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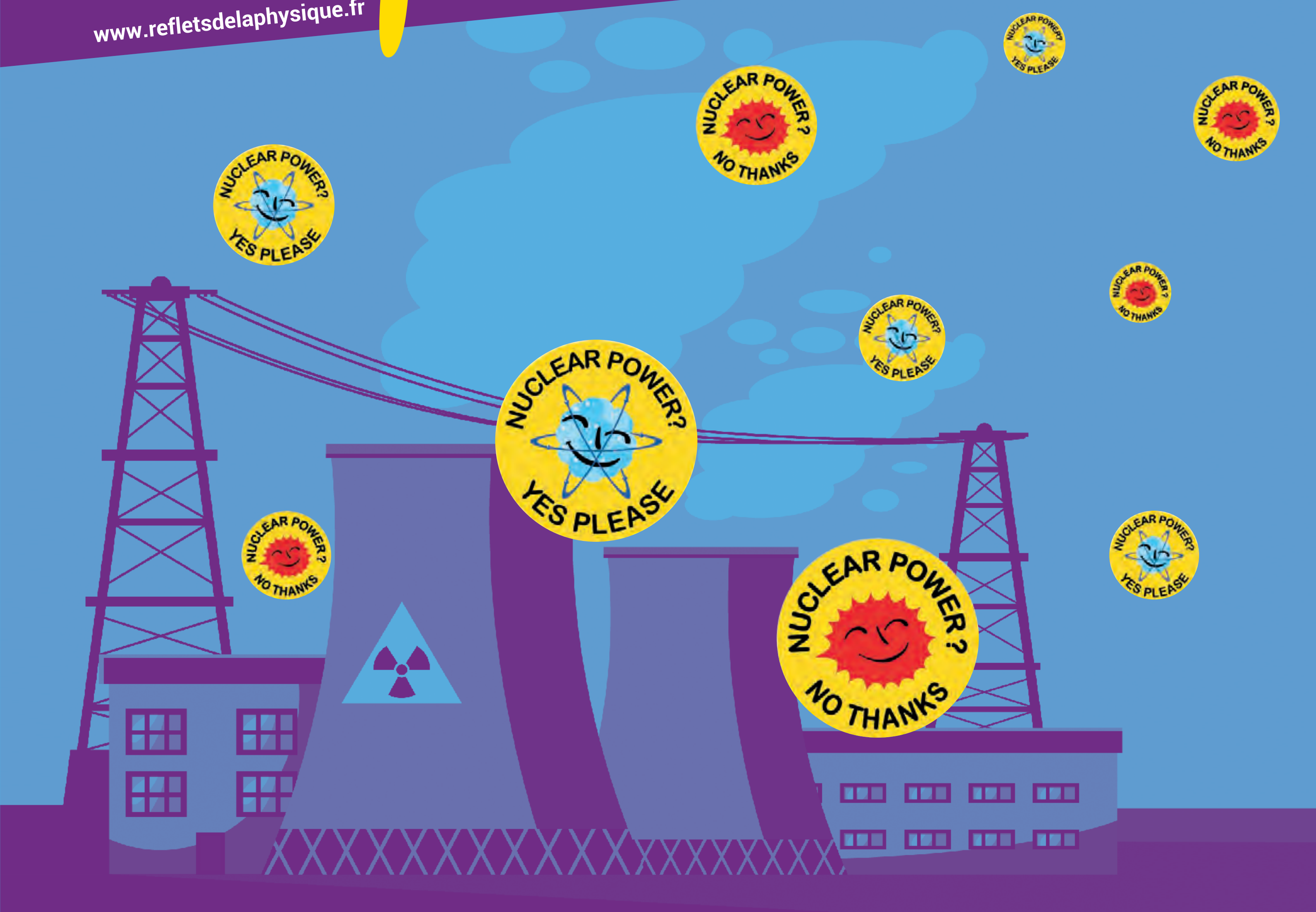

Nuclear Power

Open-ended questions and points of view

n° 60 - December 2018

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cnrs

The French Physical Society encourages the nuclear debate.

Energy and the environment are at the heart of current debates: the threat of climate change and dwindling fossil resources are causing global problems to which physicists cannot remain indifferent. The French Physical Society (La Société Française de Physique or SFP) and the science community in general have a responsibility to shed light on these debates.

SFP's "Energy and Environment" group has historically been a forum for the sharing and dissemination of information; they provide frequent and scientifically-rigorous briefings for societal and political decision-makers.

The SFP and the French Chemical Society have recently called on the French government and Parliament to set up a body for the scientific assessment of energy policy. They stated their position in an online stakeholders' consultation [1] in the context of the public debate on the revision of the Multiannual Energy Program.

Nuclear power cannot be excluded from this debate into energy sources and their future. Whilst each source of energy has its own unique features, it is nuclear technology that has undoubtedly been one of the most controversial scientific and technical fields throughout the second half of the last century and which remains so today. The highly animated and contradictory nature of the debate, even within the SFP, highlights the need to take into account a variety of data in order to draw as accurate and objective a conclusion as possible in what is an extremely complex area.

The aim of this special edition of *Reflets de la Physique* is to adopt a calm editorial approach, presenting the arguments of a contradictory debate in a highly factual manner of a large (albeit limited) number of viewpoints, so that the reader can form his or her own opinion. This editorial approach is typical of the SFP's magazine, which has in the past published several very detailed articles about nuclear power and its future.

The physics community, and scientists in general, are increasingly aware of the political, societal and moral implications of their professional work. This is why the preparation of a reference document intended to be accessible to a very broad audience also needs to include contributions from non-scientists. We have therefore given them the opportunity to bring fresh insight that can sometimes be overlooked by scientists, even when it clearly influences public perception.

A further issue of *Reflets de la Physique*, currently being prepared with the "Energy and Environment" group, will soon be devoted to energy in general to extend and enrich the debate.

In the 1990s, under the presidency of René Turlay, the SFP had already published a study on nuclear waste [2], but this is the first time that we enter the debate on nuclear energy with such an extensive piece of work, including a comprehensive bibliography, and aspiring to reach a wider readership than just science enthusiasts.

With this special issue, which reflects our determination to ensure an informed debate, we hope to provide an explanation of the controversies and the knowledge that the public often lacks in order to form an opinion. Hoping that this goal will be achieved, we wish you an excellent read!

Catherine Langlais
President of the French Physical Society

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1. https://cpdp.debatpublic.fr/cpdp-ppe/cahier-dacteur-ndeg30-societe-francaise-physique.html
2. Société Française de Physique (sous la direction de R. Turlay), Les déchets nucléaires, un dossier scientifique, EDP Sciences (1997).

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Editor-in-chief: Charles de NOVION
Design: Lætitia MORIN - Keith VILLEMEUR
Graphic design: Lætitia MORIN
laetitiamorin-graphiste.fr
Editorial Assistant: Agathe CYMER
Publicity department: publicite@edpsciences.org
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Société Française de Physique
(French Physical Society)
33, rue Croulebarbe, 75013 Paris
Tel: 0144086710
Fax: 0144086719
e-mail: contact@sfpnet.fr -
Website: www.sfpnet.fr
SFP Bulletin
Institut Henri-Poincaré,
11, rue Pierre-et-Marie Curie, 75005 Paris
e-mail: sfp-bulletin@ihp.fr
Website: www.refletsdelaphysique.fr

How do we address the many facets of the nuclear debate?

François Graner, physicist, National Center for Scientific Research (CNRS), and **Stefano Matthias Panebianco,** physicist, Atomic Energy Commission (CEA), editors of this issue

A divisive subject

The story of how this special issue of *Reflets de la Physique* came about is long and tortuous. It began with the realization that nuclear power is probably the subject which most divides the physics community. Hence the initial idea, admittedly not a very original one, was to offer the readers of Reflets a short article on civil nuclear power in France; scientists with opposing views on the subject would be invited to contribute. We wanted to present the debate in a way that was both concise and comprehensive, but we soon realized that it is impossible to do justice to such a complex and multi-faceted subject in just a few pages.

The magazine's editorial board was convinced of the value of addressing the ongoing debate about civil nuclear power. They asked us to coordinate the publication of a special issue dedicated to this subject which would focus on the present-day use of nuclear fission to generate electricity in France. It has taken authors and editors two years to agree, implement and collate this collection, guided by a number of considerations, discussed below.

What will you find in this issue?

First of all, which subjects should we tackle? It is clear that the issue of power generation is the subject of intense public debate, both in France and the rest of the world. The physics, the environment, the economy and politics are inextricably linked. Any decision taken individually or collectively involves weighing up several factors and for each individual certain aspects carry more weight than others. It was obvious from the outset that, along with the more technical aspects, we would need to include insights into some areas you might not expect to find within a physics magazine.

In fact scientists, and physicists in particular, were invited into this debate, sometimes with a bit of arm-twisting, and often with views that go beyond their field of expertise. However, scientists are first and foremost citizens, inhabitants of the planet and, as such, participate in the energy choices that have an impact on it. Within this framework, physicists could hopefully apply their typical working methods, relying on critical and reasoned analysis, to express their opinions within the context of a controversial debate.

This is why you will find four types of articles in this issue. Firstly (p. 6), some factual articles on the uranium industry and French nuclear power plants, nuclear waste and plant decommissioning. Secondly (p. 16), to set the scene for the ensuing debate, articles on the environmental impact (in the broadest sense) of nuclear power under normal operating conditions, on the risk of accidents, on the control of radioactivity, subcontracting and the costs of nuclear power. Thirdly (p. 32), to put the debate in its historical context, articles on the history of civil nuclear power in France and its military origins, analyses of the relationship between nuclear power and society, and the treatment that the press gives this public debate. Finally (p. 44), we look to the future: what scenarios can be envisaged on a global scale, in terms of climate, or on a national scale, as a result of choices made by society? What technical or political decisions concerning electricity distribution networks and research avenues will come to influence the debate?

Translation: If Chernobyl made you laugh, don't miss Golfech.

Country Living - Nuclear Power at Golfech - employment - regional growth - national independence - A key ingredient for bringing about real progress in Tarn-et-Garonne.

Who are the authors?

Evidently, given the diversity of themes explored in this issue, the selection of the authors has been a crucial step. The main criterion was to represent a broad range of perspectives, so the various contributors are as representative as possible in terms of fields of expertise, including physics, mathematical modelling, ecology, security, economics, history, non-governmental organizations, geology, chemistry, journalism and politics. The opinions of each author are validated by his or her expertise and their relevance to the subject matter, and not by his or her institutional affiliation. All the authors are French or work in France; addressing issues of international interest could, in the future, enrich the debate.

Some authors are known to publicly express a « pro- » or « anti- » point of view; it was deemed necessary to include such opinions where justified by relevant arguments. It has been our role, as editors, and that of the editorial committee, to ensure the reliability and coherence of what is conveyed and to ensure balance in order to provide the authors with a forum for a genuine and fair debate, so that innovative and positive aspects can emerge alongside the most intractable problems. Illustrations also help to maintain a balance between opposing views (see example above).

And finally...

Despite the rigor of the process, there are some lingering frustrations. Many aspects that were touched on only slightly or not at all in this issue deserved much more in-depth study; the final article (p. 58) is dedicated to these aspects, with the aim of highlighting that such a rich and complex debate is far from being exhausted by a sixty-page document. And, despite everyone's efforts to make it interesting and readable, the sheer amount and density of information in this issue could discourage the usual reader of the magazine.

The document that you, the reader, have in front of you, is the result of a great deal of work by the authors, whom we warmly thank for their perseverance and patience, as well as an editorial process of which we are proud. We hope that it offers as clear and up-to-date an understanding as possible of the very many implications of the use of nuclear energy, its development and its possible future. We hope that it will provide food for thought and enable people to make an informed opinion in the context of an engaging and emotive debate, and that it encourages them to go beyond black and white thinking and instead to appreciate the numerous aspects and subtleties of this controversial topic. ▮

This is the translation of a French work published in December 2018. We have not attempted to adapt it to a more international context, nor to translate the bibliography. We hope that the questions it raises, the style of debate it introduces, and the elements drawn from the French specific context can inform the debate in any other national context.

Complete issue can be downloaded at:
www.refletsdelaphysique.fr

For questions or comments,
please contact: **sfp-bulletin@ihp.fr**

The editors, F. Graner and S.M. Panebianco, would like to thank the many people who have contributed to critical reading of this document, and Ruth Flatman for the English translation.

FRENCH CIVIL NUCLEAR INDUSTRY

Radioactivity must be controlled throughout all stages of the nuclear fuel chain, to prevent it from having any harmful effects on either humans or the environment.

Henri Safa

Electronuclear technology in France today

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As far as the energy sector is concerned, any policy adopted in the short-term via an electoral mandate, must take into account the long-term implications.

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The technical feasibility of decommissioning is hard to predict owing to the different levels of understanding of the reactor types.

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Electronuclear technology
in France today

Henri Safa, physicist, CEA

Existing French nuclear power stations are pressurized water reactors. Before being put in the reactor, the uranium-containing fuel source has been through a lengthy process starting at the mine. It passes through a series of enrichment steps before being processed into fuel rods. After being irradiated in the reactor the spent fuel is separated and treated for disposal. Additional processing steps are required if the plutonium is to be recycled and used as fuel, as is the case in France.

Nuclear Fuel

The energy density of nuclear fuel

The fission of a uranium atom releases a considerable amount of energy per unit of mass, 100,000 times more than the most concentrated fossil fuels. Thus, in our current nuclear reactors, a single uranium fuel pellet of a few grammes can provide as much thermal energy as five barrels of oil[(a)] (fig. 1). This accounts for two advantages of nuclear power: it uses only small quantities of natural resources and consequently its price does not fluctuate greatly.

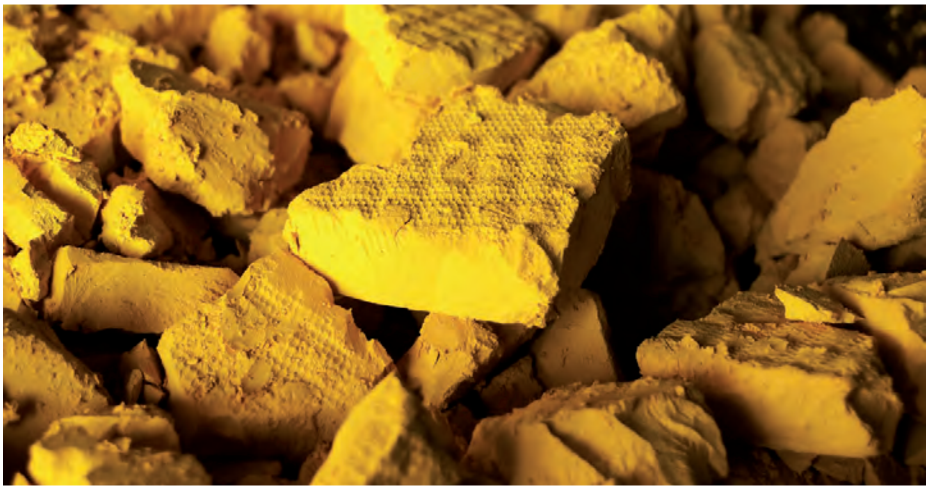
However, whilst air combustion of hydrocarbons is relatively simple, the use of nuclear power requires sophisticated technical skills. Radioactive elements must be controlled throughout the nuclear fuel chain to prevent them from having any harmful effects on either humans or the environment. Care is needed especially when the spent nuclear fuel is unloaded from the reactor due to the presence of highly radioactive elements, albeit in small quantities.

The raw material uranium

Uranium is a 'heavy' chemical element, i.e. it has a large nucleus. It is relatively abundant in the earth's crust, about the same as tin[(b)]. Uranium deposits are found throughout the world. Some deposits are very rich, with high-grade ores containing more than 20% uranium, for example Cigar Lake in Canada. Uranium is obtained by mining, using extraction techniques similar to those for other metals, but which allow for the fact that radioactivity from the radon is released into the atmosphere.

As the current contribution of nuclear power to electricity generation and more broadly to global energy output is small,

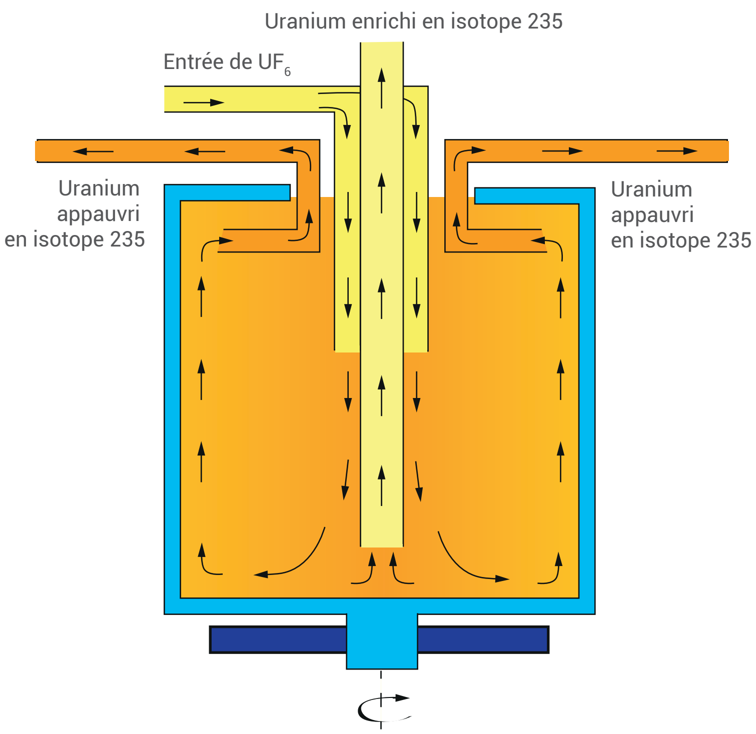
1. Image showing the size of an enriched uranium oxide pellet used in the production of nuclear fuel in a pressurized water reactor. For a given amount of energy, nuclear power uses 100,000 times less raw material than fossil fuels (oil, gas or coal).



2. The uranium ore extracted from the mine is milled and chemically-processed to produce 'yellowcake'.

uranium doesn't yet pose a significant supply problem[c]. The amount of uranium extracted from the earth, typically 60,000 tons per year, is low compared to other minerals or energy resources, which are usually in the billions of tons.

In theory, all the uranium ore required to supply the reactors in France annually could be extracted from French soil[d]. It could even be extracted from seawater, the practical limitations being the economic and energy costs. In the mines currently in operation around the world, uranium is cheap (less than 100€ per kg) and accounts for less than 3% of the cost of nuclear power per MWh[e]. Thus, unlike fossil fuels, what determines energy independence is not access to the raw material, but rather access to the specific technologies (reactors and power plants) which enable its exploitation.



3. Scheme of a centrifuge for uranium enrichment.

'Upstream' of the reactor (conversion, enrichment, fuel production)

Natural uranium is made up of three isotopes: uranium-234, present at ultra-trace levels, uranium-235, naturally present at 0.7%, and uranium-238, the most abundant form of uranium[f]. However, only isotope U-235 is fissile, i.e. can split into two parts following the absorption of a neutron into the atomic nucleus, releasing energy. It is the only fissile atom on the planet; although radioactive, it has been around since the formation of the earth due to its long half-life of 700 million years[g]. Uranium is said to be "enriched" when the proportion of its fissile atoms is increased. It is necessary to reach 4% fissile atoms in the fuel in order to maintain a chain reaction in a light water reactor.

In order to do that, the uranium must first be converted into uranium hexafluoride (UF_6), a compound which has the advantage of readily turning into a gas: it goes directly from a solid state to a gaseous state as soon as the temperature exceeds 56.4 °C. The fluorination of uranium to convert it to UF_6 is carried out in the Comurhex plant at the Malvési (Aude) then Tricastin (Drôme) sites.

Once uranium is in the gaseous hexafluorine form, the enrichment step can be carried out using ultracentrifugation[h]. This process uses the centrifugal force acting on the gas, which is contained in a vessel rotating at high speed around an axis (fig. 3). As the magnitude of the

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4. Nuclear fuel assembly of a pressurized water reactor with control rod. The grids provide mechanical support to maintain the 264 fuel rods.

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centrifugal force is proportional to the mass of the particles, the uranium-238 atoms, being slightly heavier, move to the periphery. The gas in the center of the vessel thus becomes richer in isotope 235, whilst the gas at the walls becomes poorer. The required 4% enriched uranium is reached through a series of successive centrifugation steps, using a cascade arrangement of ten or so centrifuges[i]. Factoring in losses, it typically takes 8 kg of natural uranium to obtain 1 kg of enriched uranium.

Once enriched, the gas is converted back into a solid powder of uranium oxide in a rotary kiln with steam at around 800 °C (pyrohydrolysis). The powder is then compacted and pressed into a cylindrical pellet about 1 cm in diameter and 1.3 cm in height (fig. 1). Sintering[j] in hydrogen at 1,750 °C completes the process by achieving the necessary porosity.

These pellets are then inserted one on top of the other into a long tube, a 4-metre long zirconium alloy sheath sealed at its ends. This "fuel rod" contains about 300 pellets. A fuel assembly consists of 264 fuel rods arranged in a 17 x 17 square (Fig. 4), with 25 free slots for 24 absorber rods to control the chain reaction (and one instrumentation tube). The core of a 1,300 MW Pressurized Water Reactor (PWR) is composed of 193 such assemblies. The European Pressurized Reactor (EPR) under construction in Flamanville consists of 241 assemblies.

Reactor Operation

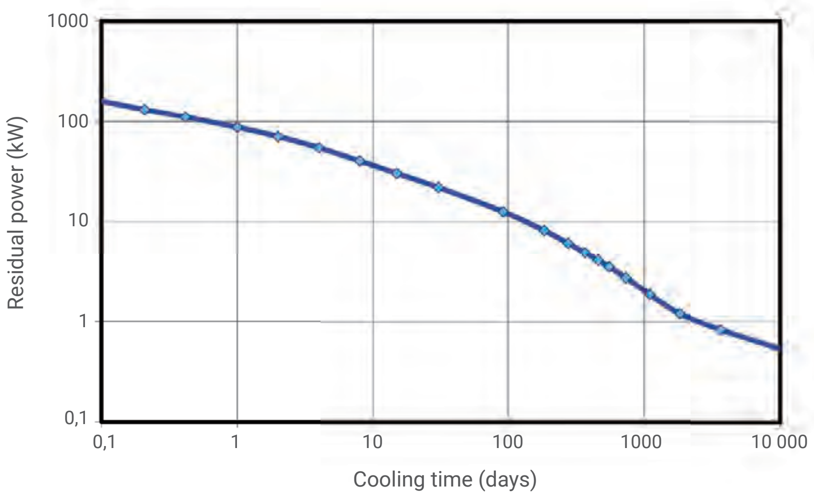
An assembly remains in the reactor core for about four years, during which time the uranium-235 nuclei fission due to an intense neutron flux produced by nuclear fission. In fact, the fission of an uranium nucleus produces an average of three neutrons. These induce the fission of other nuclei, and thus the reaction grows exponentially: it is a chain reaction.

The heat released by the nuclear reactions is carried away by a liquid, the coolant, which circulates in a closed system: this is the primary coolant system, in which the liquid becomes radioactive. To avoid contamination, this liquid passes through a heat exchanger, known as a "steam generator", which transfers the heat to a second liquid: this is the secondary coolant system. Following the same principle as in a conventional thermal power plant, because of the temperature difference between the steam generator and the source of cooling (river or sea water, or the air in the cooling towers), the coolant is able to drive a turbine that produces electricity. In the end, as in a thermal power plant, about one third of the reaction energy is actually converted into electricity; the remaining two thirds heat the atmosphere.

For electricity production, the chain reaction must be carefully regulated so that it does not run out of control. To achieve this, only one of the neutrons produced can be allowed to trigger another fission. The reactor core is then said to be "critical", a term with a positive connotation indicating that its operating regime is exactly at the desired limit. It is neither too weak nor too strong and can continue to function for as long as there is fuel remaining.

This control is ensured by fine dosing of neutron absorbing elements: either boron in the water of the primary coolant system, cadmium in the control rods, or gadolinium in the fuel. The reactor is controlled mechanically by raising or lowering the control rods in response to energy demand by the operator. This also ensures a balanced distribution of power in the core, and the absence of places where the local temperature would be too high, which could lead to boiling.

