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POUR UN PROGRÈS RAISONNÉ, CHOISI ET PARTAGÉ

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FRANCE'S PATH TOWARDS SUSTAINABLE NUCLEAR POWER

1. Context and purpose of the position paper

The challenges of energy and climate change call for technological choices that require a long-term vision if they are to be fully overcome.

This is particularly true in the field of nuclear energy. The scale and duration of the investments involved, as well as the mastery of the associated technologies and natural resources, require continuous action and stable strategic choices over many decades.

This stability requires a detailed and shared explanation of the criteria that rationalise these choices for society.

It is therefore necessary to have a reference framework that ensures consistency over time between:

- the general objectives of decarbonising our society and securing energy supplies;
- technological and strategic choices concerning the deployment of nuclear reactors and the fuel cycle with a view to the safe and sustainable management of fissile material inputs.

This document proposes a **reference framework for a sustainable nuclear cycle** that is coherent and in tune with the current context. § 2 analyses the criteria and considerations that can structure a long-term sustainable cycle policy. § 3 details this analysis by proposing an industrial roadmap for the deployment of nuclear reactors and cycle plants.

2. Criteria and objectives for a sustainable nuclear cycle

2.1. History

The history of French nuclear power is based on a so-called closed-cycle strategy that has profoundly influenced the initial industrial choices, with the treatment of spent fuel, the recycling of reusable materials in "MOX" fuel in pressurised water reactors (PWRs), the vitrification and geological disposal of final high-level waste, and the development of fast neutron reactor (FNR) technologies for efficient fuel recycling.

This initial strategy, based on a desire for long-term energy sovereignty, has enabled France to develop world -class technological capital. It has led to the rapid development of a massive and operational nuclear power industry, as well as the large-scale industrialisation of effective long-term solutions such as the recycling of recoverable materials and the vitrification of final waste.

In the 1990s, this strategy lost its clarity and overall coherence. The availability of abundant, cheap electricity has pushed the concerns arising from the oil crises that motivated investment in nuclear power into the background. Waste has become the dominant issue in the debate, to the detriment of the energy vision, both in France and in Europe. France's influence in the energy field, internationally and especially in Europe, has suffered greatly from the absence of a cutting-edge reference framework.

More recently, concerns about climate change and energy security have once again led to the need to stabilise a coherent long-term strategy that is anchored in the present and future context.

This long-term strategy is essential to provide a rational basis over time for i) national debates prior to decisions, ii) the stability of industrial investment choices and iii) negotiations on European regulatory frameworks.

2.2. Imperatives and objectives for a long-term vision of electricity generation

2.2.1. Strategic objectives

In the complex debate on electricity generation, it is useful to establish a hierarchy of criteria to justify a rational view of the subject.

The following generic imperatives are well known and are tier 1 strategic objectives for an energy policy, including nuclear energy:

- the climate imperative: even with major efforts to reduce energy consumption, decarbonisation will lead to a doubling of electricity production/consumption by 2050 for advanced societies. For decarbonisation to be effective, this electricity must itself be profoundly decarbonised and therefore make massive use of renewable and nuclear technologies;

- the security of supply imperative: growing global tensions over access to energy resources will be complicated by geopolitical risks, as the war in Ukraine recently reminded us. The geopolitical fragmentation of the world implies a structural increase in these risks. The issues of energy security and sovereignty are therefore back at the forefront;

- the imperative of secular sustainability: this imperative refers both to environmental issues and to national security of supply. This means minimising the amount of natural resources required, i.e. uranium for nuclear energy and critical materials for renewable energy. In fact, a significant reduction in the amount of natural resources extracted is a prerequisite for the sustainability of our societies. In what follows, we will refer to this as the "**sustainable nuclear cycle**". This expression is more relevant than the historical expression of a closed cycle, because it is in itself what is at stake. An energy technology can be described as sustainable if its consumption of natural resources can guarantee its operation over a few hundred years. Therefore, natural uranium consumption in a nuclear cycle deemed to be sustainable should be reduced by one to two orders of magnitude compared with current practice.

- the economic imperative: this criterion refers, among other things, to the performance of the electricity system as a whole. The ability to ensure a significant or even majority share of decarbonised production using dispatchable technology is crucial in this respect, given the high "system costs" associated with the intermittent nature of photovoltaic and wind energy. In a world moving away from fossil fuels, a growing number of countries may need to acquire or strengthen the nuclear component of their electricity mix.

In addition to these generic imperatives, there are sector-specific imperatives, particularly in the nuclear sector:

- the nuclear safety imperative is a tier 1 priority ensured by the general organisation specifying the responsibilities of each of the stakeholders;

- the imperative of managing final waste is a priority that will be met primarily by the future commissioning of geological repositories;

    - since the 1990s, major research efforts have been devoted in France and internationally to strategies for the transmutation[1] of minor actinides. Over the course of these studies, the gains appeared to be limited given the extreme complexity of such a strategy[2]. Exploring and promoting dedicated technologies for transmuting minor actinides is not a priority. However, the introduction of minor actinides into FNR fuels could be envisaged to reduce the thermal load of repository (in other words, to reduce the quantity of high-intensity waste).

- the operational management imperative[3] benefits from the recycling strategy by enabling:

    - stabilising the need for spent fuel assembly storage;

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1. Transmutation involves fission of long-lived waste using neutron flows, either in a reactor or in dedicated facilities (particle accelerators or laser beams coupled to a reactor).
2. IRSN - Separation and transmutation of long-lived waste - 2019.
3. The imperative of operational management of a nuclear fleet concerns other important criteria, which will not be mentioned here, such as the average capacity factor of power reactors .

- Disposing only final waste by separating and then recycling the energy materials. Thus, recycling plutonium provides both a major energy benefit and a significant reduction in long-term toxicity for geological repository;

- optimising the long-term management of radioactive waste. Recycling enables the spent fuel assembly package to be converted into a glass package, which offers very good performance in terms of long- term behaviour, both in interim storage and final repository.

The above imperatives are mechanically translated into a central strategic objective:

> To develop nuclear power as part of a sustainable cycle that will provide a high level of energy security for centuries to come, while at the same time providing a robust foundation for decarbonisation through its dispatchability.

2.2.2. Quantitative objectives

The electrification of uses, either directly (e.g. for road mobility) or for the production of energy carriers (such as hydrogen, methanol or synthetic fuels) will be the dominant tool for decarbonisation.

