.2	14.6	19	13,624	0	0	0	0	2	1500
China	344.7	4.9	51	49,569	17	18,616	38	41,785	168	196,86
Czech Republic	28.4	37.3	6	3934	0	0	1	1200	3	3600
Egypt	0	0	0	0	0	0	4	4800	0	0
Finland	22.4	33.9	4	2794	1	1720	1	1170	0	0
France	338.7	70.6	56	61,37	1	1650	0	0	0	0
Germany	60.9	11.3	6	8113	0	0	0	0	0	0
Hungary	15.2	48.0	4	1902	0	0	2	2400	0	0
India	40.4	3.3	23	6885	6	4600	14	10,5	28	32
Iran	5.8	1.7	1	915	1	1057	1	1057	5	2760
Japan †	43.0	5.1	33	31,679	2	2756	1	1385	8	11,562
Jordan	0	0	0	0	0	0	0	0	1	1000
Kazakhstan	0	0	0	0	0	0	0	0	2	600
Korea RO (South)	152.6	29.6	24	23,15	4	5600	0	0	2	2800
Lithuania	0	0	0	0	0	0	0	0	2	2700
Mexico	10.9	4.9	2	1552	0	0	0	0	3	3000
Netherlands	3.3	3.9	1	482	0	0	0	0	0	0
Pakistan	9.6	7.1	6	2332	1	1100	1	1170	0	0
Poland	0	0	0	0	0	0	0	0	6	6000
Romania	10.6	19.9	2	1300	0	0	2	1440	1	720
Russia ‡	201.8	20.6	38	28,578	2	2510	25	23,89	21	20,1
Saudi Arabia	0	0	0	0	0	0	0	0	16	17
Slovakia	14.4	53.1	4	1837	2	942	0	0	1	1200
Slovenia	6.0	37.8	1	688	0	0	0	0	1	1000
South Africa	11.6	5.9	2	1860	0	0	0	0	8	9600
Spain	55.8	22.2	7	7121	0	0	0	0	0	0
Sweden	47.4	29.8	6	6882	0	0	0	0	0	0
Switzerland	23.0	32.9	4	2960	0	0	0	0	0	0
Thailand	0	0	0	0	0	0	0	0	2	2000
Turkey	0	0	0	0	3	3600	1	1200	8	9500
Ukraine †	71.5	51.2	15	13,107	2	1900	0	0	2	2,4
UAE	0	0	1	1345	3	4200	0	0	0	0
United Kingdom	45.9	14.5	15	8923	2	3440	2	3340	2	2300
USA	789.9	19.7	93	95,523	2	2500	3	2550	18	8000
Uzbekistan	0	0	0	0	0	0	2	2400	2	2400
WORLD*	**2553**	**c 10.1****	**444**	**395,267**	**54**	**61,219**	100	**102,437**	**325**	**353,812**
	TWh	% e	No.	MWe	No.	MWe	No.	MWe	No.	MWe
	NUCLEAR ELECTRICITY GENERATION		OPERABLE		UNDER CONSTRUCTION		PLANNED		PROPOSED	

Fig. 9. – Panorama of world nuclear power reactors: in operation, in construction and planned as of July 2021. From [11].

resistance. Six different concepts, at different levels of development, are studied or optimized by one or several countries: Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Supercritical Water-cooled Reactor (SCWR), Sodium-cooled Fast Reactor (SFR) and Very High Temperature Reactor (VHTR).

In recent years, there has been a growing interest in small modular reactors (SMRs), which offer advantages such as a lower initial investment and construction time, the possibility of powering smaller markets and power grids or remote areas, greater flexibility and the possibility of combining non-electricity applications, such as heat or hydrogen production, or desalination.

Actually, there are many different types of SMRs. Most of them are reactors between 50 and 200 MWe, generally based on GEN-III technology (PWR, BWR, sometimes HTR). Some of them, sometimes called Advanced Modular Reactors (AMR) are based on of GEN-IV type systems. There are also Micro Modular Reactors (MMR) or Very Small Modular Reactors (vSMR) of a range power from 1 to 20 MWe.