During operation of the reactor, the fissile uranium-235 gradually disappears. At the same time, because of the continuous and intense neutron radiation, a small fraction of the uranium 238, the majority isotope, is converted by neutron capture into plutonium-239, an isotope that has a high energy value since it is also fissile. When the reactor is unloaded, the spent fuel contains only 0.85% uranium-235, whereas it now contains more than 1% plutonium atoms.



5. Decrease with time of the heat released by fission products and actinides in a fuel assembly (here a 4% enriched uranium oxide irradiated at 45 GWd/t).

The high concentration of radioactive material in the core of a reactor (more than 100 tons of fuel) requires specific risk management during operation. Indeed, the most commonly considered risk in the nuclear industry is that of a major accident in a reactor during normal operation[k]. The likelihood of a possible core meltdown, although in line with estimates made at the time they were designed, 10^{-4}/year/reactor, appears in practice to be not insignificant for second-generation reactors: three major accidents in the world in 60 years, two of which caused a release of radionuclides into the atmosphere. What was considered an impossible, or at least acceptable, industrial accident in the 1970s by the proponents of nuclear power is no longer considered to be so today.

Learning from these experiences has led to improvements in safety. The Fukushima accident taught us that the loss of any cooling system and the loss of the external power supply can under certain circumstances occur simultaneously at the same facility. In the past, we guarded against either of these two events separately. Today, all operators around the world must consider the possibility of these two risks occurring simultaneously.

Therefore, the designers of the European Pressurized Reactor (EPR) focused on improving safety by reducing the probability of core meltdown by at least two orders of magnitude, at the same time doubling the construction cost (from 1,500€/kW to 3,500€/kW). If the entire current global fleet were made up of such reactors, the probability of a major accident would decrease by 100-fold from one every 20 years to one every 2000 years or more. And in the unlikely event of an accident, the radioactivity would be contained within the reactor, and therefore not require the evacuation of the surrounding population.

6. Nuclear waste container. The cylinder is made of stainless steel with a height of 1.35 m and diameter of 0.43 m. It contains about 400 kg of borosilicate glass which traps the waste. The total weight is about 500 kg.

Spent fuel

Nuclear fission and neutron irradiation generate a variety of radioactive elements inside the fuel, called "fission products", with very different half-lives. This means that when a fuel assembly is removed from a reactor core, it is highly radioactive and the fuel continues to be heated by the residual power released by this radioactivity. This heat must be removed, otherwise the assembly would melt. The assembly is immersed in a pool of water, to allow it to cool down, for 2 to 3 years, after which time the residual power of the assembly has decreased sufficiently (fig. 5) to allow it to be transported to the La Hague plant for reprocessing.

In the reprocessing plant, the spent fuel is dissolved in nitric acid. The reusable nuclear materials such as uranium and plutonium, which form the bulk of the contents, are extracted from the solution, while any remaining products, considered as the final waste of nuclear fission, are vitrified in glass and stored in containers (fig. 6).

The reprocessing of about 70% of the spent fuel in France results in the annual production of about 650 high level waste (HLW) containers of vitrified waste (see p. 21). This vitrified waste contains 98% of the total radioactivity of nuclear waste, but represents only 0.2% of its total volume[l]. Structural waste (hulls, grids, assembly tips) is compacted in similar containers and classified as long-lived intermediate-level waste. It accounts for almost all the remaining radioactivity (2%). All other waste is low-activity waste (less than 0.03% of total radioactivity).

The flow of nuclear materials

France has 58 pressurized water reactors (PWRs) (see map on p. 42), which are supplied each year with about 1,000 tons of uranium fuel enriched to 4%. The plutonium recovered from reprocessed fuel can be used as a fissile element instead of uranium-235. It is then combined with the depleted uranium to form MOX fuel (a mixture of uranium and plutonium oxides). In recent years, all of the eleven tons of plutonium produced each year have been fully recycled in the form of MOX[m] fuel. The uranium recovered at La Hague, known as reprocessed uranium (repU), now contains about as many fissile atoms as natural uranium and can therefore be re-enriched to make fuel. This re-enriched reprocessed uranium (ERU) is used to supply the four Cruas reactors in the Ardèche[n]. The general flow of nuclear materials is shown in fig. 7. ▮

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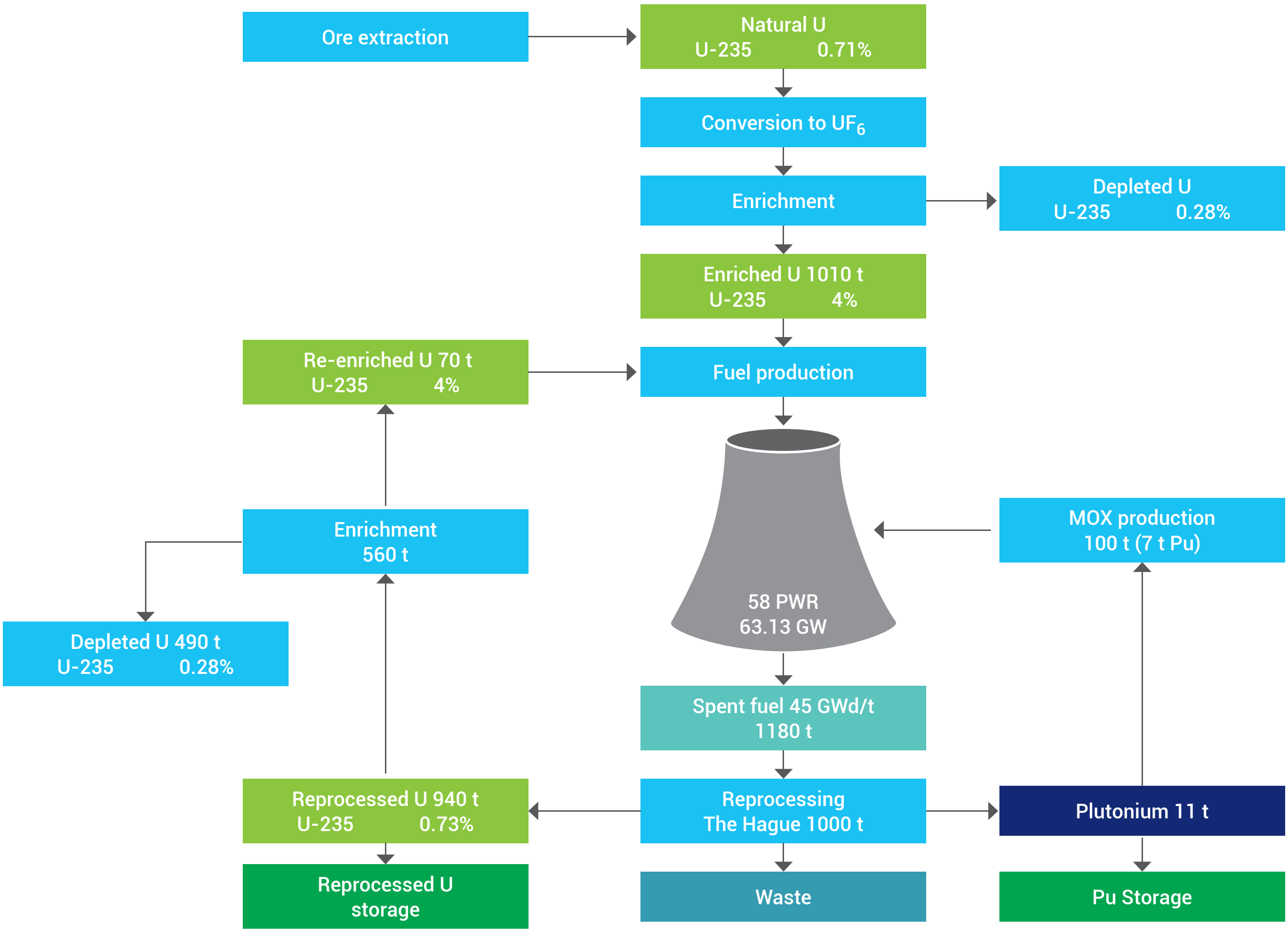

7. Annual flow of nuclear materials supplying the entire French nuclear fleet, taking 2013 as an example: from the 1000 tons of fuel in the form of uranium oxide (UOX), the recovery of plutonium enables the production of 100 tons of MOX fuel (a mixture of uranium and plutonium oxides) and 70 tons of enriched reprocessed uranium (ERU).

a. The energy density of an atomic nucleus is one billion Wh/kg. A pellet of 7.5 g of uranium enriched to 4% can provide up to 9 MWh of thermal energy, the equivalent of 5 barrels of oil or a ton of coal.

b. Uranium is present on Earth at 2 to 3 parts per million (ppm), sometimes at a concentration greater than 1000 ppm in granitic or sedimentary zones. It is 15 times less abundant than copper, as abundant as tin (but with an annual production 5 times lower), 30 times more abundant than silver, and 600 times more abundant than gold.

c. For the question of future provision, see the article by S. Bouneau (p. 46).

d. Until 2001, uranium was still mined in France. However, its production cost is not competitive on the world market because French mines have low uranium content (less than 1%).

e. See the article by A.-S. Dessillons (p. 29). Over the past 40 years, the cost per kg of uranium has fluctuated between \$5 and \$200; in 2018, it was in the range of \$40 to \$50 per kg.

f. Natural abundance: uranium-234, 0.005%, uranium-235, 0.711% and uranium-238, 99.283%.

g. Time taken for the original amount to halve. It takes at least ten half-lives for the radioactivity to decrease significantly.

h. Until 2011, enrichment was carried out at EURODIF's Pierrelatte plant by gaseous diffusion, a very energy-intensive process that has since been abandoned. Three of the four Tricastin reactors were dedicated exclusively to supplying power to the enrichment plant. Ultra-centrifugation, requiring 40 times less energy than gaseous diffusion, is now the standard technology.

i. A centrifuge enriches about 1.2 times. So ten cascade centrifuges enrich by a factor of 1.2 to the power of 10, i.e. 6 times. The proportion of uranium-235, initially 0.7%, increases to 6 times 0.7%, i.e. about 4%.

j. Heating the powder so that the grains stick together (but do not melt completely), just as in a pottery kiln.

k. The upstream stages of the fuel cycle and the transportation of either radioactive materials or nuclear waste have so far not given rise to very large accidents, except for the Mayak nuclear complex near Kyshtym (U.S.S.R.) in 1957, about which little is known.

l. The 2015 inventory of the French National Agency for Radioactive Waste Management (ANDRA) gave the following volumes at the end of 2013: 3,200 m^3 of high-level waste (HLW); 44,000 m^3 of intermediate level long-lived waste (ILW-LL); 91,000 m^3 of low level long-lived waste (LLW-LL); 880,000 m^3 of short-lived low or intermediate level waste (LILW-SL); 440,000 m^3 of very low level waste (VLLW).

m. In the past, some of the plutonium would have been retained for use as fuel in existing or future fast-neutron breeder reactors.

n. Recent trends include an increase in MOX fuel production (124 tons in 2016) and a reduction in ERU fuel to 20 tons in 2016, offset by an increase in UOX fuel to 1,070 tons. ▮

To find out more

- Presentation of the French *"Cycle du combustible"* in 2018, High Committee for Transparency and Information on Nuclear Safety (2018), www.hctisn.fr

Managing radioactive waste

The need for a long-term political vision

Jean-Yves Le Déaut, Member of Parliament (1986-2017), President of the Parliamentary Office for the Evaluation of Scientific and Technological Options (2014-2017)

The long-term management of radioactive waste from French nuclear power plants is a political issue that has been the subject of debate over many years. Since the end of the 1980s, Parliament has passed three acts enabling a national strategy to be established.

The French Parliament adressed the problem of waste management at the end of the 1980s. The government had authorized an exploratory program to search for a geological area suitable for deep disposal of waste. However, the population of the regions concerned (Ain, Aisne, Maine-et-Loire, Deux-Sèvres) reacted very strongly to the initiative because it felt its voice hadn't been heard.

The Prime Minister at the time, Michel Rocard, put an end to the program and left it to Parliament to carry out in-depth consultations to find a solution. In 1990, Christian Bataille, Member of Parliament, was given the task of submitting a report on the strategy for radioactive waste management on behalf of the Parliamentary Office for the Assessment of Scientific and Technological Choices (Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques, OPECST).

The report presented a set of measures offering a new approach to this issue, which at the time was at an impasse. These measures subsequently formed the basis of a first French law on waste management, passed on 30 December 1991, which, among other things, established guidelines for scientific research into radioactive waste[a].

Since the early 1990s, the issue of radioactive waste management has been addressed with remarkable political continuity, both by successive governments and by successive majorities in Parliament, with the support of the opposition.

For example, the 1991 act was unanimously passed in the National Assembly under a left-wing government. Fifteen years later, the first law on radioactive waste was passed unanimously by a right-wing government: the act of 28 June 2006 on the sustainable management of radioactive materials and waste[b]. This law also adheres to the timetable drawn up in 1991, which called for an evaluation of the results of research on radioactive waste after 15 years, prior to a further parliamentary vote.

Ten years later, in accordance with the requirements of the 2006 act, the act of 25 July 2016 specifies the procedures for creating a reversible deep geological disposal facility at Bure-Saudron (Meuse/Haute-Marne)[c]. It follows the filing of a number of similar bills in the French National Assembly and Senate by members of parliament with different political leanings (Gérard Longuet, Christian Namy, Jean-Yves Le Déaut, Christian Bataille). It was also passed, by a very large majority, in both houses of Parliament, with the exception of a few opponents of the nuclear industry.

Candidates in the 2017 presidential election proposed to halt the project for an industrial-scale geological disposal facility and storing the waste until a final solution is reached. However, storage could increase safety and security risks and delay the search for an agreed solution. Whether one is for or against nuclear power, nuclear waste exists and to do nothing today would be to leave it to future generations to solve the problem[d].

As far as the energy sector is concerned, any policy adopted in the short-term via an electoral mandate must take into account the long-term implications, the unit of time in this field being of the order of half a century[e]. For example, the future deep geological storage facility is planned to be built around 2035, almost 50 years after Parliament first considered the issue, and will operate for at least 100 years. The continuation of this industrial and scientific endeavor will require political decision-makers to reconcile short and long-term interests. ∎

a. Act No. 91-1381 of 30 December 1991 on research into radioactive waste management, known as the Bataille Law.

b. Act No. 2006-739 of 28 June 2006 on the sustainable management of radioactive materials and waste.

c. Act No. 2016-1015 of 25 July 2016 specifying the terms and conditions for the creation of a deep geological repository for the reversible storage of high-level and intermediate-level long-lived radioactive waste.

d. On the question of waste, see several articles, in particular that of B. Romagnan (p. 14), and the interview with C. Stéphan and P. Barbey (p. 19).

e. On the question of policy measures over a number of decades, particularly in relation to global warming, see the article by S. Bouneau (p. 46), and that of N. Maïzi and F. Briens (p. 49).

Decommissioning nuclear facilities: a technical feasibility not yet fully demonstrated

Barbara Romagnan, MP (2012-2017)

The decision to decommission nuclear facilities after they have been shut down should make it possible to reuse the space freed up. However, the technical feasibility of the decommissioning and decontamination process has not yet been proven for every type of French nuclear facility.

France is currently in an interim period as regards nuclear decommissioning, which, given the scale of the work that remains to be done, requires the utmost vigilance. Decommissioning involves the deconstruction of a nuclear reactor, the decontamination of operational buildings and the clean-up of soil that may have been contaminated. In theory and in the best-case scenario, decommissioning allows the unrestricted reuse of the cleared and fully decontaminated areas. This is known as a return to "greenfield" status, the image evoking a return to its natural state. But the reality is more complex: since total decontamination is particularly expensive, under certain circumstances and at the request of the operator the French Nuclear Safety Authority (Autorité de sûreté nucléaire, ASN) may allow the decommissioning to forgo this requirement. In the United States it is even accepted that some radioactive remains may be left in situ covered by a concrete sarcophagus; in other cases, spent fuel may be stored on sites of decommissioned reactors in sealed canisters, in which case the land has "brownfield" status and is suitable for industrial use.

France has opted in principle for the immediate dismantling of facilities after their shutdown. However, not all questions have been resolved regarding the progress of dismantling techniques and whether there has been sufficient testing of the proposed methods. In this respect, two main points should be noted: on the one hand, the knowledge gained from experience doesn't apply to all the different facilities; on the other hand, there are still questions about the management of waste resulting from the dismantling.

Disparity in the knowledge gained through experience across the different facilities

The French nuclear fleet is distinctive in being made up of two types of reactor: a first generation of "natural uranium graphite gas" (NUGG) reactors that are no longer in operation, and a second more recent fleet, still in operation, of pressurized water reactors (PWR). Électricité de France (EDF) reports that it has encountered some difficulties with the first NUGG fleet, which was initially intended to be dismantled "under water", and these technical complications have led it to reconsider its strategy. As the water was supposed to limit the release of radioactivity during the removal of the graphite layers, the main reactors have now seen their decommissioning deadlines extended considerably. For example, the Bugey reactor, whose decommissioning began in 1994, is not expected to be fully decommissioned until 2037, and the Chinon reactor until 2041. However, when ASN learned in 2016 of EDF's decision to proceed with dismantling in air, they didn't find the operator's justifications were satisfactory. Consequently, EDF intends to test its new technique on a test reactor by 2060, and to dismantle the remaining reactors by 2100.

With regard to the PWR fleet, it appears that the technical feasibility of decommissioning is more assured. However, in reality, no PWR has been decommissioned worldwide to date. Caution is called for, since unpleasant surprises in this area have been the rule up to now. EDF has 58 pressurized water reactors currently in operation and nine reactors that have

To find out more

- *Rapport sur le démantèlement des installations nucléaires de base*, Conseil supérieur de la sureté et de l'information nucléaires (CSSIN), 16 mai 2007.
- *Faisabilité technique et financière du démantèlement des infrastructures nucléaires*, rapport de la Mission d'information parlementaire (M. Julien Aubert, président, Mme Barbara Romagnan, rapporteure), 1er février 2017, www.assemblee-nationale.fr/14/rap-info/i4428.asp

Siloé experimental reactor (Grenoble), in operation from 1963 to 1997. The decontamination and dismantling phases lasted from 1998 to 2011.

been shut down: Brennilis, a heavy water reactor, Superphénix running on sodium, six first-generation reactors running on graphite gas, and the Chooz A underground reactor, the oldest French PWR. For this fleet, the difficulty lies more in EDF's plan to rebuild reactors on the sites currently in use. As a result, the operator does not refer to these reactors as being "decommissioned" but simply "deconstructed". In other words, EDF does not foresee a global and precise schedule for their decommissioning. In addition to this, there are also occasional difficulties with individual reactors, such as Superphénix and Brennilis. Superphénix entered service in 1985 and was shut down in 1996. According to EDF, Superphénix should be dismantled by 2028, which is more than 30 years after its final shutdown. This time-frame is unsatisfactory because it does not respect the principle of immediate dismantling. Brennilis, meanwhile, was shut down in 1985 and in view of the difficulties encountered by EDF, is not likely to be dismantled before 2032 i.e. 47 years after it was shut down. Moreover, such difficulties have a real financial impact: the Court of Auditors estimates that the costs of decommissioning could be multiplied by a factor of twenty, reaching almost 482 billion Euro[(a)]. The technical feasibility of decommissioning is therefore also a financial issue.

There are a number of discrepancies in the technical knowledge of the different reactor types which makes it impossible to assess the technical feasibility of decommissioning. In addition to the specific site-related issues, there is also the challenge of spent fuel disposal, which is essential for the successful completion of decommissioning.

Waste management still raises questions

Here again, the current picture does not indicate that the technical issues have all been resolved[(b)]. Whilst the waste from decommissioning will account for nearly 60% of the volume of waste to be treated by 2030, 40% will come from reactor operations, and will cause certain facilities to be over-filled, depending on the category of waste to be treated.

The method used for reprocessing and storage of waste depends on its level of radioactivity. 60% of it has very low activity (VLL), but the National Agency for Radioactive Waste Management (Agence nationale pour la gestion des déchets radioactifs, ANDRA) storage center located in the Aube region will reach full capacity in 2025.

More broadly, the issue of storage questions the wisdom of setting a disposal limit for nuclear waste. At present, everything that leaves a power plant must be stored in specialized centers; however, some waste has not been contaminated and perhaps therefore saturates the centers unnecessarily. ANDRA estimates that 30 to 50 per cent of the waste has little or no radioactivity. This would therefore be an avenue to explore in order to respond to the very imminent problem of saturation of our storage facilities.

The methods used for storing waste are also a cause for concern, particularly deep geological storage. The Industrial Center for Geological Storage (Centre Industriel de stockage Géologique, Cigéo) project located at Bure in the Meuse region plans to bury the most radioactive waste from the nuclear industry for hundreds of thousands of years. In view of the long-term consequences and the effectively irreversible nature of this choice[(c)], the wisdom of underground disposal is highly questionable, although it is possible to store the waste underground whilst at the same time pursuing research in parallel in the hope of one day being able to recycle it satisfactorily. The limitations of underground storage have been illustrated by a former salt mine in Lower Saxony: access corridors do not remain straight at the scale of a human lifetime so how can we hope to guarantee safety over thousands of years? All these questions may be the focus of different strategic choices, but no irreversible decision should be taken because waste storage, like reactor decommissioning, is a decisive step for the successful dismantling of nuclear infrastructure. It must be said that in this area, too, the current outlook is unsatisfactory. ▮

a. Court of Auditors, *Le coût de production de l'électricité nucléaire*, updated May 2014, www.ccomptes.fr. See also the article by A.-S. Dessillons (p. 29).

b. Several articles address this question, in particular that of J.-Y. Le Déaut (p. 13), and the interview with C. Stéphan and P. Barbey (p. 19).

c. Act No 2016-1015 of 25 July 2016 theoretically requires reversibility, defined as "the capacity, for successive generations, either to continue the construction and then the operation of successive sections of a storage facility, or to reassess the choices previously defined and to develop management solutions [...]. It includes the possibility of recovering waste packages already stored." [Ed.].

NUCLEAR ISSUES

Translation: Saying yes to nuclear technology is helping to cure advanced neuroendocrine tumors. The Bordet Institute in Belgium has been the first Belgium hospital center to produce, in 2012, a new radioactive tracer which targets cancer cells. For numerous Belgium cancer patients this is a game-changer.

During normal operation, the main environmental impact of a nuclear power plant is exposure of nuclear workers and the public to thermal, chemical and radioactive emissions.

Conversation with Claude Stéphan and Pierre Barbey

Impact of nuclear power plants during normal operation on health and the environment.

page 19

Some accidents may call for an immediate response. Significant and short-lived release can lead to residents being asked to take shelter.

Conversation with Jean-Christophe Gariel and Sophia Majnoni d'Intignano

The risk of a nuclear accident: prevention and management

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By actively engaging in the monitoring, the public has transformed a purely technical subject into a political one.

David Boilley

Radioactivity in the environment: the role of monitoring bodies

page 24

The strong partnership between operator and subcontractors, which has been damaged by economic factors, is essential and must be restored.

Interview with Gilles Reynaud

Subcontracting and quality in a nuclear power plant

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The Court of Auditors has estimated the average generation cost for the period 2011-2025 for a life-span of 50 years at 61.6 €/MWh.

Anne-Sophie Dessillons

The cost of producing nuclear electricity

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An introduction to two conversations on the **impact of nuclear power**

François Graner, physicist, CNRS, and **Stefano Matthias Panebianco,** physicist, CEA, editors of the issue

Nuclear incidents, as well as articles in the press, influence and change the way in which nuclear power is perceived by the public. These perceptions mirror the contradictory nature of the views held by scientists, politicians and any other sector of society. This polarization of views is a defining feature of the nuclear debate. However, the arguments of both opponents and supporters of nuclear power merit careful consideration and critical appraisal.

In order to assess the environmental impact of civil nuclear power, as with any large-scale, complex technological process, all the many steps that make up the industry must be taken into account. The potential risks differ, depending on the region, and, despite preventive measures taken during the design and operation of installations there is still the chance of an accident, whether caused by a natural event, human error or malevolence. In the case of nuclear power, the aspects related to energy production range from the conditions under which the fuel is mined to the fate of spent fuel, and there are a number of key issues at the heart of the debate, for example the risk of irradiation, contamination, chemical pollution or explosion.