Three quarters of Europe's energy consumption[4] is still based on fossil fuels (this ratio is 50% in France thanks to its nuclear power stations), which justifies the strong growth in electricity demand. In its scenario "*Net Zero by 2050, A Roadmap for the Global Energy Sector*" in 2021, the International Energy Agency (IEA) anticipates a doubling of electricity consumption in advanced countries and a tripling in emerging countries. Recent studies[5] by the Ministry of Economic Affairs and Energy (BMWi) predict that electricity consumption in Germany will increase by a factor of 2.5 by 2045.

Putting an exact figure on these massive electrification needs remains a delicate matter, as it depends on the level of sobriety that is socially acceptable, the level of industrialisation that is necessary for the country's economy and sovereignty and, finally, the technological performance of the processes deployed for decarbonisation. The continuous exercises carried out by the French electricity transmission system operator will enable the trajectory for France to be progressively refined. Furthermore, thanks to its decarbonised and largely dispatchable production, France will continue to export its surplus electricity to its neighbours.

With French consumption likely to be around 800 TWh in 2050, it would seem necessary to maintain a nuclear installed capacity of around 60 GWe. Such capacity ensures the stability of electricity networks by producing half of this consumption, i.e. 400 TWh, in a dispatchable manner. France's low-carbon electricity mix is an asset today. With a dispatchable nuclear component of 60 GWe in line with its historical value, France will retain this advantage and its attractiveness as a location for the development of new low-carbon industrial sectors.

The dimensioning parameter for the nuclear trajectory considered below is a stable installed nuclear capacity close to 60 GWe, providing an annual production of 400 TWh.

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[4] BP statistical Review of World Energy, june 2021, 70th edition

[5] Long-term Scenarios, scientific analyses on the decarbonization of Germany

2.3. A constrained medium-term framework (till 2050) for France

Although France benefits from a heritage of low-carbon electricity generation, the country faces the dual challenge of increasing its electricity production and renewing its historic nuclear fleet, which is gradually reaching its end of life.

As will be illustrated in § 3, this logic of renewing a fleet built in the last quarter of the previous century is a key factor in steering investment trajectories in the future mix.

The historical nuclear fleet will be referred to as the first fleet. Its replacement, notably by EPR2s, will be referred to as the second fleet, which will itself be followed by a third fleet, and so on. In the short and medium term, the priority is to extend the life of the historical nuclear fleet and replace it with the second fleet.

Between now and 2035, only growth in wind and photovoltaic capacity and satisfactory availability of installed nuclear capacity will be able to ensure the necessary increase in the production of low-carbon electricity.

Beyond 2035, only the sustained deployment of new nuclear reactors and the continued growth of wind power and photovoltaic power will enable us to produce the desired level of low-carbon electricity. Figure 1 shows that a stable nuclear capacity of around 60 GWe requires an EPR-2 deployment rate of around one pair every two years.

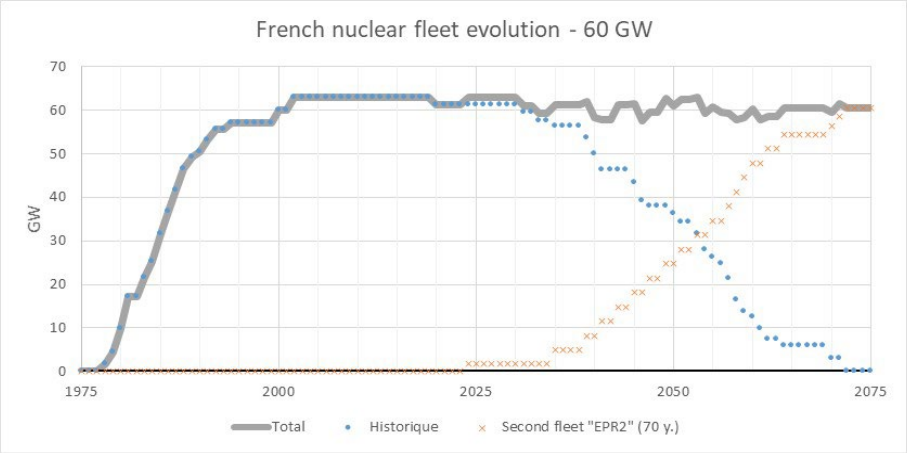

Figure 1. Evolution of the PWR fleet to ensure a stable output of 60 GWe of nuclear power.
This illustration is based on an EPR-2 construction rate of one pair every two years, assuming a plausible lifetime for the historical fleet of 70 years for 60% of reactors, 60 years for 32% of reactors and 50 years for 9% of reactors.

2.4. The long-term framework calls for a sustainable nuclear cycle

2.4.1. Natural uranium resources in the context of an increase in the world's nuclear fleet

The nuclear power plants currently in service for the most part use the thermal spectrum (pressurised or boiling water), and therefore directly use only a tiny proportion of natural uranium, mainly the isotope 235 (content 0.7%), which is the only fissile element in the thermal spectrum. To ensure sufficient reactivity for the operation of power reactors and to maintain neutron balance in these reactors, natural uranium must be enriched to around 5% U-235. For the same electricity production, the direct use of U-238 (99.3% natural uranium) in fast spectrum decreases the need for natural uranium by a factor of at least 100 and therefore drastically alters the extraction of natural uranium reserves and their eventual depletion.

The limit to the availability of natural uranium depends on the growth of the world's nuclear fleet, driven by decarbonisation objectives. The timeframe that needs to be considered here is 2150, in line with the industrial deployment of nuclear power and the long lifetimes of reactors: an EPR-2 commissioned in 2060 should be able to operate until 2140.

According to the *Red Book 2022*[6], a joint publication by the IAEA and the OECD/NEA, identified natural uranium resources range from 6 MtU (at a price of less than $130/kgU) to 8 MtU (at a price of less than $260/kgU). In addition, prognosticated and speculative resources (referred to as "undiscovered") are estimated at around 7 MtU. Access to these resources presupposes a resurge in mining investment.

Consumption of this global resource depends on the installed capacity of nuclear reactors. This growth will be driven by the pace of new construction. Two reasonable assumptions are considered here, with the global rate of new construction limited to either 15 GWe/year or 25 GWe/year. These two assumptions lead to a 3-fold or 5-fold increase in the world's nuclear fleet by 2100.

With unchanged reactor technologies, the needs of the world's reactor fleets are illustrated in the two figures below. They show that the resources identified today will be largely consumed before 2100 in the two growth scenarios for the world's nuclear fleet. All of the identified and undiscovered resources would be consumed between 2100 and 2120, depending on the rate of growth of the fleet.

