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Risk Assessment in Construction Process in Nuclear Sector within the Central and Eastern Europe

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ABSTRACT

This article assesses various risks arising within the process of building, running and decommissioning of nuclear units with the Central and Eastern Europe (CEE) where nuclear power is still perceived as a reliable and widely utilized energy source. The region is specific for its relations with Russia which is a dominant provider of technologies and fuel thanks to former ties between the region and the Soviet Union. The debate on building new nuclear producing units with Russian companies as potential contractors is thus echoing old concerns about the rise of Russian influence and one-sided dependency. The main conclusions are twofold. First, financing is the key issue to be addressed in order to conduct a successful project with current electricity prices undermining any new project not only in the region but also in Europe as a whole. Second, precise formulation of project documentation is crucial to avoid hidden costs, delays and potential disputes with contractors.

Keywords: Central and Eastern Europe, Nuclear Energy, Power Generation, Russian Federation
JEL Classifications: H76, Q38, Q40, Q41, Q49

1. KEY ISSUES SURROUNDING THE CHOICE OF A NUCLEAR POWER OPTION

Nuclear energy has been an important part of the power generating capacities worldwide for many past years and Europe is no exception. Despite several setbacks in recent years (e.g. Fukushima disaster, Germany's nuclear phase-out, unstable price of electricity, etc.; Plumer, 2014) it is still far from being obsolete. On the other hand, the choice of building nuclear units comes at a price. As several European countries have plans to build new units, sometimes also as a way to curb their one-sided energy dependency, it is definitely an issue worth deeper examination.

The choice of nuclear power as an option in the power generation sector is a multi-layered issue and sometimes controversial issue relating to many issues that need to be taken into account. The most immediate question asked by those outside the industry concerns the risk of a major incident. With the Chernobyl, Three Mile Island and most recently Fukushima-Daiichi accidents in mind this risk can of course not be discounted, and must be addressed in safety regulations. However, there are many other more immediate issues that need to be addressed. The capital cost of a nuclear unit is high and must be financed; the operation of a plant is a complex affair and must be managed with regard to output efficiency, cost effectiveness and safety; fuel supplies must be secured; waste disposal and decommission must be solved, etc. Furthermore all this needs to be controlled by an experienced management team, which may not be available in a country new to nuclear industry. We address each of these issues in the following analysis, as each is vital to an understanding of whether nuclear power can provide an effective source of secure electricity supply over the long term. Initial comparison of various energy sources regarding their key features can be found in the Table 1.

2. ISSUES TO BE ADDRESSED IN CONSTRUCTION PROJECTS

2.1. Delays as an Endemic Problem in the Industry

The construction of the nuclear reactor and supporting infrastructure is the primary concern within each project. In general the

Table 1: Considerations on the fuel choices for power generation

Fuel type	Capital cost	Variable cost	Capacity	Speed of connection to network/flexibility	Share of fuel costs (%)	Security of imported supply	Environmental impact
Coal	Low/ Medium	Medium	Constant capacity, a medium degree of regulation capacity	Tens of minutes	50-66	Good - reliant on international coal markets. Some storage issues; required approximately 1 train of coal per day	High carbon emissions
Gas	Low/ Medium	High	Constant capacity, can be well regulated	Tens of seconds up to several minutes	66-75	Imports reliant on pipelines, backed up by LNG. Reliant on infrastructure	Low carbon emissions
Nuclear	High	Low	Constant, a rather low degree of regulation capacity	Hours up to days	20-25 of total costs	20 tons of fuel per year for 1000 MW of capacity. Uranium traded globally	Zero carbon emissions, but waste storage risk
Hydro	Medium	Low	Constant capacity, dependent on the flow, can be well regulated	Tens of seconds	0	Indigenous supply, generally available, but ultimately rainfall dependent	Zero carbon emissions
Wind	High	Low	Varying capacity, cannot be regulated, completely dependent on regulation capacity	Unstable, unreliable and hard to anticipate, but under windy conditions, tens of seconds	0	Wind dependent, unpredictable and intermittent	Zero carbon emissions
Solar PV	High	Low	Varying capacity, cannot be regulated, completely dependent on accumulation capacity	Unstable, unreliable and hard to anticipate. When sun shines, tens of seconds	0	Sun dependent, unpredictable and intermittent	Zero carbon emissions

Source and compilation: Vlcek and Henderson

typically takes 5-7 years, although this can vary with location and specification. Currently in countries such as South Korea and China, typical assembly times range from 4 to 6 years while in European countries construction may take between 6 and 8 years (Nuclear Energy Agency, 2012). However, delays and additional work have tended to be an inevitable part of the process. For example the in-service dates of the pilot project of Westinghouse's AP1000 design at the Vogtle nuclear power plant (NPP) have been moved recently from April 2016 to December 2017 (Unit I) and December 2018 (Unit II), with the additional work adding $650 million to the budget (Patel, 2004). In Russia Rosatom's VVER-1200 design at the Novovoronezh II site has been postponed from the original in-operation date (2012 for Unit I and 2013 for Unit II) to a current estimate of 2014 for Unit I and 2016 for Unit II, and further delays seem inevitable (World Nuclear News, 2012). An even more extreme example is AREVA's pilot EPR design at the Finnish Olkiluoto-3 plant, which has been also postponed several times, with the original in-service date of 2009 now having been moved to the end of 2018. Furthermore, Olkiluoto-3's construction costs were first estimated at 3.2 billion euros, but late in 2012, the CEO of AREVA estimated that the overall cost would end up closer to 8.5 billion Euros (Rosendahl and De Clercq, 2014).

These three examples essentially represent a general theme in the industry basically related to majority, if not all, contractors. Currently, 50 of the 67 reactors under construction in 2014 have met with significant delays, ranging from several months to several years, while the other 17 units are currently in their initial stage of construction, making it difficult to assess whether they are on schedule (Schneider et al., 2014, p.34). Although the reasons for the delays and cost overruns are unique to each project, some of the more generic causes include rising material costs, delays with subcontractors, work accidents, increasing safety requirements and public opposition. It would increasingly appear that these delays are an endemic element in the process of building nuclear units, caused predominantly by the vast complexity of the task.

