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Dependencies of the European Union and the world on Russian nuclear fuel cycle services, and how to reduce them

Nils Haneklaus [a,b,*], Tomáš Vlček [c], Andrej Nosko [d], Hendrik Brink [e], Jakub Ochmann [f], Anna Skorek-Osikowska [f], Paweł Gładysz [g], Paweł Gajda [g], Matúš Mišík [h], Łukasz Bartela [f]

[a] North-West University, Unit for Energy and Technology Systems - Nuclear Engineering, 11 Hoffman Street, Potchefstroom, 2520, South Africa
[b] Universität für Weiterbildung Krems,Td-Lab Sustainable Mineral Resources, Dr.-Karl-Dorrek-Straße 30, 3500, Krems an der Donau, Austria
[c] Department of International Relations and European Studies, Faculty of Social Studies, Masaryk University, Jostova 10, 60200, Brno, Czech Republic
[d] Matej Bel University in Banská Bystrica, Kuzmányho 1, 974 01, Banská Bystrica, Slovakia
[e] University of Pretoria, Department of Chemical Engineering, South Africa
[f] Silesian University of Technology, Department of Power Engineering and Turbomachinery, 44-100, Gliwice, Poland
[g] AGH University of Krakow, Faculty of Energy and Fuels, al. Mickiewicza 30, 30-059, Krakow, Poland
[h] Comenius University Bratislava, Department of Political Science, Gondova 2, 811 02, Bratislava, Slovakia

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ABSTRACT

While the European Union (EU) and other Western nations are weaning themselves off the Kremlin's fossil energy resources, global nuclear energy producers remain closely tied to Russia's nuclear industry. One in four nuclear reactors worldwide is connected to Russia (either operating domestically, built abroad, or under construction using Russian technology), and relies on spare parts, maintenance, and fuel from state-owned Rosatom. Russia contributes approximately 6 % of global uranium production, 20 % of conversion capacity, 46 % of enrichment capacity, and 10 % of nuclear fuel fabrication capacity. This work explores the EU's and the global community's dependence on Russian nuclear fuel cycle services. In response to growing geopolitical tensions, particularly after Russia's invasion of Ukraine, the EU has taken steps to reduce this reliance and enhance self-sufficiency. Key measures include expanding uranium conversion capacity, increasing fuel production for VVER-440 reactors, and better utilization of existing enrichment infrastructure. Reducing Russia's influence is possible but will require long-term commitment, political determination, and acceptance of higher nuclear energy costs, especially for conversion and enrichment services. With continued effort, full independence from Russian nuclear fuel cycle services is considered achievable between 2030 and 2035.

1. Introduction

Russia is a major energy supplier to the world. As a result of Russia's invasion of Ukraine, numerous Western countries, as well as the European Union (EU), dramatically reduced their energy imports from Russia particularly imports of coal, oil, and natural gas [1–3]. In parallel with this development, nuclear power is gaining momentum as a potentially more resilient energy source that can operate more independently from geopolitical maneuvering that is presently affecting global fossil fuel supplies [4–8]. Through the Russian State Atomic Energy Corporation Rosatom and its subsidiaries (some 400+ nuclear companies and R&D institutions), Russia is, however, also a major player in nuclear power production, and particularly successful in the construction of nuclear power plants (NPPs) abroad.

This fact is widely known, and Thomas [9,10] recently conducted a comprehensive analysis of Rosatom's export program, particularly emphasizing its successful ventures in constructing NPPs abroad. Prior to Russia's invasion of Ukraine, it was commonly believed that Rosatom's motivations were primarily driven by economic considerations [11,12] and a recent analysis by Siddi and Silvan [13] concluded that this is still the case more than 3 years after the start of the war. However, the Russian invasion of Ukraine led to an increased interest in Russia's nuclear industry, Western countries' reliance on it, and the potential exploitation of its nuclear industrial complex for political purposes [14–18]. Pan [19,20] recently provided an excellent analysis of the challenges that particularly Central and Eastern European (CEE)

* Corresponding author. Karl-Dorrek-Straße 30, 3500, Krems, Austria.
E-mail address: nils.haneklaus@donau-uni.ac.at (N. Haneklaus).

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countries, a region where Russian NPP designs are common, might face when trying to decouple from Rosatom in favor of other, preferably Western, vendors. Specifically, the work identifies Russian nuclear reactor fuel used to operate NPPs built by Rosatom (or its predecessor organizations during the Union of Soviet Socialist Republics, USSR) as a high-tech product that will be challenging to replace. The analysis aligns with previous observations by Vlček [21] that focused on Russian pressurized water reactors (PWRs) or VVERs (vodo-vodyanoi enyergeticheskiy reaktor) [22] of which different types are operated in Europe.

On a broader level, Rothwell [23] provides analysis about the projected electricity costs of future NPPs and supports the idea that Russian (and also Chinese) large commercial nuclear reactor designs are technically sound and are presently, in a direct cost-comparison, ahead of the designs offered by Western vendors. Besides potential design advantages, Rosatom is supported by the Russian sovereign wealth fund, which allows the company to offer attractive financing models [24–26]. The capital costs for erecting a NPP are tremendous [27,28] so that the importance of such a buyer-friendly business model cannot be overstated.

This financing approach is also discussed by Szulecki and Overland [29] who provided further analysis of the success of Rosatom as a nuclear ‘one-stop-shop’ that is particularly attractive for nuclear newcomer countries. The researchers analyzed a dataset of all current and planned international engagements involving Rosatom to assess varying levels of cooperation between Rosatom and different countries. This allowed them to identify potential vulnerabilities, should the Kremlin choose to use Rosatom as a geopolitical tool. Here again the focus is on nuclear-generated electricity supply (present and future) as an indicator of vulnerability.

While Szulecki and Overland [29] view it as a possible weakness, it is important to highlight that the construction of NPPs by Rosatom, as well as its predecessor organizations, has significantly contributed to the development of advanced energy infrastructure, resulting in a paradoxical reduction in energy dependencies. This is for instance well-illustrated for Bulgaria [30,31], where it can be argued that Soviet engineers, by erecting several large coal-fired and nuclear-powered plants, actually helped reduce the country’s energy dependence on the USSR and now Russia. Similar arguments can be made and are indeed used by the proponents of nuclear power projects supported by Rosatom. Presently Rosatom is building NPPs in Bangladesh, Belarus, China, Egypt, Hungary, India, as well as Turkey and once completed these power plants will indeed tremendously help those countries [32].

In the early 2010s there was also a significant push for Russian nuclear energy into Africa, with the strong USSR-era links between Russia and former liberation movements providing potential points of exploitation. These connections led to the negotiation of a NPP construction deal worth USD 76 billion between Russia and South Africa. However, the deal was ultimately abandoned following legal challenges, driven by institutional oversight, civil society activism, and investigative reporting by independent media that uncovered irregularities in the procurement processes [33–35].

Rosatom’s ability to build NPPs and organize the financing for doing so is impressive, and probably the most visible activity of the company. Less visible but equally, if not more impressive, is Rosatom’s (and subsidiaries’) ability to offer fuel cycle services to a considerable number of countries worldwide. This includes, as noted by Bowen and Dabbar [36], even the US, which is typically cautious about foreign involvement and the resulting potential dependencies in the nuclear sector and other critical industries. Rothwell [37] provided a detailed analysis of the US enrichment market in which Rosatom was the largest single provider of enrichment services to US utilities covering 24 % and 27 % of the demand in 2022 and 2023 [38].