The dynamism of the SMR field is clearly evidenced in the recent report on the Advances in Small Modular Reactor Technology Developments published by IAEA [13], which lists more than 50 SMR designs under development for different application, many of them proposed by newly created companies. A few of them are in an advanced stage of construction in Argentina, China and Russia.

3. – Nuclear waste management and environmental impact

3˙1. *Nuclear waste.* – After irradiation during 3 years, the fuel unloaded from pressurized water reactor, which originally was composed of about 3.3% of ^{235}U and 96.7% of ^{238}U, contains around 35 kg of fission products, 9 kg of plutonium and 1 kg of minor actinides (MA), *i.e.* isotopes of neptunium, americium, and curium, per ton of fuel. Many isotopes of fission products are highly radioactive but most of them are rather short lived or with a half life shorter than 30 years. On the contrary, minor actinides are mostly long-lived isotopes, some with half-lives of million years. To evaluate the potential danger of spent fuel for humans, rather than radioactivity, radiotoxicity is used, which takes into account the nature of the radioactivity and the biological effects of a possible ingestion. The evolution of spent fuel radiotoxicity over a period of 1 million years is presented in fig. 10 with the different contributions. It can be seen that in the short term, radiotoxicity is dominated by fission fragments, and then plutonium takes over. The time required to reach the level of the initial uranium ore is of the order of several hundred thousands of years.

There are actually two options for the management of spent fuel, which are illustrated in fig. 11, either what is called open or one-through cycle, which consists simply in a direct disposal in a deep underground repository —this is the choice for instance of US, Sweden, Finland— or a partially closed or twice-through cycle, in which the spent fuel is reprocessed to extract plutonium. Plutonium is then used to make a new type of fuel composed of a mixture of uranium and plutonium oxides, the MOX fuel, which can be easily burnt in current commercial reactors. This option has been adopted for instance by France, Japan, Russia, China.

As plutonium is the main contributor to the radiotoxicity after a few tens of years, as shown in in fig. 10 and also to the residual heat, reprocessing reduces the amount,

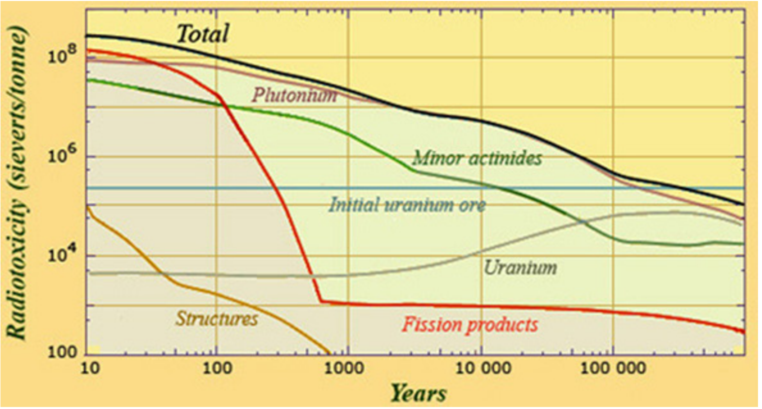

Fig. 10. – Evolution of spent fuel radiotoxicity over a period of 1 million years. © Source: CEA.

volume and radiotoxicity of the high-level waste to be stored, and of the size of the deep underground storage since the waste packages can be stored closer together. However, it leads to additional volumes of intermediate wastes during the reprocessing and fuel fabrication processes. In any case a final deep geologic disposal of the remaining long-lived high-level wastes will be necessary.