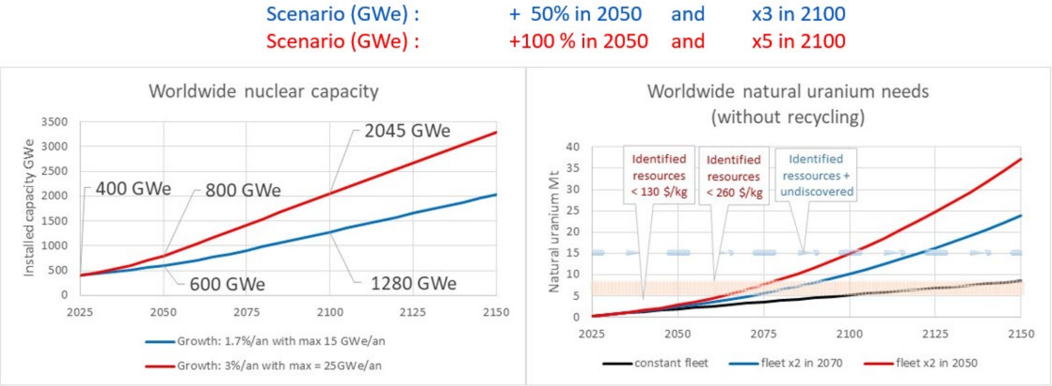

Figure 2: Two growth scenarios for the world's nuclear fleet (left chart) are considered in order to compare (right chart) uranium requirements with identified and undiscovered resources (as defined in the Red Book).

There is considerable uncertainty about the rate of growth of the world's nuclear fleet and about the actual

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[6] https://www.oecd-nea.org/jcms/pl_79960/uranium-2022-resources-production-and-demand

availability of natural uranium resources.

It should be noted that the uranium supply-demand balance (for identical reactor technologies) depends on a number of factors, including in particular the U-235 rejection rate during enrichment, fuel management methods in reactors, etc. The impact of so-called non-conventional resources is difficult to quantify, but may be significant due to the increase in market prices. These resources and reserves particularly include uranium recoverable as a by-product of mining activities with low uranium content (phosphate rock, non-ferrous ores, monazite, black shale, lignite, etc.). The case of phosphates is all the more interesting because the producing countries are different from the traditional uranium exporting countries. Lastly, the extraction of uranium from seawater (with a concentration of 3 parts per billion) continues to be the subject of research and experimentation, particularly in China, a country with few uranium reserves. These factors will have to be reassessed periodically to steer a sustainable nuclear strategy. In this respect, it would be useful to strengthen the assessments of non-conventional resources in future editions of the *Red Book*.

The systemic and strategic issue of natural uranium resources needs to be addressed now.

Uncertainties about uranium resources are similar to uncertainties about alternative technologies more generally. In the insurance logic proposed here, steering the trajectory, and in particular the decisions to launch the various phases of industrial deployment, requires periodic reviews, both of the general context and of the maturity of the alternative solutions.

2.4.2. Recycling nuclear materials is the key to security of supply

There is a risk of severe pressure on natural uranium supplies before the end of the century. The fragmentation of the world implies a structural increase in geopolitical risks. The current situation in Niger and China's takeover of uranium resources in Namibia are examples of this. This geopolitical uncertainty is also weighing on Kazakhstan, Uzbekistan and Mongolia.

The scale of these risks, and their timeframes, mean that they need to be anticipated.

One effective solution is to multiply the utilisation rate of natural uranium by a factor of 100 to 200 compared with today's technologies. This can be achieved by recovering almost all the initial uranium-238 by recycling all the plutonium and uranium, which is what FNR technology is all about. The systemic limit imposed by natural uranium then mechanically increases from a few decades to a few millennia.

In the context of the profound decarbonisation of society and the challenges of sustainability, it is indeed the strategy of recycling nuclear materials as completely as possible that can ensure sufficient availability of natural resources in the very long term and thus justify the paradigm of a "sustainable nuclear cycle". This paradigm enables nuclear power to be a relevant answer, alongside renewable energies[7], to the central issue of a sustainable energy supply for our societies.

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[7] Renewable energies use technologies that consume natural resources, which must also be saved through recycling to ensure their sustainability.

2.4.3. Recycling, a justified and feasible strategic choice for France

The recycling of nuclear materials is an answer to the sustainability of nuclear power, which requires major industrial and financial commitments over many decades. The term "sustainable nuclear industry" is used to refer to all the facilities and activities that implement the concept of a sustainable nuclear cycle at the industrial level.

Few countries are currently in a position to go down this road. Recycling is a potential solution on a global scale, but it is unlikely to be deployed on a significant scale for many decades. The growth of an average global nuclear fleet using natural uranium alone is therefore the global reference scenario to be considered until the end of this century, and even beyond.

In the absence of a global solution, the imperative of national energy security must take priority[8]. Its ability to operationally deploy a sustainable nuclear industry before the end of this century makes France one of the few countries that can ensure its energy security without having the natural resources to do so.

Through the operation of its nuclear fleet, France has built up a valuable long-term energy reserve on its soil, with uranium depleted in uranium-235 from enrichment and materials from reprocessing. The stock of depleted uranium stored in France will reach 400,000 tonnes in 2040, representing a considerable energy source. In principle, with the right technologies, this stockpile will make France virtually self-sufficient in energy, eliminating the need to import natural uranium and without mobilising mining resources, for several thousand years. It is therefore necessary to secure the strategic resource that is the stockpile of depleted uranium.

The size of this stockpile in relation to the consumption flow that could be envisaged by FNRs deployed in France is sometimes the subject of debate due to its magnitude. This stockpile does not pose any long-term management problems[9]. It is therefore appropriate to postpone consideration of its future until Europe's energy context, in terms of needs and available technologies, has been clarified and, above all, stabilised.

Together with reprocessing-recycling and fast neutron reactor technologies, the depleted uranium present in France represents an energy potential that meets France's very long-term energy security requirements.

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[8] The question of energy on a European scale is not addressed here. Nevertheless, it is worth noting that the introduction of sustainable nuclear power automatically strengthens the European electricity mix.

[9] Depleted uranium is very weakly radioactive, less so than natural uranium, and is managed in an inert form.

2.4.4. Specifications for a sustainable nuclear industry

A sustainable cycle is feasible in France thanks to the existing industrial base (mastery of the uranium-plutonium cycle) and the existing stock of depleted uranium[10].

