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Critical assessment of diversification of nuclear fuel for the operating VVER reactors in the EU

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ABSTRACT

The current pressure for the diversification of nuclear fuel for VVER reactors in the EU is traceable to the proposed European Energy Security Strategy of May 2014, and to the recent Euratom call for the licensing of non-Russian fuel for VVER reactors won by a Westinghouse-led group in June 2015. The VVER-440 fuel market is monopolized by Russia's OAO TVEL, and this development indeed is related to the supply security of the EU's VVER-440 fleet. But the evidence shows that only Slovakia's NPPs can effectively diversify the fuel for the VVER-440 fleet, as Slovakia is the only country without long-term contractual obstacles to changing suppliers. The European Commission is thus supporting primarily the diversification activities of the Slovak Republic.

1. Introduction

Utilities in the European Union are under marked pressure to diversify their nuclear fuel supply sources. This is especially true with regard to supplies for plants built using Russian VVER reactor design technology. The urgency stems from a priority contained in the proposed new European Energy Security Strategy (EESS), which dates to May 2014, and calls for reducing EU dependence upon external suppliers. Nuclear energy is to play a major role in this effort: the pressure to diversify is prompted by the guarantee of energy security that such diversification would afford. Euratom opened call NFRP-16-2015 to support the licensing of Western nuclear fuel for reactors in VVER units in December 2013, with an application deadline of November 2014. Six months later, Westinghouse Electric Company LLC led a group that won €2 million in backing from the EU to diversify nuclear fuel supplies to these reactors, with a focus on licensing alternative nuclear supplies for Russian-designed pressurized water reactors operating inside the EU.

This is not to say that the notion of diversifying nuclear fuel supplies for VVER units is completely fresh: in the Euratom Supply Agency's 2013 Annual Report, concern was raised about '100% reliance on a single supplier for VVER fuel fabrication' [1]. And indeed this same wording appeared in the 2014 Annual Report and is expected in succeeding reports. But the concern is nowhere to be found in any annual report prior to 2013; it emerged at the same time a grant scheme was put in place to support the licensing of alternative nuclear fuel sources. In 2003–04, long before the most recent Report of the Advisory Committee to the Euratom Supply Agency on the Analysis of Nuclear Fuel Availability at the EU Level from the Security of Supply Perspective [2], a comparable committee had been at work on a similar topic. Its report, rendered irrelevant by the EU enlargement, was forgotten almost immediately [3]. But the current 2015 Advisory Committee Report is basically an enhanced version of that 2005 Report using the same methodology.

Abbreviations: AP, Advanced Passive – designation of Westinghouse Electric Company LLC's Pressurized Water Reactor design; BNFL, British Nuclear Fuels Limited Ltd; CEE, Central and Eastern Europe; CNNC, China National Nuclear Corporation; EC, European Commission; EESS, European Energy Security Strategy; EPR, European or Evolutionary Pressurized Reactor – designation of AREVA SA's Pressurized Water Reactor design; EU, European Union; IUEC, International Uranium Enrichment Centre; LEU, Low Enriched Uranium; LLC, Limited Liability Company - United States-specific form of a private limited company; LTA, Lead Test Assembly; NPP, Nuclear Power Plant; OAO, Open joint-stock company (Открытое Акционерное Общество) – type of a private limited company in the Russian Federation; PWR, Pressurized Water Reactor; USEC, United States Enrichment Corporation; VVER, Water-Water Energetic Reactor (Водо-Водяной Энергетический Реактор) – designation of Rosatom State Nuclear Energy Corporation's Pressurized Water Reactor design.

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Additionally, a 2009 journal article by Geoffrey Rothwell in Energy Economics [4] examined whether fuel fabrication services were reliable, concluding 'While generic LEU fuel capacity has been shown to be competitive, suppliers of some fuel types, such as fuel for the VVERs, could be less competitive, and rents could be extracted from customers.' And in 2011, a superbly researched report by the Pacific Northwest National Laboratory entitled 'Redundancy of Supply in the International Nuclear Fuel Market: Are Fabrication Services Assured?' [5] stated that 32 reactors in six countries are most vulnerable to delays in the fabrication of nuclear fuel. In the event of a 90-day outage at the primary supplier, such delays might extend from 50 to 70 days. None of these reactors is of VVER design. The reactor types are: the Korean Standard Nuclear Plant (KSNP), KSNP System 80+, B&W Lowered Loop, Framatome 1450-N4, Combustion Engineering System 80, Combustion Engineering System 80-, CNP 600, and BWR-1. It should be noted, however, that such delays would have a limited impact on NPP operation: NPP operators usually stockpile fuel assemblies in numbers adequate for at least one full fuel campaign (i.e. enough for at least one year).

Interest in the topic area does, then, extend partially back to the past. But it is only recently that this interest has risen abruptly. The task of this article will be to analyse the reasons behind the efforts currently being made to understand the issue, and to examine why they have been focused exclusively on the fabrication and licensing of fuel. Also explored is whether these efforts could in fact positively impact supply security within the EU's nuclear industry, and what the real reasons are that pressure is being applied to diversify nuclear fuel supply sources in the industry.

What follows is broken down into several sections. The first is entitled Research Framework and Basic Presumptions, and considers the Nuclear Fuel Cycle approach and why discussion should be limited to the Fabrication step of the cycle. This chapter lays out the field and sets the boundaries for subsequent assessment in the next section. It also provides the reader with an assessment of the EU supply security within the VVER fuel market segment. The ensuing section discusses the results and provides a critical analysis, an alternative explanation, and additional findings. The Conclusion then summarizes what has been said.

