Degree Project in Sustainable Energies Engineering

Double Degree Program Masters Thesis, 30 credits

From pressurized water reactors to sodium fast reactors

A multicriteria roadmap for closing France's nuclear fuel cycle

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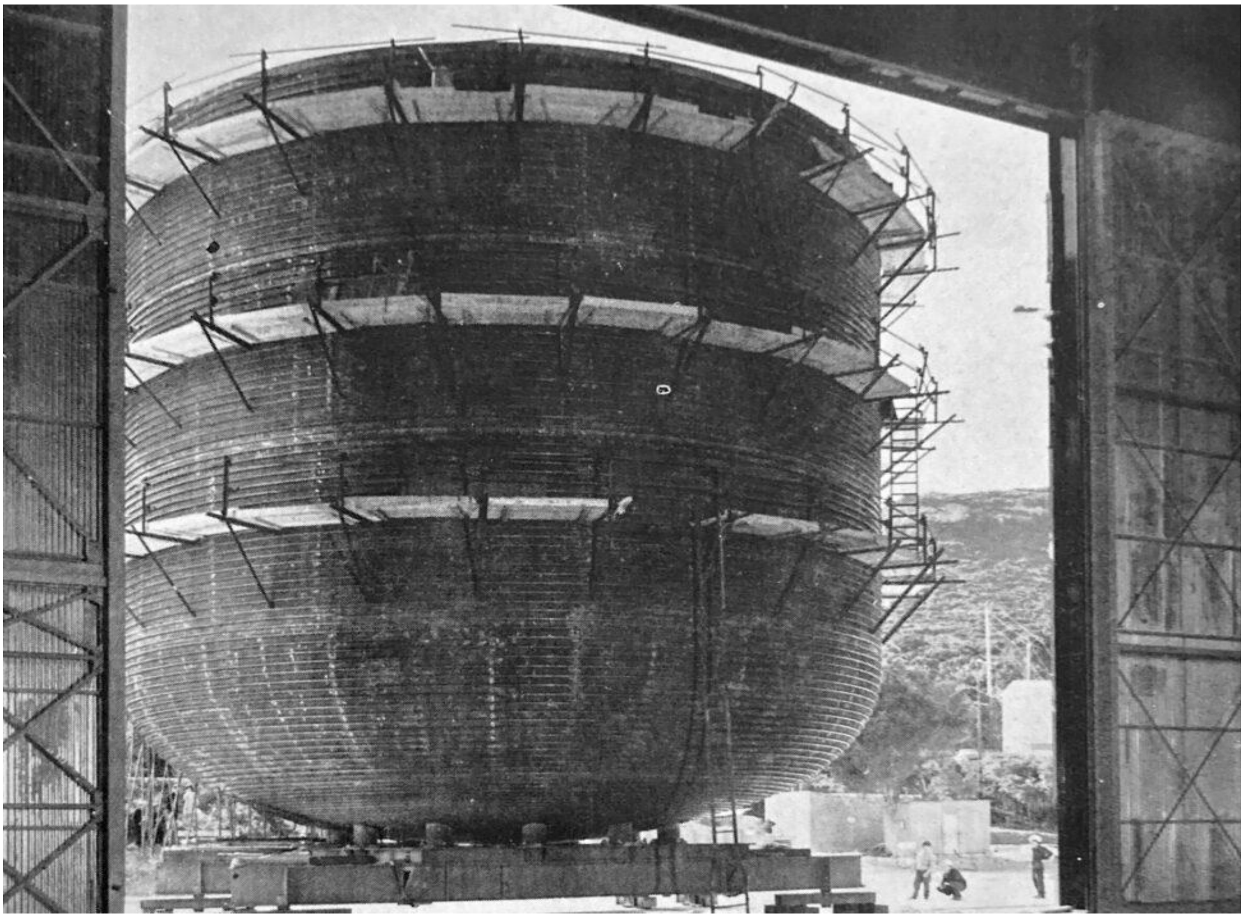

Arrival of Phénix's core reactor, CEA, France

Master of Science Thesis

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From pressurized water reactors to sodium fast reactors

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Master's Thesis

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MSc in Sustainable Energy Engineering
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Summary

This thesis explores the feasibility and implications of transitioning France's nuclear system from pressurized water reactors (PWRs) toward generation IV sodium-cooled fast reactors (SFRs) to achieve a closed nuclear fuel cycle : the absence of need for natural uranium to fuel the nuclear reactors. Four chosen scenarios, from an open fuel cycle to a fully closed SFR fleet, are modeled with a multi-criteria framework to evaluate strategic, economic, industrial and sociopolitical challenges. The framework constructed suggests that while SFRs are still economically uncompetitive under current economic conditions, their strategic value in reducing dependency on natural uranium and industrial deployment span justifies their current consideration. The study concludes that transitioning from current PWRs to SFRs should be analyzed not solely as a short-term economic optimization, but as a long-term national strategy requiring political stability and industrial readiness.

Sammanfattning

Denna avhandling undersöker genomförbarheten och konsekvenserna av att övergå från Frankrikes nuvarande kärnkraftsystem med tryckvattenreaktorer (PWR) till fjärde generationens natriumkylda snabba reaktorer (SFR), i syfte att uppnå en sluten kärnbränslecykel – det vill säga ett system utan behov av naturligt uran som bränsle. Fyra scenarier, från en öppen bränslecykel till en helt sluten SFR-flotta, modelleras med ett multicriteriellt ramverk för att utvärdera strategiska, ekonomiska, industriella och sociopolitiska utmaningar. Det framtagna ramverket visar att även om SFR-teknologin fortfarande är ekonomiskt mindre konkurrenskraftig under rådande förhållanden, motiveras dess övervägande av det strategiska värdet i att minska beroendet av naturligt uran samt möjligheterna till industriell utbyggnad. Studien drar slutsatsen att en övergång från dagens PWR-system till SFR bör betraktas inte enbart som en kortsiktig ekonomisk optimering, utan som en långsiktig nationell strategi som kräver politisk stabilitet och industriell beredskap.

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Chapter 1

Introduction

1.1 Background and Context

1.1.1 France's Current Fuel Cycle and Nuclear Fleet

France operates the world's second largest nuclear power electrical system, consisting of 57 operable pressurized water reactors (PWRs) enabling an installed capacity of 63 GW_e, which historically supplies a major share of national electricity generation (67% in 2024). [1]

Sustaining this fleet requires a large and continuous supply of nuclear fuel. The natural uranium needs of this fleet are approximately 7000 tU (tons of natural uranium), representing around 12% of the global demand worldwide for uranium ore. [2]

In parallel, France has developed industrial-scale fuel reprocessing and recycling facilities that are unique in Europe and allow a strategy that can be qualified of a "partially" closed fuel cycle: Spent fuel from the PWRs is reprocessed at Orano's La Hague plant. Approximately 96–97% of the mass of used fuel is recoverable, primarily as uranium and plutonium, which are separated using the PUREX process and subsequently recycled. The recovered plutonium is then recycled through MOX ("Mix of oxides" fuel, combining plutonium oxide PuO2 and depleted uranium oxide UO2) fabrication at the Melox plant and deployed in 23 reactors. The entire flow of spent fuel is reprocessed which amounts to approximately 1200 tHM (tons of Heavy Metal per year, meaning uranium and plutonium) per year[3]. The remaining fission products and minor actinides are vitrified in borosilicate glass to ensure long-term containment of their radio-toxicity. This strategy of recycling the spent nuclear fuel to sustain a part of the nuclear fleet has been in operation since 1987 in France. [4]

A partially closed fuel cycle entails additional industrial complexity, including multiple transport steps, secondary waste streams, and stringent safety and safeguards requirements associated with plutonium separation. These challenges are addressed in France through tight regulatory oversight and the systematic recycling of separated plutonium, avoiding long-term storage of free fissile material.

1.1.2 Historical Development of Fast Reactors in France

The breeding capability of fast reactors (meaning their ability to produce excess plutonium) positioned this technology as a mean to extend nuclear energy over very long time horizons, far beyond the limits imposed by the relative scarcity of uranium-235, which represents only 0.7% of natural uranium, compared to uranium-238. This vision led many nuclear countries, including France, to deploy experimental sodium-cooled fast reactors (SFRs) in the 1960s such as *Rapsodie*, followed by prototype reactors in the 1970s (such as *Phénix*) and early pre-industrial demonstrations of fuel reprocessing and recycling.

However, the same characteristics that make fast reactors attractive from a resource perspective also rendered them politically sensitive. In the United States, industrial development was abandoned in the early 1980s due to concerns over nuclear proliferation associated with multiple fuel recycling, while in Europe the shutdown of Superphénix in 1997 occurred in the context of declining political support for nuclear power following the Chernobyl accident. Its shutdown highlights broader issues regarding fast reactors concerning public acceptance and market conditions, which remain relevant for contemporary nuclear projects. However, fast reactor development has continued in France and in other leading countries, with national programs in Russia, China and Japan notably. In 2010, the *ASTRID* project was launched in France to develop a Generation IV SFR. Although *ASTRID* was aborted in 2019, it highlights the persistent French strategic interest for fast reactors as a key to long-term nuclear sustainability. [5]

Sodium-cooled reactors emerged as the reference coolant for experimental and prototype fast reactors in the 1960s, proving great heat transfer properties, low corrosiveness to structural materials, weak neutron activation, abundance and low cost. Despite its high melting point and strong chemical reactivity with water, advances in sodium technology enabled its safe implementation.

The focus on SFRs in this study is therefore motivated by their high level of technological maturity compared to other types of fast reactors, the availability of extensive experimental and operational data and their demonstrated compatibility with plutonium multi-recycling strategies.

Hence, achieving an advanced fuel cycle depend not only on reactor deployment, but also on all of the fuel cycle constraints : the reprocessing capacity, fuel fabrication capacity, temporary storage constraints and plutonium stock management.

1.2 Motivation: Closing the Fuel Cycle as the “Last Chapter” of Nuclear Energy

The reprocessing and recycling of plutonium in the partially closed fuel cycle allows to recover the energetic value of spent nuclear fuel, but the long-term sustainability remains incomplete in the absence of fast reactors. Indeed, without fast-spectrum reactors capable of multi-recycling plutonium, spent MOX fuel must ultimately be conditioned and stored. Therefore reprocessing in light water reactors only postpones, rather than resolves, the back-end challenge. By enabling the repeated recycling of plutonium and the transmutation of minor actinides, the deployment of a fast reactor fleet only requires a small input of depleted uranium, which France has a consequential inventory due to enrichment activities. Clsoing te fuel cycle can then be interpreted as the logical completion of nuclear energy, ensuring its long-term viability under constraints of resource scarcity, waste management, and intergenerational responsibility.

1.3 Problem Statement

Despite the historical research and national programs, the transition toward fast reactor deployment has not yet materialized at an industrial scale. The highly debated shutdown of Superphénix and the cancellation of the ASTRID program have interrupted the continuity of fast reactor development. In March 2025, the French government has reiterated the will to build a national program to ensure a closed fuel cycle by the end of the century [6]. In this context, one can challenge the physical and industrial feasibility of such a transition toward a SFR fleet. The central problem addressed in this thesis is therefore how France can effectively plan and assess an industrial transition toward a sodium fast reactor fleet while ensuring physical and industrial feasibility, taking into account the economic and political constraints.

1.4 Objectives and Research Questions

- Identify key strategic, economic and industrial challenges in deploying a French fast reactor fleet, by assessing the feasibility of a closed fuel cycle under realistic plutonium and uranium constraints.
- Derive strategic recommendations for relaunching the transition, based on the analysis of various scenarios representing steps of a possible industrial deployment.

1.5 Scope and Limitations

This study focuses on the French nuclear system, its existing PWR fleet, its future designs and SFR technologies. Regulatory considerations are addressed through the European and international frameworks governing nuclear materials and safeguards (notably *Euratom*. Even though some findings may apply to other countries, the thesis' scope is therefore limited to the French context. Consequently, the thesis does not aim to assess other national strategies, which may be shaped by different technological, historical or industrial trajectories.

Chapter 2

Methodology

This thesis adopts a methodological approach aimed at evaluating the practical feasibility of a transition in France from the existing fleet of PWRs to SFRs, with the goal of achieving a closed nuclear fuel cycle. To do so, a multi-parameter modeling of the present nuclear system and its possible evolutions was created.

2.1 Model description

The model was designed by structuring and joining three fundamental aspects of the nuclear system : the nuclear reactor, the nuclear fuel and the industrial constraints associated with those two aspects.

2.1.1 Nuclear reactor technologies

Four nuclear reactor technologies are considered in the simulation framework:

- the existing French pressurized water reactor (PWR) fleet,
- Generation III+ French EPR2 pressurized water reactors,
- PWRs operated with 100% MOX fuel, not yet operational but a likely evolution of the EPR2, named EPR*
- sodium-cooled fast reactors (SFRs).

Each reactor technology is characterized by a set of physical parameters that define its operating conditions and fuel requirements.

