

# Master in Advanced European and International Studies

Mediterranean Studies

*How does the structure of  
uranium supply chains shape the  
nature of France's strategic  
dependency?*

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2026



Co-funded by  
the European Union



## Acknowledgements

*I would like to express my sincere gratitude to my thesis supervisor, Mr Jean-Claude Vérez, whose guidance, rigour, and thoughtful feedback shaped this work at every stage.*

*I am also grateful to the teaching staff of the Master in Advanced European and International Studies at CIFE for the intellectual foundation that made this research possible, and to my fellow students, whose discussions enriched my thinking throughout the year.*

*My thanks go as well to Laura Gettemans and Stéphane Hemelaer for their careful proofreading, which greatly improved the clarity of the final text.*

*Finally, I thank my family and friends for their patience and unfailing support during the months devoted to this thesis. Any errors or shortcomings that remain are my own.*

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# Introduction

## A) Research Question and Objectives

France relies almost entirely on imported uranium to sustain its nuclear system, which occupies a central place in both electricity production and national defence. Nuclear power accounts for a substantial share of France's low-carbon electricity generation, around 60 to 70 percent, and remains a defining feature of the country's energy system, although the exact contribution varies by year (RTE 2025; EDF, 2024). At the same time, uranium is a critical input for France's nuclear deterrent, whose strategic role has become more visible again in the European security debate.

In recent years, France has further reinforced the centrality of nuclear capabilities within its broader strategy of autonomy. This includes the modernisation of its deterrent through new-generation ballistic missile submarines, as well as renewed political debates on the possibility of extending France's nuclear umbrella to European partners (Élysée, 2026). These developments have taken place in a wider international context marked by the modernisation of nuclear arsenals and growing concern over the resilience of strategic supply chains.

Against this backdrop, France's dependence on external uranium sources raises a critical question: how resilient is its supply system in an increasingly unstable geopolitical environment? The issue became especially salient after the 2023 coup in Niger, which disrupted one of the historically central pillars of French uranium supply (Reuters, 2025). At the same time, France has intensified its diplomatic and industrial engagement with Kazakhstan, including high-level cooperation aimed at reinforcing nuclear-sector supply relations (World Nuclear News, 2024).

Existing analyses of uranium dependency often focus on import volumes and supplier diversification. From this perspective, France appears relatively secure, since it sources uranium from several countries, including Niger, Kazakhstan, Canada, Australia, and Uzbekistan (Portail IE, 2024). Yet such volume-based assessments can obscure more fundamental changes in the nature of dependency.

This thesis begins from a simple puzzle: how can similar levels of import dependence generate different forms of strategic vulnerability?

It argues that dependency in strategic resources such as uranium cannot be understood through quantitative indicators alone. Instead, it must be analysed through three interrelated dimensions: the degree of control over supply, exposure to political and geopolitical risk, and the structure of the supply chain.

To address this, the thesis first examines France's uranium needs and the organisation of the nuclear fuel cycle, from extraction to reactor use. France consumes approximately 8,200 tonnes of natural uranium per year, all of which is imported (World Nuclear Association, 2026). It then situates France within this global system by highlighting both its industrial capabilities and the structural limits to full autonomy. Although France retains strategic stocks and industrial capacities in conversion and enrichment, these do not amount to complete independence (ASNR, 2025).

Building on this foundation, the analysis compares two key suppliers, Niger and Kazakhstan, over the period 2010-2025. While both countries have played comparable roles in terms of supply volumes, they represent fundamentally different supply models. Niger reflects a historically embedded and relatively direct relationship shaped by post-colonial ties and visible geopolitical exposure. Kazakhstan, by contrast, is embedded in a much larger and more globally integrated industrial system, characterised by indirect dependencies and complex links to actors such as the Russian Rosatom (World Nuclear News, 2024; Portail IE, 2024).

## **B) Central Argument: From Controlled Bilateral Dependence to Entangled Network Dependence**

The central argument of this thesis is that France has not reduced its uranium dependency, but transformed it. Over the past fifteen years, it has shifted from a controlled bilateral dependency, exemplified by the Niger model, toward an entangled network dependency, exemplified by the Kazakhstan model. This transformation is not captured by import statistics, which tend to interpret diversification as an increase in security. In reality, it reflects a shift from visible, rupture-prone risks, where a single political event can abruptly sever supply, toward more diffuse and systemic vulnerabilities embedded in global supply chains, where risks are harder to identify, attribute, and mitigate.

This distinction is analytically and politically interesting because the two dependency models imply fundamentally different policy responses. A bilateral dependency can, in principle, be managed through diplomatic engagement, political leverage, or supplier diversification. A network dependency, by contrast, requires a comprehensive understanding of the full supply chain architecture, including the role of intermediaries such as Rosatom, which exerts structural influence over uranium processing and transport in Central Asia, and cannot be addressed by adding suppliers alone (World Nuclear News, 2024; Portail IE, 2024).

Methodologically, this thesis combines quantitative trade data with qualitative analysis of industrial structures, geopolitical dynamics, and supply chain organisation. It explicitly acknowledges the limitations of trade statistics, which fail to capture the complexity of the nuclear fuel cycle and the existence of indirect dependencies embedded in processing, enrichment, and transport stages.

By integrating insights from energy security studies, political economy, and global value chain analysis, this research contributes to a more nuanced understanding of strategic dependency in critical resources. It proposes an analytical framework that reconsiders the relationship between diversification, control, and vulnerability in the context of contemporary geopolitical tensions.

### **C) Theoretical Framework: Control, Geopolitical Exposure, and the Structure of Global Value Chains**

This thesis draws on three bodies of literature. First, it builds on Hirschman's foundational insight that trade dependency can function as a source of political leverage, an observation developed by Baldwin (1985) and more recently reformulated by Farrell and Newman (2019) in their concept of weaponised interdependence. In this framework, states that occupy chokepoint positions in global networks can convert economic relationships into instruments of coercion. The thesis applies this logic to uranium supply chains to assess where France sits relative to such chokepoints.

Second, it draws on Global Value Chain analysis to map the structural organisation of the nuclear fuel cycle, from extraction through conversion, enrichment, and fuel fabrication, and to identify where dependencies are concentrated and by whom they are controlled. Third, it

engages with the energy security literature, particularly its emphasis on the dimensions of availability, reliability, and resilience in critical resource supply (Cherp and Jewell, 2011).

By combining these three frameworks, this thesis proposes a three-dimensional analytical grid (control, geopolitical exposure, and supply chain structure), to compare the Niger and Kazakhstan dependency models. This grid allows for a qualitative differentiation between forms of dependency that appear equivalent when measured by import volume alone.

#### **D) Methodology, Sources and Limits of the Study**

Methodologically, this thesis combines quantitative trade data with qualitative analysis of industrial structures, geopolitical dynamics, and supply chain organisation. Import volumes and supplier shares are drawn from Euratom Supply Agency reports and World Nuclear Association data. Qualitative analysis relies on official documents, industry sources, and academic literature in political economy and energy security. The thesis also acknowledges the limits of trade statistics, which do not fully capture indirect dependencies, particularly those arising from the role of third-party actors in processing, transport, and finance.

This thesis adopts a structured, focused comparison of two cases, Niger and Kazakhstan, selected according to three explicit criteria.

First, joint and comparable supplier importance: for most of the study period, until the 2023 rupture, Niger and Kazakhstan each supplied a broadly similar share of France's natural uranium and, taken together, accounted for roughly half, and in several years more than half, of total deliveries (Euratom Supply Agency, 2024). The two cases are therefore not marginal but quantitatively dominant, and matching them on supplier importance holds constant the variable that volume-based assessments treat as decisive. That this combined share fell sharply after 2023, as Niger's deliveries collapsed, is itself part of what the comparison sets out to explain.

Second, contrasting supply-chain governance: the two relationships are organised through structurally opposite mechanisms, direct equity ownership in a post-colonial setting versus a joint venture embedded in a globalised, multi-actor chain.

Third, a shared observation window containing two exogenous shocks, the 2022 invasion of Ukraine and the 2023 Niger coup, that function as a natural stress test of each model.

This case structure follows the logic of a controlled comparison: by matching the cases on supplier importance and contrasting them on governance structure, any systematic difference in the resulting form of vulnerability can be attributed to structure rather than to volume. The comparison is conducted through a fixed analytical grid (developed in Part III, §3.1) whose criteria are defined in advance and applied identically to both cases, rather than through narrative juxtaposition alone

Any analytical framework produces knowledge within boundaries that must be made explicit. This thesis operates within four sets of limitations that the reader should bear in mind when assessing its conclusions.

The first concerns data availability. The Euratom Supply Agency provides annual aggregate supply data by country of origin but does not publish transaction-level data on individual contracts, conversion routing, or enrichment service agreements. The analysis of French dependency on Russian processing infrastructure developed in this thesis therefore relies on reconstruction from multiple industry sources, corporate reporting, and academic literature rather than on direct measurement of material flows. Similarly, the classified nature of French strategic stockpile levels means that the buffer analysis in Part I rests on publicly available estimates whose precision cannot be independently verified.

The second limitation concerns geographical and comparative scope. The thesis examines France's uranium supply chain over the period 2010 to 2025 and focuses specifically on the Niger and Kazakhstan cases. It does not attempt to generalise its conclusions to other nuclear states (the United Kingdom, Germany, Sweden, or Belgium...) which operate under different supply chain configurations, different institutional frameworks, and different exposure profiles. The analytical framework proposed here has broader applicability, but testing that applicability across multiple national cases lies beyond the scope of this work.

The third limitation is material scope. The analysis focuses exclusively on natural uranium and the conversion, enrichment, and fabrication stages of the front-end fuel cycle. The supply chains for other materials critical to reactor operation are not addressed. A comprehensive strategic vulnerability assessment of France's nuclear supply chain would need to cover these materials, several of which present concentration and dependency profiles comparable to uranium itself.

The fourth limitation is temporal. The 2025 analytical cut-off means that the full outcomes of France's post-Niger supply chain restructuring are not yet visible. The ramp-up of South

Tortkuduk production under the KATCO joint venture, the resolution of Orano's legal challenge against the Nigerien junta under the bilateral investment treaty, and the completion of Georges-Besse II's capacity expansion all fall within or beyond this horizon and would constitute important updating information for any revision of this work.

## **E) Structure of the Thesis**

The thesis is organised in three parts. Part I examines France's uranium needs and the structure of the nuclear fuel cycle, establishing both the scale of French dependence and the analytical significance of the full chain, not only its extraction stage. It highlights why France's domestic capabilities, while substantial, do not translate into genuine autonomy. Part II provides historical and structural case analyses of the Niger and Kazakhstan supply models, tracing their evolution over the period 2010-2025 and mapping the transformation of intermediaries and risk profiles. Part III compares the two models through the three-dimensional analytical grid, demonstrating how similar import volumes produce structurally different vulnerabilities. It concludes by treating the period 2020-2025, marked by the Ukraine war, growing Rosatom influence, and the Niger coup, as a natural stress test of the two models.

# **I. France's Uranium Dependence and the Structure of the Nuclear Fuel Cycle**

## **1.1 Civil and Military Dimensions of France's Uranium Requirements**

Nuclear power occupies a central and distinctive position in France's national energy system and strategic posture. In 2024, nuclear energy accounted for approximately 67.4% of France's total electricity generation, producing around 361.7 TWh out of a national total of roughly 536.5 TWh (Réseau de Transport d'Électricité, 2025; International Energy Agency, 2024). This share places France among the most nuclear-dependent countries in the world and underscores the technology's role as the cornerstone of the country's low-carbon electricity mix.

The continuous operation of France's fleet of 56-57 pressurised water reactors (PWRs) creates a structural and predictable demand for nuclear fuel (World Nuclear Association, 2024). Unlike intermittent renewable sources, nuclear reactors require a steady supply of fissile material to maintain criticality and generate baseload power. Each reactor consumes fuel assemblies on a cycle typically lasting 12 months, or 18 months with a partial refueling occurring at least annually (OECD Nuclear Energy Agency, 2021). As a result, France requires a reliable annual input of natural uranium to sustain its civil nuclear program. Current estimates place this requirement at approximately 8,200 tonnes of uranium per year (equivalent to about 9,700 tonnes of uranium oxide concentrate, or  $U_3O_8$ ), all of which must be imported since France ceased domestic uranium mining in the early 2000s (Euratom Supply Agency, 2024; WNA, 2024; ESA, 2024).

This civil demand is not static. It is influenced by reactor performance, plant availability, and long-term fleet modernisation plans, including the extension of existing reactors' lifetimes beyond 40 years and the prospective construction of new EPR reactors. Any disruption in the front-end of the fuel cycle (uranium supply, conversion, or enrichment) can rapidly affect electricity output, as demonstrated by the production shortfalls experienced in 2022 due to corrosion issues and maintenance delays (RTE, 2023). Secure uranium supply is therefore not an industrial concern but a prerequisite for energy security and the decarbonisation objectives embedded in France's national energy strategy. Nor is this demand profile static in the upward direction. The new-build programme announced in 2022 foresees six EPR2 reactors with an option for eight more, alongside reactor lifetime extensions beyond fifty years and emerging small modular reactor projects. Every current scenario of French energy planning therefore implies a higher, not lower, natural uranium requirement over the 2035-2050

horizon, raising the strategic stakes of the supply chain architecture analysed in this thesis (EDF, 2024).

Beyond the civil domain, uranium also underpins France's independent nuclear deterrent. The military dimension, quantitatively smaller but strategically decisive, is analysed in section 1.4.

## **1.2 Uranium as a Geological and Strategic Material: Why It Differs from Other Commodities ?**

Uranium is, in the words of Grenèche (2016), *the only natural element with which it is possible to sustain a chain reaction and therefore operate a nuclear reactor to produce energy, but also to manufacture atomic bombs*. This dual-use characteristic, simultaneously a fuel and a weapons material, distinguishes uranium from all other traded commodities, and shapes the institutional framework within which its supply chains operate. Natural uranium contains two isotopes in fixed proportions: uranium-238 (U-238), which constitutes approximately 99.3% of natural uranium and is not itself fissile but can be converted through neutron capture into fissile plutonium-239, and uranium-235 (U-235), which constitutes only 0.7204% of natural uranium but is the isotope that undergoes fission in light-water reactors and, at very high enrichment levels, in nuclear weapons (Hore-Lacy, 2016; Grenèche, 2016).

This isotopic structure has a decisive consequence for the supply chain: natural uranium as it leaves the mine cannot power any of the world's 400-plus commercial light-water reactors. It must be physically transformed, step by step, through a sequence of chemical and physical processes before it acquires the isotopic and geometric properties required to sustain a controlled nuclear chain reaction. Each of those transformation steps represents a stage in the supply chain where additional actors, additional infrastructure and additional technical expertise are introduced, and where new dependencies can be created or deepened.

Uranium is also characterised by what Hore-Lacy (2016) terms the *ubiquity of occurrence and the scarcity of economic concentration*: the element occurs everywhere in the Earth's crust at an average concentration of approximately 3 parts per million, but economically recoverable deposits require concentrations typically one hundred to several thousand times higher. As of 1 January 2023, globally identified recoverable uranium resources totalled 7.93 million tonnes with an extraction cost below 260 USD per kilogram. Approximately 64% of

those resources are concentrated in just five countries: Australia, Kazakhstan, Russia, Canada and Niger (OECD-NEA and IAEA, 2024). Canada's high-grade deposits in the Athabasca Basin represent the world's richest uranium ores, with average grades up to 25% uranium at McArthur River (compared to the 0.3% to 1.8% typical of Nigerien and Kazakhstani ores). This geographic concentration is moreover not uniform across deposit types and extraction methods: Kazakhstan hosts sandstone-hosted deposits largely suited to in-situ leaching (ISL, a well-based extraction method described in §1.3.1), while Niger's historical production has relied mainly on conventional mining (notably open-pit mining at Somaïr and underground mining at Cominak). (Hore-Lacy, 2016).

This geological heterogeneity matters for supply chain analysis because deposit type determines extraction method, extraction method determines capital intensity and switching costs, and capital intensity determines the degree of lock-in that a long-term supply relationship generates. As the following sections will demonstrate, the contrast between Niger's underground and open-pit mining operations and Kazakhstan's ISL technology is not only a technical detail: it is also a structural variable that directly shapes the governance of the supply relationship and the nature of France's exposure to disruption in each case.

### **1.3 The Front-End of the Nuclear Fuel Cycle: From Mine to Fuel Assembly**

#### ***1.3.1 Stage 1: Mining and Milling***

The first stage of the nuclear fuel cycle is the extraction of uranium ore from the Earth's crust and its initial concentration into a commercially transportable product. Grenèche (2016) identifies three principal extraction methods with distinct implications for supply chain structure: open-pit mining for shallow deposits, underground mining for deeper high-grade ores, and in-situ leaching (ISL), which has covered nearly half of global uranium production since 2013. ISL involves injecting a chemical solution directly into the ore-bearing formation and recovering the uranium-bearing solution through extraction wells without bringing the host rock to the surface.

The ISL method is worth underlining for this thesis for two reasons. First, it is the method mainly used by Kazakhstan, which produced approximately 21,227 tonnes in 2022 (43% of global primary production), of which Kazatomprom's attributable share was around 11,373 tonnes (23%) (Wimmers et al., 2026). Hore-Lacy (2016) notes that ISL's *low capital intensity*

*relative to conventional mining, its ability to exploit deposits that would be uneconomic by conventional methods, and its smaller surface footprint* made it the key to Kazakhstan's emergence as the world's dominant uranium producer. Second, ISL induces a supplier with a fundamentally different cost structure and asset configuration than a conventional miner: Kazatomprom's ISL operations do not require the massive surface infrastructure, workforce housing, or ore processing plants that characterised Orano's Nigerien operations, which reduces both the sunk costs and the political exposure of the Kazakhstani production model.

Niger's operations were organised around conventional mining. Somaïr operated an open-pit mine at Arlit extracting ore with grades averaging 1.81% uranium in its later years, while Cominak operated an underground mine in the Akouta deposit at depths of approximately 250 metres with 250 kilometres of tunnels (World Nuclear Association, 2026). These operations required substantial fixed infrastructure: processing facilities, water management systems, logistics connections to the export corridor via Benin, and a permanent local workforce. They lead the deep operational knowledge and sunk costs that Grenèche (2016) identifies as characteristic of conventional uranium mining, and that made France's Nigerien dependency simultaneously highly controlled and highly irreversible.

Whichever extraction method is used, the immediate product is uranium ore or uranium-bearing solution, which must be processed at or near the mine site to extract *yellowcake* ( $U_3O_8$ ), the concentrated uranium oxide that forms the standard traded commodity in the international uranium market.

This yellowcake is then packaged in 200-litre steel drums and transported from the mine site. It is at this stage that the institutional structure analysed by Hecht (2012) becomes analytically decisive: the IAEA statute of 1957 classified yellowcake as a '*source material*', subject only to restricted international oversight, rather than as a nuclear material requiring full safeguards application. Hecht demonstrates that this classification was shaped by the competing interests of uranium-producing states seeking commercial access, and of nuclear weapon states seeking to maintain control over downstream transformation. It implies that yellowcake could be traded on international markets without the regulatory burden attached to enriched uranium, simultaneously facilitating the globalisation of uranium supply and obscuring the political dimensions of resource dependency (Hecht, 2012).

### ***1.3.2 Stage 2: Conversion***

Yellowcake cannot be used directly in commercial enrichment facilities. Before it can be enriched, it must be converted into uranium hexafluoride (UF<sub>6</sub>), the only gaseous compound of uranium that can be processed in gas centrifuge enrichment cascades at technically manageable temperatures. The conversion process transforms U<sub>3</sub>O<sub>8</sub> into uranium hexafluoride (UF<sub>6</sub>) through a two-stage fluorination process.