2. Research framework and basic presumptions

The most common method used for analysing issues related to nuclear energy invokes the steps of the Nuclear Fuel Cycle. This approach is widely recognized [see Refs. [6–13] for its ability to aid understanding and analysis by dividing the entire nuclear energy process into three primary progressive phases and then subdividing these phases further into individual steps. The three primary phases are: the Front End, the Service Period, and the Back End. These phases track the process from the initial mining of fissile materials to their final disposition underground. The steps that precede the insertion of nuclear fuel into the reactor are referred to as the Front End; those that take place after the fuel is removed from the reactor are referred to as the Back End [9]; and the Service Period is the actual 'fuel campaign', i.e., the period of time during which the fuel is in use in the operating reactor. The limitation of this approach lies in the fact that it considers only steps related to fissile elements—construction of the nuclear power plant and the investment in it are left out of the picture. Since this paper aims to analyse the diversification of nuclear fuel supplies, the Service Period and Back End are excluded from the analysis; the production of nuclear fuel relates only to the Front End phase. The phase is itself further divided into four steps: Uranium Production, Conversion, Enrichment, and Fabrication [8,10].

When it comes to uranium production, the popular view is that physical supplies are under pressure and form a source of concern to the EU. But this is unfounded. Although global uranium production forecasts based upon current prices and levels of demand indicate supplies will run out in 95 years, when one adds in all of the envisaged conventional uranium resources, the estimate stretches to 300 years [10]—and this still leaves out of consideration unconventional sources such as uranium extracted from seawater, phosphate deposits, black shale, etc., and secondary sources like stockpiles, reprocessed uranium, re-enriched uranium tails, weapons-grade uranium, plutonium, thorium, and so on. If nuclear plants continue to be constructed, uranium demand will rise, and the price will likely follow suit. In all probability, this will have the benefit of stimulating uranium extraction from deposits and sources that are not yet viable economically.

Uranium is, after all, a globally traded commodity whose characteristics are not dependent upon source. It is a naturally occurring mineral, produced in 21 different countries in 2011–13 [14], and since the beginning of world industrial production and use, production has exceeded requirements (including for military purposes) by roughly 20% [14]. In addition, both the Conversion and the Enrichment portions of the Nuclear Fuel Cycle include overcapacities, with nameplate capacity exceeding demand by more than 10% (13% for Conversion and 12% for Enrichment in 2014) [15]. These overcapacities might even grow due to market developments, especially due to reduced demand by the still-offline Japanese reactors. The character of the enrichment trade is such that the industry will construct new capacity once long-term contracts are in place. There is, therefore, no indication of any potential supply constraints at this stage of the process. It must be stressed that both Conversion and Enrichment are globally traded on functioning markets; seven companies are active in the conversion end and six in the enrichment end [16]. Any one of them could replace any other, since their production inputs and outputs are interchangeable (natural uranium oxide is an input for Conversion and enriched uranium oxide an output of Enrichment; UF_6 gas is an input for Enrichment and an output of Conversion). Utilities may meet their requirements using any of these companies (with the exception of Japan Nuclear Fuel Limited, whose capacity is minuscule) with no technological constraints.

Fabrication, however, as the last step in the Front End of the Nuclear Fuel Cycle, differs from the preceding steps since it is a bespoke high tech service rather than a commodity. Various types of nuclear fuel assembly exist for varied reactor technologies. But even when the technologies concerned are identical, fuel campaigns may differ in length, and there may be differences in the adjustments made to individual reactors or in their modernization. Fuel is manufactured on the basis of public tenders that specify the product in detail. When it comes to VVER technology, it is true that the Rosatom State Nuclear Energy Corporation subsidiary OAO TVEL has a near monopoly position within the CEE region and in markets around the globe (see Table 1). But this is not a planned policy outcome: it is a legacy of the competition between Western and Russian fuel producers that dates to the Cold War period, when VVER technology evolved in parallel with Western technology. In both systems, the main fuel producers were the suppliers, and technology providers had relatively closed markets. Twenty-five years later, each side has learned about the other's markets and has begun to compete in them.

By examining the methodological division into four steps, then, our analysis shows that the current pressure for the diversification of nuclear fuel sources in the European Union basically concerns only the Fabrication segment of the Front End of the Nuclear Fuel Cycle. For the three preceding steps, diversification is adequate and there are functional markets that will allow further diversification if necessary. This is not true, though, of the final step. With the

Table 1
Operating VVER design nuclear units outside the Russian Federation.