To envisage a path for implementing such a sustainable cycle (see § 3), objectives need to be clarified.

1. A sustainable nuclear cycle is first and foremost designed with the objective of massive and sustainable energy production, with a very high level of long-term security of supply.

2. This implies the deployment of an industrial sector adapted to such a sustainable cycle. This is referred to as a "sustainable nuclear industry".

3. Since the risks associated with natural uranium resources will become significant before the end of this century (uncertainties by 2070 and major risks by the end of the century), this sustainable industry must be able to grow significantly by the same dates.

4. For the impact to be real, energy production from this sustainable source must represent a significant percentage of nuclear production. For an installed nuclear capacity of around 60 GWe, the term sustain- able only makes sense if the installed FNR capacity is between 20 GWe and 60 GWe (i.e. 30% to 100% of the productive capacity). A sustainable nuclear industry is first and foremost an industrial sector with its own chain of companies. A volume of 20 GWe will ensure the performance of an industrial sector. In turn, the availability of a high-performance industrial sector means that the construction ramp-up can be effectively managed to meet any future needs.

5. Points 3 and 4 show that the aim is not to develop a research infrastructure, but to invest in the stages leading to a productive and growing industrial sector by the end of the century.

6. For the term of sustainable industry to be justified, the consumption of natural uranium must be significantly reduced. Current MOX and URE mono-recycling technology can reduce natural uranium consumption by around 20%. This technology is of interest as a transitional strategy, but does not meet the need for sustainable nuclear power.

7. By satisfying the above points, a sustainable nuclear industry meets the imperatives of climate, energy security and secular sustainability.

8. Fast neutron power reactors have been deployed in France in the past and are now in operation or under construction elsewhere in the world (see Appendix). Despite this, the implementation of a sustainable industrial sector, as defined above, requires investment in technological development to guarantee the right levels of safety and economic performance.

9. The need for and impact of a sustainable industry in terms of anticipated changes in stockpiles of nuclear materials (uranium and plutonium) must be assessed and explained. The notion of a sustainable nuclear industry implies, by definition, forward-looking management over many decades of these stockpiles of materials, which directly structure the industry's electricity production.

10. In line with the previous points, the evaluation criteria for a trajectory aimed at developing a sustainable nuclear industry are:

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[10] The thorium cycle is an alternative to the uranium cycle that has never been deployed industrially. These two cycles require similar technologies, i.e. recycling and FNR. India, which has significant thorium resources but no uranium, is talking about switching to a thorium cycle. France has an industrial base and a strategic stockpile enabling it, with reasonable investment and time, to implement a sustainable uranium cycle; France therefore has no incentive to consider a thorium cycle.

- meeting safety requirements; these requirements have changed significantly for reactors since the shut- down of the FNRs deployed in France;

- reducing consumption of natural uranium, with an initial reduction target of an order of magnitude (factor 10) within the next century and with a long-term capacity for autonomy (reduction by a factor of 100 to 200 through the use of stored depleted uranium);

- the evolution of the plutonium stockpile in terms of its capacity to support the growth kinetics of the sustainable FNR sector; this point is dealt with in § 3.2.2 ;

- the economic performance. A sustainable cycle and the current cycle share the same functions and should have an operating cost in the same orders of magnitude. The economic stakes are therefore essentially focused on the construction costs of FNRs and the associated cycle plants. Upstream studies should focus in particular on the major design and construction simplifications that have already been identified;

- operational issues such as storage requirements for spent fuel assemblies.

11. A final essential specification is based on the fact that a sustainable nuclear industry is a component of an integrated electricity production system. This sustainable component will replace some or all of the current PWRs (mainly EPR-2 for the second fleet). However, this balance must comply with the overall constraint introduced in § 2.2.2: the sum of the installed nuclear capacity must remain at around 60 GWe. This objective has a dimensional impact and mechanically sets the deployment windows for a sustainable industry.

3. Roadmap for the development of a sustainable nuclear industry

This paragraph proposes a roadmap for the implementation of a sustainable nuclear industry, as explained in § 2.4.4.

A sustainable nuclear industry is part of the circular economy and coherently integrates a reactor component (§ 3.1) and a cycle component (§ 3.2), all of which are linked by the strong constraint of balanced input and output material flows.

The deployment of a sustainable nuclear industry therefore requires consistency between the construction kinetics of facilities (reactors and cycle plants) and the trajectory of availability of materials from recycling. Market forces alone cannot steer the implementation of a sustainable nuclear industry over several decades. The State must promote a trajectory whose objectives, planned with sufficient foresight, enable public and industrial entities to mobilise the skills and investment needed to build and manage the industrial building blocks of a sustainable nuclear cycle.

This roadmap takes into account the priority that must be given, in the short term, to the successful launch of the construction of the first EPR-2 reactors by the French nuclear industry.

3.1. Fast neutron reactors

3.1.1. Desirable deployment schedule

The trajectory for the deployment of a sustainable nuclear industry is structured around the commissioning of a fleet of fast neutron reactors to complement the PWRs. The timetable for the deployment of FNR proposed here meets the challenges set out in § 2, but it remains indicative and requires more detailed appraisal by the stakeholders concerned.

2025-2030	Strengthening of upstream studies on an FNR technology, focusing on safety, in particular on aspects specific to FNR, and on reducing construction costs. The aim is to justify the choice of FNR technology and the power of a demonstrator that can be extrapolated to a 1 GWe reactor. The objective given to these studies is clearly the deployment of the industrial sector, the timetable of which is shown below.
2030	Launch of the FNR-Dem demonstrator project, which can be scaled up to 1,000 MWe. The capacity of the FNR-Dem (a few hundred MWe) will be determined by studies carried out in 2025-2030.
2040	Commissioning of the FNR-Dem demonstrator, the aim of which is to acquire national technological control of a future industrial sector that meets the imperatives of modern safety standards and economic performance compatible with large-scale deployment.
2050-2060	Launch of studies for the FNR-Ind industrial prototype (e.g. 1 GWe, the actual capacity resulting from technical and economic studies). In-depth review of the need and alternatives to support the decision to launch an FNR industrial sector; this includes in particular i) updating the need resulting from the assessment of the energy context and outlook and ii) assessing potential technological alternatives such as, for example, nuclear fusion, natural hydrogen, long-term energy storage technologies and non-conventional uranium resources.
2060	If the decision is positive at the end of the review, launch of a FNR industrial sector with the start of construction of a prototype in the form of a first pair of FNR-Ind.
2070	Commissioning of the first unit in the FNR-Ind prototype series.
2070-2100	Commissioning of 10 GWe of FNR-Ind.
2100 and beyond	Steering of the installed FNR capacity according to needs and advances in alternative technologies.