NPPs erected by Rosatom can most certainly create a potential dependency, or vulnerability for exploitation by the Kremlin. As a result of the importance of Russia as a provider of nuclear fuel cycle services a good amount of dependency does, however, already exist. Meyer [39] provided a recent analysis of the possible weaponization of the enriched uranium trade between the EU and Russia. The study concluded that Russia’s capability to weaponize the uranium enrichment market against the EU is very limited, but not non-existent and encouraged further studies on the whole nuclear fuel cycle.

This work examines the extent of dependency on Russian nuclear fuel cycle services, focusing specifically on the EU (Section 3.1) and the world (Section 3.2), to assess whether nuclear power can truly be considered a source of energy relatively insulated from recent geopolitical tensions between Russia and the West. The methodology underpinning the assessment is outlined in Section 2, and the conclusions are presented in Section 4.

2. Methods

Fig. 1 provides an overview of the nuclear fuel cycle. In this work we consider (i) uranium mining and milling (or uranium production), (ii) uranium conversion, (iii) uranium enrichment, and (iv) nuclear fuel fabrication as the main nuclear fuel cycle services [40] even though it is noteworthy that some of the NPP operators prefer bundled contracts [28]. We only consider presently used fuel cycle options [41], and do not, for instance, discuss the potential large-scale deployment of fast reactors that would dramatically reduce uranium requirements [42] or the potential use of thorium as a future reactor fuel [43]. It is noteworthy that the four different fuel cycle services considered are closely interlinked.

Most mining facilities include a mill, but when mining facilities are close, one mill may process the uranium ore concentrate from more than one mine. The solid uranium oxide (U_3O_8) from mining and milling (see Fig. 1) that is often referred to as yellow cake needs to be converted to gaseous uranium hexafluoride (UF_6) for the subsequent enrichment from natural uranium (0.7 % ^{235}U) to low-enriched uranium (LEU) (3–5 % ^{235}U) [44]. The material is then deconverted again to solid uranium dioxide (UO_2) that is used in nuclear fuel fabrication. Transportation of UF_6 can be cumbersome and therefore conversion, deconversion, and enrichment facilities are often at one location (particularly in France and Russia that have integrated nuclear supply chains) as the conversion and deconversion capacities are closely aligned with the enrichment capacity and *vice versa*. Used fuel can be further processed to recover reprocessed uranium (RepU in Fig. 1) and plutonium (PuO_2 in Fig. 1) that can be fed back into the nuclear fuel cycle as indicated in Fig. 1. Typically, the costs for conversion and enrichment services are separated, as noted by Kidd [40], and organizations like the Euratom Supply Agency (ESA) distinguish between conversion and enrichment capacities. It is common for the relatively small volumes of materials, compared to fossil energy resources, to be transported globally across all four services. Hence, we made the decision to evaluate each of the four steps individually. In addition, uranium mining companies (particularly Cameco from Canada and Kazatomprom from Kazakhstan) offer conversion services in addition to selling U_3O_8 so that the lines between (i) uranium production and (ii) uranium conversion are sometimes blurred. The services are, again, generally charged separately.

We further argue that a key distinction must be made between, on the one hand, uranium production, conversion, and enrichment (i–iii), which yield standardized products (U_3O_8, UF_6, and UO_2 respectively) where price is the dominant factor for consumers, and, on the other hand, nuclear fuel fabrication (iv), which produces a highly specialized product tailored to a specific nuclear reactor design and often even a specific nuclear reactor if different refueling lengths are taken into consideration. This means, for instance, that desired nuclear fuel fabrication capacity for Russian VVER reactors outside Russia (there are presently 37 reactor units operational in geographical Europe [32]) cannot simply be provided by Western fuel producers that are specialized on the different Western reactor designs. Contrary to this, replacing capacity in uranium production, conversion, and enrichment is technically straightforward, and the relatively small volumes of uranium

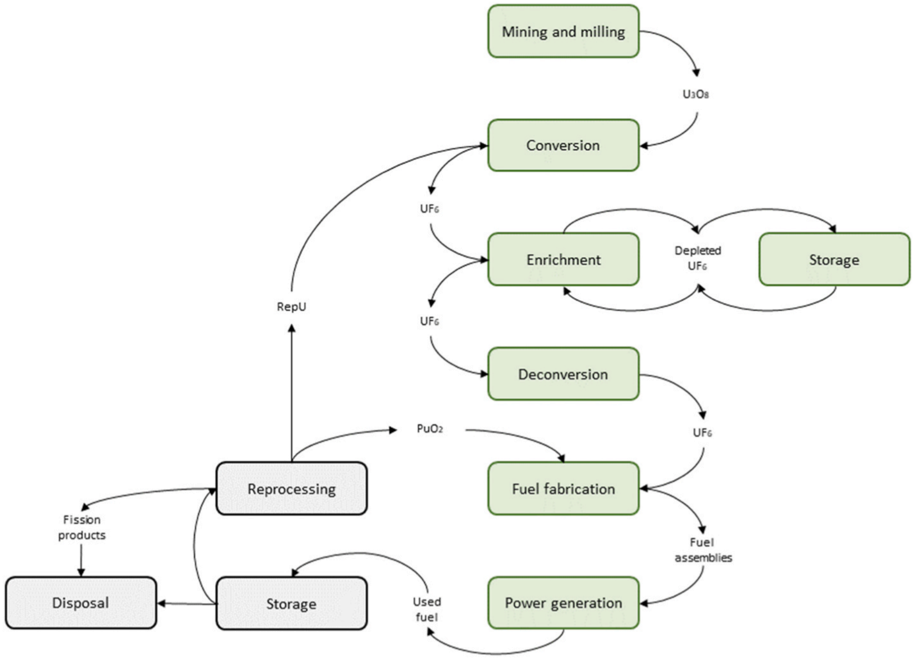

Fig. 1. Overview of the nuclear fuel cycle.

products (if compared to the amount of coal, oil, or natural gas needed to operate fossil fuel-fired power plants with comparable power output) allow for economic global shipments (or even delivery by airplane) over larger distances. This specific distinction among the four nuclear fuel cycle services is explicitly addressed in the results and discussion section. Consequently, market concentration was quantified using the Herfindahl-Hirschman Index (HHI) primarily for uranium production, conversion, and enrichment services. For the global market we also determined the HHI for fuel fabrication but provided detailed discussion on the limited use of this data.

The HHI is considered to be the most widely used index to quantify market or industrial concentration, and it is generally believed that market concentrations can indicate market power with the lack thereof indicating potential market weakness resulting in a possible strategic dependence that could be exploited [45]. The HHI gained increased popularity when the US Department of Justice (DOJ) and the US Federal Trade Commission (FTC) began using it instead of the concentration ratio as part of the Horizontal Merger Guidelines in the 1980s [46,47]. Although widely used the HHI is not without limitations and a market concentration does not automatically result in market power or a strategic dependence [47,48].