With this in mind, we wanted to question scientists both for and against civil nuclear power about its impact on health and the environment under normal operating conditions[(a)]. To do this, we asked Claude Stéphan, a nuclear physicist who has written extensively on the civil nuclear industry and who is more of a proponent, and Pierre Barbey, a biologist from the University of Caen, Director of the Implementation and Management of Radioelements (IMOGERE) facility, who has been critical of reactor emissions. Likewise, we asked Jean-Christophe Gariel of the Institute for Radiological Protection and Nuclear Safety (IRSN) and legal expert Sophia Majnoni d'Intignano, formerly very active within Greenpeace, to comment on the prevention and management of a possible accident[(b)].

In each case, the authors presented a number of complementary arguments. We offer you a selection of them, which although arbitrary, is as comprehensive as possible. The two articles that follow are our responsibility and not those of the people interviewed. They illustrate the debate that is ongoing within the scientific community and in society as a whole, a debate that incorporates a wide range of fields such as physics, nuclear engineering, economics and health, and also includes sociological and moral considerations.

To illustrate this wide range of topics in more detail, these two discussions are followed by other more specialized texts dealing with the role of organizations and subcontractors in the nuclear industry, as well as the operating costs of the industry. ■

a. See the conversation on page 19 with C. Stéphan and P. Barbey.

b. See the conversation on page 22 with J.-C. Gariel and S. Majnoni d'Intignano.

The impact of nuclear **power plants under normal operation on health and the environment**

Conversation[(a)] with **Claude Stéphan,** physicist, CNRS, and **Pierre Barbey,** biologist, University of Caen

What is the impact of a functioning nuclear power plant on the surrounding environment, land and people? Which industrial stages of the process, from ore extraction to plant operation, are the most controversial in terms of their perceived effects? Two researchers answer our questions from opposing sides of the debate.

From ore extraction to reactor

When we think of the environmental impact of civil nuclear power, we immediately think of the reactor, its emissions and its potential danger to the surrounding population. However, it is also important to consider the issues upstream and to look at the journey of the nuclear fuel before it is loaded into the reactor. Although it is the case that a few thousand tons[(b)] of natural uranium are sufficient to power all of France's nuclear reactors for one year, the process of ore extraction has consequences for the environment and the local population.

Firstly, there is the radioactive decay of uranium which leads to, among other things, the formation of radon, a radioactive gas which is present in large amounts in mines; the radioactivity level in a uranium mine is between ten and one hundred times greater than the background level[(c)]. Secondly, both these radioactive elements are released from the mineral texture in which they are contained and readily mobilized in water through the mechanical processing (crushing and grinding) involved in uranium extraction.

Uranium mining on French soil began in 1949 and was largely abandoned in the 1990s. During this time, some 250 mining sites in 27 departments produced 76,000 tons of uranium. Although all the uranium used by France is now imported (mainly from Niger, Canada, Australia and Kazakhstan), this has not always been the case and the environmental impact hasn't gone away. For example, the choice of importing raw materials from foreign countries only shifts the impact of the mining industry away from France. Furthermore, ongoing monitoring is still required even though the French mines are now closed[(d)].

Claude Stéphan acknowledges that the conditions under which the first mines were established and the working practices at the time fueled the negative image of

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uranium mining. Public perception is largely based on the health and environmental impacts resulting from practices applied in a bygone era when there was little regulation. Indeed, in the early days, workers were exposed to levels of radiation that are now considered dangerous, in particular as a cause of lung cancer.

Following the closure of most French mining sites, the mobilization of community action groups in response to radioactive pollution and handling of mining waste and slag heaps has led the public authorities to take action. They responded by initiating a major multi-stakeholder consultation process between 2006 and 2010, by setting up local "monitoring bodies for former mining sites", and also by strengthening the regulatory framework for the management of these former sites.

The necessary controls are now in place, with a system of regulatory and administrative inspections and controls carried out by the Regional Environment Directorates under the authority of the prefects (government representatives at the regional level). The system reduces the possibility of regulatory decisions being influenced by a political or an economic agenda. This has led to a shift from virtually non-existent planning to multi-stage effluent treatment processes and management systems designed specifically for the sector.

Although the radiological impact seems to be under control in the former French mining sites, which are now closed, Pierre Barbey reminds us that the impact on the environment is also of a chemical nature. Uranium, as well as being radioactive, is first and foremost a highly toxic chemical element. It is on the basis of this toxicity that the World Health Organization (WHO) set the uranium concentration limit for drinking water at 15 µg/l. It should be noted, however, that setting limits and making recommendations based on toxicity is not straightforward. One of the difficulties, in the context of former uranium mine sites, is that the toxic substances extracted or produced are of natural origin and that anthropogenic activity adds to a natural background noise, which itself fluctuates. In order to assess the dose-dependent impact and to help set limits, WHO opted to estimate the transfers of toxic pollutants into the environment and to take into account all routes of human health damages using exposure scenarios based on lifestyles.

A further point to stress, with regard to the environmental impact, is that the restoration of former mining sites is a major industrial undertaking. The French government assigned Areva (now Orano) to manage and monitor all former French sites, including those that were not under its jurisdiction. The aim of redevelopment is to minimize any environmental effects by making the sites safe for the public, by providing radiological and environmental monitoring, and by providing water treatment should that be required. Some 100 specialists are deployed each year to carry out nearly 7,000 environmental, geological, radiological and health analyses.

Transportation of the uranium is the second major issue after mining. The main difficulties associated with transporting radioactive substances are the risk of inhalation or ingestion of radioactive particles, the risk of external irradiation, and the risk of radionucleotide release to the environment. About 10% of the nuclear packages transported in France are connected to the nuclear power industry and this represents about 19,000 annual journeys, for 114,000 packages[(e)]. The movement of dangerous goods by road, rail or sea is regulated by the national authorities. The package itself must provide sufficient protection to avoid any harmful consequences on people or the environment. The radioactive material is enclosed in leakproof steel drums loaded into containers certified by the International Organization for Standardization (ISO) with appropriate marking and placarding. Therefore, in a non-accident situation, transporting nuclear materials does not appear to have a significant impact on the environment or the general population.

From reactor to waste

The impact of a normally-functioning nuclear power plant on the environment is essentially due to exposure of nuclear workers and the public to thermal, chemical and radioactive discharges. Nuclear-related industrial discharges are not very different from those produced by any other thermal power plant. However, the post-Chernobyl era saw the creation, under public pressure, of two independent regulatory bodies, the French Nuclear Safety Authority (ASN) and the Institute for Radiological Protection and Nuclear Safety (IRSN), to manage all nuclear risks (electronuclear, medical, etc.). The ASN contributes to the drafting of regulations relating to nuclear energy and overseeing their compliance, while the IRSN coordinates research in connection with nuclear safety and keeps a record of any feedback from the plants. Both organizations, together with the operator, also participate in ten-yearly inspections designed to assess whether or not a power plant can continue to operate and to carry out checks and confirm the necessary safety requirements are met.

Finally, the ASN sets the regulatory limits for all emissions that a nuclear power plant is authorized to produce during operation, the main ones being production of water, waste gases and heat. In France, regulatory limits prevent excessive local heating of the cold source (river, sea) due to water being returned at a temperature slightly higher than the temperature at which it was taken. Consequently, production must be reduced or suspended if the water returned is too hot compared to the cold source (dilution effect).

With regard to radioactive emissions, Claude Stéphan points out that over the last twenty years, EDF's nuclear fleet has reduced the level of its radioactive emissions 100-fold except for the noble gases, tritium and carbon-14. In the latter case, the release of this isotope into the environment is extremely low and, as it is essentially in a form (methane) that cannot be assimilated by plants, it represents only about 1% of the average background level. The epidemiological impact on populations living near French nuclear power plants is considered insignificant. However, many local residents' groups are concerned and closely monitor changes in radioactivity levels in the soil and groundwater[(f)].

The maximum permissible annual radiation dose for nuclear energy workers is 20 millisieverts[(g)], which is just over four times the natural background radiation dose. In practice, the level of radiation received is much lower and the number of times this threshold is exceeded is decreasing year on year. Is this radiation dose dangerous? The question remains open. The available studies show no effects at doses below 100 millisieverts, either because there are none or because the statistical significance of the surveys was insufficient to detect them[h]. The public in the immediate vicinity of a nuclear power plant receives ten thousand times less, or 0.002 millisieverts per year, which is negligible compared to what is received from natural background radiation (especially radon) and medical examinations.

The reprocessing of spent fuel like plutonium from EDF's nuclear power stations, as well as from other countries, is more controversial. Pierre Barbey points out that, compared to other processes in the industry, reprocessing is a particularly polluting step. An inventory carried out in the second half of the 1990s by a multidisciplinary group of experts, the North-Cotentin Radioecology group (Groupe Radioécologie Nord-Cotentin, GRNC), led to the identification of 73 radioactive elements (excluding elements with short half-lives) from reprocessing operations, i.e. double the radioelements declared by the operator at that time. The La Hague site currently benefits from ASN an authorization to release radioactive and chemical pollutants into the environment. Commissioned in 1966, the La Hague reprocessing facilities generated increasing discharges, due to the increase in activity, until the mid-1980s. It was at that time that the operator introduced a new effluent management system and, since then, a gradual decrease in discharges has been observed. However, this new system does not address certain non-retained radioelements (tritium, noble gases, etc.) which continue to increase in proportion to the amount of reprocessed fuel. It should be noted that, unlike nuclear power plants, the carbon-14 released is mainly in the form of CO_2, which can be assimilated by plants, and is the main contributor to the dose received by the local population.

There is currently no simple solution when it comes to managing spent fuel end-of-life and hence produced waste[i]. Claude Stéphan begins by reminding us that fission fragments account for almost all the radioactivity produced and the vast majority of them have a half-life that does not exceed 30 years. This category of waste is stored in metal casks contained in concrete overpacks at the Aube Storage Center (Centre de Stockage de l'Aube, CSA) and is the responsibility of the National Agency for Radioactive Waste Management (ANDRA). The radioactivity of these materials, known as short-lived low and intermediate-level radioactive waste, will have decreased by a factor of 1,000 after about 300 years, and their storage above-ground is currently considered a solution that significantly limits the impact on the environment.

On the other hand, the rest of the spent fuel, which constitutes the ultimate waste (other fission products and minor actinides such as americium, neptunium, etc.), of intermediate or high activity with a long life, poses greater technological challenges. This waste is nowadays vitrified, i.e. mixed with a glass matrix, a material known for its good resistance to heat and radiation, and stored pending a decision on long-term storage. The solution presently being considered in France, which is the subject of debate, involves deep-layer storage, of the order of 500 m, in the Industrial Center for Geological Storage (Centre Industriel de stockage Géologique, Cigéo), which requires geological and seismic stability on a scale of tens of thousands of years.

Pierre Barbey notes that this and other waste disposal routes are currently only in draft form. At present there are only two surface storage centers: the Aube center and the historic Channel waste-disposal center (Centre de Stockage de la Manche, CSM), the subject of much controversy because of its location in a marshy area that is regularly flooded. Some organizations have disputed whether the radioactivity is actually contained[j], and it is in the process of being closed down. The Industrial Center for Grouping, Warehousing and Storage (Centre industriel de regroupement, d'entreposage et de stockage, CIRES), another waste disposal facility in Aube and managed by ANDRA, is dedicated to very low-level radioactive waste.

In summary, the closure of uranium mines in France appears to have greatly reduced the harmful effects, although there is still a need for constant monitoring of the resulting contamination. Meanwhile the impact has been transferred to the countries that are now producing uranium. The transport of fissile materials appears to be under control. Discharges from operating plants are considered insignificant. Pollution from fuel reprocessing is decreasing but is still detectable. However, the storage of long-lived intermediate or high-level radioactive waste is a considerable problem which is still under debate. ▮

a. See the introduction to the conversations by F. Graner and S. M. Panebianco (p. 18).

b. By way of comparison, this mass is equivalent to only a few percent of the load of a single supertanker.

c. Uranium-238 has been around since the formation of the Earth and has a half-life of around 4.5 billion years and uranium-235 has a half-life of 700 million years, which means that their natural activity is low. Some decay products have short half-lives: the main radioelements of concern to man and the environment are radium-226, polonium-210 and lead-210. By way of comparison, the order of magnitude of natural background radioactivity is 100 Bq/kg for basaltic or sedimentary rocks and 1,000 Bq/kg for granitic rocks. The radioactivity of residual rock (known as "waste rock") from uranium mines is typically 10,000 Bq/kg, that of uranium ore processing tailings is 500,000 Bq/kg, which is strikingly similar to the tailings of lignite power plants operating in Germany or Poland. Uranium ores themselves have a typical activity of 1,000,000 Bq/kg.

d. Since a mine is not considered a Basic Nuclear Installation (BNI), it is not subject to a decommissioning procedure.

e. Other nuclear packages are mainly from nuclear sources used in industry such as food sterilization (60%), or medical uses (30%). In total, these nuclear packages account for a few percent of all hazardous material packages. Source: ASN.

f. See the article by D. Boilley (p. 24).

g. Sievert: unit measuring the impact of radiation on humans.

h. Very small doses may damage one strand of DNA, but not both strands, and in this case the cell can repair it properly. A higher dose is statistically more likely to cut both strands, so it has a much greater effect.

i. On the question of waste, see several articles, in particular those by J.-Y. Le Déaut (p. 13) and B. Romagnan (p. 14).

j. See the criticisms made by the "Nuclear Phase-Out" (« Sortir du Nucléaire ») network, ACRO or Greenpeace e.g. the 2006 ACRO report revised in 2009, www.acro.eu.org/Archives/CSM_GP09.pdf.

The risk of nuclear accidents: prevention and management

Conversation[a] with **Jean-Christophe Gariel,** Institute for Radiological Protection and Nuclear Safety, and **Sophia Majnoni d'Intignano,** lawyer, former nuclear energy expert at Greenpeace France

There is seldom consensus when it comes to assessing the risk of a nuclear accident and being prepared for one. The issue is fraught with challenges and assumptions. As for handling a potential accident, history has shown that operational decisions and actions depend on the political and social structures of the regions concerned. Opposing views from two experts in the field.

Prior to the Chernobyl disaster, it was left to the discretion of the operator to assess the severity of an accident. After Chernobyl, an International Nuclear Event Scale (INES) was created to describe and classify nuclear incidents and accidents. An accident can involve reactors, fuel pools, as well as waste storage centers (such as the Mayak center in Kyshtym, Russia, also a plutonium production center, and the site of a major accident in 1957 about which the general public was largely unaware).

The main risks identified at French civil nuclear facilities are the fullness of the spent fuel pools at La Hague, the ageing of the production equipment and the risk of an incident at any point in the chain. Also, in France lorries are used for transporting radioactive material (and used more frequently because of reprocessing). Whilst this allows EDF to handle all transport in-house, and results in greater safety control of the fuel cycle overall, it is a fact that accidents involving lorries are more likely than those involving trains.

Taking risks into account

Rare and significant risks are difficult to assess, and they are also difficult for experts and the public to take into account when making decisions. Moreover, in the case of nuclear power, the effects of low-dose radiation are not visible to the naked eye or directly observable in our daily lives. Finally, the debate on risk is marred by the lack of consensus on the effect of exposure to low doses of radioactivity, and the link, for example, with the occupational illnesses of nuclear workers. This concerns the entire chain, including the non-accident stages upstream, such as mining, as well as disposal centers.

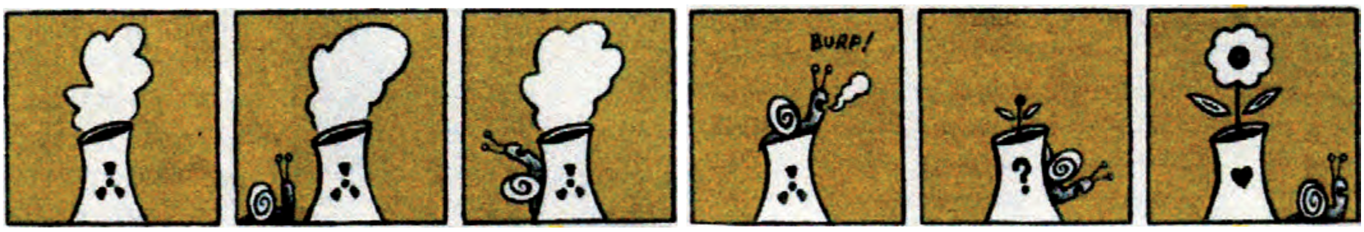
Political decisions and accident preparedness require proper consideration of risk. However, the probabilistic approach, developed for repeatable and insurable events, is less well accepted when applied to significant and rare risks and has long been the subject of deep disagreement between anti-nuclear activists and regulators. The prime example is the risk of aircraft crashes. Moreover, an INES level 7 accident in the middle of a desert might be more politically and socially, but not ecologically, acceptable than a level 6 accident at the Indian Point power plant less than 40 kilometers from New York City. An international risk insurance system has been set up, requiring each reactor to be insured for 750 million euros and in which the state takes over up to 1.5 billion. This compares with the cost of a Fukushima-type disaster, estimated by the Court of Auditors at several hundred billion euros[b].

Risk prevention

Risk prevention is the subject of debate on several points. For example, the Fukushima accident showed that the containment systems, although redundant, could fail. The choice to store high-level waste with a half-life of several thousand years underground raises difficult questions of forecasting, particularly in terms of seismic activity or political risks. Sophia Majnoni d'Intignano stresses that underground storage poses moral problems with regard to future generations; is it better not to publicize the storage facility, or even deliberately count on its being forgotten, or to try to explain its existence (how?) and associated dangers[c]?

It is vital to retain skilled workers for decades or even longer (this applies both to maintenance and dismantling, and in order to be prepared in case of a possible accident). However, the different elements of the nuclear industry are intertwined; any decision, even a small one, can have long-term repercussions for the industry as a whole. For example, even if there are major disagreements about the date, the 15 years old 900 MW reactors will have to be shut down one day. As they are the only ones using "Mixed Uranium and Plutonium Oxide" (MOX) fuel, their closure will have an impact on the Melox plant at Marcoule which manufactures it, on the reprocessing plant at La Hague which supplies the plutonium, and more generally on the industry, its 5,000 jobs, and the expertise of the sector.

For Sophia Majnoni d'Intignano, the solution may lie in the German approach, where an ethics committee incorporates a long-term view, showing that it is possible to recognize a moral, intellectual or societal dimension in the managing of nuclear liabilities for the benefit of future



generations. It is a way of maintaining a positive dynamic in the long term which may be an alternative to or complementary to the development of new nuclear programs, and attracting competent people for decontamination and decommissioning (which will also require sources of funding and energy).

Preparing for a possible accident

Arrangements are in place at local, national and even international levels ready to be implemented in the case of an accident. In Japan, the issue of risk and its management is very important, particularly because of the frequency of earthquakes, and schoolchildren are all aware of them. After Fukushima, Japan's social cohesion made it possible to evacuate the contaminated area, which might not have gone as well in another social group.

To limit panic in an accident situation, it is important to train local communities (about means of transport for residents, temporary accommodation and where to find information), firefighters, pharmacies, etc. Jean-Christophe Gariel emphasizes that protective measures for the general public are aimed at limiting their radiation exposure to as low a level as reasonably possible. The intake of stable iodine is advisable in the event of a release containing radioactive iodine (which may be the case for a nuclear reactor accident for example). It aims, by early saturation of the thyroid gland, to limit the absorption of radioactive iodine by this gland. In France, at present, it is the people living less than 15 km from a nuclear reactor (i.e. in the zone known as the "special intervention perimeter") who are specifically informed about the nuclear risk, who take part in a nuclear exercise and who can find potassium iodide tablets in their local pharmacy. It could be useful to extend these zones, given that 75% of people in mainland France live less than 75 km from a nuclear reactor; for them, iodine is available from regional suppliers.

Some accidents may require a very quick response. Large and short-term discharges can lead to residents being asked to take shelter. Jean-Christophe Gariel points out that this reduces both exposure to external radiation and the risk of breathing in contaminated air. This type of measure can be implemented for a period of about twelve hours, or even several days if it has been appropriately planned for in good conditions, although by then the air inside the buildings may also be contaminated. However, one might wonder about the degree of compliance of the people concerned: for example, who would agree to leave their children in the care of a school?

The protective measures to be taken in an emergency are determined in advance and depend on the particular situation. The advice to take stable iodine is disseminated through the media, specifying when and how it is to be taken, who is affected and who has priority (children and pregnant women in particular). At the same time, public security measures (e.g. traffic restrictions on public roads) and law enforcement measures are implemented. The local authority may decide to restrict the consumption of certain foods or specific activities. Finally, a decision to evacuate the area may be taken, in which case the public authorities will have to take care of people who are not self-sufficient.

The post-accident phase

In the post-accident phase, the primary issues of concern relate to the quality of the environment, public health, the continuity of social and economic life and international relations. At this point the decisions are taken nationally, and decision-making may closely involve the various stakeholders, primarily the inhabitants of the affected areas. How do we determine the size of restricted or even completely prohibited areas? Is it better to allow a population to live in contact with doses of radioactivity that are higher than the standards (and up to what limit), or is it better to close off an area by keeping people out and ceasing all activity?

Therefore, the question of the effect of low doses of radiation has far-reaching practical consequences. There are areas with low levels of contamination that we may want to be able to inhabit for social, human and economic reasons. However, below a certain dose, it is not possible to determine statistically significant effects, nor is it possible to extrapolate to low doses what is known about the effects of medium and high doses. If defining a threshold is impossible, the principle guiding political action is to minimize, whatever happens, the dose of radioactivity that can be added to the background dose, by influencing behavior (diet, routines) and by encouraging those affected to take radioactivity measurements. Politicians must decide on the various measures by weighing up all the risks and consequences: environmental, social and economic. ▮

a. See the introduction to the conversations by F. Graner and S. M. Panebianco (p. 18).

b. See the article by A.-S. Dessillons (p. 29).

c. Olivier Le Naire, « Enfouissement des déchets nucléaires: comment alerter nos descendants? », lexpress.fr, 8 November 2014, www.lexpress.fr/actualite/sciences/enfouissement-des-dechets-nucleaires-comment-alerter-nos-descendants_1619017.html

Radioactivity in the environment
The role of regulatory bodies

David Boilley, Physicist, President of the Association for the Control of Radioactivity in western France (ACRO)

Since the Chernobyl disaster, public opinion has demanded greater transparency in assessing the impact of nuclear accidents on people and the environment. To this end, both in France and abroad, various organizations are involved in monitoring the operation of nuclear power plants, in particular through radioactivity measurements.

Chernobyl and the emergence of the community measurements

For a long time, only specialists had access to the results of environmental radioactivity measurements. Following the Chernobyl disaster in 1986, which led to contamination to varying degrees of the whole of Europe, Europeans realized that they could all be potentially exposed to radioactive fallout. In France, the government sparked a serious crisis of confidence by denying the impact on French soil.

In response, scientists and non-scientists came together to create non-governmental laboratories to monitor radioactivity independently. Thus, the Munich Environmental Institute (Umweltinstitut München) [1], the Commission for Independent Research and Information on Radioactivity (CRIIRad) in Valence [2] and the Association for the Control of Radioactivity in western France (ACRO) in Caen [3] were created. Initially, they had to demonstrate to the authorities that their measurements were as reliable as the official ones. To do this, they had to set up a quality assurance system and carry out inter-laboratory tests. The two French non-governmental laboratories were only approved in 1997. Their monitoring services have been extended to include gamma spectrometry analyses, measurements of tritium levels in water, and measurement of radon in buildings. The Umweltinstitut, meanwhile, also investigates GMOs and electro-magnetic fields. This article focuses on ACRO, of which the author is president [4].