Country	Reactor	Type	In operation from	End of life-cycle	Fuel supplier	Fuel contract until
Operating VVER design nuclear units inside the European Union						
Bulgaria	Kozloduy 5	VVER-1000/V-320	1987	2017[a]	OAO TVEL	2020
	Kozloduy 6	VVER-1000/V-320	1991	2019[a]	OAO TVEL	2020
Czech Republic	Dukovany 1	VVER-440/V-213	1985	not set[h]	OAO TVEL	2028
	Dukovany 2	VVER-440/V-213	1986	2016[a]	OAO TVEL	2028
	Dukovany 3	VVER-440/V-213	1986	2016[a]	OAO TVEL	2028
	Dukovany 4	VVER-440/V-213	1987	2017[a]	OAO TVEL	2028
	Temelín 1	VVER-1000/V-320	2000	2020	OAO TVEL	2020
	Temelín 2	VVER-1000/V-320	2002	2022	OAO TVEL	2020
Finland	Loviisa 1	VVER-440/V-213	1977	2027	OAO TVEL	2027[c]
	Loviisa 2	VVER-440/V-213	1980	2030	OAO TVEL	2030[c]
Hungary	Paks 1	VVER-440/V-213	1982	2032	OAO TVEL	2032
	Paks 2	VVER-440/V-213	1984	2034	OAO TVEL	2034
	Paks 3	VVER-440/V-213	1986	2016[a]	OAO TVEL	2016[d]
	Paks 4	VVER-440/V-213	1987	2017[a]	OAO TVEL	2017[d]
Slovak Republic	Jaslovské Bohunice V2 1	VVER-440/V-213	1984	2024[a]	OAO TVEL	2021
	Jaslovské Bohunice V2 2	VVER-440/V-213	1985	2025[a]	OAO TVEL	2021
	Mochovce 1	VVER-440/V-213	1998	2028	OAO TVEL	2021
	Mochovce 2	VVER-440/V-213	2000	2030	OAO TVEL	2021
Operating VVER design nuclear units outside the European Union						
Armenia	Metsamor 2	VVER-440/V-270	1980	2026	OAO TVEL[b]	2026
China	Tianwan 1	VVER-1000/V-428	2006	2046	OAO TVEL	2023[e]
	Tianwan 2	VVER-1000/V-428	2007	2047	China Jianzhong Nuclear Fuel Company, Ltd. (CNNC)	2047[e]
India	Kudankulam 1	VVER-1000/V-412	2013	2073	OAO TVEL	2073[f]
	Kudankulam 2	VVER-1000/V-412	2016	2076	OAO TVEL	2076[f]
Iran	Bushehr 1	VVER-1000/V-446	2011	2071	OAO TVEL	2021
Ukraine	Rivne 1	VVER-440/V-213	1980	2030	OAO TVEL	2030[g]
	Rivne 2	VVER-440/V-213	1981	2031	OAO TVEL	2030[g]
	Rivne 3	VVER-1000/V-320	1986	2016[a]	OAO TVEL	2030[g]
	Rivne 4	VVER-1000/V-320	2004	2034	OAO TVEL	2030[g]
	Khmelnitsky 1	VVER-1000/V-320	1987	2017[a]	OAO TVEL	2030[g]
	Khmelnitsky 2	VVER-1000/V-320	2004	2034[a]	OAO TVEL	2030[g]
	South Ukraine 1	VVER-1000/V-302	1982	2023	Westinghouse EC LLC	2020[g]
	South Ukraine 2	VVER-1000/V-338	1985	2025	Westinghouse EC LLC	2020[g]
	South Ukraine 3	VVER-1000/V-320	1989	2019	Westinghouse EC LLC	2020[g]
	Zaporizhzhya 1	VVER-1000/V-320	1984	2015[a,i]	OAO TVEL	2030[g]
	Zaporizhzhya 2	VVER-1000/V-320	1985	2016[a,i]	OAO TVEL	2030[g]
	Zaporizhzhya 3	VVER-1000/V-320	1986	2016[a]	OAO TVEL	2030[g]
	Zaporizhzhya 4	VVER-1000/V-320	1987	2017	OAO TVEL	2030[g]
	Zaporizhzhya 5	VVER-1000/V-320	1989	2019	OAO TVEL	2030[g]
	Zaporizhzhya 6	VVER-1000/V-320	1995	2025	OAO TVEL	2030[g]

Note: Research and school reactors not included. 'End of life-cycle' figures depict the situation as of August 2016.
Source: [19]; public sources; company information; compiled by T. Vlček.
[a] Reactors where procedures for extending the life-cycle are in progress.
[b] All fuel has been supplied by OAO TVEL, but this incurred significant foreign debt. As a result, the plant has been operated by a subsidiary of the Russian ZAO INTER RAO UES since 2003. Profits from the sale of electricity generated by the NPP have gone to pay off those debts ever since.
[c] The Loviisa NPP signed a contract with OAO TVEL in 2007 after 1999–2007 period, when 50% of the fuel was supplied by BNFL.
[d] The Paks NPP signed a contract with OAO TVEL in 1999 and the contract is valid for the lifetime of the reactors, including new service life extensions.
[e] In 2010, OAO TVEL and China National Nuclear Corporation signed a contract for nuclear fuel deliveries of Russian TVS-2M fuel for Tianwan 1 (to begin in 2014, with fuel for six reloads made at the Novosibirsk plant in Russia). TVS-2M fuel for the second unit will be made in China at Yibin using Russian technology and zirconium components.
[f] Under a cooperation framework with the Indian Department of Atomic Energy, OAO TVEL supplies nuclear fuel for Kudankulam NPP Units 1 and 2 under a life-cycle contract.

[g] Ukraine's State Concern Nuclear Fuel sells natural uranium to JSC IUEC (International Uranium Enrichment Centre) in Russia for enrichment, while OAO TVEL fabricates fuel assemblies and supplies them to DP NNEGC Energoatom (National Nuclear Energy Generating Company Energoatom, operator of all nuclear power plants in Ukraine); as the Ukrainian share of IUEC capacity is very low, DP NNEGC Energoatom signed a long-term contract until 2030 with OAO TVEL for all 15 reactors at a substantial discount; Ukraine's diversification efforts led to Westinghouse Electric Company LLC supplying VVER design fuel assemblies for the South Ukraine NPP; after the Russian annexation of Crimea, the contract with Westinghouse was extended until 2020.

