From Nuclear Spring to Fuel-Cycle Bottlenecks

Securing Europe's Nuclear Fuel Cycle between Market Logic, Strategic Dependencies and Proliferation Sensitivity

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Abstract

This paper examines how the possible expansion of nuclear energy may turn the nuclear fuel cycle into a strategic governance bottleneck. It argues that nuclear supply security cannot be assessed solely through reactor deployment or uranium availability, but must also be understood through the governance of conversion, enrichment, fuel fabrication, safeguards, export controls and reactor-specific licensing.

The analysis focuses on the nuclear fuel framework and its interaction with global non-proliferation rules, EU-related capacity constraints and national regulatory approval. Particular attention is given to Russian fuel-cycle dependencies, VVER fuel diversification in Central and Eastern Europe, and future challenges related to small modular reactors and High-Assay Low-Enriched Uranium (HALEU). The paper argues that fuel-cycle diversification is shaped by the interaction of energy security, industrial strategy and non-proliferation governance, and that these dimensions are not automatically aligned.

Keywords: nuclear fuel cycle; EU/Euratom governance; VVER reactors; fuel diversification; small modular reactors (SMR); non-proliferation; energy security; Russian dependency

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1 Introduction

This paper's starting point is the **renewed strategic relevance of the nuclear fuel cycle**. Recent debates on global electricity demand, decarbonisation and energy security have brought nuclear energy back into the centre of policy discussions. Yet the possible “nuclear spring” is not only a question of reactor construction. If nuclear power is expected to contribute to low-carbon electricity generation, energy security or industrial strategy, the availability and governance of the entire nuclear fuel cycle become equally important.

The **objective** of this paper is therefore to examine how nuclear fuel-cycle governance may become a strategic bottleneck in a period of possible nuclear expansion. The analysis focuses on the interaction between three dimensions that are often treated separately – namely energy security, industrial capacity and non-proliferation governance. It asks how the supply of uranium, conversion, enrichment and fuel fabrication is shaped not only by market conditions, but also by geopolitical exposure, safeguards, export controls, Euratom supply governance and national safety licensing.

Methodologically, the paper is based on qualitative document and source analysis, complemented by semi-structured expert interviews. The documentary analysis covers international energy and nuclear outlooks, EU and Euratom legal and policy documents, Euratom Supply Agency reports, industry assessments and academic literature on the related issues. The interviews are used to refine the practical understanding of fuel qualification, licensing, supply-chain constraints and the technical-institutional limits of diversification.

The **structure of the analysis** proceeds in several steps. First, it situates the research problem within the broader context of rising electricity demand, climate targets and the conditional revival of nuclear energy. Second, it examines the structure of the nuclear fuel cycle, with particular attention to uranium supply, conversion, enrichment and fuel fabrication. Third, it analyses the multi-level governance framework in which these activities take place, including global safeguards and export controls, Euratom-level supply and safeguards governance, and national nuclear safety licensing. Fourth, it turns to the EU and Central and Eastern Europe, where VVER fuel diversification (involving Soviet-designed pressurised water reactors historically tied to Russia- and Rosatom-related fuel supply) provides a concrete example of how inherited technological dependencies can constrain supply substitution.. Finally, the paper connects this experience to future challenges surrounding small modular reactors (SMRs), which are promoted as smaller, more standardised and potentially more flexible reactor designs, but whose advanced variants may depend on specialised fuel supply chains, including High-Assay Low-Enriched Uranium (HALEU), a higher-enriched fuel type expected to be relevant for several advanced reactor concepts.

The **central hypothesis** is that a significant expansion of nuclear energy would not only create a reactor-deployment challenge but also a fuel-cycle governance challenge. In the EU context, this problem is particularly evident because efforts to reduce Russian energy dependence intersect with long-standing nuclear fuel-cycle vulnerabilities, especially with regard to VVER reactors. At the same time, emerging SMR and HALEU-related requirements show that similar vulnerabilities may arise in new technological contexts if fuel-cycle readiness, safeguards capacity and licensing pathways are not considered from the outset. The paper therefore argues that nuclear supply security cannot be understood separately from industrial capacity, non-proliferation control and reactor-specific regulatory approval.

2 Global energy demand and the "nuclear spring"

2.1 Structural growth in electricity demand

The starting point of the analysis is that future energy security will be shaped not only by total energy demand but also by the structural growth of electricity demand. Global population growth, urbanisation, rising living standards, industrial development, and the electrification of end-use sectors all point in the same direction: future energy systems will need to supply significantly larger quantities of electricity while also reducing emissions and maintaining reliability. According to United Nations projections, the world's population is expected to increase from approximately 8 billion in 2024 to nearly 9.8 billion by 2050 (United Nations, 2024). This demographic trend will be accompanied by expanding infrastructure, higher consumption, and ongoing industrialisation across several regions, all of which will increase demand for energy-intensive services.

The most significant shift, however, is not merely that the world will require more energy. It is anticipated that a growing proportion of this demand will be for electricity. Electrification is becoming increasingly central to decarbonisation strategies, particularly in transport, heating, and certain industrial processes. Electric vehicles, heat pumps, electric industrial equipment, and new forms of digital infrastructure all direct energy demand towards the power system. In this context, growth in electricity demand should be viewed as structural rather than cyclical. It is connected to long-term changes in technology, infrastructure, and climate policy, rather than solely to short-term economic recovery (IEA, 2025a; IEA, 2025b).

Several drivers are particularly important:

- **Demographic and economic growth:** A larger and more urbanised global population will require more electricity for housing, transport, cooling, public services and industrial activity.
- **Electrification of end uses:** Transport, heating and parts of industry are increasingly expected to shift from direct fossil-fuel use to electricity-based systems.
- **Digitalisation and artificial intelligence:** Data centres, cloud computing and AI-related infrastructure are emerging as major new sources of electricity demand.
- **Industrial competitiveness:** In advanced economies, access to affordable low-carbon electricity is becoming an important condition for industrial strategy and technological competitiveness.

International energy outlooks increasingly reflect this structural shift. The International Energy Agency projects that electricity will play an increasingly important role in meeting energy-service demand across all major scenarios. In the Stated Policies Scenario, peak electricity demand rises by around 40% by 2035, while in the Net Zero Emissions scenario, electricity becomes even more central to final energy consumption, accounting for around one-third of all energy consumption by 2035 (IEA, 2025a). The scale of the increase differs across scenarios, but the direction is consistent, as electrification, industrial electricity use, cooling demand and digital infrastructure are expected to make electricity one of the central variables of the energy transition.

The **European Union** illustrates both the *short-term volatility* and the *longer-term structural character* of this trend. EU electricity consumption fell in 2022 and 2023, returning to levels not seen for around two decades, largely due to high energy prices, weak industrial activity, and the broader effects of the energy crisis. In 2024, demand *began to increase again*, though only moderately, driven mainly by residential, commercial and transport uses, including heat pumps, electric vehicles and data centres. Industrial electricity demand remained weaker, reflecting sluggish economic conditions and the continuing competitiveness challenge faced by energy-intensive sectors (IEA, 2025c). This shows that electricity demand growth is *not linear* in the short term. Yet it also shows why the underlying trend remains important, as even after a crisis-driven decline, *electrification and digitalisation* continue to push electricity demand upwards.

Industrial and transport electrification should also be treated as major structural drivers of future electricity demand. In industry, decarbonisation increasingly involves the replacement of fossil-fuel-based heat and production processes with electricity-intensive alternatives, including electric furnaces, industrial heat pumps, electric boilers and other power-based process-heat technologies (Fraunhofer ISI, 2024) Transport electrification points in the same direction, as electric vehicles, charging infrastructure, and electrified rail systems increase electricity demand while also changing where and when electricity is needed (EEA, 2025). Future demand growth should therefore not be understood mainly as an IT or data-centre phenomenon, but as the combined effect of wider economic electrification, industrial decarbonisation, transport transformation and digital infrastructure.

However, **digital infrastructure** deserves particular attention because it creates a new and concentrated form of electricity demand. *Data centres* currently account for a relatively small share of global electricity consumption, but their demand is expected to grow rapidly during the 2020s. The IEA estimates that data-centre electricity consumption could more than double by 2030, reaching approximately 945 TWh, slightly above Japan's current total electricity consumption (IEA, 2025d). In the EU, data centres already account for a visible share of electricity demand, and in some Member States the share is much higher, particularly where *large digital infrastructure clusters* have developed (IEA, 2025d).

This trend is also visible in more concrete accounts of **AI-related infrastructure**. Wong describes large AI data centres as highly concentrated electricity consumers, where individual facilities may require power on a scale comparable to hundreds of thousands of households or even major urban areas (Wong, 2026). These examples should not be treated as global averages, but they illustrate the *changing physical character of digital electricity demand*. Instead of being dispersed across millions of small users, demand is increasingly concentrated in large, power-intensive facilities.

Artificial intelligence reinforces this trend because advanced AI models require large-scale data processing, specialised hardware and continuous operation. Goldman Sachs Research projects a sharp increase in global data-centre power demand by 2030, driven significantly by AI-related computing needs (Goldman Sachs Research, 2024). A more technical perspective is provided by Chen et al., who show that AI data-centre loads raise power-system challenges across several timescales, from long-term generation and grid planning to short-term operation and real-time system stability (Chen et al., 2025). This makes AI-related electricity demand not only a question of additional consumption but also *one of system planning, grid capacity, and reliability*.

At the same time, this trend should not be overstated in a deterministic way. **Efficiency improvements, demand flexibility, better cooling technologies and smarter grid management** may moderate the pace of growth. Nadel argues that energy efficiency and demand flexibility can *reduce* both total data-centre electricity use and peak-demand pressure, suggesting that the eventual scale of the problem will depend partly on technology choices and operational practices (Nadel, 2025). AI may also support the energy transition by improving grid operation, forecasting, demand management and the integration of variable renewable energy sources (IEA, 2025d). In this respect, digitalisation is both a source of additional electricity demand and a potential tool for *managing more complex energy systems*.

The broader implication is that future energy systems will need not only more electricity, but more reliable, affordable and low-carbon electricity. This distinction is crucial for the argument of this paper. Rising electricity demand does not by itself determine the future role of any single technology. It does, however, explain why dispatchable low-carbon generation is receiving renewed attention in energy and climate policy debates. The next section, therefore, turns to nuclear energy as one possible response to this structural demand problem, while also stressing that any future nuclear expansion would create new pressures on the nuclear fuel cycle.

2.2 The renewed interest towards nuclear energy

The structural rise of electricity demand matters because climate policy does not only require more energy, but more **low-carbon electricity**. As transport, heating, industry and digital infrastructure become increasingly electrified, decarbonisation depends on whether the additional electricity demand can be met without locking in new fossil-fuel dependence. This is the point at which *nuclear energy re-enters the debate*. Nuclear power is not the only low-carbon option, and its role remains politically contested, but it is again being discussed as a source of dispatchable low-carbon electricity that may complement variable renewable generation in deeply decarbonised power systems (IEA, 2021; IEA, 2022; Papadopoulou et al., 2021).

International projections reflect this **renewed attention**. The International Atomic Energy Agency (IAEA) has revised its long-term expectations for nuclear power upwards, with high-case scenarios indicating that global nuclear generating capacity could approximately double by 2050 (IAEA, 2025a). The International Energy Agency's *Net Zero by 2050* roadmap points in a similar direction, although within a broader technology portfolio dominated by renewables, electrification, energy efficiency and innovation (IEA, 2022). The common message is not that nuclear energy will automatically expand everywhere, but that *several decarbonisation pathways keep nuclear energy* within the low-carbon electricity mix.