In France, this conversion is performed at two sites operated by Orano: the Malvési plant near Narbonne, which produces UF<sub>4</sub> from U<sub>3</sub>O<sub>8</sub>, and the Pierrelatte site, which converts UF<sub>4</sub> to UF<sub>6</sub> using fluorine gas (produced continuously by electrolysis of hydrofluoric acid). Grenèche (2016) notes that the Georges-Besse I gaseous diffusion plant, and the Georges-Besse II centrifuge plant (both used for Uranium enrichment in a later stage) were also built on the Tricastin site, adjacent to the Pierrelatte conversion facilities. This created a geographically integrated front-end cluster whose spatial concentration itself constitutes a vulnerability. (Hore-Lacy, 2016).

The conversion stage is the supply chain's first major structural chokepoint. In 2022 the only commercial conversion plants in operation were located in France (Orano, 9,000 t/year, then at around 60% capacity), China (CNNC, 11,000 t/year), Canada (Cameco, 10,600 t/year) and Russia (Rosatom/Seversk, 12,000 t/year at 96% capacity), the American ConverDyn plant having been halted since 2017 (Wimmers et al., 2026). Russia's plant thus operated at near-full capacity while the US plant was entirely offline, so Kazakhstani yellowcake destined for Western enrichment frequently passed through Russian conversion infrastructure as the path of least resistance. France's Malvési-Pierrelatte capacity, expanded from 2,500 t/year in 2018 to 9,000 t/year in 2022, provides a measure of domestic autonomy that most other nuclear countries lack. But for uranium sourced from Kazakhstan, conversion routing through Russian infrastructure remained a commercially attractive path of least resistance until political considerations after February 2022 forced a reassessment (Wimmers et al., 2026).

The attractiveness of Russian conversion and re-enrichment services was not simply geographic but structurally economic, and quantifying that attractiveness reveals the concrete price of French autonomy. Rosatom's competitive advantage in enrichment derives from three compounding factors: 1) the full depreciation of Soviet-era centrifuge infrastructure, 2) the continuous modernisation of its machine park across nine generations of centrifuges without

interruption since the 1950s, and 3) a state-owned commercial structure that does not require private returns on capital. The consequence is a levelised cost of enrichment at Russian facilities estimated at roughly two-thirds of comparable Western levels of the cost at comparable Western plants. (Bukharin, 2004).

In practice, when European utilities compared bids, this differential manifested in reported contract premiums of approximately EUR 150 million per enrichment contract in favour of Rosatom. A figure so large that one Czech utility explicitly cited it as the reason for renewing its Russian supply relationship despite political concerns after February 2022 (Rosatom Newsletter, 2022).

The conversion stage also reveals the first instance of the Niger-Kazakhstan structural divergence. Niger's uranium was converted by Orano at its French facilities as a matter of operational routine: yellowcake from Arlit was shipped in drums to Malvési, converted to UF<sub>6</sub>, and then transferred to Tricastin for enrichment, all within Orano's integrated operational control. Kazakhstan's yellowcake, by contrast, enters a more complex routing system. Kazatomprom's export of uranium as U<sub>3</sub>O<sub>8</sub> yellowcake or as UO<sub>2</sub> requires conversion services that are contracted separately from mining. The use of the Trans-Caspian International Transport Route (TITR), developed since 2022 as an alternative to the Russian rail corridor, adds further complexity: Kazatomprom's test delivery to Canada in autumn 2022 demonstrated the feasibility of the Middle Corridor bypass, but the route's bottlenecks in port capacity at Aktau, rail gauge changes through Georgia, and terminal capacity at Turkish ports mean that it cannot currently substitute for the Russian corridor at the commercial scale for France's annual requirements of approximately 8,200 tonnes of natural uranium (FIIA, 2024).

### ***1.3.3 Stage 3: Enrichment***

Enrichment is the most technically demanding and most strategically sensitive stage of the nuclear fuel cycle. Its purpose is to increase the concentration of the fissile isotope U-235 from its natural level of 0.7204% to the 3 to 5% required for commercial light-water reactor fuel, or to the over 90% required for weapons-grade highly enriched uranium (HEU). Grenèche (2016) provides a detailed technical analysis of the two principal commercial enrichment technologies: gaseous diffusion (GD), which dominated the industry from the 1950s through the 1990s and exploited the marginally higher diffusion speed of lighter <sup>235</sup>UF<sub>6</sub> molecules through porous barriers, and gas centrifuge technology, which has now completely displaced GD in commercial applications. Grenèche (2016) notes the decisive economic comparison: a gaseous diffusion plant of 10 million SWU per year capacity (such

as the Georges-Besse I plant that France operated at Tricastin until 2012) consumed approximately 2,500 megawatts of electricity, equivalent to the output of nearly three 900 MWe nuclear reactors, while a centrifuge plant of equivalent capacity consumes 50 times less energy. This energy efficiency differential made the transition to centrifuge technology economically irresistible.

The Separative Work Unit (SWU) is the standard measure of enrichment capacity. Hore-Lacy (2016) provides the practical calculation: producing 1 tonne of enriched uranium at 4% U-235 (typical for modern PWR fuel) from natural uranium feed at 0.71% with tails at 0.30% requires approximately *7.3 to 8 tonnes of natural uranium and approximately 4.3 tSWU of enrichment capacity* (the prefix *t* denoting thousands of SWU). A typical 1,300 MWe PWR, the dominant reactor type in France's fleet, requires approximately 25 tonnes of enriched uranium per year, produced from around 210 tonnes of natural uranium and having used approximately 120 tSWU. France's fleet of 56 to 57 reactors therefore requires approximately 8,200 tonnes of natural uranium and approximately 6,700 tSWU of enrichment capacity annually (Hore-Lacy, 2016; World Nuclear Association, 2026).

France's enrichment capacity is provided by Orano's Georges-Besse II plant at Tricastin, which reached its designed capacity of 7.5 million SWU per year in 2016. It uses TC12 centrifuge technology, developed jointly with Urenco through their 50-50 joint venture “*Enrichment Technology Company*”. The plant's capacity will be expanded by approximately 30% to serve both French domestic demand and to help reduce European dependence on Russian enrichment services (Grenèche, 2016; IAR, 2026). Even without this expansion, France's own enrichment capacity is important enough to cover its domestic low-enriched uranium (LEU, 3–5% U-235) requirements for civil reactors. However, another dependency concerns reprocessed uranium (RepU), the uranium recovered when France reprocesses its spent fuel at La Hague under its closed-cycle strategy (detailed in §1.5). Because this recovered uranium can be re-enriched and reused, it reduces the volume of fresh natural uranium France must import; but re-enriching it historically relied on Rosatom's Seversk facility. Between 2021 and 2022, Orano sent 1,150 tonnes of RepU to Russia for re-enrichment, precisely because dedicated centrifuge lines for RepU feedstock did not exist at commercial scale (Wimmers et al., 2026).

This RepU dependency illustrates, at the enrichment stage, the same structural pattern just described for conversion: a Russian facility that is not technically irreplaceable but commercially decisive. The cost penalty of re-enriching RepU at Georges-Besse II rather than

at Seversk is amplified by a technical asymmetry, since RepU contains uranium-236, a neutron-absorbing isotope requiring a higher enrichment assay to compensate for its parasitic neutron capture, and Orano did not, prior to the post-2022 expansion programme, possess dedicated centrifuge lines calibrated for this heterogeneous feedstock (Orano, 2022; Al Habtoor Research Centre, 2026; OECD-NEA, 2021). The question of full autonomy is therefore one of cost, not of technical impossibility. France's annual RepU output of approximately 1,045 tonnes (recovered from the ~1,050 t of spent fuel reprocessed annually) implies a re-enrichment requirement of roughly 700 to 900 tSWU per year, around 10 to 12% of Tricastin's current capacity, indicating that the infrastructure gap is closable, but at a premium estimated across the industry at 30 to 40% above Russian prices (Bukharin, 2004; Guzman, 2025). At the 2025 SWU spot price of approximately USD 188, against a pre-Ukraine level of approximately USD 60, re-enriching France's entire RepU output domestically rather than through Rosatom implies an annual differential of the order of USD 90 to 120 million, well under 0.1% of EDF's annual revenue (Guzman, 2025; TradeTech, 2024). The cost of sovereignty, in this case, was always affordable; what was lacking was not the financial means but the political will and the regulatory framework to prioritise security of supply over marginal cost reduction.

The global enrichment market is highly concentrated in ways that the front-end of the supply chain reveals with particular clarity. Rosatom controls approximately 44% of global enrichment capacity at approximately 27.1 million SWU out of a global total of approximately 61.5 million SWU. They are operating through four enrichment plants: Novouralsk (10 million SWU per year), Zelenogorsk (8.7 million SWU), Seversk (3 million SWU) and Angarsk (2.6 million SWU) (in addition to which there is spare capacity) (Hore-Lacy, 2016; Al Habtoor Research Centre, 2026). Urenco holds the second position at approximately 16.5 million SWU, followed by Orano at 7.5 million SWU. CNNC of China controls approximately 9 million SWU but its capacity is not accessible to Western utilities (Guzman, 2025). As Grenèche (2016) notes with striking historical context, Russia's dominance in enrichment reflects not commercial strategy alone but the inheritance of a Soviet enrichment programme developed from the late 1940s, which pursued gas centrifuge technology at industrial scale decades before Western competitors, accumulating generations of machine improvements that gave Russian centrifuges their current cost and capacity advantages.

The enrichment market's concentration generates an HHI of approximately 3,200 points, well above the 2,500-point threshold at which US antitrust authorities classify markets as highly

concentrated (US Department of Justice, 2023). For France, this concentration means that even if Kazakhstani yellowcake is converted at the Malvési-Pierrelatte facilities and enriched at Tricastin, the RepU generated by France's reprocessing operations has historically required Russian enrichment infrastructure, creating a circular dependency that persists beneath the surface of apparent domestic self-sufficiency.

#### ***1.3.4 Stage 4: Fuel Fabrication***

Following enrichment, uranium hexafluoride must be converted back to uranium dioxide (UO<sub>2</sub>) powder through a defluorination process, and then fabricated into the engineered fuel assemblies that are loaded into reactor cores. Hore-Lacy (2016) provides a detailed account of this manufacturing process. The enriched UF<sub>6</sub> is converted back into UO<sub>2</sub> powder and fabricated into ceramic pellets, which are loaded into zirconium alloy cladding tubes, M5 alloy in French-designed reactors, and assembled into fuel assemblies whose geometry is specific to the reactor design and the nuclear steam supply system vendor (Hore-Lacy, 2016; Grenèche, 2016).

This dimensional and material specificity of fuel assemblies is one of the most telling features of the nuclear supply chain for this thesis. A PWR fuel assembly designed for an Orano-Framatome reactor cannot be substituted with a fuel assembly designed for a VVER reactor without regulatory re-licensing, physical modification of the reactor internals, or both. A process that typically requires 2 to 5 years (Wimmers et al., 2026). This asset specificity means that France's fleet of 56 to 57 PWRs is locked into Framatome fuel assembly specifications, which in turn locks France into a supply chain that passes through Orano's fuel fabrication facilities at Romans-sur-Isère. This is a structural dependency that does not appear in uranium import statistics but is as real and as costly to exit as any upstream supply relationship.

France's fuel fabrication stage is relatively autonomous by international standards. Framatome, jointly owned by EDF and Orano, operates one of the world's largest PWR fuel fabrication facilities, capable of supplying all of EDF's annual requirements as well as exporting fuel assemblies to foreign customers. The fabrication stage therefore represents a point of genuine French control in the supply chain, in contrast to the upstream extraction and conversion stages where foreign dependencies are concentrated. However, this autonomy is conditional: it depends on the uninterrupted supply of enriched UF<sub>6</sub> from Tricastin and, indirectly, on the enriched uranium produced from Kazakhstani and other foreign-sourced

natural uranium.

#### **1.4 From Civil Fuel to Military Application: The Dual-Use Architecture**

The nuclear fuel cycle described above serves France's civil electricity program. But uranium also feeds France's independent nuclear deterrent, the *Force de Frappe*, and the relationship between civil and military applications of nuclear materials is both technically distinct and politically intricate. Understanding this dual-use architecture is essential for grasping why France's uranium dependency is not simply an energy security question but a national sovereignty question.

France maintains an independent nuclear arsenal estimated at approximately 290 warheads as of 2025, with President Macron announcing plans in March 2026 to increase this number while refining the doctrine of 'strict sufficiency' toward what is now described as 'forward deterrence' in a European strategic context (Élysée, 2026). The military nuclear program relies on two fissile materials: *highly enriched uranium (HEU), defined as uranium enriched to over 90% U-235, and weapons-grade plutonium-239 of high isotopic purity*. These materials are categorically different from the low-enriched uranium (LEU, 3-5% U-235) used in civil power reactors. France ceased production of new weapons-grade fissile material in the 1990s: HEU production for military purposes stopped in 1996, and weapons-grade plutonium production stopped earlier. The arsenal is now only sustained through existing stockpiles, estimated at approximately 25 plus or minus 6 tonnes of military HEU and 6 tonnes of weapons-grade plutonium, supplemented by ongoing maintenance, disassembly and reassembly programs that do not require new fissile material production at scale (ASNR, 2025; Grenèche, 2016).

Grenèche (2016) is explicit about the historical entanglement of civil and military nuclear activities in France: the CEA and later Cogema-Areva-Orano maintained *technological synergies between the two domains, particularly in enrichment and reprocessing know-how*. The Pierrelatte enrichment facility was originally built to manufacture HEU for military purposes and was subsequently converted to civil enrichment after France joined the Nuclear Non-Proliferation Treaty (NPT). La Hague's reprocessing capabilities, now used exclusively for civil spent fuel reprocessing under NPT commitments, share the same PUREX chemistry originally developed for military plutonium separation. This entanglement creates an important analytical dimension: France's formal separation of civil and military material

flows, required by its NPT commitments and its self-imposed moratorium on fissile material production for weapons purposes, does not mean that the industrial knowledge base is separable.

This historical continuity carries a contemporary implication: the civil enrichment programme is, in effect, the custodian of the industrial knowledge base that France's status as a nuclear-weapon state presupposes. A sustained interruption of civil enrichment operations would erode this base through workforce dispersal within a few years, a form of non-material asset specificity that conventional supply chain analysis underweights

The civil-military entanglement has a direct consequence for supply chain vulnerability analysis. A disruption severe enough to compromise France's enrichment or conversion capacity would not only threaten the fuel supply for EDF's reactors, it would raise longer-term questions about France's capacity to maintain the industrial base that the credibility of its nuclear deterrent indirectly depends upon. The stockpiles of military HEU and weapons-grade plutonium provide a substantial buffer: a disruption at the natural uranium supply level would not immediately compromise the arsenal. But a sustained disruption of the front-end fuel cycle infrastructure would, over time, erode France's industrial nuclear sovereignty in ways that extend well beyond electricity prices.

Tritium illustrates this industrial lock-in in its most concrete and least-discussed form. A hydrogen isotope required for the boosted stages of modern warheads, tritium has a half-life of only 12.3 years and must therefore be continuously replenished in the active arsenal, an operation that depends on the very front-end infrastructure analysed in this chapter. France produces tritium in dedicated facilities operated by the CEA whose fuel requirements draw on the same enrichment infrastructure as the civil programme (IPFM, 2023; Cochran and Norris, 2012). The connection is indirect but structural: while existing HEU and plutonium stockpiles insulate the arsenal from short-term supply shocks, the maintenance cycle of the deterrent depends, over a horizon of ten to fifteen years, on the continuity of the same front-end infrastructure that fuels EDF's reactors

This dual-use dimension also explains the particularly acute French sensitivity to the question of enrichment technology export. France's decision to develop the Georges-Besse II centrifuge plant using technology jointly owned with Urenco, rather than developing independent French centrifuge technology, reflected a commercial calculation whose strategic dimensions were perhaps underappreciated at the time. As Grenèche (2016) notes, the

conversion to centrifuge technology was economically compelling, 50 times less energy consumption than gaseous diffusion, but it also created a technological dependency on a joint venture whose governance involved British, Dutch and German partners. This is not a security vulnerability in the conventional sense, but it illustrates the broader principle that each stage of the nuclear fuel cycle involves choices between autonomy and efficiency that have long-term structural consequences.

## **1.5 France's Position in the Global Nuclear Industry: Capabilities and Structural Limits to Autonomy**

Having traced the full technical architecture of the nuclear fuel cycle, it is now possible to position France within the global industry and to identify, with analytical specificity, the stages at which France retains genuine operational control and the stages at which its dependence on external actors is structurally unavoidable.

France occupies a commanding position at several points in the global nuclear industry. Through Orano, it is the world's third largest uranium mining company by production, with operations in Kazakhstan, Canada and historically Niger, holding proven and probable reserves covering over 20 years of supply requirements across its portfolio (Orano, 2024). Through its Malvési-Pierrelatte conversion complex, it controls one of only five operational uranium conversion facilities in the world, with a capacity of 9,000 tonnes per year. Through Orano's Georges-Besse II facility, it operates the third largest commercial enrichment plant in the Western world at 7.5 million SWU per year, rising toward 10 million SWU as the expansion progresses. Through Framatome, it is one of the world's two principal Western PWR fuel fabricators. Through La Hague, it operates *far and away the most important reprocessing plant of this type in the world*, in Grenèche's (2016) assessment, with a total treatment capacity of 1,700 tonnes of spent fuel per year and a total storage capacity of 17,600 tonnes, an industrial asset without parallel in the Western nuclear world.

Yet despite this formidable industrial position, France cannot be considered self-sufficient in uranium supply. It ceased domestic uranium mining in 2001 when the last mine, Jouac in the Haute-Vienne, was exhausted, and all subsequent domestic production has been zero. Its identified domestic resources, including the potentially significant Coutras deposit in the Gironde, have grades of 1 to 5 kilograms of uranium per tonne of rock, compared to grades of 100 kilograms per tonne in world-class Canadian deposits. The extraction cost of French

domestic uranium resources is estimated above 130 USD per kilogram, at or above the prevailing spot price for most of the post-2011 period, making domestic production economically irrational under normal market conditions (Planet-Terre ENS Lyon, 2021; Connaissance des Energies, 2024).

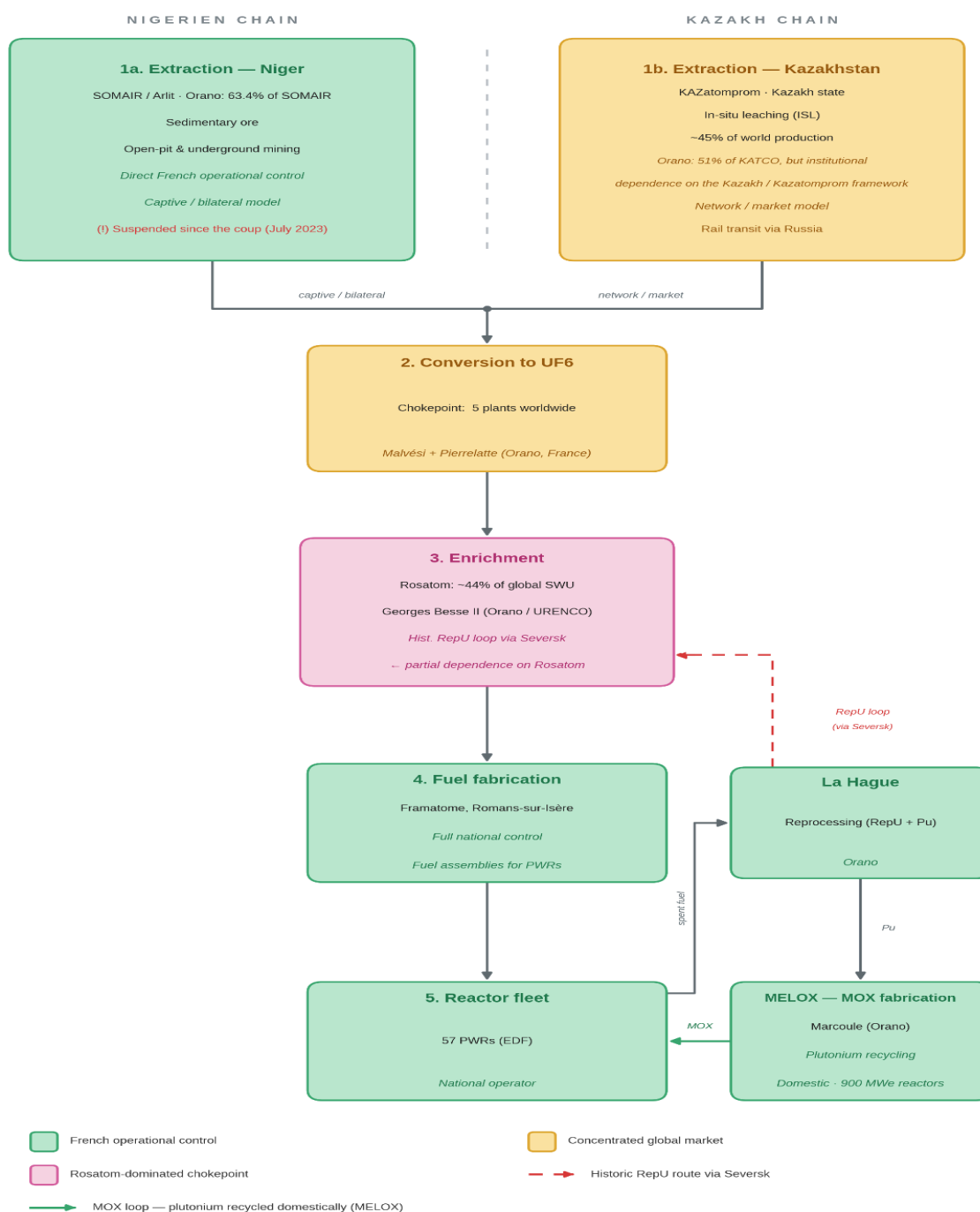
The structural limits to France's autonomy therefore concentrate at the first stage of the fuel cycle: extraction. Everything that follows extraction, conversion, enrichment, fabrication, and recycling, is either controlled by French-owned entities or can be performed within French territory. But the 100% of France's natural uranium requirements must be sourced abroad, a dependency that reflects not geological impossibility but the rational economic choice of a country that found it cheaper to purchase uranium from low-cost producers in Central Asia and West Africa than to develop its own high-cost domestic deposits. That rational economic choice, made and remade over five decades, has created the structural dependency that this thesis analyses.