Despite such limitations the HHI is widely used to quantify energy security [49–51] and also raw material supply security [52–54]. DOJ, FTC and other agencies usually use the HHI for monitoring and start closer investigations when larger changes are noticed. The HHI is thus not used as a single metric for decision making but rather as an indicator that can help quantify market trends. In this work the HHI is used to quantify market concentrations, and thus potential dependency on Russia as an important market supplier in three different steps (uranium production, -conversion, and -enrichment) along the nuclear fuel cycle. The HHI is determined (1) with N being the number of suppliers in the regarded market, and MS being the specific market share (in %) of the regarded supplier i, so that the scale ranges from 0 (infinitely many competitors) to 10,000 (single monopoly).

$$HHI = \sum_{i=1}^{N} (MS_i)^2 \tag{1}$$

A HHI of $\leq$100 usually indicates a highly competitive market. A HHI $\leq$1,500 but $>$100 indicates unconcentrated industry, a HHI between 1,500–2,500 indicates moderate concentration, and a HHI $\geq$2,500 suggests a highly concentrated market [55]. All data used for the analysis is openly accessible and has been referenced appropriately. The data for the EU has been sourced from the latest annual reports of the ESA [56,57] that seeks to guarantee a consistent and fair supply of nuclear fuels to EU users, in accordance with the goals set out in Article 2(d) of the Euratom Treaty, the world data was sourced from the World Nuclear Association (WNA) [58].

3. Results and discussion

3.1. EU dependencies on Russia's nuclear industry

The EU is largely dependent on uranium imports as indicated in Fig. 2a. In 2023, EU utilities sourced more than 91 % of their uranium imports from just four countries: Canada accounted for 33 %, Russia for 23 %, Kazakhstan for 21 %, and Niger for 14 %. In 2024, 93 % came from five countries: Canada accounted for 34 %, Kazakhstan for 24 %, Russia for 16 %, Australia for 11 % and Niger for 8 % (see Fig. 2b). The remaining percentage in 2024 was supplied by China (5 %) which did not show up as an exporter before 2024, Uzbekistan (2 %), and Namibia (1 %). Other sources listed in Fig. 2a consider smaller amounts of uranium supplied by Malawi, South Africa, Ukraine and the US as well as uranium from re-enriched tails. It is noteworthy that there is an increase in overall natural uranium imports of more than 24 % from 2022 to 2023 and a slight decrease of 4 % from 2023 to 2024. The sharp increase can be attributed to stockpiling by EU utilities as a result of potential supply uncertainties associated with the Russian invasion of Ukraine. Slight reduction in total imports from 2023 to 2024 indicate that utilities do not see this as a big risk anymore or that their capacity to store are full. EU utilities have indeed on average stored approximately 40,000 t of U_{eq} so that they can operate for approximately three years [57].

The ESA and other European agencies [59] are strongly advocating for domestic EU uranium mining although this is currently not playing any role. These efforts are supposed to result in the planned production of 200 t uranium per year from 2026 as a byproduct from zinc and nickel production in Finland [60]. It is possible that more byproduct uranium will be recovered in the EU in the near future as for instance proposed for mineral fertilizers [61,62]. Traditional primary uranium mining in the

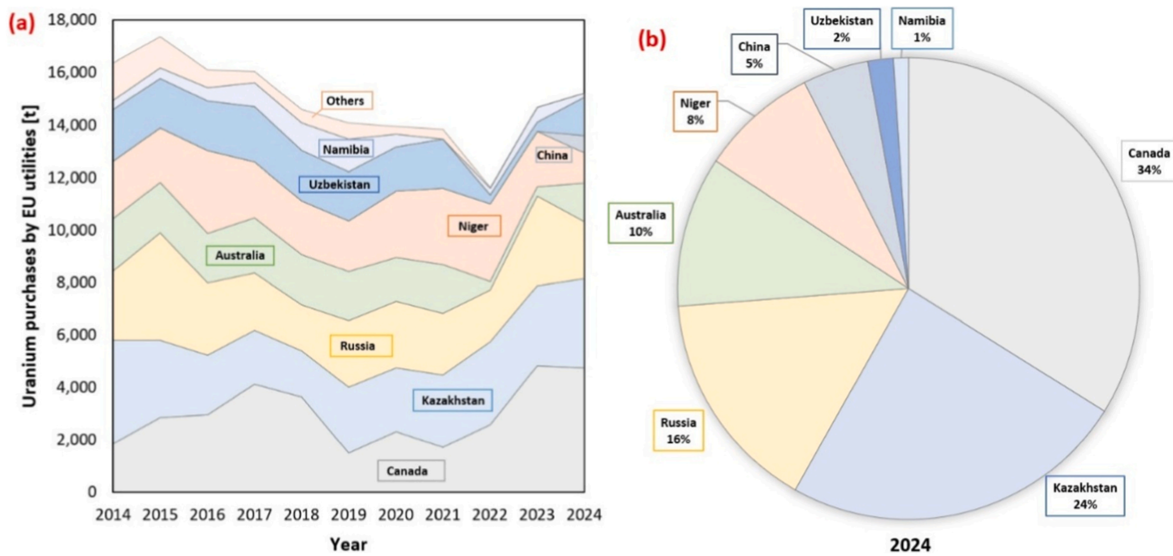

Fig. 2. (a) Historic uranium purchases of EU utilities by origin from 2014 to 2024, and (b) uranium purchases of EU utilities by origin in 2024 (Data source: ESA [56]).

EU is unlikely given the environmental and social obstacles, and even if successfully implemented [63], byproduct uranium recovery will most probably only cover the uranium demand in single digit percentages, given the relatively large number of nuclear reactors operated in Europe.

It is noteworthy that companies and not countries mine uranium. There are only a handful of uranium mining companies operating globally, and these companies often team up to explore or mine uranium deposits. In Kazakhstan, for instance, uranium mining is done by state owned Kazatomprom. Kazatomprom does, however, not completely own all uranium mining projects. Cameco from Canada holds for instance a 40 % share in the Inkai mines operation (responsible for 16 % of Kazakh uranium production in 2021). In a similar fashion Uranium One, a subsidiary of Russia's Rosatom holds a 70 % share in the Betpak Dala operation (South Inkai, and Akdala mines responsible for 11 % of Kazakh uranium production in 2021), a 50 % share in the Karatau project (responsible for 12 % of Kazakh uranium production in 2021), another 50 % share in the Akbastau project (responsible for 7 % of Kazakh uranium production in 2021), a 30 % share in the Khorosan-U project (responsible for 7 % of Kazakh uranium production in 2021) and a 49.67 % share in the Zarechnoye project (responsible for 3 % of Kazakh uranium production in 2021) [64]. Russia, through Uranium One thus held at least a minority share in approximately 37 % of Kazakh uranium production in 2021, or 17 % of world uranium production that year (excluding uranium production in other countries than Kazakhstan).

The authors did not consider shared mine ownership in the quantitative HHI analysis but feel that it is important to mention these structures. It is further noteworthy that at present the most preferred shipping route for uranium from Kazakhstan and also Uzbekistan (24 % and 2 % of EU imports in 2024, and about 43 % and 7 % of global uranium production in 2022 [65]) is by rail through Russia and then through the port of St. Petersburg that is licensed to handle uranium (most ports do not have such a license [39]). Transportation through the Middle Corridor or along the Trans-Caspian International Transport Route (TITR) that connects China with Europe is possible but comparably complicated and presently rare. The route entails crossing the Caspian Sea by ship after which goods are loaded on trains and trucks in Azerbaijan from where they move onwards to Georgia and Turkey that have access to the Black and Mediterranean Sea used for global shipment [66].