The **renewed interest** in nuclear energy rests on several overlapping arguments:

- **Low-carbon electricity:** Nuclear power can provide large volumes of electricity with very low operational carbon emissions, which makes it relevant for long-term climate targets (IEA, 2021; IAEA, 2025).
- **System reliability:** Unlike variable renewable sources, nuclear power can provide dispatchable generation, which may support system stability in electricity systems with growing shares of wind and solar (IEA, 2022; Papadopoulou et al., 2021).
- **Energy security:** For some states, nuclear energy is also attractive because it can reduce exposure to fossil-fuel imports and price volatility, particularly after the European energy crisis following Russia's invasion of Ukraine. In the EU context, however, this also makes the issue geopolitically sensitive, as nuclear power may ease one form of external dependence while leaving *Russia-related fuel-cycle vulnerabilities* in place (IEA, 2022).
- **Industrial strategy:** Nuclear technologies, including small modular reactors (SMRs), are increasingly linked to questions of industrial competitiveness, technological

autonomy and supply-chain resilience (European Commission, 2026; OECD NEA, 2024; World Nuclear Association, 2026).

For this reason, the current debate is better understood as a possible "**nuclear spring**" than as a simple nuclear renaissance. The term captures both renewed *political and industrial interest* and its *conditional character*.

National strategies still diverge significantly:

- while some countries are **extending the lifetime of existing reactors** or planning **new units**;
- others have **phased out nuclear power** or remain politically opposed to it;
- several are **exploring SMRs** without yet committing to large-scale deployment.

This divergence shows that nuclear expansion is **not a universal trend**, but a set of national and regional strategies shaped by *climate targets, energy-security concerns, public acceptance and industrial capacity*.

The **constraints** are equally important. Scaling nuclear power requires h*igh upfront investment, long planning and construction periods, regulatory capacity, waste-management solutions, qualified supply chains and public acceptance* (OECD NEA, 2024; Sovacool et al., 2020; World Nuclear Association, 2026). These limits are particularly relevant for **SMRs**. They are often presented as more standardised, modular and financeable than conventional large reactors, but their large-scale deployment still depends on *licensing readiness, design maturity, serial production, supply-chain capacity and credible fuel availability* (OECD NEA, 2024; World Nuclear Association, 2026).

The **European Union** provides a particularly important setting for this debate. The European *Green Deal* and the *European Climate Law* establish the EU's *objective of climate neutrality* by 2050 and a legally binding target of reducing net greenhouse gas emissions by at least 55% by 2030 compared with 1990 levels (European Commission, 2019; Regulation (EU) 2021/1119). These objectives are linked to the *Paris Agreement* and require deep decarbonisation across power generation, industry, transport and buildings. Nuclear energy fits into this framework in a specific way, as it is neither mandated by EU climate law nor excluded from the low-carbon transition.

This reflects the **legal structure of EU energy policy**:

- Article 194 TFEU **gives the EU competence** in energy policy, including the internal energy market, security of supply, energy efficiency and the development of renewable energy.
- At the same time, it preserves the **right of Member States to determine their energy mix** and the general structure of their energy supply (TFEU, Art. 194)
- The **Euratom Treaty** adds a *separate nuclear-specific layer*, covering nuclear research, safety, investment, safeguards and the regular and equitable supply of ores and nuclear fuels (Euratom Treaty, Arts. 2, 52, 77–81).

Taken together, these rules create a **pluralistic framework**, as the EU can coordinate, regulate and support *nuclear-related activities*, but the decision to *rely on nuclear power remains primarily national*.

This also explains why nuclear energy remains **politically contested** within EU climate governance. The debate is often framed through **technological neutrality**:

- Supporters argue that nuclear energy should be treated as **one low-carbon technology** among others, especially where it contributes to *security of supply and decarbonisation*.
- Critics argue that technological neutrality may **dilute the priority given to renewables and energy efficiency**, or allow politically contested technologies to *be presented as equivalent climate solutions* (Papadopoulou et al., 2021; EEB, 2025).

The result is not a settled consensus, but a **continuing regulatory and political dispute** over how the EU's low-carbon transition should be technologically organised.

For the purposes of this paper, the decisive question is not whether nuclear energy will expand everywhere. It will not. The more relevant question is what follows in those countries and regions where nuclear power is expected to support decarbonisation, energy security or industrial strategy. In such cases, expansion is not only a matter of reactor deployment. It also depends on the **availability and governance of the entire nuclear fuel cycle** – namely, uranium supply, conversion, enrichment, fuel fabrication, as well as licensing, safeguards, and export controls. The "nuclear spring" is therefore conditional in a deeper sense. It depends not only on climate ambition and reactor construction, but on whether **fuel-cycle governance** can sustain a larger, more diversified and more geopolitically sensitive nuclear sector.

2.3 From nuclear spring to fuel-cycle bottleneck as the main hypothesis

Against this background, the current "nuclear spring" should be understood less as a settled global renaissance than as a **conditional expansion scenario**. Recent projections suggest that global nuclear capacity could grow substantially if governments implement their announced energy, climate and industrial strategies:

- The World Nuclear Association estimates that global nuclear capacity could reach around 1,446 GWe by 2050 if existing reactors remain in operation, units under construction are completed and planned or proposed national programmes are realised (World Nuclear Association, 2026).
- The IAEA's high-case projection similarly envisages a significant increase in global nuclear capacity by 2050, with small modular reactors expected to contribute to this growth (IAEA, 2025a).
- These projections, however, should be read cautiously. Nuclear expansion depends not only on climate ambition, but also on *financing, regulatory capacity, supply-chain delivery, construction performance, public acceptance and long-term state support*. More critical assessments emphasise that the global nuclear sector continues to face *ageing fleets, delays, high construction costs and competition* from rapidly expanding renewable energy technologies (Schneider et al., 2025).
- Similarly, the SMR literature shows that the promise of smaller and more modular reactors depends on whether *standardisation, serial production, licensing simplification* and *credible cost reductions can be achieved in practice* (Mignacca and Locatelli, 2020).

This **conditional character** matters because nuclear expansion would not only increase demand for reactors. It would also increase demand for the entire *front end of the nuclear fuel cycle*. The World Nuclear Association estimates that global reactor requirements for uranium could rise from approximately 68,920 tU in 2025 to just over 150,000 tU by 2040 in its Reference Scenario (World Nuclear Association, 2025b). This does not necessarily imply a physical shortage of uranium resources. The more relevant issue is whether mining, conversion, enrichment, fuel fabrication, as the four elements of the fuel cycle, are to be elaborated thoroughly below, and furthermore, transport, licensing and regulatory oversight *can expand in time, and in politically reliable forms*.

The strategic vulnerability is therefore not simply a shortage of uranium, but the concentration of conversion, enrichment and reactor-specific fuel capabilities (Castillo-Peters and von Hippel, 2022; Haneklaus et al., 2025):

- This becomes especially visible in the *VVER context*, where Soviet-designed pressurised water reactors remain in operation in several EU and neighbouring countries and have historically relied on Rosatom-related fuel supply, making diversification dependent on the qualification of alternative fuel for specific reactor designs.
- It may also reappear in a forward-looking form in the *SMR context*, especially if advanced reactor deployment depends on specialised fuels such as High-Assay Low-Enriched Uranium (HALEU).

The **European Union** provides a particularly useful case for examining this problem. Since Russia's invasion of Ukraine, the EU has moved rapidly to reduce **Russian** fossil-fuel dependence, but **nuclear fuel-cycle dependencies** have proven more difficult to unwind. The reason is structural, as nuclear fuel supply is shaped by long-term contracts, safeguards, export controls, industrial capacity and national safety licensing. VVER fuel diversification illustrates the difficulty of changing supply routes once reactor operation, fuel design and licensing practice have become tied to inherited technological dependencies. SMR and HALEU-related developments raise the same question in reverse, as how to avoid building new dependencies before advanced reactor deployment begins.

The **central research claim** follows from this dynamic: *If nuclear capacity expands significantly, the governance of the nuclear fuel cycle may become a strategic bottleneck for both energy security and non-proliferation. The EU experience is especially instructive because it shows both sides of the problem: VVER fuel diversification demonstrates how difficult it is to unwind existing dependencies, while SMR and HALEU requirements show how new vulnerabilities may emerge if fuel-cycle readiness is not built into nuclear strategy from the outset.*

3 Market structure and EU dependency in the nuclear fuel cycle

3.1 EU nuclear fuel supply in recent years - evolving map of dependencies

Recent geopolitical developments, particularly *Russia's invasion of Ukraine*, have fundamentally altered the security environment of nuclear material and fuel-cycle services in the European Union, transforming what had previously been a largely market-driven system into one increasingly shaped by strategic and geopolitical considerations (ESA, 2022; ESA, 2023; ESA, 2024: 20). These developments have brought renewed attention to long-standing structural dependencies within the nuclear fuel cycle and have strengthened the momentum for diversification, stockpiling, and the gradual phase-out of Russian nuclear supplies, in line with broader EU energy-sovereignty objectives (ESA, 2023: 21–24; ESA, 2024: 20–23). Recent strategic analyses similarly emphasise that Russia's civil nuclear exports have acquired increasing geopolitical significance since the invasion of Ukraine, reinforcing the strategic rationale for fuel-cycle diversification (Nakano, 2026).

At the same time, nuclear fuel occupies a *peculiar position* within the *broader sanctions landscape*. While EU sanctions after February 2022 targeted several parts of the Russian energy sector, nuclear fuel and related services have so far remained largely outside direct restrictions (ESA, 2023: 22; Haneklaus et al., 2025). This is not only a matter of politics, but also reflects the specific material and regulatory logic of nuclear supply. Unlike coal, oil, or gas, nuclear fuel is high-value, low-volume, can be stored for several reloads, and, in exceptional cases, can even be delivered by air, as illustrated by Slovakia and Hungary in 2022 (Haneklaus et al., 2025; ESA, 2024: 21–22). At the same time, any shift in nuclear fuel supply is embedded in safeguards, export-control and licensing frameworks, meaning that sanctions and diversification cannot be treated simply as trade restrictions, but must also remain compatible with non-proliferation control and nuclear safety requirements.

This makes nuclear dependency *less immediately disruptive* than fossil-fuel dependency, but also more ambiguous. It can be managed for longer through inventories, transport workarounds, and long-term contracts, yet, precisely for that reason, it may remain structurally embedded in reactor operation, fuel qualification, and supply-chain planning (ESA, 2023; ESA, 2024).

The recent factors affecting the security of uranium (fuel cycle) supply can be summarised based on recent years' ESA annual reports as follows:

- **Demand stability:** Nuclear fuel demand in the EU remains structurally stable, reflecting the baseload character of nuclear energy and the technical constraints of reactor operation, which limit short-term flexibility in fuel consumption (ESA 2024: 22). This stability has been a persistent feature across recent years, with only marginal fluctuations observed between 2022 and 2024 despite external shocks, indicating that demand-side adjustment plays a limited role in supply security strategies (ESA 2024; ESA 2023; ESA 2022). In 2025, 1,795 tU of fresh fuel was loaded into EU commercial reactors, broadly confirming the stability of annual fuel requirements.

- **Market outlook:** In 2024, the volume of fuel loaded into reactors remained broadly unchanged at 1,761 tU, while deliveries continued to exceed reactor requirements, reflecting precautionary procurement and inventory-building behaviour that intensified after 2022 (ESA 2024; ESA 2023). This pattern continued in 2025. Looking forward, projections suggest a moderate decline in uranium and enrichment demand over the next decade, primarily driven by reactor lifetimes and efficiency gains rather than structural contraction of nuclear energy within the EU (ESA 2024, ESA 2025).