[h] In March 2016, Dukovany NPP Unit 1 was licensed for continued operation subject to ongoing reporting.

[i] A draft decision of the State Nuclear Regulatory Inspectorate of Ukraine for lifetime extensions of Zaporizhzhya NPP Unit 1 and Unit 2 until 2025 was issued in May and August 2016.

exception of three reactors at the South Ukraine NPP, OAO TVEL is the supplier of nuclear fuel for every reactor of VVER design.

3. Analysis of the supply security of VVER reactors in the EU

Five EU member countries currently possess VVER reactors—Bulgaria, the Czech Republic, Hungary, the Slovak Republic, and Finland. Four use exclusively Russian technology in their nuclear fleet. In Finland, there are two Western reactors in operation (designed by Asea Atom Ab, now Westinghouse Electric Company LLC) at Olkiluoto, in addition to two VVER-440 units at Loviisa. The share of total electrical production in these countries attributable to nuclear is high: 57.5% in the Slovak Republic, 49% in Hungary, 33.9% in Finland, 33.3% in the Czech Republic as of 2014 [17], and 30.7% in Bulgaria as of 2013 [18]. In the European Union as a whole, nuclear power plants are responsible for 26.9% of electricity production [15].

These proportions are considerable, and the importance of nuclear energy is evident. Any interruption of electricity production from nuclear in these countries would have clear negative ramifications for national economies and potentially for national security, as well as for the stability of the European electricity market itself. And electrical production on such a scale would be immensely difficult to supplant from sources elsewhere.

Since the nuclear sector is considered strategic, all NPP operators are state-owned, although not always wholly. According to the public sources of information available for each operator, state ownership shares are as follows: the Republic of Bulgaria (100%) through Bulgarian Energy Holding, the Ministry of Finance of the Czech Republic (69.78%) through ČEZ, a.s., the Office of the Prime Minister of Finland (50.76%) through Fortum Oyj, Privatisation and State Holding Company Ltd. of Hungary (100%) through MVM Group, and the Ministry of the Economy of the Slovak Republic (34%) through Slovenské Elektrárne, a.s [19]. Unexpected outages would thus have a strong negative impact as well on the states' asset values and tax income.

All the nuclear power plants shown in Table 1 are supplied with fuel by OAO TVEL. In fact, OAO TVEL is the supplier for all VVER design reactors worldwide, with the exception of three units at the South Ukraine NPP. The Euratom Supply Agency understands the importance of the security of supply, mandating that there should always be at least two alternative fuel designs from two different suppliers qualified for each reactor [2]. Within the VVER design, one must distinguish among three evolutionary types. Westinghouse Electric Company LLC is the sole alternative supplier for the VVER-440 and the VVER-1000. For the former design, the company has had no operating contract since 2007 and has no license anywhere in the world; for the latter, it has a running contract in Ukraine. There will be a second alternative supplier for the VVER-1000 in the near future, the China National Nuclear Corporation (CNNC), but only for the Chinese market. Finally, there is no alternative supplier for the new VVER-1200 reactors. The situation is described in detail in Table 2.

Westinghouse has its own fuel design for the operation of VVER-1000 reactors. Since it supplies the South Ukraine NPP, and since it has recently been awarded a new contract to deliver Fuel Test Assemblies to the Zaporizhzhya NPP [20], its product may be seen as competitive, with its own—albeit small—market being developed. From the Euratom Supply Agency's perspective, then, there is an alternative fuel design from a different supplier available that is qualified for the VVER-1000 reactor family. When it comes to the VVER-440 family, however, the situation is different. The last time an alternative fuel design was licensed was in 2008 in Hungary, and the lost market share is a considerable obstacle in the way of re-entering the market.

Unlike with other power plants, the price of nuclear fuel accounts for only about 26% of the maintenance and operating budget of NPPs. (With coal, by contrast, the fuel price makes up about 80% of running costs; with gas and oil, more than 90%.) This makes nuclear plants also much less vulnerable to fluctuations in the price of nuclear fuel: a 50% rise in price will only increase electricity-generating costs by roughly 2% [10]. Changes to the fuel price are thus negligible, with no substantial impact on NPP operating costs.

In spite of this, nuclear power plant operators are pushing hard to save money on fuel, since they see it as a cost they can influence [10]. What stands in the way of their accepting a lower price from western suppliers able to beat OAO TVEL—one that they would otherwise be happy to take— is that they are risk-averse. The quality of fuel used in NPP production is critical—the financial implications of reduced plant performance or unplanned outages would quickly outweigh any benefit to be gotten from lower fuel prices. Companies would forfeit income for electricity production and face fines from transmission system operators for outages. It is the sense of caution this provokes that is a major hindrance to the EU's plans to encourage the diversification of nuclear fuel supplies. An additional factor is that many utilities have been doing their own research on optimal fuel performance and implementing the results in fuel designs using standard customer-supplier contracts. They operate with unique fuel types. This is the case, for example, with the Dukovany NPP in the Czech Republic, which started using the new Gd-2Max + fuel type in 2015 (becoming the first OAO TVEL fuel type to use uranium pellets with no central cooling hole), and with the Paks NPP in Hungary, which began using the Gd-2_4.7 fuel type (a Hungarian innovation developed with international cooperation) the same year [21]. The effort and funding invested in this development are unlikely to be compensated by licensing an alternative supplier.