It is highly unlikely that Russia can control uranium exports from Central Asia to Europe by blocking passage through its territory, but we presented a HHI case in which EU uranium imports from Kazakhstan, Uzbekistan, and Russia are all considered as one market share to indicate how such a scenario would play out.

In addition to uranium imports from Russia, the EU is further dependent on uranium conversion- and uranium enrichment services provided by Russian companies to EU utilities. Fig. 3 shows the historic uranium conversion services (Fig. 3a) measured in tU and uranium enrichment services (Fig. 3b) measured in metric tons separative work (tSW) (1 tSW = 1,000 SWU) provided to EU utilities by origin from 2017 to 2023 [56,57]. In 2023 for instance EU utilities used 12,260 tSW that resulted in 1,791 t LEU from 14,205 t natural uranium feed. In 2022 the EU conversion requirements were covered by Orano-EU (37 %), Rosatom-Russia (22 %), Cameco-Canada (21 %), ConverDyn-USA (16 %) and others (3 %). The Rosatom-Russia share increased to 27 % in 2023 before it fell again to 22 % in 2024. Generally, it can be observed that conversion services to EU utilities became more balanced in 2024 when compared to 2022 and also 2023.

Enrichment services in 2023 were met by the EU itself (55 %), Russia (38 %) and others (7 %). This changed in 2024 when the EU itself provided 65 % of enrichment services, Russia 23 % and others 12 %. When comparing Fig. 3a and b the aforementioned coordination between conversion and enrichment facilities in Russia can clearly be seen. Fig. 3a further shows that conversion needs to be considered as a separate fuel cycle service since Canada and the US (as well as others) offered conversion services, but not enrichment services to EU utilities from 2017 to 2024.

Overall conversion and enrichment services measured in tSW increased by 22 % and 14 % from 2022 to 2023 but then stayed fairly constant from 2023 to 2024. Remarkably the conversion and enrichment services provided by Russian companies to EU utilities showed an increase of 45 % and 44 % from 2022 to 2023 but then decreased again from 2023 to 2024 to roughly 2022 levels. The rapid increases can be explained by market uncertainties and the desire to stockpile products in the face of potential sanctions while the subsequent decreases indicate that these uncertainties are not felt that strongly anymore.

Fig. 4a shows the HHI of the uranium production, conversion, and enrichment services provided to EU utilities from 2017 to 2024. Fig. 4a shows that in case of uranium supply to EU utilities a moderately concentrated market existed during 2017–2024. Specifically, the HHI rose from 1,846 in 2021 to 2,153 in 2022 and 2,305 in 2023 before it decreased again to 2,185 in 2024. Interestingly the increases can be attributed to rising uranium imports from Canada (1,714 tU in 2021,

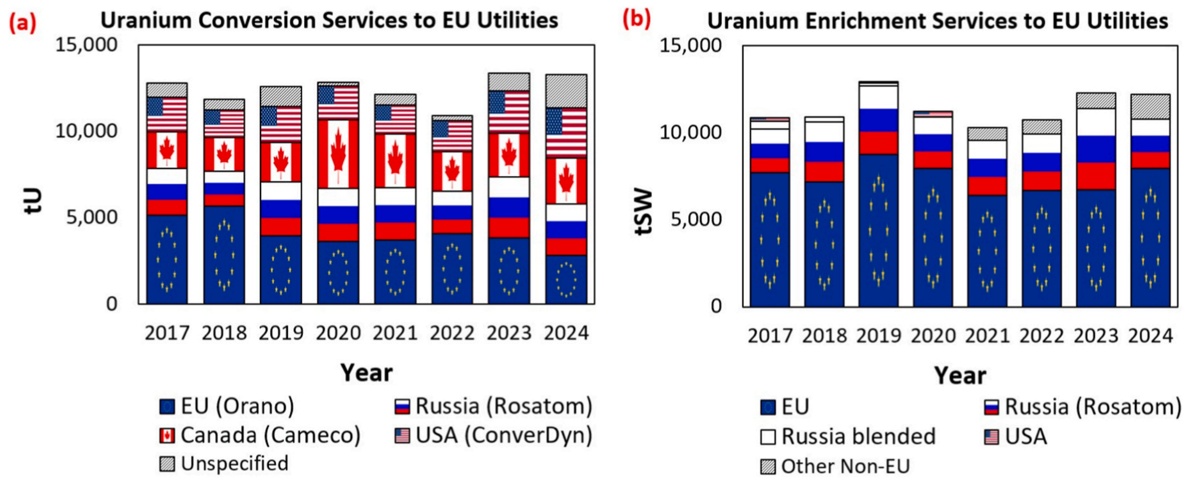

Fig. 3. (a) Historic uranium conversion services and (b) uranium enrichment services provided to EU utilities by origin (Data source: ESA [56,57]).

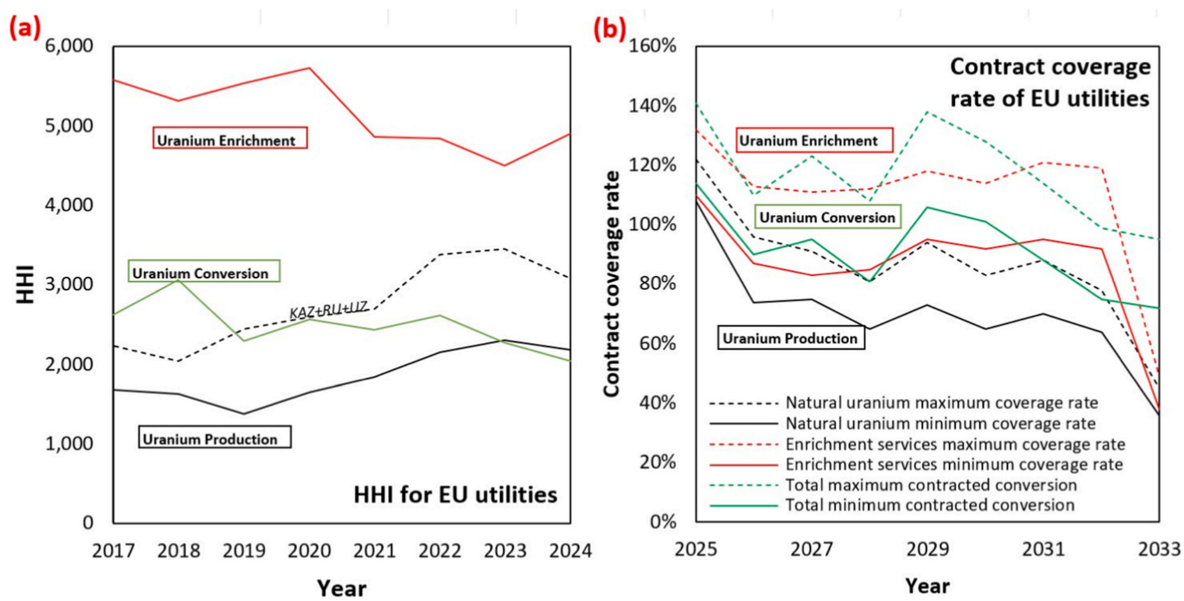

Fig. 4. (a) Herfindahl-Hirschman Index (HHI) for uranium production, conversion, and enrichment services to EU utilities and (b) contract coverage rates for uranium production, conversion, and enrichment services provided to EU utilities (Data source: ESA [56,57]).