- **Supply diversification:** Diversification of nuclear fuel supply has become a central strategic objective, particularly under the sanctions-related REPowerEU framework, which explicitly links nuclear supply security to broader efforts to reduce dependency on Russian energy imports and enhance resilience across critical supply chains (ESA 2024: 22–25). Compared to earlier years, the post-2022 period has seen a more coordinated and policy-driven approach to diversification, although implementation remains uneven across Member States, especially in Central and Eastern Europe, where legacy technological dependencies persist, linked to the later discriber VVER reactors of the CEE region (ESA 2024; ESA 2023).

This paper analyses the front end of the nuclear fuel cycle through four main stages: **1) uranium mining and milling, 2) conversion, 3) enrichment, and 4) nuclear fuel fabrication**. This framework is useful because the first three stages generally produce more standardised products, whereas fuel fabrication is highly reactor-specific and often tied to particular reactor designs and operational requirements. Although these stages are technically interconnected and sometimes commercially bundled, separating them analytically helps identify where dependency is primarily market-based and where it becomes a technological bottleneck. This distinction is central to assessing whether Russian exposure in the EU nuclear fuel cycle is a temporary procurement issue or a deeper structural supply-chain dependency, including with respect to market concentration. The analysis uses the Herfindahl-Hirschman Index (HHI) as a supporting indicator of market and industrial concentration (Haneklaus et al., 2025; Pavic–Galetic–Piplica, 2016; U.S. Department of Justice 1982.), while recognising that concentration alone does not automatically imply market power or strategic dependence, particularly where supply risks depend on broader market, technological and geopolitical conditions (Bucciarelli–Hache–Mignon, 2024; Krivka, 2016). At the same time, the HHI is used here only as a limited proxy for concentration, not as a comprehensive measure of strategic dependence (Krivka, 2016; Bucciarelli–Hache–Mignon, 2024). Strategic exposure in the nuclear fuel cycle also depends on factors that concentration indicators cannot fully capture, including geographical concentration, critical supply-chain nodes, technological dependence, supplier substitutability, and the resilience of processing and fabrication capacities (Christopher–Peck, 2004; Craighead et al., 2007; Ivanov–Dolgui, 2020). This is particularly important in strategically sensitive industries, where a supplier, country or region may represent a bottleneck not simply because of its market share, but because it controls an indispensable stage of the supply chain or a technology that cannot be rapidly replaced (Baldwin–Freeman, 2022; Bucciarelli–Hache–Mignon, 2024). A further distinction should therefore be made between firm-level and country- or region-level concentration, since a market may appear relatively diversified in terms of company shares while remaining geographically or geopolitically exposed. The HHI should consequently be read as a useful supporting indicator, while strategic dependence is understood more broadly as the interaction of market concentration, technological capability, supply-chain resilience, geographical exposure and geopolitical risk. Against this methodological background, the following section briefly draws on the findings of Haneklaus et al. and the data and assessments of the Euratom Supply Agency, while referring to selected HHI results where relevant:

- **Uranium supply:** In data terms, Russian and CIS-related exposure remained significant, even though the trend moved gradually towards diversification. In 2022, Russia supplied 1,980 tU of natural uranium to EU utilities, corresponding to 16.89% of total deliveries; together, Russia, Kazakhstan and Uzbekistan accounted for 5,565 tU, or 47.47% of total EU deliveries (ESA, 2022: 17). In 2023, Russian deliveries increased to 3,419 tU, reaching 23.45% of total deliveries, while CIS-origin uranium amounted to 6,750 tU, or 46.30% of the total, partly reflecting stockpiling behaviour after the Russian invasion of Ukraine (ESA, 2023: 13–14). In 2024, Russian deliveries fell again to 2,185 tU, or 15.63% of total EU deliveries, representing a 36.08% year-on-year decrease; however, CIS-origin uranium still accounted for 5,825 tU, or 41.66% of total deliveries (ESA, 2024: 12–13). The 2025 data confirm that there is no a linear disengagement from Russia- and CIS-related exposure. Russian-origin uranium deliveries amounted to 2,346 tU, or 15.98% of total EU deliveries, while CIS-origin uranium increased to 6,871 tU, corresponding to 46.81% of total deliveries. Uzbekistan also became the fourth-largest source of uranium delivered to EU utilities, which shows that diversification away from direct Russian supply does not necessarily eliminate broader CIS-linked exposure (ESA, 2025: 21).

This pattern should be read cautiously. The 2023 increase in Russian and CIS-related deliveries can partly be identified as a stockpiling response after Russia's invasion of Ukraine, especially in connection with VVER fuel inventories, while the 2024 figures indicate at least a visible reduction in direct Russian uranium deliveries. However, this should not be understood as a complete structural disengagement from Russia-related exposure. One reason is that the uranium market is not organised simply along state lines: uranium is mined and marketed by companies and corporate groups, often through joint ventures, and Russian-linked ownership interests in Kazakh production complicate a purely country-based assessment (World Nuclear Association, 2025c). In this broader sense, CIS exposure includes not only direct Russian supply, but also corporate ownership structures and regional production links. EU-based uranium recovery may appear at the margins, for example, as a by-product of other mining activities, but it is unlikely to become significant enough to alter the EU's import dependence (ESA 2024: 23–24; Terrafame 2024).

Transport routes further complicate the picture. Even where uranium is formally sourced from Kazakhstan or Uzbekistan, parts of the supply chain may still depend on transit through Russia. A complete Russian blockage appears unlikely, but HHI-based sensitivity scenarios show that Russian, Kazakh, and Uzbek supplies may need to be considered not only separately but also as a broader exposure category (Haneklaus et al., 2025).

- **Conversion services:** The conversion segment shows a more uneven and less transparent diversification pattern than the natural uranium supply. In 2022, Orano (FR) remained the dominant provider of conversion services to EU utilities, with 4,083 tU and a 37.34% share, while Rosatom (RU) accounted for 2,444 tU, or 22.35%; Cameco (CA) and ConverDyn (US) followed with 21.16% and 16.30%, respectively (ESA, 2022: 18). In 2023, total conversion service deliveries increased by 22.22%, and Russian deliveries rose sharply to 3,543 tU, giving Rosatom (RU) a 26.51% share, while Orano (FR) declined to 28.69% despite remaining the largest supplier (ESA, 2023: 16). This 2023 increase should again be read cautiously, since ESA links the higher Russian contribution partly to VVER fresh fuel stockpiling and to bundled contracts in which conversion, enriched products and fuel fabrication are often supplied together (ESA, 2023: 23–24).

  In 2024, the market became more balanced, but not necessarily less vulnerable. Rosatom (RU) deliveries fell to 2,977 tU, or 22.37%, yet it remained the single largest supplier; ConverDyn (US) increased its share to 21.78%, Orano (FR) fell to 21.34%, and Cameco (CA) accounted for 19.86% (ESA, 2024: 15). The most notable change is the rapid growth of services reported with unspecified origin, from 2.84% in 2022 to 7.58% in 2023 and 14.65% in 2024, which makes the supply picture less transparent and complicates a straightforward assessment of diversification (ESA, 2022: 18; ESA, 2023: 16; ESA, 2024: 15).

  In 2025, conversion services remained relatively balanced but still exposed. Orano became the largest supplier with 3,292 tU, or 24.85% of deliveries, while Rosatom followed closely with 3,233 tU, or 24.40%. The share of services reported with unspecified origin fell to 8.36%, but bundled contracts still accounted for 40% of conversion service deliveries, confirming that transparency and substitutability remain limited in this segment (ESA, 2025: 24).

The overall trend, therefore, points to some reduction in direct Russian exposure after the 2023 peak, but not to a clean structural shift, as conversion remains a constrained fuel-cycle segment with continued Russian involvement and growing reliance on non-Russian alternatives.

- **Enrichment services:** A more substantial structural shift can be observed in enrichment, although the 2022–2024 data also show a temporary fluctuation linked to the post-invasion security-of-supply response. In 2022, EU-based enrichment services (EU) accounted for 6,678 tSW, or 62% of total deliveries to EU utilities, while Russian suppliers (RU) provided 3,239 tSW, corresponding to 30%; other non-EU sources accounted for 815 tSW, or 8% (ESA, 2022: 19). In 2023, Russian enrichment deliveries increased sharply to 4,647 tSW, raising Russia's share to 37.90%, while the EU share declined to 54.88%, even though EU-based volumes remained broadly stable in absolute terms (ESA, 2023: 17). As with natural uranium and conversion, this 2023 increase should be read cautiously, since it coincided with broader stockpiling and supply-security measures after Russia's invasion of Ukraine, rather than necessarily indicating a durable return to Russian services.

  In 2024, however, the rebalancing became much clearer. EU-based enrichment services (EU) increased their share to 63.95%, with 6,654 tSW, while Russian suppliers (RU) fell to 2,450 tSW, or 23.55%, representing a 47.3% year-on-year decline; other non-EU sources also increased to 1,301 tSW, or 12.50% (ESA, 2024: 16).

  The 2025 data point to a stronger EU position in enrichment, but not to the disappearance of Russian involvement. EU enrichers increased their share to 72.91%, while Russia's share declined slightly to 22.55%. In absolute terms, however, Russian enrichment deliveries still increased year on year, which confirms that diversification remains a managed transition rather than a completed structural break (ESA, 2025: 26). The overall trend is therefore more favourable than in conversion, but it still points to a managed and capacity-dependent diversification process rather than an automatic market adjustment.

Haneklaus et al.'s HHI analysis adds a useful structural layer to these ESA-based trends. For natural uranium, the market for EU utilities remained only moderately concentrated in the baseline calculation, with the HHI rising from 2,153 in 2022 to 2,305 in 2023, before declining to 2,185 in 2024, broadly confirming the diversification signal visible in the ESA data. However, when Kazakhstan, Russia and Uzbekistan are treated as a single broader exposure category, the HHI exceeds the high-concentration threshold, reaching 3,384 in 2022, 3,455 in 2023 and 3,085 in 2024, underscoring that CIS-linked exposure cannot be assessed solely through direct Russian deliveries. Conversion services appear more structurally constrained, with several years above the 2,500 HHI threshold, while enrichment is even more concentrated, with values around or above 5,000, reflecting a market largely organised around EU and Russian capacities. This is particularly important because enrichment is not just an industrial bottleneck but also a non-proliferation-sensitive segment, where the limited number of suppliers is partly the result of deliberate controls on the spread of enrichment capacity (Haneklaus et al., 2025; ESA, 2022; ESA, 2023; ESA, 2024). These HHI results are therefore most useful for identifying concentration risks in the more standardised stages of the front end of the fuel cycle. They become less directly applicable as the analysis moves towards fuel fabrication, where the relevant question is not only how many suppliers there are in the market, but whether a given fuel design can be used safely in a specific reactor.

- **Fuel fabrication:** At the level of fuel fabrication, most EU utilities benefit from access to at least two alternative suppliers, which reduces dependency risks across much of the reactor fleet (ESA, 2024: 24). However, this diversification is not consistent across reactor technologies. VVER-type reactors remain more exposed because fuel assemblies are not standardised commodities but reactor-specific products, tied to a particular design, safety case, licensing process and body of operational experience (ESA, 2022: 30; ESA, 2023: 24–25; ESA, 2024: 24). This is not only a legal or procurement constraint. Interview evidence gathered for this research indicates that a fuel assembly has to satisfy reactor-physics, thermal-hydraulic, mechanical and safety requirements at the same time: the uranium-water ratio, fuel-rod geometry, spacer-grid design, cladding material, coolant flow, control-rod system and core-loading pattern all matter for safe operation (Expert interview No.1.).
- For this reason, fuel fabrication is less suitable for the same type of HHI-based market-concentration analysis applied to uranium supply, conversion and enrichment. In those earlier fuel-cycle stages, the products and services are more standardised and therefore more comparable across suppliers. By contrast, fabricated fuel must be qualified for a specific reactor type and, often, for a specific operating context. The existence of a supplier in the wider market therefore does not automatically translate into an available alternative for a given reactor. The VVER case developed below illustrates this particularly clearly, since VVER-440, VVER-1000 and VVER-1200 reactors differ not only in size and generation, but also in fuel assembly geometry, control-rod arrangements, core design, fuel-management practice and accumulated operational experience (Expert interview No.1.). Fuel diversification therefore requires more than a commercially available alternative supplier as it also requires a technically compatible design, validated safety analyses, manufacturing qualification, operating experience and national regulatory approval.