Two additional structural limits deserve explicit identification. The first is the reprocessing-dependent nature of France's fuel strategy. EDF has chosen the *closed fuel cycle*: rather than treating spent fuel as waste, it reprocesses it at La Hague using the PUREX process, which separates the reusable materials from the fission products. This yields two recyclable streams. The recovered plutonium is fabricated into mixed-oxide (MOX) fuel assemblies at the MELOX plant in Marcoule and reloaded into EDF's 900 MWe reactors; the recovered uranium (RepU) can be re-enriched and recycled into standard reactor fuel, the dependency analysed in §1.3.3. Grenèche (2016) notes that the roughly 1,050 tonnes of spent fuel reprocessed annually at La Hague generate both streams, whose management requires the continuous operation of the entire closed-cycle infrastructure. If any stage of that infrastructure, reprocessing, MOX fabrication, or RepU re-enrichment, is disrupted, the coherence of the strategy is compromised.

The second structural limit is the front-end inelasticity documented throughout this chapter. Uranium demand from France's operating reactor fleet is technically rigid and contractually locked-in: each reactor requires continuous fuel supply, fuel assemblies are designed to reactor-specific specifications, and the typical refuelling outage cycle of 12 to 18 months means that a supply disruption must be anticipated and compensated well in advance, not in real time. France's strategic stockpiles, estimated at approximately 2 years of natural uranium and 7 to 8 years of enriched uranium equivalent in depleted and reprocessed stocks, provide a buffer that allows time for supply route adjustments but do not eliminate the underlying

structural dependency on imported natural uranium (Orano, 2023).

**Figure 1 - A comparison of France's uranium supply chains: the Nigerien captive model and the Kazakhstani network model**



Note: the Nigerien chain = direct Orano control (captive/bilateral model); the Kazakh chain = market purchase via KAZatomprom (network/market model). Both chains converge at conversion (Malvési/Pierrelatte, Orano), then feed a common cycle under national control. Spent fuel is reprocessed at La Hague into two streams: RepU (re-enriched, historically via Seversk) and plutonium (MOX, fabricated at MELOX, fully domestic).

Source: Author's own table, Empirical data drawn from World Nuclear Association, Uranium Mining Overview, Conversion and Deconversion and Uranium Enrichment; IAEA/OECD-NEA, Uranium 2022: Resources, Production and Demand ('the Red Book', 2023); Orano, Annual activity reports (2021-2023) and institutional documentation on the Malvési, Pierrelatte and La Hague sites; KAZatomprom, Annual Reports; EDF, Le parc nucléaire français; Framatome institutional documentation; and the French Cour des comptes reports on the nuclear fuel cycle

## **II. Historical and Structural Foundations of France's Uranium Supply: Niger and Kazakhstan**

The preceding chapter traced the nuclear fuel cycle as a universal technical sequence. Its analytical value lies not in the technical description itself but in what it reveals about the structural configuration of France's dependency within that sequence, which differs fundamentally between its two principal supplier relationships. Before retracing the history of each model, it is worth stating the two structural configurations that this history produced.

In the Niger model, France's integration into the supply chain began at Stage 1 and extended through the beginning of Stage 2. Orano and its predecessors held majority equity stakes in both Somaïr (63.4%) and Cominak (34%), operating the mines directly with French technical management and locally recruited Nigerien labour. Yellowcake from Arlit was transported in sealed drums via the road corridor through Agadez to the Benin port of Cotonou, then to the Malvési conversion plant and on to Pierrelatte, the entire sequence from extraction to enrichment feedstock remaining within Orano's operational control, with the Nigerien state as a minority financial participant rather than an operational counterpart. This corresponds to what Gereffi and Fernandez-Stark (2016) characterise as a captive-to-hierarchical governance structure.

In the Kazakhstan model, France's integration begins at Stage 1 but through a fundamentally different mechanism. Orano participates through a joint venture, KATCO, at the South Tortkuduk site, as a commercial partner (51% stake) alongside the state-owned Kazatomprom. Kazakhstani yellowcake is produced by ISL operations that do not require French operational management, sold under commercial contracts referenced to the international spot market, and exported through transport corridors France does not control. Its conversion may occur at Malvési-Pierrelatte or, historically, through Russian infrastructure; enrichment of the resulting UF<sub>6</sub> may be performed at Tricastin or, for RepU, at Rosatom's Seversk facility. At no point does France exercise the operational control it held in Niger.

This structural contrast is what Part III will analyse through the three-dimensional framework of control, geopolitical exposure and supply chain structure. It is precisely because each stage of the cycle creates its own governance structure and its own form of lock-in that the shift from Niger to Kazakhstan represents not a reduction of dependency but its transformation into a qualitatively different and less manageable form. This chapter now turns to the

historical and institutional construction of those two models: each agreement examined below represents a layer of institutional lock-in that shaped France's dependence long before uranium volumes became an object of policy concern.

## **2.1 The Niger Model: Post-Colonial Integration and the Construction of Bilateral Dependence**

### ***2.1.1 The 1960 Defence Accords as the Institutional Foundation***

France's uranium dependency on Niger did not begin with the construction of a mine. It began with a set of political agreements signed at the moment of Nigerien independence that embedded resource access within a comprehensive framework of mutual obligation. The defence and cooperation accords signed between France and Niger in April 1960, part of a wider set of bilateral treaties concluded with twelve former African colonies at independence, established what Hecht (2012) describes as the foundational architecture of la Françafrique: a system in which France guaranteed the external security and internal political stability of newly independent African governments in exchange for privileged access to their strategic resources and continued influence over their foreign policy.

These accords were not entirely diplomatic instruments. Bayart (1989), in his foundational analysis of African post-colonial states, demonstrates that such agreements created a specific political economy in which the extraction of resource rents by ruling elites became structurally dependent on the maintenance of preferential relationships with the former colonial power. Under what Bayart terms the '*politique du ventre*', the ability of African political leaders to distribute patronage to their networks of political support depended directly on the flows of royalties, dividends, development assistance, and military guarantees that France made available through these bilateral arrangements. This was not a passive relationship: successive Nigerien presidents actively sought to maximise their extraction from the French connection, while France systematically managed the terms of that extraction through its control over mining contracts, pricing mechanisms, and the institutional architecture of the joint ventures.

The defence accords thus constituted the first form of asset specificity in France's Nigerien dependency, preceding the physical investments in mining infrastructure by a decade. The lock-in was political before it was economic: Niger's ruling elite had, from the moment of

independence, calibrated its political survival strategies around the maintenance of the French relationship, making a clean rupture intrinsically costly for both parties in ways that went well beyond the commercial value of the uranium traded.

### ***2.1.2 The Creation of Somaïr and Cominak: Joint Ventures as Control Instruments***

The first uranium mine at Arlit was developed between 1967 and 1971 under the auspices of the Société des Mines de l'Air (Somaïr), a joint venture in which the French Atomic Energy Commission (CEA) and later Cogema held the majority shareholding. The capital structure of Somaïr, in which Orano's predecessor entities ultimately held 63.4%, was not the result of commercial negotiation between equal parties but of a design in which the majority position was treated from the outset as a prerequisite for French operational control. The Nigerien state's minority shareholding (initially 33%, later consolidated to 36.6%) was structured to provide royalty income and political legitimacy without conferring operational authority over extraction decisions, pricing terms, or export arrangements.

The second joint venture, Cominak (Compagnie Minière d'Akouta), was established in 1974 to exploit the underground Akouta deposit at depths of approximately 250 metres. Its capital structure was more complex, involving Spanish and Japanese partners alongside the French and Nigerien shareholders, with Orano holding a 34% stake and the Nigerien state 33%. Despite this more diversified ownership, operational management remained under French technical authority: the CEA and Cogema provided the engineering, geological, and hydrogeological expertise without which the underground mine could not be exploited, and this technical indispensability was the operational foundation of French control irrespective of the equity distribution.

Applied to these joint ventures, Gereffi and Fernandez-Stark's (2016) three governance variables (information complexity, codifiability, and supplier competence) point unambiguously toward the captive or hierarchical end of the governance spectrum. This diagnosis is developed in full in Part III, section 3.2.1.

### ***2.1.3 The Price Negotiations of the 1970s: Statecraft Behind Banalisation***

The 1973 oil shock created the first sustained political challenge to the terms of France's uranium relationship with Niger. President Hamani Diori, observing that the quadrupling of oil prices had transferred enormous rents from consumer to producer states, proposed in 1974 that the price of Nigerien uranium would be indexed to the price of oil,

arguing that uranium's role in fuelling both France's nuclear power programme and its force de frappe conferred an exceptional strategic value that should be reflected in the contract price.

The French response, documented in detail by Hecht (2012), was to invoke the logic of the international uranium market: uranium was an ordinary commodity whose price was determined by supply and demand, not by its geopolitical function for France's energy security. Nigerien uranium should be priced at the market rate, not at a strategic premium. This position was maintained through three successive renegotiations in 1974, 1976, and 1978. These negotiations did produce significant economic gains for Niger, but they fell short of the oil-indexed or strategically revalued price that Nigerien negotiators had sought. The price paid for Nigerien uranium rose from around 5,000 CFA francs per kilogram in 1971 to 24,500 CFA francs per kilogram in 1980. Combined with rising production, this helped Niger's state budget increase from about 11 billion CFA francs in 1971 to 93.8 billion in 1982, while uranium came to represent more than 80% of exports and around 50% of state revenue (Grégoire, 2011)

Baldwin (1985), in his foundational analysis of economic statecraft, demonstrates that economic instruments, including the management of pricing relationships, access to markets, and the terms of contractual arrangements, constitute forms of political leverage as consequential as military or diplomatic tools, precisely because they operate below the threshold of political visibility. The French refusal to acknowledge uranium's strategic value was not a commercial position; it was an act of economic statecraft that maintained France's privileged access to African uranium by denying the political significance of that access. In Baldwin's framework, the success of this instrument depended on the asymmetry of information between the parties: French negotiators knew the full strategic value of the resource; Nigerien negotiators were systematically denied the institutional and technical capacity to calculate it independently. Hecht's concept of banalisation is, in this analytical register, the rhetorical form that economic statecraft takes when it seeks to efface its own exercise of power.

#### ***2.1.4 Operations Barkhane and Serval: The Military Architecture of Supply Security***

The security dimension of France's Nigerien uranium relationship extended well beyond the 1960 defence accords. France's sustained military presence in the Sahel, formalised through operations Serval (2013, Mali) and Barkhane (2014-2022, multi-country)

(Ministère des Armées, 2023; Le Monde, 2022), was never officially presented as a resource security instrument. Its stated objectives were counter-terrorism and state stabilisation. Yet the structural function of this presence in the context of uranium supply security is undeniable: French military capacity in the Sahel constituted an implicit guarantee of political stability in the states from which France sourced its uranium, and the revocation of that guarantee, through the withdrawal of French forces following the Malian coup of 2021 and the Nigerien coup of 2023, directly preceded the rupture of the supply relationship.

This relationship between military presence and resource access illustrates a broader dynamic in the Françafrique model that Bayart (1989) captures through his analysis of the '*extraversion*' strategies of African elites: the capacity of ruling groups to mobilise external resources, including military protection, in the service of their internal political consolidation. For successive Nigerien governments, the French military presence was a resource to be extracted from the bilateral relationship just as uranium was. When that presence became politically delegitimised, first in Mali, then in Burkina Faso, finally in Niger, the political calculus changed: the costs of maintaining the French relationship (popular delegitimation, exposure to the 'neo-colonial' critique amplified by Russian information operations) began to exceed its benefits (military protection, development assistance, dividend income from the mining JVs). The coup of July 2023 was, in this analytical framework, the moment at which a new coalition of Nigerien political actors recalculated this balance and found it no longer in their favour.

### ***2.1.5 The Russian Factor: Catalyst or Cause?***

The role of Russian actors in the rupture between France and Niger requires careful analytical treatment. The temptation to read the coup of July 2023 as a Russian operation, exploiting anti-French sentiment to disrupt France's uranium supply, is superficial and empirically contested.

Le Billon (2004, 2012) provides the more consequential rigorous framework. In his theory of the geopolitics of resource wars, Le Billon demonstrates that states whose economies are structured around extractive resource rents develop a specific form of political instability: the control of resource access becomes the central prize of elite competition, making coups structurally rational as a mechanism for new coalitions to capture rents previously monopolised by incumbent governments. In this framework, the coup of July 2023 and the subsequent revocation of Orano's licences are not irrational acts of Russian manipulation:

they are the expression of a coherent political rationality within a rentier state in which uranium represented approximately 31% of export revenues in 2022 (IMF, 2024) and in which the terms of the mining agreements had been a contested political issue since the price negotiations of the 1970s.

What Russia provided was not the cause but the permissive context: the Wagner Group's presence in neighbouring Mali and Burkina Faso demonstrated that an alternative security architecture existed that did not require the maintenance of the French relationship, reducing the cost of rupture for Nigerien military actors who had already concluded that the Françafrique bargain no longer served their interests. Bloomberg's reporting in June 2024 that Rosatom had contacted the junta regarding the potential acquisition of Orano's assets confirms that Russian strategic actors were ready to exploit the rupture (Bloomberg, 2024), but exploitation of an opportunity is distinct from its creation.

It is worth clarifying what Russia stood to gain, since its interest was strategic rather than geological. Russia did not need Nigerien uranium to fuel its own reactors: it holds ample domestic resources and already controls a substantial share of Kazakhstan's output through Rosatom's subsidiaries. The value of capturing Nigerien assets was subtractive rather than additive (each asset redirected toward Rosatom is one removed from the Western chain) and consolidative, extending Russia's position as a vertically integrated market-maker whose dominance lies in the downstream stages where Nigerien yellowcake would ultimately be processed. Acquiring Nigerien uranium was therefore not a supply requirement but a network move: a way to deny France a historic source while reinforcing Moscow's leverage over the global fuel cycle, and to anchor its broader political substitution for France in the Sahel.

The analytical implication for this thesis is significant: if the Russian role is catalytic rather than causal, then the counterfactual in which France maintained better relations with Nigerien civil society, distributed more of the uranium rents to the population, and avoided the delegitimation of the Françafrique model would have been more effective than any counter-information strategy against Russian influence. The structural conditions for the rupture were internal to the bilateral relationship. Russia accelerated a dynamic, it did not create it.

### ***2.1.6 The Dismantlement of the Niger Model: Sequence and Implications (2020-2024)***

The institutional dismantlement of the Niger model followed a sequential logic that mirrors, in reverse, the order of its construction. First, (1) the political legitimacy of the relationship was contested (decades of popular mobilisation against Françafrique, accelerating from 2020). Second, (2) the military guarantee was withdrawn (Barkhane terminated, French troops expelled, 2023). Third, (3) the mining licences were revoked (Imouraren, June 2024; Arlit operations suspended, October 2024). Each layer of the institutional architecture collapsed in the order of its political contestability, with the most visible and publicly debated elements (military presence) falling first and the most deeply embedded (operating licences) falling last.

The economic costs of this dismantlement for Niger were substantial: uranium exports had represented approximately 31% of export revenues (IMF, 2024), and Orano's local recruitment meant that several thousand Nigerien workers lost their livelihoods directly. For France, the immediate supply impact was significant but manageable within the buffer provided by strategic stocks, and procurement was partially redirected toward Kazakhstan within eighteen months. The long-term structural consequence, France permanently losing its direct operational presence in one of the historically significant uranium districts of the world, and the possibility of Russian or Chinese actors acquiring those assets, is more difficult to quantify but potentially more consequential.

## **2.2 The Kazakhstan Model: Industrial Partnership in a Globalised Chain**

### ***2.2.1 The Post-Soviet Context: From Soviet Infrastructure to Kazakhstani Sovereignty***

Kazakhstan's emergence as the world's dominant uranium producer is inseparable from the dissolution of the Soviet Union in 1991. The Kazakh Soviet Socialist Republic had hosted significant uranium extraction operations since the 1940s, producing uranium for the Soviet military programme from sandstone deposits in the Chu-Saryssu and Syr Darya basins using a combination of conventional mining and early in-situ leaching techniques. At independence, the new Kazakhstani state inherited this infrastructure, along with a trained technical workforce and a portfolio of partially developed deposits, but without the institutional framework to commercialise these assets on international markets or the political relationships to attract Western capital.

Kazatomprom was established by presidential decree in 1997 as the national nuclear holding company, bringing together the previously fragmented uranium mining enterprises under state control. Its creation was explicitly conceived as an instrument of economic sovereignty: uranium was to be the resource through which Kazakhstan would build an independent industrial base and attract foreign investment on its own terms, rather than as a subordinate supplier to Russian nuclear infrastructure. This founding logic, state-directed resource nationalisation as a vehicle for functional upgrading, distinguishes the Kazakhstani model from the Niger model at the level of political economy: whereas Niger was designed from the outset as a subordinate extraction territory within a French-controlled value chain, Kazakhstan entered the international uranium market as a state with pre-existing technical capacity and a deliberate strategy for expanding its role in the chain.

This distinction maps directly onto the third governance variable of Gereffi and Fernandez-Stark (2016): supplier competence. Kazakhstan entered its joint ventures with Western partners not as a passive host territory requiring imported expertise, but as a technically sophisticated partner with its own geological knowledge, extraction capabilities, and institutional infrastructure. The joint ventures that Kazakhstan negotiated with Orano, Cameco, and other Western partners were designed by the Kazakhstani side as vehicles for technology transfer and market access, not as instruments of foreign operational control. This asymmetry with the Niger case has profound implications for the governance structure of the resulting supply relationships.

### ***2.2.2 The Creation of KATCO and the KATCO Contract Architecture***

KATCO (Kazakhstan-Total-Cogema) was established in 1996 as a joint venture between Cogema (subsequently renamed Areva and then Orano) and Kazatomprom, with Orano holding a 51% majority stake and Kazatomprom 49%. Its objective was the development and operation of in-situ leaching uranium mines at the Muyunkum and Tortkuduk deposits in the Turkestan region of southern Kazakhstan. The subsoil use contract governing KATCO's operations was concluded with the Kazakhstani government for an initial period and has been extended and renegotiated on several occasions, most recently in August 2022 when an addendum to the existing subsoil use contract (August 2022), securing production for around fifteen years, ensured the development of the South Tortkuduk parcel (estimated reserves of 46,000 tonnes of uranium).