In the above timetable, the first phase up to 2060 is based on an insurance logic and should be undertaken. The next phases concern industrial deployment based on decisions requiring regular review of the general context and, above all, technological alternatives.

3.1.2. Justification of the proposed timeline

The dates proposed in §3.1.1 need to be justified.

- § 2 highlighted a growing risk to security of supply from 2070 and a significant risk by 2100. This fully justifies the efforts to develop sustainable cycle technologies to insure against these risks. However, this insurance-based rationale alone cannot determine a precise timeline for industrial deployment. Indeed, a more or less cautious anticipation of uranium supply risks mechanically translates into industrial deployment targets that are a few decades off in one direction or another.

- The imperative of security of supply therefore determines a timeframe of 2100 for the deployment of a sustainable cycle, but without justifying a precise decade.

- The nuclear power generation requirement has been quantified at 60 GWe, which needs to be maintained over the long term. However, because of the lifespan of the reactors, the nuclear fleet retains, over time, the memory of its genesis, with a major ramp-up in the 1980s. As a result, maintaining the target capacity of 60 GWe implies clearly defined periods for the construction of new reactors. The renewal cycles of the nuclear fleet create windows of opportunity for the insertion of a significant FNR fleet.

- A sustainable nuclear industry with around ten GWe of FNR by 2100 will provide the experience and capacity needed to effectively manage the constraints and opportunities that will be assessed from 2100 onwards. Its construction between 2070 and 2100 is the right period, as it will enable the growth of a sustainable industry as the third fleet ramps up.

- With 2100 as the pivotal date for a target of 10 GWe of FNR, the timetable proposed in § 3.1.1 is simply a countdown logic.

- In the period 2025-2030, studies need to be carried out to ensure that the technology selection process is based on robust justification. The criteria governing this technological selection process have been set out in § 2.4.4. To meet these criteria, the FNR-Dem demonstrator must be designed to be scalable to 1,000 MWe by 2070.

- The 2025-2030 study phase is very important. It should enable the scientific and technical skills to be strengthened to the necessary level. The aim of this phase is to make significant progress on two key issues: safety and the economics of the future industry. There is a legacy of knowledge about FNR technology in France. This legacy showed greater complexity and a significant cost premium compared with PWR. It is therefore necessary to carry out an in-depth review of the design, including safety studies specific to FNR, using current standards and incorporating the technological advances and simplifications available to reduce construction costs. It will also be necessary to analyse the constraints that governed technological choices in the past in order to assess their relevance today. As an illustration, the design of Superphénix was heavily constrained by the contingent scarcity of plutonium; the context is now different on this point, allowing better optimisation of the reactor's design. The studies will have to determine the breeding ratio to be taken into account in the design.

- Over and above the technical and economic challenges, the 2025-2030 study phase is also important for putting France back on a positive and visible dynamic, with a vision of the future based on sustainable nuclear energy. This kind of dynamic will help to inspire the younger generation, attract foreign talent and motivate international collaborations (e.g. with Japan) at the right level.

The proposed timetable takes into account the priority that needs to be given to the construction of the second fleet of EPR-2 plants. Figure 1 shows that the EPR-2 construction sequence is a priority, with an average rate of one pair of EPR-2s every two years, combined with the majority of the historical fleet being extended to 70 years. The post-2070 construction of the very first industrial FNRs will replace the last reactors of the historical fleet in operation and therefore replace the last EPR-2 reactors of the second fleet. In this way, the development of FNR technology does not interfere with the priority given to the construction of the EPR-2s that will make up the second fleet.

The timetable imposed by the objectives of decarbonisation and energy security makes it necessary to choose a reference technology for industrial deployment as proposed in § 3.1.1. This is not in contradiction with parallel research efforts on more forward-looking alternative paths to maintain the long-term trajectory on the basis of the best state-of-the-art.

3.1.3. Illustration of two paths towards a sustainable nuclear industry

The figures below illustrate the dimensional constraint imposed on the deployment kinetics with a stable nuclear fleet of 60 GWe (with an average lifespan of 70 years for new reactors). The 2100 goal of 10 GWe in FNR offers room for manoeuvre in deciding on the nature of the third fleet (FNR/PWR ratio) depending on the energy context and the assessment of potential alternatives.

Depending on the context and the need, the nuclear fleet of the next century could be provided by a balance between PWRs and fast neutron reactors. The two figures below illustrate a post-2100 nuclear fleet with 30% and 100% fast neutron reactors respectively.

With a first industrial stage of 10 GWe of FNR in 2100, society will be able to choose the right technological mix for the third nuclear fleet, depending on the constraints and technological alternatives available at the time. The aim of this position paper is not to predict the post-2100 mix, but to propose a trajectory between now and 2100 that will make these future choices possible.

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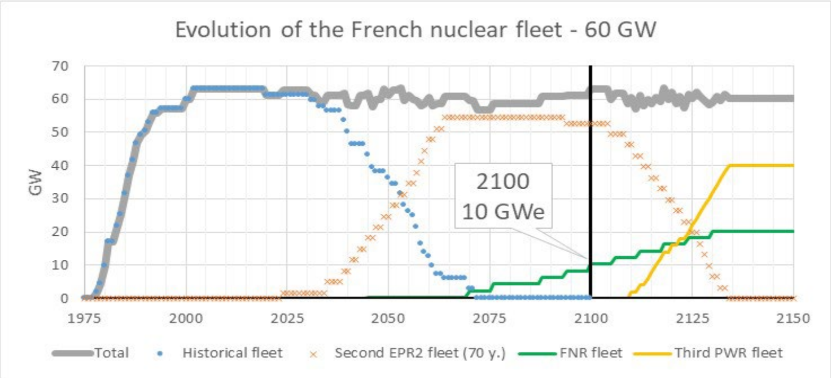
<td>
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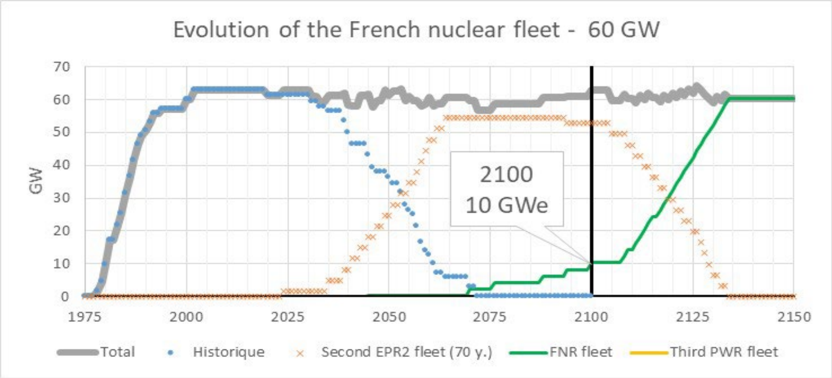
<td>
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Figure 3. Illustration of the construction programmes for the second and third nuclear fleets, with the objective of stable installed capacity of 60 GWe. The deployment window for FNRs is necessarily associated with the scaling up of the third fleet.