Table 1 summarises the main dependency patterns that emerge from this stage-by-stage analysis:

Fuel-cycle stage	Main trend 2022–2025	Key dependency issue	Strategic interpretation
Uranium supply	Russian direct share fluctuates around 16%, while CIS exposure increased again in 2025	Russia/Kazakhstan/Uzbekistan exposure	Diversification visible, but no full structural break
Conversion	Russian role remains relevant; Rosatom and Orano remained almost level in 2025	Limited Western capacity, bundled contracts and transparency issues	Constrained and only partially transparent segment
Enrichment	EU share improves strongly in 2025; Russian share remains significant	High concentration, slow capacity expansion	Managed diversification, not automatic adjustment
Fuel fabrication	Most EU reactors have alternatives; all EU VVER utilities had alternative fuel contracts by the end of 2025	Reactor-specific fuel qualification	Technological and licensing bottleneck

Recent ESA reports (2022–2025) show that the EU nuclear fuel cycle is increasingly shaped by geopolitical risk and diversification efforts rather than purely market dynamics. While demand remains stable and short-term supply is relatively secure, dependency patterns are evolving unevenly across the fuel cycle. In particular, midstream segments and reactor-specific fuel fabrication, as later examined in the VVER case, continue to face structural and technological constraints that limit rapid diversification. These developments suggest that the key challenge is no longer the immediate availability of supply, but the sustainability of diversification and supply security over longer time horizons. This, in turn, requires closer examination of contractual coverage, capacity constraints, and the differing risk profiles associated with short- and long-term fuel-cycle arrangements.

3.2 Contractual coverage and processing capacity as long-term bottlenecks

According to the ESA Annual Reports 2024 and 2025, the EU's nuclear fuel supply remains relatively secure in the short term, but becomes *increasingly uncertain* over the longer term. The central issue is not simply access to uranium, but the timing of contractual coverage and the availability of processing capacity across the fuel cycle:

- ESA's forward-looking data show that **natural uranium demand** is well covered in the near term, but contractual coverage declines markedly after the early 2030s. This temporal asymmetry had already been evident in earlier ESA assessments, but the 2024 and 2025 reports make the structural pattern clearer: existing contracts provide an important buffer, but they do not remove the need for new long-term arrangements and additional capacity. In the 2025 data, EU utilities remain well covered until around 2030, but minimum contractual coverage for natural uranium falls to 36% by 2033 and 26% by 2034 (ESA, 2022; ESA, 2023; ESA, 2024; ESA, 2025).
- A similar logic applies to **conversion services**, although the underlying constraint is more industrial than contractual. On paper, EU utilities remain relatively well covered through the early 2030s, but this does not automatically translate into resilience in the event of disruption. The EU depends on a single major conversion facility in France, with current capacity estimated at around 11,000 tU per year, slightly below the needs of the EU reactor fleet; this capacity is expected to rise to around 13,500 tU by 2029 if Orano completes the planned ramp-up (ESA, 2024: 27). At the broader Western level, the picture is even more fragile, as ESA estimates that current conversion capacity in the Western geopolitical region is insufficient, with a gap exceeding 10,000 tU per year and remaining above 5,000 tU even by 2029 (ESA, 2024: 27). This confirms the warning already present in the 2022 ESA report that the "global West" may not be self-sufficient in conversion and enrichment unless plants ramp up production and new investments are made (ESA, 2022: 27).
- The **enrichment segment** presents a similar, but even more sensitive, bottleneck. Contractual coverage remains high in the short and medium term, with maximum coverage above 100% until 2032 in the 2024 data, but it drops sharply thereafter, while minimum coverage also declines substantially (ESA, 2024: 19–20). The 2025 data confirm the same pattern: minimum coverage remains high in the short term, but falls to 42% by 2033 and 34% by 2034 (ESA, 2025). At the capacity level, EU-based enrichment facilities are sufficient to meet current EU needs, but the wider Western system remains constrained. ESA estimates Western enrichment capacity at around 25,300 tSWU per year, which is insufficient to supply the reactor fleet in the Western geopolitical region; the missing capacity exceeds 9,000 tSWU per year and may remain relevant even after new centrifuge capacity is installed after 2027 (ESA, 2024: 29). This

bottleneck may become more serious if demand increases because of lifetime extensions, new reactor construction, or advanced fuel requirements such as HALEU for SMRs and advanced modular reactors (ESA, 2024; ESA, 2025).

As shown in the previous subsection, the broader global market context reinforces this concern because *concentration tends to increase as one moves further along the fuel cycle* from natural uranium supply towards conversion and, especially, enrichment. While uranium mining is still carried out by several producing countries and corporate actors, conversion and enrichment are controlled by a much smaller number of industrial providers, with enrichment being the most concentrated and strategically sensitive segment. Haneklaus et al. and Castillo-Peters and von Hippel show that *the market is already highly concentrated*. The global enrichment HHI reached 3,546 in 2020, while Russian suppliers accounted for more than 46% of global enrichment capacity (Haneklaus et al., 2025; Castillo-Peters and von Hippel, 2023/2024). This also explains why market adjustment is slow. Conversion and enrichment are not simple spot-market commodities, as contracts often run for several years, investment decisions require long-term demand certainty, and new industrial capacity cannot be created quickly (Haneklaus et al., 2025; Castillo-Peters and von Hippel, 2023/2024). ESA's 2024 report makes the same policy point in practical terms, stressing the need for *long-term contractual and political commitments, diversification, stockpiling and recycling* to support fuel security (ESA, 2024: 4, 29).

Short-term technical workarounds may reduce pressure, but they do not solve the structural problem. One example is *uranium overfeeding*, where more natural uranium is used to reduce the amount of separative work required in enrichment. Castillo-Peters and von Hippel estimate that the EU and the US could theoretically offset Russian enrichment services by using an additional 4,900 tonnes of natural uranium per year, of which around 1,900 tonnes would be needed for the EU and 3,000 tonnes for the US (Castillo-Peters and von Hippel, 2023/2024; Haneklaus et al., 2025). This shows that mitigation options exist, but they mainly buy time. They do not remove the longer-term need for non-Russian conversion and enrichment capacity.

Taken together, the evidence from 2022 to 2025 suggests that the EU nuclear fuel cycle is entering a phase in which supply security is determined less by raw-material availability alone and more by processing capacity, contractual timing and reactor-specific fuel constraints. Inventories, MOX fuel, reprocessed uranium and overfeeding can provide flexibility, but they cannot fully compensate for a major disruption in conversion, enrichment or fuel fabrication. This is why nuclear fuel supply cannot be treated as a purely market-driven system: it is shaped by technological lock-in, limited industrial capacity, geopolitical exposure and long regulatory lead times.

4 The Governance of the Nuclear Fuel Cycle

4.1 Global-level governance architecture of the nuclear fuel cycle

The previous sections showed that nuclear fuel-cycle diversification cannot be understood as a simple market adjustment. As the analysis moved from natural uranium supply to conversion, enrichment and fuel fabrication, the constraints became progressively more technical, capacity-based and governance-dependent. This does not mean that civil nuclear energy production is itself a non-proliferation activity. Rather, the fuel-cycle transactions that make it possible operate within a governance framework designed to ensure peaceful use, safety, security and controlled technology transfer. Diversification may require the transfer of nuclear material, enrichment-related services, fuel-cycle technology, fuel design know-how, and fabrication capacity. These transactions are therefore shaped not only by commercial availability, but also by safeguards, export controls and licensing requirements.

At the global level, this architecture rests on two complementary governance logics:

- **Safeguards operate primarily as post-transfer peaceful-use verification**, ensuring that nuclear material and facilities remain in declared peaceful use after transfers have taken place.
- **Export controls operate primarily as pre-transfer risk management**, determining whether sensitive nuclear or nuclear-related items, technologies and services may be transferred in the first place.

This distinction is central to the fuel-cycle vulnerabilities discussed above. Diversification requires new supply routes, industrial partnerships and, in some cases, new technological capabilities. In the nuclear fuel cycle, however, these developments cannot be organised solely through market access. They must remain compatible with peaceful-use verification, supplier-state export controls and the safety requirements of the receiving nuclear programme.

The main post-transfer verification backbone is operated by the **International Atomic Energy Agency** (IAEA). Its safeguards mandate is anchored in the IAEA Statute, which requires the Agency to ensure that nuclear materials, facilities and related items are not diverted to military purposes (IAEA Statute, Art. III.A.5). Within the framework of the Treaty on the Non-Proliferation of Nuclear Weapons, non-nuclear-weapon States conclude safeguards agreements with the IAEA. Operationally, the system rests on two main legal instruments:

- Comprehensive Safeguards Agreements, based on INFCIRC/153, require States to accept safeguards on all nuclear material in peaceful nuclear activities (IAEA, 1972).
- The Additional Protocol, based on INFCIRC/540, strengthens this system by extending the IAEA's access rights and information base (IAEA, 1997).

This matters because verification strength is not uniform. Safeguards conclusions depend on the applicable legal framework, access rights and the practical verifiability of the relevant fuel-cycle activity. The diversification of activities involving more sensitive materials or technologies, therefore, increases the verification burden and requires a robust safeguards framework. This will become particularly relevant in the later discussion of HALEU, which remains below the highly enriched uranium threshold but is still more proliferation-sensitive than conventional low-enriched reactor fuel.

The second layer is the **export-control system**. While safeguards verify peaceful use after transfer, export controls condition the transfer itself. The Nuclear Suppliers Group provides the principal global reference point for this supplier-side system. Its guidelines distinguish between Part 1 trigger-list items and Part 2 nuclear-related dual-use items. This layer is especially important for enrichment and reprocessing, which are directly relevant to weapons-usable capabilities:

- Under the Part 1 guidelines, transfers of especially sensitive nuclear items are subject to stricter conditions and are generally linked to robust safeguards in the recipient State.
- Part 2 extends this logic to dual-use items through catch-all controls, allowing authorities to deny exports where proliferation risk is identified even beyond listed items (N Rózsa-Péczeli, 2013).

The implication for energy security is direct. Diversification, stockpiling, capacity expansion and supplier replacement all require cross-border transactions, new contracts and industrial cooperation. Yet in the nuclear fuel cycle, these steps are filtered through safeguards obligations, export-control licensing and, at the next level, nuclear safety approval. The result is not a contradiction between energy security and non-proliferation, but a structural feature of civil nuclear governance, as the same controls that make international nuclear cooperation politically acceptable also shape the pace, scope and direction of fuel-cycle diversification. The same logic is reflected in bilateral nuclear cooperation agreements, such as US Section 123 Agreements, which enable civil nuclear transfers precisely by attaching them to peaceful-use assurances, safeguards, conditions, and restrictions on retransfer, enrichment, or reprocessing (U.S. NNSA, 2025).

This governance architecture is also visible in the VVER context discussed below. Replacing or supplementing Rosatom-related fuel supply is not simply a matter of finding a new commercial supplier. It may require transfers of technology, qualification data, safety analyses, fuel design information, and fabrication capacity, all of which interact with safeguards, export control rules, and national licensing procedures. The same logic will also reappear in the discussion of SMRs. If advanced reactor deployment depends on new fuel types and enrichment capabilities, then supply-chain readiness cannot be separated from peaceful-use assurance, export-control compliance and regulatory approval.