In contrast, there is no track record and no evidence of any specific delays being motivated by politics. Although it is possible that the prolongation of any construction process could be politically motivated, in the case, for example, when a foreign power might want to disrupt the timing of a project which is crucial for another country's energy economy, our research suggests that this is unlikely to be a primary reason for delays occurring. Given the limited amount of contracts in the nuclear sector and the revenue implications of each one of them, contractors need to proceed very carefully in order the protect their chances of winning future projects. Clearly, any attempt to use a nuclear contract as leverage on a particular country would cause substantial damage to any contractor's reputation, and would make it very unlikely that it would ever get any further contracts. Although there have been some rumours about unusual delays, in particular with reference to Russian projects, we believe that all of the examples offer clear alternative reasons for any problems that occurred.[1] Additionally,

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[1] Examples of these alleged non-standard delays are for instance the construction of the Iranian Bushehr NPP and situation of the Czech Temelin NPP in early 1990s. The Iranian Bushehr NPP built by Russian companies was subject to major delays that prolonged the original construction time to more than three times its original length. It is rumoured that Russians used this opportunity for consolidation and capitalization of their nuclear industry after it was seriously harmed by the collapse of the Soviet Union. Although this may be partially true the major reason for those delays was the vast complexity of this project that was originally built by Germans, then abandoned and damaged during the war between Iran and Iraq (Khlopkov and Lutkova, 2010).

no contractor, including Rosatom, can afford to be to be found to be misusing a particular project to assist the political goals of its domestic government, as it would essentially destroy not only its long term future but also its immediate market capitalization.

A key tactic for any contracting party as it seeks to avoid unforeseen delays or hidden cost increases is to ensure that the procurement procedure and its related documentation is formulated very precisely, leaving no room for further "behind-the-scenes" negotiations. The example of Hungary's Paks NPP can serve as a negative example as the decision to grant the project to the Russians was made by the prime minister and his closest collaborators without any consultations with other interested parties, industry experts or the public at large (Field, 2014). In this situation the state (i.e. the contracting party) lefts itself extremely vulnerable due to a lack of expertise on its side in a complex negotiation, with the lack of transparency only adding to the sense of an improper deal being concluded. In contrast, in the procurement procedure for the Czech Temelin NPP just the documentation specifying the conditions of the project took 3 years to prepare and was created by group of several tens of experts. Ultimately this documentation comprised more than 6,000 pages establishing over 11,000 criteria that needed to be met by any successful bidders. In return each bidder provided the Czech side with documentation exceeding 10,000 pages each (Horacek and Topic, 2012; interview with a Czech official responsible for the process) while the procurement period itself took several years.

However, having excluded political pressure as a reason for delays in construction, it would be wrong to suggest that no political influence takes place in the bidding process. There are a limited amount of power station contracts and nuclear contractors worldwide, and so it is natural that these contractors give each contract opportunity a very high priority. Furthermore it is also not surprising that the governments from the contractors' homeland show significant support for their efforts, displayed in several different forms varying from rhetorical encouragement, visits by state officials, support for partnership-building programs or state guarantees and loan offers at conditions better than a standard financial institution would provide. This is clearly a sensitive part of any negotiation with a foreign government, but in reality is one of the very few times when political influence might be effective, since once the contract is granted and the financing is agreed there is very little room for exerting further pressure as the whole process becomes more technical and operational.

2.2. The Nuclear Option as a Double-Edged Sword

Nuclear power still remains an attractive option thanks to its great potential for power generation. On the other hand, even from the brief analysis of the initial stages of any negotiation it is clear that building a NPP is, without doubt, a risky business. However, this risk is not necessarily connected with actors that are involved in the project or their state of origin, be it the technology supplier or the provider of financing or the operator. What makes it risky for the contracting authority in the first place is the fact that building even a single power generating unit costs a significant amount of money and that the resulting power generating capacity of such a unit usually makes up a large share of the whole electricity mix of the respective country. This applies especially in Central and Eastern Europe (CEE), where even a single nuclear reactor makes a significant contribution to overall power supplied to the grid.[2] At the same time nuclear power is typically a base-load source of electricity and is therefore a vital part of the power generating capacity of every country where it is used, with the CEE countries being no exception. The decision to build or not build nuclear power generating units thus implies a substantial change to any countries' power generating capacity especially when other base-load sources need replacement. Given the rather lengthy construction process and the current uncertainty over electricity prices nuclear energy is clearly a great challenge for CEE countries regardless of the choice of contractor to undertake the project and its country of origin.

2.3. Bulgaria and Hungary as Examples of the Financing Issue

The examples of Bulgaria and Hungary demonstrate that the issue of financing in the nuclear business has proved to be the most pressing concern, as both countries have been facing serious issues raising adequate funds for the construction of new nuclear units.[3] Bulgaria, for its part, has had plans since the 1970 and 1980s to build two new units at the Kozloduy NPP site but the economics of the project have consistently undermined progress. A key feature of this project has been the fact that no state funding or guarantees will be provided for the construction phase, which made it essential to find an investor to finance the plant. Plans have also been made to build other units at the Belene site which was also selected back in the 1970s. These units were later intended to replace the Kozloduy 1-4 units that were shut down during the EU pre-accession period. This project, which was set to utilize the Russian VVER-1000 design, has also had significant financial difficulties and has been offered a Russian loan to support the atomstroyexport-led consortium. However, a succession of Bulgarian governments have refused this offer and a further Russian proposal to take an equity stake in the plant in return for financial and technical support, fearing a security of supply risk from being over-exposed to a Russian contractor. Instead the Bulgarian authorities decided to try and find a European partner, but without success (Bivol, 2010; Commission wants EU, 2010). Indeed, eventually financial concerns followed by a legal dispute between Atomstroyexport and Bulgaria's National Electric Company NEK prompted the Bulgarian government to start considering a brand new solution to the problem (Russia offers Bulgaria, 2011). This involved

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The Czech example relates to the situation when Russian engineers were forced to leave the Temelin NPP project due to political changes following the fall of communist regimes in CEE countries. The hand-over of the project documentation was in this case slower than it should have been. But again, this was rather caused by the financial situation and the fact that Russian companies were losing their position in the FSU economies. Even if the delays were financially motivated it's not clear that politics was also involved, as this would have caused lasting damage to the contractor's reputation.