The impact on the material cycle associated with the two scenarios illustrated in Figure 3 is analysed in the following paragraph.

3.2. Towards a sustainable cycle

The quantities mentioned in this paragraph are order-of-magnitude estimates that will need to be assessed in detail. Precise calculations are needed to validate the scenarios, taking into account the detailed isotopes of plutonium and non-fissile isotopes, which are crucial to the neutron operation of the reactors. These detailed calculations are essential to determine, when the time comes, the precise transition to a sustainable nuclear cycle and the associated performance in terms of saving natural resources. The roadmap sketched out here can only be refined by updating the material flow calculations on the basis of the objectives considered, i.e. a 60 GWe fleet, the priority of which is to significantly reduce dependence on natural uranium.

Given their age, over the next two decades, the fuel cycle plants will have to undergo a renewal phase to ensure their continued operation. As with the reactors, this phase should be used to update the specifications of these facilities and prepare them for the future needs of the nuclear cycle.

3.2.1. The existing cycle

Quantifying the material flows associated with a nuclear fleet depends on the energy produced. Here we consider a cycle standardised to a 60 GWe fleet producing 400 TWh annually.

The open cycle is the benchmark for natural uranium consumption. The production of 400 TWh consumes 1,200 t/year of enriched natural uranium (ENU) in the open cycle, or 9,000 t/year of natural uranium.

In the current cycle, known as "mono-recycling", most of the fuel is enriched natural uranium (ENU, 1,000 t/ year), with a supplement based on a mixture of depleted uranium and plutonium (MOX, 120 t/year) on the one hand and enriched reprocessed uranium (ERU, 80 t/year) on the other. The production of 400 TWh is based on the reprocessing of 1,000 t/year of ENU. Figure 4 illustrates the characteristic flows of the mono- recycling cycle.

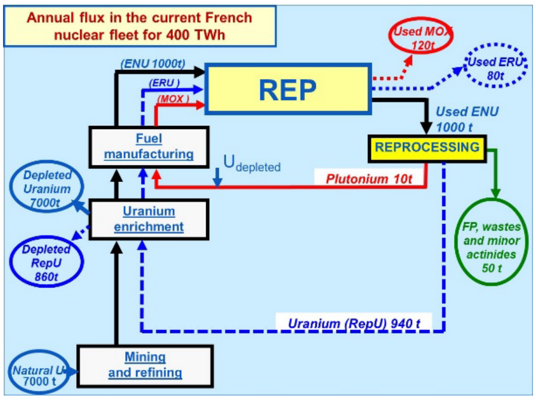


Figure 4. Annual material flow in a reference "monorecycling" cycle associated with the production of 400 TWh.

The saving in natural resources made possible by the "monorecycling" cycle (1,000 t/year of ENU and 7,000 t/year of natural uranium) compared with the open cycle (1,200 t/year of ENU and 9,000 t/year of natural uranium) is therefore 20%.

This saving in natural resources is significant, but it does not meet the imperative of sustainability or ensure long-term energy security. On the other hand, the "monorecycling" cycle offers France the benefit of a proven industrial system, making the move towards a sustainable cycle credible, and of the initial availability of the plutonium needed to launch the FNR industry.

Today, the stockpile of separated plutonium from reprocessing is around 100 tonnes, to which should be added around 300 tonnes of non-separated plutonium present in spent fuel (UOX, MOX or ERU) in storage[11]. This stockpile is continually increasing, with an annual flow of 7 t of additional plutonium stored in spent MOX that is not currently reprocessed.

3.2.2. The FNR cycle

The trajectory towards a FNR cycle requires a long transition period to allow the deployment of FNRs and the required plutonium inventory to scale up in parallel.

In an equilibrium cycle, a one GWe FNR will mobilise 15 to 20 tonnes of plutonium, half of which will be loaded into the reactor and the other half into the cycle plants. The trajectories for plutonium availability and the commissioning of the FNRs must therefore be carefully planned.

France has an initial stockpile of plutonium that will enable it to start on this trajectory. When the installed capacity of the FNR increases, the growth in the stockpile of plutonium required will accelerate by the FNR's ability to transform the depleted uranium existing on national soil into plutonium. The growth trajectory of the plutonium inventory required for a sustainable cycle must be anticipated, as it will determine the technical specifications of the fast FNRs to be developed.

In line with Figure 3, we consider a third fleet made up of either 20 GWe of FNR (one-third of the installed nuclear capacity of 60 GWe) or 60 GWe (100% of the nuclear fleet).

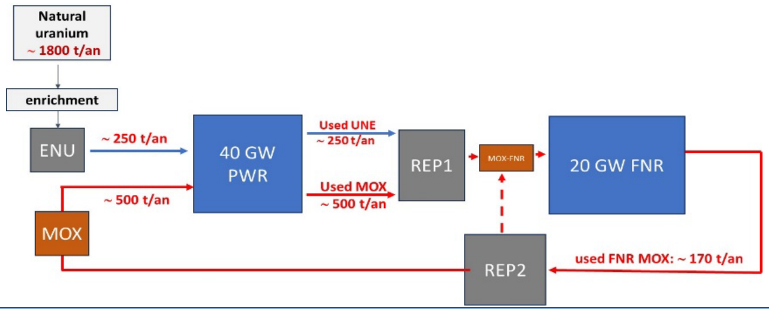
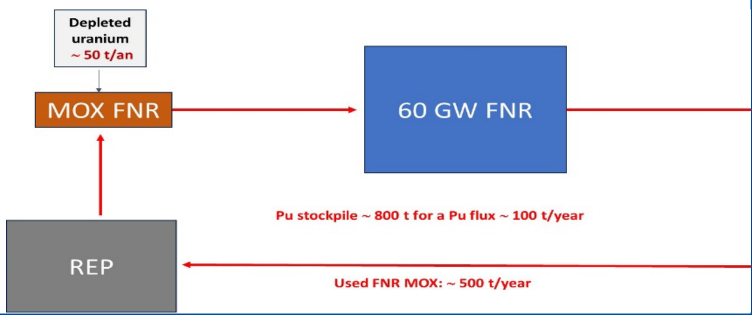
Illustration of annual flows for a cycle producing 400 TWh/year with 20 GWe of FNR and 40 GWe of PWR. At equilibrium, natural uranium consumption is reduced by a factor of 4 compared with the current reference cycle.	
Illustration of annual flows for a cycle, at equilibrium and iso-generator, producing 400 TWh/year and with 60 GWe of FNR. At equilibrium, natural uranium consumption is reduced to zero thanks to the large stock of depleted uranium available on national soil.	