Light water reactors

Light water reactors rely on enriched uranium-235 fuel subject to fission in their core.

For light water reactors, including the existing fleet, EPR2 and EPR* reactors, the following physical parameters are explicitly modeled.

The *thermodynamic efficiency* η_{th} characterizes the conversion of nuclear heat into electrical power and is defined as:

$$\eta_{\mathrm{th}} = \frac{P_{\mathrm{el}}}{P_{\mathrm{th}}}, \tag{2.1}$$

where P_{el} is the net electrical power output and P_{th} is the thermal power produced in the reactor core. For pressurized water reactors, this efficiency is primarily limited by the maximum coolant temperature and the constraints of the Rankine steam cycle.

Secondly, the model accounts for the *natural uranium consumption*, expressed in $\mathrm{t_{U,nat}}$/GWe/year. Indeed, PWRs require a supply of natural uranium to realize enrichment activities prior to PWRs fuel fabrication.

Sodium fast reactors

Unlike light-water reactors, fast reactors operate without a neutron moderator (in pressurized water reactors, this role is fullfiled by light water). Fission neutrons are therefore not slowed down (i.e thermalized) and retain high kinetic energies, resulting in a fast neutron spectrum. This spectrum enables nuclear reactions that are inaccessible in thermal reactors. In particular, fertile uranium-238 can capture fast neutrons and undergo transmutation into plutonium-239 that produces energy through fission. The absence of moderation is therefore a key feature that enables plutonium breeding and supports a regenerative fuel cycle in fast reactors.

For sodium-cooled fast reactors (SFRs), the model represents different physical parameters that have an impact on the overall system.

The *thermodynamic efficiency* η_{th} is defined as for the PWRs. In the case of SFRs, the efficiency is higher thanks to an increased core outlet temperature compared to standard PWRs. While PWRs display a core outlet temperature around 330°C, SFRS can reach above 500°C. [7]

The *plutonium inventory* required per reactor, expressed in $\mathrm{t_{Pu}}$/GWe, represents the plutonium mass required to reach criticality in the core and operate it. This inventory constitutes a key parameter on the deployment rate of SFRs, as the availability of plutonium is a prerequisite for operating new cores. In the absence of an adequate global plutonium inventory, large-scale deployment of SFRs is physically infeasible, regardless of industrial or economic considerations. For sensitivity reasons, the specific numerical values of plutonium inventories are therefore not disclosed in this work.

Finally, the *generation ratio* (GR) characterizes the balance between fissile material production and consumption in the reactor core and is defined as:

$$GR = \frac{M_{\mathrm{Pu,\,produced}}}{M_{\mathrm{Pu,\,consumed}}}, \tag{2.2}$$

where $M_{\mathrm{Pu,\,produced}}$ and $M_{\mathrm{Pu,\,consumed}}$ denote the masses of plutonium produced and consumed over a reactor cycle, respectively. Values of GR close to unity correspond to a self-sustaining fuel cycle, while $GR > 1$ enables net plutonium production and supports fleet expansion. One can note that several definitions of the generation ratio exist in the literature, which may lead to different numerical values depending on the adopted definition. In the absence of detailed neutronic information and for the sake of model simplicity, the present work adopts the above definition.[8]

2.1.2 Nuclear fuel designs

Several nuclear fuel designs are simulated, each adapted to the corresponding reactor technology and fuel cycle strategy:

- **Enriched natural uranium fuel**, consisting of 5% U-235 enriched uraniumand fabricated into conventional UO_2 fuel assemblies for use in PWRs.

- **Reprocessed enriched uranium fuel**, derived from the re-enrichment and refabrication of recovered uranium extracted from spent fuel.

- **Plutonium-based MOX fuel**, composed of a mixture of plutonium oxide PuO2 and depleted uranium oxide UO2.

- **Advanced plutonium-based MOX fuel**, designed to enable two successive recycling loops in PWRs, hence extending plutonium utilization. Such fuels could be available by 2050. [9]

- **Generation IV plutonium-based fuel for fast reactors**.

Similarly to reactor technologies, fuel designs are characterized by a set of adjustable physical parameters that directly influence reactor operation and fuel cycle performance:

- **Fuel burn-up** BU, defined as the thermal energy extracted per unit mass of heavy metal,

  $$BU = \frac{E_{\mathrm{th}}}{M_{\mathrm{HM}}}, \tag{2.3}$$

  and expressed in GWd/tHM. For PWRs, achievable burn-up values depend on the specific PWR technology and fuel design.

- **Plutonium content in the fuel** x_{Pu}, defined as the mass fraction of plutonium in the heavy metal inventory,

$$x_{\text{Pu}} = \frac{M_{\text{Pu}}}{M_{\text{HM}}}, \tag{2.4}$$

- **Plutonium production rate** $\dot{M}_{\text{Pu}}$, corresponding to the net annual production of plutonium in uranium-based fuels in PWRs, through neutron capture in ^{238}U, expressed in t_{Pu}/GWe/year.

The industrial deployment of fuel cycle strategies is represented through the following parameters:

- **Deployment date of multi-recycling in PWRs**.
- **Deployment duration of multi-recycling in PWRs**, representing the time required to reach full implementation across the eligible reactor fleet.
- **Deployment date of over-generation in sodium fast reactors**, corresponding to the onset of net plutonium production in SFRS. This date may be different than the commissioning date for technological or industrial reasons.

In addition to this parameterization, each reactor fleet is associated with a specific fuel management strategy, based on a combination of uranium-based fuels (natural and reprocessed) and plutonium-based fuels.

2.1.3 Industrial constraints

Industrial constraints of the reactor fleet

The evolution of the reactor fleet is governed by a set of industrial parameters that constrain deployment rates, operational continuity, and system capacity:

- **Decommissioning schedule**, defining the retirement dates of existing reactors as well as future EPR2, EPR* and sodium fast reactors, depending on their estimated operating time (which can vary between 60 years to 80 years in the model).
- **Construction rate**, representing the maximum number of reactors that can be commissioned per year, expressed in reactors/year. Each reactor technology has a specific construction rate.
- **Load factor** LF, defined as the ratio between the actual annual electricity production and the maximum possible production at nominal power,

$$LF = \frac{E_{\text{el}}}{P_{\text{nom}} \times 8760}, \tag{2.5}$$

where E_{el} is the net annual electrical energy produced by the reactor (in MWh), P_{nom} is the nominal electrical power of the reactor (in MW), and 8760 is the total number of hours in a year. The load factor is expressed as a percentage (%). Each reactor technology has a specific load factor.

Industrial constraints of the nuclear fuel cycle

The operation of the nuclear fuel cycle is subject to additional industrial constraints related to material flows, processing capacities, and temporary storage:

- **Fuel residence time in reactors** t_{res}, defined as the average duration for which fuel remains in the reactor core prior to discharge, expressed in years.
- **Reprocessing time** t_{repr}, corresponding to the average time required for spent fuel to be processed in fuel cycle facilities, expressed in years.
- **Temporary storage capacity for spent fuel** C_{stor}, representing the maximum amount of spent fuel that can be stored prior to reprocessing or disposal, expressed in tonnes of heavy metal (tHM).

2.1.4 Economic metrics

The economic assessment of the different transition scenarios relies on a set of cost parameters and discounting assumptions that determine the temporal valuation of investments and operating expenditures:

- **Capital expenditure of an EPR2 reactor**, denoted C_{EPR2}, expressed in constant euros per unit of electrical capacity (G€$_{2026}$/GWe). This parameter represents the reference investment cost for new reactor construction. It should be noted that the selected range of values is an estimate that accounts for the learning effects associated with constructing a series of PWRs : the initial units may incur higher capital expenditures.
- **Overcost ratio of EPR* reactors relative to EPR2 reactors**, denoted $\alpha_{\text{EPR}*}$, defined as:
$$C_{\text{EPR}*} = \alpha_{\text{EPR}*} \times C_{\text{EPR2}}, \tag{2.6}$$
where $C_{\text{EPR}*}$ is the capital expenditure of an EPR* reactor.
- **Overcost ratio of sodium fast reactors relative to EPR2 reactors**, denoted α_{SFR}, defined as:
$$C_{\text{SFR}} = \alpha_{\text{SFR}} \times C_{\text{EPR2}}, \tag{2.7}$$

where C_{SFR} is the capital expenditure of a sodium fast reactor.

- **Discount rate**, denoted $r(t)$, used to convert future costs into present values. The model allows for different discount rates over short-, medium-, and long-term horizons and will be discussed thoroughly below. The present value of a cost C_t at time t is formulated as:

  $$PV(C_t) = \frac{C_t}{(1 + r(t))^t}. \tag{2.8}$$

  The different values of the discount rate are based on conventional UK's HM Treasury Green Book which provides guidance for long-term projects economic assessment. [10]

2.2 Scenarios Studied

To address the objective of identifying the key challenges associated with the deployment roadmap of a sodium fast reactor fleet, four transition scenarios are analyzed in order to span a broad range of plausible long-term evolutions. Each scenario is defined by a target configuration to be achieved. While many parameters mentioned above are fixed by reactor physics, some model parameters are adjusted accordingly, to ensure consistency with the physical constraints of the system, such as the availability of plutonium inventories at given dates and the limits imposed by temporary fuel storage capacities. In addition, all scenarios are constrained to deliver a quasi-steady annual electricity production between 370 TWh and 430 TWh [1], thereby ensuring a comparable level of nuclear electricity supply to that of the current French system. Therefore, each scenario can be described as a set of variables, a nuclear fleet deployment and its associated electrical production. To account for all energy being produced by the entire system for economic analysis, the decommissioning of the reactors are taken into account, occurring around 2150.

Some variables remain constant over the 4 scenarios. To simplify the description, they are described below for all scenarios. The specific numerical values are not displayed for sensibility reasons. Instead, a range of values are displayed which can be found in the associated literature :

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[1] The electrical production for each scenario is shown in the Appendices section

Table 2.1: Summary of constant parameters used across all scenarios

Parameter	**Value and unit**	**Reference**
Nuclear reactor technologies		
Thermodynamic efficiency (LWRs)	33–36 (%)	[11]
Thermodynamic efficiency (SFRs)	38–40 (%)	[7, 12]
Natural uranium consumption (LWRs)	170–190 (tU/GWe/year)	[2, 13]
Plutonium inventory per SFR	6–8 (tPu/GWe)	[7]
Nuclear fuel designs		
Plutonium production rate in U-based fuels	0.20–0.30 (tPu/GWe/year)	[14, 13]
Fuel burn-up (LWR fuels)	45–55 (GWd/tHM)	[15]
Fuel burn-up (SFR fuels)	80–120 (GWd/tHM)	[15]
Plutonium content in fuel	7–10 (%)	[16, 13]
Economic assumptions		
CAPEX of an EPR2 reactor	6.5–7.5 (G€$_{2022}$/GWe)	[17]
Overcost ratio (EPR*, SFR vs EPR2)	1.10–1.30 (–)	[18, 19]
Short (<30 years), mid (<71 years) and long-term discount rates	3.50% / 3% / 2.5% (%/year)	[10]

2.2.1 Scenario 1: Open Cycle with Enriched-Uranium Thermal Reactors

National fleet operates exclusively on once-through LEU fuel in thermal reactors (e.g., PWRs). Spent fuel is cooled in pools, transferred to dry storage, and ultimately destined for deep geological disposal. No chemical separation or recycling is performed. There is no industrial program on fast reactors therefore there is no deployment of a SFR fleet during the scenario. Each EPR2 reactor has a nominal power of 1650 GWe.

Table 2.2: Additional model parameters for Scenario 1

Parameter	**Value and unit**
Industrial constraints	
Total number of reactors built	30 (units)
Construction rates (EPR2)	1 until 2055, 2 after (reactors/year)
Spent fuel storage capacity	14 000 (tHM)

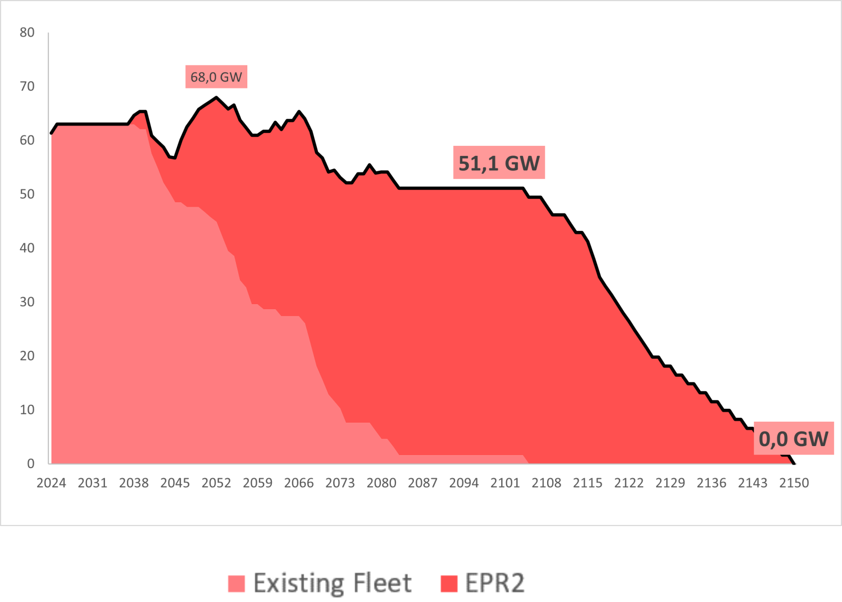

Figure 2.1: Nuclear power capacity (GW) in Scenario 1. Light red represents the existing PWR fleet, while dark red indicates newly deployed EPR2 reactors (PWR technology).