4.2 EU-level governance between Euratom safeguards and supply governance

The global safeguards and export-control architecture defines the outer boundaries of nuclear fuel-cycle diversification. Within the EU, these global rules are complemented by a distinct regional governance layer under the Euratom Treaty, which establishes a dedicated safeguards system alongside the IAEA framework:

- The **European Commission** is entrusted with ensuring that ores, source materials and special fissile materials are not diverted from their declared uses. This is translated into practice through reporting duties, material accountancy, operator obligations, inspections and supervision (Euratom Treaty, Arts. 77–81). Euratom safeguards, therefore, operate as a regional verification layer within a coordinated multi-level safeguards structure, rather than as a substitute for the IAEA system.
- A major recent development is the update of the Euratom safeguards implementation rules. **Commission Regulation (Euratom) 2025/974** entered into force on 6 July 2025, replacing Regulation (Euratom) No 302/2005. The new framework updates reporting and verification requirements in light of changes in the nuclear sector and information technology. It is particularly relevant for future fuel-cycle governance because it introduces a more graded approach, strengthens safeguards-by-design for complex installations and new builds, and adapts reporting obligations to emerging nuclear technologies (Commission Regulation (Euratom) 2025/974).

This matters for diversification because expanded conversion, enrichment, fuel fabrication or advanced-fuel activities not only create new industrial capacity. They also generate additional nuclear material movements, reporting obligations, inspection-relevant events and verification needs**.** In this sense, safeguards supervision is structurally linked to industrial policy. If Europe seeks to reduce dependency by expanding or relocating sensitive fuel-cycle capabilities, the Euratom verification burden will also increase.

Euratom also establishes a distinct governance instrument for nuclear fuel supply through the **Euratom Supply Agency** (ESA):

- Under the Euratom Treaty, ESA plays a central role in the common supply policy and in the conclusion of contracts for the supply of ores, source materials and special fissile materials. This makes ESA more than a market observer, as it functions as a gatekeeper of nuclear material supply in the EU, combining contract oversight, supply monitoring and security-of-supply analysis.
- ESA's role has become more strategic since Russia's invasion of Ukraine. Its annual reports increasingly frame nuclear fuel supply in terms of inventories, high-risk suppliers, contractual coverage, VVER fuel diversification, and long-term processing capacity (ESA, 2022; ESA, 2023; ESA, 2024). This links directly to the previous analysis, as the EU's vulnerability is not limited to natural uranium imports but is more pronounced in conversion, enrichment, and reactor-specific fuel fabrication.

This EU-level governance layer is also connected to broader **energy policy**. The Commission's 2025 REPowerEU Roadmap does not point to a general phase-out of nuclear energy in the EU. Rather, it frames the removal of Russian-linked nuclear materials and fuel-cycle dependencies as part of the *wider objective of ending the Union's dependence on Russian energy*. In the nuclear field, this includes proposed measures on Russian-enriched uranium imports and restrictions on new ESA-co-signed supply contracts for uranium, enriched uranium, and other nuclear materials derived from Russia (COM, 2025). However, the analysis above has shown that replacing these dependencies is constrained by a wider set of industrial, technical, contractual and regulatory conditions. Capacity expansion by actors such as Orano and Urenco should be read in the same context - not only as a commercial response to market demand, but also as part of a broader Western effort to reduce reliance on Russian conversion and enrichment services (ESA, 2024; Orano, 2024; Urenco, 2025). Fuel-cycle diversification, therefore, requires long-term investment, predictable contracts and a supportive regulatory framework, rather than short-term procurement decisions alone.

The **VVER fuel segment** captures this EU-level logic particularly well. Diversification is no longer only about replacing Rosatom-related supply with another commercial supplier, but about combining licensed production, European fuel design, fabrication capacity and national licensing in a coherent pathway. In this sense, the Euratom layer links supply security, safeguards supervision and industrial strategy. The same logic will remain relevant beyond the current VVER debate, especially if HALEU and other advanced reactor fuels in SMRs create new fuel-cycle requirements.

4.3 National licensing and reactor-specific fuel qualification

Even where global safeguards and EU-level supply governance allow diversification, the final decision **remains national**, as an alternative fuel can only be loaded if the competent *(national) nuclear safety regulator* accepts the safety case for the specific reactor. Within the EU, this follows from the Nuclear Safety Directive, which requires Member States to maintain independent and effective national regulatory systems (Council Directives 2009/71/Euratom and 2014/87/Euratom).

IAEA safety standards provide the wider reference framework for this process. The *Licensing Process for Nuclear Installations* identifies the main licensing stages, documentation requirements and the use of a graded approach, while IAEA guidance on plant modifications shows why fuel changes are treated as safety-relevant modifications rather than simple supplier substitutions (IAEA SSG-12; IAEA SSG-71, 2010). In practice, fuel switching usually requires updated core design and safety analyses, validated calculation methods, manufacturing qualification, quality assurance evidence and staged in-reactor testing, such as lead test assemblies. As noted during our expert interview, the practical logic behind this staged approach is that a new fuel type is not typically introduced by replacing a large share of the core at once. Instead, a limited number of introductory or lead assemblies may be loaded first, allowing the operator and the regulator to assess actual in-reactor behaviour before wider use. This is important because the "proof" of a fuel design is not only documentary compliance, but also operational demonstration under reactor conditions (Expert interview No. 1.).

This is why licensing can become a **real bottleneck** even where an alternative supplier is already commercially available. EU-supported VVER diversification projects, such as APIS and SAVE, reflect this logic, as they are not only about developing alternative fuel, but also about qualification, benchmarking and regulatory acceptance (APIS; SAVE; ESA, 2024). In this respect, licensing should be understood as a bridge between market diversification and operational safety, as a commercially available fuel remains only a potential alternative until it has been translated into a validated safety case for the relevant reactor type.

In the Hungarian context, interview evidence also shows that alternative fuel licensing is not only a nuclear safety issue, but also interacts with *safeguards-related control of nuclear material*. While safety approval focuses on the fuel's in-reactor behaviour and the adequacy of the related safety case, safeguards-related regulation concerns material accountancy, reporting, inspection, and design information interfaces with the national authority, Euratom, and the IAEA. An alternative VVER fuel project therefore has to be accommodated not only within the reactor-specific safety case, but also within the relevant national and international safeguards reporting framework (Expert interview No. 2.).

Hungary illustrates this proportionality of the licensing burden particularly well. Paks I operates four VVER-440/213 units, so any new or modified fuel assembly must fit a reactor-specific licensing basis. Even the introduction of SLIM fuel assemblies (a comparatively incremental fuel development step rather than a full supplier change) was treated by the Hungarian Atomic Energy Authority as a staged process, involving limited loading, commissioning-related tests, supporting safety documentation, and regulatory approval (HAEA, 2020; HAEA, 2025). Framatome-related discussions may indicate a potential future diversification route, but they should not be treated as a near-term operational supply option for Paks I, since no substantive fuel-supply contract has yet been concluded and the Hungarian licensing process has not started; in any event, such a route would still require national safety review, fuel qualification and operational demonstration (Framatome, 2024; Expert interview No. 1). If even a more limited fuel-design modification requires staged regulatory control, a broader shift towards an alternative supplier logically raises a more complex licensing and qualification burden.

In this sense, VVER diversification is a practical test case for the wider fuel-cycle governance challenge. It shows how market diversification, industrial capacity, safeguards-sensitive technology transfer, and national safety licensing must come together before a new fuel supply route becomes operational. The interview evidence reinforces this conclusion, as fuel diversification is not only a question of whether Westinghouse, Framatome or another supplier can offer a fuel assembly, but whether that assembly can be shown to behave safely in the specific reactor. In practice, this requires general nuclear safety requirements to be translated into detailed fuel-specific criteria, including fuel-rod geometry, cladding behaviour, thermal limits, core-loading patterns and compatibility with existing monitoring and evaluation systems. The Russian practice has traditionally benefited from the possibility of first testing new or modified VVER fuel designs in domestic reactors, often in limited quantities, before wider commercial deployment. This route is not automatically available to non-Russian VVER fuel suppliers, precisely because VVER technology is historically tied to Soviet/Russian reactor fleets and because Western suppliers do not necessarily possess an equivalent domestic VVER testing base (Expert interview No. 1.).The same pattern is likely to reappear in future fuel-cycle debates, especially where new reactor types depend on specialised fuels, qualified suppliers and regulatory readiness from the outset.

4.4 Competing Logics of European Nuclear Fuel Governance

The previous subsections identified three layers of constraint: global non-proliferation rules, Euratom-level supply governance and national safety licensing. Taken together, these layers show that European nuclear fuel governance operates at the intersection of three closely connected but not fully aligned policy dimensions:

- **Energy policy** focuses on supply security, diversification and resilience, as reflected in EU efforts to reduce dependence on Russian energy imports and in the Euratom Supply Agency's treatment of nuclear materials as strategic security-of-supply concerns.
- **Industrial policy** addresses the material basis of diversification: supply security cannot be achieved through contracts alone, but requires sufficient conversion, enrichment and fabrication capacity, coordinated investment and resilient supply chains. This is visible in capacity-expansion projects undertaken by actors such as Orano and Urenco, which are explicitly framed as responses to geopolitical dependency risks.
- **Non-proliferation policy**, however, imposes structural constraints on this process through safeguards, export controls and the strict governance of sensitive technologies, especially enrichment. This dimension becomes even more important as the fuel cycle diversifies, whether through VVER fuel switching or through new fuel types such as HALEU, discussed below.

The core argument is that these three dimensions are broadly compatible, but they do not operate according to the same institutional logic. Energy policy seeks resilience through diversification; industrial policy seeks strategic autonomy through capacity-building; non-proliferation governance prioritises control, verification and restraint. The result is not a simple contradiction, but a recurring set of governance frictions that shape the pace and form of fuel-cycle diversification:

- **Diversification vs export control:** Energy policy requires new suppliers, routes and industrial partnerships, while export-control rules condition precisely these transfers. The Nuclear Suppliers Group guidelines prioritise restraint in sensitive exports and link authorisation to safeguards coverage and non-proliferation assurances. In practice, diversification may therefore be delayed, narrowed or reshaped by licensing requirements, end-use assurances and controls extending beyond fuel itself, including enrichment- or fabrication-related components. This is not an external obstacle to diversification, but an integral part of the non-proliferation framework.
- **Capacity expansion vs safeguards burden:** Industrial policy pushes towards expanding conversion, enrichment and fuel fabrication capacity as part of Europe's strategic autonomy agenda. Yet these are also the activities that trigger more intensive safeguards requirements, including material accountancy, containment and

surveillance, reporting obligations, information evaluation and inspections. Scaling up sensitive fuel-cycle capacity may therefore strengthen supply security, but it also increases the verification workload and the complexity of governance. This requires corresponding investments not only in industrial infrastructure, but also in safeguards capacity, data flows, and inspection systems at both the Euratom and IAEA levels.

- **Market logic vs licensing constraints:** From a market or energy-security perspective, diversification may appear to mean replacing one supplier with another. Nuclear safety licensing operates differently. Fuel switching is a safety-relevant change that requires updated core design and safety analyses, validated calculation methods, manufacturing qualification, quality-assurance evidence and staged operational testing. EU-supported VVER alternative-fuel initiatives explicitly recognise this by focusing on coordinated licensing, qualification and benchmarking. In practice, this means the licensing pathway is not a secondary technical detail but a central bottleneck to diversification.

Table 2 summarises how the main policy logics identified above translate into distinct objectives, constraints and implications for nuclear fuel diversification.