Figure 5. Order of magnitude of annual equilibrium flows in a fleet containing 30% and 100% FNR respectively. The precise values will depend on a number of operational parameters. The impact on natural uranium consumption makes It possible to refer to a sustainable nuclear cycle.

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[11] French communication to IAEA 2023; https://www.iaea.org/sites/default/files/publications/documents/infcircs/1998/infcirc549a5-27.pdf

Compared with the open cycle, which consumes 9,000 tonnes of natural uranium per year to produce 400 TWh/year, a 100% FNR fleet will only consume around fifty tonnes per year of material taken from the stockpile of depleted uranium available in France (400,000 tonnes in 2040).

The figures above illustrate the orders of magnitude of the quantities that need to be mobilised to make the transition from the current cycle to a sustainable FNR-based cycle. They require in-depth technical work to ensure that the quantity and quality of the material flows required to feed the reactors and size the cycle plants are consistent throughout the trajectory. This technical complexity is inherent in the concept of the circular economy in which a sustainable nuclear cycle is embedded.

3.2.3. The development of cycle plants

Cycle plants need to evolve with an overall long-term vision of the need for successive developments to enable a transition to a sustainable nuclear cycle.

This implies in particular i) adapting to high plutonium contents of around 20%, ii) increasing the capacity of the Pu purification and conversion workshops, iii) adapting the plant head to accommodate FNR fuels. In addition to these key issues, there are a number of other areas of concern, such as waste permits and radioelements affecting the manufacture of MOX fuel (Pu238, Pu240, Am241).

On a large scale, the sequence of developments in the cycle plants can be structured around a few key dates:

- development between now and 2040-2050 for the reprocessing and manufacture of MOX fuel incorporating FNR characteristics, such as a high Pu content (20%);

- developments up to 2080 for the reprocessing of FNR fuels, which will require additional workshops (dismantling of fuel assemblies, dissolution, etc.). In this respect, France has unique experience in the world with the reprocessing of Phénix FNR fuel.

With the current production of MOX, France is one of the very few countries that can implement a sustainable nuclear cycle in just a few decades. The detailed specifications for the developments that will make it possible to scale up towards a sustainable cycle have yet to be drawn up, and constitute a sensitive stage. The transformation of cycle plants will have to meet a number of needs:

- the updating of facilities to ensure the continued production of MOX fuel, with the possible development of a second plutonium recycling process in dilution with the plutonium extracted from the stockpile of stored UOX fuel;

- preparing for a future sustainable nuclear cycle, with industrial capacities adapted to the recycling of FNR fuels.

4. Conclusions and recommendations

The purpose of this position paper is to propose a path towards sustainable nuclear power for France.

The secular timescales that need to be considered make it impossible to be certain about the advent or otherwise of alternative technologies such as fusion, natural hydrogen, long-term energy storage technologies or non-conventional uranium resources. It is therefore prudent and responsible to adopt an insurance approach based on three pillars.

- The first pillar is **to invest in an open portfolio of technologies** that will ensure staying at the forefront of alternative solutions. This pillar comes under Research, which determines how it is managed, with collaboration and funding strategies tailored to each prospective technology and its level of maturity.
- The second pillar is investment in **a technology that can be industrialised within the timeframe of the problem posed by the decarbonisation of society.** § 2 has shown that nuclear technology meets this challenge, while however presenting a supply risk that could limit its relevance from the end of the century onwards. The insurance rationale justifies basing this second pillar on a sustainable nuclear industry that will ensure the sustainability and safety of electricity production.
- The third key pillar is **steering**. This involves periodically reviewing both the general context and the ability of alternative technologies to be deployed on a scale that modifies the situation. Given the timescales required for a technology to mature industrially, it makes sense to carry out such reviews every twenty or thirty years, and in any case before any major industrial deployment decision is taken. It will therefore be up to the State to adjust the trajectory over time, in terms of acceleration or delay, depending on its assessment of the geopolitical and technical context.

With this in mind, deploying an active programme on the sustainable cycle is a no regret decision[12]. It includes i) the objective of having a demonstrator by 2040 that can be scaled up to industrial scale and ii) the inclusion of the objective of compatibility with a FNR cycle in the renewal of cycle plants.

In line with this insurance-based approach, the dates mentioned below after 2050 will be subject to steering depending on the context at the time.

The objective of a stable nuclear fleet of 60 GWe will maintain a robust and dispatchable component in the electricity mix. This objective means that there will be preferred periods for renewing the fleet, periods during which it will be possible to develop a first industrial stage for FNR technology. The period 2070-2100 is therefore a window of opportunity for commissioning an initial 10 GWe of FNR.

By establishing a 10 GWe FNR industry by 2100, France will have an industrial energy system whose future growth can be steered in line with changing strategic requirements.

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[12] No regrets means that whatever happens in the future, the decision will be useful and profitable.

By limiting this technology to 30% of the fleet, dependence on uranium is already reduced by 4 times compared with the current cycle. If circumstances require, the growth of the FNR sector could make France independent in terms of uranium resources over the next millennium.

This positive outlook leads to a number of conclusions and recommendations.