Waste

At the end of the 1990s a significant milestone was reached in the recognition of independent monitoring of radioactivity in the environment. This was through the work of the Groupe Radioécologie Nord-Cotentin (developed under the auspices of ASN and managed by IRSN, and in which ACRO participates). For the first time, some 50 experts from all walks of life worked together to try to respond to the concerns raised by an epidemiological study that had revealed an increase in the number of leukemia cases among young people within a 10-km radius of the La Hague reprocessing plant. Community-based sampling (including by ACRO) represented only a small part of the compiled results, but included samples or locations that had been little or never studied elsewhere. The groups' experts acquired new skills in radioecology, modelling, etc., which went beyond simply measuring radioactivity.

Through its direct involvement in monitoring, the public has transformed a purely technical subject into a political one. The result has been greater transparency and better monitoring of the impact of discharges. Since 2010, the National Measurement Network [5] (set up by the health and environment ministries) has been collecting the results of statutory measurements of radioactivity in the environment, and also those of other organizations, including ACRO, and these have all been made available to the public. This development is part of a more general process of democratization of those decisions which impact the environment, facilitated by the emergence of the Internet and marked by two key texts: the Aarhus Convention (1998) [6] and the Environmental Charter which was incorporated into the French Constitution in 2005. Public consultation on technical subjects becomes all the more meaningful when experts can provide a detailed analysis. For this reason, ACRO participates in several institutional working groups: this allows it to better understand the issues and to raise citizens' concerns.

All nuclear facilities, including storage centers, release radioactivity into the environment at varying levels. Incidents or accidents can result in much larger discharges. Globally, the highest radioactive releases in history were caused by the

Algae sampling carried out by ACRO.

atmospheric nuclear tests of the 1950s and 1960s. Many artificial radioelements resulting from these tests are still found in the environment, such as cesium-137, strontium-90, isotopes of plutonium, etc.

During normal operation, the Orano (ex-Areva) reprocessing plant at La Hague has the highest levels of environmental discharges of all the French facilities. For some radioelements, such as krypton-85 (a noble gas) or tritium, separation and disposal are complex. For others, such as iodine-129, which has a half-life of 16 million years, sea disposal is the preferred option. It can be detected in algae all along the coastline of the Channel and North Sea at levels, per kilogram of dry algae, ranging from a few becquerels[a] to a few dozen becquerels near the outflow of the La Hague plant. For tritium, about ten becquerels are measured per liter of seawater.

Fukushima and volunteer samplers

Over the past 30 years, the NGOs have had to adapt to remain relevant. ACRO responds to people's concerns by monitoring radioactivity in the environment through a network of volunteer samplers. This is intended to complement official environmental monitoring.

In 2011, when the "radioactive cloud" arrived from Fukushima and caused great concern, ACRO initiated nationwide fallout mapping based on plant samples. This confirmed that the impact of the accident was very small, but nevertheless detectable. This approach was complementary to that of the Institute of Radiological Protection and Nuclear Safety (IRSN), which was based on highly efficient measurement networks and modelling.

More recently, in 2016, on the occasion of the 30th anniversary of the Chernobyl disaster [7] (30 years is symbolic because it is the half-life of cesium-137), a complementary approach was taken again when mapping residual pollution: ACRO favored a grassroots approach by leaving the initiative to the samplers on the choice of samples and sampling locations, and by forging partnerships with local groups such as mushroom-picking associations. IRSN studied those areas where deposits had been shown to be highest.

Measurements taken by ACRO have shown that all soil samples are contaminated with cesium-137, due both to fallout from atmospheric nuclear tests and the Chernobyl disaster, at widely varying levels. This ranges from a few becquerels to 68,000 becquerels (per kilogram of dry soil) at the Col de Restefond in the French Alps. As far as foodstuffs are concerned, it is, unsurprisingly, mushrooms that remain the most contaminated, at highly variable levels of up to 4,000 becquerels per kilogram for 'sheep's foot' mushrooms taken from Luxembourg. Obviously, in the Ukraine and Belarus, or in the vicinity of the Fukushima power station, contamination levels are much higher and justify the maintenance of exclusion orders.

Following the disaster at the Fukushima power plant, Japan saw the emergence of community measurements [8]. It was the local inhabitants who mapped the contamination, sometimes with the help of local authorities. They soon identified hot spots that had escaped official surveillance. Hundreds of measuring stations were set up by producers, vendors and consumers to monitor food. The numerous controls imply that there is no longer any scandal and internal contamination of the inhabitants via food is very low, if not undetectable. This is very different from the situation in the land contaminated by the Chernobyl disaster, where the main contributor to the dose received is the consumption of contaminated food.

ACRO backed the creation of a laboratory in Japan, Chikurin-sha [9], by providing two gamma-ray spectrometry measurement systems and by training scientists. This was made possible due to a subscription and support from the Ile-de-France region. The laboratory has quickly established links with some thirty

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measuring stations equipped with less efficient but simpler to use equipment, which is appropriate in a post-accident situation (see box). Together, they have developed an online intercomparison system and database [10].

From the measuring crisis to crisis measures

Having a skilled and reputed laboratory, alongside a network of trained samplers, is essential for maintaining oversight and reacting quickly in the event of an incident. The most symbolic case dates back to 2001, following an incident at the La Hague reprocessing plant. As soon as the atmospheric release was reported, local residents were on site taking samples and it became apparent that the resulting release, dominated by the ruthenium/rhodium 106 pair, was in fact greater than the quantity reported. An atmospheric dispersion model showed that the operator had underestimated the quantity released by a factor of 1000. It was ACRO that discovered this error, which was due to a long-standing detection issue. More recently, they have identified plutonium pollution near the plant at levels of sufficient concern that the operator is now required to clean up the contaminated land.

In the event of a nuclear accident, the impact of radioactive releases is of a completely different magnitude. It may justify the long-term evacuation of more than 100,000 people, as was the case in Chernobyl and Fukushima. In addition, people living in contaminated areas must be able to monitor the radioactivity in order to adapt their daily lives. Access to measurements therefore becomes paramount. Independent laboratories and experts can complement the authorities and provide the public with solutions tailored to their problems.

The French authorities now recognize the value of community-based monitoring of radioactivity in the environment, even under normal circumstances. After a possible serious accident, they are counting on the population to take over part of the monitoring. IRSN, for its part, supported the creation of a system which uses Geiger counters coupled to interactive smartphone software and digital mapping to collate, share and use data.

Measuring radioactivity

Small field devices measure the ambient level of radiation, which includes natural radioactivity and possibly an artificial contribution. Some only consider gamma radiation and others gamma and beta radiation. They are especially useful in the event of a severe accident, with sufficiently high pollution levels that induce an increase in detectable ambient radiation compared to variations in natural background noise. They do not detect the impact of normal releases from nuclear facilities.

In order to distinguish artificial radioactivity from natural radioactivity in environmental samples, the radiation must be separated depending on its energy using a gamma spectrometer. Gamma radiation can be identified using different types of detector. The simplest, based on a NaI crystal at room temperature, have a fairly limited resolving power and a detection limit of about ten becquerels per kilogram. They are useful after a nuclear accident involving significant levels of a limited number of persistent radioelements. For best performance, a liquid nitrogen-cooled germanium semiconductor crystal is generally used. This type of detector, which is more expensive and complex to use, has sufficient resolution to distinguish many radioelements and a detection limit of less than one becquerel per kilogram. It is therefore appropriate for detecting the impact of routine releases. The identification of pure beta emitters, such as tritium, is more complicated because the energy of the electron is not unique. A chemical separation must therefore be carried out in order to be able to distinguish possible pollutants.

Although the Japanese authorities are still struggling to recognize the importance of these community measuring systems, it is undeniable that they have contributed to a better diagnosis of the impact of discharges. Accessing the data allows the people concerned to have a partial answer to their questions, but this is not enough. Japan, for example, lacks a strategy for compiling and analyzing data in order to extract additional information.

Community radioactivity measuring still has many days ahead of it and should be extended to other types of pollutants. The publication of the Houllier report [11] on participatory science and research in France showed the interest and richness of this approach. Whilst non-governmental organizations may have brought about the sharing of expertise as far as monitoring radioactivity in the environment, there is still scope for greater research collaborations in this field. ▮

a. Becquerel: number of radioactive disintegrations per second in a given quantity of material.

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Subcontracting and quality in a nuclear power plant

Interview with **Gilles Reynaud,** President of the association "My controlled zone"

As with most industrial sectors, the nuclear industry uses subcontractors to operate its power plants. However, the role of non-statutory employees has evolved considerably and includes specific elements that contribute to the safety of a nuclear power plant. Interview with a subcontractor.

How important is subcontracting in nuclear power plants?

The major companies in the nuclear sector (the "principals") have certain jobs carried out either by their own statutory employees or by employees of other companies (the "subcontractors"). In turn, these may subcontract to even smaller companies ("cascading" subcontracting). The 160,000 employees of the subcontracting companies thus play an invisible but crucial role in the production of electricity, carrying out 80% of the activities in various fields including sanitation, maintenance, logistics, radiation protection, waste treatment and dismantling.

How is the sector changing?

We are concerned about the aging of installations and the financial situation of the major employers, as this directly affects the duration of contracts to external contractors. This is currently between 1 and 6 years, which in our opinion is too short for stable recruitment: this encourages a massive and carefully organized recourse to subcontracting.

Our work is related to the metallurgy or public building-works sector. However, we are increasingly subject to the so-called "Syntec" collective agreement for the design and engineering sector. This is inappropriate, but 30% cheaper for the operator[a]. Similarly, the collective agreement for cleaning is applied to employees carrying out sanitation operations, which is less costly. In this way, the use of less socially-responsible companies is often aimed at circumventing the statutory benefits of the employees of large contractors.

Not only is this illegal (it is called "labor lending"), but we also see the direct repercussions of this purely economical decision on the ground. The employees, who are rapidly replaced, are demotivated and the final quality of the work carried out seems to us to be declining.

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How are subcontracting and quality linked?

First of all, we argue that, for several years, the major companies have not sufficiently monitored the activities of their subcontractors. Secondly, as a result of subcontracting and not having sufficiently anticipated the loss of several key core businesses, the operator is gradually, but irretrievably, losing control of the production base. Finally, depending on the sites where we operate, specific training or retraining is given to prospective employees. In the past, essential questions relating to radiation protection, safety, security and quality were addressed: why are they no longer being addressed?

A dedicated committee has done a great deal of work(b) to identify the wide variety of incidents, classify them, analyze their causes (organizational, technical or human), and propose improvements. On the positive side, according to the ASN, there are virtually no workers posted in restricted areas, nor any examples of dose levels being exceeded. On the other hand, due to a lack of adequate operational procedures and a lack of human resources, the basic rules are sometimes flouted. There is an increase in incidents during routine maintenance, internal contamination, subcontractors who reach the dose limit and are then sent to other sectors, and so on.

What lessons have been learned from Fukushima?

The accident highlighted the vital skills of subcontracted employees at another site, Fukushima daini, 40 km from Fukushima daiichi. This site, also by the sea, had also lost the power source for the backup circuits. TEPCO's emergency response teams were unable to restore power to the site. The subcontractors, who were familiar with the installations, were able to connect the cables properly.

Following the Fukushima accident, safety assessments were conducted throughout the French fleet. They included the staffing aspect and subcontracting. In 2012, this led to a new code of employers' obligations which obliges companies taking over a contract to also take over its employees. Despite this protection, the company taking over the contract is not obliged to safeguard the previous status of employees (seniority, qualifications, collective agreement). In practice, employees are paid less, have less security, and are less recognized for their skills and professional expertise, which reduces their motivation.

What do you propose?

The close ties that should exist between operator and subcontractors, which have been eroded by economic factors, must be restored. For example, we consider it necessary that the permanent employees of the subcontracting companies join, on a voluntary basis, the Internal Emergency Plan teams of the various operators. They will be able to demonstrate their professional responsibility and civic commitment, including by raising alerts in time and taking action in the event of an accident.

We are calling for, at a national level, the dedicated and protected status of all employees doing the same work. In this sector, which is in the throes of reorganization, the possible extension of the lifespan of power plants, as well as their future decommissioning, can only be done when the professionalism of these employees is finally recognized. ▮

a. In a note published on July 31, 2018, EDF indicated (p. 12) that according to its calculations, the change in the collective agreement represents a 12% decrease for the highest wages, and even a 1.2% increase for the lowest wages. In the same note (p. 4, p. 5 and p. 14), EDF indicates that the number of subcontracting levels is limited to 3, and that "significant safety events" are decreasing (600 per year, of which 50 are attributable to subcontractors). Source: www.edf.fr/sites/default/files/contrib/groupe-edf/producteur-industriel/hydraulique/Notes%20d%27info/note_info_pompili.pdf

b. *La sous-traitance en situation de fonctionnement normal : organisation et conditions d'intervention,* Comité sur les facteurs sociaux, organisationnels et humains (COFSOH), January 2017.

Translation
EDF is working to provide all the country's electricity needs

Translation
30 years of EDF reports
1970 You're absolutely safe
1980 You're in very little danger
1990 Hopefully, we'll get through this

To find out more

- C. Dubout, *Je suis décontamineur dans le nucléaire,* Ed. Paulo Ramand(2010).
- G. Reynaud, *in Nucléaire et territoire,* livre blanc de l'ANCCLI, January 2017, p.26.
- See also the website of the association, www.ma-zone-controlee.com
Its purpose is to encourage exchanges between employees, whether statutory or mainly subcontractors, in high-risk industries (nuclear, chemical, petrochemical) to improve the operational safety and overall security of the facilities, for future generations and the environment.

The Cost of Generating Nuclear Electricity

Anne-Sophie Dessillons, reporter of the Court of Auditors

The cost of generating one megawatt-hour (MWh) of nuclear electricity is an essential parameter when assessing the economic value of the sector. The Court of Auditors has produced a very detailed report which has caused much debate and whose figures give a clearer idea of the current operating cost (excluding research and development) of nuclear power and how this will change in the future.

In the current climate there are growing fears surrounding nuclear safety (post-Fukushima, problems at the Flamanville site, precautionary reactor shutdowns in the autumn of 2016, etc.) as well as an increasing use of renewable energies with significant cost reductions. The cost of nuclear power has therefore become more critical than ever, particularly because of the uncertainties over investments in major refurbishments and the financing of third generation reactors. The Court of Auditors has had the opportunity to examine the issue twice, in 2012 [1] and then in 2014 [2]: its findings inform the following observations.

A production cost of around 60€/MWh, which is rising sharply

The Court of Auditors has estimated the cost of generating electricity with the existing nuclear fleet at 60€/MWh in 2013 compared to 50€/MWh in 2010[a]. This 20% increase in three years can be explained by three factors.

Firstly, maintenance costs, which are the largest item of expenditure and account for half of the increase in production costs. The increase in maintenance costs is due to three factors:

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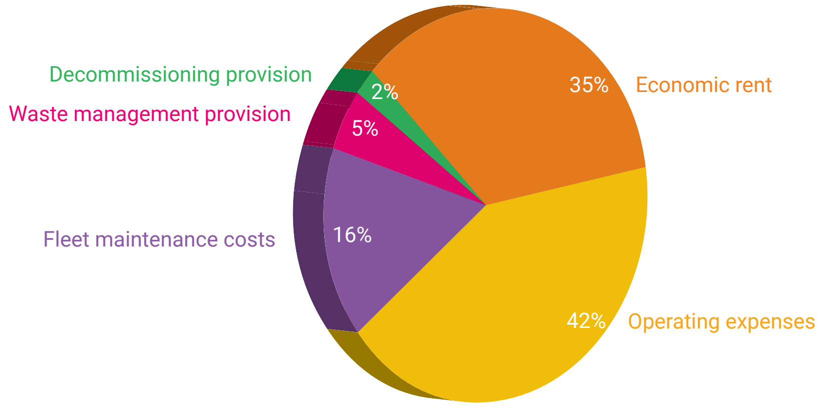

1. Share of the various contributions to the cost of production of French nuclear electricity.

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- they have needed to catch up with the level of « normal » investment (21% of the maintenance costs), following under-investment in the early 2000s which had a negative impact on operations and output;
- the need to refurbish or replace certain large components with a service life of less than 40 years (29% of the maintenance costs): these include steam generators, alternators, condensers and cooling tower components;
- the sharp increase in safety spending (50% of the maintenance costs) following Fukushima; the Nuclear Safety Authority (ASN) have made extending the operating life of reactors conditional on an improvement in safety to ensure they meet the safety requirements for third generation reactors.

Secondly, the large increase in operational spending (+31% in real terms) accounts for a quarter of the increase in production costs. This increase is partly a result of the increased maintenance costs, causing a rise in procurement and logistics expenses, and is also due to a large increase in the number of employees, and the cost of refreshing skills and speeding up the maintenance program.

Finally, changes in the calculation parameters explain the remaining increase: decline in annual production, change in the discount rate[b] for future decommissioning and waste management expenses, and change in the rate of return on capital and inflation.

This production cost is not directly comparable to the cost of renewables, which have been estimated in various studies, notably by the French Environment and Energy Management Agency (Agence de l'environnement et de la maîtrise de l'énergie, ADEME). Indeed, the latter are calculated for an investor who would enter the market today with new power plants (which would need to be paid off financially, but whose maintenance costs would be lower); the current nuclear equivalent would be the EPR, which will be discussed below. Similarly, this production cost figure cannot be used to dictate the choice between continuing to operate by extending the life of the plants or replacing them in the short term with more modern plants or even other energy sources[c].

Sensitivity to operational and capital costs

The cost of producing nuclear power, as indicated above, is known as the "economic running cost". It includes operating costs, maintenance spending and provisions to cover future expenses (decommissioning and waste and spent fuel management). It also includes an economic rent that takes into account the initial investments and their remuneration over the entire planned operating life. Three-quarters of this cost is dominated by operating expenses and the cost of using the nuclear facilities (42% and 35% respectively, see fig. 1). The economic running cost, on the other hand, excludes research and development and safety/security, which are financed from public funds. Furthermore, it does not take into account the history of the fleet and the fact that the initial investments have already been largely recouped. This production cost differs from EDF's actual current cost, which is lower and must be covered by tariffs.

The cost of production is very sensitive to changes in operational expenses and maintenance costs (16%). Even if EDF's strategic planning is based on the assumption of "controlled operating expenses", operating expenses should increase by 1.4%/year in real terms between now and 2025. Maintenance costs, meanwhile, are expected to continue to rise to an intermediate level, 16% higher than the level of investment included in the 2013 cost. However, this level of maintenance spending is only justified in view of the longer lifetime of the plants. Thus, if political decisions made this extension impossible or too uncertain, EDF would have to revise its industrial program: indeed, it would seem economically irrational to undertake major renovations of large components around 30/35 years of life, if the remaining operating life did not exceed ten years. Similarly, it wouldn't make sense to invest to raise safety standards to those of the third generation.

On the other hand, due to discounting, the calculations are not very sensitive to changes in costs in the future. Therefore, the uncertainties that currently hang on the estimation of these costs have in reality only a very small impact on the cost of production, as calculated by the Court. A decrease (or conversely an increase) in the discount rate leads to a change in production costs of +0.8% (or -0.6%). If the decommissioning estimate were to increase by 50%, the production cost would increase by only 2.5%.

The impact of extending the life of power plants on production costs

The operating life of a nuclear power plant is a strategic issue. Although the current economic cost, and therefore the production cost, is not very dependent on the operating life of the installations, the operating life is still a determining factor in assessing the profitability of nuclear assets.

The effect on costs of extending the operating life of power plants cannot be measured by a simple sensitivity analysis. Such an extension has a number of effects on the cost of electricity generation:
- decreasing economic rent (impact however limited to 2 or 3% for a ten-year extension of the operating life);
- increasing maintenance costs required for this extension;
- decreasing provision for future expenditure due to the decommissioning schedule.

Taking into account these various elements and the above-mentioned assumptions for the increase in operating expenses, the Court of Audit estimated the average cost of production for the period 2011-2025 for a 50-year lifetime at 61.6€/MWh. If the lifetime of the installations is not extended, there is then uncertainty as to the level of maintenance investment to be retained, and calculations of the average production cost over the same period become very uncertain. EDF may also conclude that it is economically profitable to close plants before they are 40 years old in order to avoid undertaking major renovations the cost of which cannot be recouped.

It should also be noted that this estimate makes the assumption that the entire fleet will be extended beyond 40 years for a period of 10 years, whereas it is more likely that decisions will be more heterogeneous (some reactors closing at 40 years and others being extended to 60 years), given the differences in performance between the different reactors and to meet the political challenges of diversifying the energy mix.

Uncertainty about the cost of next-generation nuclear power

Regardless of their operating life, the current reactors can only be replaced, in the long term, by "third generation" reactors, whose safety standards are superior to those of the current reactors. The medium/long-term production costs of nuclear electricity will therefore be those of the EPR, which are difficult to assess in detail today. The Flamanville EPR cannot be used as a basis for calculating the average production cost of the EPR. This project, which is subject to significant delays and overruns, is suffering from the "head of series" effect and the restarting of the industry, which has lost the practice of building reactors on French soil.

However, in view of the high construction costs compared to those of the second generation reactors, and even if the EPRs are expected to have lower operating costs, it is likely that the production costs will be significantly higher than those of the current fleet. This is the conclusion that can also be drawn from the agreement signed in October 2013 between EDF and the British government, with a sale price of £92.5/MWh (approximately 106 €/MWh), even though there are many differences between the Flamanville EPR and those at Hinkley Point (site specificity, British standards, waste storage, land price, etc.) and the price calculation is sensitive to the choice made for the discount rate.

To get an idea of the order of magnitude of these future costs, we can also look at the assumptions made by the ADEME in the establishment of different scenarios of energy mix by 2050: the production cost of new nuclear power is then estimated at 80€/Mwh.

The cost of a potential accident

An international risk insurance system has been set up, obliging each reactor to be insured at up to 750 million euros and states to take over up to 1.5 billion. For its part, the Court of Auditors has cautiously attempted to extrapolate the experience of Fukushima. The order of magnitude used for the total cost of an accident in France is estimated at between 120 and 585 billion euros. This range is largely based on the work of the French Institute for Radiological Protection and Nuclear Safety (IRSN) [3]. It aims to include all costs, even those that cannot be precisely quantified and independently of what is or is not eligible for compensation, from the rehabilitation of the site and radiological monitoring, to the health and psychological effects, to changes in electricity production, as well as the consequences in terms of image on tourism, agricultural activity and exports.