[2] In Hungary, it is estimated that the new units in the Paks NPP will double the share of electricity generated in nuclear stations up to approximately 80% of the total electricity produced in the country (World Nuclear Association, 2014c).

[3] This applies also to the other post-communist countries in the region.

installing the equipment originally designed for the Belene 1 unit at the site of Kozloduy 7 (Bulgaria to sue Russia, 2011; World Nuclear Association, 2014b), as it was becoming clear that the Belene NPP project was about to be terminated. However, the procurement procedure for new unit at the Kozloduy site eventually led to selection of the Westinghouse AP – 1000 design (Bulgaria picks Westinghouse,2012; World Nuclear Association, 2014b), and this again prompted a lawsuit brought by Atomstroyexport claiming around EUR 1 billion in damages for the aborted Belene project. Overall, though, the problems that both Bulgarian projects have faced highlight the importance of financing and to lesser extent a complicated perception of Russian involvement in nuclear projects in CEE countries. The fact that the technical features of each design were treated as rather second-tier priority,[4] indicates that it was the potential stake of Russian state-owned companies and the form of financing which has been of most concern.

Hungary provides a similar example. A project involving two Russian design VVER-1000 units has been planned since the 1980s but the project was cancelled after the fall of the communist regime, due to both economic issues and a decrease in energy demand. A later initiative to build the new units in the mid-1990s also stalled, but the project has been revived due to the need to replace obsolete power generating plants and supplement them with 6000 MWe of new capacity by 2030 (World Nuclear Association, 2014c). Although the Hungarian parliament has agreed to expand the capacity, it has been clear from the very beginning that the project could not be carried out without the financial support of an external project partner. Furthermore it also became evident that the Russian VVER-1000 units were the preferred option and a deal was eventually cemented in January 2014. However, it is the conditions of the deal and the way they were negotiated that have raised concerns about Hungarian dependency on Russia. Not only was Hungary granted a loan of EUR 10 billion to co-finance the project by the Russian Federation,[5] but the deal was negotiated by the Hungarian prime minister and was granted to Rosatom without any official procurement procedure caused great outrage among the opposition parties in the parliament (Nolan, 2014). The specific terms of the loan have been called into question amid fears that Hungary could face significant losses in future.[6] Many also fear that the deal will tie Hungary to the Russian Federation for many years to come, as part of an apparent foreign policy turn to the East conducted under the Prime Minister Viktor Orban's administration in recent years (Buckley and Eddy, 2014; "Atment a parlamenten," 2014). Furthermore, Hungary may also be accused of breaching EU rules by omitting to carry out a proper procurement procedure[7]. Overall, though, the crux of the issue remains the financing of the deal, with the loan being offered by Russia being a crucial element in the choice of reactor. Other issues have also undermined the credibility of the project, but essentially the need to raise funds to pay for construction have been at the heart of the decision-making process.

2.4. Critical Role of Electricity Prices in Nuclear Power Economy

The economics of a nuclear power project are therefore driven by the high initial cost of construction. These can run into many billions of Euros but are offset to an extent by the low variable costs of actually running a nuclear plant, thanks to the abundance of fuel on a global basis and the relative durability of the technology being used. As a result, contractors are attracted to the business as it can be very profitable once the fixed initial costs have been repaid. However, the key issue is therefore ensuring that electricity prices are high enough to allow this to happen on a reasonable timescale, and certainly before the life-cycle of the plant comes to an end.

Unfortunately, this is becoming increasingly difficult due to electricity price uncertainty[8] in majority of European countries. This situation thus increases the uncertainty surrounding the commercial viability of nuclear projects. Two contrasting examples can be seen in the Czech Republic and the United Kingdom. In the Czech Republic the procurement procedure for building two new units at the Temelin NPP stalled due to the uncertain economics of the project resulting from the unwillingness of the government to provide electricity price guarantees (Bauerova, 2014; CEZ zrusil tendr, 2014). In contrast a British project at Hinkley Point NPP is moving ahead as the European Commission has approved a UK government decision to provide a guaranteed feed-in tariff for the project at levels well above the current market price[9]. This outcome came as a great surprise as it appeared to contradict EU competition rules, and although it has been called the most controversial decision in the last 15 years it may become a "game changer" for the industry (Renssen, 2014).

2.5. Alternative Models for Nuclear Plant Construction and Operation

The need for financial support and investment can also affect the operating model chosen for the construction and running of a nuclear project, with potential security of supply implications.

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[4] The technology issue was addressed rather with connection to the already installed Russian equipment at the Belene site and its possible utilization at the Kozloduj site.

[5] The Russian side was allegedly the only one prepared to offer financing to support the project. The loan equals 80% of the total costs of the project ("A Brief Summary, n.d.").

[6] Some sources claim that one of the catches within the agreement is the price of particular construction work that is to be defined by the contractor. Also the payment conditions are allegedly very strict and may lead to severe financial losses for the Hungary since the interest rates are quite high (around 4% at the beginning and rising progressively during the contract duration) and the penalties for overdue payments are also harsh ("A Brief Summary, n.d.").

[7] Similar concerns have also been expressed by domestic Bulgarian critics of the contract awarded to Westinghouse to build an AP-1000 unit at Kozloduy ("Russia, Hungary sign," 2014).