2,578 tU in 2022 and 4,802 tU in 2023) and Russia (2,358 tU in 2021, 1,980 tU in 2022 and 3,419 tU in 2023) as well as declining uranium imports from Niger (2,905 tU in 2021, 2,975 tU in 2022 and 2,089 tU in 2023) and Australia (1,869 tU in 2021, 327 tU in 2022 and 372 tU in 2023). The subsequent decrease of the HHI can be explained by increased diversification of supply. China for instance emerged as a supplier to EU utilities in 2024 (see Fig. 2a).

If uranium production from Kazakhstan, Russia, and Uzbekistan is all lumped together (dashed black line in Fig. 4a), to simulate a strong Russian influence as discussed before, the HHI for uranium supply to EU utilities is above 2,500 (2,697 in 2021, 3,384 in 2022, 3,455 in 2023 and 3,085 in 2024) indeed suggesting a highly concentrated market. It is noteworthy that the relatively high concentration of the HHI is also a result of how the HHI is determined, specifically the relatively low number of suppliers (compared to what is common in other markets) or uranium producing countries that export to EU utilities.

The supply risk of a resource can also be determined based on their production concentration, scarcity, reserve distribution, substitutability, recycling rate, and governance aspects of the top-producing and reserve-hosting countries (approach of the British Geological Survey) [67,68]. For the EU the European Commission (EC) published supply risk indicators for 41 materials, considering political stability of the producing countries, production concentration, and substitutability as well as potential recycling of the materials [69]. Uranium is presently not considered a critical raw material (CRM) in the EU by the EC yet [59] although it is worth mentioning that Japan recently added uranium to the country's list of CRMs [70].

Uranium conversion services to EU utilities show higher HHI values if compared to uranium production. In 2017, 2018, 2020 and 2022 the HHI was higher than 2,500 (2,627, 3,060, 2570 and 2,616 respectively). For enrichment services to EU utilities even higher HHI values (around or more than 5,000) can be reported. The fact that most enrichment services in 2017–2024 were largely provided by companies from only two regions (the EU and Russia) as indicated in Fig. 3b explains this. In this context it is worth mentioning that enrichment is usually considered to be the most relevant aspect of nuclear non-proliferation with nuclear weapons states actively discouraging the erection of enrichment capacity in non-nuclear weapons states, effectively resulting in a highly concentrated market dominated by only a handful of players [37,71].

In the short-term Fig. 4b shows that EU utilities reach relatively high contract coverage rates for uranium conversion and enrichment. In the long-term the ESA strongly recommends strengthening the conversion and enrichment capacity in the EU [56], as a result of potentially higher uranium demands globally [72]. The companies operating conversion and enrichment facilities in the EU do not only provide these services to EU utilities but generally offer their services to the best paying customers. Potentially global increases in uranium demand may therefore result in higher costs for conversion and enrichment services to EU utilities or even supply bottlenecks, even if EU utilities are not necessarily the primary drivers behind a potentially increasing uranium demand.

The HHI can be helpful to quantify the market concentration for standardized products like uranium production, uranium conversion and enrichment services. For nuclear fuel fabrication it is not particularly helpful since the product is so specialized that there are often only 1–2 potential suppliers that are technically capable to deliver the product. Usually, the company that erected the NPP in question will also provide the operation and maintenance, as well as the nuclear fuel supply [40].

There are presently five countries in the EU (Bulgaria, the Czech Republic, Finland, Hungary, and Slovakia) that are operating Soviet/Russian-designed VVERs. Ukraine, not part of the EU but part of Europe, could be counted as well, as it was even part of the USSR itself and not only part of the larger Eastern bloc like Bulgaria, the Czech Republic, Hungary and Slovakia. The main historical reason for VVER constructions in Europe was the political influence of the USSR/Russia. In total 19 (soon to be 20 when Mochovce 4 goes online) VVER reactors are in operation in the EU and 15 more in Ukraine. For completeness there is presently also one VVER operated in Armenia, two in Belarus and 22 in Russia itself. Globally, Bangladesh, Belarus, China, Egypt, India, Iran, and Turkey are operating or constructing VVERs [73].

There are companies in the Czech Republic, France, Slovakia, Ukraine and elsewhere, that have experiences with VVER technologies and which have already been providing maintenance for VVER operators. Hence, these operators are not dependent on Russian companies alone for maintenance and service (anymore). The situation is, however, still more complicated in the nuclear fuel segment. After the Russian invasion of Ukraine in February 2022, sanctions were imposed on the Russian energy sector (among others) in several rounds [14,74]. These sanctions are thus far not targeting the Russian nuclear sector, and we have been witnessing airborne nuclear fuel supplies to CEE countries even during the conflict (for example, Slovakia [75]). Something that would not be possible for coal, oil or gas, and underlines the peculiarity of the nuclear industry and NPP fuel supply.

It is useful to differentiate between subtypes of the Russian nuclear reactor family. The VVER-440 from 1970s to 1980s, the VVER-1000 from the end of the 1980s, and the VVER-1200/VVER-TOI (from 2018) under construction in Kursk, Russia. These subtypes are further distinguished by model numbers. The VVER-440 subtype is reactor technology introduced in these countries at the turn of 1970s/1980s as the first commercial designs of this reactor family, while the VVER-1000 is an evolutionary design introduced at the end of 1980s. Technologically, both designs are pressurized water reactors, but with different capacities. VVER-440s reactor units have a nameplate capacity of 440 MWe while the nameplate capacity of a VVER-1000 unit is 1,000 MWe. The newer generation of VVER units are not of concern in this work as there are only two units in Belarus outside the EU and two units still planned for Paks II in Hungary.

In Europe VVER-1000 units are operated in Bulgaria (2 units), the Czech Republic (2 units) and Ukraine (13 units). Historically, the primary supplier of fuel for these reactors is TVEL, a subsidiary of Rosatom. However, since the 1990s, Westinghouse Sweden (located in Västerås) worked with Enusa Industries from Spain and became an alternate supplier with its own VVER-1000 fuel design, securing elementary market competition and security of supply. Westinghouse designed and developed the first generation of VVER-1000 fuel already in the 1990s and it was used in the Czech NPP Temelín between 2000 and 2009 and later in some of the Ukrainian reactors [21]. Issues with geometric stability initially led to frequent outages at the Czech facility and was the main reason to return to Russian fuel after 2009 [21]. The experiences gained in the Czech Republic and later in Ukraine led to Westinghouse adjusting the fuel, and the company is now already producing the third generation of it (under the name RWFA). This fuel is presently being supplied to three units in Ukraine without any reported operational issues.