In summary, if we try to establish a guiding principle from these multi-parameter calculations, major renewal investments are only viable for a sufficiently long operating life. If the existing plants are upgraded, an increase of 40-50% in the cost of electricity production is to be expected, and roughly the same for the EPR plants. While uncertainties relating to the cost of decommissioning have little impact on the overall cost of nuclear power, there are much greater uncertainties relating to the financial situation, the possible decision to not extend the lifetime of the nuclear plants, and above all the risk of accidents. Finally, the Court of Auditors points out that cost is not the only criterion for decision-making, and that many indicators relevant for making comparisons are simply not quantifiable in financial terms. ▮

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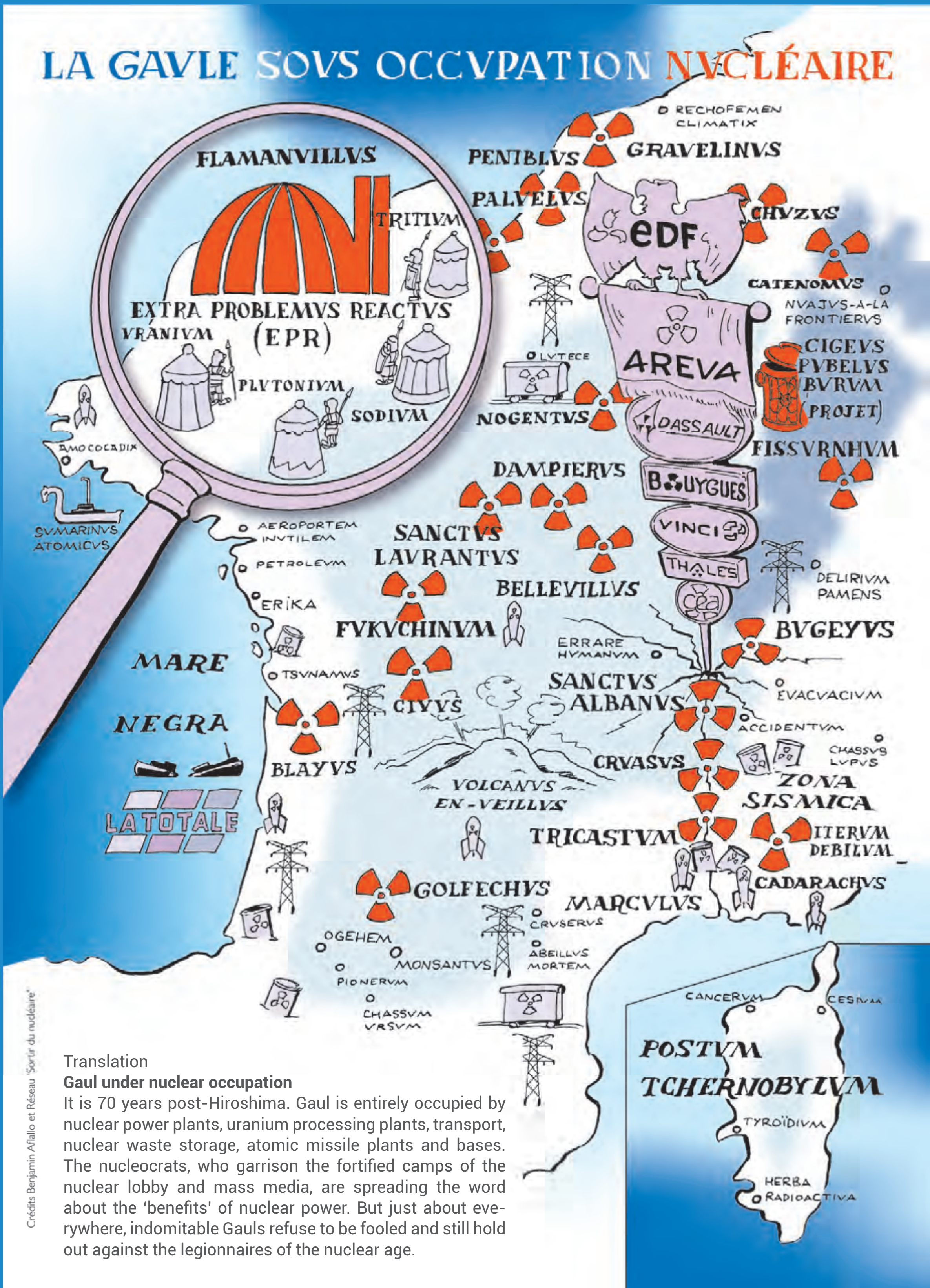
a. It should be remembered that 50 €/MWh is equivalent to 5 cents/kWh, compared to the public electricity sale price of around 13 to 17 cents/kWh in 2018, and a similar cost if the same amount of energy is purchased as fuel at the petrol pump.

b. The discount rate is a parameter that helps in the decision-making process when comparing current and future costs. A greater focus on future generations leads to an increase in projected costs.

c. See the article by S. Huet (p. 41).

NUCLEAR POWER AND FRENCH SOCIETY



Translation

Gaul under nuclear occupation

It is 70 years post-Hiroshima. Gaul is entirely occupied by nuclear power plants, uranium processing plants, transport, nuclear waste storage, atomic missile plants and bases. The nucleocrats, who garrison the fortified camps of the nuclear lobby and mass media, are spreading the word about the 'benefits' of nuclear power. But just about everywhere, indomitable Gauls refuse to be fooled and still hold out against the legionnaires of the nuclear age.

Crédits Benjamin Aflallo et Réseau 'Sortir du nucléaire'

Contrary to the image that has long prevailed of a nuclear deterrent strategy promoted solely by de Gaulle and his supporters after they took power, changed the Constitution and founded the "Fifth Republic" in 1958, it was in fact the leaders of the Fourth Republic who decided to develop military nuclear power between 1950 and 1958, alongside the development of its energy policy.

Hervé Bercegol

The applications of nuclear power in France: the historical civil-military link

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The dual system of research funding is only justified if nuclear weapons are developed, and this is a political decision.

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Local people are expressing two distinct views, representing two socially different groups of speakers: the "Disappointed" and the "Entrepreneurs".

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Public debate of nuclear power in France is still burdened by a fueled ignorance over its advantages, disadvantages and economics

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The technological priorities of French nuclear power: the historical civil-military ties

Hervé Bercegol, physicist, CEA

During the Second World War an intense war effort led scientific research to pioneer a new form of energy, demonstrated in a radical and cataclysmic way by the American nuclear bombings. The energy of the atom has come into the world marked by the seal of geopolitics, the military and science. The subsequent development of nuclear energy in France will not escape these three determinants: throughout the years 1945 to 1970, the civil-military link is evident in the reactor technologies developed by the two major French institutions in charge of this energy, the CEA at first and EDF from the mid-1950s onwards.

In October 1945, the provisional government created the French Atomic Energy Commission (Commissariat à l'Énergie Atomique, CEA) by decree "so that France can take its place in the field of atomic energy research" [1]. Two months earlier, the United States of America had used atomic bombs and thus placed itself in a position of power among the allies in the Second World War. Between 1940 and 1945, the Manhattan Project mobilized up to 130,000 employees [2]. French atomic scientists, who were very active in the inter-war period and among the first to begin the secret study of a nuclear weapon in 1939, were kept out of the project.

With the discovery of fission, it soon became clear that the release of nuclear energy in a chain reaction makes possible self-sustained "nuclear combustion", which can be used to run an electricity generator or an engine if combustion is controlled, or to trigger an explosion if not. To obtain the fissile isotopes that were used in the Trinity test and the Hiroshima and Nagasaki bombings, it was necessary to design and control nuclear reactors of several hundred megawatts as well as industrial processes for isotopic or chemical separation. Since the knowledge acquired by the Americans and British was protected by very strict secrecy [3], the French government decided to launch large-scale multidisciplinary scientific research, and the 1945 decree did not specify either its civil or military nature or its purpose[(a)].

The CEA was created as a hybrid organization, comprising both a scientific institution and a technical and industrial development agency. This duality is demonstrated by the management structure, with scientific decisions coming under the office of the High Commissioner for Atomic Energy, entrusted to Frédéric Joliot-Curie, and the administrative and financial organization to a "general administrator", Raoul Dautry, Minister of Reconstruction and Town Planning in the interim government. Although the military aspect was not ruled out, it seemed secondary in France to reconstruction, which was desperately lacking in technical capacity and energy resources. Though less well supplied with coal than its main European competitors, France had the uranium resources of its colonies in Africa and Madagascar at its disposal, and then the mines discovered in France itself. Nuclear research therefore held out great hope in terms of energy, technological progress and modernity, objectives which the country's main political leaders subscribed to.

In 1949 the Cold War deepened with the formation of the NATO alliance and the explosion of the first Soviet atomic bomb. From then on, the nuclear threat and the need to respond with similar weapons became a concern for all Western governments. In France, several political forces, including the communists, became increasingly opposed to the military use of the atom. Communists or sympathizers were gradually removed from the nuclear program, beginning with Joliot-Curie in April 1950. While Francis Perrin had not yet replaced the former as High Commissioner, the French Atomic Energy Commission was reorganized in early 1951, concentrating decision-making powers on the position of the general administrator [4]. After Dautry's death, his successor Pierre Guillaumat developed a program that pursued energy and defence objectives together. In 1952, Parliament approved the development of Natural Uranium fuel, Graphite moderator and Gas (CO_2) coolant

reactors, or NUGG. The NUGG is a first-generation reactor that has the advantage of being able to operate with raw materials that were accessible at the time. It does not require the use of heavy water[(b)], the separation of which from normal water is very costly in terms of energy, nor the use of fuel enriched in uranium-235, the fissile isotope of uranium, which at the time could be produced in France only in small quantities. A crucial characteristic of NUGGs is the possibility of their being used to produce plutonium-239: this isotope is of interest both for military use and for the prospect of fast neutrons breeder breeder reactors, considered at the time to be the most promising energy option.

Starting in 1953, the CEA built the G1, G2 and G3 reactors at Marcoule, as well as a plant for the chemical extraction of plutonium. In addition to plutonium, the three reactors also provided electrical power from the outset in collaboration with EDF, the purpose of the military plutonium remaining confidential until 1958[(c)] [4]. In the meantime, the government took successive decisions which led towards nuclear armament. At the end of 1954, shortly after the rejection of the European Defense Community by the National Assembly, Pierre Mendès-France created a specific defense branch at the CEA, the Bureau for General Studies, which in 1958 became the Military Applications Directorate (Direction des Applications Militaires, DAM), and also a Committee on Nuclear Explosives.

In December 1954, Mendès-France also asked the CEA to develop a submarine reactor. The *Nautilus*, an American submarine, had just been inaugurated. A little later, in 1958, it achieved the feat of reaching the North Pole under the Arctic ice pack. Directly inspired by the *Nautilus* nuclear boiler, the CEA's Onshore Prototype at Cadarache is a second-generation reactor running on pressurized light water and uranium enriched in uranium-235. In 1957, the Americans agreed to supply fuel for the Onshore Prototype. In the same year, the French Parliament also approved funding for an isotope separation plant at Pierrelatte. Enriched uranium, crucial for thermonuclear weapons and naval propulsion, is, like plutonium, a strategic objective.

Contrary to the image that has long prevailed of a deterrence project promoted solely by de Gaulle and his supporters after they took power, changed the Constitution and founded the "Fifth Republic" in 1958, it was in fact the leaders of the Fourth Republic who were responsible for military nuclear development between 1950 and 1958[(d)] [3], while at the same time pursuing the energy objective [4]. In the last years of the Fourth Republic, military nuclear projects were intensified and developed in a tripartite approach with West Germany and Italy [3]. In April 1958, Félix Gaillard, Prime Minister, decided to test a French bomb. De Gaulle confirmed the decision to build and test the bomb as well as to develop nuclear submarine "missile launchers". Stopping the planned military nuclear cooperation with Italy and West Germany, he took a diplomatic approach of bilateral cooperation with the European allies. However, France and its neighbors are now members of the European civil collaboration *Euratom*, whose activity since 1958 has been focused on the development and implementation in Europe of the light water and enriched uranium technology known at the time as the Light Water Reactor (LWR) and nowadays as the Pressurized Water Reactor (PWR). It is directly inspired by

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submarine boilers, as is the American Shippingport reactor. The latter is a prototype energy reactor built by Westinghouse, inaugurated by President Eisenhower in 1954 and which became the spearhead of his *Atoms for peace* policy.

Under the fifth Republic, the CEA continued to develop NUGGs at Marcoule, for plutonium-239 and power, as well as PWRs and uranium enrichment for naval propulsion. EDF, associated with the CEA since the early 1950s, developed its own NUGGs at Chinon and then Saint-Laurent des Eaux, and its PWRs first of all through the European *Euratom* collaboration.

At the end of the 1960s, France opted for electrical energy shared between these two reactor technologies, both of which had originally been designed and developed for military use, either for nuclear weapons or propulsion. Much has been said and written about the now famous « Guerre des Filières » (war of the sectors), which was also a long struggle between and within EDF and the CEA [4,5]. The main argument in favor of PWRs over NUGGs at the end of 1969 was their economic superiority, but this has since been questioned [6]. However, as naval propulsion is probably a much more demanding application than plutonium production, PWRs have benefitted from major development and improvement efforts(f). Naval propulsion is still a widespread use of nuclear energy: the largest number of nuclear reactors until the end of the Cold War was at sea – mainly in warships, surface ships or submarines – and not on land [7]. When the oil crisis occurred in 1973, the technical justifications for favoring PWRs in 1969 were still valid, hence the PWR is the only reactor in the Messmer plan dedicated to civil nuclear power since 1974 [5].

As they were designed and built at the time when France acquired nuclear weapons and nuclear submarines, French reactors for energy are therefore marked by civil-military duality. The first-generation reactors were first optimized for the production of military plutonium; the second-generation reactors were primarily designed for naval propulsion. This duality is still present in the current fleet of PWRs which are similar to naval boilers. ▮

Translation: Nuclear: the zero-carbon asset

a. Beyond "pursuing scientific and technical research for the use of atomic energy in the various fields of science, industry and national defence" [1].

b. Heavy water D_2O is the moderator used in the first French "atomic pile", ZOÉ, which operated from 1948 to 1976 in the CEA's Fontenay-aux-Roses center.

c. G1, air-cooled, then G2, cooled with pressurized CO_2, and therefore the first of the NUGG type, were ready to supply plutonium 239 for the first French nuclear test at Reggane in 1960.

d. Some even speak of a taboo, on the right as well as on the left, regarding the decisions of the fourth Republic about military nuclear power [3]. The Gaullists would like to magnify the role of the General, whilst the non-communist left would like to conceal its pioneering role. This taboo would be preserved by closing government archives.

e. Throughout the period under consideration, the CEA grouped together all its nuclear programs, whether scientific or industrial. These activities were not separated until the 1970s. Meanwhile, EDF worked on the design and construction of NUGG power plants with CEA, and PWRs with the Franco-American company Framatome, a joint subsidiary of Westinghouse, Schneider and Merlin-Gérin.

f. See also the article by J. Bordé and M. Leduc (p. 37).

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Civil and military nuclear power: related research

Jacques Bordé, physicist, retired from the CNRS and **Michèle Leduc**, physicist, CNRS

The development of nuclear power in France is the result of political choices that have established a close link between military research and research on civilian applications. The consequences of this link are numerous and have led physicists to question their role.

The development of civil and military nuclear power in France is closely linked. From the outset, particularly throughout the history of the CEA, the study of nuclear physics has developed through the constant interaction between basic research and industrial, civil and military applications[(a)]. Even today, civilian nuclear research is still tackling some key problems whose solution is of interest to the military in order to improve, diversify and better control their nuclear arsenal. Similarly, military research on nuclear weapons is seen as dual-use by policy-makers, i.e. it should have benefits for civilian research, not just nuclear, as well as for industry in general (particularly, but not only, the arms industry). As such, the State gives a substantial budget to the military, justified to the people by claiming that part of it is used for civilian research, and boosts our industry through technological excellence[(b)]. This was the thrust of two recent parliamentary reports [1, 2].

Many overlaps

In addition to the in-depth knowledge of nuclei and nuclear reactions, many research fields are common to both military and civil nuclear power. Examples include isotope separation, waste treatment and equipment dismantling, safety and cyber security issues, sustainable fuel supply, miniaturization of components, understanding seismology, etc. Nuclear medicine has long benefited from better resourced military equipment, in particular regarding the supply of radioactive products from enriched weapons-grade uranium. Similarly, the military has

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benefited from the expertise of nuclear doctors for the radiation protection of soldiers and public health in nuclear test zones. Today there is justification for cooperation in the medical field because of the impact of so-called dirty bombs and depleted uranium weapons.

There has always been a cross-fertilization of knowledge and innovation back and forth between civilian and military applications of nuclear power. For example, it is likely that the potential near doubling of the budget for nuclear deterrence (from 3.5 to 6 billion euros per year), due to the dismantling and modernization of nuclear-powered ballistic missile submarines, will have repercussions on civil nuclear research and industry. The 2016 parliamentary report [1] details the industrial duality in many areas, for example in ballistics, with the parallel between the Ariane program and the M51 missile.

The example of the "Simulation" program

To illustrate the duality within the world of university research, we can take as an example the « Simulation » program. Since France committed itself to no longer causing nuclear explosions by signing the Comprehensive Nuclear Test Ban Treaty (CTBT), it has been improving its equipment through simulation[c]. It has equipped itself with supercomputers: the Tera 100 was co-developed with the CEA's Military Applications Directorate (DAM) in 2010, then the Tera 1000 in 2017 and an even more powerful one is expected by 2023. These are used to test and numerically verify certain theories involved in the operation of nuclear bombs and missiles. The "Simulation" program, managed by the DAM, is based on data taken during past explosions. It is also based on new data taken using a very high-powered laser, the MegaJoule Laser (LMJ) recently built in Bordeaux. By focusing a beam of light energy of more than a million joules on a target of a few millimeters in a few billionths of a second, matter is transformed to a state comparable to that of an atomic bomb.

The Center for Scientific and Technical Study of Aquitaine (Centre d'Etudes Scientifiques et Techniques d'Aquitaine, CESTA), like its American and British counterparts, respectively the National Ignition Facility (NIF) and the Atomic Weapons Establishment (AWE), with its Orion laser is available for academic research purposes. It has an entirely smaller-scale civilian laser facility, PETAL, which cost 54 million euros, compared with 3 billion euros over 15 years for the LMJ. Its purpose is to acquire knowledge on laser-matter interaction and plasmas for research related to astrophysics, such as stellar plasmas, or civilian energy using fusion. According to those responsible for academic collaboration at NIF and AWE, who have more experience than at the LMJ, this cooperation is mutually beneficial [3]. The military benefits from fresh perspectives and new ideas from the facility on a small part of their work, the rest being "military secrets". Academics are able to use the laser equipment of the military center of Bordeaux, but only for about 10% of the time. This complements the powerful lasers of the laboratory of the École Polytechnique (the LULI) in Palaiseau.

Do we need a nuclear weapon?

One may wonder about the relevance of dual technologies for nuclear power. Wouldn't it be much more efficient to directly finance the needs of civilian research and industry in the nuclear field (as is the case, for example, in Germany or Japan, which do not have nuclear weapons), without having to resort to crumbs of military funding? Moreover, military nuclear power may cease: the 2012 Senate report on the "future of French nuclear forces" [4] already stated: "If we had to design a new army format from scratch today, it is highly likely that the need to acquire a nuclear strike force [...] would not be part of our defense ambitions." The dual system of research funding is only justified if we want to develop nuclear weapons, which is a political decision. However, there are political reasons for the decline and eventual cessation of funding for nuclear weapons in view of the recent Nuclear Weapons Treaty that the UN opened for States to sign in July 2017.

Some scientists, including ourselves and the global Pugwash [5] movement, do not want civilian nuclear research to contribute directly to military applications. They also believe, along with the International Campaign to Abolish Nuclear Weapons (ICAN), the 2017 Nobel Peace Prize winner, that nuclear deterrence is not a lasting solution for world peace. They are aware of the risks associated with the development of these weapons, which are increased through the risk of their proliferation, computer hacking, maintenance accidents or the outbreak of nuclear war through misunderstanding [6], or by the creation of small "dirty" bombs from radioactive materials, etc. Not to mention the horror and immorality that a nuclear war, even a small one, would represent. ▮

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a. See the article by H. Bercegol (p. 34).

b. It should be noted that the military sector is pushing to develop systems with superior technical requirements but which go beyond the requirements for civilian use (the average person's car does not need to meet Formula 1 specifications).

c. The parliamentary reports referred to above state that "the fact that France has a high-performance computing sector is due to deterrence".

Taking part in the nuclear debate

Françoise Lafaye, ethnologist, École Nationale des Travaux Publics de l'État

**Participation in the nuclear energy debate takes different forms: from rallying others to take action to simply welcoming facilities in one's own region. The humanities and social sciences (HSS) have long taken an interest in the nuclear protest movement, and are increasingly examining other social and political aspects of this form of electricity generation.
Whether considering the inhabitants who are obliged to incorporate this industry into their daily lives or the various stakeholders who take part in the public debate, researchers highlight a variety of perceptions of nuclear power that push the former to act or, in the case of the latter, to confront each other in the public arena.**

Promoting a controversial means of energy production

As with all scientific and technical fields, the use of nuclear power involves an appreciation of the issues that go beyond the technology itself. It is these issues - from the social to the political, the cultural and economic - that human and social scientists are wrestling with. These researchers approach nuclear energy from different periods in its history and from global or local perspectives, incorporating aspects from national or international contexts that presuppose specific nuclear-related policies, legislative and institutional frameworks.

Thus, while Germany is planning to stop its civil nuclear electricity production in 2022, France is making it a flagship of its industry and defending this strong element of its national influence and identity. Gabrielle Hecht [1] has shown how the merger of political and technological decisions, under the auspices of the CEA and EDF, has led to this French technological exception[a]. In this article, we will show how different perceptions of nuclear power continue to clash in the public domain, but are also embodied in a variety of attitudes and behaviors.

In France, perceptions of nuclear technology have changed over time. Initially it was considered a valuable and beneficial resource in health care, from the X-rays used at the end of the 19th century in the first radiology departments to the radium used to treat skin diseases. Advertising at the beginning of the 20th century promoted the health benefits of radium regenerating creams, radioactive mineral waters, or "atomic sodas".

Later the image of nuclear power became tarnished by its military use: the explosion of two atomic bombs over the cities of Hiroshima and Nagasaki in 1945, and the fear of a new world conflict which, this time, would destroy humanity.

During the 1970s, it gradually became a subject of controversy. The dangers linked to the fuel used in nuclear power plants were exposed through protests at the sites where such operations were being carried out. Opponents raised various objections, from questioning ("all nuclear" in 1974) to the issue of dealing with the waste produced at the sites. Finally, the accidents at Chernobyl in 1986 and Fukushima in 2011 have largely revived the debate on the dangers of radioactivity and have brought home the real threat of a nuclear accident.

From one movement to the next

The anti-nuclear movement has a unique place among the protests that emerged after May 68 (regionalist, feminist, self-management demands, etc.). HSS researchers quickly came to see it as a "new social movement", recognizing that social conflicts no longer pitted workers against their bosses, but communities against their machines. They saw it as the beginnings of a new approach to democracy specific to a post-industrial society or as a foundational element of an environmental movement, close to political ecology.

There has been a shift in the type of opposition to nuclear power. The forms of militant action have changed from site occupations to the use of the media. In the age of globalization, activists struggle to engage with international action because of their affiliation to their respective national political contexts and their membership of more or less formalized groups [2]. However, a number of issues continue to be discussed, including long-term waste management, involving unusually long time-scales, which will affect future generations. In this context, the deep geological repository for

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long-lived waste at Bure in Meuse and Haute-Marne continues to be hotly debated, both because of the challenges it raises and because of the public policies that are emerging in a climate of great technical uncertainty[b]. The ageing of power plants and the closure of certain nuclear sites are also fueling the controversy.

These protests have often highlighted a nuclear world divided into two irreconcilable camps: those in favor of nuclear power and those opposed to it. However, the stakeholders with an interest in this source of energy are numerous: experts from nuclear institutions and organizations, technicians responsible for its exploitation or activists, citizens, etc. Each in their own way contributes to the nuclear power situation in France.

Living near a power plant

At the local level, nuclear facilities have received a mixed welcome depending on the specific socio-historical context. In Plogoff[c], the protests and campaigns carried out by many locals (allied with others) have made the site a symbol of the anti-nuclear struggle. At Golfech, one of the most recent power plants, the dispute was more peaceful. But the rejection or acceptance of such a project does not reflect the range of opinions. The views expressed show that protest is not the only way to show one's opposition, that an objection can be specific to the local area and that the consequences of this type of facility go beyond the simple technical aspects or the disputed risks etc.

The one constant of all the sites is a lack of discussion about nuclear power and its dangers. This public silence[d] is interpreted differently depending on the facilities considered and the interests of the authors. The anthropologist Françoise Zonabend [3] conducted a survey in La Hague (Manche), where a waste reprocessing plant is located. She tried to understand the everyday language, strategies and tactics at La Hague used to ignore what she defines as "a threat accepted and known by all" and sees in this silence a sign of denial surrounding the fear of nuclear power.

This silence can be found among the inhabitants of Braud-et-Saint-Louis [4], the village where the Blayais nuclear power plant is located (Gironde). They view this facility not as the introduction of a sophisticated and controversial technology, but as the creation of a single industry in a rural environment, which changes their familiar surroundings and where nuclear risk is ranked among others. Residents express two distinct attitudes, held by two socially different groups of speakers. The "Disappointed" are farmers, with little to gain from an economic perspective. They express their relative frustration, feeling that they have not benefited from the nuclear power plant in a way that would compensate for the upheavals in their daily lives. The « Entrepreneurs », on the other hand, are municipal councilors with viable farms. They underline the new attractivity of the village, highlighting the new amenities (swimming pool, multi-purpose hall, tennis courts, etc.) made possible by this facility and the financial manna that accompanies it. These two views are based on different land claims and identity concepts. The "Disappointed" claim that they belong in this area and, even if it has a negative image[e], it gives them an identity (the only one they have) and grants them a right to the land. The "Entrepreneurs" try to escape from the initially devalued image of the region – made up in part of marshlands generally considered repellent and unfit for human habitation – and use the new community projects they have instigated to gain the social recognition they were previously denied.