[8] The price of electricity for end users is composed of two parts; the electricity bought at the market (the unregulated component of electricity end prices); and the regulated components. These components are regulated by national regulator (these are for example VAT, contribution to renewable sources, support services, regulating electricity, grid development etc.). They are subject to specific national regulation and are derived from the domestic electricity sector situation. The end price of electricity may thus vary substantially even among the neighboring EU countries; and it is a matter of fact the market price of electricity is currently very low and uncertain for the future.

[9] Including guaranteed electricity price and state credit provided to the contractor (Renssen, 2014).

There are a number of models that can be used to establish the main contractor[10] for a project, but in general it is likely to be a state or state-owned company; or a state or state-owned company in partnership with a third party; or a (future) consumer; or a contractor. Naturally, this is not an exhaustive list of the possible models but rather a list of basic principles that may appear in different forms, varying in terms of respective shares, participants, and governance structure.

In terms of a state or state-owned company as contractor, very few, if any, countries and/or companies are able to build and particularly to finance the whole process of constructing a NPP. Considering the economic situation in the CEE region after the 2008 economic crisis, where most of the countries find themselves struggling with a deficient state budget and slow economic growth, finding a strategic partner for financing the enormous task of building a NPP is effectively essential.

As a result, the most typical scheme under which nuclear units are usually built is the state or state-owned company in partnership with a third party. This model is used in the majority of cases and can appear in many different forms, with differences in the share of the financing partner and the source of his revenues.[11] As stated above, the enormous price of every NPP construction project per se makes it extremely attractive for the contractors given the limited amount of such projects worldwide. However, given the financial burden of such projects, the contractors are often forced to financially participate in the schemes or to secure financing from another source since the governments simply cannot afford such an enterprise by themselves. Quite understandably in such situations the contractors try to decrease the risk of financial loss or at least to secure their position in terms of future revenues by using various financing schemes, sometimes supported by their home governments. This can then lead to a certain dependency being created between nation building the power plant and the nation providing the loan, with possible future political consequences.

In most cases the state would naturally want to keep a majority stake in the project since, as stated above, the nuclear sector and NPPs are perceived as a strategic asset usually accounting for a great deal of any country's power generating capacity.[12] Furthermore the state often serves as a guarantor for loans taken by the state-owned company or other partners, as banks would otherwise be reluctant to lend the vast amounts of capital needed over an extended period.

As far as the (future) consumer option is concerned, the most typical example is the Olkiluoto-3 NPP in Finland, where major electricity consumers are in charge of the project. It is financed by Teollisuuden Voima Oy, a consortium of shareholders operating in the industrial and electricity generation sectors. In this case the security of supply risk for the country involved is mitigated to an extent by the involvement of key companies in its economy in the construction and operation of the new plant.

In the fourth model it is the contractor himself who oversees and pays for the construction, and a new type of contract has recently been introduced to the nuclear industry in this regard. It is called "Build-Own-Operate" (BOO) or "Build-Own-Operate-Transfer." The Russian company Rosatom presents this type of contract as an "approach to support newcomers" that are not experienced in the field to help them enter the nuclear industry (Sokolov, 2013). This logic has been applied for the first time in the case of the Turkish NPP Akkuyu, which will be the country's first nuclear unit World Nuclear News (2010b). In the BOO model it is the contractor who not only builds but also runs the facility and simultaneously is the principal owner. However, it is clear that this model reverses the usual security of supply logic under which the strategically important nuclear power unit should be kept in the host state's hands. Under the terms of a BOO contract the state enjoys a beneficial financing arrangement in exchange for just hosting the facility on its soil.[13]

An obvious potential threat caused by this scheme is that a state could become a "hostage" of the contractor running the facility, although again it seems very unlikely that any contractor would ever do this as future potential clients would clearly be put off. This would seem particularly relevant as the Russians claim the BOO scheme is a way to attract newcomers to the nuclear club, and this strategy would surely fail if there was any sense of a "contractor trap" (Sokolov, 2013).

2.6. Importance of the İnsurance Process

One final point to be made about the initial part of the nuclear process is that financing is generally only secured if the project has adequate insurance, which has become more important since the recent Fukushima disaster. Often insurance companies can specify particular financing and technical requirements before they provide cover, and this can offer another opportunity for contractor influence to ensure that its own plans are incorporated in any policy. Again, though, complicity in such "behind the scenes" activity is unlikely to foster long term business opportunities for any of the participants, and can be countered by the appointment by the state or an independent oversight body which can monitor all the parts of the bidding and procurement processes. Nevertheless it does underline once again that the initial part of the contracting process is vital in terms of establishing the foundation for future reliability of supply and the financing of projects. It is clear that offers of financial support can be more important than the technical specification of nuclear reactors in the decision making process, and also that the need for financing can influence the model of partnership that is used to run the overall project. All of the outcomes have their own risks and benefits, with the BOO model appearing to offer the most influence to an outside contractor in return for full delegation of the financing, construction and

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[10] In this sense the contractor means the actor responsible for the project realization.

[11] Of course in such a case the contract must be interesting for a bidder, that is there must be a defined prognosis for the profitability of the project. If electricity prices in the market are low then profitability this can be typically achieved through electricity price guarantees. See above.

[12] The logic underlying this assumption is that once the financing is secured the facility remains controlled by the state.

[13] Under the "Build-Own-Operate-Transfer" variant the facility is transferred to the state after certain, previously agreed, period of time.

operating responsibilities. However, these issues are not unique to any one operator, and need to be considered as general problems to be addressed by any government considering a new nuclear plant investment.