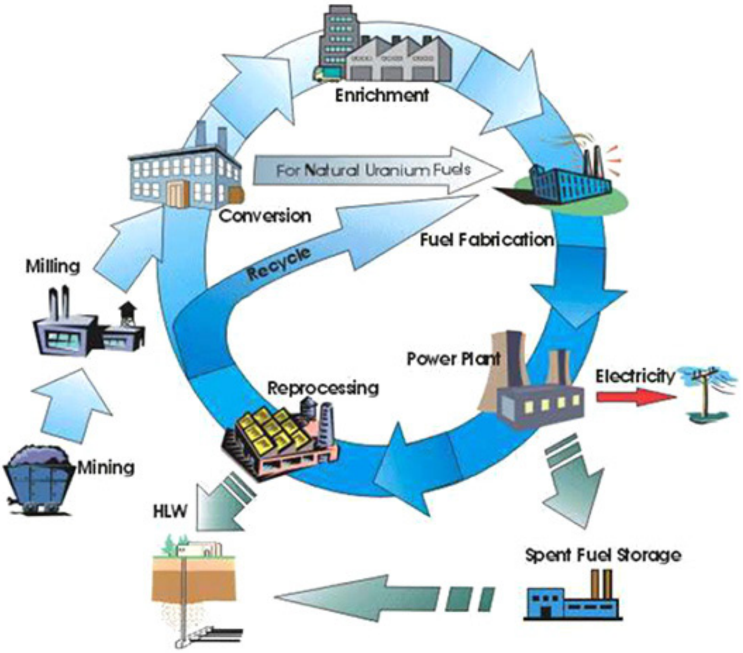

Fig. 11. – The open and closed spent fuel cycles. From [14].

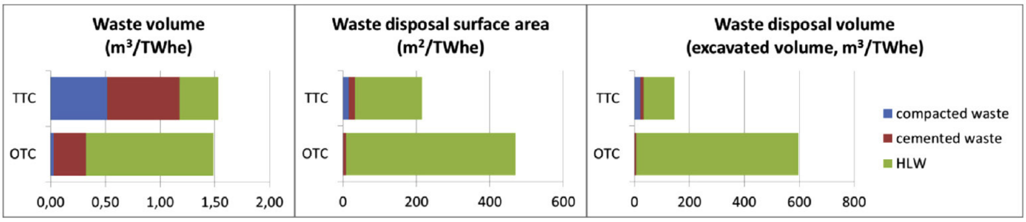

Fig. 12. – Comparison of the waste volumes, waste disposal surface areas and waste disposal excavated volumes for the Once-Through (OTC) and Twice-Through Cycles (TTC). From [16].

There are different types of nuclear waste, which are generally classified according to their activity [15]:

- High-level waste (HLW): used fuel or separated waste from reprocessing of used fuel, with a decay heat higher than $2\,\mathrm{kW/m^3}$, which leads to significant temperature increase. They account for only 3% of the volume, but 95% of the total radioactivity of produced waste and contain both long-lived and short-lived isotopes.

- Intermediate-level waste (ILW): comprises resins, chemical sludges, and metal fuel cladding, as well as contaminated materials from reactor decommissioning. They are highly radioactive but have a low decay heat. They represent 7% of the volume and 4% of the total radioactivity.

- Low-level waste (LLW): waste with radioactive content not exceeding 4 GBq/t of alpha activity or 12 GBq/t beta-gamma activity such as tools, clothing, filters, etc., which contain small amounts of mostly short-lived isotopes. They constitute 90% of the volume, but 1% of total radioactivity.

- Very low-level waste (VLLW): in fact, radioactive materials at a level not considered harmful to people or the surrounding environment, essentially material produced during rehabilitation or dismantling operations.

3˙2. *Nuclear energy environmental impact*. – An interesting and in-depth comparison has been done, in the French case, by Poinssot *et al.* in [16] between the Once-Through (OTC) and Twice-Through Cycles (TTC), which correspond, respectively, to the open and closed cycles presented in fig. 11. It uses a simulation tool compiling and relating together all the energy and matter fluxes along the nuclear fuel cycle. In fact, the analysis compared the actual situation of the French TTC to a virtual scenario in which France would produce the same amount of electricity with the actual reactor park but without operating any recycling operations. Figure 12 shows the results concerning the total volume of waste, which is very similar in the two cases, and the repository (for long-lived waste) excavated volume and surface area, which are significantly lower for high-level waste (HLW) in the case of TTC.