Stakeholders' involvement in the consultation process

This disparity in the ways of seeing a nuclear site and the ignorance we have about it for most nuclear sites in France partly explains the difficulties encountered by the organizations (Nuclear Safety Authority, Local Information Commission, etc.) in charge of providing nuclear information for the public, or of carrying out consultations. The public is perceived as a single homogeneous audience and this perception ignores the diversity of points of view [5]. These organizations seek to avoid the « pro » / « anti » dichotomy. Two reasons are put forward by their leaders to explain the difficulty in communication: the lack of technical knowledge in communities and their total lack of interest in the nuclear issue. This makes it easier to understand why, in the various open discussions [6], the public is confined to the role of mere audience [7] and why newcomers to the consultation process, whether they are organizations, independent experts or regional representatives, are rarely given a central role in safety management [8]. ▮

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a. See the article by H. Bercegol (p. 34).

b. Expert opinion was not unanimous, which led former Minister Nicolas Hulot to say that it was "the least bad solution".

c. This power plant project was abandoned in 1981.

d. Analyzing a silence is a real challenge for ethnologists.

e. The area around Braud-et-Saint Louis is characterized by an ecosystem made up of two complementary habitats, the marshland and the "mainland", a history marked by a major capital-intensive operation (the draining of the marshland in the 17th century) and by the social identity of its inhabitants, heavily dependent on original immigration, which made the inhabitants, the Gabayes, foreigners on Gascon soil.

The constant tension between the press and nuclear power

Sylvestre Huet, author of the blog {sciences²}

Informing the public, as with the role of scrutinizing and challenging that the press embodies, or should embody, finds an additional dimension in nuclear power. Indeed, the technical nature of the subject requires an effort of explanation and scientific outreach in order to help citizens form their opinion. However, history has shown that in the field of nuclear energy, the press has had difficulty playing this role, to the extent of being responsible for clear cases of disinformation.

Nuclear power has come to symbolize the ambivalence of technology. It has the potential to provide enormous benefits yet its loss of control can lead to intolerable devastation. The question of whether to use it or do without it is therefore not only subject to the ability to use and control it, or simply its usefulness, but also that of its social acceptance. In a democratic political system, such as is the case in France, it must also satisfy the will of the people, as expressed by the popular vote when legislators and elected representatives are chosen.

This requirement seems simple but comes up against a number of difficulties, including the quality of information provided to the public. For democracy not to be an illusion, choices must be made "in full knowledge of the facts". This democratic prerequisite, in this case, cannot be limited to the often caricatural form of "declaration of principles", on a double-sided page, distributed shortly before the election of the people's representatives. Does the press, which is supposed to make a decisive contribution to democratic debate, play its role in the debate on nuclear power?

Public subjugation

The story of this question goes back more than half a century, with not very encouraging precedents. The discovery and first uses of radioactivity led to the publication of articles extolling the "benefits" of radioactivity in … drinking water. By the early 1950s, the "technological promise" dominated. Magazines and journals uncritically promoted adverts for nuclear cars and rockets, spreading the illusion of unlimited and almost free electricity. Opinion then diverged into two opposing standpoints. When the French nuclear program was launched in 1974, it was either presented as a panacea capable of solving all the country's economic problems … or, conversely, it was presented as a path that would inevitably lead to the subordination of the people in a police state, subject to secrecy and destroying individual and collective liberties.

Misinformation and disinformation

Recent years have not been much better. The accident in Fukushima in March 2011 gave rise to many blunders and misinformation that are of interest to media sociologists. In March 2016, Le Figaro announced that children's thyroid cancers were due to radioactive contamination, but this was a confusion between epidemiological incidence and systematic screening[a]. This misunderstanding was found in the majority of articles on the subject, despite the clear warning of specialists. The Institute for Radiological Protection and Nuclear Safety (IRSN) in a document intended for journalists and the public stated that "only if the annual incidence of thyroid cancer in children increases from 2016-2018 (or during subsequent periods) can a link with the Fukushima accident be made".

Le Nouvel Observateur, in August 2012, sounded the alarm: "It's a small pool – and a potential global disaster. A concrete cube 11 meters deep, filled with water and stuffed with spent nuclear fuel: 264 tons of highly radioactive rods!

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Civil and military nuclear power in Sarkozy's France, illustrated by Cabu. Research reactors, such as the Laue-Langevin Institute situated in Grenoble city, are not shown.

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For a year and a half, this so-called 'deactivation' basin has been resting thirty meters above the ground on the shaken building of reactor number 4 of the Fukushima-Daiichi power station. It is no longer protected by a solid roof or walls, but by a simple white plastic sheet." At the time of publication of this alarmist article in Le Nouvel Observateur, the pool was covered with a 60-tonne metal structure and not a plastic sheet. It will eventually be completely emptied of its nuclear fuel. Among the erroneous press coverage of the Fukushima accident, on the anniversary of the event in 2016 the French newspaper 'L'Humanité' attributed the 20,000 deaths of the March 2011 tsunami to the nuclear accident.

With this sort of treatment, is it any wonder that, according to the IRSN's annual sociological survey(b), a majority of French people consider the Japanese accident to be "more frightening" than Chernobyl, which had a much more serious health impact?

Rational considerations

The manufacturing anomaly on the lower head and closure head of the Flamanville EPR reactor pressure vessel resulted in hundreds of articles being published. Most of them preceded the work of analyzing the consequences of this anomaly on the vessel's ability to perform its function. Suggestions or claims that the vessel could certainly not be used ultimately turned out to be poor "intelligence". Following the authorization given by the Nuclear Safety Authority (ASN) for the vessel to be used, all that remained was the accusation of collusion with the manufacturers to justify the articles published beforehand.

The public debate on the economy or an assessment of the advantages and disadvantages of the nuclear choice for France is still burdened by a fueled ignorance. When the Court of Auditors provides a very thorough assessment of the costs of nuclear power since its inception(c), the press emphasizes the billions but doesn't compare them with other possible sources of electricity. The former "levies on profits" and the subsequent billions of dividends paid to the State since 2006 by EDF, which mainly come from nuclear power production, are ignored. A simple calculation, such as comparing the cost of the "big refit" and post-Fukushima measures to the cost of an identical investment in generation capacity to ensure continuity of supply, is never made (see box, Ed.).

As a result, Le Monde headlined with a mysterious "French Obsession" to explain the choice of a majority nuclear base for electricity, made since 1974 by all governments and parliamentary majorities. It even suggested military nuclear power as the source of this obsession. However, the economy, the cost of electricity for businesses and households and the original intention to loosen the grip of external forces - financial and oil supply - are enough to explain this choice by questionable but logical reasons.

Since the international community became aware of the climate problem, the crucial advantage of a carbon-free source of electricity has been added to these considerations. However, IRSN's annual sociological survey indicates that nearly half the French public continues to believe that nuclear power plants contribute "a lot or enough" to climate change. While the press is not solely responsible for this gross misunderstanding, how can it be totally exonerated from this pitiful lack of basic knowledge on this crucial subject?

Public Conversation

Why is the press doing such a bad job on this subject[d]? There are many reasons, from ideology to incompetence, as well as the objective difficulty of the subject, which requires an investment of time rarely available to journalists. These are compounded by most editors' total disinterest in technology, and often even in the industry's infrastructure. Is the press alone responsible for the state of the democratic debate on the subject?

That would let off the nuclear industry far too lightly. The latter have often used and abused the language of advertising by hiding the real difficulties, such as the recurrent image of nuclear waste reduced to the volume of an "Olympic swimming pool". Considering the magnitude of the Industrial Center for Geological Storage (Centre Industriel de stockage Géologique, Cigéo) project to bury this waste - underground galleries of several dozen kilometers, caverns of several hundred industrial-size surface facilities - the deliberate deception is clear. Although the law and the rules oblige the industry to report every incident to the authorities, the rhetoric is routinely aimed at minimizing the risks. For every incident or technical problem encountered, the industry prefers to use language typical of an advertising or propagandist approach, to the detriment of detailed and honest information. From personal experience, many EDF managers consider the French (and even journalists) too "stupid" to understand the technology they use. Hence the use of advertising slogans rather than reasoned explanation. If industry always appears to react to information disseminated by ASN and IRSN, it is because they never take the initiative to report on the problems they encounter and even less on their errors or mistakes, as was seen in the case of the falsification of documents relating to the manufacture of heavy components at the Creusot Forge plant, before and after its acquisition by Areva.

This attitude is in contrast to that of ASN and IRSN which, on the other hand, are valuable sources of reliable information for journalists. At the time of the Fukushima accident, the soothing words of the management of Areva and EDF were in sharp contrast to those of ASN, which were realistic about the scale of the disaster. However, we should point out a paradox: the severity and ability to "speak the truth" of the ASN (independent administrative self-rule since 2006) and IRSN may be seen as a positive effect of the very high safety requirements of the French people, as demonstrated by the media coverage of nuclear risk and its shortcomings. ∎

Data for the calculation proposed by Sylvestre Huet

The Court of Auditors estimates that a "major refurbishment" will cost 100 billion euros (75 in investment + 25 in operation) by 2025, i.e. approximately 1.7 billion euros per reactor. However, by 2025, 34 reactors will reach the 40-year limit which represents 31.6 GW installed capacity, to be replaced if they are not refurbished. This would require the construction of about twenty 1.6 GW EPRs. Assuming the cost of an EPR in ongoing production falls to 5.6 billion euros (i.e. 3500 euros/kW installed), the total cost would be around 112 billion euros. The two estimated costs, although only an approximate order of magnitude, are therefore comparable. However, building some twenty EPRs over the next seven years would appear to be an impossible task. If wind or photovoltaic power is developed instead, the costs of additional natural gas installations to compensate for intermittency, and the restructuring of the grid to accommodate the peaks in production which must be absorbed so as not to lose the electricity produced, must be included in the calculation[e]. The other solution is to reduce electricity consumption[f].
Thanks to Roland Lehoucq, Ed.

a. Routine screening shows an incidence of 11 thyroid cancers per 100,000 children per year in the Fukushima prefecture compared to 23 to 130 in three other prefectures (Aomori, Hiroshima and Yamanashi) free of contamination for the period 2011-2014.

b. http://barometre.irsn.fr/barometre2017/#page=1

c. See the article by A.-S. Dessillons (p. 29).

d. Editor's note: see at the end of this issue (p. 62) some examples of competent press articles, which include criticisms of nuclear power.

e. See the article by J. Percebois (p. 52).

f. See the article by N. Maïzi and F. Briens (p. 49).

WHAT IS THE FUTURE OF FRENCH NUCLEAR POWER?

Translation: Once again this year, nuclear power has given rise to a saving of almost 50 billion francs.

In a million years, our descendants will still be paying for the safe monitoring of the nuclear waste we produce today.

The scenario is often relegated to the role of a tool designed to validate and support choices that have already been made.

Sandra Bouneau

Nuclear power in global energy transition scenarios

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Switching to the scenarios with lower greenhouse gas emissions leads to an additional cost of 16% in the case of renewable green growth compared to the green growth scenario and a cost reduction of 4.5% in the degrowth scenario.

Nadia Maïzi and François Briens

Envisioning the energy future: from societal aspirations to technical challenges

page 49

The development of intermittent renewable energies (solar and wind) would not resolve the issue, as these energies are not necessarily available at peak times.

Jacques Percebois

Electricity distribution: advantages and limitations of the European electricity grid

page 52

It often takes several decades of research, design, development and experimentation to arrive at a system that is ready to be scaled up for industrial use.

Annick Billebaud

New nuclear reactor designs

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Nuclear power **in global energy transition scenarios**

Sandra Bouneau, physicist, University of Paris Sud

Studies on energy transition, aimed in particular at reducing greenhouse gas emissions, are based on the development of scenarios. Designed to quantitatively evaluate the impacts of an energy policy on the climate, they represent real decision-making tools. However, scenarios should be handled with caution because they are built on complex models and use a large number of poorly-defined hypotheses, which are sometimes based more on political than technical or scientific considerations.

In order to stem climate change, the use of fossil fuels, which today account for 80% of the world's energy consumption, will have to decrease drastically. A scenario is a scientific tool that can be used to analyze future energy production and consumption. While most of the global scenarios[a] envisage a large increase in the use of renewable energies, nuclear energy production may stop by 2050 or could increase ten-fold. It is therefore important to understand the reasons for the marked variability of the proportion of nuclear energy in prospective studies.

Building Global Energy Transition Scenarios

The purpose of a scenario is to explore possible energy futures by providing, among other things, a trajectory of energy consumption and production to 2050 or beyond. The scenario is based on a set of hypotheses and variables to model the socio-economic evolution of the world (population, urbanization, GDP, consumption), itself coupled with models describing the evolution of the availability of energy sources, the cost of technologies and their performance. Moreover, a given parameter – e.g. the trend in GDP – is sometimes a hypothesis and sometimes the result of modelling.

In most scenarios, the energy production system is optimized to meet energy demand at all times at the lowest cost. The cost of a technology is therefore an input whose value over time determines its share in the energy mix. A scenario based on a large increase in emerging renewable electricity sources (wind, solar) assumes a cost reduction of up to a factor of 10 compared to today's costs. Conversely, a technology considered undesirable to meet future demand, from a societal or climatic point of view, has an artificially increased cost so it doesn't feature significantly in the projected energy mix.

Without a quantitative objective set in advance, the scenarios are called "trend scenarios". Depending on the assumptions and parameters chosen, energy consumption in 2050 can be increased by 20% or multiplied by a factor of 3 compared to today's consumption. When a target is set for a given time frame, for example the halving of greenhouse gas emissions worldwide by 2050, the scenario attempts to describe a trajectory to reach it subject to additional constraints and assumptions.

Many of the scenarios in the scientific literature are complex to grasp, making comparative analysis difficult or even impossible. A scenario is not intended to be predictive but rather to represent an energy trajectory, through a set of hypotheses and values attributed to economic and technological variables. While it sometimes serves to inform the debate and to feed into the reflective process prior to decision-making, it is often relegated to the role of a tool designed to validate and support choices that have already been made.

Taking climate constraint into account in global scenarios

By integrating climate modelling, some scenarios can also predict trends in greenhouse gas concentrations through to 2100. On the basis of several hundred of these scenarios, the Intergovernmental Panel on Climate Change (IPCC) has defined four reference pathways of greenhouse gas concentration trajectories (Representative Concentration Pathway, or RCP). These pathways result in four values of additional energy fluxes received on average per m^2 of the Earth's surface causing it to warm ("radiative forcing"). The lowest value, 2.6 W/m^2, induces an average increase in temperature by 2100 that does not exceed 2 °C; the highest, 8.5 W/m^2, leads to a rise of more than 4 °C. These profiles provide a common framework for developing new scenarios, known as "climate scenarios", aimed at assessing the impact of an energy policy on the climate in relation to trend scenarios.

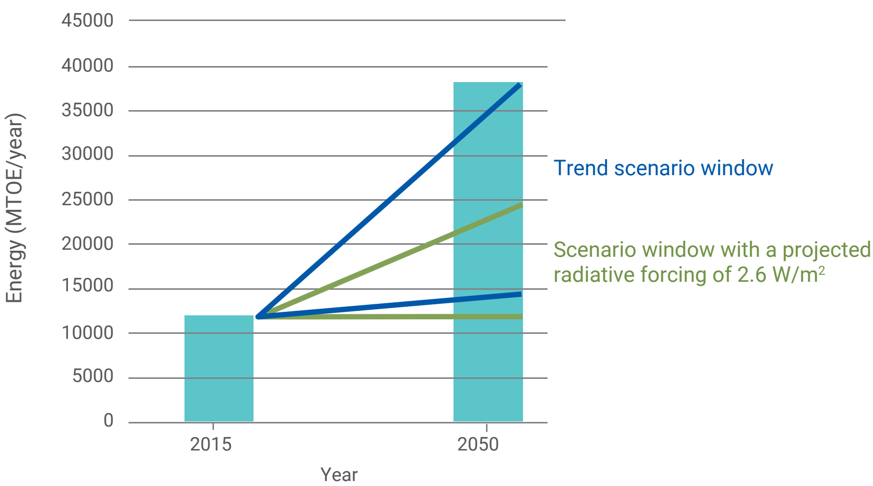
In most of the trend scenarios, fossil fuels remain the main source of energy and the associated CO_2 emissions give radiative forcing greater than 2.6 W/m^2. The increase in energy needs, whether moderate or strong, comes from the

Translation: In the time it takes to read this statement, you emit more CO_2 than a nuclear power station

populations of Asia and, to a lesser extent, Africa. Depending on the assumptions of the capacity of countries to control their energy consumption in the future, and the degree of progress of developing countries, global energy consumption in 2050 varies from a very slight to a three-fold increase (fig. 1, in blue).

On the basis of the trend scenarios used as a reference, additional hypotheses to do with energy consumption and technological progress of non-CO_2 emitting sources are introduced. These assumptions simulate more proactive policies to reduce greenhouse gas emissions than are currently in place, thus making it possible to achieve quantitative targets compatible, for example, with a RCP of 2.6 W/m^2. In most scenarios, setting ambitious climate targets is accompanied by a signifi c ant reduction in energy consumption by 2050 compared to the trend scenarios (fig. 1, in green).

In some scenarios, this reduction is presented as desirable and remains compatible with sustained economic growth through, for example, ambitious assumptions about the ability of societies to change their lifestyles and improve the performance of energy installations. In others, the reduction in energy consumption is lowered, since it results from a very restrictive greenhouse gas emission reduction policy, such as the introduction of a high carbon tax, and induces a slowdown in economic growth.



1. World energy consumption, in megatons of oil equivalent per year, estimated in the trend (blue) or climate (green) scenarios.

The conditions for carbon-free energy generation

Depending on the assumptions in the scenarios, the transition towards a carbon-free world is more or less rapid and can take place according to several options: maintaining the use of fossil fuels by favoring the substitution of coal and oil by natural gas with large-scale recourse to CO_2 Capture and Sequestration (CCS) technology, use of renewable energies including biomass (wood and biofuels) or nuclear power.

In most of the scenarios put forward, production of electricity or heat from nuclear power, although competitive, does not emerge as an efficient way to provide the world with the non CO_2-emitting energy it needs. However, the underlying arguments are rarely explained. Sometimes, the difficulty of mastering this complex technology while respecting Western safety standards is invoked, or the fact that this technology would not be accepted by future societies. These arguments result in an artificial extra cost

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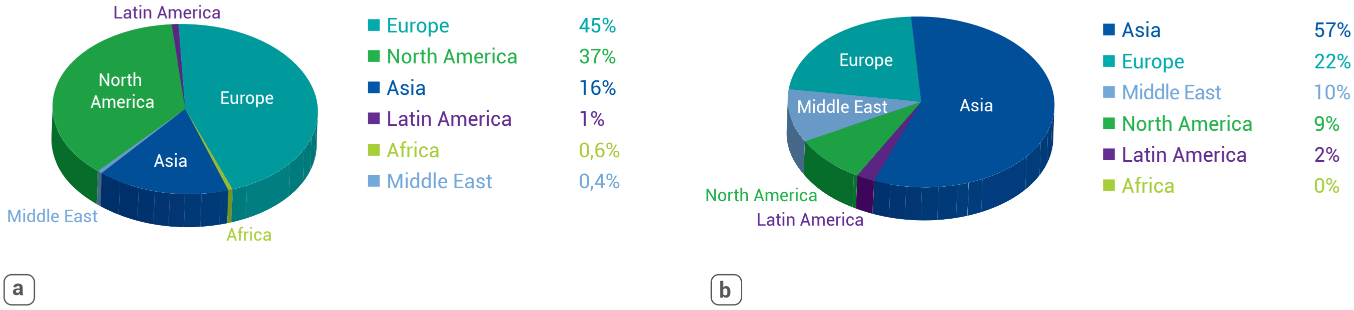

2. Proportion of nuclear reactors (a) existing and (b) under construction in the world.

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attributed to nuclear power, which ranks it last among non-CO_2 emitting energies in the energy mix. Limiting global nuclear use is therefore often an input assumption rather than an outcome.

On the other hand, in the scenarios that remove these constraints, nuclear production in 2050 is multiplied by a factor ranging from 2 to 10 compared to today, depending on future energy demand.

Currently, there are more than 400 nuclear reactors in the world, mostly pressurized water reactors, generating 2.4 million GWh electricity annually with an operating capacity of 350 GW, which represents 10% of total electricity production, and their geographical distribution is shown in fig. 2a. In addition, 68 reactors are under construction, more than half of which are located in Asia, with the remainder divided between Europe, North America and the Middle East (fig. 2b).

In the 2000s, nuclear power appeared to be on the rise again, but the Fukushima accident brought it to a halt, making any prediction of a move towards deployment or decline somewhat uncertain. Nevertheless, whatever the decision of European countries regarding nuclear power, its use seems to be continuing in the rest of the world and is now taking place mainly in Asia.

In a high nuclear growth scenario, world nuclear power output could reach 20 million GWh per year by 2050. Assuming that the main populations concerned would be located in the cities (where demand is concentrated) of countries already nuclearized, particularly in Asian countries such as China and India, about 5 billion people would benefit. On the basis of 1 GW reactors operating at full power 85% of the time, the total number of corresponding reactors is about 2300, i.e. about 450 reactors for one billion people. Compared to France, which has built 60 reactors in 25 years for 60 million inhabitants, this type of global deployment does not seem so unrealistic. Even if there are currently questions about the ability of the Western nuclear industry to engage in ambitious reactor construction programs, Asia could soon have the means to do so.

Increasing nuclear output by a factor of 10 over the next century would come up against the issue of uranium reserves. Estimated today at around 15 million tons, these reserves are incapable of fueling such an increase of current systems, which consume 150 to 200 tons of uranium to deliver 1 GW over a year. Moreover, the mining industry's capacity to make these resources available remains to be seen. Finally, the oceans contain several billion tons of uranium, but the concentrations are so low that the energy efficiency of extraction and the associated environmental impact make it hard to imagine exploiting this resource today. Carbon-free energy development would therefore seem possible only through a transition to renewable industries, making it possible to reduce uranium consumption by a factor of 200. The development and operation of hundreds of fourth generation reactors worldwide, meeting the highest safety standards, would represent a major technological and industrial challenge.

In conclusion, scenarios relying on sustained growth of nuclear power to meet climate challenges do not feature highly in the political, technical-economic and media spheres. Significant deployment at the global level would require tough political choices to be made that would involve future generations and make nuclear power a serious gamble on the future. But scenario analysis shows that doing without nuclear power is also a gamble on the future. Indeed, the corresponding scenarios are based on the ability of societies to reduce their energy consumption and improve energy efficiency very significantly, and are based on very optimistic assumptions about CCS technology and the means to manage substantial intermittent electricity production. If we fail to meet these ambitious targets, fossil fuels will remain the main source of energy for a very long time to come and we will have irreversibly set the world on a major climate change trajectory. ▮

To find out more

- This document is mainly based on the International Institute for Applied Systems Analysis (IIASA) scenarios developed as part of the IPCC work: https://secure.iiasa.ac.at/web-apps/ene /SspDb/dsd?Action=htmlpage&page=about
- Figures on nuclear power generation are taken from the ENERDATA database: www.enerdata.net/
- "Building future nuclear power fleets: The available uranium resources constraint", Resources Policy **38** (2013) **458**-469.
- "The representative concentration Pathways: an overview", Climatic Change **109** (2011) 5-31.

a. For a study of scenarios on a French scale, see the article by N. Maïzi and F. Briens. (p. 49).

Envisioning the energy future: from societal aspirations to technical challenges

Nadia Maïzi, mathematician, Mines ParisTech, and **François Briens**, PhD in Applied Mathematics

Mathematical models, which can arbitrate between several strategies, or even societal choices, allow the exploration of different scenarios and can help decision-making. A family of models allows a detailed comparison of three scenarios, which are based on a so-called "green" growth in energy consumption, involving either an increase or a phasing out of nuclear power, or a decrease in energy consumption.