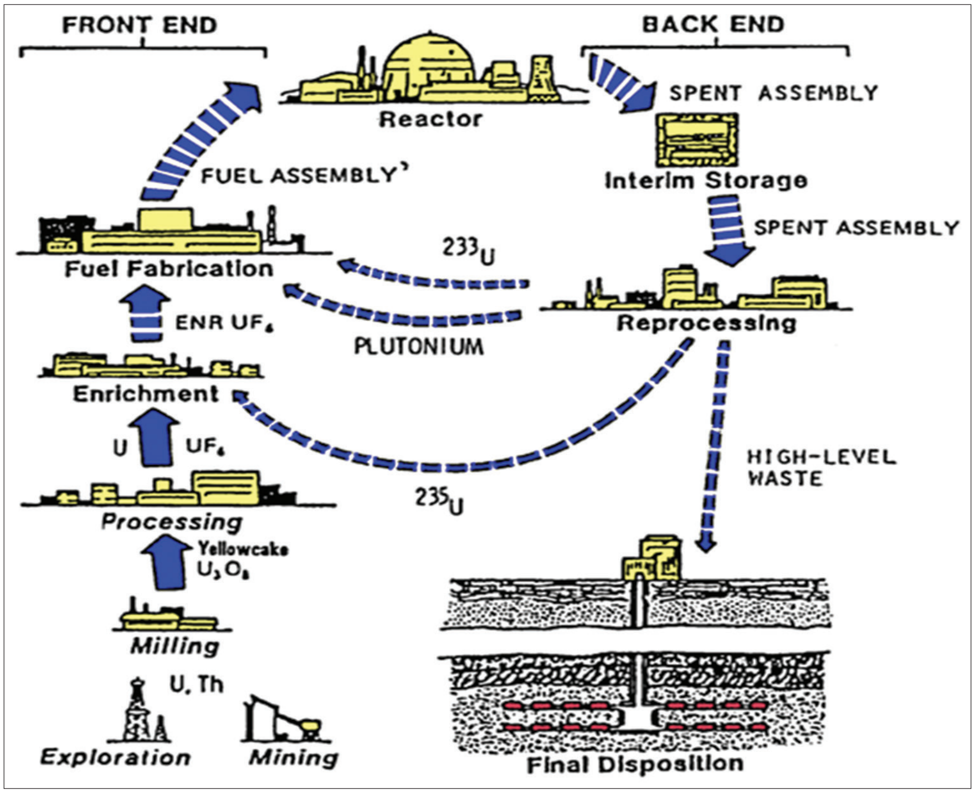
3. ASSESSMENT OF OTHER RİSKS WİTHİN THE NUCLEAR FUEL CYCLE

Once a nuclear power station has been constructed the risk profile moves to the operational cycle of the plant. The nuclear fuel cycle (Figure 1) can then be divided into three parts, the Front End, the Service Period and the Back End. These three parts cover the entire uranium cycle from exploration and mining to the final disposition of used nuclear fuel. The Front End of the cycle consists of exploration, mining, milling, processing, enrichment, fuel fabrication and fuel assembly. The Service Period is basically the use of the fuel in the nuclear reactor, and the Back End consists of storing, reprocessing and final disposition of the used fuel.

The nuclear fuel cycles differ slightly according to the technology used in the power plant,[14] but it is generally very similar across different technologies. In this report we are focusing on the examples of the Bulgarian and Hungarian nuclear industries and so we will analyze the cycle for the Russian-developed VVER design.[15] The VVER design is the most widespread type of nuclear reactor in use in CEE and CIS[16] nuclear countries, thanks mainly to the historical ties between the region and Russia rather than due to any major benefits of the design. The historical links do bring one key advantage though, namely that many countries have domestic experts in the technology who bring experience in maintaining and running the reactors, as well as having a developed industrial base connected to supplying the plants. Both Hungary and Bulgaria's NPPs are equipped with the VVER models; the VVER-440 series in Hungary and the evolutionary VVER-1000 series in Bulgaria.

The key inputs to all NPPs are the uranium fuel rods which are central to the nuclear fission reaction. Natural uranium is relatively abundant and evenly spread in the earth's crust, its occurrence being about 500 times higher than gold (Osicka et al., 2012, p.284). However, the concentration of uranium in uranium ore is low, varying from 0.03% up to 20% or more. In this natural form it is unusable and transporting it in this state would be unnecessarily expensive, so it is first milled and processed at plants located close to the mines. First, the uranium is cleaned from the so-called uranium tailings (waste rock). The refined ore is then ground into mash. Chemical leaching with sulphuric acid is the

Figure 1: The nuclear fuel cycle



Source: McFadden, 2009

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[14] For example, Pressurized Heavy Water reactors, such as the Canadian CANDU (CANada Deuterium Uranium) reactor use natural (non-enriched) uranium as fuel. The heavy water absorbs less neutrons, and so this design is able to both moderate the nuclear reaction and secure criticality without enriched fuel.

[15] VVER means water cooled, water moderated energy reactor (or water – water energy reactor), in Russian водо-водяной энергетический реактор (Vodo-Vodyanoi Energetichesky Reaktor). In Western Europe and elsewhere in the world it is also known as Pressurized Water Reactor.

[16] Central and Eastern Europe countries and The Commonwealth of Independent States.

next step, and this processes the matter into uranium concentrate (U_3O_8, yellow cake).[17]

The Front End continues with conversion of the uranium concentrate to a gaseous form, because enrichment using existing technology can be done only in this state. Enrichment is required because the natural concentration of the uranium isotope ^{235}U, which has to date almost exclusively been used for fission reactions and use in the nuclear industry, is not high enough for most reactors. As a result the uranium concentrate is converted into uranium hexafluoride, which is normally in a gaseous state, after which it can receive a greater concentration of the isotope ^{235}U, taking it up to the 3.6-4.4% level that is used in most VVER designs.[18]

Enrichment is followed by reconversion and the process of fabrication, where fuel gets processed into pellets (0.8 cm in diameter and 1 cm in height) which are then fitted into fuel rods, a specific number of which are then placed into fuel assemblies in fuel assembly facilities. These assemblies are then directly inserted into the active zone of a reactor.