The capital structure of KATCO appears, at first glance, to give France a governance position analogous to that which it held in Niger: a majority equity stake in the operating entity. But the analogy is misleading. In the Niger case, majority equity translated into hierarchical operational control because the Nigerien state had no independent technical capacity and could not credibly threaten to operate the mines without French involvement. In the Kazakhstan case, Kazatomprom's technical mastery of ISL extraction (it was already the world's most experienced ISL operator at the time KATCO was created) means that the majority equity stake does not confer operational indispensability. Orano is a financial and technical partner in KATCO; it is not the sole technically capable actor in the relationship.

This distinction between equity control and operational control is central to understanding the governance type of the Kazakhstan model. A majority equity stake does not, here, translate into the operational indispensability that defined the Niger relationship: Kazatomprom is a technically autonomous partner, not a captive supplier. The full diagnosis through Gereffi and Fernandez-Stark's (2016) three governance variables; information complexity, codifiability, and supplier competence; is developed in Part III, section 3.2.2, where it places the Kazakhstan model at the relational to modular end of the spectrum: Orano is a buyer in a chain it does not govern, rather than the lead firm of a chain it controls.

### ***2.2.3 The Enrichment Agreements with Rosatom: The Hidden Dependency***

The most consequential dimension of the Kazakhstani supply model is not visible in the KATCO joint venture structure or in the bilateral France-Kazakhstan import statistics. It lies in the downstream processing agreements through which Kazakhstani uranium was converted and enriched before being loaded into French reactors.

Kazakhstan produces uranium as yellowcake (U<sub>3</sub>O<sub>8</sub> concentrate), which must be converted to uranium hexafluoride (UF<sub>6</sub>) before it can be enriched. Until the post-2022 expansion of Orano's Malvesi-Pierrelatte conversion complex, the most commercially attractive route for Kazakhstani yellowcake destined for enrichment was through Russian conversion infrastructure: the Seversk plant operated by Rosatom at 96% of capacity in 2022, the highest utilisation rate among all global conversion plants, while the American ConverDyn plant had been entirely offline since 2017 (Wimmers et al., 2026). The physical geography of Central Asian nuclear logistics reinforced this routing: the primary export corridor for Kazakhstani

uranium ran through Russian territory, making Russian processing infrastructure the path of least commercial and logistical resistance.

The re-enrichment of reprocessed uranium (RepU) constituted an additional and more politically sensitive dependency. As analysed in Part I (§1.3.3), France's closed fuel cycle produces RepU that, lacking dedicated domestic centrifuge lines, was routed to Rosatom's Seversk facility under commercial contract, at a cost differential over domestic re-enrichment small enough (well under 1% of EDF's revenue) to confirm that the choice reflected commercial optimisation rather than financial necessity.

These enrichment and conversion agreements represent the mechanism through which the Kazakhstan model generated its characteristic form of network dependency. France was not dependent on Kazakhstan through a bilateral relationship as it was on Niger; it was dependent on a supply chain architecture in which Kazakhstan provided the upstream resource, Russia provided critical midstream processing services, and the commercial logic of cost minimisation made this architecture appear rational at each individual contracting decision. This is the dynamic that Keohane and Nye (1977) capture through their distinction between sensitivity and vulnerability: France had low sensitivity to this dependency (the arrangements were cost-competitive, the reactors ran without interruption, no political crisis was visible) while its structural vulnerability, the cost of adapting if the Rosatom processing nodes were closed, was high and growing with each renewal of enrichment contracts.

#### ***2.2.4 Rosatom's Expanding Equity Presence in Kazakhstan (2022)***

The Russian invasion of Ukraine in February 2022 allowed an acute strategic dissonance in France's Kazakhstan model: the political imperative to reduce dependence on Russian nuclear services coincided with a commercial and logistical reality in which the supply chain remained deeply entangled with Russian infrastructure. The dissonance was further deepened by Rosatom's acquisition: In late 2022, of a 49% equity stake in the Budenovskoye uranium deposit in Kazakhstan, expected to become the world's single largest uranium source once fully developed, with all output reserved for Russian industry until 2026 (Caspian Policy Center, 2024).

Rosatom's Uranium One subsidiary was already active in Kazakhstani uranium mining before this acquisition, and Russia controlled approximately 26% of uranium deposits in Kazakhstan by 2022. The Budenovskoye acquisition therefore represented not a new entry but a

deepening of an existing structural presence at the moment when France was increasing its procurement from Kazakhstan as a substitute for the lost Nigerien supply. This created a structural situation in which France's post-Niger diversification strategy was simultaneously increasing its commercial reliance on Kazakhstani supply and increasing the proportion of that supply flowing through assets in which Rosatom held financial interests.

### ***2.2.5 The Macron-Tokayev Strategic Agreement (November 2023)***

President Macron's visit to Astana in November 2023, conducted in the immediate aftermath of the Niger coup and Orano's suspension of operations at Arlit, produced a set of agreements that represented France's most explicit attempt to formalise and deepen the Kazakhstan model as a strategic substitute for the lost bilateral Niger relationship. The visit produced a joint declaration on strategic minerals cooperation, an agreement between Framatome and Kazatomprom on nuclear fuel cycle projects, and a public reaffirmation of the South Tortkuduk joint venture. The signing of an addendum reaffirming the 2022 new fifteen-year subsoil use contract for KATCO was presented as evidence of Kazakhstan's status as a reliable long-term partner.

These agreements are revealing, not only for what they contain, but for what they expose about the strategic logic driving France's Kazakhstan pivot. The framing of the agreements, strategic partnership, reliable supply, long-term security, applied to Kazakhstan the vocabulary of bilateral relationship management that had characterised the Niger model, while the actual supply chain architecture continued to operate on the networked, multi-actor logic of the Kazakhstan model. The diplomatic register of the Macron visit treated the France-Kazakhstan relationship as a bilateral dependency that could be managed through political engagement; the supply chain reality documented in this chapter is of a networked dependency whose critical governance nodes lie with actors over whom neither France nor Kazakhstan exercises controlling authority.

## **2.3 Quantitative and Qualitative Evolution of French Imports (2010-2025): What the Data Conceals**

The quantitative evolution of France's uranium imports over the period 2010-2025 is characterised by a surface stability that masks profound structural transformation. Data from

the Euratom Supply Agency (ESA) annual reports over this period shows that France consistently sourced its natural uranium from a diversified portfolio of suppliers, Niger, Kazakhstan, Canada, Australia, Uzbekistan and others, with no single supplier exceeding 37% of annual deliveries in most years. This diversification has been routinely presented in official reporting as evidence of supply security.

The distributional data, however, obscures three structural changes that are worth underlining. First, (1) the governance structure of the dominant supply relationships changed fundamentally over this period, from the captive-hierarchical Niger model to the relational-modular Kazakhstan model, without any corresponding change in the import volume statistics. Second, (2) the downstream processing routes for imported uranium shifted progressively toward Russian infrastructure during a period in which the political relationship with Russia was deteriorating, creating a growing divergence between the political logic of diversification and the operational logic of cost minimisation. Third, (3) the functional upgrading of Kazatomprom as a supplier, its acquisition of conversion capacity, its joint ventures in fuel fabrication with Chinese and Russian partners, was systematically shifting the governance of the supply chain toward the supplier side, eroding France's effective leverage as a buyer without appearing in any bilateral import metric.

The period also saw a structural repricing of the entire front-end. The uranium spot price rose from below USD 30 per pound in 2020 to a peak of around USD 106 in early 2024, its highest level since 2007, while SWU prices roughly tripled. This repricing matters analytically: it alters the economics of every option discussed in Part III, from domestic mining to RepU re-enrichment, and indicates that the market itself has begun to price the geopolitical risks that volume statistics conceal (TradeTech, 2024).

The period 2020-2025 marked the inflection point at which these structural changes became visible: the Niger coup eliminated approximately 18% of French uranium procurement at a stroke, while the simultaneous deepening of Rosatom's equity presence in Kazakhstan demonstrated that the substitute supply relationships were structurally more entangled with Russian interests than the relationships they were replacing. France's uranium supply statistics for 2024-2025 show a successful reorientation toward Kazakhstan, Canada, and other suppliers at the volume level; the structural analysis developed in this chapter and the preceding one suggests that this reorientation has deepened rather than resolved the strategic vulnerability of France's supply position.

## **2.4 From Bilateral to Network: The Transformation of Intermediaries and Risk Profiles**

The historical account developed above makes the transformation mechanism explicit. In the Niger model, the chain from extraction to enrichment was managed within a single governance structure under Orano's operational authority, minimising the number of interfaces across which supply risk could propagate. In the Kazakhstan model, the same material flow is distributed across actors France does not control: Kazatomprom at extraction, Russian or Trans-Caspian routing in transport, and Rosatom's Seversk facility for RepU re-enrichment. This transformation of intermediaries, from Orano's integrated chain to a multi-actor network, is the structural mechanism that the following chapter analyses through the three-dimensional framework of control, geopolitical exposure and supply chain structure.

### **III. Comparing Dependency Models: Control, Exposure, and Structural Vulnerability**

#### **3.1 Analytical Framework: Three Interconnected Dimensions of Strategic Dependence**

The preceding chapters have established the empirical architecture of France's uranium dependency: a country that imports 100% of its natural uranium requirements, historically anchored to two dominant supply models that are structurally and qualitatively distinct. The question that now arises, and that constitutes the analytical core of this thesis, is not simply how much France depends on external uranium, but how that dependency is organised and what kinds of vulnerability it produces? To answer this question, it is necessary to move beyond volume-based analysis and toward a framework capable of distinguishing between forms of dependency that aggregate data systematically flatten.

##### ***3.1.1 Three Dimensions of Strategic Dependence: Control, Exposure, and Structure***

This section proposes a three-dimensional analytical framework for comparing strategic dependencies in critical resource supply chains: 1) control over supply chain stages, 2) exposure to political and geopolitical risks, and 3) the structural organisation of supply relationships. These three dimensions are not independent; they interact and reinforce one another in ways that the following subsections will make explicit. Together, they allow for a qualitative differentiation between the Niger model and the Kazakhstan model that import statistics alone cannot provide. Each dimension is operationalised through a set of explicit indicators, applied identically to both cases, so that the comparison rests on stated criteria rather than impression:

**Figure 2 - Indicators for the three dimensions of strategic dependence**

Dimension	Indicators used to assess it
<b>Control</b>	<ul style="list-style-type: none"> <li>• Equity ownership stake</li> <li>• Operational control of extraction</li> <li>• Degree of contract dependence</li> <li>• Domestic processing (conversion / enrichment) capacity</li> <li>• Control over transport routing</li> </ul>
<b>Exposure</b>	<ul style="list-style-type: none"> <li>• Political instability of the supplier state</li> <li>• Transport chokepoints</li> <li>• Exposure to sanctions</li> <li>• Leverage held by third-party actors over critical stages</li> </ul>
<b>Structure</b>	<ul style="list-style-type: none"> <li>• Number of distinct actors in the chain</li> <li>• Degree of vertical integration</li> <li>• GVC governance type (Gereffi &amp; Fernandez-Stark, 2016)</li> <li>• Substitutability of suppliers and stages</li> </ul>

Sources: author's own table, inspired by Gereffi & Fernandez-Stark (2016), Farrell & Newman (2019) and Cherp & Jewell (2011).

These indicators are not weighted into a single score: the aim is not to rank the two models on a common scale but to show that, on identical criteria, they occupy intrinsically different positions that produce qualitatively different vulnerabilities.

### **3.1.2 Theoretical Foundations: Weaponised Interdependence, GVC Analysis, and Energy Security**

The framework draws on three complementary bodies of scholarship. The first (1) is the theory of weaponised interdependence developed by Farrell and Newman (2019), which argues that global economic networks are not flat or symmetrical but are structured around central nodes that some states can exploit to coerce others. In their formulation, states with political authority over these nodes can weaponise network positions either to gather strategic information or to deny access to adversaries. This framework applies directly to the uranium supply chain, where nodes in conversion, enrichment and transport represent structural chokepoints through which resource flows necessarily pass.

The second body of literature (2) is Global Value Chain (GVC) analysis, and in particular the governance typology developed by Gereffi and Fernandez-Stark (2016). Crucially, Gereffi and Fernandez-Stark (2016) do not simply name five governance types (market, modular, relational, captive, hierarchical) but derive them rigorously from three measurable variables:

1) the complexity of information exchanged between buyers and sellers, 2) the codifiability of that information, and 3) the level of supplier competence relative to the lead firm. This derivation is what makes the framework analytically productive rather than merely taxonomic: it allows one to determine, from structural evidence, which governance type characterises a given supply relationship rather than asserting it by impression. Applied to the nuclear fuel cycle, this typology allows for a precise characterisation of the type of relationship that ties France to each supplier, with fundamentally different vulnerability implications depending on which end of the governance spectrum each model occupies. The distinction matters because, as Gereffi (1994) argued, governance structure determines the degree of power asymmetry in the chain and therefore the conditions under which each actor can exert leverage over others.

The third reference point (3) is the energy security literature, and specifically the conceptualisation of vulnerability as the product of availability, reliability and resilience (Cherp and Jewell, 2011). This literature draws attention to a dimension that purely geopolitical frameworks tend to underweight: the difference between risks that are visible and attributable, and risks that are diffuse and systemic. A supply disruption following a coup is a visible, rupture-prone event that can be anticipated and managed through stockpiles or short-term diversification. A systemic dependency embedded in the architecture of processing and transport networks is far more difficult to detect and address through conventional policy tools.

### ***3.1.3 Critical Resource Competition and the Political Economy of Supply***

The three frameworks outlined above; weaponised interdependence, GVC governance, and energy security; provide the analytical tools for comparing the two dependency models. A fourth body of literature, drawn from the political economy of critical resources, provides the macro-political context in which those models are embedded.

Hirschman's (1945) foundational analysis of trade dependency establishes the structural asymmetry at the origin of all the vulnerabilities this thesis examines. In Hirschman's framework, trade flows generate political leverage for the exporter when those flows represent a large share of the importer's total supply but a small share of the exporter's total revenues. Applied directly to France's uranium position: France's annual purchases from Kazakhstan represent approximately one to two per cent of Kazakhstan's total export revenues, while they constitute 37% of France's uranium supply for the relevant contract

periods. This asymmetry (high dependence for the buyer, low dependence for the seller) is the structural condition that makes commercial relationships exploitable as instruments of coercion, the mechanism that Baldwin (1985) formalised and Farrell and Newman (2019) extended to networked global supply chains.

Klare (2012) situates uranium within the broader political economy of 21st-century resource competition. His concept of 'life-critical minerals' (materials whose strategic irreplaceability and geographic concentration make them fundamentally prone to geopolitical weaponisation) directly contextualises the competitive dynamic between Russian, Chinese, and Western actors in Kazakhstan's uranium sector. The simultaneous expansion of Rosatom's equity presence in Kazakhstani mining assets and China's growing ownership stake in Namibian uranium operations are not commercially driven anomalies: they are instances of what Klare terms the '*race for what's left*', a systematic effort by state-backed actors to acquire structural positions in critical resource chains whose geopolitical significance will increase as Western energy systems become more dependent on nuclear power.

Le Billon (2004, 2012) provides the final dimension: the relationship between resource dependency and political instability in supplier states. His argument that the form of resource extraction shapes the form of political risk. For example, point-source resources such as mines generating rent-seeking, coup dynamics, and elite capture, while diffuse resources generate different instability patterns explains why Niger and Kazakhstan generate structurally different vulnerabilities even when their aggregate supply volumes are comparable. Niger's conventional mining operations, concentrated at a single site accessible by road and managed by a single joint venture, created a point-source resource economy of the kind Le Billon identifies as structurally prone to coup dynamics: the control of Arlit was the prize, and seizing it required only political will and a critical mass of military actors. Kazakhstan's ISL operations, distributed across multiple sites and integrated into global commercial networks, generate a diffuse dependency whose disruption would require a structural reconfiguration of the entire supply chain architecture rather than a single political act. Le Billon's framework thus provides a supply-side complement to Gereffi's buyer-side governance analysis: the governance type of the supply relationship and the political economy of the supplier state are jointly determined by the physical characteristics of the resource deposit itself.

### 3.1.4 Comparative Analytical Grid: Niger and Kazakhstan

Taken together, these three frameworks induce the following analytical grid. It has been enriched below to incorporate the six GVC governance variables identified by Gereffi and Fernandez-Stark (2016), which allow each row to be grounded in structural evidence rather than general impression:

**Figure 3: Enriched Comparative Framework - Niger and Kazakhstan Dependency Models**

Dimension	Niger Model	Kazakhstan Model	Nature of Vulnerability
<b>Control over supply chain</b>	High (direct equity ownership via Orano; Somaïr 63.4%, Cominak 34%)	Moderate (joint ventures, market intermediaries; Orano 51% at South Tortkuduk)	Visible and manageable vs. diffuse and indirect
<b>GVC governance type (Gereffi &amp; Fernandez-Stark, 2016)</b>	Captive → Hierarchical: Orano as sole operational lead firm	Relational → Modular: ambiguous lead firm (Kazatomprom / Rosatom / market)	Clear hierarchy vs. contested governance
<b>Supplier competence (Gereffi variable)</b>	Low: Niger had no domestic technical capacity; all expertise held by Orano/CEA	Very high: Kazatomprom = world's largest producer (23% global share, Wimmers et al., 2026)	Determines which actor holds structural power in the chain
<b>Codifiability of supply specifications (Gereffi variable)</b>	Low: Sahelian geological expertise, non-transferable without on-site presence	High: ISL contracts standardised, spot price referenced, IAEA-codified yellowcake	Determines ease of switching suppliers and exit costs
<b>Geopolitical exposure</b>	Post-colonial political instability; Françafrique contestation	Russian infrastructure dependency (Rosatom); transport chokepoints	Rupture-prone vs. systemic and hidden
<b>Supply chain structure</b>	Bilateral, vertically integrated, short chain	Networked, multi-actor, long chain with chokepoints; EU = 96% supply from 5 countries (Wimmers et al., 2026)	Single-point failure vs. distributed systemic risk
<b>Upgrading of supplier (Gereffi 2016)</b>	Absent or blocked: Niger maintained in pure extraction stage	Active: Kazatomprom pursuing functional upgrading into conversion and fuel fabrication	Upgrading shifts power from buyer to supplier over time
<b>Switching costs</b>	Very high (loss of sunk mining assets; geological knowledge non-transferable)	Very high (infrastructure, transport routes, enrichment contracts, asset specificity)	Both models generate lock-in, but through different mechanisms
<b>Identifiability of risk</b>	High: political events create visible, attributable ruptures	Low: risks embedded in supply chain architecture and ownership structures	Measurable vs. opaque
<b>Resource extraction type (Le Billon, 2004)</b>	Point-source: single captive site, structurally prone to coup dynamics and elite rent capture	Diffuse: distributed ISL operations across multiple sites, generating less visible but systemic instability	Rupture by political seizure vs. gradual structural erosion

<b>Trade dependency asymmetry (Hirschman, 1945)</b>	France's purchases represented ~18% of France's uranium supply and ~31% of Niger's export revenues: high mutual dependency	France's purchases represent ~1-2% of Kazakhstan's export revenues but 37% of France's supply: asymmetric dependency favouring the seller	Bilateral leverage vs. structural buyer vulnerability
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Sources: Author's own table, inspired by Gereffi and Fernandez-Stark (2016), Farrell and Newman (2019), Cherp and Jewell (2011), Wimmers et al. (2026), Hirschman, 1945, Le Billon, 2004 and Hecht (2012)

This grid is not intended as a static classification but as a diagnostic tool. Its purpose is to make visible the structural differences between two dependency models that produce, on the surface, comparable import volumes, and to demonstrate that those structural differences have measurable consequences for the nature and manageability of France's strategic vulnerability.