When it comes to long-term energy issues, the question of the suitability of the various technologies arises. Models from the TIMES family *(The Integrated MARKAL-EFOM System)* [1] allow forecasting studies to be carried out from this perspective. The models are driven by a scenario of changes in demand up to 2050 and provide a detailed description of the technologies available, evaluating them in order to minimize the total actualized cost of the energy system over a given time-frame.

In order to feed such models, the following question must be addressed: *how will energy demand change over the next 50 years?* This is a complex question, as energy is used in a variety of ways: for heating, transportation, entertainment, manufacturing, etc. Moreover, energy use is influenced by infrastructures, behavior, consumer choices and, more broadly, by lifestyles and how societies are structured(a). In order to explore the impact of different societal choices (including different nuclear options) and lifestyles on energy demand, we have developed a macroeconomic simulation model [2] for France(b).

We can therefore look at how the application of our models allows us to shed light on two options recommended as viable alternatives to current trends (see box, p. 51). The first is in line with the prospect of *green growth*. It is presented as a technological gamble: innovation and technical progress play a critical role, both as the drivers and fruits of economic growth, and also as expected sources of solutions to the depletion of natural resources. Translated into our macroeconomic model [2], this strategy leads to a 15% reduction in electricity consumption between 2012 and 2050.

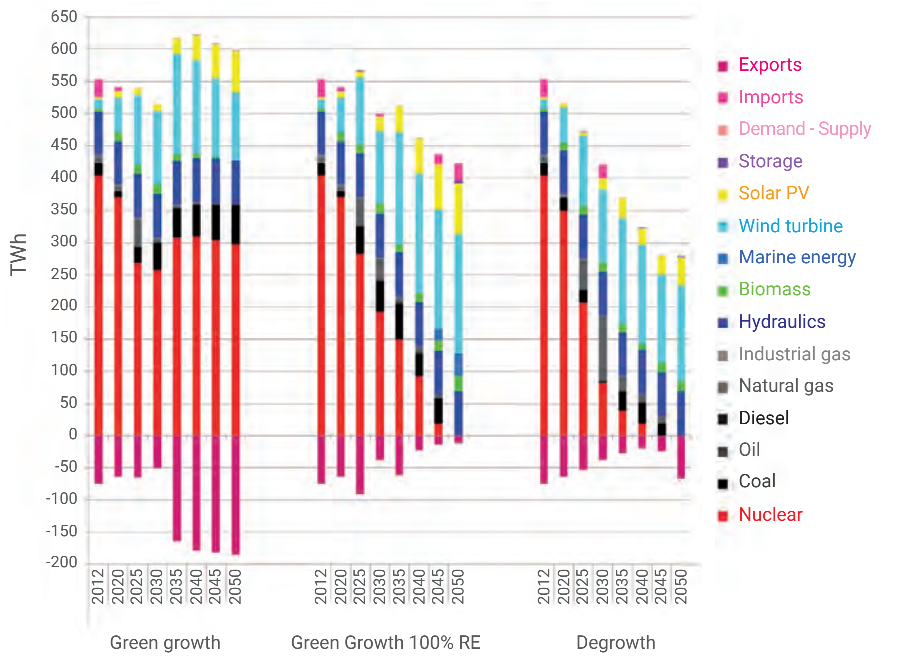
The second option is intended to reflect the perspective of protagonists of the *degrowth* movement. It is more of an anthropological gamble: that of a cultural revolution resulting in a profound change in values, norms, behaviors, lifestyles and social organization, and a change from systems of needs towards greater sobriety. To understand this ambition, a series of interviews were conducted with people close to the degrowth movements, each interview being then translated into a scenario. We propose here to analyze the scenario reflecting the most ambitious of the visions gathered during the interviews. Our macroeconomic modelling [2] indicates that this scenario entails a 56% decrease in electricity demand between 2012 and 2050.

These two electricity demand scenarios, with their specific constraints, are used as a basis for developing the electricity sector's most cost-effective technology package for the period up to 2050.

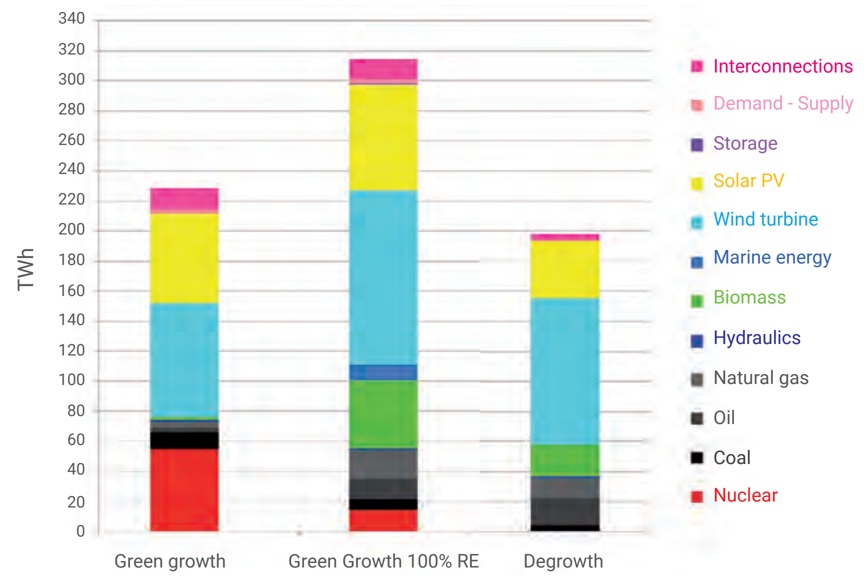
The green growth scenario will be considered in terms of two options: a first option opens up the possibility of investing in new nuclear capacity, while a second option pursues a policy of nuclear phase-out and the aim of achieving a 100% renewable electricity mix by 2050. In the latter case, a 20-year extension of the life of existing reactors, at an additional cost, is envisioned.

The degrowth scenario advocates a nuclear phase-out hypothesis with no possibility of extension beyond the lifetime of the reactors (40 years). In keeping with the underlying spirit of technological austerity, it doesn't permit phase-out technologies, which enable a delay in electricity consumption (such as optimized networks, known as smartgrids), or new storage technologies(c) dedicated to electricity generation.

The first trade-off factor highlighted by the results of our model (fig. 1) is the level of electricity exports, which decreases drastically in the two "100% renewable" options. If the share of nuclear power changes according to the assumptions made, the levels of investment in electricity generating capacity are contrasted: the "100% renewable green growth" scenario comes first in terms of the total amount of new capacity built over the study period (fig. 2). The two nuclear phase-out scenarios use technologies based on the use of fossil resources. This result, recurrent in our studies [3], indicates that, beyond the question of decommissioning, a nuclear phase-out will have to be carefully environed to limit the use of high carbon-emitting technologies. The significant differences in investment levels between the scenarios have repercussions on the total projected cost of the electricity system: ›››



1. Different shares of electricity generation, over time, in the "green" growth scenarios with and without nuclear power, and in the degrowth scenario.



2. Installed power generation capacities by 2050 according to the three scenarios.

The kinetic indicator

Provided that synchronism is ensured at network level [5,6], this indicator corresponds to the depletion time of the kinetic energy[(d)] stored in the power system in relation to the maximum possible fluctuation either in consumption (peak deviation) or in generating losses. It is expressed as

$$\frac{E_{kin}}{max(\Sigma_k S_k . P_{peak} - \Sigma_k S_k)}$$

where E_{kin} is the kinetic energy distributed on the network, $\Sigma_k S_k$ is the maximum apparent power supplied by the generator, before they fluctuate, and P_{peak} is the peak power demand.

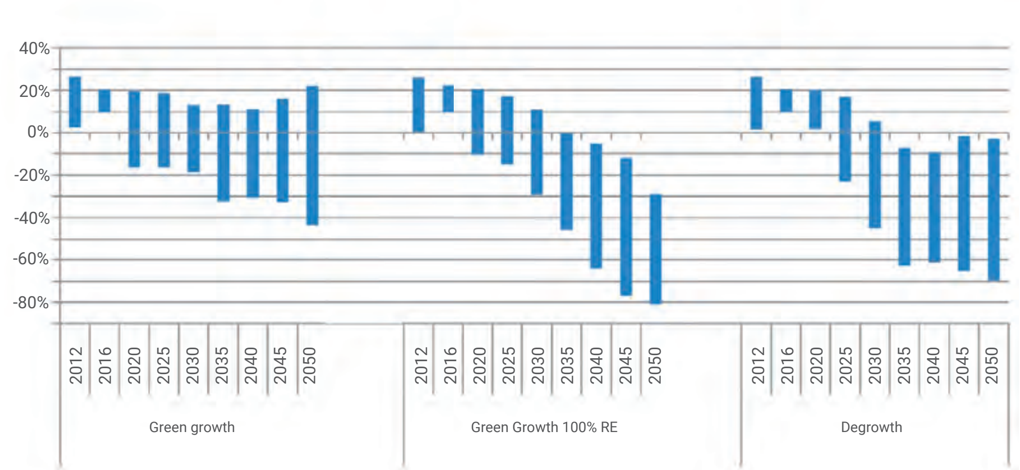
›››

the transition to the scenarios with lower greenhouse gas emissions leads, compared to the green growth scenario, to an additional cost of 16% in the case of 100% renewable green growth and a cost reduction of 4.5% in the degrowth scenario.

While a given electricity generation mix seems to meet environmental criteria, the question remains as to its ability to meet demands in order to avoid a disruption of electricity supply due to an imbalance between supply and demand (black-out). To address this problem, which involves transient events of the order of a second or even a millisecond, we have developed an indicator [4] which makes it possible to estimate the time needed for the system to recover a satisfactory operating state following a significant power disturbance (see box). In order to guarantee the stability of the power system, a minimum level[(e)] of this indicator must be maintained corresponding to the time needed to use the primary reserve, whose role is to restore a balance between production and consumption, independent of considerations of nominal regime or economic optimum. However, it can be seen (fig. 3) that the value of the indicator declines (compared to its 2012 baseline) for the two scenarios with a "100% renewable" objective. Indeed, with the introduction of variable renewables, the technologies in question have no (solar) or little (wind) mechanical inertia. The stability of the power system is therefore strongly impaired in both scenarios.

Far from invalidating the options tested and their aim of limiting the carbon emissions of the power system, these results encourage us to think about how the solutions proposed can be adapted to the operating requirements of the system. Through a case study of Reunion Island to 2030, we were able to show that a technical design that meets the requirement of maintaining the level of the kinetic indicator makes it possible to envisage a 100% renewable mix [6, 7] that allows both a share of more than 50% of intermittent energy sources and a reduction in newly-created capacity.

The forecasting tools we have developed, illustrated through these analyses, highlight the possible but sometimes overlooked consequences of certain choices, be they technical, linked to behavioral changes, lifestyles or social organization. By enabling an informed debate, they provide politicians "wishing to embark on a chosen path" [8] with the means to achieve it. ∎



3. Kinetic indicator as a function of time in the three scenarios. The higher this indicator, the more stable the system is with respect to fluctuations. The value indicated is the relative value compared to the minimum observed in 2012.

a. Including demographic choices.

b. For a study of scenarios on a global scale, see the article by S. Bouneau (p. 46).

c. For example, high-capacity batteries and super-capacitors, thermal storage.

d. Kinetic energy due to the rotation of mechanical parts.

e. Of the order of a few tens of seconds, this time is 40 s on average for France in 2013, and 25 s for an island such as Reunion Island in 2008. The higher the indicator, the more the system can cope with significant fluctuations.

f. The annual rate of improvement in energy efficiency is assumed to be twice the average rate observed in France for each sector over the period 1996-2012.

g. Marginal gains in energy efficiency are assumed to be increasingly small and zero after 2050.

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Green Growth and Degrowth

Green Growth

The size of households continues to decrease, end-user consumption increases, long-distance mobility continues to grow, local mobility continues to develop, local mobility relies partially on public transport, electric vehicles are spreading rapidly, the economy is modestly continuing its tertiary sector development, the residential sector is benefiting from an increased rate of heating upgrades, and the assumptions of technical progress and energy efficiency of manufacturing processes and machinery are very strong[f].

Degrowth

Household consumption is changing and decreasing significantly as a result of the gradual adoption of "frugal" lifestyles and the development of pooling practices, long-distance travel is decreasing sharply, travel is largely shifting to less polluting modes (bicycle, public transport, train, etc.), the economy is being relocalized, agriculture is becoming essentially "organic", heating upgrades in the residential sector are limited, and the assumptions for improving the energy efficiency of production processes and household equipment are very modest[g].

Electricity transmission
Strengths and limitations of the European network

Jacques Percebois, economist, University of Montpellier

Until the end of the 1990s, electricity was generated, transmitted and delivered to European countries by so-called "integrated" public or private companies. In some countries, such as Germany, there were several regional companies; in others there was a single national company with a monopoly, such as EDF in France. The European Directive of 1996 put an end to monopolies in the generation and supply of electricity. Transmission and distribution networks, which functioned as "natural monopolies", became "essential infrastructure" open to all producers and suppliers, with access tariffs set by an independent regulatory commission. These networks are at the heart of current debate because they are needing to absorb a growing share of renewable energies and cope with increasing home energy generation.

Electricity is a product that cannot be stored, at least economically on a large scale. The quantity supplied upstream of the network must therefore be equal at all times to the quantity withdrawn downstream, adjusting for line losses due to the Joule effect. In principle, water can be stored in dams or pumping stations at off-peak times to use at peak times, but there are technical limits to pumping water from dams, especially for multi-purpose dams (power generation and irrigation). Although the introduction of increasingly efficient batteries on the market makes it possible to store a little electricity over short periods, and great progress is being made, particularly in reducing the cost, this is not currently profitable on the scale of a national network. This may soon change thanks to electric vehicle batteries[(a)].

The main problem is seasonal storage. The European electricity network is a highly interconnected grid, which is a safety feature and a means of building a single electricity market. However, the differences between the electricity mixes observed between European countries, sometimes make it difficult to achieve electricity price convergence for consumers. Some countries, such as France, have an electricity mix largely dominated by nuclear power; others, such as Germany, have a mix that relies heavily on coal or lignite power plants. The development of renewable energies, such as solar or wind farms, requires local network reinforcements to absorb this production on the distribution grid and sometimes feed it back into the transmission grid: injection points are not necessarily located close to the network, which complicates the task of grid operators and can increase the cost to the consumer.

A Europe-wide grid

The electricity network is now highly interconnected, but this was not always the case. In France, it is the local authorities, particularly the municipalities, which have been at the heart of creating small networks. This explains why these municipalities still own the distribution

networks today, even if Enedis (ex ERDF, Electricité Réseau de Distribution France) is the operator, except when Local Distribution Companies (municipal boards or mixed economic companies) remain [1]. It was between the two wars that the State intervened to encourage or force local networks to interconnect, both to supply regions with little electricity and to guarantee greater security of supply. It should be noted that the linking of the network makes it possible to take advantage of an "expansion" effect, as the installed capacity on a national scale can then be much lower than the sum of the installed capacities of all consumers. After the Second World War, and well before the signing of the Treaty of Rome in 1957, European electricity companies understood the need to develop transnational networks, mainly for mutual assistance. Thus "electric Europe" preceded economic Europe.

The liberalization of the electricity sector, which began with the adoption of the First European Directive in 1996, obliges member states to open up electricity production and supply to competition. The public company EDF, which had achieved a virtual monopoly on the generation, distribution and marketing of electricity and a total monopoly on transmission since the nationalization law of 1946, is no longer the only producer or supplier in France.

The networks are still "natural monopolies" due to the existence of high fixed costs, but they must be "regulated" by law, and the tariff for the use of public electricity networks is an important component of the price of electricity (about one third of the price including tax for a domestic consumer) [2]. In mainland France, the Electricity Transmission Network (Réseau de Transport de l'Électricité, RTE) is responsible for power transmission, i.e. the high-voltage public network, above 50,000 volts. Enedis manages distribution, i.e. medium and low-voltage lines below 50,000 volts, to end users. These two companies are still subsidiaries of EDF, 50% for RTE and 100% for Enedis, but they must act as independent network managers and not favor the original operator EDF. In other European countries, these network managers are mostly private companies that have cut all links with their parent company. To enable the creation of a genuine European electricity market, the European Commission is encouraging member states to develop transnational interconnections, this time not only for security reasons, but to facilitate electricity trade and allow relative convergence of kWh prices for consumers.

Investments in networks are costly and there are still some bottlenecks in Europe; this is particularly the case between France and Italy and between France and Spain, for both historical and geographical reasons (mountains make the construction of high-voltage lines expensive). Interconnections with Germany are better, which explains why electricity prices on the wholesale markets (where the kWh produced are traded) are often the same in France, Germany and Belgium. It should be noted that the connection with England, which is a submarine high-voltage power line, is a direct current line

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and not an alternating current line. Alternating current must be transformed into direct current at the French border and the reverse must be done at the entrance to England. This means that the British grid and the continental grid are not synchronized[b].

Diverging electrical mixes

Every country is free to choose its electrical mix and the means to produce it. As a result, the make-up of the electric mixes is very different from one European country to another, for reasons that have to do with both geography and history. In Germany, the structure of electricity production in 2015 was as follows: 42% coal- and lignite-based, 34% renewables (solar, wind, biomass, hydro), 14% nuclear, 9% natural gas and 1% oil-based. In France, in the same year, the composition was as follows: 76% nuclear, 17% renewables, 3% natural gas, 3% coal and 1% oil-based.

This explains why the price paid by the consumer can be very different from one country to another, because the cost of these energies is different [3]. Since renewables are heavily subsidized through guaranteed purchase prices and the extra cost of renewables compared to wholesale market prices is financed through taxes borne by the end-user, the German price per kWh including taxes paid by a domestic consumer is almost twice as high as the French one, as the share of renewables is much higher in Germany and the guaranteed purchase prices are higher [4]. However, with the falling production costs of renewables, subsidies are tending to fall sharply.

It should be recalled that the price of the domestic kWh, including tax, breaks down as follows in France: 36% for the generating and marketing cost of the kWh, 30% for transmission and distribution and 34% for taxes (which notably include the additional cost linked to the subsidies granted to renewables). It should also be noted that European interconnections sometimes lead the French grid to prioritize importing German renewable electricity, to the detriment of domestic production which may be nuclear. Trade-offs are made on the European wholesale market according to the increasing fringe costs of energy. Nuclear power is thus being squeezed out by surplus renewable electricity, supplied at virtually zero cost but with a very high level of subsidy.

Networking doesn't solve everything

The priority given to nuclear energy in France at the time of the oil crises (the 1974 Messmer Plan) explains why the heating of buildings relies heavily on electricity, making the demand for electricity highly temperature-dependent. Almost 50% of the increase in electricity demand in Europe during periods of extreme cold is from France. One degree Celsius less in winter means 2,400 MW more power is required on the French network. If the availability of nuclear power is momentarily lower, which was the case at the end of 2016 or early 2017 at the request of the Nuclear Safety Authority for technical reasons, operators fear load shedding, and the price of electricity on the wholesale market soars. Networks then become saturated, they are unable to stop this surge, and French and German prices may diverge. The available interconnexion capacity between France and Germany is around 5 GW, and 4 GW between France and Belgium, for a peak demand which is around 90 GW on average in France (it even reached a peak of 102 GW in 2012).

The development of intermittent renewable energies (solar and wind) would not resolve the issue, as these energies are not necessarily available at peak times (in the morning around 9 a.m. or in the evening around 7 p.m., particularly in winter). It is therefore necessary to plan reserve power plants or consider large-scale storage, via water electrolysis for example[b]. The development of renewables also means that the network has to be upgraded to absorb this electricity, which is sometimes produced far from the grids, and this reinforcement is costly. This also places a strain on the equilibrium of the network, since the injection of renewables is not modular: this is particularly true for wind power, whose injection is more random than that of solar power. Connecting a number of small sites is also more expensive than connecting large power plants, especially since the French network is now largely paid for; creating a new line is much more expensive than reinforcing an existing line.

Coexistence and coordination

Grid networks remain at the heart of the European electricity market, both for back-up and economic reasons. In the future, we will increasingly have to rely on the coexistence of two types of networks: on the one hand, large networks interconnected at the European level; and on the other hand, small networks developed at the level of a shopping center, a housing estate, a group of buildings or a new district if self-generation increases, in particular cooperative self-generation which is encouraged by law. It is the coordination of these two models that is an issue for network grid managers. The policy to encourage solar home energy-production off-grid is a way to alleviate these pressures, since the producer will theoretically no longer need to inject and withdraw electricity from the existing distribution network. But this does not solve everything, as the producer-consumer will sometimes want to remain connected to the national interconnected grid to cope with the failure of his installation when there is neither wind nor sun, at least until individual, low-cost and efficient means of storage are developed. ▮

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a. (Editor's note) On the consequences of the proliferation of electric vehicles, see « Voiture électrique, une aubaine pour la Chine », Le Monde Diplomatique, n°773 (August 2018).

b. See on this issue the article of N. Maïzi et F. Briens (p. 49).

c. Using electricity, we can obtain hydrogen that can be combined with CO_2 to obtain methane, which can be stored for later use during peak periods.

New nuclear reactor designs

Annick Billebaud, physicist, CNRS

Developing new types of nuclear reactors to replace existing ones is a long-term process. Many new designs are under study but, since 2000, an international forum has been encouraging research which focusses on a few promising systems which meet the new criteria of fourth generation reactors. In France, the systems studied in this context are sodium-cooled fast neutron reactors and molten salt reactors. Accelerator-driven reactors, as part of a waste-incineration strategy in dedicated facilities, have also been studied over the past twenty years.

Why study new systems?

In a nuclear reactor core, the reactions at work that ultimately lead to the production of thermal energy, and in particular fission, are well known and common to all reactors. However, the ways of exploiting the chain reaction, controlling it, consuming the fuel, or extracting heat from the reactor can be achieved in different ways that meet various priority criteria that we will see later.

However, a new design, different from those previously in use or currently in operation, takes time to demonstrate and be approved; it requires modelling and, at some point, model experiments and then the construction of prototypes to support its feasibility. It often takes several decades of research, design, development and experimentation to arrive at a system ready for scaling-up to industrial level, which often exceeds the length of an individual's professional career.

This time scale is the main reason why scientific and technological research organizations try to anticipate future needs. In the case of nuclear power, this involves revisiting old reactor concepts or proposing new ones in the light of the latest knowledge and advances. France is a country with strong expertise in nuclear sciences and reactor-related technologies, and therefore has a melting pot favorable to this type of research. The objective is to have solutions that have demonstrated their feasibility beyond 2030 (or even 2040 or 2050 for the most innovative ones). This research explores possible solutions and does not predict future choices to be made by politicians and society. Nevertheless, for the same reasons of temporal inertia, the choices of research directions are somewhat binding for the future.

What is "Generation IV"?

The nuclear reactors currently operating in France are part of what is called the second generation. Improved versions under construction, such as the EPR, are considered to be third generation. In many countries, prospective research is being carried out to imagine future-oriented fourth-generation reactors. At the instigation of the United States Department of Energy, an international forum, the Generation IV International Forum (GIF), bringing together a dozen countries including France, was formed in 2000. Its objective is to encourage international research on a few reactor designs that will meet specific criteria with possible implementation by 2030-2040. These criteria are defined as targets for the economic, environmental and social improvements needed if nuclear energy is to make a significant contribution to meeting the global energy demand of the twenty-first century. They cover four main areas:

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- Sustainability: the aim is to be able to place nuclear energy on a long-term footing by optimizing both fuel supplies and waste generation, with a view to their long-term management. Existing systems are essentially based on the use of enriched uranium 235, which requires the processing of large quantities of uranium from which this isotope can be extracted; it takes about 200 tons of uranium each year to operate a 1 GW pressurized water reactor core that will fission only one ton of material. In the future, it is hoped to be able to use a system that allows the full potential of the ore extracted to be used and thereby enable energy production on a global scale for several centuries.
- Safety and reliability: the aim here is, on the one hand, to minimize the risk of nuclear accidents leading to disasters such as Chernobyl or Fukushima and, on the other hand, in the event of an accident, to minimize the impact on people and the environment. To this end, the emphasis is placed on the passive safety of the systems and in particular the withdrawal of residual power in the event of a core shutdown.
- Economic competitiveness: a new system must be able to compete in a free energy market where sources of energy generation are increasingly diverse.
- Proliferation-resistance and physical protection: the diversion of civil nuclear facilities and materials for military purposes has long been a risk that has been under international scrutiny. This risk is now compounded by the risk of malicious or even terrorist acts. It is therefore proposed that protection against theft of radioactive materials and acts of sabotage which could occur in facilities or in the transport of materials should be built into the design of new systems.