Policy logic	Primary objective	Main constraint	Relevance for fuel diversification
Energy security	Diversification and resilience	Exposure to high-risk suppliers	Pushes towards alternative fuel routes
Industrial policy	Capacity-building and strategic autonomy	Long investment timelines	Requires conversion, enrichment and fabrication capacity
Non-proliferation governance	Control, verification and restraint	Safeguards and export controls	Slows and conditions sensitive fuel-cycle transfers
Nuclear safety licensing	Reactor-specific safety approval	Testing, qualification and regulator confidence	Determines whether the alternative fuel can actually be loaded

This framework explains why nuclear fuel diversification is slower and more complex than ordinary supplier substitution. The various governance layers are cumulative rather than fully harmonised. Each is rational in its own terms: energy security favours diversification, industrial policy favours capacity expansion, and non-proliferation governance favours caution and verification. The challenge is that these logics must operate simultaneously. This is particularly evident in the VVER context, where replacing Rosatom-related fuel supply requires not only alternative suppliers but also fuel qualification, technology transfer, safeguards supervision, and national licensing. The same pattern is likely to reappear in the SMR/HALEU context, where new reactor strategies may create new fuel-cycle dependencies unless supply-chain readiness, regulatory capacity and non-proliferation controls are built in from the outset.

5 VVER Reactors Fuel Diversification in Central and Eastern Europe

5.1 From Rosatom's One-Stop-Shop Model to Decoupling Strategies

VVER fuel diversification provides a particularly clear empirical lens because it brings together several policy tensions that are otherwise often analysed separately. At a broader level, the international success of Rosatom has frequently been linked not only to the technical competitiveness of Russian reactor designs, but also to its attractive financing model and integrated "one-stop-shop" offer, combining reactor technology, construction, fuel supply, engineering support and long-term services (Rothwell, 2022; Szulecki and Overland, 2023). This model is especially appealing where nuclear investment depends on large upfront capital costs and where the supplier can offer a comprehensive package rather than isolated components.

In Central and Eastern Europe, however, the VVER question is more complex than the usual "newcomer country" narrative. Most countries in the region are not new nuclear entrants, but operators of reactor fleets inherited from the Socialist era and now embedded in liberalised European energy markets. Their dependence is therefore not simply a matter of choosing Rosatom for a new project; it is also the result of decades of technological path dependency, operational routines, regulatory experience and fuel supply arrangements built around Soviet/Russian reactor designs. In this sense, Soviet-era reactor choices created not only an installed technological base but also a longer-term fuel design and licensing path dependency, since VVER fuel is not a standard commodity but a reactor-specific product (N Rózsa-Péczeli, 2015).

This makes VVER diversification a useful policy case for three reasons:

- **Energy supply diversification:** since the war in Ukraine, reducing reliance on Russian nuclear fuel and fuel-cycle services has become a much more visible part of European energy-security policy. In this context, diversification is not only about price or contractual flexibility, but about limiting exposure to geopolitical disruption and ensuring that nuclear power can continue to support electricity security under changing external conditions.
- **Technological and industrial adaptation:** VVER reactors have been operated in the region since the 1970s and 1980s, and their fuel systems were originally optimised for Soviet/Russian fuel assemblies. Western alternatives, therefore, require more than a simple replacement of suppliers, as they depend on design adaptation, fuel testing, qualification, manufacturing capacity and national licensing approval. This explains why the pace of diversification differs significantly across VVER-440, VVER-1000 and newer VVER-1200 units.
- **Market diversification under constraints:** alternative suppliers such as Westinghouse and Framatome are increasingly entering the field, but they do so within a market shaped by reactor-specific requirements, limited fabrication capacity, licensing timelines and long-standing vendor relationships. In other words, the emergence of competition does not automatically produce immediate substitutability; it creates a gradual transition in which commercial, technical and regulatory conditions must align.

The CEE VVER experience, therefore, shows that diversification is not simply a political decision to "change supplier". It is a gradual governance process in which energy security, industrial capacity, fuel qualification, export controls, safeguards and national licensing all interact. The following section uses the VVER-440, VVER-1000, and VVER-1200 segments to show why the pace and feasibility of diversification vary across reactor generations and why the issue is especially relevant for projects such as Paks II in the current Hungarian energy system.

5.2 VVER Fuel Diversification - Reactor-Specific Dependencies and Alternative Supply Pathways

The dependency challenge is particularly visible in Central and Eastern Europe, where several countries operate Soviet-designed VVER reactors and have historically relied on *Rosatom-related TVEL* fuel supplies. At the same time, VVER does not refer to a single reactor design but to several reactor generations and variants, each with distinct technical and licensing characteristics. While VVER fuel remains one of the most important technological bottlenecks in the EU nuclear fuel cycle, decades of operational experience have generated growing knowledge on alternative fuel qualification and supplier diversification. This distinction matters because VVER diversification cannot be assessed at the level of the reactor family alone. VVER-440, VVER-1000 and VVER-1200 reactors differ in fuel assembly geometry, control-rod arrangements, active fuel length, structural materials and accumulated operating experience.

Diversification is therefore not merely a procurement issue but a governance challenge involving fuel qualification, safety assessment, and regulatory approval. The following examples illustrate how different countries have addressed these challenges in practice and what this reveals about the opportunities and constraints of VVER fuel diversification. Earlier ESA assessments highlighted the persistence of *fuel fabrication dependency*, noting limited availability of alternative suppliers, complex qualification procedures, and extensive licensing requirements (ESA 2022, 2023). This dependency is reinforced by the Rosatom's traditional "one-stop-shop" model of the nuclear sector, where reactor technology, fuel design, engineering support, and related services are often provided by the same vendor, particularly in the case of newly constructed reactors (Szulecki and Overland, 2023). At the same time, the pace of diversification has varied considerably across reactor types, reflecting differences in operational experience, the maturity of alternative fuel designs, and the extent to which the necessary qualification and licensing processes had already been undertaken before the current geopolitical shift.

The 2025 ESA Annual Report marks an important step in this process, noting that by the end of 2025 all EU operators of VVER reactors had secured alternative fuel supply contracts from non-Russian suppliers. This does not remove the licensing and qualification bottleneck, but it shifts the main policy question from whether alternative contracts can be concluded to whether alternative fuel designs can be qualified, licensed and deployed in time (ESA, 2025: 37).

- **VVER-440:** First-generation commercial VVER reactors were introduced in Central and Eastern Europe during the 1970s and 1980s, with a nominal capacity of around 440 MWe and a central role in current fuel diversification efforts. Outside Belarus and Russia, VVER-440 units remain in operation in Armenia (1), the Czech Republic (4), Finland (2), Hungary (4), Slovakia (5–6), and Ukraine (2). Most units are expected to operate for around 60 years, with some already receiving lifetime extensions to 70 years or beyond, ensuring continued demand for fuel supply and diversification solutions (World Nuclear News, 2026).
  Westinghouse's current VVER-440 fuel design originates from the NOVA fuel programme developed by BNFL in the 1990s and was subsequently further developed and optimised through Euratom-supported research and qualification activities, eventually forming the basis of Westinghouse's present VVER-440 fuel offering (EC, 2015). Technically, this development also involved material and design choices that differed from the traditional Russian VVER fuel line, including Westinghouse's own

zirconium-alloy cladding materials and modified spacer-grid solutions. These differences should not be read as a response to deficiencies in Russian VVER-440 fuel, but rather as reflecting the materials, design experience and qualification basis available within Westinghouse's own fuel-technology platform (Expert interview No. 1.). By the early 2020s, Westinghouse's VVER-440 development had resulted in commercial fuel supply contracts with several operators, although diversification remains constrained by production capacity, licensing requirements and the fact that experience and fuel designs developed for other reactor types, including VVER-1000 units, cannot be automatically transferred to the VVER-440 segment (Haneklaus et al., 2025).

More recent initiatives point towards a *dual-track approach*, with Framatome emerging as a key actor. Diversification is pursued both through licensed production based on existing Rosatom/TVEL technology and through the development of independently qualified European fuel solutions under projects such as SAVE and APIS (World Nuclear News, 2026). This distinction matters because licensed or assembly-based solutions may reduce immediate supply risk, whereas fully European fuel designs require a longer process of material selection, manufacturing qualification, safety analysis, testing and regulatory approval. Although diversification has moved from planning to implementation, rapid replacement of Rosatom-related fuel fabrication remains constrained by technical qualification, licensing requirements and limited alternative supply capacity, especially in the CEE region. A fuel supply disruption in this segment would therefore represent not only a nuclear industry issue but also a broader energy security concern for several Central and Eastern European countries (ESA, 2024).

- **VVER-1000:** An evolutionary VVER design introduced from the late 1980s onwards, with a nominal capacity of around 1,000 MWe. Within the EU, VVER-1000 reactors are currently operated in Bulgaria (2 units) and the Czech Republic (2 units), while Ukraine operates 13 units, making this the largest VVER segment outside Russia. Historically, fuel supplies have been dominated by Rosatom-related TVEL, although diversification efforts have progressed considerably further than in the VVER-440 segment.

  Diversification in the VVER-1000 market began already in the 1990s, when Westinghouse Electric Company developed its own VVER-1000 fuel design and gradually emerged as an alternative supplier to Rosatom-related TVEL. The Czech and Ukrainian experience demonstrates that diversification is rarely a linear process, as early alternative fuel designs encountered operational challenges, requiring years of redesign, qualification, testing and regulatory approval before they could be deployed successfully (Vlček, 2016: 77–85). Temelín is particularly important in this respect. The Westinghouse VVER-1000 start-up core experience showed that introducing alternative fuel may entail practical operational difficulties, including fuel-rod damage, spacer-grid issues and fuel-assembly bowing, with implications for control-rod insertion and reactor operation. These issues translated into concrete operational constraints, including additional testing requirements and repeated shutdowns to verify the proper functioning of control and safety systems. At the same time, such problems should not be read as specific only to non-Russian fuel designs, since operational experience with Russian VVER-1000 fuel also revealed design-specific performance issues. The broader lesson is that any new or modified VVER fuel design must pass through operational learning, feedback, redesign, testing, licensing and operator confidence-building before wider deployment becomes credible (Expert interview No. 1.; IAEA, 2025b).

The developments of recent years in the VVER-1000 segment, most notably the Czech and Bulgarian decisions to replace Russian fuel with supplies from Westinghouse and Framatome (ESA, 2024), appear to confirm Pan's argument that, despite persistent technical and licensing challenges, energy-security considerations have become a primary driver of the shift towards Western fuel designs (Pan, 2023; Pan, 2024). The successful deployment of Westinghouse fuel in Ukraine and Framatome's prospective involvement also support the *dual-track* diversification logic outlined above. Dependence on Russian suppliers is reduced both through the qualification of alternative fuel designs and through the localisation of fuel fabrication within Europe (Haneklaus et al., 2025). However, Framatome's independently developed VVER-1000 fuel should still be treated as the more demanding branch of this approach. Unlike licensed or TVEL-derived production, a fully European design must still pass through design validation, manufacturing qualification, in-reactor testing and regulatory approval. Testing capacity and VVER-specific operating evidence therefore remain technological bottlenecks in their own right (Expert interview No. 1.).

- **VVER-1200:** An evolutionary successor to the VVER-1000 design, the VVER-1200 has a nominal capacity of approximately 1,200 MWe and represents Rosatom's flagship export reactor technology. In Europe, the design is currently in operation in Belarus (2 units) and has two additional units under construction at Paks II in Hungary. The technology has also been deployed or is under construction in several non-EU countries, including Bangladesh, Egypt, and Turkey (Rosatom, 2026). In contrast to the VVER-1000 segment, diversification in the VVER-1200 market remains at an earlier stage. Nevertheless, the existence of qualified non-Russian VVER-1000 fuel designs means that alternative pathways are already emerging (Westinghouse, 2026). This should not, however, be understood as automatic transferability. The VVER-1200 fuel assembly builds on VVER-1000 design experience, but it has a longer active fuel length and is embedded in a newer reactor design, an initial core configuration, and a commissioning safety case. For an alternative supplier, VVER-1000 experience therefore provides an engineering starting point, but not a substitute for VVER-1200-specific compatibility, qualification and operating evidence (Expert interview No. 1.).