It is here that Euratom makes its entrance. The Euratom funding noted earlier is targeted directly at diversifying the VVER-440 fuel market by qualifying a second supplier for the EU's VVER-440 reactor fleet. The program will chiefly focus on establishing the methods and methodology required to license a VVER-440 fuel design [22]. The EU Community Research and Development Information Service remarked as follows:

"State-of-the-art methods will be verified against an extensive database, including operating experience from several VVER-440 reactors as well as a number of other reactor designs and a wide range of operating conditions. The ability to accurately predict the fuel behaviour will be improved and thereby also the safety margins. New knowledge as well as identification of needs of technology development and improvements will be created in the fields of technologies for mechanical design, thermo-mechanical fuel rod

Table 2
Alternative fabricators of VVER design nuclear units fuel.

Reactor type	Company	Previous experience	Current contracts	Operational experience and limitations
VVER-440	Westinghouse Electric Company LLC[a]	Nova E-3 fuel type for Loviisa NPP Unit 1 (Finland) in 1998–2007	–	The fuel performed in accordance with expectations during operation. BNFL signed a contract with Finnish NPP operator IVO and Hungarian Paks NPP in 1996 for the design, development, licensing and supply of test fuel assemblies for the VVER-440 reactor at Loviisa NPP. At the same time, Hungarian Paks NPP was considering using an alternative supplier for at least one reactor. But no BNFL fuel was ever loaded into Hungarian reactors (likely because of the Hungarian-Russian contract for fuel supply until the end of plant's life-cycle) and BNFL's fuel was licensed in Hungary only until 2008.
VVER-1000	Westinghouse Electric Company LLC	VVANTAGE-6 fuel type for Temelín NPP (Czech Republic) in 2000–2009; VVANTAGE-6 (TVS-W) fuel type for South Ukraine NPP (Ukraine) in 2009–2014; TVS-RW fuel type for South Ukraine NPP since 2015	South Ukraine NPP (Ukraine) until 2020	Temelín NPP experienced massive malfunctions related to the geometric stability of the fuel that eventually led to premature unloading of all of Westinghouse's fuel assemblies despite financial losses, and replacement with TVEL fuel. Problems with fuel recurred in Ukraine to a lesser extent, but still enough to cause a lengthy unscheduled outage at two of the units, which eventually led to technological adjustments to the fuel and consequent relabeling to Robust (TVS-RW).
	China National Nuclear Corporation (CNNC)	–	Tianwan NPP (China) until the end of plant's life-cycle	As part of the 2008 contract with TVEL and CNNC, TVEL sold production technology for TVS-2M fuel for VVER-1000 units. China's Yibin fabrication plant will thus produce the fuel for Tianwan Units 1 and 2 and future Units 3 and 4 (currently under construction) from fourth refuel onwards. The contract is for Tianwan NPP only.
VVER-1200	–	–	–	–

Source: public sources; company information; compiled by T. Vlček.
[a] This contract was operated by British Nuclear Fuels Limited (BNFL), owner of Westinghouse Electric Company LLC between 1999 and 2006. All Westinghouse's nuclear power business was restructured by BNFL, including ABB Group's nuclear power business, bought and merged into Westinghouse in 2000. In 2007, BNFL sold Westinghouse Electric Company LLC to Toshiba Corporation and Toshiba sold shares of the company to minorities (20% to The Shaw Group and 3% to Ishikawajima-Harima Heavy Industries Co. Ltd.; later in 2007 10% to Kazatomprom) leaving the Japanese company with 67% share. When BNFL bought Westinghouse, it was decided that the reload fuel for Loviisa NPP Unit 1 would be assembled via a manufacturing license by Enusa Industrias Avanzadas, S.A. in Spain instead of at Westinghouse's Springfields plant in UK.

design, and safety analysis for VVER fuel. In addition to the technological advances, the project will identify the variation in licensing requirements between the authorities in the different countries. Through such identification, it will become clear that standardization would be beneficial and will foster a dialogue between the authorities/regulatory bodies." [23].

Potentially the biggest single obstacle to fuel market diversification is the license. The utility, not the manufacturer, must apply for the license to operate the reactor with alternative fuel, a process which demands documentation and involves the bureaucracy. Most importantly, it usually requires some operational experience, either with Lead Test Assemblies or with live operation of the fuel to be licensed in another reactor. This is the sticking point. Utilities are generally unwilling to take the risk of reducing their economic performance by operating with Lead Test Assemblies, and this makes them hesitant to invest in the licensing process for alternative supplier. On the other hand, the utilities are keen to have more types of fuel and more suppliers licensed: to do so could give them leverage over the nuclear fuel price and guarantee the security of supply. As Geoffrey Rothwell noted in a 2009 paper [4] another reason for licensing more fuel types and suppliers is that the failure of one reactor may lead to forced shutdowns in others. In a later report, the Euratom Supply Agency came to the same conclusion [2]. The local nuclear safety authorities might *in extremis* not allow the use of fuel assemblies that have suffered serious malfunctions in other reactors elsewhere.

The Euratom grant for the Westinghouse–led consortium should make the licensing process cheaper and easier, and thereby allow utilities to license alternative fuel for their operating reactors. It is aimed at finding synergies by screening the licensing process in the countries where the VVER fleet operates and synthesing a common basis for the process that is consistent across countries. The countries might then share the costs of the licensing basis, as it will be applicable in each.

The company plans to build on the Nova E-3 fuel type originally designed for Loviisa and Paks NPPs, and after necessary modernization to re-enter the VVER-440 fuel market. The Nova E-3 fuel was developed by BNFL in the early 1990s at the request of operators in Finland and Hungary, who wanted an alternative supply at a time of economic uncertainty in Russia [24,35].