### **3.2 Control over the Supply Chain: Direct Ownership versus Indirect Influence**

#### ***3.2.1 The Niger Model: Vertical Integration as a Form of Control***

France's relationship with Niger's uranium sector was, for most of its history, one of the most vertically integrated extractive relationships in the post-colonial world. From the early 1970s through the 2020s, Orano and its predecessors (Cogema, then Areva) held majority stakes in Niger's two main mining companies: Somaïr, operating the Arlit mine, and Cominak, which ceased operations in 2021 after the exhaustion of its reserves. These were not commercial arrangements but direct equity ownership positions that gave France operational control over extraction decisions, pricing terms and output volumes (Hecht, 2012). Orano's majority share in Somaïr meant that France occupied the lead firm position in Niger's nuclear fuel chain, a position it is now necessary to examine with the analytical precision that Gereffi's framework provides.

Applying Gereffi and Fernandez-Stark's (2016) three governance variables to the Niger relationship yields a specific and demonstrable diagnosis rather than a general impression. First (1), the complexity of information exchanged between Orano and the Nigerien state was low: yellowcake (uranium oxide concentrate) is a relatively standardised product whose physical specifications are codified by international agencies. Second (2), however, the codifiability of the operational knowledge required to make that yellowcake in the Sahelian geological context was structurally low: the extraction of uranium from the sandstone deposits of the Air region required decades of site-specific geological expertise, specialised

hydrogeological management and logistical infrastructure (export corridor through Benin, processing facilities at Arlit) that no other actor possessed and that could not be transmitted remotely through contracts or standards alone. Third (3), and most decisively, the level of supplier competence was extremely low: Niger had no domestic nuclear engineering capacity and was entirely dependent on French state institutions, first the CEA, then Cogema, for the technical conduct of the mining operations. All three variables pointed unambiguously toward the captive or hierarchical end of Gereffi's governance spectrum: Orano was not purchasing uranium from a capable supplier but extracting it from assets it technically controlled and operationally managed (Gereffi and Fernandez-Stark, 2016).

This governance structure produced a specific and paradoxical form of security: the security of the producer. France did not depend on Niger's willingness to sell, it depended on Niger's political stability as the host territory of its own assets. The distinction is significant. In a pure market dependency, a buyer can respond to a supply disruption by turning to alternative sellers; the risk is commercial. In a captive-hierarchical ownership model, a disruption is instead a loss of asset access, which cannot be resolved by changing suppliers because the supplier *is* the asset. This explains why the 2023 coup and the subsequent revocation of Orano's mining licence at Imouraren in June 2024, followed by the suspension of operations at Arlit in October 2024, represented not a simple commercial disruption but a structural loss of production capacity that France had spent decades building (Reuters, 2025; Portail IE, 2024).

At the same time, vertical integration gave France a form of operational knowledge that is difficult to replicate through market purchase. Wimmers et al. (2026) note, in their system good analysis of the nuclear front-end, that uranium mining projects typically take many years to move from discovery to production and that this developmental lead time creates a form of asset specificity that makes the mining stage uniquely resistant to rapid substitution. Orano's decades of presence in Niger produced technical expertise in the geology, hydrology and logistics of Sahelian uranium extraction, as well as a workforce that was, by the time of the coup, overwhelmingly Nigerien by recruitment (France 24, 2023). This depth of integration created both an asset, in the form of operational continuity, and a liability, in the form of sunk costs that made exit costly and disruption irreversible.

Beyond the operational dimension, the captive governance of the Niger chain was also embedded in a wider institutional architecture that Hecht (2012) analyses under the framework of *la Françafrique*. The 1960 defence accords that France signed with Niger and

Gabon at the time of independence were not simply diplomatic documents: they created a system of mutual obligation in which France obtained privileged access to uranium and other strategic raw materials in exchange for guarantees of military security and political support for the newly independent African leaders. The promises of development aid that accompanied the mining agreements were the financial face of this arrangement, but its political architecture rested on Jacques Foccart's network of personal relationships, covert financial flows and secret protocols that committed France to defending sitting governments against coups, except, crucially, when those governments had become too costly to maintain (Hecht, 2012, p. 109-117). This institutional history is decisive: the path dependency of the Niger model did not begin with Orano's sunk mining assets in the 1980s. It began with the decolonisation accords of 1960, which structurally locked Niger into a post-colonial supply relationship whose terms it could contest but never fundamentally renegotiate.

As established in Part II (§2.1.3), the price negotiations of the 1970s institutionalised this asymmetry through the rhetorical instrument of banalisation, which preserved France's privileged access precisely by denying its political significance. This mechanism is directly relevant to the transition from the Niger to the Kazakhstan model: the shift toward a market-mediated dependency on Kazatomprom can be read as an advanced form of banalisation, in which France purchases uranium through standardised contracts priced on the spot market, without even the politically explicit bilateral relationship that had given Niger a platform from which to contest the terms of trade. In Hecht's terms, the Kazakhstan model is a more thoroughly banalised, and therefore less visible and less contestable, dependency (Hecht, 2012, pp. 77-78)

### ***3.2.2 The Kazakhstan Model: Shared Ownership in a Contested Chain***

France's relationship with Kazakhstan's uranium sector is by design different at every level, and applying Gereffi and Fernandez-Stark's (2016) three governance variables makes that difference precise. First (1), the level of supplier competence is radically different from the Niger case: Kazatomprom is the world's largest uranium producer, with a market share of approximately 23% of global supply (11,373 tonnes in 2022) and a state-of-the-art mastery of in-situ leaching (ISL) extraction technology that gives it a genuine competitive advantage in low-cost production (Wimmers et al., 2026). This is not a captive supplier dependent on its buyer's technical knowledge; it is a commercially and technically sophisticated actor with its own strategic interests and its own portfolio of international partnerships. Second (2), the codifiability of supply specifications is high: ISL-produced yellowcake meets standardised

international quality specifications, can be priced by reference to publicly quoted spot markets, and is traded under contracts that do not require on-site operational presence by the buyer. Third (3), the complexity of information exchanged is moderate to high at the level of the overall supply chain, not because the yellowcake itself is technically complex, but because the routing of conversion, enrichment and transport services through multiple intermediary actors introduces coordination challenges that cannot be resolved through bilateral contracts alone (Gereffi and Fernandez-Stark, 2016).

These three variables produce a governance diagnosis at the relational to modular end of Gereffi's spectrum: France is a buyer in a chain it does not govern, rather than a lead firm in a chain it controls. This distinction carries a specific analytical implication that the existing literature on French uranium dependency tends to understate. The lead firm concept in GVC analysis refers to the actor that governs the chain by setting standards, selecting suppliers, coordinating flows and appropriating the strategic rents generated at key nodes (Gereffi, 1994). In the Niger model, Orano was unambiguously the lead firm. In the Kazakhstan model, the question of who governs the chain has no clear answer, and that ambiguity is itself a structural vulnerability. Kazatomprom governs the extraction stage commercially; Rosatom governs the enrichment and conversion stages technically; and the market governs the pricing stage financially. France, as a buyer, has influence at none of these governance nodes.

A dimension of control that the equity analysis alone does not capture is contractual lock-in. Williamson (1985), in his transaction cost economics framework, distinguishes between governance by ownership and governance by contract: long-term supply agreements with fixed price schedules and delivery obligations create switching costs that are as structurally binding as equity stakes, even in the absence of ownership control. France's multi-year uranium contracts with Kazatomprom, typically running five to ten years, represent this form of contractual lock-in: they constrain France's ability to exit the Kazakhstan relationship even if the geopolitical context deteriorates, because the penalty clauses and replacement timelines for alternative supply make rapid exit commercially irrational. This contractual architecture differs fundamentally from the concession model of the Niger relationship, in which Orano's operational presence gave it unilateral authority to manage output decisions irrespective of contract terms. In the Kazakhstan model, the contract is the governance instrument, and its terms are negotiated between commercially equal parties rather than dictated by a technically indispensable lead firm.

Rosatom's position in Kazakhstan's uranium sector is extensive and has deepened since 2022. Rosatom's acquisition of a 49% stake in Budenovskoye in 2022, documented in Part II,

section 2.2.4, is the most telling illustration of this dynamic: France's growing commercial reliance on Kazakhstani supply is increasing, not decreasing, the proportion of that supply flowing through assets in which Rosatom holds financial interests. More importantly, as established in Part I (§1.3.2), the global conversion market is structurally concentrated: in 2022 Russia's Seversk plant ran at near-full capacity while the US ConverDyn plant was offline, so Kazakhstani yellowcake destined for Western enrichment frequently passed through Russian conversion infrastructure. France's exposure to this bottleneck is therefore not a matter of political choice but of physical infrastructure geography.

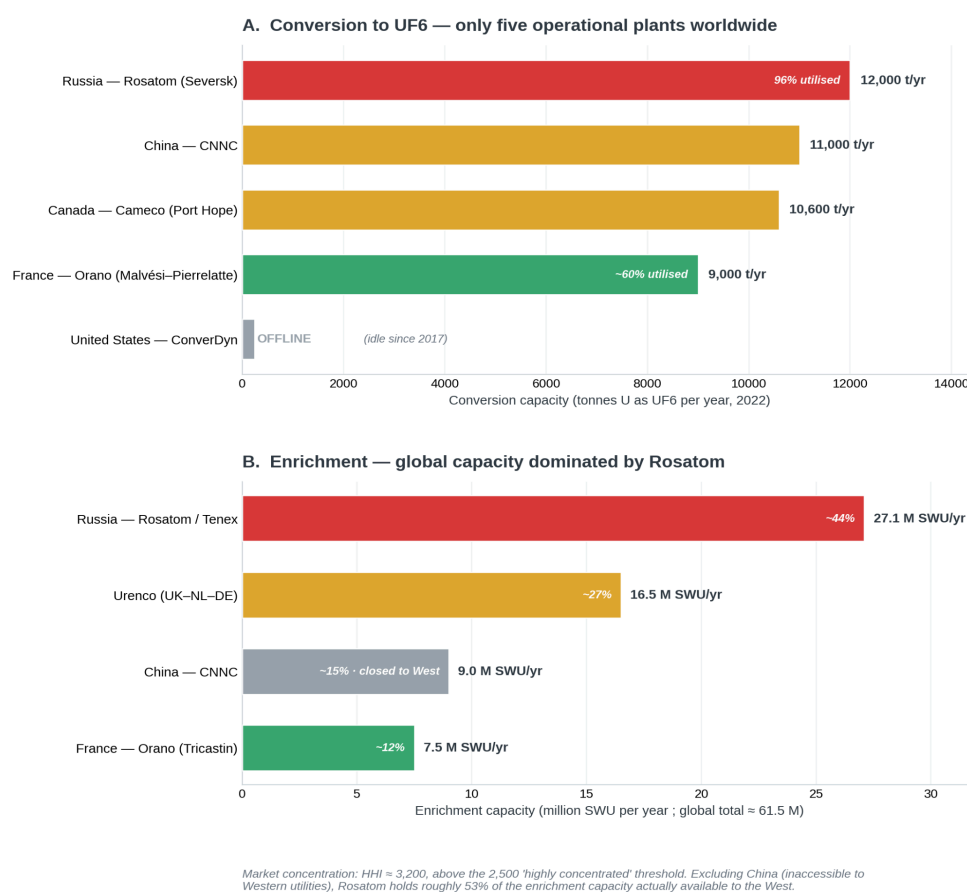
Wimmers et al. (2026) further document that the enrichment market is even more concentrated: Rosatom/Tenex operates by far the largest commercial enrichment capacity globally, followed by Urenco (UK-Netherlands-Germany) and Orano (Tricastin). Critically, only states possessing nuclear weapons have enrichment technologies on a commercial scale, with Urenco as the sole exception. This means that the commercial enrichment market is systemically controlled by the same states that possess nuclear weapons, a structural chokepoint that Farrell and Newman (2019) would identify as a *panopticon node*. In their framework, a network hub generates two distinct forms of power: (1) a chokepoint effect, the capacity to deny adversaries access to the flow, and (2) a panopticon effect, the capacity to observe that flow and extract strategic information from it. Control over enrichment confers both. France's own Tricastin facility provides some autonomy for LEU civil fuel, but the re-enrichment of reprocessed uranium (RepU) was historically routed to Rosatom's Seversk plant; as analysed in Part II, section 2.2.3; creating a circular dependency in which France's own reprocessing strategy deepened its reliance on Russian enrichment infrastructure. (Wimmers et al., 2026).

A further dimension of structural change in the Kazakhstan model concerns the upgrading trajectory of Kazatomprom as a supplier. Gereffi and Fernandez-Stark (2016) identify functional upgrading as the process by which suppliers acquire new functions in the chain, moving beyond their original stage of operation to control higher-value activities upstream or downstream. Kazatomprom is currently pursuing this form of functional upgrading: it has announced joint ventures in fuel fabrication with Chinese and Russian partners, has invested in conversion capacity, and is positioning itself as a full fuel-cycle actor rather than simply a yellowcake exporter. This upgrading has a direct consequence for the buyer-supplier power balance that GVC theory makes explicit: as a supplier acquires competence across more stages of the chain, the buyer's ability to govern the relationship from above decreases and the supplier's bargaining power increases (Gereffi, 2005). In the Niger model, France's lead

firm position was structurally secure because Niger had no competing technical competence. In the Kazakhstan model, Kazatomprom's ongoing functional upgrading means that France's commercial leverage is systematically eroding.

The role of recycled uranium partially offsets this upstream dependency. France's reprocessing capabilities at La Hague, operated by Orano, allow the country to recover uranium from spent nuclear fuel, producing what is known as reprocessed uranium (RepU), which can be re-enriched and used in reactors. This capacity reduces the proportion of natural uranium that France needs to source externally on a year-to-year basis and provides a buffer that has historically allowed the country to weather short-term supply disruptions. However, RepU accounts for only a fraction of total civil uranium requirements and cannot substitute for natural uranium at the scale of France's fleet of 56 to 57 reactors. It is a mitigation mechanism, not a structural solution to upstream dependency (ASNR, 2025).

**Figure 4: Chokepoints Répartition - Conversion to UF6 and Enrichment**



Sources: Author's own figure; capacity data from Wimmers et al. (2026), World Nuclear Association and Al Habtoor Research Centre (2026).

### **3.3 Exposure to Geopolitical Risks: Visible Rupture versus Diffuse Systemic Risks**

#### ***3.3.1 Niger: High Political Vulnerability and the Logic of Rupture***

The geopolitical risk profile of the Niger model is, in retrospect, highly legible. France's post-colonial relationship with Niger was structured around what Hecht (2012) calls the asymmetric nuclearity of African uranium production. The concept of nuclearity, as Hecht develops it, refers to the contested technopolitical category that determines whether something or someone is designated as 'nuclear', a designation that carries high political, economic and regulatory stakes. Hecht's central empirical demonstration is that this designation was systematically applied in an asymmetric fashion: the yellowcake that Niger and Gabon produced was classified as a non-nuclear 'source material' in the 1957 IAEA statute, a classification actively promoted by South Africa's delegation to the 1954-1956 IAEA statute negotiations as a means of facilitating uranium sales while avoiding IAEA safeguards inspections, which meant that Niger could export its uranium without triggering nuclear non-proliferation oversight, while France's enrichment facilities, where the yellowcake was transformed into genuinely fissile material, remained under strict national control (Hecht, 2012, p. 33-34). The practical consequence was that Niger was formally excluded from the category of 'nuclear activities' even as it supplied more than 18% of France's annual uranium requirements: Niger's uranium made France nuclear, but it did not make Niger nuclear. As observed in part II, the rhetorical banalisation of uranium was itself an instrument of power: by denying the political dimension of the resource, France maintained its commercial advantage while exploiting the resource's political importance.

The July 2023 coup that brought General Abdourahmane Tchiani to power was the proximate cause of France's rupture with Niger, but the structural conditions that made that rupture possible had been accumulating for decades. The coup crystallised a political dynamic that combined three mutually reinforcing forces: (1) the delegitimisation of the Françafrique framework across the Sahel, (2) the spread of anti-French sentiment amplified by Russian information operations, and (3) the economic grievances of Nigerien populations who had seen decades of uranium extraction create limited domestic development (SPF, 2025; Africa Analyst, 2024). When Tchiani's junta revoked France's military cooperation agreements, expelled French troops and ultimately cancelled Orano's mining licences, it was executing a rupture that the underlying political economy had been preparing since the 1970s price negotiations documented by Hecht.

What is revealing about this rupture is its visibility. The risk was bilateral, attributable and, in principle, manageable through the kind of diplomatic insurance that France maintained through its military presence, its development assistance and its management of the Somair joint venture. When the rupture occurred, it was immediately identifiable: the border closure by Benin blocked the export corridor, Orano suspended operations, and France could calculate, in real time, the tonnage of uranium it was losing access to. This visibility allowed the French state and Orano to activate contingency arrangements, including accelerating negotiations with Kazakhstan and drawing on strategic reserves, even if the loss of Niger's production capacity had longer-term structural consequences that those arrangements could not fully compensate for. (Portail IE, 2024).

The Niger model thus corresponds to what might be called a rupture-prone dependency: a form of strategic vulnerability that is politically exposed, temporally concentrated and spatially localised. The risk is high in the sense that a single political event can sever the supply relationship entirely. But it is, paradoxically, the kind of risk that states have historically developed the most sophisticated tools to manage, precisely because it is visible and attributable.

### ***3.3.2 Kazakhstan: Diffuse Exposure and the Architecture of Systemic Risk***

The geopolitical risk profile of the Kazakhstan model is fundamentally different in character, and that difference is what makes it challenging and strategically underappreciated. France's pivot toward Kazakhstan as the primary alternative to Niger is understood by most volume-based assessments as a diversification success: Kazakhstan is politically stable relative to the Sahel, Kazatomprom is a reliable commercial partner, and the joint venture at South Tortkuduk provides a measure of industrial participation (World Geostrategic Insights, 2024). These assessments are not wrong, but they systematically underweight the risks embedded in the supply chain architecture through which Kazakhstani uranium reaches French reactors.

The central structural risk in the Kazakhstan model concerns the concentration of global conversion and enrichment capacity in a small number of state-controlled actors, of which Rosatom is the most significant. As established in Part I, section 1.3.3, global enrichment capacity is dominated by Rosatom with approximately 44% of world supply, well above the concentrated market threshold. The geopolitical consequence for the Kazakhstan model is

direct: Kazakhstani uranium, which must be converted to UF<sub>6</sub> before it can be enriched, frequently passes through Russian processing infrastructure regardless of the political intentions of France or Kazakhstan. The physical infrastructure of the nuclear fuel cycle has its own geopolitical logic that is not captured in bilateral supply statistics.

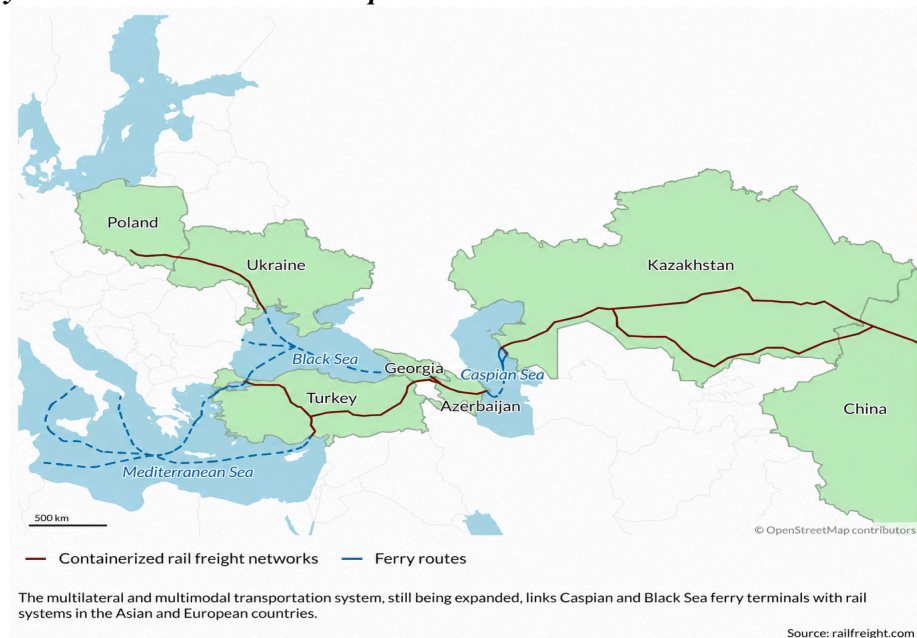
This structural chokepoint is what Farrell and Newman (2019) identify as the mechanism of weaponised interdependence: a node in a global economic network through which most of the relevant traffic passes, and which therefore confers on its controller the ability to deny access to adversaries or extract concessions from dependent actors.