4. THE URANIUM MARKET AN ASSESSMENT

4.1. Uranium Supply and Prices

The uranium market is a globally competitive commodity market, as producers not only compete with each other worldwide, but also with supplies from military sources (decommissioned military stocks and inventories of enriched and natural uranium) (Osicka et al., 2012, p.322). World annual uranium requirements amounted to 61,600 tU in 2012, declining slightly from 2011 due to the closure of several nuclear units after the Fukushima disaster (OECD NEA and IAEA, 2014, p.77; OECD NEA and IAEA, 2012, p.75). Historically much of the required uranium has come from secondary supplies (ex-military sources), but recently the balance has shifted back towards primary supplies from mining. In 2012, world uranium production (58,816 tU) provided about 95% of world reactor requirements (OECD NEA and IAEA, 2014, p.107), with the output coming from 21 different countries (Table 2) (OECD NEA and IAEA, 2014, p.59).

Table 2: Uranium production in selected countries (tones U)

Country	2010	2012
Australia	5900	7009
Brazil	148	326
Canada	9775	8998
China	1350	1450
Kazakhstan	17803	20981
Malawi	681	1103
Namibia	4503	4653
Niger	4197	4822
Russian Federation	3563	2862
South Africa	582	467
Ukraine	837	1012

Source: OECD NEA and IAEA, 2014, p. 60

Table 3 shows the price of uranium has been somewhat volatile over the past decade, rising to a peak in 2007 and again in 2011 but then going into a decline since then. The unexpected peak in 2007 (the so called "uranium bubble") occurred due to a combination of factors, including flooding in the world's largest undeveloped high-quality uranium deposit in Saskatchewan (the Cigar Lake mine); expectations around possible high demand connected to the Chinese and Indian nuclear programs; and investor concerns about a uranium shortage. The economic crisis of 2008/09 then caused a general decline in commodity prices, including uranium, but the latter recovered in the second half of 2010 on news that China was active in the long-term market, stimulating speculative activity on perceptions of a tightening supply-demand balance. However, the Fukushima Daiichi accident in early 2011 then precipitated a rapid decline in price that has continued more gradually through to the end of 2013 as reactors were shut down in Germany and gradually laid-up in Japan as a new nuclear safety regime was established (OECD NEA and IAEA, 2014, p.121). In terms of the outlook for prices, historically around 30% of supply has come from high-enriched uranium formerly used in nuclear weapons, but as the key driver of this supply, the Megatons to Megawatts program, expired in December 2013, it appears likely that the market price of uranium may recover towards previous levels as supply becomes somewhat more constrained.[19] Furthermore demand may also start to recover as Japan's nuclear plants are gradually brought back online.

4.2. Securing Uranium Supply

The operator of a power plant has basically two options available to secure the fuel for his nuclear station. He can choose to interact with the participants, or even to actively participate, in some or all of the elements of the Front End segment step by step as there are world competitive markets for every part of the chain (mining and processing, enrichment, fuel fabrication and fuel assembly). In other words, it is possible to purchase raw uranium, have it enriched and turned into fuel before assembling it into fuel rods on an individual basis. Indeed, one of the easiest ways to cut fuel expenditures is to build a fuel assembly facility in the home country, as it is a relatively unsophisticated process in which fuel pellets are assembled into fuel rods and fuel assemblies. This particularly makes sense when a country has a number of reactors,[20] and by constructing a domestic facility one can easily lower the dependency on outside sources of fuel (although of course the raw material (zirconium rods etc.) would still be purchased from the world market). Alternatively the plant operator can buy the final product from market participants that offer fully assembled fuel rods, and Hungary (where demand for uranium was 430 tons in

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[17] The remainder of the ore, containing most of the radioactivity and nearly all the rock material, becomes tailings, which are placed in engineered facilities near the mine (often in a mined out pit). Tailings need to be isolated from the environment because they contain long-lived radioactive materials in low concentrations and may also contain toxic materials such as heavy metals. However, the total quantity of radioactive elements is less than in the original ore, and their collective radioactivity will be much shorter-lived (World Nuclear Association, 2014a).

[18] From the point of mining through to enrichment, the volume of exploitable uranium rapidly declines. During the enrichment process at the level of approximately 4% 235U, the volume of material decreases eight to eight and a half times.

[19] However, many analysts have indicated that the price is difficult to predict as many transactions are not public.

[20] For example, this facility was recommended in the Czech Republic should the tender for the new two blocks at Temelin site realize. The total number of reactors in operation would be then 8.

Table 3: NYMEX uranium futures price of uranium concentrate (U_3O_8)

2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
21.16	22.71	34.17	46.30	82.67	165.35	171.96	110.23	93.70	158.73	114.64	97.01	62.28

Values as of January end close price. Data indicated in USD per kilogram. Source: Uranium Miner; calculation by Vlcek

2012 (0.7% of global demand) and Bulgaria (310 tons, 0.5%) opt for this route (OECD NEA and IAEA, 2014, p.78).

While this dependence could create a security of supply issue, it is easily possible to store fuel for many years without it degrading, although very few companies do this as there has been little incentive to hoard such an expensive product for long in a market where prices are very competitive. As a result the demand for storage space is low, and operators of power plants usually only store fuel for one fuel campaign[21] or for 1-year.

The markets for conversion and reconversion of uranium and for enrichment are also relatively competitive, with a number of players active in both markets as can be seen from the following Tables 4-6. There are also a number of companies who fabricate the final fuel rods, again creating reasonable levels of competition.