All three European countries using the VVER-1000 units are indeed switching to Westinghouse fuel. The Czech Republic completed a fuel tender for both units at Temelín in April 2022, where Westinghouse (along with Framatome) has been selected as the new supplier of fuel for the next ten years [76]. In addition, Bulgaria signed a 10-year deal with Westinghouse for one unit at Kozloduy in December 2022, and diversification from Russian fuel in the second unit is expected to follow swiftly [77]. These results were not purely based on techno-economic performance, but already considered strategic considerations as pointed out by Pan [19] recently.

In June 2022, Ukraine signed a contract with Westinghouse to supply all fuel for its nuclear power fleet [78]. The fact that with Westinghouse there is now a supplier other than TVEL/Rosatom that has substantial operational experience and can produce technologically as well as economically competitive and safe fuel is the reason that we will most likely not see Russian fuel in the VVER-1000 segment in Europe within the foreseeable future. The Ukrainian case also shows that switching from TVEL to Westinghouse fuel is not necessarily accompanied with higher costs. The price for fuel was in fact 18–30 % lower with Westinghouse compared to TVEL (USD 0.74 vs. USD 0.9 million per t of fuel in 2019, USD 0.75 vs. USD 1.07 million in 2020, and USD 0.83 vs. USD 1.1 in 2021) [79]. Besides Westinghouse, the French company Framatome also has the capacity to assemble VVER-1000 fuel under license agreement with Rosatom, that are presently being discussed and negotiated. The entry of a potential second Western VVER-1000 fuel producer (although it is expected to be only Rosatom-licensed assemblies of fuel elements by Framatome, rather than a new design) indicates that the supply of VVER-1000 fuel in Europe should not be a concern. Given Rosatom's activity in NPP construction worldwide, VVER-1000 and rather similar VVER-1200 fuel can be considered a large and growing market, so that it is economically attractive for fuel producers worldwide to enter it.

Fuel supply of the ageing VVER-440 reactors, a shrinking market, is however very different. VVER-440 units (outside Belarus and Russia) are currently operated in Armenia (1 unit), the Czech Republic (4 units), Finland (2 units), Hungary (4 units), Slovakia (5 units, soon to be 6), and Ukraine (2 units) as depicted in Fig. 5. Most units are expected to run for

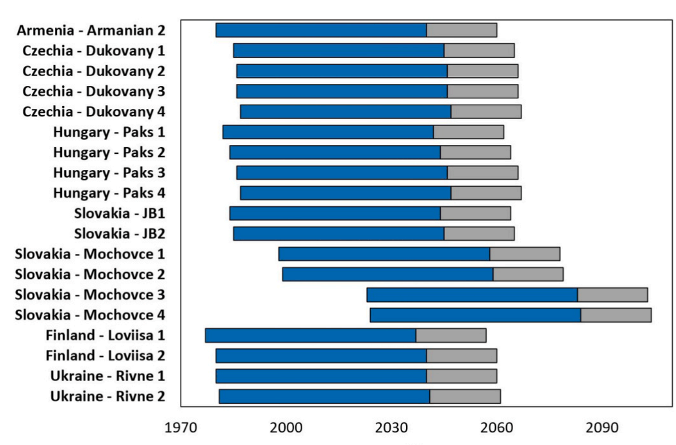

Fig. 5. Projected potential 60 (blue) and 80 (grey) years operation of VVER-440 reactors in Europe (without Russia).

60 years (blue bar in Fig. 5) with this lifetime potentially being further extended. The Finnish VVER-440 reactors at Loviisa recently received a lifetime extension to operate for up to 70 years [80]. In Fig. 5 a potential operation of up to 80 years is shown (grey bar) to indicate for how long these reactors might still be operational, and for how long they will therefore require refueling.

Besides TVEL (Rosatom), there is only one alternative supplier, Westinghouse. However, the company is rather new in this market segment and has limited production capacity to cope with potential interest from many NPP operators. In the 1990s the British company BNFL (British Nuclear Fuels Limited) designed NOVA-E3 fuel for VVER-440 units in Finland and Hungary as a result of the 1996 contract with Finnish and Hungarian operators. BNFL later acquired and owned Westinghouse's nuclear divisions from 1999 to 2006. Toshiba took over these divisions from 2006 to 2018, eventually sold them to Brookfield Business Partners who then sold 49 % to Cameco from Canada in 2023. The fuel developed by BNFL was used in the Finnish Loviisa NPP in 2001–2007 [21]. Besides Loviisa, none of the VVER-440 operators showed interest in this fuel and the company did not succeed in promoting its product. It was as late as 2013, when Euratom opened a Horizon 2020 project call aimed at fuel diversification for the VVER-440 reactor segment, a topic Euratom has been raising for quite some time. The EUR 2 million project was won by a Westinghouse-led consortium of companies with VVER-440 operation, design, and production experience [81]. The project was completed in 2017 and resulted in a second-generation design of the NOVA-E3 fuel.

Only as late as 2021 was Westinghouse able to close its first contract for VVER-440 fuel supply, to the Ukrainian Rivne NPP. In 2022–2023, Westinghouse signed VVER-440 fuel supply agreements with Finland (November 2022), the Czech Republic (March 2023), and Slovakia (August 2023) [82–85]. European VVER-440 operators are thus in a situation where there is an alternate supplier now with its own fuel design. Westinghouse's production capacity of VVER-440 fuel is, however, very limited. In case of continuing fuel deliveries from Russia, diversification will be possible without interruptions in electricity generation, but it may take a few years. The fact that the market is functional with VVER-1000 fuel does not mean that the companies producing that fuel are automatically able to create a reliable VVER-440 fuel design from this experience overnight. Variations in materials, operating temperatures and pressures, fuel sizes, enrichment levels, pellet shapes and dimensions, licensing requirements, pricing, and other undisclosed factors all complicate a rapid transition of VVER-440 fuel supply from TVEL to Westinghouse. An abrupt halt in Russian fuel deliveries to this reactor subsegment could lead to fuel shortages, rising costs, and potentially even interruptions in electricity generation.

Part of the solution also depends on the actions of operators and other market participants. These include financial support from operators to accelerate the expansion of Westinghouse's production capacity, as well as licensed production of VVER-440 fuel, whether from Westinghouse or TVEL, by other European fuel manufacturers such as Framatome, who recently signed contracts to supply fuel to Hungarian VVER-440 reactors. Framatome will use similar logic as in the VVER-1000 fuel segment, Rosatom-licensed assemblies of nuclear fuel in the EU. Westinghouse recently partnered with ENUSA from Spain in VVER-440 fuel production [86]. The partnership constitutes a refurbishment of an earlier (2001–2007) partnership to develop Loviisa VVER-440 fuel. In addition, the APIS (led by Westinghouse ElectricSweden AB) and SAVE (lead by Framatom) projects with EUR 10 million each co-funding from the EU were recently launched to develop VVER-440 reactor fuel [80, 87].