A saturated chokepoint compounds this vulnerability in a way that an underused one would not. Operating near full capacity (§1.3.2), Seversk holds almost no residual slack: should demand rise or another plant fall offline, Russia could no longer serve every customer and would face a rationing decision, an allocation that need not follow commercial logic and could privilege its own VVER fleet or politically aligned buyers over Western utilities. The absence of spare Western capacity means there is no buffer to absorb such a reallocation. Saturation therefore does not weaken the node's leverage but extends it: beyond the capacity to deny access entirely, it confers the subtler power to decide whose supply is served first.

Wimmers et al. (2026) add a further dimension to this analysis through their concept of asset specificity: the enrichment centrifugation technology used by Rosatom is highly specific, it cannot be repurposed for other industrial functions and the transition to alternative enrichment suppliers requires not just commercial renegotiation but physical reconfiguration of fuel supply chains, a process that takes years and involves substantial capital investment. This asset specificity is what prevents France from rapidly exiting its partial dependence on Russian enrichment services, even when the political motivation to do so is strong, as it became after February 2022. In the case of uranium enrichment, Rosatom has not yet weaponised this position against France specifically, a point noted by Lanoszka (2024), who argues that Russia has shown restraint in not disrupting Rosatom's international business even after its invasion of Ukraine. This restraint, however, should not be read as a structural constraint: it is a strategic choice. Russia is preserving Rosatom's commercial relationships as a form of insurance leverage: the threat of disruption is more valuable than its exercise, precisely because it generates ongoing compliance by European utilities without requiring any overt coercive act. This is exactly the '*panopticon*' node logic that Farrell and Newman (2019) identify: the value of the chokepoint position lies not in its activation but in the behavioural adjustments it produces in dependent actors who know the capacity exists.

This dynamic acquires additional analytical weight when placed alongside Russia's simultaneous acquisition of equity stakes in Kazakhstani uranium assets. The Niger coup and the deepening of Rosatom's Kazakhstani presence represent two vectors of the same strategic logic: Russia is systematically expanding its structural leverage over both the upstream dimension of France's supply chain, through ownership of mining assets, and the downstream dimension, through enrichment contracts, while preserving the formal appearance of commercial normality at both levels. This dual-vector strategy is what makes the Kazakhstan model's risk profile uniquely difficult to manage through conventional policy tools: each individual commercial relationship appears rational and depoliticised, while the aggregate architecture constitutes a structural exposure whose depth is only visible when the full supply chain is mapped. A second dimension of Kazakhstan's geopolitical risk profile concerns transport. Kazakhstan is a doubly landlocked country, meaning that uranium exports must transit at least two national borders before reaching the sea. The primary export route historically ran through Russia to Baltic ports. Since the invasion of Ukraine, Kazakhstan has been developing the Trans-Caspian International Transport Route (TITR), which bypasses Russia via Azerbaijan, Georgia and Turkey (FIIA, 2024). However, Wimmers et al. (2026) note that the uranium market is characterised by inelastic demand, there is no real substitute for uranium as nuclear fuel, and long-term contracts that lock buyers and sellers into multi-year delivery schedules. This inelasticity means that transport bottlenecks on the TITR cannot be bridged quickly by shifting to spot purchases: France's reactors require continuous fuel supply that cannot be interrupted for the duration of an infrastructure bottleneck. Kazatomprom used the TITR for a test delivery of natural uranium to Canada in autumn 2022, but at commercial scale the route faces significant bottlenecks in port capacity, rail infrastructure and political coordination among the transit states.

**Figure 5: The Trans-Caspian International Transport Route (Middle Corridor): Kazakhstan's rail-and-ferry alternative to the Russian export corridor**



A third risk dimension is ownership: as documented in section 2.2.4, Rosatom's equity expansion in Kazakhstani mining means that France's growing reliance on Kazakhstani supply increases the share of its uranium flowing through Russian-held assets. This dependency is invisible in bilateral trade data: it is embedded in the ownership structure of the chain, not in the nationality of the seller.

The visible/diffuse dichotomy should not, however, be overdrawn. Kazakhstan is not immune to rupture-type risk: the violent unrest of January 2022, which prompted a CSTO intervention led by Russian forces, demonstrated that the political stability underpinning the Kazakhstani model is itself partly guaranteed by Moscow. The two risk profiles are thus ideal types rather than watertight categories; what distinguishes the Kazakhstan model is the relative weight of systemic over rupture-prone exposure, not the absence of the latter. (Hedenskog and von Essen, 2022)

### **3.4 Structural Vulnerability: Bilateral Dependence versus Entangled Network Dependence**

#### ***3.4.1 Why Similar Volumes Produce Different Vulnerabilities***

The preceding analysis makes it possible to return to the central puzzle that animated this thesis: how can similar levels of import dependence generate fundamentally different forms of strategic vulnerability? The answer lies not in the quantity of uranium flowing from each source but in the structural architecture of the relationships through which those flows are organised.

In the Niger model, France's dependency was bilateral in its essential structure: a direct relationship between a lead firm (Orano) and a territorial state, mediated by equity ownership in the extractive assets themselves. The supply chain was short, in the sense that extraction, initial processing and export were all managed under Orano's operational authority, and the risks were concentrated at a single point: the political relationship between France and the Nigerien state. This concentration of risk is, paradoxically, a form of simplicity. A bilateral dependency can be insured against through diplomatic management, military presence, development assistance and stockpile accumulation. When it ruptures, it ruptures cleanly, at an identifiable point and at a calculable cost. France lost access to approximately 18% of its

uranium supply when Niger's junta cancelled Orano's licences, a loss that was immediately quantifiable and that France was able to partially compensate within 18 months through expanded Kazakhstani procurement (France 24, 2023; Portail IE, 2024).

The Kazakhstan model produces a fundamentally different form of vulnerability, one that this thesis characterises as an entangled network dependency. The supply relationship is not bilateral but triadic, involving at minimum Kazakhstan, Russia (through enrichment and transport) and a growing ecosystem of commercial intermediaries, trading firms and financial institutions that operate between Kazatomprom and Orano's procurement desk. In Gereffi's governance typology, this is closer to a modular or relational chain structure in which the lead firm has less direct control over the conditions of production and transport, and in which the risks are distributed across multiple nodes rather than concentrated at a single point. Critically, as Wimmers et al. (2026) demonstrate through their system good analysis framework, the interfaces between the stages of the nuclear fuel cycle, particularly between conversion and enrichment, represent the most coordination-intensive points in the entire chain. A buyer who does not control these interfaces has no reliable way to predict where disruptions will emerge, how they will propagate through the chain, or what leverage they can exercise to prevent them. This is structurally different from the Niger model, where the interface between Orano's mining operations and the French fuel cycle was entirely under Orano's operational management.

The concept of entangled network dependency captures three structural features of this model.

First (1), the opacity of the dependency: France's exposure to Russian enrichment capacity or to Rosatom's ownership of Kazakhstani mining assets is not visible in bilateral import statistics. A policymaker examining the share of France's uranium sourced from Kazakhstan would see a diversification success; a policymaker examining the full supply chain architecture through the lens of Wimmers et al.'s (2026) system good framework would see a complex web of Russian adjacencies at the conversion, enrichment and ownership levels simultaneously.

Second (2), the difficulty of attribution: if France's uranium supply were disrupted through a Russian decision to restrict enrichment services or through the exercise of Rosatom's ownership rights over Budenovskoye output, it would be far more difficult to identify the proximate cause of the disruption than in the Niger case.

Third (3), the limited efficacy of conventional diversification: adding suppliers at the extraction stage does not reduce the dependency if the new suppliers' output must still pass

through the same enrichment chokepoints or transit the same bottlenecked transport corridors, particularly given the inelastic demand for uranium that Wimmers et al. (2026) document, demand that cannot be managed down through substitution (Farrell and Newman, 2019; FIIA, 2024).

### ***3.4.2 The Gereffi Governance Framework Applied: From Captive to Relational Chains***

The five governance types derived in section 3.1.2, and the two axes of explicit coordination and power asymmetry that order them, can now be applied directly to the two supply models, where the same logic that governs manufacturing value chains determines which actor appropriates rents, bears risks, and can exit at acceptable cost.

Applied to the uranium supply chain, Niger's model was closest to the captive or hierarchical end of the spectrum. Orano's majority ownership of Somaïr gave France the control associated with hierarchical governance, but the political vulnerability of a post-colonial territorial relationship introduced a form of captive dependency in reverse: France was dependent on Niger's territorial stability in a way that an abstract lead firm in a manufacturing chain would not be dependent on the political conditions of its supplier country. The operational knowledge embedded in Orano's decades of Nigerien presence compounded this dependency, Wimmers et al. (2026) note that uranium mining projects typically require many years from discovery to production because of this site-specific knowledge accumulation, making the sunk cost of Orano's presence in Niger the largest single source of lock-in in the bilateral relationship.

Kazakhstan's model corresponds more closely to the relational or modular end of the spectrum. Orano participates in extraction through a joint venture, purchases uranium through long-term contracts and spot market transactions, and relies on Kazatomprom as a commercially autonomous and strategically sophisticated partner rather than as a captive supplier. This modality offers greater flexibility at the extraction stage, but it transfers control over the downstream stages, conversion, enrichment and transport, to actors whose strategic interests are not aligned with France's. In GVC terms, France is no longer the lead firm that governs the chain; it is a buyer in a chain governed by a combination of Kazatomprom's commercial logic and Rosatom's strategic interests. This is a fundamentally different structural position from the Niger model, and it entails a fundamentally different relationship to risk: whereas in the Niger model France could observe, anticipate and to some extent manage the political dynamics that threatened its supply, in the Kazakhstan model the

governance of the critical stages of the supply chain is exercised by actors over whose decisions France has no direct influence.

### ***3.4.3 The Asymmetry of Lock-In: How Both Models Generate Path Dependency***

One of the most important structural features shared by both dependency models, despite their qualitative differences, is the generation of path dependency: the tendency for initial choices about supply relationships to constrain future options through the accumulation of sunk costs, technical compatibility requirements and institutional arrangements that are costly to reverse. In the Niger model, path dependency manifested in the decades of investment that Orano made in mining infrastructure, local workforce development and geological knowledge, all of which became stranded assets when the junta revoked the operating licences. But this path dependency did not begin with Orano's operational investments: as Hecht (2012, p. 109-117) demonstrates, it was institutionalised at the moment of decolonisation, when the 1960 defence accords embedded France's access to Nigerien uranium within a comprehensive political bargain that exchanged strategic resource access for military security guarantees. The lock-in of the Niger model was therefore political before it was economic, the *Françafrique* network was the first form of asset specificity, long before the Arlit mine was sunk.

In the Kazakhstan model, path dependency is accumulating through a different and less visible mechanism. The growing technical integration of French and Kazakhstani nuclear fuel cycle activities, the fifteen-year subsoil utilisation contract signed in August 2022, and France's reorientation of its procurement strategy toward Central Asian suppliers following Niger's exit; all make exit from the Kazakhstan dependency increasingly costly over time. Wimmers et al. (2026) formalise this dynamic through their analysis of asset specificity in the nuclear front-end: the enrichment by centrifugation technology is a highly specific asset that cannot be repurposed; the fuel assembly specifications are reactor-specific and cannot be rapidly changed; and the long-term contracts that govern uranium supply, typically lasting five to ten years with fixed-price schedules, create contractual switching costs in addition to the technical ones. The result is that France's growing reliance on Kazakhstani supply is generating a new form of path dependency whose contours are not yet fully visible, precisely because the lock-in is accumulating through technical standards, financial contracts and ownership structures rather than through the publicly debated political relationship that characterised the *Françafrique* model.

The critical difference lies in the visibility of the lock-in. In the Niger model, the sunk costs were largely visible and politically legible: France's military presence, Orano's mining assets and the long-standing Françafrique relationship were all publicly documented and regularly debated, both in France and in Niger. In the Kazakhstan model, the lock-in is accumulating in ways that are less visible and less politically contested: the technical terms of uranium contracts, the routing of enrichment services through Rosatom's facilities and the ownership stakes that Rosatom is quietly accumulating in Kazakhstani mining assets, are not the subject of parliamentary debate or public scrutiny in France (World Geostrategic Insights, 2024). This asymmetry of visibility is itself a form of strategic vulnerability, because risks that are invisible are risks that cannot be politically managed.

### **3.5 The Period 2020-2025 as a Natural Stress Test**

#### ***3.5.1 Two Shocks, Two Models, Two Responses***

The period from 2020 to 2025 provides a rare opportunity to observe how two fundamentally different supply models respond to real-world disruptions. Two events stand out as direct tests of the Niger and Kazakhstan models: the Russian invasion of Ukraine in February 2022, and the military coup in Niger in July 2023.

The Ukrainian war shock affected both models, but through different mechanisms. For the Niger model, its primary effect was indirect: it accelerated the strategic repositioning of Nigerien military and political elites who saw in Russia's willingness to contest Western influence a geopolitical opening for renegotiating the terms of their relationship with France. This dynamic is consistent with Hecht's (2012) framework of nuclearity as a resource for sovereignty claims: just as Diori and Kountché had used uranium's strategic value to extract concessions from France in the 1970s, Tchiani's junta used the geopolitical rupture created by the Ukrainian war to assert a more radical form of resource sovereignty, the complete termination of French extractive presence. The difference is that in the 1970s France had the diplomatic and military tools to manage the challenge; by 2023, those tools had been delegitimised by decades of Françafrique contestation. Russia's active engagement with Nigerien elites, including Bloomberg's reporting in June 2024 that Rosatom had contacted the junta regarding the acquisition of Orano's assets, was part of a broader Russian effort to exploit anti-French sentiment across the Sahel (SPF, 2025).

For the Kazakhstan model, the Ukrainian war shock had direct structural effects. It immediately exposed the degree to which European uranium supply chains, including France's, were entangled with Russian infrastructure. Wimmers et al. (2026) note that Orano's French conversion plant at Pierrelatte increased its output from only 2,500 t/yr in 2018 to 9,000 t/yr in 2022 as a direct response to the Russian invasion, an expansion that itself reveals how much conversion capacity had previously been redirected to Russian facilities. The war revealed the depth of the structural entanglement, but increasing domestic conversion capacity does not resolve the enrichment dependency, where Rosatom's scale advantages remain overwhelming. The war also increased the strategic salience of Rosatom's growing equity positions in Kazakhstani mining assets, making France acutely aware that its pivot toward Kazakhstan might be trading one set of vulnerabilities for another, differently structured set.

### ***3.5.2 The Niger Coup: Rupture as a Diagnostic Event***

The July 2023 coup in Niger functions as a diagnostic event for the Niger model because it reveals both the model's defining vulnerability and the limits of its manageability. The coup demonstrated that the bilateral, vertically integrated dependency model is fundamentally hostage to the political stability of the supplier state, and that no amount of operational control over extractive assets can substitute for the political legitimacy of the bilateral relationship itself. In Hecht's (2012) analytical terms, the coup demonstrated that the Françafrique model had reached the limit of what institutional and military guarantees could sustain: once the post-colonial bargain, resource access in exchange for security guarantees and development aid, was perceived by a sufficiently large portion of the Nigerien political elite as illegitimate, the formal instruments of the relationship (joint venture agreements, mining licences, bilateral defence protocols) became inoperable. The junta's ability to revoke Orano's licences without triggering a French military response illustrated that the enforcement mechanisms of the Françafrique model had been eroded beyond the point of viability.

The coup also revealed the asymmetric consequences of the model's post-colonial structure. For Niger, the rupture with France carried significant economic costs: uranium exports accounted for approximately 31% of Nigerien export revenues, and Orano's local recruitment meant that several thousand Nigerien workers lost their livelihoods (France 24, 2023). For France, the immediate supply impact was significant but manageable in the short term, given existing stockpiles and the ability to accelerate Kazakhstani procurement. The long-term

consequences are more structural: France has permanently lost its direct operational presence in one of the world's historically significant uranium districts, and the possibility of reconstituting that presence under a future Nigerien government is uncertain and politically complex.

What the coup demonstrated most clearly for the purposes of this thesis is the diagnostic clarity of the rupture-prone model. The event was attributable, the cause was identifiable, the quantitative impact was calculable and the policy response was activable. This clarity is not a virtue of the Niger model as such; it is a feature of bilateral dependencies in general that makes them legible, and therefore manageable, in ways that network dependencies are not.

### ***3.5.3 The Kazakhstan Trajectory: Integration without Transparency***

The same period 2020 to 2025 reveals a different dynamic in the Kazakhstan model: a progressive deepening of supply relationships that is not accompanied by a commensurate increase in strategic transparency. France's procurement from Kazakhstan grew substantially following Niger's exit, and the November 2023 visit of President Macron to Astana produced a joint declaration on strategic minerals cooperation, an agreement between Framatome and Kazatomprom on nuclear fuel cycle projects and a public reaffirmation of the South Tortkuduk joint venture (Caspian Policy Center, 2023). These are the visible markers of a deepening bilateral relationship. What is not visible, and what Wimmers et al.'s (2026) system good analysis makes fundamentally legible, is that each deepening of the France-Kazakhstan commercial relationship simultaneously deepens France's technical integration into a supply chain architecture in which Rosatom occupies multiple critical nodes. As Kazatomprom pursues its functional upgrading strategy and moves into conversion and fuel fabrication services, it will increasingly do so through partnerships with Rosatom and Chinese state actors, because those are the actors with the existing technical infrastructure. France's commercial engagement with Kazatomprom therefore does not produce independence from Rosatom; it produces further entanglement, through a different pathway.

The stress test of 2020 to 2025 therefore demonstrates the central argument I defend in this thesis with empirical precision. The Niger model ruptured visibly, at an identifiable moment, through an attributable political cause, with a quantifiable supply impact, a form of vulnerability that Hecht's (2012) framework explains as the structural consequence of a post-colonial bilateral relationship whose legitimacy was always contested and whose

enforcement depended on political tools that could not withstand a full sovereignty challenge. The Kazakhstan model deepened silently, accumulating structural exposure to Russian infrastructure and ownership, a form of vulnerability that Wimmers et al.'s (2026) system good analysis reveals as the structural consequence of a supply chain whose critical governance nodes (conversion, enrichment) are controlled by an actor whose strategic interests are not aligned with France's, and whose asset specificity prevents rapid exit. France's dependency has not been reduced through the pivot from Niger to Kazakhstan; it has been transformed from a form of vulnerability that is difficult to manage politically, because of its post-colonial entanglements, to a form of vulnerability that is difficult to manage, because it is embedded in supply chain architectures that are not visible in bilateral trade statistics. The question that follows, and that the conclusion of this thesis will address, is which form of vulnerability is ultimately more dangerous for France's strategic autonomy.

### **3.6 Pathways to Reducing Structural Vulnerability: Analytical Reflexions**

The framework developed in this thesis makes it possible to assess not only the nature of France's dependency but the structural conditions under which it could be reduced. This closing section applies the three-dimensional grid to the principal options available to France, distinguishing interventions that address the dependency at its structural roots from those that merely redistribute its surface configuration.