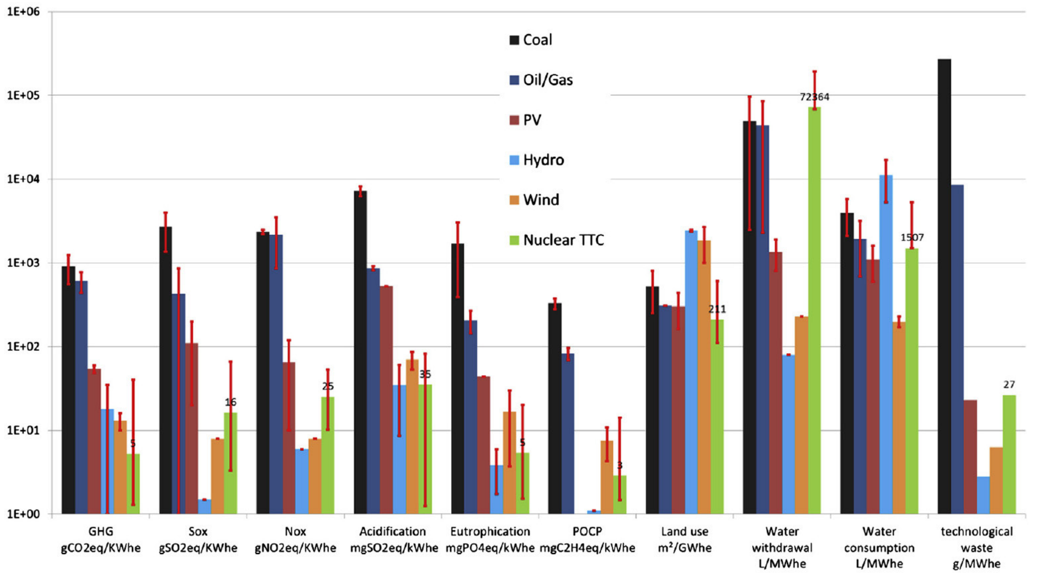

Fig. 13. – Comparison of the selected indicators between the French TTC and other energy sources. The error bars represent the gap between the minimum and maximum values found in the literature. From [16].

In the same paper, the non-radioactive impacts of nuclear energy, through the example of the French TTC, was also analysed and compared to other sources of energy. Some indicators have been selected to perform a comprehensive life cycle analysis of energy production from coal, oil or gas, photovoltaic, hydro, wind and nuclear power. These indicators are:

- green-house-gases emissions (GCG, gCO2eq/kWhe);
- atmospheric pollution (mg/kWhe), in particular SOx and NOx;
- water pollution (mg/kWhe), *i.e.* acidification, eutrophisation and POCP (photochemical ozone creation potential);
- land-use (m^2/GWhe);
- water consumption (l/MWhe);
- water withdrawal (l/MWhe);
- production of technological waste (g/MWhe).

Figure 13 shows the results, which clearly indicate that nuclear energy has the lowest impact regarding GHG emission and land use (which is in fact dominated by mining), has an impact close to renewable energies regarding atmospheric and water pollution and technological waste generation, obviously better than fossil energies. On the opposite, in terms of water consumption and withdrawal, nuclear energy is in the range of fossil fuels.

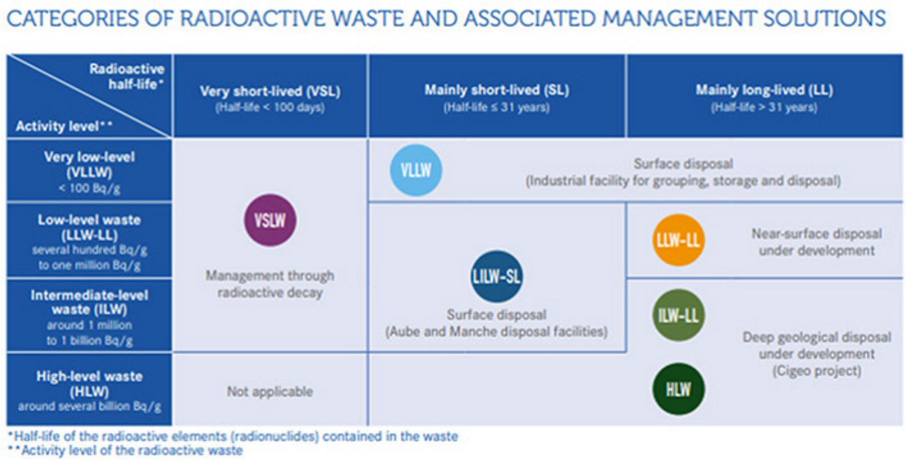

Fig. 14. – Categories of waste and management solutions. From [15].