Besides the technical aspects of developing VVER-440 fuel, there are also legal aspects to replacing TVEL/Rosatom as a fuel supplier. Current fuel contracts with TVEL (usually life-long in this specific reactor subsegment [21]) would most likely be terminated to fully switch to a new supplier. The operators would thus face either high fees for contract terminations or even international arbitrage. Hence, this segment usually searches for another supplier in public procurement that would supply its product with the primary one, i.e. TVEL/Rosatom. It is again noteworthy that nuclear reactor fuel is a high-tech product and that with basically no operational experience, fuel switches come with economic and safety concerns related to operational behavior of the new fuel. We thus consider the dependency on VVER-440 fuel a severe issue that will probably be on the table for the next 10 years, with high concerns related to immediate cut-offs because of Western or Russian sanctions that could have dramatic effects for the countries in which these reactors are operated. For instance, in the Czech Republic more than 1/3 of the electricity is produced from six nuclear power plants (all VVER reactors) of which four are VVER-440 reactors, that contribute more than 48 % of the current nuclear electricity generation capacity [88] or in other words roughly 1/6 of all electricity produced in the country. In Hungary and Slovakia all operating NPPs are VVER-440 units, and these reactors contribute 46 % and 54 % of present annual electricity production [89, 90], so that supply interruptions would indeed result in serious shortcomings.

In summary it is important to understand that the trade of nuclear fuel cycle services between the EU and Russia is relatively small if compared to fossil fuel imports (EUR 1 billion vs. EUR 23 billion in 2024 [87]) so that most analyses on the EU energy dependency on Russia do not even consider nuclear fuel cycle services (see, for instance, Ref. [91]). Similarly, sanctions on nuclear fuel cycle services have probably also not been implemented by the EU (yet) since they result in relatively little economic damage to Russia compared to what can be achieved with sanctioning fossil fuel imports, and may hold potentially large retributions to the EU, and here specifically VVER-440 operating countries in the EU, itself [83].

3.2. *World dependencies on Russia's nuclear industry*

Compared with the fossil fuel market the market for nuclear fuel cycle services is relatively small. However, given the global importance of nuclear power in electricity production, about 10 % of all electricity worldwide is produced from nuclear reactors worldwide, it is a strategically relevant market and the declaration of the United Kingdom (UK), US, Canada, Japan, and France alongside the Group of Seven (G7) summit in Sapporo in April 2023 made it clear that these countries intend to isolate Russia, and Russian nuclear fuel cycle service providers [92].

Fig. 6 provides an overview of Russia's share in world uranium production, as well as conversion, enrichment, and fuel fabrication capacity in 2020, before the invasion of Ukraine [58]. To quantify the market concentration the HHI was again determined (even for nuclear fuel fabrication). Russian suppliers are particularly strong in providing enrichment services to the world, and specifically the West, since China is in all services (except for uranium production) relatively self-sufficient and thus independent from the rest of the world (see Fig. 6 and also [93]). The HHI (3,546 in 2020) indicates that the global enrichment market is highly concentrated. Specifically, Russian suppliers commanded more than 46 % of the global enrichment capacity in 2020. Castillo-Peters and von Hippel [94] argued that it is theoretically possible to reduce the dependency of the West (specifically the EU and the US) from Russian enrichment services and that companies are already independently and voluntarily moving in this direction to reduce supply uncertainties and not to be associated with Russian producers. A similar trend can also be observed in uranium production and will be more visible within the coming years. The relatively long (2–5 years or even longer) contract times common in this fuel cycle segment result in a delayed market response.

We concur with the analysis by Castillo-Peters and von Hippel [94], and believe that strong government incentives, potentially through long-term purchase agreements, will be essential to stimulate investment in new enrichment and conversion infrastructure over the long term. In the short term it will also be possible to offset the enrichment

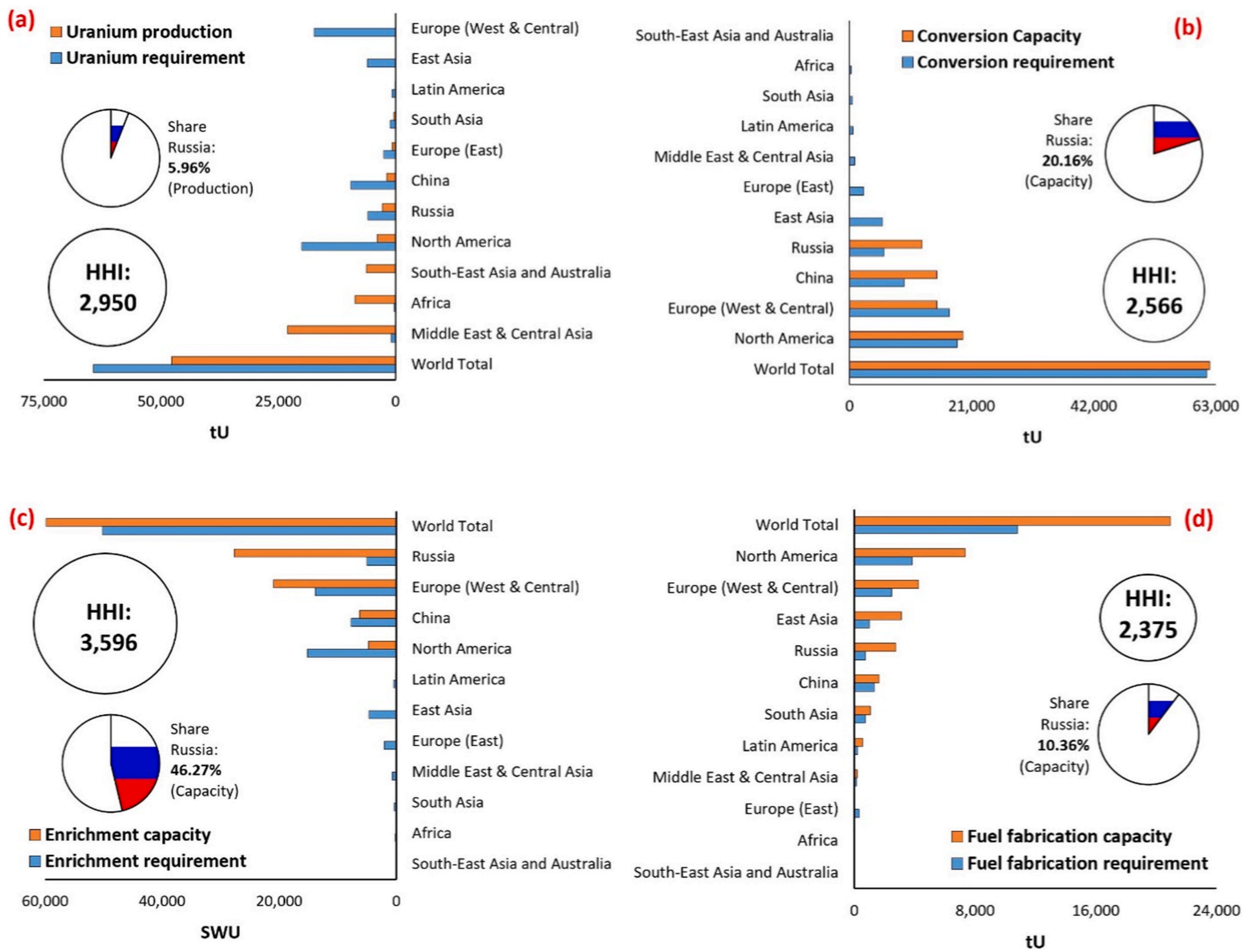

Fig. 6. Demand and supply of nuclear fuel cycle services worldwide in 2020 with Russia's share as well as the market specific Herfindahl-Hirschman Index (HHI) for (a) uranium production, (b) uranium conversion, (c) uranium enrichment and (d) nuclear fuel fabrication indicated (data source: [58]).