Table 4: World primary conversion capacity

Company	Nameplate capacity (tU as UF6)	Approximate capacity utilization 2013 (%)
Cameco, Port Hope, Ont, Canada	12,500	70
Cameco, Springfields, UK	6000	83
JSC Enrichment and Conversion Co (Atomenergoprom), Irkutsk and Seversk, Russia	25,000*	55
Comurhex (Areva), Malvesi (UF_4) and Tricastin (UF_6), France	15,000	70
Converdyn, Metropolis, USA	15,000	70
CNNC, Lanzhou, China	3650?	unknown
IPEN, Brazil	40	70
World Total	c. 77,000 nameplate	

*Operating capacity estimated at 15,000 tU/year. Source: World Nuclear Association, 2014a

Although there are many market participants in every segment of the Front End process, it should nevertheless be highlighted that the dominant producer of final fuel rods for the VVER design is Russian company TVEL. The VVER type fuel assemblies are hexagonal, while the Western reactors use square-shaped fuel assemblies, and although the VVER type fuel can be produced by Western companies, existing Russian experience and facilities are much more competitive in terms of price. AREVA, Westinghouse[22] or other companies[23] could supply a consumer with VVER design fuel assemblies, but they would almost certainly be more expensive than Russian-produced fuel.[24] For example, Westinghouse says it could undertake VVER fuel rod production with an investment of $20 million if customer demand was high enough, but cautioned that such a plan would take at least 2 years (Lenoir, 2014). Indeed the problem of alternative supply is a clear "chicken and egg" issue. Western suppliers could offer hexagonal fuel rods if demand was present, but demand will only be present at a competitive price, which western suppliers cannot offer until they have invested in the equipment which requires a higher price to justify its construction. Perversely TVEL is able to manufacture nuclear fuel assemblies also for Western type reactors, leading to the conclusion that market principles do work in the nuclear fuel business, but that customers may have to pay a higher price is they want to secure diversity of supply for VVER design NPPs, where Russian company TVEL currently holds an almost exclusive position. The issue is currently being addressed at an EU level, as the European Commission quite recently offered a research grant of EUR 2 million for safety analyses, tests and studies required for the licensing of hexagonal fuel rods other than those produced by TVEL ("Kdo nahradi ruske," 2014). Clearly this will support diversification of nuclear fuel supplies, although it might be regarded as anti-competitive given the benefit it offers Westinghouse and AREVA over TVEL, but it does demonstrate that political will is able to affect a seemingly unchangeable situation.

5. SERVICE PERIOD AND BACK END OF THE NUCLEAR FUEL CYCLE

Once the fuel has been procured and inserted into the nuclear reactor the service period of the process can begin. The pressurized water reactors (PWR) (Figure 2) used in Hungary

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[21] The fuel campaign is the overall time the fuel is used in the reactor. The campaigns vary from three to six years according to technology used and many other aspects, which mean the fuel is used for three to six years until it is no longer usable in the reactor. Also, the fuel is changed continuously during the fuel campaign, i.e. 1/3 (to 1/6 accordingly) of the fuel assemblies in the reactor´s active zone is changed every year.

[22] The Czech Republic experience: The long-term and permanent fuel supplier for the Dukovany NPP is the Russian company TVEL. From 2002, when the plant was launched, to the end of 2009, fuel for the Temelin NPP was supplied by the American company Westinghouse Electric Company, LLC. Very well known is the affair of the fuel rods deflections in the active zone of reactor at that time, because Western nuclear reactors have square-shaped fuel assemblies, while the Russian ones are hexagonal. Hexagonal assemblies for Temelin were initially provided by Westinghouse Electric Company, LLC and caused fuel rods torsion, which resulted in forced operational interruption, limited production and inability to produce electricity to its full capacity. Westinghouse´s experience with VVER design fuel assemblies were short, they started providing this product in 1997. That is why technological issues occurred. In 2010, a selection process for a new supplier took place, which was won by the Russian TVEL by submitting a financially unbeatable offer. TVEL will be until 2020, therefore, the exclusive fuel supplier for both Czech nuclear power plants (Vlcek and Cernoch, 2013, p.134-135).

[23] For example, since 2010 is part of the nuclear fuel for Chinese VVER design reactors produced by Chinese China National Nuclear Corporation. (World Nuclear News, 2010a).

[24] Westinghouse for example supplies VVER design fuel assemblies to Ukraine. Although the price of the contract was not published, the logic is obvious. The Ukrainian political decision was clearly to diversify the supply of nuclear fuel even at higher costs. And although there are similar problems with the diversified fuel as in the Czech Republic's case, after the Russian annexation of Crimea the contract with Westinghouse was extended until 2020 (World Nuclear Association, 2014d). This is clearly an evidence of political decision.

Table 5: World enrichment capacity - operational and planned (thousand SWU/year)

Country	Company and plant	2013	2015	2020
France	Areva, Georges Besse I and II	5500	7000	8200
Germany-Netherlands-UK	Urenco: Gronau, Germanu; Almelo, Netherlands; Capenhurst, UK	14,200	14,200	15,700
Japan	JNFL, Rokkaasho	75 (1050 mid 2014)	1050	1500
USA	USEC, Paducah and Piketon	0*	3800?	3800
USA	Urenco, New Mexico	3500	5700	5700
USA	Areva, Idaho Falls	0	1500	3300?
USA	Global Laser Enrichment	0	1000?	3000?
Russia	Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	26,000	30,000	37,000
China	CNNC, Hanzhun and Lanzhou	2200	3000	8000
Other	Various	75	500	1000?
	Total SWU/year approximately	51,550	65,900	87,200

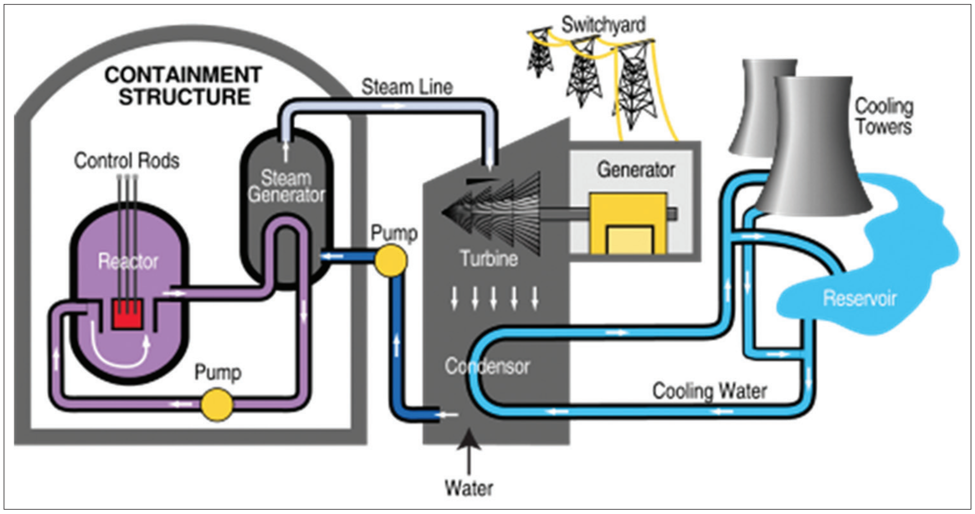
*Diffusion, closed mid-2013. Source: World Nuclear Association, 2014a