#### ***3.6.1 The Limits of Extraction-Stage Diversification: The Canadian Question***

The most frequently invoked response to the Niger rupture is supplier diversification, and the most obvious candidates are Canada and Australia: politically stable, institutionally aligned with France, and in Canada's case offering both the world's highest-grade ores in the Athabasca Basin and independent conversion capacity at Cameco's Port Hope facility (Hore-Lacy, 2016; OECD-NEA and IAEA, 2024). The analytical question this raises is why France has not already reoriented its supply massively toward these sources. The answer lies in the contractual architecture analysed in section 3.2: EDF's procurement is locked into multi-year agreements with fixed delivery schedules whose renegotiation carries substantial penalty and replacement costs (Williamson, 1985), Canadian production capacity is itself committed under long-term contracts to American and Asian utilities, and the price differential of Central Asian supply remained, until 2022, commercially decisive. The

post-2023 contracting cycle appears to be correcting this orientation, with Orano publicly identifying Canada and Kazakhstan as its security anchors after the loss of Niger (Orano, 2024). But the deeper point stands: even a fully Canadian extraction portfolio would not, by itself, dissolve the network dependency, because the chokepoints identified in this thesis lie downstream of extraction, in conversion and enrichment, where Canadian capacity is limited and Australian capacity non-existent. France is, in this respect, in a singular position: unlike most nuclear states, it already possesses the domestic downstream capacity that diversification elsewhere cannot provide. The constraint on French autonomy at these stages has never been technical capability but commercial routing choices and the absence, until the post-2022 expansion programme, of dedicated RepU re-enrichment lines. Extraction-stage diversification toward Canada therefore complements, rather than substitutes for, the completion of France's own downstream sovereignty.

### ***3.6.2 The Chinese Counterfactual: Entanglement as a Structural Pattern***

If diversifying extraction toward Canada leaves the downstream chokepoints untouched, a second question follows: is the entanglement those chokepoints create specifically Russian, or a more general pattern? The thesis has analysed network entanglement primarily through the Rosatom case, but the pattern is not specifically Russian. China's state-owned nuclear corporations are pursuing an identical strategy by design: CGN holds 45% of Namibia's Husab mine, CNNC acquired a controlling 52% stake in Rössing in 2019, and CNNC's approximately 9 million SWU of enrichment capacity remains inaccessible to Western utilities (Guzman, 2025; Wimmers et al., 2026). Kazatomprom's functional upgrading into conversion and fuel fabrication is proceeding through joint ventures with both Russian and Chinese partners, because those are the actors with existing infrastructure (Gereffi and Fernandez-Stark, 2016; Wimmers et al., 2026). This parallel matters: it demonstrates that the entangled network dependency identified in this thesis is not an accident of Russian strategy but a structural pattern of state-backed actors acquiring positions in critical resource chains, precisely the competitive logic that Klare (2012) describes as the race for what is left.

The most telling confirmation of this pattern is that the Russian footprint is not even stable in its nationality. In December 2024, Rosatom's subsidiary Uranium One sold its 49.98% stake in the Zarechnoye uranium mine in the Turkestan region of southern Kazakhstan to Astana Mining Company, an entity owned by China's State Nuclear Uranium Resources

Development Company, a divestment that Kazatomprom attributed to the growing difficulty of selling Russian-linked uranium to Western buyers under sanctions exposure (RFE/RL, 2024). At the same time, Russia was consolidating its position at a different node of the chain, having been selected in June 2025 to lead the international consortium tasked with building Kazakhstan's first nuclear power plant (Sukhankin, 2025). The equity footprint that Part II documented as a deepening Russian presence in Kazakhstan's uranium sector is therefore partly migrating toward Chinese ownership rather than receding. This does not weaken the entanglement diagnosis; it confirms it in its strongest form. The vulnerability France faces is not a Russian problem that supplier diversification could dissolve by substituting a Chinese counterparty, because the governance of the chain is consolidating among non-aligned state actors irrespective of which one holds legal title at any given moment.

For France, the implication is sobering: diversification away from Russian-adjacent supply chains risks substituting Chinese-adjacent ones, unless the diversification operates at the level of chain governance rather than country of origin.

### ***3.6.3 The Fate of the Nigerien Assets: Convergence of the Two Models***

This same logic of state-backed entanglement clarifies what is now becoming of the very assets France lost in Niger, whose trajectory since 2023 offers an unexpected confirmation of this thesis's central argument. In December 2024, the junta seized operational control of Somaïr; in June 2025, the Council of Ministers announced its formal nationalisation, accusing Orano of having taken a disproportionate share of historical production, while Orano initiated international arbitration proceedings (World Nuclear News, 2025; Al Jazeera, 2025). For more than a year this rupture produced not a transfer but a freeze: an interim arbitration ruling in September 2025 barred any transfer of Somaïr's output to third parties, and not a single tonne was exported, leaving accumulated yellowcake stranded at the mine (Ecofin Agency, 2025). In late November 2025, the junta announced it would place Somaïr's uranium on the international market in open defiance of that ruling, with French officials reporting a deal to sell roughly 1,000 tonnes of yellowcake to Rosatom. This volume, however, corresponds largely to stock produced under Orano's prior management rather than to new output: selling an existing stockpile requires no extractive capability, and the continuity of actual production since the departure of Orano's technical teams has not been independently verified (Ecofin Agency, 2025; bne IntelliNews, 2025).

The junta simultaneously created a state uranium company, the Timersoï National Uranium Company, and entered discussions with Russian and other state-backed actors regarding the future operation of the assets (RFI, 2024; Bloomberg, 2024). This pivot was formalised in 2025: Niger signed a memorandum of understanding with Rosatom in July and, in September, its mines minister publicly invited Russia to help develop the country's deposits (Valdai Club, 2025; Ecofin Agency, 2025). The analytical significance of this sequence is that the Niger model has not disappeared; it is being converted.

Two distinct dynamics must be separated here. First, Orano's former assets are being re-allocated: Somair's output is being redirected toward Rosatom, a once-French-operated asset passing under the governance of a strategic rival, which is convergence in the strong sense. Second, the Dasa deposit, is of a different kind. It is not a recovered French asset but a new discovery developed from scratch by the Canadian junior Global Atomic, with production scheduled for 2026 (Global Atomic, 2025). Dasa therefore illustrates not a transfer to a rival but something equally telling: even Niger's new uranium is brought to market without any French operator. The common thread is not the nationality of the new operator, which may be a rival (Rosatom) or an ally (Global Atomic), but the structural outcome: Nigerien uranium re-enters the global market through actors over whom France exercises no operational control. France has lost not only its historic mines but its standing in the country's uranium sector as a whole, present and future. The two dependency models analysed in this thesis thus converge toward the same structural endpoint: network entanglement under the partial governance of actors France does not control.

### ***3.6.4 The Buffer as a Strategic Variable***

If neither extraction diversification nor the avoidance of any single state dissolves the network dependency, the question shifts to what cushions its shocks in the meantime. France's strategic stocks, approximately two years of natural uranium and seven to eight years of enriched uranium equivalent in depleted and reprocessed form (Orano, 2023), have appeared throughout this thesis as background context. They deserve to be treated as an analytical variable in their own right, because they are what made the Niger rupture manageable: the buffer converted what would otherwise have been a supply emergency into a procurement adjustment executed over eighteen months. The buffer is thus the operational complement of the rupture-prone model: visible risks plus deep stocks equal manageable dependency. The critical question is whether the same buffer performs equally well against

the network model, and the answer is less reassuring. Stocks insure against interruptions of flow; they do not insure against the gradual capture of chain governance, the erosion of negotiating position, or the accumulation of contractual lock-in, none of which manifest as a supply gap that a stockpile can fill. Moreover, the stocks are managed by EDF and Orano as commercial working capital rather than as state reserves with mandatory floors. A formal minimum strategic reserve framework, analogous to the International Energy Agency's ninety-day oil stock obligation, would institutionalise the buffer and decouple it from commercial optimisation (IEA, 2024).

### ***3.6.5 Domestic Options: Deposits, Depleted Uranium, and the Closed Cycle***

Yet the buffer only buys time; reducing the dependency at its source requires looking inward, to three domestic levers. Three domestic options complete the picture. First, France retains identified recoverable resources of approximately 20,000 to 30,000 tonnes in the Massif Central, Limousin and Gironde, at extraction costs above 130 USD per kilogram (Planet-Terre ENS Lyon, 2021; *Connaissance des Energies*, 2024). At post-2022 price levels this approaches commercial viability, and the analytically correct comparison is in any case not with the spot price but with the cost of disruption: a modest domestic capacity of 500 to 1,000 tonnes per year would preserve geological expertise and reduce the Hirschmanian asymmetry at the margin (Hirschman, 1945). Second, France holds approximately 300,000 tonnes of depleted uranium at Tricastin and Pierrelatte, re-enrichable at SWU prices that current market levels have made economically rational; this constitutes an indigenous feedstock reserve equivalent to several decades of requirements that depends on no foreign supplier (Schneider and Froggatt, 2024). Third, the closed cycle directly reduces natural-uranium demand: industry estimates place the combined saving from MOX recycling and RepU re-enrichment in the range of roughly 10 to 12% of the fleet's natural-uranium requirement, though figures up to a quarter are sometimes advanced and the real benefit is contested (Orano, 2024; Schneider and Froggatt, 2024). Were France to re-enrich its RepU domestically rather than through Rosatom, this saving would be fully sovereign rather than partly outsourced. The 2019 cancellation of the Astrid fast-reactor programme, which would have allowed depleted uranium itself to serve as fuel, now appears as the single most consequential foreclosure of a path to structural independence (Schneider and Froggatt, 2024).

### ***3.6.6 The European Dimension: Whose Sovereignty?***

These domestic levers all operate at the scale of the French state, which raises a final question: whether that is even the right scale. A final reflexion concerns the level at which sovereignty is most meaningfully pursued. This thesis has treated France as the unit of analysis, but nuclear fuel supply is formally a shared competence: the Euratom Supply Agency holds, under the 1957 Euratom Treaty, a right of option over ores and nuclear materials produced in the Community and an exclusive right to conclude supply contracts, although in practice its role has been reduced to monitoring and co-signature (Euratom Supply Agency, 2024). The ESA cannot compel diversification, impose stock obligations, or veto routing decisions on strategic grounds, which is why the migration of European fuel flows through Russian infrastructure proceeded without institutional friction. The EU's Critical Raw Materials Act of 2024, which establishes benchmarks for supply concentration and strategic stock coordination, creates for the first time a regulatory vocabulary applicable to the vulnerabilities this thesis has analysed (European Commission, 2024). Whether uranium supply is ultimately a French sovereignty question or a European one is therefore not merely semantic: the chokepoints identified in Part III, conversion and enrichment, operate at a continental scale, and the only actors with the aggregate demand to underwrite new Western capacity at those stages are collective. France's enrichment expansion at Georges-Besse II is, in this sense, already a European public good, and the strategic logic of the thesis points toward its explicit Europeanisation.

The asymmetry between American and European responses to the Rosatom chokepoint is itself diagnostic. In May 2024, the United States adopted the Prohibiting Russian Uranium Imports Act, banning imports of Russian enriched uranium (with waivers expiring by 2028) and unlocking some USD 2.7 billion to rebuild domestic enrichment capacity. The European Union, by contrast, has imposed no sanctions on Rosatom or on Russian fuel-cycle services, partly because several member states operating VVER reactors remain contractually captive to Russian fuel. The divergence illustrates the central finding of this thesis: where dependency is made visible and politically attributed, as in Washington, policy responses follow; where it remains embedded in commercial routing, the chokepoint persists without institutional friction (US Congress, 2024).

## IV. Conclusion

This thesis set out to answer a deceptively simple question: how does the structure of uranium supply chains shape the nature of France's strategic dependency? The preceding analysis has demonstrated that this question cannot be answered by reference to import volumes alone. France's uranium dependency is a structural configuration rather than a fixed quantity, and that configuration has changed in ways that aggregate statistics systematically conceal.

Part I established the technical architecture of the nuclear fuel cycle and France's position within it. France controls the downstream stages of the cycle, conversion, enrichment, fabrication, and reprocessing, with a degree of industrial integration that few nuclear states can match. Yet every stage of this downstream capacity is conditional on the continuous supply of natural uranium that France cannot produce domestically. The 100% import dependency at the extraction stage is the structural foundation of all the vulnerabilities analysed in this thesis. It reflects not geological impossibility but decades of rational commercial choice whose strategic costs were systematically underweighted in the face of short-term cost optimisation.

Part II traced the historical construction of two structurally distinct models of that dependency. The Niger model was not a commercial arrangement: it was a post-colonial political economy in which resource access was embedded within a comprehensive architecture of military guarantees, elite patronage networks, and institutional lock-in predating the mines themselves. The July 2023 coup did not disrupt this model; it terminated it, revealing that the enforcement mechanisms of the *Françafrique* system had been eroded to the point where France could no longer sustain the bilateral relationship against a determined political challenge. The Kazakhstan model, constructed in parallel over the same period, represents a structurally different form of dependency: one that relies not on bilateral political relationships but on the commercial logic of global supply chains, in which the governance of critical processing stages, conversion and enrichment, is exercised by actors, principally Rosatom, whose strategic interests are not aligned with France's.

Part III compared these two models through the thesis's three-dimensional analytical framework, demonstrating that similar import volumes produce fundamentally different

forms of strategic vulnerability. The Niger model generated a rupture-prone dependency: visible, attributable, and ultimately manageable through stockpile buffers and rapid supply reorientation. The Kazakhstan model generates an entangled network dependency: diffuse, opaque, and resistant to the conventional tools of supply security precisely because its risks are embedded in supply chain architectures that do not appear in bilateral trade statistics. France's pivot toward Kazakhstan following the Niger coup has not reduced its strategic vulnerability; it has transformed it into a form that is consequently harder to see and politically harder to manage.

To the question left open at the close of Part III, which form of vulnerability is ultimately more dangerous for France's strategic autonomy, the analysis supports an unambiguous answer: the entangled network dependency. A rupture-prone dependency is violent but legible; it triggers the institutional reflexes, stockpiles, diplomacy, supply reorientation, that states have developed precisely for such events, as the managed absorption of the Niger shock demonstrated. A network dependency defeats those reflexes: it does not appear in the statistics that inform policy, it resists attribution when it materialises, and it cannot be insured by stocks, because what it erodes is not the flow of material but the governance of the chain. The most dangerous dependency, in short, is the one a state does not know it has.

The thesis's central argument, that France has not reduced its uranium dependency but transformed it, carries a specific and actionable implication for French nuclear policy. The dominant policy response to the Niger crisis has been diplomatic diversification: the Macron-Tokayev agreements of November 2023, the expansion of KATCO's production mandate, the acceleration of procurement from Canada and Australia. These responses are necessary but insufficient, because they address the symptom (dependence on a single bilateral supplier) without engaging the structural cause (dependence on a supply chain architecture in which Russia occupies critical midstream processing nodes).

An organisationally adequate response would require at least three simultaneous interventions: (1) the completion of the domestic conversion and enrichment capacity expansion already under way at the Tricastin complex; (2) the adaptation of Georges-Besse II centrifuge lines for reprocessed uranium feedstock, eliminating the circular dependency that currently requires Russia to re-enrich France's own spent fuel; and (3) a formal 'minimum sovereign supply' framework that mandates a geographic and institutional diversification of

supply chain stages, not merely extraction sources. France possesses the industrial infrastructure, the technical expertise, and, critically, the financial capacity to implement all three. The cost of sovereignty, as the thesis has shown in the case of RepU re-enrichment, was always affordable. What has historically been lacking is the political will to prioritise security of supply over marginal cost reduction.

The period 2020 to 2025 represents a structural inflection point in France's nuclear supply chain. The Niger coup removed the most visible layer of bilateral dependency. The simultaneous deepening of Rosatom's equity presence in Kazakhstan added a new layer of network dependency beneath the surface of apparent diversification. Whether France uses this inflection point to address the underlying structural vulnerability, or merely to redistribute its supply portfolio while preserving the same architecture of network dependence, will determine the nature of its strategic exposure to the next geopolitical shock in the global uranium market.

## V. Glossary

### ■ THE NUCLEAR FUEL CYCLE

#### **Natural Uranium (U natural)**

A radioactive metal extracted from mines. In its natural state, it contains two variants (isotopes): U-238 (99.3%) and U-235 (0.7%). Only U-235 can sustain a nuclear chain reaction in a standard civil reactor. The ore must therefore be chemically transformed before it can be used as fuel.

*Source: Grenèche (2016), p. 1-15; Hore-Lacy (2016), ch. 1*

#### **Yellowcake (U<sub>3</sub>O<sub>8</sub>)**

A yellow-orange powder obtained after crushing and chemically processing uranium ore. It is the first commercially tradeable product from a mine: a concentrated uranium oxide containing approximately 70% uranium. It is packaged in 200-litre steel drums for international transport.

*Source: Grenèche (2016); Hecht (2012), p. 33-34*

#### **Conversion (UF<sub>6</sub>)**

The process of transforming yellowcake into uranium hexafluoride (UF<sub>6</sub>), a gas that is indispensable for enrichment. In France, this operation is carried out by Orano at its Malvesi plant (near Narbonne) and then at Pierrelatte.

*Source: Grenèche (2016); Wimmers et al. (2026)*

#### **Enrichment**

A process that artificially increases the proportion of U-235 in uranium. For a civil reactor, the concentration rises from 0.7% to around 3-5% (Low Enriched Uranium, LEU). For a nuclear weapon, it must exceed 90% (Highly Enriched Uranium, HEU). The dominant technique today is gas centrifuge technology, which consumes 50 times less energy than the older gaseous diffusion method.

*Source: Grenèche (2016); Hore-Lacy (2016), ch. 5*

#### **SWU - Separative Work Unit**

The standard unit of measurement for enrichment work. Producing 1 tonne of uranium enriched to 4% from natural uranium requires approximately 4.3 tSWU. A 1,300 MWe reactor consumes around 120 tSWU per year.

*Source: Hore-Lacy (2016); WNA (2026)*

#### **Fuel Fabrication**

The final step before the reactor: enriched UF<sub>6</sub> is converted back into UO<sub>2</sub> (uranium dioxide) powder, pressed into ceramic pellets, then loaded into zirconium alloy cladding tubes to form fuel assemblies that are placed in the reactor core.

*Source: Hore-Lacy (2016); Grenèche (2016); OECD-NEA (2021)*

#### **Closed Fuel Cycle**

The strategy chosen by France: spent fuel is not permanently stored but reprocessed at La Hague to recover plutonium (recycled into MOX fuel) and reprocessed uranium (RepU), which can be re-enriched and reused. This reduces, but does not eliminate, dependence on fresh natural uranium imports.

*Source: Orano (2024); OECD-NEA (2021); ASNR (2025)*

#### **PUREX**

The chemical reprocessing process used at La Hague to separate uranium, plutonium and fission products from spent fuel. Originally developed for military plutonium separation, its continued civil use embodies the civil-military entanglement of the French nuclear industry.

*Source: Grenèche (2016); Orano (2024); OECD-NEA (2021)*

#### **MOX - Mixed Oxide Fuel**

Nuclear fuel made from a mixture of depleted uranium oxide and plutonium oxide recovered during reprocessing. Used in EDF's 900 MWe reactors. Manufactured at the MELOX plant in Marcoule, southern France.

*Source: Orano (2024); OECD-NEA (2021)*

#### **Astrid**

A French sodium-cooled fast-neutron reactor programme cancelled in 2019. Because fast reactors can use depleted uranium as fuel, its cancellation foreclosed a domestic pathway toward structural independence from imported natural uranium.

*Source: Schneider and Froggatt (2024)*

## **RepU - Reprocessed Uranium**

Uranium recovered during spent fuel reprocessing at La Hague. It contains uranium-236 (a neutron-absorbing isotope) and must be re-enriched before reuse. France historically sent its RepU to Rosatom's Seversk plant in Russia for re-enrichment: 1,150 tonnes were shipped between 2021 and 2022.

*Source: Wimmers et al. (2026); Orano (2022); Guzman (2025)*

## **ISL - In-Situ Leaching**

A uranium extraction technique that avoids bringing ore to the surface: an acid solution is injected underground into the ore-bearing rock, dissolving the uranium in place. The uranium-rich solution is then pumped to the surface. This is the method used by Kazakhstan's Kazatomprom: low cost, small surface footprint. ISL accounts for roughly 50% of global uranium production since 2013.