2.2.2 Scenario 2: Partially Closed Cycle with PWRs

Spent UOX fuel is reprocessed in nuclear fuel cycle facilities to enable the fabrication of MOX fuel. Multi-recycling of plutonium in PWRs is deployed in this scenario. Irradiated MOX fuel is then temporary stored until final disposition. High-level waste residues generated during reprocessing are vitrified for disposal. As an additional benefit of spent UOX fuel reprocessing, recovered uranium is re-enriched to produce reprocessed enriched uranium fuel, thereby reducing the consumption of natural uranium.

Table 2.3: Additional model parameters for Scenario 2

Parameter	**Value and unit**
Fuel cycle deployment assumptions	
Deployment date of multi-recycling in PWRs	2050 (year)
Duration of multi-recycling deployment in PWRs	10 (years)
Industrial constraints	
Construction rates (EPR2 & EPR*)	1 until 2055, 2 after (reactors/year)
Total number of reactors built	30 (units)
Fuel residence and reprocessing times	5+10 (years)
Spent fuel storage capacity	17500 (tHM)

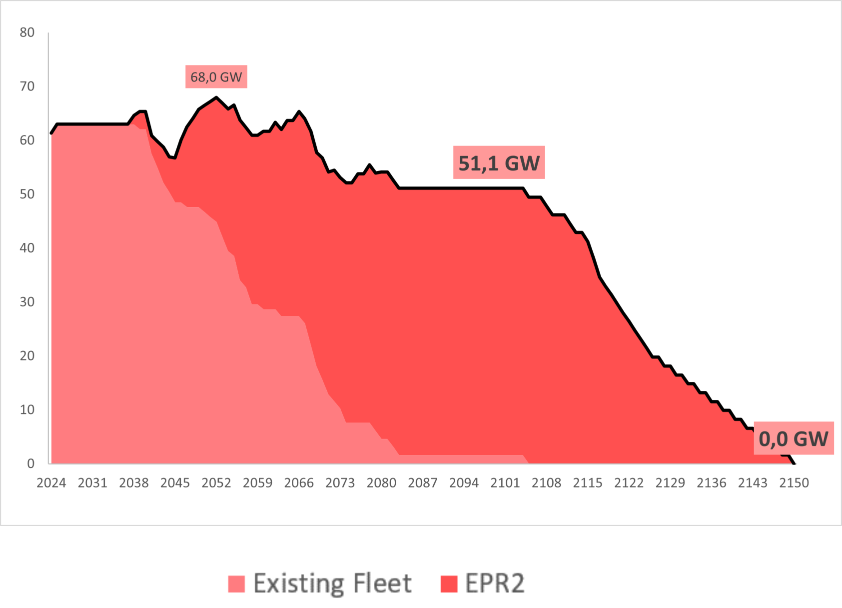

Figure 2.2: Nuclear power capacity (GW) in Scenario 2. Light red represents the existing PWR fleet, while dark red indicates newly deployed EPR2 reactors (PWR technology). Note : Since EPR2 technology is supposedly adapted to MOX fuel and multi-recycling, no difference is visible with Scenario 1.

2.2.3 Scenario 3: Deployment of a Mixed Fleet—4/5 Thermal + 1/5 Fast Reactors : hybrid closed fuel

This scenario investigates the industrial deployment of a mixed reactor fleet achieving a closed fuel cycle through the coexistence of thermal and fast reactors, with approximately 25% of electricity production provided by conventional reactors (PWRs) and 75% by SFRs, in line with configurations proposed in the literature [20].[a] Plutonium flows generated in both conventional and fast reactors are jointly reprocessed and recycled. To allow the active deployment of reactors, the SFR fleet is operated with a generation ratio greater than unity. To achieve a fully closed fuel cycle, the PWRs have to operate with a 100% MOX fuel strategy, usually named EPR* (as explained in Section 2.1.1).

Table 2.4: Additional model parameters for Scenario 3

Parameter	**Value and unit**
Nuclear reactor technologies	
Generation ratio (SFRs)	1.2
Fuel cycle deployment assumptions	
Deployment date of multi-recycling in PWRs	2050 (year)
Duration of multi-recycling deployment in PWRs	10 (years)
Deployment date of over-generation in SFRs	2065 (year)
Industrial constraints	
Total number of reactors built	8 PWRs & 37 SFRs (units)
Construction rates (EPR2, EPR*)	1 (reactors/year)
Construction rate (SFRs)	1.5 (reactors/year)
SFR Fuel residence and reprocessing times	5+10 (years)
Spent fuel storage capacity	15500 (tHM)

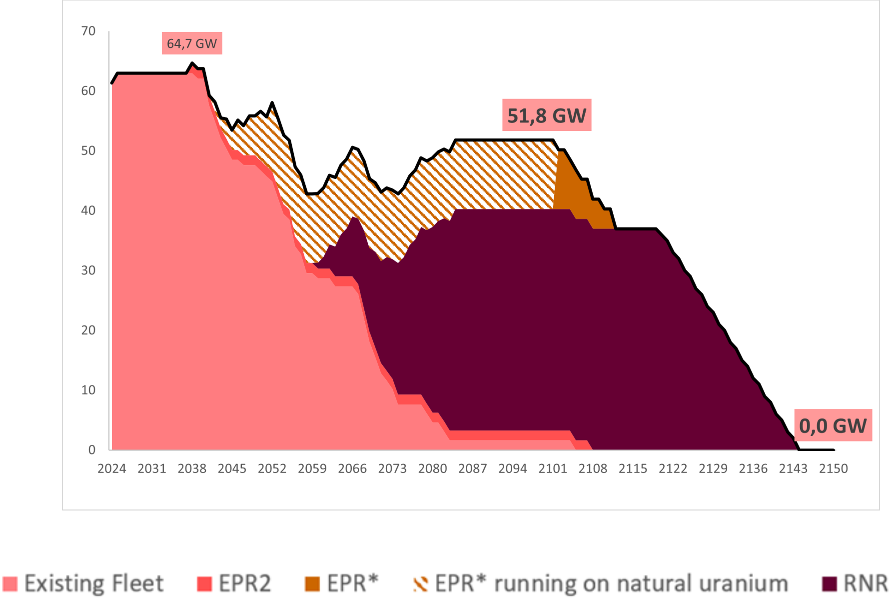

Figure 2.3: Nuclear power capacity (GW) in Scenario 3. Light red represents the existing PWR fleet, while mid-dark red indicates newly deployed EPR2 reactors (in this case, solely Flamanville 3, already operating since 2025); orange indicates EPR* reactors; dark red indicates sodium fast reactors. *Note:* The dashed orange zone indicates a multi-recycling strategy instead of a 100% MOX strategy, due to a lack of plutonium inventory, discussed thoroughly in Chapter 3.

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[a] Because of industrial constraints (fixed power capacities for EPR2 designs and fast reactor designs), the actual mix of reactors is 26% PWRs and 74% SFRs.

2.2.4 Scenario 4: Fully Closed Fast-Reactor Fleet

By the end of the scenario, the reactor fleet consists solely of SFRs operating within a fully closed fuel cycle. During the deployment phase, SFRs are operated with a generation ratio greater than unity to maximize the plutonium inventory and allow a strong industrial deployment. At the system equilibrium, the reactors then operate at iso-generation conditions. Plutonium and minor actinides are continuously recycled within the fast reactor fleet, supported by an industrial ecosystem capable of managing intensive plutonium flows throughout the fuel cycle. During the transition phase, no recycling of spent fuel is implemented, as the priority is to increase the plutonium inventory.

Table 2.5: Additional model parameters for Scenario 4

Parameter	**Value and unit**
Nuclear reactor technologies	
Generation ratio (SFRs)	1.2 (–)[2]
Fuel cycle deployment assumptions	
Deployment date of over-generation in SFRs	2050 (year)
Industrial constraints	
Construction rates (SFRs)	1(reactors/year)
Fuel residence and reprocessing times	5+10 (years)
Spent fuel storage capacity	13500 (tHM)

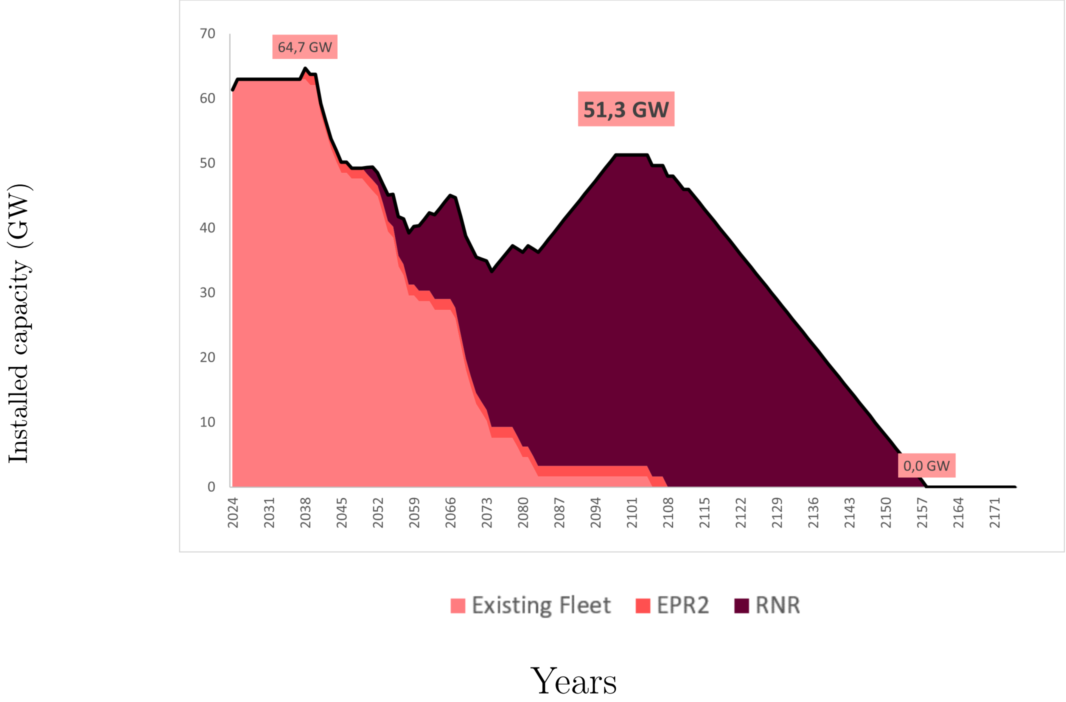


Figure 2.4: Nuclear power capacity (GW) in Scenario 4. Light red represents the existing PWR fleet, while mid-dark red indicates newly deployed EPR2 reactors (in this case, solely Flamanville 3, already operating since 2025). Orange indicates EPR* reactors, and dark red indicates sodium fast reactors.

2.3 Analytical Framework

The transition scenarios introduced in this study are intentionally simplified and idealized. Their purpose is not to predict a single most-likely future, but rather to establish boundary conditions within which more realistic transition strategies are expected to lie. The assessment is structured around four thematics, described below.

2.3.1 Strategic Assessment

This section evaluates the robustness of each pathway with respect to external resource constraints and vulnerability to uranium market crisis. A first objective is to characterize the vulnerability of the fleet to disruptions in natural uranium supply. This is quantified through the *natural uranium sensitivity* (in %), defined as the share of total electricity generation that remains directly dependent on natural uranium inputs over the considered horizon, considering the overall natural uranium consumption of the system. A second objective is to assess resilience under stress conditions by calculating the *autonomy time*, i.e. the duration over which the fleet can continue operating in the absence of natural uranium supply (given existing inventories, recycled material flows, and industrial constraints). Together, these metrics provide a measure of resource exposure and strategic flexibility across scenarios. Finally, the plutonium requirements and availability are compared and will be discussed furthered in the next Chapter.