With all this said, the connection to the Euratom Supply Agency's understanding of the security of supply, as well as the connection to the Euratom diversification grant is crystal clear. Current diversification pressure is truly rooted in efforts to the enhance supply security of VVER reactors in the EU.

4. Discussion of results

As has been noted, the sole alternative manufacturer of fuel for the VVER-440 and VVER-1000 reactor fleets is Westinghouse Electric Company LLC. Since it is the sole such manufacturer, immediate objections have been raised to the funding Euratom has provided the company. The financing provided amounts to direct support, and given that the point of the funding program is to encourage the diversification of nuclear fuel supplies for VVER reactors, is in obvious contradiction to EU legislation.

Much evidence suggests this criticism is just. Westinghouse is the only company with the technology, experience, and capability to manufacture VVER-type nuclear fuel. But the company is facing trouble on several fronts in the marketplace. We have already noted the issue of entry barriers to the VVER-440 market. But the company has also recently lost market share. After the Fukushima Daiichi nuclear disaster, in which a tsunami resulted in three nuclear meltdowns in Japan in March 2011, Germany declared an ‘Energiewende’. Eight German nuclear power reactors (Biblis A and B, Brunsbüttel, Isar 1, Krümmel, Neckarwestheim 1, Phillipsburg 1, and Unterweser) were permanently shut down, and a ninth reactor followed in June 2015 (Grafenrheinfeld). The remaining eight reactors have pledged to close down between 2017 and 2022. The reactors already shuttered got their fuel from Westinghouse, and their closure meant a 6% loss of market share for the company. (Currently, the company provides nuclear fuel to 145 plants around the globe [25]; the loss of nine reactors in 2011 and 2015 is equal to 6% of its customer base.) Of those still awaiting closure, half are supplied by Westinghouse, which means further loss of market share and revenues in the future.

In general, major changes in the European nuclear market have led to a poor market outlook for Westinghouse Electric Company LLC and the nuclear industry in general. The European Commission's 2011 Stress Tests of European nuclear power plants and the changing perception of nuclear energy by the general public and politicians alike after Fukushima have brought about a deceleration in nuclear development, and future prospects and expectations for nuclear construction are fairly poor.

Complicating matters further is that the Westinghouse-designed Ringhals 3 NPP in Sweden handed OAO-TVEL its first real fuel supply contract for a Western PWR in 2012, using the company's TVS-K fuel, starting with the qualification of fuel manufacture and the supply of four or eight LTAs [26]. This development suggests that OAO-TVEL will enter the European fuel market for Western reactor designs in upcoming years, and this may put pressure on manufacturers' fuel price policies. OAO-TVEL knows Western technology well: since 1994 it has manufactured nuclear fuel assemblies for AREVA SA to fit nuclear reactors in Germany, Switzerland, Sweden, Great Britain, and the Netherlands. The notion that OAO-TVEL would gain expertise manufacturing fuel for Western-designed reactors, thereby making it an alternative supplier of Western-design nuclear fuel in the future, was pointed out as early as 2008 [24].

In this difficult environment, Westinghouse Electric Company LLC needs to enter new markets to stabilize current and future losses. The marketplace for nuclear fuel within the CEE is relatively closed and monopolized. The company was initially well-positioned because of its experience with VVER fuel assemblies, but aside from Ukraine, no one other than OAO TVEL is licensed to provide nuclear fuel in any CEE country. It may therefore seem suspicious that the 2014 application term for the Euratom grant coincided with a statement by the company that it ‘could resume VVER fuel production with an investment of $20 million if allowed back into the market, [while cautioning] that such a plan would take at least two years’ [27].

The suspicion seems further backed by comparison of the markets and business activities of both parent companies. Tables 3 and 4 list Rosatom State Nuclear Energy Corporation's and Westinghouse Electric Company LLC's nuclear units (VVER and AP1000 designs) currently under construction worldwide.

But there are also almost 30 VVER reactors in preparation, planned or proposed worldwide (4 units at Ruppur, Bangladesh; 1 at Hanhikivi, Finland; 2 units at Kudankulam, India; 4 units at Akkuyu, Turkey; 4 units at El Dabaa, Egypt; 2 units at Ostrovets, Belarus; 2 units in Jordan; 2 units at Paks, Hungary; 1 unit at Jaslovské Bohunice, Slovakia; 4 units at Ninh Thuận, Vietnam; 2 units at Bushehr, Iran), some in very advanced phases of pre-construction process, compared to 4–6 AP1000 reactors (1 unit at Kozloduy, Bulgaria; 3 units at Moorside, United Kingdom; possible 2 units at Khmelnitsky, Ukraine). Rosatom State Nuclear Energy Corporation's success in expanding its customer portfolio is well in advance of any other nuclear provider worldwide. AREVA SA's EPR reactor design was selected as an additional Western company for the sake of comparison in Table 5. Moreover, 8 EPR reactors (2 units at Sizewall, United Kingdom; 6 units at Jaitapur, India) are in preparation, planned or proposed worldwide.

Carefully considered, though, the allegations that Westinghouse Electric Company LLC is getting special favours seem somewhat unreasonable. To support the business of a Western nuclear company by removing market barriers to allow entry to the relatively small EU market for VVER-440 reactors—fourteen in operation, two in construction—seems nonsensical from at least two vantage points. First, it normally makes much more sense to support the expansion of research and development programs and industrial capacity and capability to allow businesses to position themselves better for the future. To support the company in such a restricted segment of the Nuclear Fuel Cycle as nuclear fuel licensing would seem an ineffective strategy.