Table 3 summarises these three reactor-specific diversification profiles.

Reactor type	Diversification maturity	Main bottleneck
VVER-440	Emerging alternatives through the Westinghouse and Framatome routes	Fuel qualification, licensing and limited alternative fabrication capacity
VVER-1000	More advanced diversification experience, especially in Ukraine, Czechia and Bulgaria	Operational learning, redesign, regulatory acceptance and supplier confidence
VVER-1200	Earlier-stage diversification, with limited non-Russian operating experience	Non-automatic transferability from VVER-1000, initial-core qualification and commissioning safety case

Taken together, the VVER experience demonstrates that fuel diversification is not a simple supplier substitution, but a staged governance process shaped by reactor-specific fuel design, operational experience, qualification and licensing requirements, fabrication capacity and geopolitical pressure to reduce dependence on Rosatom-related supply chains. Alternative routes are now emerging, but with different strengths and limits: Westinghouse benefits from accumulated VVER operating experience, especially in the VVER-1000 segment, while Framatome's role combines shorter-term licensed or TVEL-derived solutions with the longer-term prospect of independently qualified European fuel designs. The comparison between VVER-440, VVER-1000 and VVER-1200 therefore shows that diversification is most credible where operating evidence and regulatory acceptance already exist, while less mature routes still depend on testing, qualification and industrial scale-up. Paks II is relevant mainly as a future VVER-1200 case, where the same question arises: whether fuel flexibility can be considered early enough to avoid creating a new long-term reactor–fuel dependency.

5.3 Hungary's Paks as a Supply Chain Test Case

Hungary has a relatively long history of nuclear energy, rooted in both domestic scientific traditions and the Soviet-led nuclear energy cooperation of the Cold War period (Marx, 1996; Zachmann, 2015). The commercial use of nuclear power became institutionalised through the construction of the four VVER-440 units at Paks, which entered operation between 1982 and 1987 and have since formed the backbone of Hungary's nuclear electricity production (IAEA, 2023). From the outset, Paks I was therefore not merely a power plant but a core element of Hungary's electricity system, with nuclear power later becoming a stable pillar of national energy policy and decarbonisation planning (Kratochvíl and Mišík, 2020; ITM, 2020). The historical trajectory also explains why Hungary's nuclear sector has remained closely connected to Soviet/Russian reactor technology and fuel supply chains.

The idea of expanding Paks is not new. Additional units were already considered during the Socialist period (Bosák, 2017), but the project only became politically and contractually concrete in the 2010s. In 2014, Hungary and Russia concluded intergovernmental and financing arrangements for Paks II, covering two new VVER-1200 units and a Russian state loan of up to EUR 10 billion, within a project estimated at around EUR 12 billion (Court of Justice of the European Union, 2025). From the outset, the project formed part of a broader domestic policy debate on economic viability, sustainability, transparency and long-term dependency risks (Sáfián, 2015; Clean Air Action Group, 2015). Nevertheless, Paks II was incorporated into Hungary's medium- and long-term energy strategy, particularly through the National Energy and Climate Plan, where new nuclear capacity is treated as an important component of electricity supply security and climate policy (ITM, 2020). Progress, however, has remained slow, with repeated delays pushing the expected completion date into the early 2030s, assuming the project ultimately proceeds as planned.

- **VVER-440/Paks I:** The existing Paks I units are VVER-440 reactors, and their fuel diversification follows the broader regional pattern discussed above: ageing Soviet-designed reactors, long-standing reliance on Rosatom-related supply chains, and the gradual qualification of alternative suppliers. Recent developments show that Hungarian VVER-440 fuel diversification is moving towards implementation, but the two supplier routes are not at the same stage. While Framatome has been reported as a future supplier, detailed plant-level preparation and the compilation of the licensing application currently appear to be more advanced in the Westinghouse track, following its agreement with MVM Group for VVER-440 fuel deliveries from 2028 (World Nuclear News, 2026; Expert interviews No. 1.). The Framatome case nevertheless remains relevant because it reflects the dual-track approach analysed above, as diversification is pursued both through licensed production based on existing VVER fuel technology and through the development of an independently qualified European

VVER-440 fuel design for a "100% sovereign European" fuel solution. Interview evidence from the Hungarian context adds that Paks I links fuel diversification to continued operation, ageing management and reactor-specific licensing. Reactor-vessel surveillance and accelerated irradiation testing can support the evidence base for lifetime extension, while alternative VVER-440 fuel must be assessed according to the extent of the design change and translated into the national safety and safeguards-reporting framework. This is particularly relevant for independently developed European VVER-440 fuel solutions, where the absence of a comparable non-Russian VVER testing base increases the importance of staged qualification, documentary safety analysis and regulator confidence (Expert interviews No. 1 and No. 2.).

- **VVER-1200/Paks II:** Paks II raises a different, more forward-looking supply chain issue. As a new VVER-1200 project, it is more closely linked to the traditional Rosatom "one-stop-shop" model, in which reactor design, construction, fuel supply, engineering support, and related services are bundled into a long-term technological relationship (Paks2, 2014). While future diversification is not excluded—especially in light of growing non-Russian VVER fuel experience in the VVER-440 and VVER-1000 segments—fuel supply flexibility should be treated as a policy question from the outset, rather than as a corrective measure after a new dependency has already been locked in (World Nuclear Association, n.d.). This is particularly important because VVER-1200 fuel may build on VVER-1000 experience, but it still requires VVER-1200-specific compatibility, qualification and operating evidence, especially in relation to the initial core configuration and commissioning safety case (Expert interview No. 1.). From a Hungarian regulatory perspective, this constraint is reinforced by the cancellation of the planned Finnish VVER-1200 project, which left Paks II without a potential EU reference case; third-country VVER-1200 projects may offer useful technical background, but they cannot fully substitute for licensing and operational experience under stricter and more institutionalised EU and Hungarian regulatory expectations (Expert interview No. 2.). This policy point is reinforced by the Court of Justice of the EU's 2025 Paks II judgment. The case concerned the direct award of the construction of the two new Paks II units to a Russian contractor and the extent to which such an integrated project structure had to be assessed under EU internal market and procurement-related rules (Court of Justice of the European Union, 2025). While the judgment does not prohibit the Rosatom "one-stop-shop" model as such, it makes clear that large integrated nuclear projects cannot be treated as closed technological packages insulated from EU scrutiny. In policy terms, this weakens the assumption that reactor construction, fuel supply, and related services can be locked together in a long-term, vendor-dependent arrangement, and strengthens the case for considering diversification options from the outset of design and contracting.

The policy relevance of Paks, therefore, lies in the contrast between the two layers of the same site. Paks I shows how diversification can gradually move from planning to implementation, but only through contracts, licensing, qualification and industrial capacity-building. Paks II, by contrast, illustrates the risk that a new reactor project may reproduce long-term supply chain dependencies unless diversification options are considered early in the project architecture. For this reason, the Paks case is not only about Hungarian energy policy or the legal controversies surrounding the investment; it is also a concrete example of the broader European challenge of aligning nuclear supply security, industrial autonomy and governance constraints in the post-2022 geopolitical environment.

6 Future Fuel-Cycle Governance Challenges: SMRs, HALEU and Advanced Fuel Types

6.1 SMRs, HALEU and the Question of Fuel-Cycle Readiness

The preceding sections have shown that fuel supply is not a secondary technical issue, but a central element of nuclear energy governance. This point becomes even more important when looking beyond the existing reactor fleet towards advanced reactor technologies, including *small modular reactors (SMRs)*. SMRs are increasingly presented in European policy as part of a future clean-energy and industrial strategy, with potential relevance for decarbonisation, security of supply, industrial competitiveness and more flexible deployment models (European Commission, 2026). ESA's 2024 Annual Report also notes that the Commission launched the European Industrial Alliance on SMRs to support demonstration and deployment of Europe's first SMR projects by the early 2030s (ESA, 2024).

This framing is also reflected in the *Draghi Report*, which notes that several Member States have expressed interest in deploying SMR technologies and have called for EU-level collaboration. Compared with traditional large nuclear power plants, SMRs may rely less on economies of scale and more on an "economy of numbers", as standardised, serially manufactured components could make deployment costs more predictable. At the same time, a smaller output may reduce environmental footprint and ease some siting constraints. Certain advanced modular reactor designs could also provide high-temperature heat, making them relevant not only for electricity generation but also for the decarbonisation of industrial sectors (Draghi Report, 2024).

A recent IAEA analysis (Podkopaeva, 2026) shows several new or modified fuel concepts are being developed or tested, including:

- **LEU+ fuels**, with enrichment above the traditional 3–5% range but still below HALEU levels, intended to support higher burnup, longer fuel cycles and improved reactor efficiency;
- **accident-tolerant fuels (ATFs)**, which rely on improved materials and designs to better withstand severe operating conditions and enhance safety margins;
- **TRISO particle fuel**, especially relevant for high-temperature gas-cooled reactors and microreactor concepts, where each fuel particle contains multiple ceramic containment layers;
- **advanced oxide, thorium-based and liquid fuels**, which are being explored for fast reactors, molten salt reactors and other next-generation reactor systems;
- **HALEU-based fuels**, which are expected to be central for several advanced reactor and SMR designs because higher enrichment can support smaller cores, longer operating cycles and higher fuel utilisation.

This broader fuel-innovation context is important because each new fuel type creates its own supply chain and governance requirements. Advanced fuels may promise better performance, longer cycles or improved safety margins, but they also require appropriate enrichment, fabrication, testing, transport, safeguards and licensing infrastructure.

Among these emerging fuel concepts, HALEU is particularly relevant for the present analysis because it links advanced reactor deployment directly to fuel-cycle readiness. Its significance lies not only in reactor performance, but also in the need for adequate enrichment capacity, fuel fabrication, transport arrangements, safeguards and regulatory control. HALEU is generally defined as uranium enriched to 5–20% U-235 (US NRC, n.d.; OECD/NEA, 2024). It is attractive for several advanced reactor designs because it can enable smaller cores, longer operating cycles, higher power density and better fuel utilisation (OECD/NEA, 2024). However, these advantages come with a supply-chain and governance cost.

The key point is that HALEU shifts the SMR discussion from reactor innovation to fuel-cycle readiness. A future reactor design may be technically promising. However, it cannot be commercially deployed at scale if enrichment, deconversion, fuel fabrication, transport and licensing capacities are not available in parallel (OECD/NEA, 2024). ESA's reporting points in the same direction. This is also visible in ESA's treatment of HALEU over time. In 2022, HALEU emerged mainly as a security-of-supply issue for research reactors and medical radioisotope production, with the ESA noting that HALEU was not produced in the EU and that supplies came from the US and Russia, both of which raised long-term uncertainty (ESA, 2022). In 2023, ESA again linked HALEU to medical radioisotopes and research reactors, and noted that interest in HALEU had grown due to its relevance for certain advanced reactors (ESA, 2023). By 2024, the framing had become even broader, as the ESA described HALEU as vital to research. ESA's 2024 Annual Report frames HALEU as relevant beyond research reactors and radioisotope production, identifying it also as a prerequisite for advanced nuclear reactors such as SMRs. It also presents the PreP-HALEU project as an early step towards building European HALEU production capability. (ESA, 2024). The 2025 ESA Annual Report further strengthens this framing. It treats HALEU not only as a research reactor and medical radioisotope supply issue, but also as a strategic material for advanced reactors. ESA estimates that the HALEU needs of EU research reactors may rise from the current annual level of approximately 200–300 kg to around 800 kg from 2040 onwards, while also noting that HALEU is not currently manufactured in the EU (ESA, 2025: 30).