2.3.2 Economic Assessment

Levelized Cost Of Electricity Formulation

We adopt the standard definition of the Levelized Cost Of Electricity Formulation (LCOE) :

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{T} \frac{I_t + O\&M_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{E_t}{(1+r(t))^t}}, \tag{2.9}$$

where I_t are investment costs, $O\&M_t$ operating costs, E_t net generation, and $r(t)$ the discount rate.[21]. It has to be noted that fuel cycle facilities costs are not estimated here for the sake of simplicity : it is commonly assumed that their influence is marginal compared to the costs of deploying a reactor fleet. [22]

All costs and energy outputs are evaluated in present-value terms to ensure temporal consistency in economic comparisons. Discounting is applied not only to monetary flows but also to electricity production, reflecting the economic principle that future services have a lower present value than immediate ones. The analysis horizon extends until the decommissioning of the last reactor, ensuring that all construction, operation and dismantling phases are fully captured.

Uranium market model

To quantify the fuel costs, uranium prices have to be modelized. The uranium market is not assumed to be constant over time. Instead, uranium price evolution is modeled using a simplified dynamic framework intended to capture long-term structural trends rather than short-term market behavior. The reference uranium price market is assumed to follow a constant annual growth rate, in the range [1%;3%]. On the period 2017-2024, where the annual growth rate of the uranium market was approximately 0.07%. This interval of higher values is therefore reflecting anticipation of increasing long-term uranium demand due to nuclear power capacity set to increase.[23]

Market prices are commonly quoted for uranium oxide concentrate (U_3O_8); these values are systematically converted into equivalent €/kgU prices to ensure consistency with fuel consumption expressed in terms of natural uranium. In addition, a stochastic variability of 3% is introduced to represent some market volatility around the long-term trend.

Formally, the uranium price trajectory is defined as:

$$P_{\mathrm{U}}(t) = P_{\mathrm{U}}(t_0) \prod_{\tau=t_0+1}^{t} \left(1 + g + \varepsilon_\tau\right), \tag{2.10}$$

where:

- $P_{\mathrm{U}}(t)$ is the uranium price at year t, expressed in €/kgU;
- $P_{\mathrm{U}}(t_0)$ is the reference uranium price at the initial year t_0;
- g is the long-term real growth rate of uranium prices, set to 1% per year;
- ε_τ is a stochastic variability term applied at each year τ, drawn from a zero-mean distribution with a standard deviation of 3%.

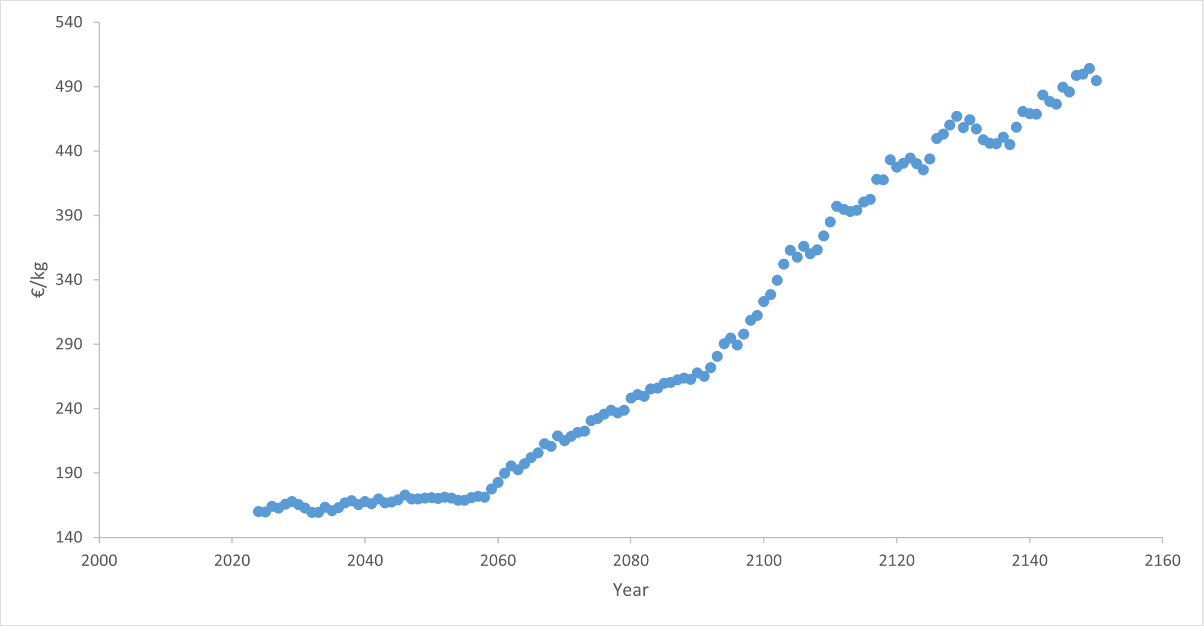


Figure 2.5: Uranium Market model : price of uranium oxide concentrate (U_3O_8) (in € per kg) projected until 2150, for a annual growth rate of 1%.

Actualized economics vs industrial view

In order to distinguish economic comparability from industrial considerations, the results are presented using two complementary cost perspectives.

First, a discounted economic metrics are calculated to compare alternative deployment scenarios in a consistent manner. All cost streams and electricity production are discounted to a common reference year (2025). This approach allows the computation of the LCOE and enables meaningful comparisons between nuclear fleets with different sizes, construction schedules and operational profiles.

Secondly, non-discounted *overnight* economic metrics are used to report an intuitive measure of the physical and industrial scale of the investment program, independently of discounting assumptions. It is particularly relevant for discussing construction effort and the overall magnitude of financial resources required by the decision takers.

These two perspectives are complementary and should not be directly compared. Discounted metrics are used for economic decision-making and scenario comparison, while non-discounted values provide contextual information on industrial feasibility and investment scale.

Comparative Base Reference Scenario

The economic analysis is focused on the *relative* impacts of each scenario compared to another : considering the very long term analysis and the uncertainty of the hypothesis associated with such timeline, the analysis of the absolute value of the economic metrics is of limited relevance. Therefore, the analysis is based on comparing the scenario studied with a base study reference : **in the case of this study, the reference scenario is Scenario 1.**

2.3.3 Industrial Assessment

The industrial metrics assess the feasibility of each transition scenario from the perspective of supply-chain readiness and implementation capacity. They aim to evaluate whether the industrial system can realistically support the pace and scale of reactor deployment and fuel cycle operations implied by each scenario. In particular, the analysis quantifies the requirements associated with nuclear fuel fabrication, spent fuel reprocessing, and temporary storage capacities.

Fuel fabrication demand is evaluated by relating the net electrical energy generated by the reactor fleet to the amount of nuclear fuel required to sustain this production. For a given fuel design and reactor technology, the annual fabrication demand expressed in tonnes of heavy metal is computed as:

$$M_{\text{fuel}} = \frac{E_{\text{el}}}{\eta_{\text{th}} \times BU}, \tag{2.11}$$

where:

- M_{fuel} is the mass of fabricated nuclear fuel, expressed in tonnes of heavy metal (tHM);
- E_{el} is the net electrical energy generated over the considered period, expressed in TWh;
- η_{th} is the thermodynamic efficiency of the reactor;
- BU is the fuel burn-up, expressed in TWh/tHM.

2.3.4 Sociopolitical Assessment

Beyond the physical, industrial and economic feasibility of a given scenario, political and social dimensions such as perceived waste burden, risk and vulnerability narratives and more generally public acceptance of the nuclear deployment is qualitatively assessed. The regulatory readiness is qualitatively assessed by studying the extent to which the required licensing and safety frameworks are compatible with the proposed transition timelines.

2.4 Validation and Limitations

The modeling framework developed in this thesis is designed to ensure internal consistency across physical, industrial, and economic analysis performed. Its results are to be interpreted with a *relative* approach rather than an *absolute* and predictive approach, given the several sources of uncertainty that can affect the model throughout the long term period of analysis . On the economic side, significant uncertainties remain regarding capital expenditures and operational costs of both existing and future reactor fleets, as well as the long-term evolution of uranium market prices. From a physical perspective, the plutonium isotopic degradation and fuel performance over successive recycling loops may affect achievable burn-up and recycling efficiencies but is not simulated here.

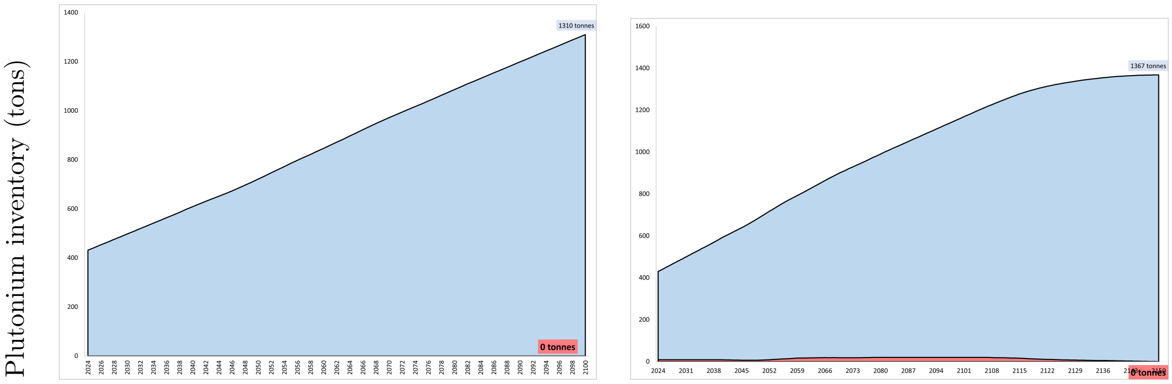
Chapter 3

Results and Discussion

3.1 Strategic, economic, industrial and socio-political challenges for the deployment of a french fast reactor fleet

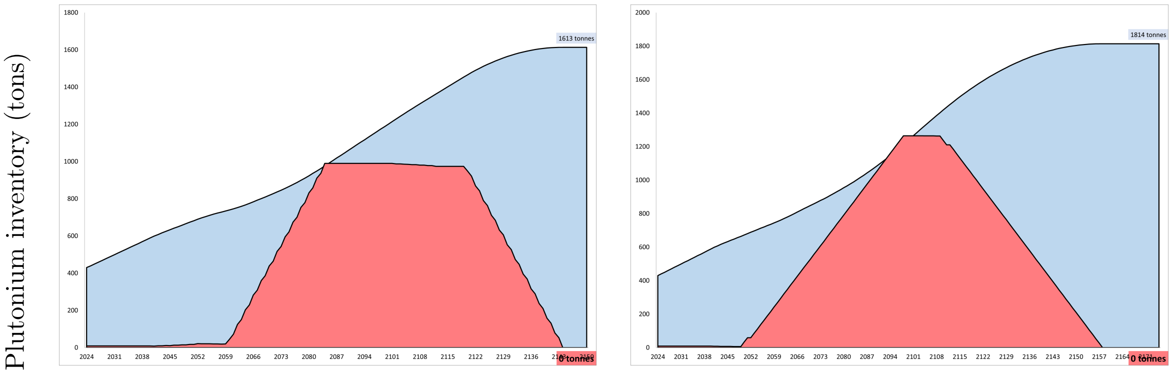
3.1.1 Strategic Vulnerability to Uranium Supply

Firstly, the different scenarios differ in the **margin of plutonium availability**, which depends on the evolution of the plutonium inventory and on the plutonium needs for deploying the fast reactors. Indeed, different fuel management strategies in PWRs lead to slightly different plutonium inventories. This arises from the fact that plutonium production mainly results from fertile uranium-238 absorbing neutrons in PWRs. Consequently, uranium-based fuel strategies in PWRs determine the plutonium inventory available to the system. In other words, if insufficient uranium is consumed in the PWR fleet, the resulting plutonium inventory will be inadequate to enable the deployment of the SFR fleet.