requirements (at least to some degree) by leaving a higher tails assay behind. A practice referred to as uranium overfeeding that is typically used to decrease the number of SWU by the centrifuges used in uranium enrichment. If natural uranium is relatively cheap and SWU is relatively expensive, uranium overfeeding can be economically beneficial. In such a scenario more natural uranium than typically needed is used to reduce the amount of energy-intensive enrichment work. This has also been pointed out by Castillo-Peters and von Hippel [94] who estimated that the EU and the US would need an additional 4,900 t of natural uranium per year (1,900 t for the EU and 3,000 t for the US) to do so but could then completely offset enrichment services currently provided to them by Russia. Since the fuel costs for a typical commercial reactor contribute to only 4 % of the price of supplied electricity, even a doubling of costs for nuclear fuel cycle services would theoretically not result in a high increase of the overall price for nuclear electricity production [87,94]. In practice the situation is, however, more complicated since the nuclear fuel costs, that might only be a small fraction of the final electricity price that the end user pays, are a relevant factor (typically one fifths) of the running costs for a NPP operator [95]. Nuclear utilities often have to bid into the electricity market or compete by other economic means to get the electricity they produced distributed to the final consumer. Here increases in nuclear fuel prizes could be a relevant factor and longer-term support assurances would help those utilities plan and ultimately secure the needed grid access to sell the electricity they produce.

Since the overall costs of nuclear electricity only slightly increase for the final consumer, nuclear power can be seen as a relatively independent form of large-scale, baseload energy production. It is further noteworthy that most NPP operators have fresh nuclear fuel for the next three or more years on site, and that even nuclear fuel deliveries by plane for the next production cycle of 1–2 years are not unheard of (this was done, for example, by Slovakia in 2022, [75]). A complete impossibility for coal, gas, and oil plants that require constant supplies of large quantities of fossil fuels.

It is noteworthy that there are specific elements within the enrichment services where Russia is presently the only commercial supplier globally. Specifically, Russia is currently the sole larger-scale supplier of High-Assay, Low-Enriched Uranium (HALEU), which is not required for today's large, gigawatt-scale commercial light water reactors but is essential for several advanced nuclear reactors under development [96]. The limited availability of HALEU could for instance delay the commissioning of Bill Gates' TerraPower Natrium reactor project in the US by at least two years [97]. A HALEU consortium that aims to fill this supply gap has already been formed in the US in 2020, but this consortium is still far away from larger-scale industrial HALEU production and in need of longer-term financial support that does not seem to be secured right now [98].

The potential larger-scale deployment of advanced nuclear reactors, particularly small modular reactors (SMRs), may further result in an increased demand for uranium in the longer-term as well [99]. In the near future it will primarily be increased uranium demand from newly erected large, gigawatt-scale NPPs build in China that might increase near-term uranium demand globally if it is not balanced out by closures of older NPPs in other regions. Uranium is fairly common in nature, and we will most likely not run out of it in the near future [100]. Besides, it is likely that it will take some time until advanced SMRs have proven their techno-economic feasibility [101–103]. Russia is not a major uranium producer (see Fig. 6) although it should be mentioned that through company shares abroad it theoretically controls more uranium than it domestically produces (see Section 3.1). With building a uranium reserve [104] the US is already conducting first steps to assure a more diversified supply of natural uranium. The near-term options are indeed multiple and range from re-starting idle uranium mines, of which plenty exist in Western countries, to byproduct uranium recovery. In this context, Steiner et al. [105] recently estimated that as much as 10 % of the US's natural uranium demand could also be covered through byproduct recovery from phosphates that are primarily mined for mineral fertilizer production (globally it is around 16 % [106]). These plants could theoretically be operational within 2–3 years [107], while starting a new uranium mine usually takes 10–15 years, and a considerably higher upfront investment.

The potential vulnerability of CEE countries in VVER-440 nuclear fuel needs that could be exploited by Russia is not of relevance to other parts of the world that do not operate these reactors. There are newer Russian reactor designs that have been constructed or are under construction for which Russian companies are presently the only source of fuel. The ability of Western nuclear fuel producers such as Westinghouse to now reliably produce VVER-1000 fuel and other local companies to provide maintenance services, shows, however, that if needed and political will is present Russian fuel can be substituted. As was the case for the VVER-1000 fuel, substituted fuel designs will need testing in the nuclear reactor designs that they should supply before they work reliably, but we do not see reasons why Western, Chinese, or other companies would not be technically able to substitute the fuel of newer Russian reactor designs if these companies were given sufficient lead time (5–10 years) to do so. The EU as the region that is most affected is indeed going exactly in this direction as was recently outlined in the "Roadmap towards ending Russian energy imports" [87] from May 2025. It is noteworthy, that Fig. 6d reveals that there is currently an overcapacity in nuclear fuel production in all listed regions. This could dampen market incentives to invest in new, additional fuel fabrication, but could also create incentives for companies to move into new fuel submarkets that are not oversupplied yet.

Listing the dependencies of the EU on the world and the Russian nuclear industrial complex it should for completeness also be mentioned that there are also relevant dependencies of Russian utilities on the West. Rosatom is successfully building NPPs whose instrumentation and control (I&C) technology is largely provided by Siemens from Germany and whose turbines are (at least in part) provided by EDF from France (which recently bought the Arabelle turbine business from General Electric) [38,108].

4. Conclusions and policy implications

Russia, through state owned Rosatom, is presently a major nuclear fuel cycle service provider to the world. The quantified market concentrations using the HHI as well as Rosatom's market share show that Russian suppliers are particularly strong in providing enrichment services to the EU and the world. They also have considerable uranium conversion capacities to support their enrichment activities, and Russian nuclear fuel producers are presently the only (larger scale) suppliers of VVER-440 reactor fuel and HALEU. We argue that both the EU and the world can reduce these dependencies on Russian nuclear fuel cycle services without much technical difficulty, and reasonable additional costs. We do, indeed, already see a strong trend from Western companies in this direction with the goal to reduce the uncertainties of potential sanctions from either Russia or the West. Political will in the form of financial incentives and longer-term commitments will nonetheless be needed to motivate larger investments in production facilities such as enrichment and conversion complexes, and to a lesser extent uranium mines that are already supported by the increasing global uranium demand. In the last two years we have already experienced significant financial incentives provided by western agencies, particularly those of the US and the EU. Recent uncertainties fueled by the Trump administration in the US question these achievements and as the time of writing it needs to be seen how the current president of the US influences the US and Western nuclear supply chains.

Credit author statement

Nils Haneklaus: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Tomáš Vlček**, **Matúš Mišík**, **Hendrik Brink**: Conceptualization, Formal analysis, Funding acquisition, Project administration, Writing – original draft, Writing – review & editing. **Jakub Ochmann**: Visualization, Writing - review & editing. **Andrej Nosko**, **Anna Skorek-Osikowska:** Writing – review & editing. **Paweł Gładysz, Paweł Gajda**, **Łukasz Bartela**: Conceptualization, Formal analysis, Funding acquisition, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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