It would be much more logical to support the company if there were strong future business prospects. But, except for Slovakia's Mochovce NPP Units 1 and 2—in potential operation until 2050—and Units 3 and 4 at the same facility, which are currently under construction, worldwide operation of VVER-440 reactors will come to a halt around 2030 (see Table 1). As noted above, many of them use specialized fuel types that require further investment in

Table 4
AP1000 design nuclear units under construction outside the USA.

Country	Reactor	Type	Construction start	Expected start-up
China	Sanmen 1	AP1000	2009	2016
	Sanmen 2	AP1000	2009	2016
	Haiyang 1	AP1000	2009	2016
	Haiyang 2	AP1000	2010	2016

Note: four AP1000 design units, two each at the Vogtle and Virgil C. Summer sites, are under construction in the USA.
Source: public sources; company information; compiled by T. Vlček.

Table 3
VVER-design nuclear units under construction outside the Russian Federation.

Country	Reactor	Type	Construction start	Expected start-up
Belarus	Ostrovets 1	VVER-1200/V-491	2013	2018
	Ostrovets 2	VVER-1200/V-491	2014	2020
China	Tianwan 3	VVER-1000/V-428M	2012	2018
	Tianwan 4	VVER-1000/V-428M	2013	2018
Slovak Republic	Mochovce 3	VVER-440/V-213+	1985, 2008	2017
	Mochovce 4	VVER-440/V-213+	1985, 2008	2018

Note: six VVER design units, two units at Leningrad (VVER-1200), two units at Novovoronezh (VVER-1200), and two units at Rostov (VVER-1000) sites, are under construction in the Russian Federation.
Source: public sources; company information; compiled by T. Vlček.

Table 5
EPR design nuclear units under construction outside France.

Country	Reactor	Type	Construction start	Expected start-up
China	Taishan 1	EPR	2009	2016
	Taishan 2	EPR	2010	2017
Finland	Olkiluoto 3	EPR	2005	2018
United Kingdom	Hinkley Point C 1	EPR	Not set	2025
	Hinkley Point C 2	EPR	Not set	2025

Note: one EPR design unit is under construction in France at Flamanville.
Source: public sources; company information; compiled by T. Vlček.

research and production of any alternative supplier. This ties to the fact that for safety and economic reasons the mere existence of a licensed alternative supplier is unlikely to persuade utilities to switch sources.

Another argument, this time connected to the future of the market and Slovakia, comes from examining current nuclear fuel supply contracts with OAO TVEL (see Table 1). The Dukovany NPP in the Czech Republic, the Loviisa NPP in Finland, and the Paks NPP in Hungary all have lifetime fuel contracts with OAO TVEL for all their VVER-440 units. Only at the Jaslovské Bohunice and Mochovce NPPs in Slovakia do the contracts expire in 2021. There are thus no contractual obstacles to changing suppliers in subsequent years, and the plants will continue in operation well beyond that point: up to 30 years for Mochovce NPP Units 1 and 2; up to 10 years for Jaslovské Bohunice V2 Units 1 and 2; and up to 60 years for Mochovce NPP Units 3 and 4. This prompts the question, is all of the pressure for diversification directed exclusively at the Slovak Republic?

The answer, perhaps surprisingly, is yes. The evidence noted confirms this, and Slovak diversification efforts in recent years provide more ballast for the argument. The Slovak Government has discussed the possibility of cutting dependency on Russian nuclear fuel, and in November 2014, information emerged about a contract for uranium fuel supply being signed with a non-Russian company, but there were no further details. The contract was later specified to be for the supply of enriched uranium only, and this product will still be processed into nuclear fuel elements by OAO TVEL. Supply began in 2015, and unofficial information suggests that the new supplier of enriched uranium is AREVA SA [19,28,29].

Additionally, in 2014 Slovakia began a diversification effort targeting not only uranium enrichment, but also nuclear fuel manufacture, crude oil and natural gas infrastructure, and military equipment based on Resolution 146 of the Committee of the Slovak Republic National Council for Defence and Security [37,30] Slovakia, as stated above, gets 100% of its nuclear fuel elements (except for uranium enrichment) from Russian company, but the country is also fully dependent on Russian crude oil and nearly 100% dependent on Russian natural gas. This is a considerable liability: together, these three sectors comprise 86.1% of Slovak TPES and 66.8% of the country's electricity generation share [19]. There are suggestions that these efforts are tied to EU and US sanctions against the Russian Federation [30,31] and to a possible Slovak fear of Russian retaliation. It is, however, important to note that the EU and US sanctions do not target the Russian nuclear industry, though the energy industry in general is being subjected to sanctions. For example, OAO NK Rosneft, OAO Gazprom Neft, OAO Transneft, OAO Novatek, PAO NK Lukoil, and OAO Surgutneftegaz are under EU or US financial sanctions, or US technology sanctions [32,33]. But the Russian nuclear industry will never come under these sanctions because of the high share of nuclear energy in total electricity production in the EU countries we have been discussing and their dependence upon Russia for nuclear fuel. The US Centrus Energy Corp (created from restructuring of United States Enrichment Corporation, USEC) also closed a long-term contract extending until 2022 for the supply of LEU from Russia's commercial enrichment business, and recently prolonged the contract to 2026 [36]. Any such sanctions, then, would backfire to a considerable extent on EU members and on the US nuclear energy sector.