(a) Scenario 1

(b) Scenario 2

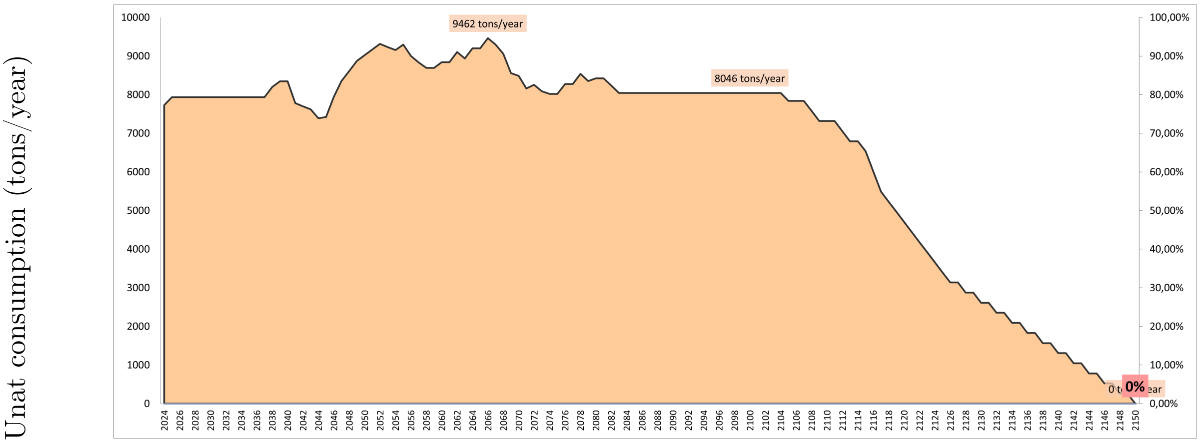


(c) Scenario 3

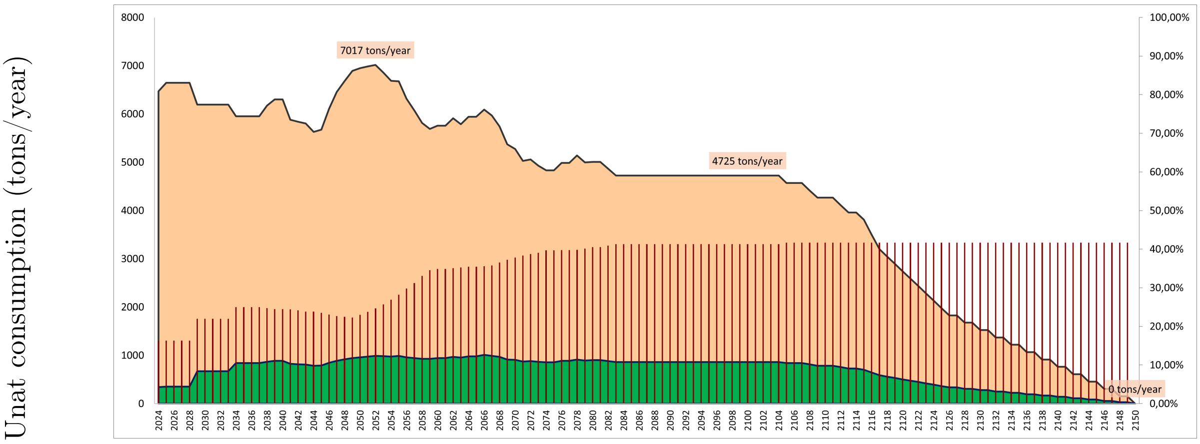
(d) Scenario 4

Figure 3.1: Plutonium inventory evolution for the four considered scenarios.

Secondly, the scenarios also differ in their **vulnerability to external supply of natural uranium** over time. This vulnerability is directly linked to date of deployment of the SFR fleet and its construction rate. The fuel cycle strategy and the level of plutonium recycling implemented in PWRs have also an influence on the level of vulnerability.



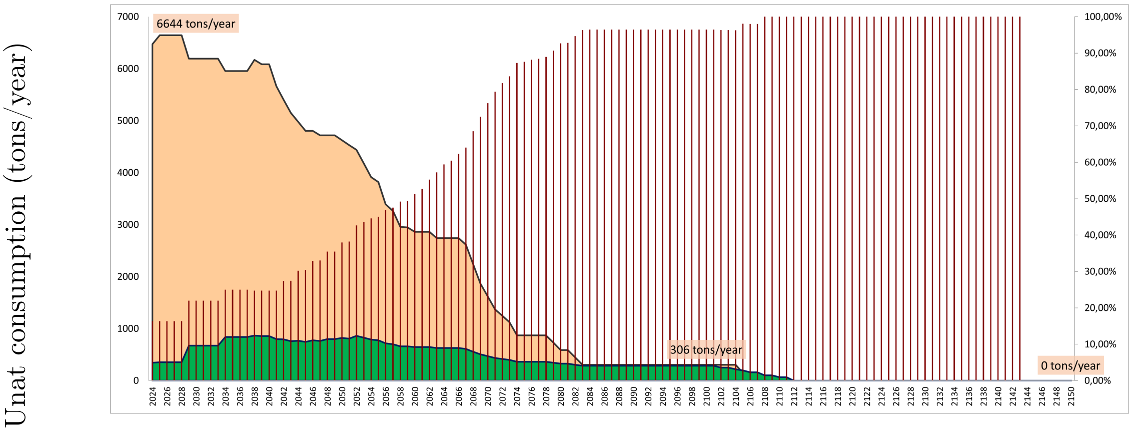
(a) Scenario 1



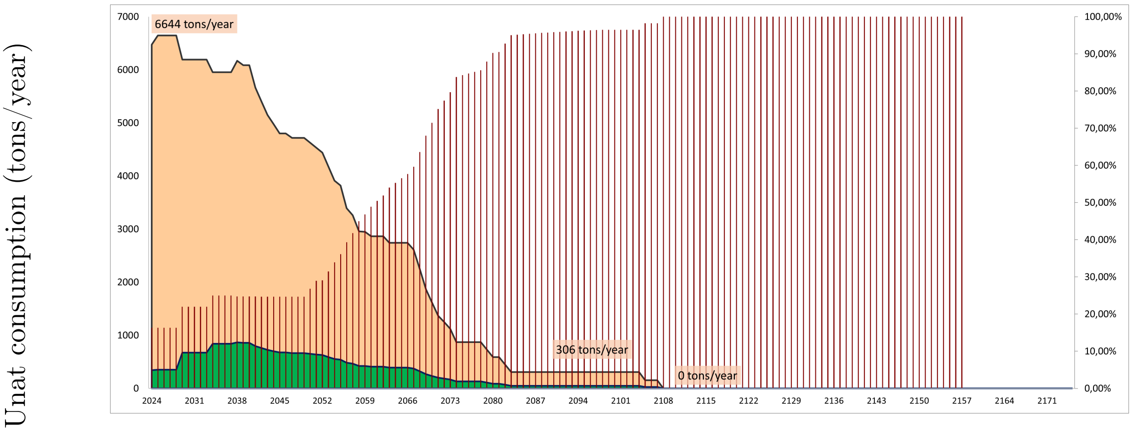
(b) Scenario 2

Years

Figure 3.2: Annual natural uranium (Unat) requirements for the scenarios 1 and 2, expressed in tons per year. The beige area represents the demand for natural uranium, while the green area indicates the contribution of reprocessed uranium. The right axis represents the desensitization of the nuclear fleet to Unat in %.



(a) Scenario 3



(b) Scenario 4

Figure 3.3: Annual natural uranium (Unat/year) requirements for the scenarios 3 and 4, expressed in tons per year. The beige area represents the demand for natural uranium, while the green area indicates the contribution of reprocessed uranium. The right axis represents the desensitization of the nuclear fleet to Unat in %.

Several key observations can be drawn from Figure 3.2 and Figure 3.3.

First, the multi-recycling of plutonium in PWRs leads to a significant reduction in dependence on natural uranium, from approximately 25% to nearly 40% by 2060. Depending on the global geopolitical context, such a reduction may be of major strategic interest for countries without domestic uranium resources, such as France. However, multi-recycling plutonium in PWRs also induces a slight decrease in the total plutonium inventory. While this reduction does not hinder the deployment of the first SFR units, it limits the physically achievable deployment rate of the SFR fleet and may delay the theoretical achievement of a fully closed fuel cycle.

Second, a substantial decrease in natural uranium consumption is observed only when the SFR fleet reaches a significant level of industrial deployment. This highlights that the key driver is not the commissioning of the first SFR unit, but rather the large-scale industrial deployment of the technology.

Finally, the closed fuel cycles (scenario 3 and 4) provide a significantly greater tool to uranium market failures as their natural uranium needs drop to 0 around the beginning of the 22^{th} century.

Also, from the perspective of natural uranium consumption alone, hybrid nuclear fleets combining EPR* and SFR reactors exhibit a performance comparable to that of a fully SFR-based fleet. The differentiation between these scenarios will therefore rely on additional criteria, which will be addressed in the other thematics.

3.1.2 Economic Analysis

Considering the very long-term projects of this paper, it is clear that across all scenarios, the main parameter influencing the *absolute* economic indicators is the discount rate that substantially affects the economic analysis. For very long-term projects, constant exponential discounting tends to severely underweight distant future impacts, raising conceptual difficulties in intertemporal economic evaluation. The relevant valuation of such projects, from a socio-economic perspective, must therefore rely on a variable discount rate, based on the evolution of the certainty of the factors affecting the discount rate [24]. This approach leads to a certainty-equivalent discount rate that declines over time and gradually converges toward the lowest plausible long-term rate. Consequently, distant future impacts should be discounted at lower rates than near-term effects, even if short-term discounting remains relatively high. Declining discount rates allow to preserve the relevance of long-term and inter-generational effects in present-day investment decisions.

Table 3.1: Comparison of economic indicators across scenarios

Economic indicator	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Total discounted CAPEX ($\text{G€}_{\text{discounted}}$)	102.80	102.80	95.67	92.53
Total electricity production (TWh)	26710.99	26710.99	24901.88	25110.01
Discounted total electricity production ($\text{TWh}_{\text{discounted}}$)	4097.55	4097.55	2991.37	2719.61
LCOE (EPR2 $\cup$ EPR $\cup$ RNR) (€/MWh)	[31.04 ; 112.92]	[29.91 ; 96.28]	[32.62 ; 34.19]	[34.12 ; 36.64]

The Table 3.1 displays several economic indicators for the four analyzed scenarios. Among these indicators, LCOE is the only metric that is directly comparable across scenarios, as it is intrinsically normalized to the amount of electricity produced. Because the scenarios differ in terms of reactor technologies and deployment schedules, direct comparisons of total CAPEX or total system costs would be misleading in a socio-economic assessment. These aggregate cost indicators are therefore not used for cross-scenario comparison here and are instead examined within the industrial assessment. The LCOE associated with each scenario is given in a range of values, based on the sensitivity analysis displayed in Figure 3.4, revealing the effect of uranium prices on the LCOE, depending on the annual growth rate of uranium market (between 1% and 5%).

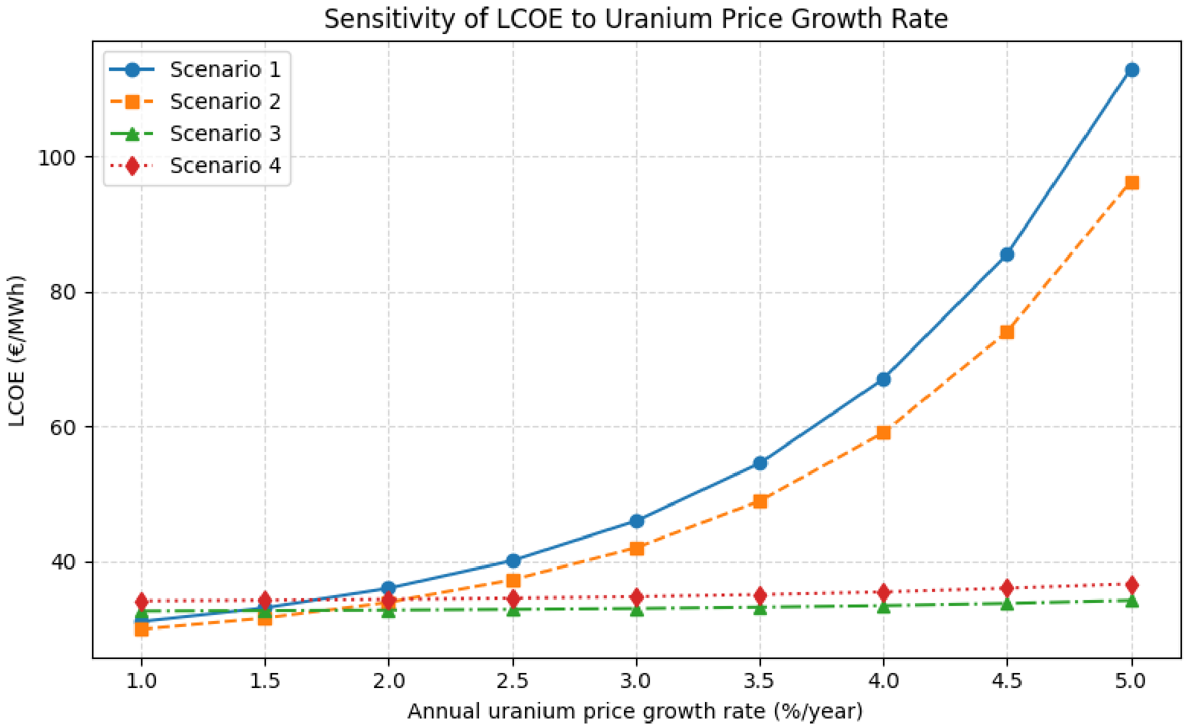


Figure 3.4: Sensitivity of LCOE to Uranium Price Growth Rate.

Scenarios 1 and 2 differ from their fuel management only therefore the total electricity produced is equal in both scenarios, as the same nuclear capacity is installed for the same period of time. We find that reprocessing spent uranium fuels lowers the LCOE by 7% (1% annual growth rate of uranium prices)to 15% (5% annual growth rate) relative to the open-cycle scenario. This is due to operational costs being limited to fuel costs and supposing the reprocessing and fabrications units for uranium-based and plutonium-based have identical costs.