Which systems are available to meet these criteria?

A nuclear reactor is defined in terms of its three main components: the fuel, not only the type but also its geometry, composition and chemical form; the moderator, a material present in the core that optimizes the use of the fuel by slowing down the neutrons to a greater or lesser extent; and the coolant, which is used to transfer thermal power from the core to the heat exchangers to convert it into electricity. For most reactors currently in operation, water acts as both moderator and coolant. There are a very large number of possible combinations of these three elements, and thus many potential nuclear reactor variants. Throughout the history of nuclear power, a few hundred have been studied theoretically, but in total, fewer than 20 have been built to provide power. There are still many possible options for meeting the new requirements. The GIF has decided to concentrate research on six of what are considered the most promising designs.

Three of them are so-called "fast" neutron systems, i.e. those that conserve as much of the original neutron energy as possible. This has several advantages with respect to the sustainability requirements. In order to optimize the use of uranium ore, it is conceivable to regenerate the fuel by transforming the so-called "fertile" uranium-238 nuclei into "fissile" plutonium-239 nuclei[(a)]. If each uranium-238 nucleus produces a plutonium-239 nucleus by neutron capture, the full energy potential of the uranium ore, 99.3% uranium-238, is used. Fast neutrons minimize parasitic neutron capture and thus maintain the criticality of the system and the regeneration of the plutonium.

These fast neutron reactors can use different moderating and heat transfer fluids; the three models studied are the Sodium Fast Reactor (SFR), the Lead Fast Reactor (LFR) and the Gas Fast Reactor (GFR). They all have good thermal efficiency. Sodium combines a low melting temperature with a very high boiling point, providing good thermal inertia to the primary circuit. However, the SFR and LFR have to cope with the chemical properties of a liquid metal: reactivity with water and air for sodium, corrosion for lead. The third model has the advantage of using a chemically inert gas, helium, but its relatively low thermal inertia during a forced circulation shutdown is not optimal for safety, and requires the development of a very specific fuel.

The Very High Temperature Reactor (VHTR) would operate between 800 and 1,000 °C. It uses slower neutrons, known as "thermal" neutrons. It is also cooled with helium, but moderated with graphite. Its main advantage is that the gas can be used directly in a turbine on the primary circuit. The heat produced by these systems can also be used in different ways on an industrial level, in particular for the production of hydrogen.

A type of water reactor model, the SuperCritical Water-cooled Reactor (SCWR), is also being explored. It operates at a temperature and pressure above the critical point of water (374 °C, 221 bars), hence its name. It can be designed for either thermal or fast neutrons. The extremely hot steam produced can be sent directly to the turbine and, after condensation, the water is returned to the core. This process benefits from the long experience of fossil-fueled thermal power plants using supercritical water. It has an economic efficiency advantage as its thermal efficiency can be as high as 44%, compared to 33% for today's pressurized water reactors. However, technological challenges remain to be addressed, such as: modelling heat transfer during accidents, depressurization and loss of supercritical conditions, qualification of materials for high temperatures, especially steels for fuel cladding; and demonstration of the passive safety of the system.

The sixth concept, one of the most innovative, uses molten salts (Molten Salt Reactor, MSR). It is presented later on.

Fourth-generation systems studied in France

On the basis of estimated finite uranium resources and significant use of nuclear power worldwide, France had already devised a strategy in the 1960s that began with the development of thermal reactors using enriched uranium. The idea was to build up a stockpile of plutonium (nuclei produced during operation), which could then be used to power fast neutrons breeder reactors and ensure sustainable energy production. France thus very early on concentrated its research efforts on fast neutron reactors, and opted for liquid sodium as a coolant, bringing the idea to fruition. However, only two liquid sodium units were built on an industrial scale in France: Phénix (1973-2010), then Superphénix, which was prematurely shut down in 1997 for industrial, economic and political reasons, linked to the post-Chernobyl context. This type of reactor is again the subject of research for the fourth generation because of its clear advantages with regard to fuel and waste requirements and the added benefit of being based on a technology already implemented in several countries. Thus the CEA, EDF and Framatome have devoted major research efforts to revisiting this concept, notably with the 600 MW pilot sodium reactor project ASTRID.

The molten salt reactor (MSR) concept was studied in the United States from the 1950s and abandoned in the 1970s. In this system, the fuel is dissolved in a molten fluoride salt, which also acts as a coolant and can flow directly through the heat exchangers. A reactor moderated by graphite in its early versions, it was recently revisited as a fast neutron reactor by French academic research teams, in particular to make it regenerative with simplified in-line reprocessing, using thorium and uranium fuel. The molten salt fuel has many advantages. On the one hand, the salt has favorable thermodynamic properties: high boiling temperature, good calorific capacity and thermal conductivity. On the other hand, in the event of a system malfunction, the liquid salt can be passively reconfigured, for example, dispersed in a network of tanks designed to withstand high temperatures, allowing different options for dissipating its residual power. On-line reprocessing of the salt makes it possible to maintain a neutron balance in the core that is conducive to using different fuels. In a complete technological break with existing and well-tested reactors, it requires a reappraisal of the safety approach and a considerable research effort to remove the scientific and technological barriers, firstly with regard to salt and materials (corrosion, reprocessing, physico-chemistry, etc.), and the neutronics of a liquid fuel (fuel-coolant, criticality control), all steps needed before an industrial prototype can be built. The natural inertia of nuclear processes is a hindrance to the deployment of these highly innovative technologies, even if they potentially represent interesting solutions for the future.

Accelerator-driven reactors

Although not part of the fourth generation systems studied by the GIF, Accelerator Driven Systems (ADS) are still the focus of major feasibility studies because of their potential to incinerate some of the nuclear waste produced through existing processes, making it possible to reduce radiotoxicity and residual heat and consequently the storage space the waste requires. These reactors are said to be "subcritical", i.e. the chain reaction can neither start nor maintain itself spontaneously without the contribution of external neutrons. In most designs, an accelerator provides high-energy protons, which strike a target made of a heavy metal (e.g. lead) located in the reactor core. This produces nuclear reactions that release large numbers of neutrons. These neutrons will cause fissions in the core and thus generate power that can be reduced to zero on demand by shutting down the accelerator. This control of power by the accelerator enables somewhat exotic fuels to be used such as minor actinides[(b)] whose properties do not allow them to be used in critical reactors. The ADS is then operated in a fast version, with liquid lead as moderator-coolant. The main challenge to the use of these systems (apart from the chemistry of liquid lead, a feature common with the LFR) is to reach a level of particle beam reliability never before achieved. These reactors have been studied for more than twenty years, particularly in Europe and France, with intense R&D on linear accelerators. The construction in Belgium of a demonstration reactor of about 100 MW, MYRRHA, is currently scheduled in two phases: one for the accelerator in 2026 and the other for the reactor in 2033.

Conclusion

Research on new nuclear energy production systems is not currently limited to research carried out within the framework of the GIF, whose initiative has had the merit of setting ever more demanding requirements for the development of designs, particularly with regard to nuclear safety and the issue of waste, and of reviving collaborative R&D between countries with a nuclear industry. It can be noted that the greatest misgivings expressed by society towards nuclear power have to some extent been taken into account by research. However, developing new reactors up to an industrial scale in the face of the progress made by other energy sources, particularly renewable ones, is not without its economic implications. This is why, apart from developing these new concepts, great efforts are also being made, particularly by French industry, to study third-generation reactors based on the optimization of existing water reactors.

In summary, the options for the future of nuclear power are numerous. But the research effort, which must be anticipated over decades, cannot be carried out with equal emphasis on every system. The challenge is to conduct R&D that will lead to an industrial model without refraining from investigating more ambitious avenues for the future. ■

To find out more

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- "Perspective on the use of Thorium in the Nuclear Fuel Cycle", NEA/OECD (2015) No 7224. www.oecd-nea.org/science/pubs/2015/7224-thorium.pdf

a. A nucleus of uranium-238 that captures a neutron gives a nucleus of uranium-239, a radioactive nucleus, which decays into a nucleus of plutonium-239.

b. Highly radiotoxic heavy nuclei created by neutron capture in reactors.

Some unresolved questions and unaddressed points

François Graner, physicist, CNRS, and **Stefano Matthias Panebianco**, physicist CEA,
Editors of the issue

Perhaps you, the reader, have in mind an important point that merits inclusion in the debate on civil nuclear power (French or international), but which hasn't been addressed in the previous pages. It is frustrating, but inevitable; the size constraints of a publication like this one prevent us from being able to deal with the subject exhaustively. We outline here a summary of those issues that have not been dealt with. In addition, there are some issues that we believe are still unresolved and we try to identify the most critical aspects of them.

Decisions with a long-term commitment

Civil nuclear power, perhaps more than other industrial activity, involves future generations, in the sense that they will need to be able to commit energy, money, know-how, manpower and space to deal with the impact of our existing power plants, whether or not they end their operations without incident. It is a legacy of debt that they will not even have had the benefit of, unless they in turn find sufficient resources and energy to devote to it. But even if they do, will it be an endless cycle, destined to finally burst like a bubble?

How can society, in all its diversity, collectively identify and embrace such obligations, including the moral and practical issues, in the long term? Political decisions require a global weighing of the disadvantages of nuclear power (whether proven or as a risk) against the already proven damage to the climate caused by all energy sources. To inform such decisions it would be useful to reach a consensus on the profitability of nuclear power as a source of energy[(a)] as well as in terms of complete carbon balance, including all the steps involved in its decommissioning, and to compare this with other forms of electricity or power generation.

Public debate is notoriously difficult, for deep reasons (and not only because of the bias that each side tends to accuse the other of). On the one hand there is the problem of having to weigh up and compare different kinds of arguments, many of which are not readily accessible or do not have consensus. Also, decisions are often taken within a national framework, whereas the consequences, in terms of energy use or risk of accidents, are also measured at local or international level.

Nuclear power requires stability in international relations, which in turn has consequences for geopolitics. The agreements between the World Health Organization (WHO) and the International Atomic Energy Agency (IAEA) have been criticized by some organizations.

The following affect the French nuclear industry alone: its links with the embargo on South Africa at the time of apartheid; the dispute with Iran over Eurodif; links with the regimes of producing countries such as Kazakhstan or Niger; for the latter,

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the serious impact of mining on its inhabitants; the sending of French soldiers or private military companies to the Sahel; the French proposal to sell nuclear power plants to Libya, followed shortly afterwards by military intervention which led to the fall of the government.

Practical questions

Do we have to abandon nuclear power, and can we? According to the advocates of maintaining it, it is risky to reduce nuclear power production: who can predict whether the industrial balance of the sector and the reliability of the energy supply will be maintained? They put the climate issue, which is urgent, ahead of the waste issue, which is longer-term. Those in favor of phasing out nuclear power explain that it has significant environmental impacts given that it currently accounts for only 3% of world energy, that it is itself not very resistant to global warming(b) and that its phasing out could be compensated for in other ways, including by reducing energy consumption or by replacing electricity where it can be done so easily (e.g. for heating) with more efficient forms of energy. Global and local scenarios can help us to weigh up these considerations(c), although the final outcome is more a political than a technical decision.

The possible end of nuclear power could be largely determined by our response to finite uranium resources, the accumulation of waste and the increasing number of plants to be dismantled. In October 2018, a report by the Institute for Radiological Protection and Nuclear Safety (IRSN) [1] indicated that "the shutdown of reactors loaded with MOX fuel may lead to short-term saturation of spent fuel storage facilities. However, a scenario including the shutdown of those reactors using only uranium fuel could delay or even prevent the saturation of these storage facilities." This raises the question of the technical requirements and consequences that an eventual phasing-out of nuclear power would entail.

The technology used is subject to wide-ranging debate. What are the advantages and disadvantages of the third-generation reactors under construction, the EPRs(d)? Should fuels other than uranium be included in the debate: what prospects do plutonium breeders (generation IV) or thorium (whose reserves are greater than those of uranium) offer?

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What must be made of prototypes for research on fusion (ITER), on fast reactors (ASTRID) or on spallation sources (MYRRHA) with a view to the incineration of certain waste? Will they remain prototypes or will they lead to workable solutions?

French decision-making

The waste issue also triggers endless debate. The French government has focused on deep disposal of high-level long-lived waste (HLLLW). However, this type of storage is not purely passive due to the possibility of over-heating and the release of hydrogen which makes it necessary to ventilate the underground caverns. This requires a constant power supply (without interruption of more than a week) for hundreds of years; in turn, this requires political and energetic stability. Not to mention geological stability, which must be preserved over tens or hundreds of thousands of years. Opponents of this approach consider that deep storage would be largely irreversible, without having been tested beforehand at full scale, and without any dependable means of communicating with future generations. They also point out that the current storage plans only concern waste from the current stock: if we continue to produce it, will we have enough materials (borosilicate glass and steel), power and capacity to be able to store it?

The same French political decision-makers considered, during the moratorium of the Bataille law, that storage is not the only option. They advocated developing new ways to incinerate, recycle or transmute these same high-level, long-lived wastes. However, unlike storage, these processes struggle to cope with mixed wastes: they must first be separated, which we know how to do technically, but not yet on an industrial scale (not to mention the cost effectiveness, which is not among the objectives). How would research on incinerator systems tie in with deep disposal?

Technical decisions relating to the entire sector have been made by the French government, and have been debated within, among others, the Parliamentary Office for the Assessment of Scientific and Technological Choices (Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques, OPECST). However, the political proposals on fundamental and long-term issues have not yet been debated, amended and voted on by Parliament as such, except for one very visible issue, that of waste. The importance of the political issues under consideration requires collaborative, democratic processes for debate and decision-making, in full transparency and trust, which does not seem to be widely-accepted practice within the French community at present. Is it conceivable to improve the functioning of democracy, and to better integrate experience in order to make corrections a posteriori? And how do we manage, politically and financially, risks that are very unlikely yet would have far-reaching consequences?

The structure of the French sector

Transparency and trust must also extend to operators and their regulators, and here too consensus seems far from being reached. The error and incident rate in the French nuclear industry, clearly better than in many other industries and human activities, may still seem too high in relation to community expectations. This question in particular is raised by the issues of cracks and brittleness of reactor vessel steel, including that of the EPR.

The current independence of the Nuclear Safety Authority (ASN) and the Institute for Radiation Protection and Nuclear Safety (IRSN) is underlined in the checks carried out on a day-to-day basis, but critics question the ability of the ASN to impose a rigorous review of the entire industry if it deemed it necessary. Are the inspection records accurate, and how much actual influence does the High Committee for Transparency have [2]? Why is the military secret, which is in itself a democratic issue because it safeguards the policy-makers from accountability to their fellow citizens, applied as much towards civilian nuclear energy [3] as to military use? Are the links (especially concerning the engineers of the Corps des Mines) between State structures, regulatory bodies and operators now a thing of the past[f]?

Even if it has no direct consequence on decisions taken in the future, it may be useful to recall the history of the French nuclear industry, which is only partially dealt with in this issue: the creation of the CEA and the Marcoule center, the choice of pressurized water reactors, the Messmer Plan for civil nuclear power decided in 1974 following the first oil crisis, the construction of and problems with fast neutrons breeder reactors and the EPR. All this in the context of the simultaneous development of an entire industrial sector and a movement that challenges it. It would be interesting to look more closely at this history of the French sector, including its international context.

The need to think in the long term raises the question of the political and financial stability of decision-makers and operators, whether public or private. One of the first political arguments against nuclear power (recently revived [4]) was that it led to the establishment of a centralized and authoritarian State. Does nuclear management require a certain type of State or institutions? As for the French nuclear operators, now governed by private law, they are in the midst of a reorganization, and are involved in important and delicate international negotiations[g]. Should they be protected from competition?

Health and Environment

A few pages on the impact of nuclear power on health and the environment cannot be enough to cover the entire subject. The effects (not necessarily specific to nuclear power) of mining operations on producing countries and their workforces have aroused opposition, for example in Ganbaatar in Mongolia, in Falea in Mali, or with regard to the rights of Australian Aborigines [5].

The impact of an industrial accident, which is rarely mentioned in this issue, can seem different depending on whether it is considered from a weekly, annual or generational perspective. Lessons have been learned from the accidents at Windscale/Sellafield, Three Mile Island, Chernobyl and Fukushima, based on the information available. Radioactivity in the sea affects marine biodiversity and fisheries, while airborne radioactivity can directly affect individuals and contaminate soils, with effects on food. While the consequences for Windscale were mainly in terms of the environment, Chernobyl and Fukushima also revealed (beyond profound differences in the capabilities of States and companies in responding to and managing the situation) the impact on social relationships, family ties, people's psychology, business practices, trust in the authorities and the media, animals, all of which cannot be reduced to a purely financial balance sheet(h). In the case of Chernobyl, the number of people affected, the extent of the damage to their health and the number of deaths remain controversial. In the case of Fukushima, the density of housing in the affected areas has highlighted, both for the authorities and the people concerned, the difficulties of decisions to evacuate or return, as well as those to do with daily life i.e. living, eating, playing, breathing, working, travelling.

The likelihood of a future accident involving a French reactor is difficult to predict; the nuclear fleet has had five accidents that could have become serious and which have all been brought under control(i). In addition to human error, which cannot be excluded, and extreme natural events, how can we take into account possible deliberate interventions such as attacks on a power station or spent fuel pool (storage pond) by a suicide bomber or terrorist pilot, in an era when the means of attack are rapidly changing? The debate on safety and security(j) also relates to the ageing of the power plants. In November 2017, the French press reported on the seismic risks and obsolescence affecting Armenia's only nuclear power plant, in Metsamor, and on the ruthenium-106 pollution that recalled the Mayak nuclear complex in Kyshtym (Russia), which in 1957 was the site of a serious accident that had been kept secret for a long time. Any extrapolation to the French nuclear fleet is tenuous.

In conclusion

To conclude these unresolved questions, we will recall those asked 40 years ago in the preface to a special issue on nuclear energy [6]: "How much energy do we need? Is there a relationship between energy consumption and standard of living, consuming more and living better? Who doesn't have enough energy, who wastes it, and why? What kind of energy do we need? Which one, for a given use, is the best choice from the point of view of the community and individuals? Is there a relationship between forms of energy and forms of society? Which sources of energy can we count on for the future or even for now? To what extent is nuclear energy indispensable to us? Is the French nuclear power program realistic? Is it realistic to want to stop it?" ▮

a. The "energy return on investment" (EROI) of a sector is the ratio of the energy it provides to the amount of energy used for production.

b. Power plants need to be cooled; in times of heat waves, they sometimes have to be shut down and this can happen even in Sweden.

c. See the article by S. Bouneau (p. 46) and that by N. Maïzi and F. Briens (p. 49).

d. The first generation of nuclear reactors is the now-obsolete natural uranium and graphite-gas (NUGG) reactor. The pressurized water reactors currently in operation in France are part of what is called the second generation. Pressurized water reactors under construction are called "third-generation" reactors, whose safety has been improved, such as the European Pressurized Reactor (EPR).

e. On the issue of waste, see several articles, in particular those by J.-Y. Le Déaut (p. 13) and B. Romagnan (p. 14), and the discussion with C. Stéphan and P. Barbey (p. 19).

f. Greenpeace is denouncing such links at the Conseil d'État (Le Canard Enchaîné, 3 October 2018).

g. The Uramin affair (financial scandal involving Areva), the difficulties of the EPR construction sites may have significant impacts on these operators and their prospects.

h. For an estimate of the cost of an accident, see the article by A.-S. Dessillons (p. 29).

i. St-Laurent-des-Eaux on 17 October 1969 and 13 March 1980, Le Bugey on 14 April 1984, Civaux on 12 May 1998, Le Blayais on 27 December 1999.

j. The report of the Commission of Inquiry on the Safety and Security of Nuclear Installations, known as the "Pompili Report" (28 June 2018), went well beyond the framework of safety to address various aspects of the industry. EDF responded to it on several dozen points: www.edf.fr/sites/default/files/contrib/groupe-edf/producteur-industriel/hydraulique/Notes%20d'info/note_info_pompili.pdf.
Barbara Pompili responded in turn: https://barbarapompili.fr/reponse-a-edf-concernant-rapport-de-commission-denquete/

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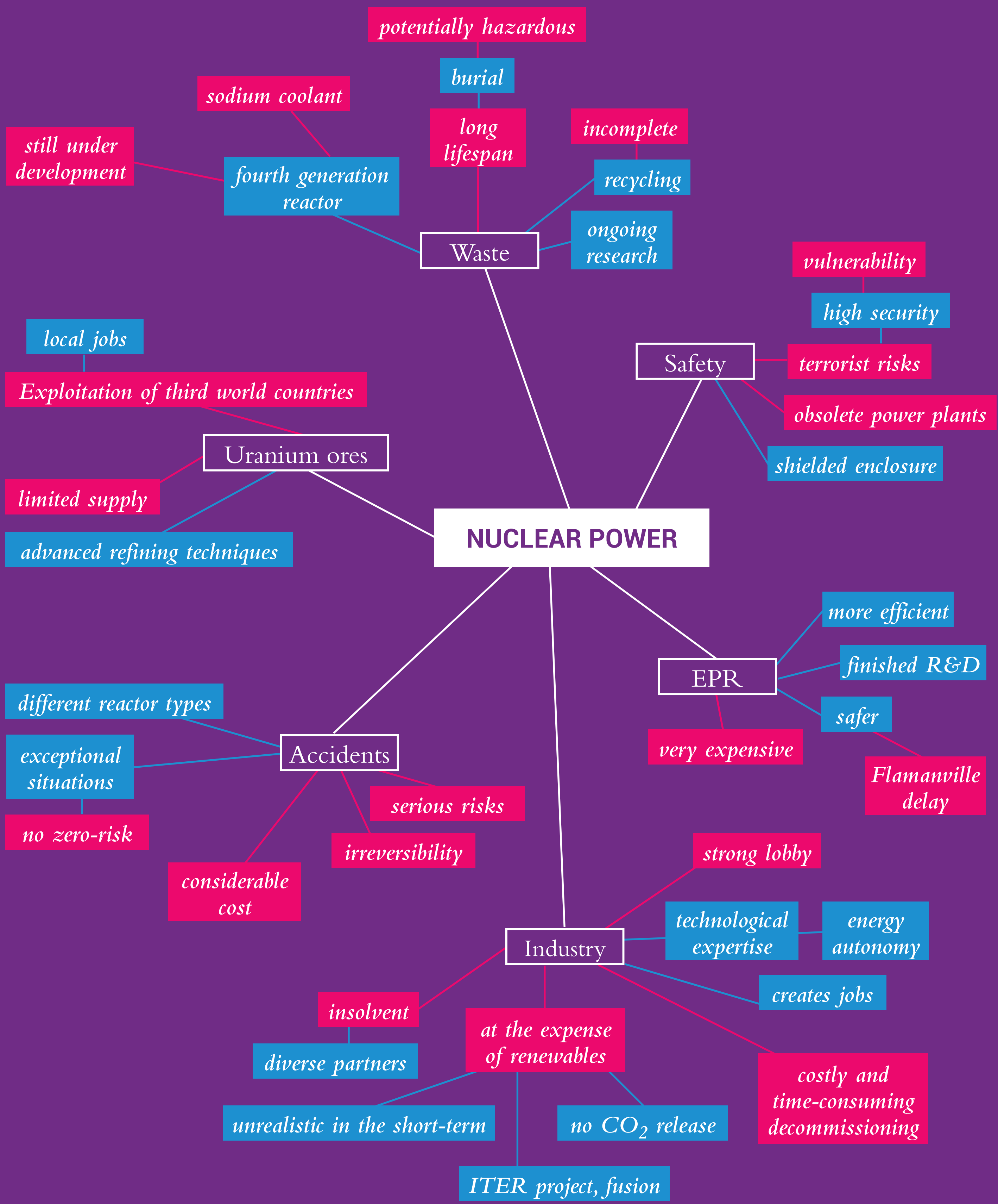
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