*Source: Grenèche (2016); Hore-Lacy (2016); Wimmers et al. (2026)*

## **PWR - Pressurised Water Reactor**

The dominant type of nuclear reactor in France (56-57 units). Water, kept under high pressure, acts both as a moderator and as a coolant. Each reactor must be partially refuelled every 12 to 18 months.

*Source: WNA (2024); OECD-NEA (2021); Euratom Supply Agency (2024)*

## **VVER**

A pressurised water reactor of Soviet/Russian design. EU member states operating VVER reactors remain contractually dependent on Russian fuel assemblies, a lock-in that helps explain why the EU has imposed no sanctions on Rosatom's fuel-cycle services.

*Source: Wimmers et al. (2026)*

## **EPR / EPR2**

The European Pressurised Reactor and its simplified EPR2 variant, the new-generation French reactor design. The 2022 programme of six EPR2 units, with an option for eight more, implies a higher, not lower, future natural-uranium requirement.

*Source: EDF (2024)*

## **HHI - Herfindahl-Hirschman Index**

An economic indicator measuring market concentration. An HHI above 2,500 indicates a highly concentrated market (the threshold used by US antitrust authorities). The global enrichment market scores approximately 3,200, signalling an oligopoly dominated by Rosatom.

*Source: US Department of Justice (2023); Wimmers et al. (2026)*

# **■ INDUSTRIAL ACTORS & ORGANISATIONS**

## **Orano**

French industrial group (formerly Areva, formerly Cogema) specialised in the nuclear fuel cycle: uranium mining (Niger, Kazakhstan, Canada), conversion (Malvesi-Pierrelatte), enrichment (Georges-Besse II at Tricastin), reprocessing (La Hague), MOX fabrication (MELOX). Formerly majority shareholder in Niger's mining companies (Somaïr 63.4%, Cominak 34%).

*Source: Orano (2024); Hecht (2012); Wimmers et al. (2026)*

## **EDF - Electricité de France**

France's public electricity utility, owner and operator of the fleet of 56-57 nuclear reactors that generate approximately 67% of French electricity. EDF is Orano's principal customer for nuclear fuel.

*Source: EDF (2024); RTE (2025); IEA (2024)*

## **Framatome**

A joint subsidiary of EDF and Orano, specialised in manufacturing PWR fuel assemblies. Its plant at Romans-sur-Isère supplies the entire EDF fleet and exports globally. It is one of the world's two principal Western PWR fuel fabricators.

*Source: Wimmers et al. (2026); Caspian Policy Center (2023)*

## **CEA - Commissariat à l'Énergie Atomique et aux Energies Alternatives**

France's public nuclear research agency, which originally developed both the civil and military nuclear programmes. It built the first enrichment facilities at Pierrelatte and remains the central actor in French nuclear R&D.;

*Source: Grenèche (2016); IPFM (2023); ASNR (2025)*

## **Kazatomprom**

Kazakhstan's state uranium company and the world's largest uranium producer, with approximately 23% of global supply (~11,373 t in 2022). It masters ISL technology and is Orano's partner in the KATCO joint venture (South Tortkuduk deposit). Listed on the London and Astana stock exchanges since 2018.

*Source: Wimmers et al. (2026); FIIA (2024); Caspian Policy Center (2023)*

## **KATCO**

A joint venture between Orano and Kazatomprom operating the South Tortkuduk uranium deposit in Kazakhstan using ISL technology. Orano holds a majority stake (51%). This is France's principal industrial foothold in Kazakhstani uranium production.

*Source: Wimmers et al. (2026); Caspian Policy Center (2023); World Geostrategic Insights (2024)*

## **Somaïr - Societe des Mines de l'Air**

Former mining joint venture in Niger operating the open-pit mine at Arlit. Orano held a 63.4% stake. Operations were suspended in October 2024 following the revocation of mining licences by the military junta that took power in July 2023.

*Source: Reuters (2025); Portail IE (2024); WNA (2026)*

## **Cominak - Compagnie Minière d'Akouta**

Former underground uranium mine in Niger (Akouta deposit, 250 metres deep, 250 kilometres of tunnels). Orano held a 34% stake. Closed in 2021 after exhaustion of its ore reserves.

*Source: WNA (2026); Hecht (2012); Wimmers et al. (2026)*

## **Rosatom**

Russia's state nuclear conglomerate, present across the entire fuel cycle: mining (Uranium One in Kazakhstan, 49% of Budenovskoye), conversion (Seversk), enrichment (four plants: Novouralsk, Zelenogorsk, Seversk, Angarsk, approximately 44% of global capacity), reactor construction (VVER design), and international services (Tenex). It serves as a key instrument of Russian energy diplomacy.

*Source: Wimmers et al. (2026); Caspian Policy Center (2024); Lanoszka (2024); IAR (2026)*

## **Uranium One**

A Rosatom subsidiary active in uranium mining in Kazakhstan and several other countries. It represents Russia's growing equity footprint in Kazakhstani uranium assets, deepening structural entanglement between France's supply chain and Russian interests.

*Source: Caspian Policy Center (2024); FIIA (2024); CSIS (2026)*

## **CNNC / CGN**

China's two state-owned nuclear corporations. CNNC controls roughly 9 million SWU of enrichment capacity inaccessible to Western utilities and, with CGN, holds stakes in Namibian uranium mines (Rössing, Husab). They illustrate that network entanglement is a structural pattern of state-backed actors, not a uniquely Russian one.

*Source: Guzman (2025); Wimmers et al. (2026)*

## **Cameco**

Canada's principal uranium producer, operating the high-grade Athabasca Basin mines and the Port Hope conversion facility. It represents the main Western alternative to Central Asian and African supply, though its output is largely committed under long-term contracts to American and Asian utilities.

*Source: Hore-Lacy (2016); OECD-NEA and IAEA (2024)*

## **ConverDyn**

The sole United States uranium conversion operator, whose plant has been idle since 2017. Its shutdown left Russia's Seversk facility as the global conversion market's swing supplier, deepening the chokepoint that Kazakhstani uranium routed for Western enrichment must navigate.

*Source: Wimmers et al. (2026)*

## **Urenco**

A trilateral consortium (United Kingdom, Netherlands, Germany) specialised in gas centrifuge enrichment. It holds the world's second largest enrichment capacity (approximately 16.5 million SWU). Partner of Orano in developing TC12 centrifuge technology through the Enrichment Technology Company (ETC) joint venture.

*Source: Grenèche (2016); Hore-Lacy (2016); Guzman (2025)*

## **IAEA - International Atomic Energy Agency**

The United Nations body responsible for promoting peaceful uses of nuclear energy and controlling non-proliferation. It manages safeguards on nuclear materials and classifies yellowcake as a 'source material' subject to a lighter oversight regime than enriched uranium, a classification that has shaped the globalisation of the uranium trade.

*Source: IAEA (2022); Hecht (2012), p. 33-34; OECD-NEA & IAEA (2024)*

## **ESA – Euratom Supply Agency**

European Union agency responsible for securing nuclear fuel supplies for EU member states. It publishes an authoritative annual report on uranium flows in Europe, a key data source for the thesis.

*Source: Euratom Supply Agency (2024)*

## **WNA - World Nuclear Association**

International industry organisation representing civil nuclear actors worldwide. It publishes reference data on uranium production, resources and consumption.

*Source: WNA (2024); WNA (2026)*

## **RTE - Réseau de Transport d'Electricité**

France's high-voltage electricity grid operator. It publishes the annual French electricity balance (Bilan électrique), the reference source for nuclear generation figures (~361.7 TWh in 2024 out of ~536.5 TWh total).

*Source: RTE (2025); RTE (2023)*

## **SIPRI - Stockholm International Peace Research Institute**

Swedish independent research institute on peace and security. Its annual Yearbook is the reference source for global nuclear arsenal estimates, including France's (approximately 290 warheads in 2025).

*Source: SIPRI (2025)*

## **IPFM - International Panel on Fissile Materials**

An independent network of researchers specialised in fissile materials (enriched uranium, plutonium). Its reports provide the key estimates of France's military stocks (~25 t of military HEU, 6 t of weapons-grade plutonium).

*Source: IPFM (2023)*

## **ASNR - Autorite de Surete Nucleaire et de Radioprotection**

France's independent nuclear safety and radiation protection regulator (formerly ASN). It publishes regulatory data on the nuclear fuel cycle and is a primary institutional source for the thesis.

*Source: ASNR (2025)*

## **NEA / OECD-NEA – Nuclear Energy Agency**

The OECD's nuclear energy body. It co-publishes the biennial 'Red Book' (Uranium: Resources, Production and Demand) with the IAEA - the definitive global reference on uranium resources and market conditions.

*Source: OECD-NEA & IAEA (2024); OECD-NEA (2021)*

## **CSTO - Collective Security Treaty Organisation**

A Russian-led intergovernmental military alliance. Its January 2022 intervention in Kazakhstan demonstrated that the political stability underpinning the Kazakh supply model is itself partly guaranteed by Moscow.

*Source: Hedenskog and von Essen (2022)*

## **■ KEY SITES & INFRASTRUCTURE**

### **Tricastin (Drôme, France)**

An integrated nuclear industrial site in the Rhone valley: home to the Georges-Besse II enrichment plant (7.5 million SWU/year, currently being expanded), the UF4-to-UF6 conversion step at Pierrelatte, and formerly the gaseous diffusion plant Georges-Besse I (shut down in 2012). Its geographic concentration is itself identified as a structural vulnerability.

*Source: Grenèche (2016); IAR (2026); Wimmers et al. (2026)*

### **Malvesi (Narbonne, France)**

Orano's conversion plant performing the first transformation step: yellowcake (U<sub>3</sub>O<sub>8</sub>) is converted into uranium tetrafluoride (UF<sub>4</sub>). Capacity expanded to 9,000 t/year in 2022 as a direct response to the Russian invasion of Ukraine.

*Source: Grenèche (2016); Wimmers et al. (2026)*

### **La Hague (Manche, France)**

The largest spent nuclear fuel reprocessing centre in the Western world, operated by Orano (capacity: 1,700 t of spent fuel per year; storage: 17,600 t). It separates plutonium, reprocessed uranium (RepU) and radioactive waste using the PUREX chemical process.

*Source: Grenèche (2016); Orano (2024); OECD-NEA (2021)*

### **MELOX (Marcoule, Gard, France)**

Fuel fabrication plant producing MOX assemblies (UO<sub>2</sub> + PuO<sub>2</sub> mixture) for EDF's 900 MWe reactors. An essential link in France's closed fuel cycle.

*Source: Orano (2024); OECD-NEA (2021)*

### **Romans-sur-Isere (France)**

Framatome's fuel fabrication plant producing UO<sub>2</sub> pellets and complete PWR fuel assemblies (M5 alloy cladding) for EDF's entire reactor fleet. Its reactor-specific fuel design creates a structural lock-in: assemblies cannot be swapped between reactor types without years of re-licensing.

*Source: Hore-Lacy (2016); Wimmers et al. (2026)*

### **Arlit (Niger)**

Mining town in northern Niger (Agadez region), the historic centre of Nigerien uranium extraction. Site of the Somaïr open-pit mine and the former Cominak underground mine. Uranium left Arlit by road convoy through Agadez to the port of Cotonou in Benin for shipment to France.

*Source: Hecht (2012); WNA (2026); Reuters (2025)*

### **Imouraren (Niger)**

A giant undeveloped uranium deposit in Niger, previously slated for development by Orano. Its mining licence was revoked by the military junta in June 2024, representing a permanent loss of future production capacity.

*Source: Reuters (2025); Portail IE (2024); Africa Analyst (2024)*

### **Athabasca Basin (Saskatchewan, Canada)**

The world's richest uranium geological basin, hosting the McArthur River mine (grades up to 25% uranium versus 0.3-1.8% in Niger and Kazakhstan). Operated by Cameco, it represents the high-grade alternative to Central Asian and African supply.

*Source: Hore-Lacy (2016); OECD-NEA & IAEA (2024)*

### **TITR - Trans-Caspian International Transport Route**

An alternative commercial corridor developed to bypass Russia: Kazakhstan to the Caspian Sea (port of Aktau) to Azerbaijan, Georgia, Turkey, and then Europe. Activated commercially after February 2022, but constrained by port capacity bottlenecks, rail gauge changes and limited political coordination among transit states.

*Source: FIIA (2024); Wimmers et al. (2026); Caspian Policy Center (2023)*

### **Budenovskoye (Kazakhstan)**

Expected to become the world's single largest uranium deposit once fully developed. Rosatom acquired a 49% stake in late 2022, with all output reserved for Russian industry through 2026; deepening Russia's structural influence over Kazakhstan's uranium sector.

*Source: Caspian Policy Center (2024); CSIS (2026); Wimmers et al. (2026)*

### **Seversk (Russia)**

Rosatom's conversion and enrichment plant (~3 million SWU enrichment capacity). It received French RepU for re-enrichment (1,150 t shipped by Orano in 2021-2022) and was operating at 96% of capacity in 2022, while the US ConverDyn plant was entirely offline - making it the global conversion market's swing supplier.

*Source: Wimmers et al. (2026); Al Habtoor Research Centre (2026); Guzman (2025)*

## ■ THEORETICAL & ANALYTICAL CONCEPTS

### **Controlled Bilateral Dependence**

A supply relationship in which a single firm (Orano) holds direct equity ownership in the extraction assets of a supplier state (Niger), creating operational control over output decisions and supply terms. Risk is concentrated and visible, but exit is costly due to sunk assets and non-transferable geological expertise. Corresponds to the Niger model in the thesis.

*Source: Hemelaer (2026), Part III; Gereffi & Fernandez-Stark (2016)*

### **Entangled Network Dependence**

A form of supply dependency where procurement passes through multiple intermediaries (Kazakhstan, Russia via conversion and enrichment, transport corridors). Risk is diffuse, opaque and difficult to attribute, because no single actor governs the full chain. Corresponds to the Kazakhstan model in the thesis.

*Source: Hemelaer (2026), Part III; Farrell & Newman (2019); Wimmers et al. (2026)*

### **Weaponised Interdependence**

Concept developed by Farrell and Newman (2019): in global economic networks, states that control strategic nodes (chokepoints) can convert economic relationships into instruments of coercion; either by denying access to adversaries or by gathering strategic intelligence on flows. Applied here to enrichment and conversion chokepoints dominated by Rosatom.

*Source: Farrell & Newman (2019); Wimmers et al. (2026)*

### **GVC - Global Value Chain**

An analytical framework developed by Gereffi that disaggregates production of a good into stages distributed across multiple countries, and examines who governs the chain, who captures the rents and who bears the risks. Applied in the thesis to map the nuclear fuel cycle from mine to reactor.

*Source: Gereffi (1994); Gereffi & Fernandez-Stark (2016)*

### **Chain Governance (Gereffi typology)**

Gereffi and Fernandez-Stark (2016) identify five governance types based on three variables: information complexity, codifiability and supplier competence. The types range from market (pure spot) through modular, relational and captive to hierarchical. Niger = captive/hierarchical (Orano controls all stages). Kazakhstan = relational/modular (Orano is one buyer among many).

*Source: Gereffi & Fernandez-Stark (2016); Gereffi (2005)*

### **Chokepoint**

A mandatory passage point in a network whose control confers structural power on its holder. In the nuclear fuel cycle: uranium conversion (only five operational plants worldwide) and enrichment (dominated by Rosatom with ~44% of global capacity) are the two principal chokepoints identified in the thesis.

*Source: Farrell & Newman (2019); Wimmers et al. (2026)*

### **Path Dependency**

The tendency for historical choices to constrain future options: past investments in mines, contracts, and reactor-specific technologies create high switching costs that perpetuate a supply relationship even when it becomes strategically suboptimal. Both the Niger and Kazakhstan models generate path dependency, but through different mechanisms.

*Source: Wimmers et al. (2026); Hecht (2012), p. 109-117; Gereffi & Fernandez-Stark (2016)*

### **Nuclearity (Hecht 2012)**

A concept developed by political scientist Gabrielle Hecht: the politically contested designation of what counts as 'nuclear'. African yellowcake was deliberately classified as a non-nuclear 'source material' under the 1957 IAEA statute, facilitating uranium trade while allowing France to exploit its strategic value without acknowledging the political significance of that dependency.

*Source: Hecht (2012), p. 33-36*

### **Banalisation**

Hecht's term for the process by which the political dimension of a strategic resource is erased by treating it as an ordinary market commodity. France deployed this argument to refuse indexing Niger's uranium price to oil prices in the 1970s, thereby maintaining its commercial advantage while exploiting the resource's strategic importance. The Kazakhstan model represents a more thoroughly banalised form of dependency.

*Source: Hecht (2012), p. 35 & 77-78*

## **Françafrique**

An informal system of political, economic and military relations between France and its former African colonies, sustained through personal networks, defence accords (signed at independence in 1960) and opaque financial flows. This system structured France's access to Nigerien uranium for decades but was progressively delegitimised, ultimately enabling the 2023 coup to sever the supply relationship.

*Source: Hecht (2012), p. 109-117; SPF (2025); Africa Analyst (2024)*

## **Asset Specificity**

The degree to which an investment (mine infrastructure, centrifuge technology, reactor-specific fuel assembly design) cannot be repurposed for other uses. The higher the asset specificity, the higher the exit costs and the more irreversible the dependency. A key variable in understanding lock-in in both the Niger and Kazakhstan supply models.

*Source: Wimmers et al. (2026); Gereffi & Fernandez-Stark (2016)*

## **Functional Upgrading**

Gereffi's term for the process by which a supplier acquires competencies across additional stages of the chain, moving beyond extraction into conversion, enrichment or fuel fabrication. Kazatomprom is currently pursuing this strategy, which systematically erodes France's leverage as a buyer over time.

*Source: Gereffi (2005); Gereffi & Fernandez-Stark (2016); Wimmers et al. (2026)*

## **HEU - Highly Enriched Uranium**

Uranium enriched to over 90% U-235, used in nuclear weapons. France ceased military HEU production in 1996. Current military stock is estimated at approximately 25 t +/- 6 t (IPFM 2023). Categorically different from the LEU used in civil power reactors.

*Source: IPFM (2023); IAEA (2022); Grenèche (2016)*

## **LEU - Low Enriched Uranium**

Uranium enriched to between 3% and 5% U-235, used as fuel in civil light-water reactors. This is the form of uranium that EDF purchases for its power plants. Produced from natural uranium by the enrichment process at Tricastin (Orano).

*Source: IAEA (2022); Hore-Lacy (2016); Euratom Supply Agency (2024)*

## **Tritium**

A hydrogen isotope used in the boosted stages of modern warheads, with a half-life of 12.3 years requiring continuous replenishment. Produced in CEA facilities that draw on the same enrichment infrastructure as the civil programme, it links the maintenance of the deterrent to the front-end fuel cycle.

*Source: IPFM (2023); Cochran and Norris (2012)*

## **NPT - Nuclear Non-Proliferation Treaty**

The 1968 international treaty limiting the spread of nuclear weapons. France, as a recognised nuclear-weapon state, committed to maintaining a formal separation between civil and military nuclear material flows, and imposed a moratorium on new fissile material production for weapons purposes from the 1990s.

*Source: IAEA (2022); IPFM (2023); Grenèche (2016)*

## **Strategic Stockpiles**

Reserves of natural and enriched uranium accumulated to buffer supply disruptions. France holds approximately 2 years' worth of natural uranium and the equivalent of 7 to 8 years in depleted and reprocessed uranium stocks, providing time to adjust supply routes but not eliminating the underlying structural dependency.

*Source: Orano (2023); ASN (2025)*

## **TWh - Terawatt-hour**

A unit of electrical energy: 1 TWh = 1 billion kilowatt-hours. France produced approximately 361.7 TWh of nuclear electricity in 2024 out of a national total of roughly 536,5 TWh (RTE 2025), placing it among the world's most nuclear-dependent countries.

*Source: RTE (2025); IEA (2024)*

## **MWe - Megawatt electric**

A unit of installed generating capacity. A 900 MWe PWR reactor produces 900 million watts of electricity. France's installed nuclear capacity exceeds 61 GWe across its fleet of 56-57 reactors.

*Source: WNA (2024); Hore-Lacy (2016)*

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