3˙3. *Nuclear waste management*. – As explained above, there are different categories of waste and, depending on their activity level and the half-life of the isotopes present, different management options are considered. This is illustrated in fig. 14 from [17], which shows the management solutions adopted or under development in in France by the national agency in charge of nuclear waste, ANDRA. Nearly 90% of countries using nuclear energy have one or more long-term management solutions for radioactive waste in operation or under development [17]. Most of the storage in operation concerns low- and medium-level short-lived waste and is mainly on the surface. Clearly, the most critical question concerns long-lived high-level waste for which deep underground geological disposal in stable geological formations is foreseen. Plans for such sites are well advanced in Finland and in Sweden, for instance.

As explained above, the removal of plutonium from spent fuel, reused in MOX fuels, reduces the radiotoxicity of the waste to be stored. To go further, it has been envisaged to also separate the minor actinides and transmute ("burn") them, *i.e.* as far as possible make them fission, in suitable reactors. This would lead to a substantial reduction of the time needed for the radiotoxicity of the waste to reach the level of natural uranium ore from nearly 1 million years to a few hundreds of years, a time scale more manageable in terms of monitoring [18]. This is illustrated in fig. 15 from [19], which shows the evolution over time of the radiotoxicity of spent fuel without any recycling, with recycling of plutonium and after transmutation of minor actinides, relative to uranium ore.

Transmutation can be achieved more efficiently in fast neutron spectrum reactors. In fact, the introduction of minor actinides into fuels leads to a degradation of certain reactor safety parameters, such as the fraction of delayed neutrons, which is lower in MAs than in uranium 235. There are therefore two possible options to burn significant quantities of MAs: either adding small amounts of minor actinides in many fast reactors at a level acceptable for the safety, with the advantage that this might be done in

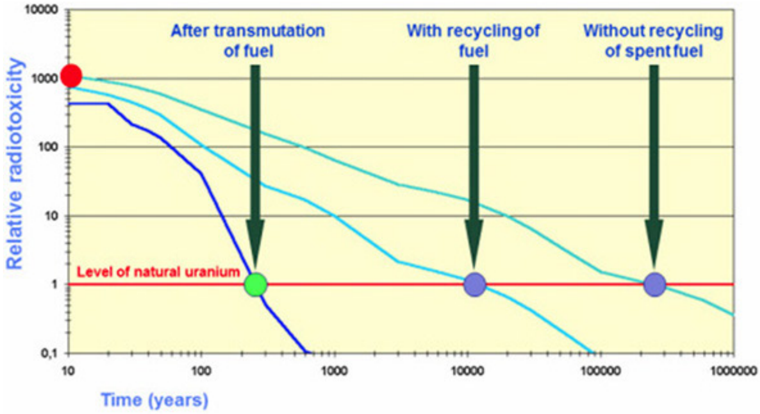

Fig. 15. – Radiotoxicity of UOX spent fuel relative to uranium ore, *vs.* time (years). From [19].

adapted commercial reactors; or burning large amount of minor actinides in dedicated accelerator-driven sub-critical systems, thus much less sensitive to the degradation of safety parameters.

Some studies about MA transmutation are conducted in Europe within the MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) project in development at SCK•CEN, which will be able to work both in sub-critical (ADS) and in critical mode.

It has to be noticed however that to reach a high rate of transmutation of the produced MAs, multiple cycles of separation, fuel fabrication and transmutation have to be performed, which imply the handling and transportation of large quantities of highly radioactive materials, and therefore limit the interest of the process.

4. – Conclusion

Fission is a highly concentrated source of energy that does not generate CO_2 emissions. Fusion is even more concentrated and would have the advantage of not generating long-lived radioactive waste, but the viability of a commercial reactor remains to be demonstrated.

In this paper, it was shown that although nuclear power currently accounts for only a small portion of the world's energy production, with the growing need for electricity, the rise of emerging and developing countries, and the need to combine all possible solutions to combat global warming, it is quite clear that it will continue to play an important role. Most of the new nuclear power reactors are being built in emerging countries and the recent interest for Small Modular Reactors may facilitate the deployment in very different areas and use for non-energy applications.

It has also been shown that the global non-radioactive environmental impact of nuclear energy is generally lower than for other sources of energy and that long-term management solutions for radioactive waste are available.

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