- It is necessary to stabilise a strategy over several decades to ensure the coherence and rationality of industrial choices. Such a strategy could have the following systemic vision:
    - nuclear electricity (for countries that have the capacity to manage its deployment under the necessary economic, safety and security conditions) has a central role to play in meeting the challenges of effectively decarbonising energy use;
    - to enable future generations to benefit from low-carbon electrification on a massive scale, the natural resources consumed need to be managed in a sustainable manner to maximise their long-term availability. This concerns both critical materials for photovoltaic and wind energy and natural uranium for nuclear energy;
    - energy issues, both present and future, are the strategic objective that should be at the core of debates on nuclear power. The important issues of safety, security, economics and waste management are the key constraints that must be overcome when implementing nuclear solutions;
    - the principle of sustainable management of natural uranium and the challenges of energy security mean that recycling uranium and plutonium are strategic issues. This means that France must maintain its technological investment in the reprocessing industry and prepare for the fast neutron reactor technologies that will enable uranium to be used almost completely. This investment will also enable the long- term recovery of stockpiles of nuclear materials already available in France, in particular depleted uranium;
    - the increase in global nuclear capacity in response to climate change will significantly increase the risks associated with uranium availability by 2100. We therefore need to move rapidly towards a sustainable nuclear cycle that can guarantee low-carbon energy production over the long term.

- Such a reference framework will make it possible to clearly and effectively convey France's position on the subject within the European Union (where the regulatory stakes are of critical importance) and bilaterally at the international level (where the strategic stakes lie in building political and industrial alliances on the nuclear issue). This European and international dimension is an important element of robustness in the path towards a sustainable cycle. The appendix illustrates the international state of play on this subject.

- In line with this reference framework, the roadmap presented in § 3 should be prepared over the next few years:

  - to stabilise the strategic nature of the nuclear materials present in France over the long term (uranium and plutonium in non-reprocessed spent fuel, stockpiles of reprocessed uranium and depleted uranium);

  - to ensure the long-term future of the French reprocessing-recycling industry and to actively conduct studies on the renewal of the La Hague facilities, with an overall long-term vision of the need for successive developments towards a sustainable cycle;

  - in the short term, to step up upstream studies on the FNR concept, focusing on safety aspects and reducing construction costs, with the aim of justifying the choice of FNR technology and the power of a demonstrator that can be extrapolated to a reactor with a power of around 1 GWe deployable by 2070.

Conceptual studies on the FNR concept must be stepped up as a matter of urgency, so that the technology for the 2040 demonstrator and the main associated specifications can be chosen by 2030. The most important criterion in the analysis of these choices is the ability to deploy this technology on an industrial scale of around ten GWe by the end of the century.

Appendix

International state of play

Fast neutron reactor (FNR) technology has a long history. The first power generating nuclear reactor commissioned (1951) was a FNR and around ten reactors were under construction in the early 1960s (United States, Russia, Germany, United Kingdom, Japan, etc.). In France, the Rapsodie (40 MWe) and Phénix (250 MWe) reactors diverged in 1967 and 1968 respectively, and were shut down in 1983 and 2009; the Superphénix reactor (1,200 MWe), the largest FNR ever built, diverged in 1987 and was shut down around ten years later. The advent of water reactors, the increase in identified uranium resources and a growing public concern about a technology that could sustain nuclear power over very long periods marked the end of this pioneering age.

Three countries have fast neutron reactors in operation and a proactive policy on this topic.

- Russia is the only country to have maintained a proactive FNR trajectory since those pioneering days. Russia currently has a BN-600 reactor (560 MWe, commissioned in 1980) and a BN-800 reactor (800 MWe, commissioned in 2016), both at the Beloïarsk power station, and is planning to build a BN1200 reactor (1,220 MWe). The BN-600 reactor has been operating for around twenty years with a high level of performance (availability rate of around 80%). The FNR strategy is clearly in place, with BN-600 currently being refurbished to ensure operation until 2040, with BN-800 switching to MOX fuel in 2021 (70% availability rate) and with construction of BN-1200 scheduled to start in 2030. BN reactors use sodium coolant. At the same time, Russia is building the lead-cooled BREST reactor (300 MWe), which will require a special fuel cycle (plutonium nitride).

- China has a Russian-designed CEFR demonstrator reactor (65 MWth), commissioned in 2012. On this basis, China has developed the CFR-600 (600 MWe), which started up in 2023 (construction began in 2017). A second reactor of the same type is currently under construction and is due to start up in 2026. A commercial unit with a capacity of between 1,000 and 1,200 MWe is currently being considered for commissioning in 2035. These reactors are sodium-cooled. In 2023, China and Russia signed a comprehensive long-term cooperation programme in the field of fast neutron reactors and the nuclear fuel cycle.

- India has completed construction of the PFBR reactor (500 MWe) with sodium coolant, and the fuel was loaded in March 2024. India's FNR programme is the historical and lasting response to the country's declared desire for self-sufficiency and independence.

Fear of proliferation led the United States to abandon fuel reprocessing at the end of the 1970s, under the Carter administration. In recent years, there have been increasing signs of openness towards this subject, both within the government and in industry, with the development of concrete projects (e.g. TerraPower/ Natrium). However, it is not possible to anticipate the date of a paradigm shift in this area.

Following the final shutdown of its Monju reactor (250 MWe) in 2016, Japan recently decided to relaunch studies into FNRs with a budget of $700 million for the period from 2023 to 2026, with a view to building an operational demonstrator in 2050. This demonstrator will be a 650 MWe sodium-cooled reactor. The design period will run until 2030. Japan is explicitly seeking collaboration with France. The FNR trajectory proposed in this position paper presents synergies with the Japanese objectives and will make it possible to envisage collaboration on design studies.

Members of the working group

Académie des technologies (National Academy of Technologies of France)
Daniel IRACANE
Patrick LEDERMANN
Philippe PRADEL
Dominique VIGNON

Expert
Bernard BOULLIS, expert on the fuel cycle

Main acronyms used

IAEA	International Atomic Energy Agency
EPR-2	Model of the pressurised water reactor to be used to equip France's future nuclear fleet
MOX	Nuclear fuel based on a mixture of uranium oxide and plutonium
MOX-MR	MOX fuel using plutonium from MOX reprocessing and depleted UOX stockpiles
MWe, GWe	Megawatt electric and Gigawatt electric, units of power produced in the form of electricity
MWth	Megawatt thermal, unit of power produced in the form of heat
OECD/NEA	Nuclear Energy Agency of the Organisation for Economic Co-operation and Development
PWR	Pressurised-water nuclear reactor
FNR	Fast neutrons nuclear reactor
TWh	Terawatt-hour, unit of energy produced in the form of electricity
ENU	Enriched natural uranium (around 5%).
ERU	Enriched reprocessed uranium
RepU	Uranium from reprocessing
UOX	Uranium oxide-based nuclear fuel