However, deploying sodium fast reactors in scenarios 3 and 4 has varying effect on the LCOE, depending on the uranium market evolution. For instance, an annual growth rate of 1% implicates that the over-cost of fast reactors is still not economically competitive compared to conventional reactors : the LCOE is increased by 10% compared to the open-cycle scenario 1.

In the case of a 5% annual growth rate however, the scenario 3 and scenario 4 are significantly more attractive compared to the scenario 1, with a approximately 67% decrease of the LCOE.

In addition, a sensitivity analysis of the overcost ratio of SFRs compared to PWRs was done. To reveal the relative impact of these two influencing parameters, Figure 3.5 presents a three-dimensional sensitivity analysis of the levelized cost of electricity (LCOE) as a function of the annual uranium price growth rate and an overcost ratio, for the four different scenarios. The left graph provides a global view of the LCOE surfaces over the full parameter space to allow a direct visual comparison of the overall trends and relative magnitudes across scenarios. The right graph highlights a zoomed-in view of the region where the LCOE surfaces intersect, from an alternative viewing angle, in order to reveal the turning point between scenarios. Intersection curves corresponding to equal LCOE values are superimposed on both panels to explicitly identify the parameter combinations at which scenario rankings change.

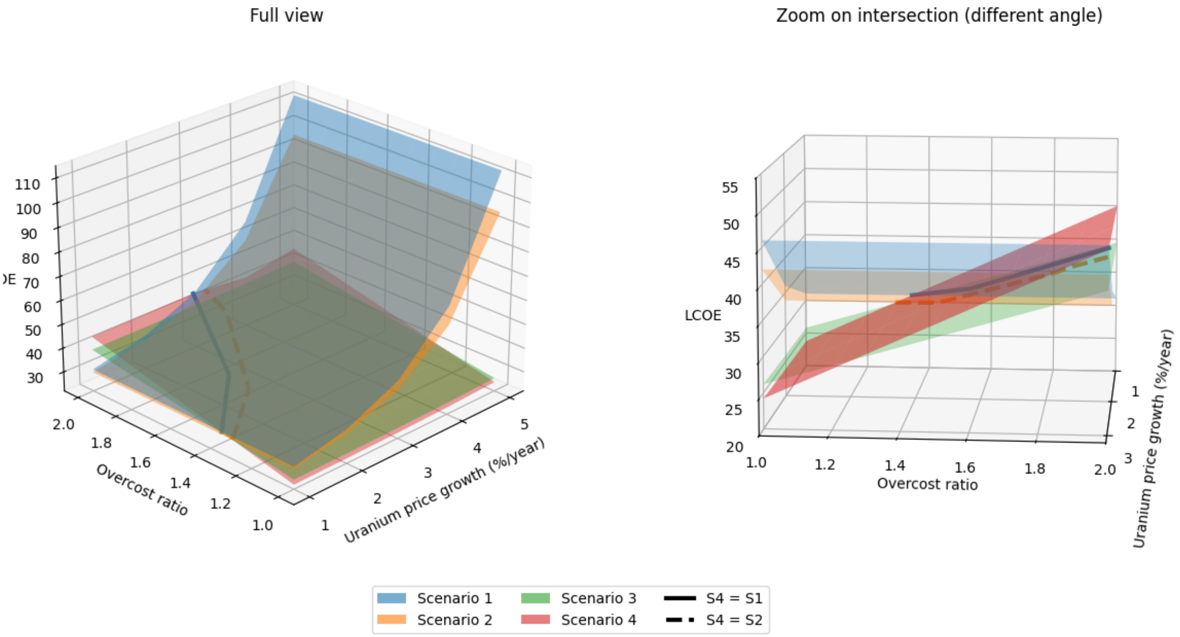
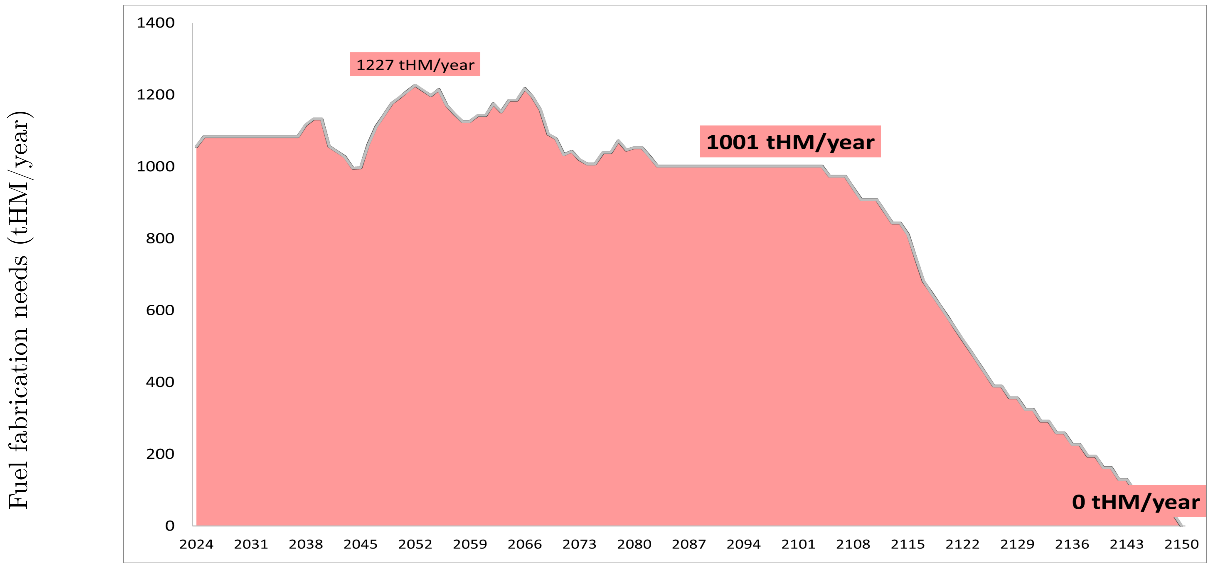


Figure 3.5: Sensitivity of LCOE to Uranium Price Growth Rate and Overcost Ratio

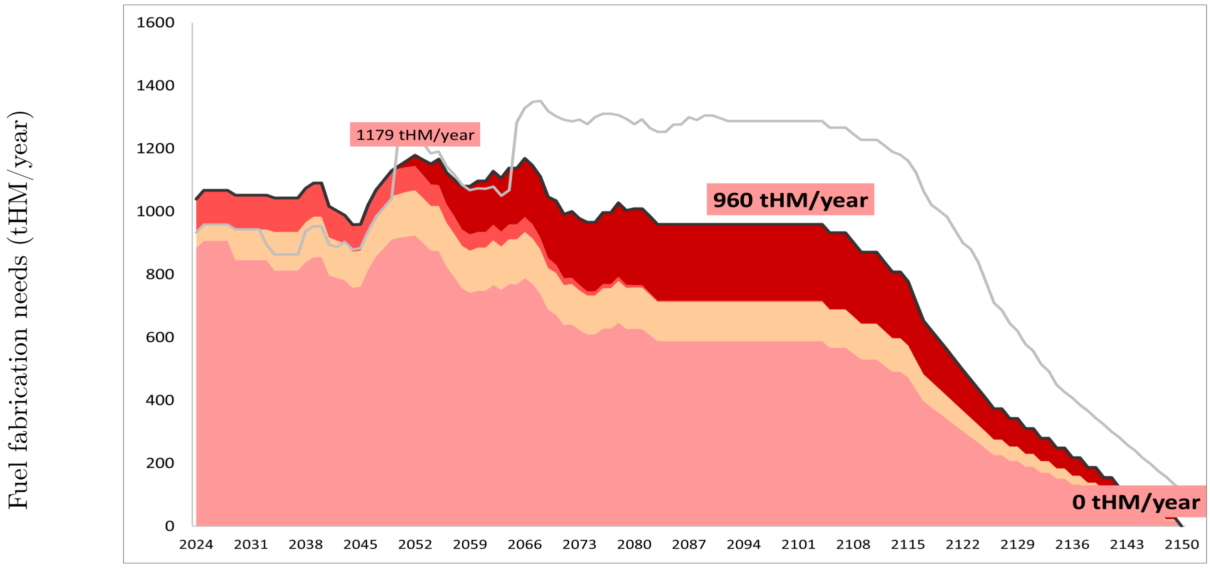
Intuitively, an increase in the overcost ratio reduces the economic attractiveness of SFR-intensive scenarios, whereas a higher annual growth rate of uranium prices increases it. Intersections between scenarios correspond to combinations of these two parameters for which identical LCOE values are obtained. It is notable that Scenarios 1 and 2 exhibit a higher sensitivity to uranium price growth, as shown by the pronounced convex curvature of the blue and orange surfaces in Figure 3.5.

3.1.3 Industrial Deployment Challenges

The existing fleet of PWRs was historically built at an intensive pace, resulting in reactors with closely clustered commission dates. Consequently, all reactors having been designed for similar operating lifetimes, the electrical system is expected to face a so-called *cliff effect* : a sudden drop in the existing installed capacity. The timing of such effect depends on the decommissioning dates of the existing reactors which may vary according to the assessment of the French Authority for Nuclear Safety and Radiation Protection (ASNR).



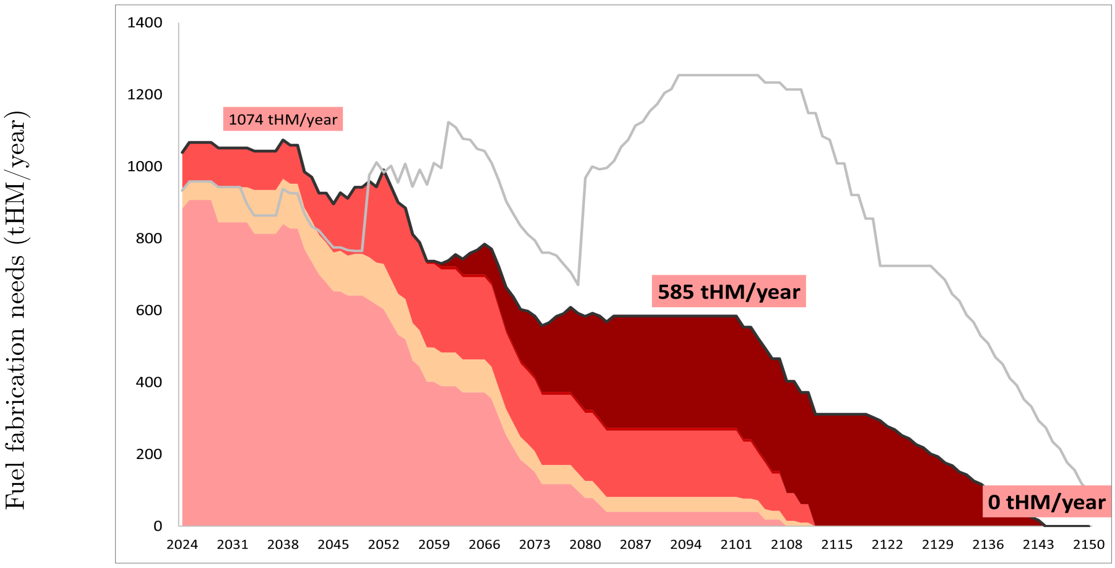
(a) Scenario 1



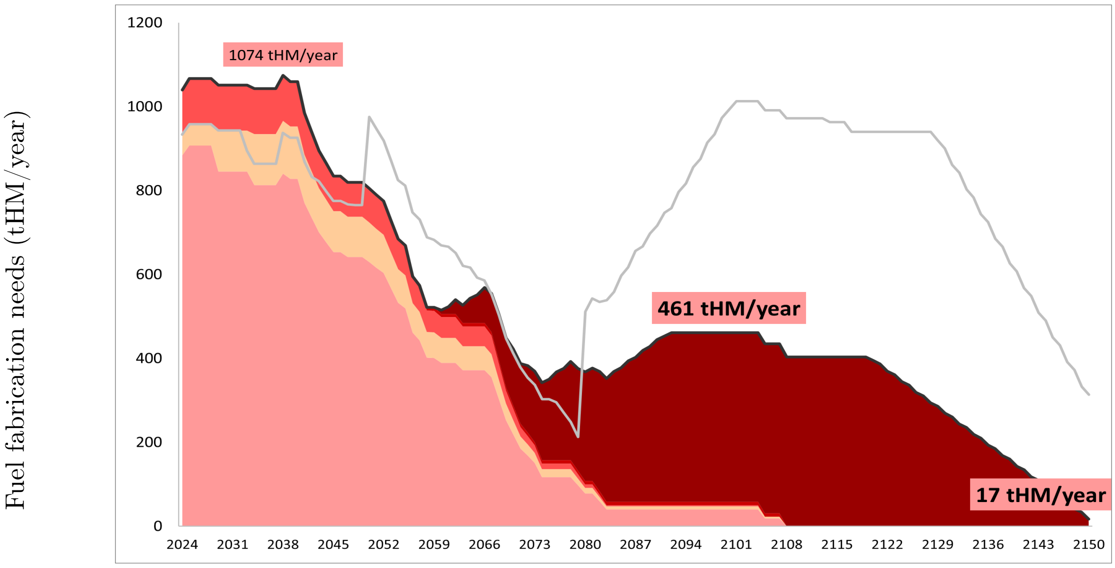
(b) Scenario 2

Years

Figure 3.6: Fuel fabrication and reprocessing demands over time for the four considered scenarios, expressed in tonnes of heavy metal per year (tHM/year). Light red bars represent enriched natural uranium fuel, red bars correspond to MOX fuel, dark red bars indicate advanced SFR fuel, and beige bars denote enriched reprocessed uranium. The grey curve shows the associated reprocessing requirements. (Scenarios 1 and 2)



(a) Scenario 3



(b) Scenario 4

Years

Figure 3.7: Fuel fabrication and reprocessing demands over time for the four considered scenarios, expressed in tonnes of heavy metal per year (tHM/year). Light red bars represent enriched natural uranium fuel, red bars correspond to MOX fuel, dark red bars indicate advanced SFR fuel, and beige bars denote enriched reprocessed uranium. The grey curve shows the associated reprocessing requirements. (Scenarios 3 and 4.)