The nuclear industry also has a kind of self-defence safeguard against political misuse as given in Ref. [19]. Because of the limited number of contracts in the nuclear sector and the revenue implications deriving from each contract, any attempt to use nuclear contracts as leverage over a particular country would cause substantial damage to the contractor's reputation. This mitigates the likelihood that a nuclear contractor would exert political pressure over a sovereign client, since the damage to the contractor's reputation would complicate future business prospects around the world. Rosatom State Nuclear Energy Corporation probably calculates that it cannot afford to be found guilty of abusing a particular project to advance its own political or strategic goals, as this would harm not only its long-term future, but its immediate market capitalization as well, and this would carry over to its nuclear fuel business.

This is also more an interest of the Slovak Government than the utility Slovenské Elektrárne, a.s. proper. Nicola Cotugno, general-director of the Slovak utility articulated the following in a recent interview: “Our business with TVEL has always been very smooth. Slovenské Elektrárne has never experienced any technical problems with the fuel, not even small leakages, which may occur in one out of a thousand fuel assemblies. The quality has been outstanding, and even during this period of tension we have not experienced any delivery disruptions. When the situation was especially tense, we used aerial transport to avoid passing through Ukraine by train.” [34] Persuading the utility could thus be another future obstacle to the Slovak government's diversification efforts.

5. Conclusion

The aim of this paper has been to analyse the reasons that new efforts are being made to diversify the supply of nuclear fuel in the European Union, and to analyse why these efforts have focused strictly on the fabrication and licensing of fuel, as well as whether they might actually positively impact the security of supply in the EU nuclear industry. A concurrent goal has been to explore and discuss the real reasons behind the pressure being felt to diversify.

We found satisfactory answers to all these questions; even better, several interesting outcomes emerged from our answers to them and the discussion of results. We have shown how different and how specialized a high-tech service Fabrication is compared to the other steps in the Front End of the Nuclear Fuel Cycle. We have also highlighted the importance of licensing and talked about why it is important, and we explored what obstacles stand in the way of licensing and what benefits derive from licensing several fuel types and suppliers.

In addition to these findings, we may also conclude:

First: The evidence supports the argument that nuclear fuel diversification efforts by Euratom and the European Commission truly are rooted in an attempt to enhance the supply security of the VVER-440 reactor fleet operating in the EU. There is truly but a single supplier of nuclear fuel for this reactor category—Russia's OAO TVEL, with a monopoly in the market. This means the VVER-440 reactors in the EU fail to fulfil even the rudimentary N-1 logic as regards the fabrication of fuel. Nuclear power plants have come to supply a considerable proportion of the electricity generated in countries where the units operate. Euratom's grant for licensing support in the EU will allow easier diversification by helping tackle one of the key obstacles in the permit process, that of licensing. The real decision, though, will rest with the utilities. They are the ones who license nuclear fuel, not the manufacturers. And since Bulgarian Energy Holding, ČEZ, a.s., Fortum Oyj, and MVM Group all hold nuclear fuel supply contracts with OAO TVEL for the lifetime of their nuclear units, only Slovenské Elektrárne, a.s., the owner of Slovakia's nuclear power plants, can effectively diversify the fuel sources for its VVER-440 reactor fleet once all contractual obstacles vanish after 2021.

Second: Since Westinghouse Electric Company LLC truly is the sole alternative provider of fuel for VVER-440 reactors, the evidence also backs the argument that financial support for the diversification of fuel to VVER reactors in fact constitutes direct support of one private company on the market. But this is not the key reason for Euratom's grant scheme, nor for the European Commission's diversification efforts. It is a mere corollary outcome; Westinghouse is indeed the only alternative supplier of nuclear fuel for this region. Further support for the argument must be gotten by observing near-future development in the market. If the European Commission ceases its intervention once the obstacle that has been blocking entry into a monopolized market has been removed, the entire effort may be seen to have been driven by reasons of supply security. If, on the other hand, the European Commission continues to intervene in the VVER nuclear fuel market, the idea of direct support for a single private company will likely have to be reconsidered, as this would speak to a different outcome than that considered here.

Even though the support Westinghouse Electric Company LLC has received is essentially an attendant result of the European Commission's diversification efforts, it will nevertheless help the company. If we perceive Rosatom State Nuclear Energy Corporation and Westinghouse Electric Company LLC as adversaries, then, we may state that the American company is losing out to the Russian in the nuclear market. By entering a market monopolized by OAO TVEL, Westinghouse may effectively compete in the fuel supply area. And if Westinghouse was able to expand the capability to produce fuel for the VVER-1000 and develop the capability for the future VVER-1200 reactor types, Russia's very success in selling their technology abroad could pose an opportunity for the American company. It could compete with OAO TVEL in producing fuel for these new reactors, opening a new global market for the company.

Third: Finally, we may expect the instalment of Lead Test Assemblies in a VVER-440 reactor in the near future. It may occur either at Ukraine's Rivne NPP, since Westinghouse already has a commercial presence in Ukraine, or at Slovakia's Jaslovské Bohunice and Mochovce NPPs. We may also expect a strong push on the part of Slovakia to diversify, particularly when a new public procurement procedure for nuclear fuel supplies is opened a couple of years from now. The evidence shows that it is diversification in Slovakia that the European Commission is primarily supporting with a €2 million grant for nuclear fuel supply to VVER-440 reactors focused on licensing alternative nuclear fuel supplies for Russian-designed pressurized water reactors operating in the EU. The rationale behind Slovakia's determined, comprehensive diversification efforts in nuclear energy and elsewhere would make a timely subject for future research.

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