In this sense, SMRs do not remove the governance tensions identified in the VVER case, as they might reproduce them in a new form. Energy policy may frame SMRs as flexible, low-carbon capacity. In contrast, industrial policy may treat them as a future European value-chain opportunity, but non-proliferation and safety governance require the fuel-cycle infrastructure to remain controllable, inspectable, and licensable (OECD/NEA, 2024; ESA, 2024). The key policy point is therefore straightforward. SMR deployment depends not only on reactor licensing or market demand, but also on whether the necessary fuel cycle can be developed in time and managed safely and securely.

6.2 The Question of Fuel-Cycle Readiness in relation to SMRs, HALEU

HALEU's relevance comes from the risk of reproducing a **familiar dependency pattern** before advanced reactors are even commercially deployed. As discussed above, the EU's current fuel-cycle dependencies are not uniform, particularly in conversion, enrichment and reactor-specific fuel fabrication. HALEU therefore raises a timing-based supply-chain problem. Like VVER fuel diversification today, it shows that a technically specific fuel requirement can become a strategic vulnerability if alternative supply chains are not prepared in advance. This risk is amplified by the broader enrichment-market vulnerabilities discussed above: high concentration, slow adjustment due to long-term contracts and capital-intensive infrastructure, and only limited short-term mitigation options such as uranium overfeeding (Castillo-Peters and von Hippel, 2023/2024; Haneklaus et al., 2025; ESA, 2023; ESA, 2024).

HALEU is where the EU's **concerns about dependency** may become particularly sharp. Russia is currently described in the literature as the only larger-scale commercial supplier of HALEU, even though HALEU is not required for today's large commercial light-water reactors

(Haneklaus et al., 2025). It is, however, essential for several advanced reactor concepts under development. The limited availability of HALEU has already had practical consequences, as the TerraPower Natrium project in the United States has been cited as an example in which commissioning may be delayed due to a lack of available HALEU (World Nuclear News, 2023). This dependency concern is already reflected in EU-level policy planning. The European Parliament's research service identifies Russia, through Tenex/Rosatom, as the only viable commercial HALEU supplier, while the Horizon Euratom PreP-HALEU initiative seeks to prepare the technical, financial, logistical and legal basis for a European HALEU production capability. HALEU, therefore, illustrates a forward-looking dependency risk. Unless alternative capabilities are developed before advanced reactors reach commercial deployment, fuel supply may again become concentrated in a politically sensitive supplier relationship (EPRS, 2024; Horizon Euratom, 2023).

ESA's annual reports support treating this as a **broader bottleneck** rather than a narrow technical input. In 2022, ESA warned that failure to ensure HALEU supply after 2035 could put the production of key medical radioisotopes at risk and listed options ranging from continued imports from the US and Russia to an ESA HALEU bank or autonomous European production. In 2024, ESA went further by describing PreP-HALEU as a project intended to generate technical, economic and regulatory information on enrichment, metallisation and transport, while fostering alignment around an EU HALEU capability as a shared asset (ESA, 2022; ESA, 2023; ESA, 2024).

From a European perspective, the issue is less about whether HALEU will be technically needed and more about whether its supply chain will be **ready in time**. If SMRs and other advanced reactors are expected to contribute to decarbonisation, competitiveness and strategic autonomy, HALEU cannot be treated as a later technical detail. It has to be built into the governance architecture of advanced nuclear deployment from the outset. Otherwise, future reactor strategies may reproduce the same kind of path dependency that the VVER diversification debate now seeks to overcome. A similar logic applies to SMRs, as modularity may improve scalability, but it does not remove fuel-cycle, safeguards, transport and physical-protection constraints, especially where higher-enriched fuels are involved; early EU pilot projects may therefore become important regulatory reference points for later deployment (Expert interview No. 2.).

The same three tensions, therefore, reappear:

- **Energy security vs supply concentration**: SMRs may support the EU's long-term resilience, but only if HALEU supply is not concentrated in a small number of politically sensitive suppliers.
- **Industrial scaling vs safeguards burden**: expanding HALEU production requires enrichment, deconversion, metallisation, fabrication and transport infrastructure, all of which increase regulatory, verification and security complexity (ESA, 2024; OECD/NEA, 2024).
- **Market ambition vs technological bottlenecks**: advanced reactor deployment may be politically attractive, but commercial rollout depends on fuel qualification, production capacity, facility licensing and long-term contractual support (ESA, 2023; ESA, 2024).

This does not mean that HALEU is merely a proliferation issue, but **proliferation sensitivity** is clearly part of the problem. HALEU remains below the threshold of highly enriched uranium. Nevertheless, its higher enrichment level makes it more sensitive than conventional reactor fuel and therefore places greater demands on safeguards, export controls, physical protection and licensing. The challenge is not only one of legal classification, but also of material proximity, as uranium enriched towards the upper end of the HALEU range requires less additional enrichment to reach weapons-grade levels than conventional LEU. Recent proliferation analyses have therefore questioned whether the traditional 20% threshold is sufficient for assessing the security implications of large-scale HALEU use, even if this claim remains debated (Kemp et al., 2024; Carlson, 2024). For this paper, the key point is more limited but still important: higher enrichment increases the governance burden associated with fuel supply, transport, storage, safeguards, and regulatory planning.

The VVER case shows how difficult it is to unwind dependencies once they have become embedded in reactor operation, fuel qualification, licensing practice and supply contracts. HALEU offers the opposite approach - first, thinking about diversification, safeguards readiness, export-control sensitivity, and industrial capacity before large-scale deployment begins, not afterwards.

7 Conclusions

This paper begins with the hypothesis that a significant expansion of nuclear energy would not only pose a reactor deployment challenge but also a fuel-cycle governance challenge. The analysis supports this hypothesis. A potential "nuclear spring" is not merely about whether new reactors can be financed, licensed, and constructed; it also depends on whether the broader nuclear fuel cycle can provide the necessary material, industrial, and regulatory conditions to sustain a larger and more diverse nuclear sector. Structural growth in electricity demand may strengthen the case for reliable low-carbon electricity, and nuclear power may contribute to this demand in some jurisdictions. However, it will not expand everywhere or automatically. Where nuclear energy is expected to support decarbonisation, energy security, or industrial strategy, its feasibility will rely on a politically dependable and technically competent fuel cycle system. Therefore, nuclear supply security cannot be reduced to uranium availability alone. Natural uranium may be globally available, but conversion and enrichment capacity are more concentrated, harder to expand quickly, and more sensitive from a peaceful-use and export-control perspective. Fuel fabrication adds another layer of complexity because it is often specific to certain reactors. Supplier diversification must be assessed not only by market share but also by industrial capacity, technological compatibility, regulatory feasibility, and operational experience.

The EU case clearly illustrates these dynamics. Since Russia invaded Ukraine, the EU has acted quickly to reduce its reliance on Russian fossil fuels, but dependencies related to the nuclear fuel cycle have proven harder to break. This does not imply that substitution is impossible; rather, it demonstrates that nuclear diversification follows a different timeline and faces more complex institutional requirements. Long-term contracts, fuel qualification, licensing procedures, safeguards obligations, and limited processing capacity make switching nuclear fuel slower than switching to other energy sources.

The VVER case exemplifies this challenge most clearly. As Soviet-designed pressurised water reactors traditionally relied on Russia- and Rosatom-related fuel supplies, VVER reactors show how inherited technological dependencies can hinder diversification. The issue is not simply whether an alternative supplier is available: alternative fuel must be designed, tested, qualified, and licensed for specific reactor types and operational conditions. Licensing, therefore, is not just an administrative hurdle but also depends on operational experience, safety data, and regulator confidence in how a particular fuel design performs in a specific reactor. The Temelín experience demonstrates this, as alternative VVER-1000 fuel required operational learning, redesign, testing, and confidence-building before diversification could be deemed credible. This also helps explain why the TVEL/Rosatom position remains difficult to challenge: it is embedded not only in supply contracts but also in reactor-specific fuel design, operational data, licensing practices, and operator familiarity. The broader governance lesson is that energy policy, industrial policy, and peaceful-use governance tend to pull nuclear diversification in different directions. Resilience and supplier diversification must be balanced with capacity expansion, safeguard obligations, export-control complexity, and national licensing requirements. The challenge is to manage these constraints coherently rather than assuming market substitution alone can resolve the issue.

The discussion on SMR and HALEU underlines the same lesson for the future. While VVER diversification demonstrates how difficult it is to unwind inherited dependencies once they are embedded in reactor operation, fuel qualification, licensing practice, and supplier relationships, deploying advanced reactors raises the question of whether similar dependencies can be avoided before they become structural. This is especially important where future strategies rely on specialised fuels, enrichment capacity, fuel fabrication, and regulatory readiness that are not yet available at scale in Europe. The technical evidence collected for this research supports the point that fuel diversification is not merely a procurement decision but also depends on qualification, operational demonstration, licensing, and operator confidence in a fuel design's performance in a specific reactor.

The main conclusion is that fuel-cycle governance should be recognised as a core element of nuclear strategy from the beginning. A credible nuclear expansion plan cannot solely focus on reactor technology, construction timelines, or electricity-market arrangements. It must also address the conditions that enable reactor operation, such as secure uranium supplies, reduced reliance on contested partners, qualified fuel fabrication, strong safeguards, effective export controls, and national licensing capacity. For the EU, this is particularly important because nuclear energy sits at the crossroads of energy security, industrial policy, strategic autonomy, and peaceful-use commitments. The experience with VVER diversification provides a tangible lesson, as dependencies that seem manageable under stable geopolitical conditions can become strategic constraints when the external environment shifts. The next generation of nuclear technologies, including SMRs and HALEU-based systems, should therefore avoid replicating the same pattern in new forms. Nuclear expansion, if it takes place, will be sustainable only if progress in fuel-cycle readiness, industrial capacity, safeguards preparedness, and regulatory approval occurs together.

8 Policy recommendations

First, nuclear fuel-cycle security should be treated as part of energy security policy, not as a narrow technical procurement issue. EU and national nuclear strategies should assess uranium supply, conversion, enrichment, fuel fabrication and licensing readiness together, since vulnerabilities may arise at any stage of the fuel cycle.

Second, diversification should be pursued before dependencies become operationally embedded. The VVER experience shows that once reactor operation, fuel qualification, regulatory practice and supplier relationships are built around a specific technological pathway, diversification becomes slower and more complex. Future projects, especially SMRs, should therefore consider fuel flexibility and alternative supply options from the design and contracting stages.

Third, European and allied conversion, enrichment and fuel fabrication capacities should be supported through long-term contractual and policy commitments. Market signals alone may be insufficient in segments where investment is capital-intensive, demand is uncertain and geopolitical risk is high.

Fourth, VVER fuel diversification should remain a coordinated European priority. Alternative fuel solutions require not only supplier contracts, but also testing, qualification, licensing, manufacturing capacity and operational experience. EU-level coordination can help avoid fragmented national approaches and support the development of credible non-Russian supply routes.

Fifth, HALEU readiness should be addressed before advanced reactor deployment accelerates. If SMRs and other advanced reactor concepts are expected to play a role in future energy systems, the EU should assess whether the necessary enrichment, fuel fabrication, transport, safeguards and licensing capacities can be developed in time. Otherwise, new reactor technologies may reproduce the same kind of fuel-cycle dependency that Europe is now trying to reduce in the VVER context.

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List of expert interviews

EXPERT INTERVIEW	INTERVIEWEE	LOCATION/PLATFORM	DATE
Expert interview No. 1	Zoltán Hózer - HUN-REN Centre for Energy Research, Fuel and Reactor Materials Laboratory	via Microsoft Teams	19 June 2026
Expert interview No. 2	Expert of a national nuclear regulatory authority	Budapest, Hungary	16 July 2026