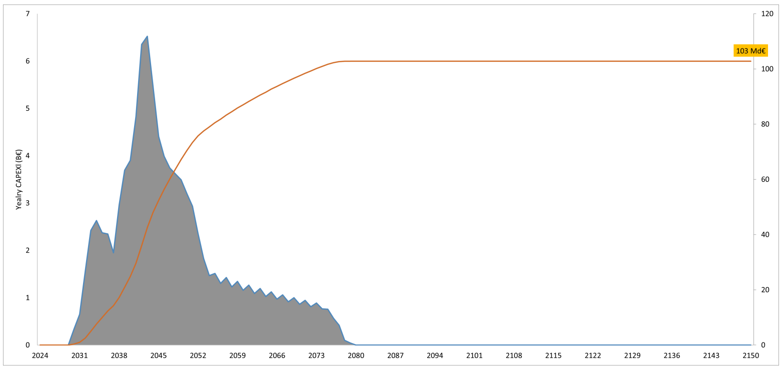
Several dynamics are shown in Figures 3.6 and 3.7. It has to be noted that the scenarios take into account the decommissioning of the entire fleet, which explains the small to none fuel needs in the vicinity of 2150.

Firstly, the total mass of fuel fabrication requirements decreases gradually from scenario 1 to scenario 4. This results from the higher burn-up associated with plutonium-based fuels, varying from approximately 60GWd/tHM for MOX-fuel [15] to 100GWd/tHM for advanced fuel for fast reactors.[25]. As successive scenarios involve a growing share of plutonium-based nuclear power generation, the overall requirements for fuel fabrication is reduced. However, reprocessing requirements do not decrease proportionally with the total fabricated fuel mass. This is because plutonium-based fuels impose more complex reprocessing activities. These additional constraints are accounted for in the model through a corrective factor applied to the annual mass of plutonium-based fuel reprocessed. For sensitivity reasons, the numerical value of this factor is not explicitly disclosed.

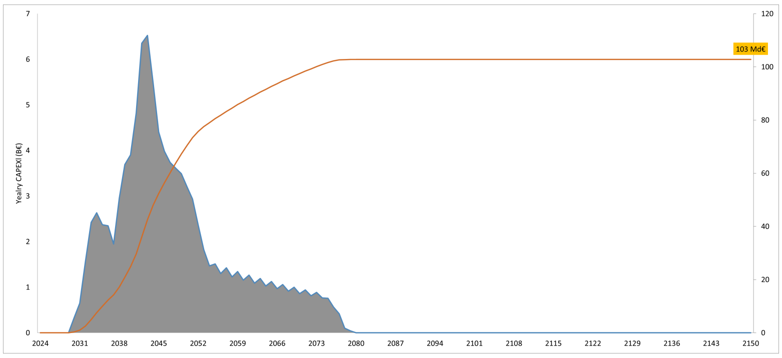
Therefore the main challenge associated with the deployment of the SFR fleet is the increased requirement for plutonium handling within fuel fabrication and reprocessing facilities. As the SFR fleet grows, these facilities must operate at a higher rate, which increases both technical and organizational constraints for the fuel cycle actors, primarily Orano and EDF.

In addition, the scenarios provide a progressively decreasing degree of resilience to industrial disruptions in the nuclear fuel cycle. Indeed, a fully closed fuel cycle requires a continuous and reliable plutonium-intensive stream in both fabrication and reprocessing facilities. Any interruption in these units directly impacts the availability of fissile material and therefore the operability of the reactor fleet. Conversely, mature and well-established enriched uranium fuel fabrication technologies provide a more reliable fuel supply for the nuclear system, supported by a global uranium fuel market that allows for diversified sourcing.

Hence, the net electricity generation becomes more strongly coupled to the operational availability of reprocessing facilities in a fully closed scenario than in a partially closed one with uranium-demanding nuclear systems. This tighter coupling increases system sensitivity to industrial performance.

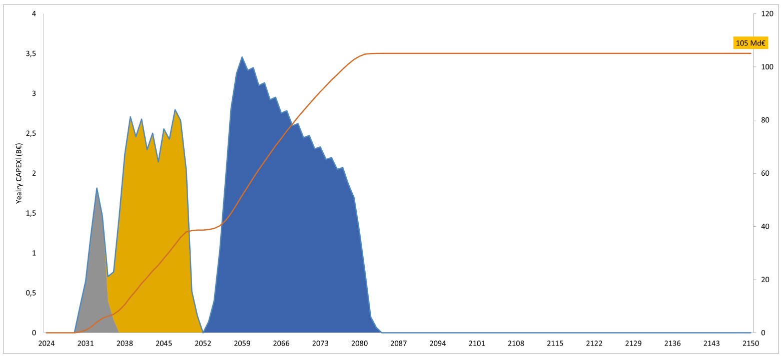


(a) Scenario 1

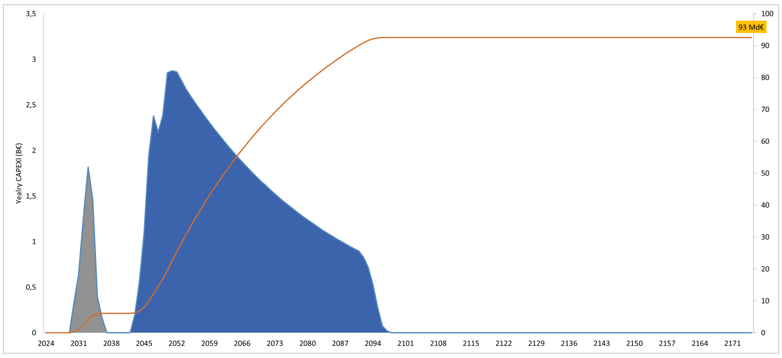


(b) Scenario 2

Figure 3.8: Yearly capital expenditures (CAPEX) required over time for the considered scenarios (Scenarios 1 and 2). The grey bars represent investments in the EPR2 fleet, the yellow bars correspond to investments in the EPR* fleet, and the blue bars indicate investments in the SFR fleet. The orange curve shows the discounted cumulative CAPEX for the entire scenario.



(a) Scenario 3



(b) Scenario 4

Figure 3.9: Yearly capital expenditures (CAPEX) required over time for the considered scenarios (Scenarios 3 and 4). The grey bars represent investments in the EPR2 fleet, the yellow bars correspond to investments in the EPR* fleet, and the blue bars indicate investments in the SFR fleet. The orange curve shows the discounted cumulative CAPEX for the entire scenario.

Table 3.2: Comparison of industrial-view economic indicators across scenarios

Economic indicator	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Total CAPEX (G€)	247.5	247.5	349.28	368.25
Capitalistic intensity (G€/GW$_e$)	5	5	6.96	7.42

In addition, Figure 3.8 & 3.9 and Table 3.2 show the investment profiles associated with the four analyzed scenarios.

While discounted economic indicators allow comparative socio-economic assessments, total CAPEX and capital intensity provide valuable insights for the industrial investments required for each scenario, particularly when this objective relies on a fleet of SFRs : scenarios 3 and 4 have a 41% and 49% over-cost compared to a full PWR fleet, for the same nuclear capacity of 50 GWe.

Furthermore, investment trajectories differ significantly across scenarios due to disparities in technological maturity, as shown in Figures 3.8and 3.9. The lower readiness level of SFR technologies leads to delayed deployment schedules relative to conventional reactors, shifting investment needs to later periods. Such differences in temporal dynamics necessitate long-term industrial planning, financial provisions, and risk anticipation, making these scenarios more complex to implement from an industrial point of view.

3.1.4 Socio-political analysis

Regulatory and Safety Considerations

While scenarios 1&2 blend in today's regulatory and safety framework, the scenarios 3&4 require intense advancements in the French regulatory framework, developed primarily for PWRs. Specific safety challenges of sodium fast reactors and advanced fuel-cycle facilities need new safeguard requirements. For instance, SFRs introduce unique risks such as sodium–air/water reactions and potential positive coolant void coefficients.[26]. In light of past public responses to advanced reactor projects in France (*Superphénix* notably), these unique challenges call for particularly focused safety assessment methodologies and intensive public communication strategies.

Beyond reactor safety, the deployment of sodium fast reactors implies a significant increase in plutonium inventories and continuous plutonium flows between reactors and the nuclear fuel cycle, fuel fabrication, and reprocessing facilities. Compared to uranium-based fuel cycles, this results in more complex safeguards requirements, both in terms of worker safety and heightened scrutiny from Euratom and international oversight bodies. Indeed, the reprocessing of plutonium remains a sensitive issue in international relations, regardless of its industrial justification within a closed fuel cycle.

In the French context, the sodium fast reactor Superphénix remains a prominent symbolic reference in public and political debates on nuclear energy, attracting particular attention beyond its technical characteristics [27]. Although the contemporary regulatory framework is characterized by strengthened safety culture and greater institutional independence compared to the 1980s, any renewed industrial fast reactor program may nonetheless inherit the legacy of past controversies associated with Superphénix.

3.2 Strategic recommendations for decision takers for relaunching the transition

3.2.1 Critical Interpretation

Considering the different scenarios analyzed, the incentive to relaunch a transition toward sodium fast reactors closing the nuclear fuel cycle cannot be simplified to a single economic parameter. LCOE comparisons are insufficient to capture the strategic value of closing the fuel cycle, as strategic parameters hae to be taken into account. Consequently, the economic evaluation of fast reactors must be inseparable from broader strategic objectives, including long-term resource sovereignty and reduction of uranium supply vulnerability.

The temporal asymmetry between the deployment of an industrial program and the actual fleet deployment can obscure the strategic advantages of closed fuel cycles if decision-making relies solely on short-term economic indicators. This is why a multi-criteria decision framework must take place, that incorporates long-term resilience and inter-generational considerations (through adjusted discount rates).

Finally, the different scenarios highlight that the strategic advantages of deploying a SFR fleet are of importance once the deployment reaches a sufficient industrial scale. Isolated or partial deployment of a small number of SFRs does not significantly reduce uranium dependency and may even exacerbate industrial complexity without delivering commensurate strategic gains. Therefore, relaunching the transition requires a credible long-term planning and commitment, with strong political stability.

3.2.2 Economics Sensitivity Summary

The economic analysis reveals that the economic indicators of open, partially closed, and fully closed fuel cycle scenarios are highly dependent on the discount rate and construction timelines of each scenario. However, with the uranium market hypothesis adopted in this study, the deployment of fast reactors is not economically attractive from a purely cost-based perspective, which is consistent with existing literature.[18]. The fuel costs associated with natural uranium–based fuels remain substantially lower than the additional capital expenditures required for fast reactor deployment. It should be noted that this conclusion is inherently dependent on the assumptions made regarding both long-term uranium price evolution and the capital cost overrun associated with fast reactor technologies.

Indeed, uranium prices throughout the scenarios are a key factor to determine the competitiveness of advanced fuel cycles and reactors. While open-cycle systems are highly sensible to uranium prices, partially and fully closed cycles show strong resistance to possible market failures. However, such resilience becomes visible and decisive in the long term, requiring strong planning and commitment to the industrial deployment. During the initial phases of the transition, such pathways remain economically unattractive, with their competitiveness emerging only under scenarios of sustained or accelerated increases in uranium price.

Uranium price trajectories emerge as a key differentiating factor between fuel cycle strategies. While open-cycle systems remain highly sensitive to sustained increases in uranium prices, partially and fully closed cycles benefit from reduced exposure to front-end fuel costs. However, this advantage only becomes decisive in the long term and under scenarios of persistent price growth or supply disruptions. Conversely, increases in reprocessing and plutonium fuel fabrication costs exert upward pressure on the LCOE of closed cycles, highlighting the importance of industrial efficiency and standardization in backend operations.

Learning effects and technological maturation represent a potential counterbalance to higher upfront costs. As fast reactor technologies and associated fuel-cycle facilities progress toward first-of-a-kind to nth-of-a-kind deployment, capital and operational costs are expected to decline, narrowing the cost gap with conventional reactors. Moreover, although repository footprint and thermal load reductions do not directly enter LCOE calculations, they constitute critical non-monetary performance indicators that strengthen the overall economic rationale for closing the fuel cycle when assessed within a multicriteria framework.

3.2.3 International Comparative Reflection

The first developments of fast reactors began in the United States, with the experimental lead-cooled reactor *Clementine* in 1949, quickly followed by the Na-K-cooled fast reactor EBR-1, first nuclear reactor producing electricity in the world. Technological advancements led to the withdrawal of NaK coolant for sodium-based coolant. In 1958, Russia deploys its first sodium cooled experimental reactor (BR 5), followed by the American EBR-2 in 1961. France initiated its fast reactor program with the commissioning of Rapsodie in 1967, while Germany and Japan respectively commissioned KNK-II and Jōyō in 1977. Collectively, these initiatives illustrate the widespread international interest in fast reactor technologies, particularly sodium-cooled systems [18].

France and Russia progressed beyond the experimental stage through the construction and operation of high-power fast reactors. Although the French Superphénix reactor was permanently shut down in 1997, Russia has maintained a continuous commitment to fast reactor development, exemplified by the ongoing construction of the BN-1200, a 1,200 MWe sodium-cooled fast reactor [28].

In addition, India has a long-term project of deploying the 500MWe Prototype Fast Breeder Reactor (PFBR). [29]

Overall, it is clear that several countries have identified the industrial programs of fast reactors as a strategic, long term investment for enabling new source of energy production. Some countries, especially Japan, faced similar social acceptance problematic as in France. The lessons drawn from international programs can be of essential guidance for any revival of sodium fast reactors in France.

Chapter 4

Conclusion and Perspectives

4.1 Summary of Findings & Strategic Recommendations

This master's thesis has investigated four long-term transition scenarios for the French nuclear system, progressively desensitizing the needs for natural uranium. The multi-criteria framework used in this paper indicates that the transition toward a closed fuel cycle cannot be justified on a single economic metric, which can explain partially the current lack of deployment.

While uranium and plutonium recycling in conventional reactors partially reduces uranium demand (up to 40%), it is not physically sustainable in the long-term. Therefore, it does not eliminate long-term vulnerability to external supply. However, scenarios deploying a significant share of SFRs (Scenarios 3 and 4) enable near-complete desensitization from natural uranium. Indeed, only a large industrial deployment of a SFR fleet, as opposed to isolated prototype reactors, unlock the benefits of uranium desensitization.

The economic assessment of this study, in accordance with existing literature, reveals that fast reactors remain uncompetitive compared to conventional reactors, with current cost assumptions and a uranium price trajectory supposed in this paper. However, the resilience provided by closed fuel cycles against uranium market disruptions represents a strategic value that is not fully captured by conventional cost metrics.

The industrial constraints of closing the nuclear fuel cycle are of paramount importance for a successful industrial program. Such technological transition from conventional reactors to advanced reactors requires strong connection between reactor deployment and reprocessing and fuel fabrication capacities. France's existing plutonium inventory and reprocessing infrastructure provide a credible basis for initiating a fast reactor program, provided that policy continuity and long-term planning are maintained.

Therefore, any program of SFR fleet deployment should be approached as a long-term national strategy rather than a short-term economic optimization, using a multi-criteria framework, not limited to economic indicators. Strategic recommendations include committing to a phased but sustained SFR deployment roadmap, maintaining plutonium recycling capabilities during the transition and assuring political stability for a stable and long-term planning required for industrial programs of this kind.

4.2 Broader Implications

Closing the nuclear fuel cycle is closely tied to national efforts to strengthen energy sovereignty. In a context of geopolitical instability, an increasing number of countries can be expected to pursue renewed and advanced reactor development programs. Moreover, such industrial program could position France as a pioneer and key player in long-term renewed European energetic strategy.

4.3 Limitations and Future Work

The simulation framework in this study is subject to several limitations.

First, economic uncertainties remain significant. Cost estimates for the different reactor technologies are still adjusting and depend on future technological advancements. Although cost ranges were considered in this work, alternative assumptions could lead to different economic outcomes in future analyses. Furthermore, fuel cycle costs were excluded from the assessment, as they were assumed to be of secondary importance relative to reactor capital costs. However, advanced reactor fuel cycles may differ substantially from current ones and could entail higher costs, thereby increasing the overall levelized cost of electricity (LCOE).

Fast reactor deployment could also be analyzed from an insurance-based perspective, in which it provides a hedge against long-term fuel price volatility, resource scarcity and geopolitical supply risks. In this framework, fast reactors can be interpreted as a form of insurance premium that enhances system resilience under adverse but plausible future states.

In addition, the plutonium inventory using a single value metric does not account for its isotopic composition, which includes both fertile and fissile isotopes. Future work could include a parametrization of the isotopic degradation resulting from storage and repeated recycling that may influence the actual usable inventory, by integrating Monte Carlo methods to dynamically simulate the isotopic evolution of the plutonium inventory.

4.4 Concluding Remarks

Closing the nuclear fuel cycle of the fench nuclear system represents both a technical challenge and a strategic choice for France's energy future. While fast reactors are not economically competitive in today's conditions , their interest lies in their capacity to withstand geopolitical and geological constraints. These benefits become decisive only under a long-term framework that recognizes the limits of short-term economic comparisons.

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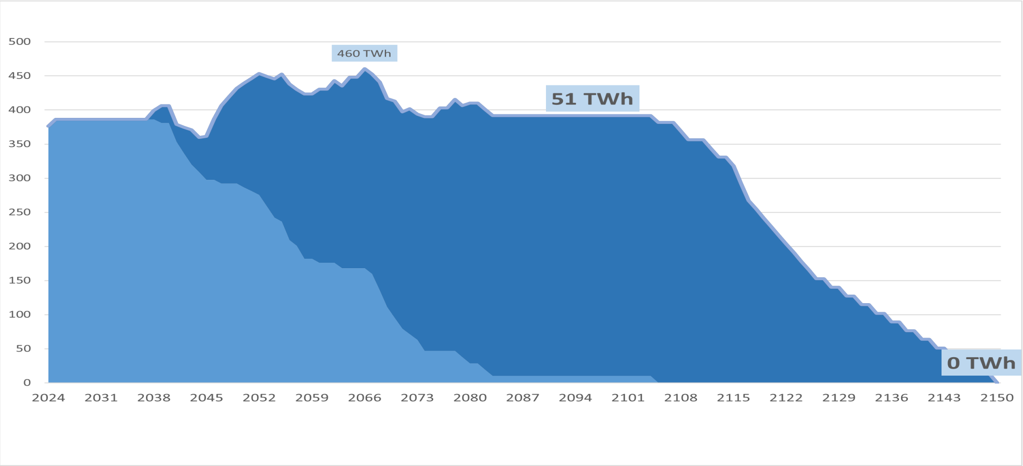
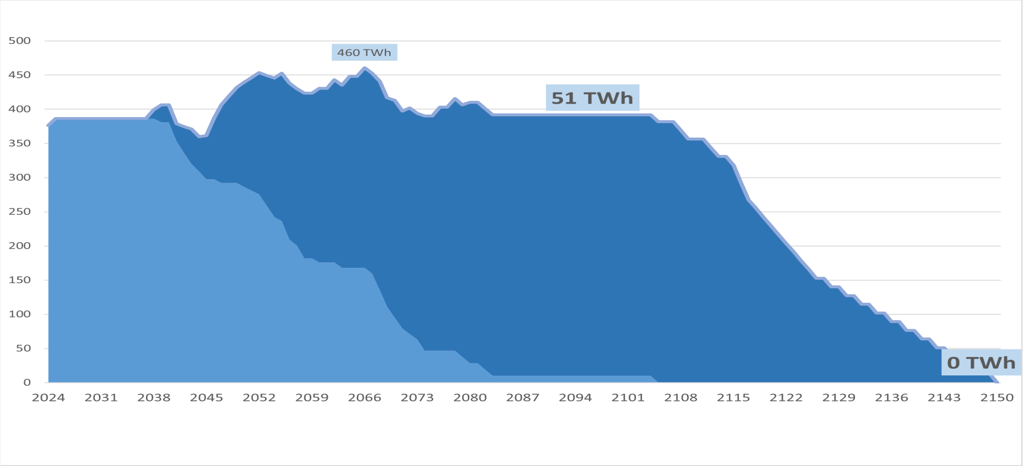
Appendices

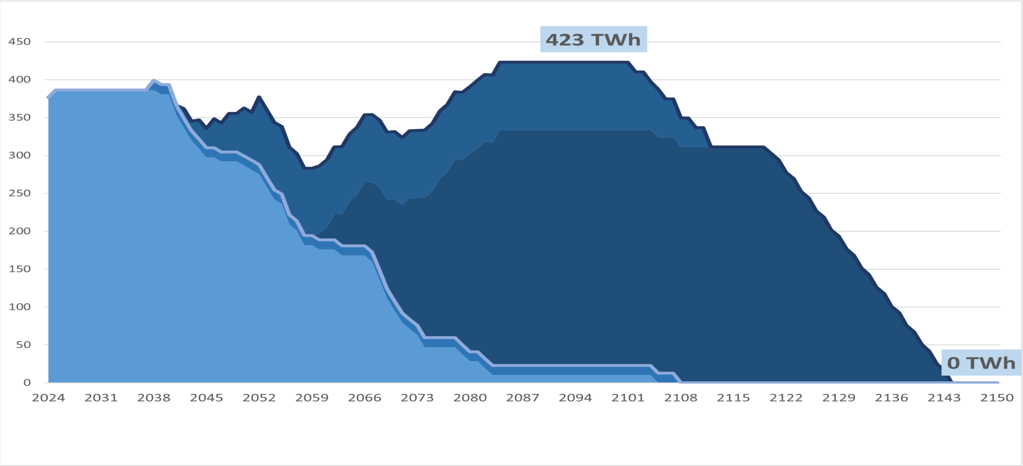


(a) Scenario 1

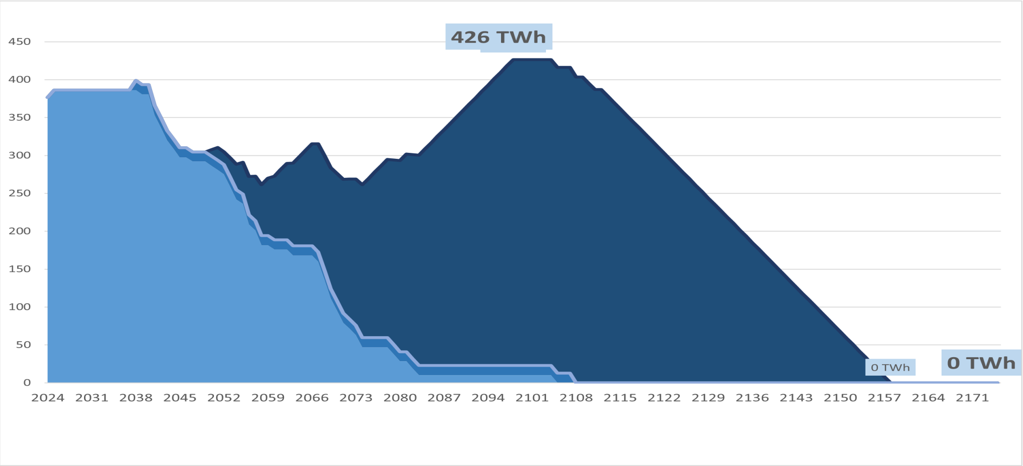


(b) Scenario 2

Figure 4.1: Annual electricity generation (TWh) over time for Scenarios 1 and 2. The contributions from the existing fleet, EPR2 fleet, EPR* fleet, and SFR fleet are shown in progressively darker shades of blue.



(a) Scenario 3



(b) Scenario 4

Figure 4.2: Annual electricity generation (TWh) over time for Scenarios 3 and 4. The contributions from the existing fleet, EPR2 fleet, EPR* fleet, and SFR fleet are shown in progressively darker shades of blue.

List of Acronyms

Acronym	**Definition**
PWR	Pressurized Water Reactor
SFR	Sodium-cooled Fast Reactor
MOX	Mixed Oxide Fuel
LCOE	Levelized Cost of Electricity
CAPEX	Capital Expenditure
EPR	European Pressurized Reactor
EPR2	Second-generation European Pressurized Reactor
EPR*	PWR operating with 100% MOX fuel
PUREX	Plutonium Uranium Redox Extraction
BU	Burn-Up
GR	Generation Ratio
LF	Load Factor
UOX	Uranium Oxide Fuel
tHM	Tonnes of Heavy Metal
Unat	Natural Uranium