Table 6: World LWR fuel fabrication capacity (t/year)

Country	Fabricator	Location	Conversion	Pelletizing	Rod/assembly
Brazil	INB	Resende	160	160	240
China	CNNC	Yibin	400	400	450
		Baotou	200	200	200
France	AREVA NP-FBFC	Romans	1800	1400	1400
Germany	AREVA NP-ANF	Lingen	800	650	650
India	DAE Nuclear Fuel Complex	Hyderabad	48	48	48
Japan	NFI (PWR)	Kumatori	0	360	284
	NFI (BWR)	Tokai-Mura	0	250	250
	Mitsubishi Nuclear Fuel	Tokai-Mura	450	440	440
	Global NF-J	Kurihama	0	750	750
Kazakhstan	Ulba	Ust Kamenogorsk	2000	2000	0
Korea	KNFC	Daejeon	700	700	500
Russia	TVEL-MSZ*	Elektrostal	1450	1200	1200
	TVEL-NCCP	Novosibirsk	250	200	400
Spain	ENUSA	Juzbado	0	500	500
Sweden	Westinghouse AB	Västeras	600	600	600
UK	Westinghouse**	Springfields	950	600	860
USA	AREVA Inc.	Richland	1200	1200	1200
	Global NF-A	Wilmington	1200	1000	1000
	Westinghouse	Columbia	1500	1500	1500
Total			13,908	14,618	12,972

*Includes approxmately 220 tHM for RBMK reactors, **Includes approxmately 200 tHM for AGR reactors. PWR: Pressurized water reactors. Source: World Nuclear Association, 2014a

Figure 2: Pressurized water reactors



Source: Tennessee Valley Authority

and Bulgaria are cooled and moderated using light water and the crucial technical specification of this type of reactor is that the water in the primary circle (inside the containment structure) must never boil. Beyond this the principle of electricity production is generally very easy and does not differ in a nuclear station from other conventional power plants. The high concentration of free neutrons in the enriched uranium fuel secures criticality in the reactor (i.e. the chain reaction continues without human influence) and the fission of heavy elements (Uranium^{235}U in this case) in the primary circle produces heat (along with fission products and ionizing radiation). This heat is used in the steam generator in the secondary circle, where high pressure and high temperature steam is created and rotates the turbine, which means that heat energy is transformed into mechanical energy. The turbine is on the same shaft as the generator (the whole device is thus called a turbo generator), where an electromagnetic field is generated due to the rotation of the turbine, and electricity is induced. There is also a cooling circle, where used wet steam coming from the turbine is cooled in the condenser. The steam is transformed into water by the flow of the cooling water from the cooling cycle. The cooled water is then pumped by circulation pumps to the steam generators and the process repeats. The water in the cooling process used to cool the steam is directed to the massive conical cooling towers, where the airflow cools the water that drops down to a pool under the cooling tower and is pumped back to the condenser again. The effectiveness of the cooling tower is limited, though, and as a result a lot of water vaporizes into the atmosphere, meaning that adequate water sources must be located near the facility as water must be regularly added to the cooling cycle.

Within this process, the nuclear reaction is obviously vital and control of it is a core skill which can lead to dependency if a country does not have experienced domestic operators. This dependency could be particularly acute if the BOO model is adopted and no domestic employees are used on-site, but a clear strategy for any country developing a nuclear facility must be to ensure a transfer of knowledge and experience to domestic employees in order to gradually reduce the risk of an operator threatening to undermining the operations of a plant. As discussed before, this is rather unlikely if any operator wishes to have a future in the industry, but is nevertheless a risk that needs to be considered, particularly if unique technology is being used. Nevertheless, from an operational perspective it should be noted that the "nuclear part" of the NPP covers only about 10% of the operation, while the rest relates to the use of water and steam and is not a particularly sophisticated technology. All conventional power plants operate basically in the same way except for the raw material input (for coal fired power plant heat is obtained by coal combustion; for PWR by fission of heavy nuclei etc.). All repairs and maintenance, but also the design and construction of different machinery and technology sets can be and usually is delivered by a range of companies around the world, and can also be produced domestically. As a result, although some specific expertise is required in the active part of the nuclear cycle, it is possible that domestic companies and/or foreign contractors can provide the majority of the services required at a NPP.

At the end of its useful life spent fuel contains approximately a quarter of the original value of the key isotope^{235}U, which means that it remains enriched at a level of 1%. Spent fuel consists of more than 96% uranium dioxide (UO_2) and other new ingredients that have emerged in the fission reaction, including plutonium oxide (approximately 1%) and other compounds (3%), meaning that the majority of fission products are radioactive isotopes (Laciok et al., 2000, p.190; Otcenasek, 2005, p.536). This means 97% of the spent fuel is a potentially reusable material, although it is not always treated as such. As a result there are two possible conclusions to the nuclear cycle. When the fuel is not reprocessed and is disposed after use, it is called the "open" or "once-through" nuclear fuel cycle. Alternatively if the fuel is reprocessed, the nuclear fuel cycle is referred to as "closed."

Not many countries decide to reprocess fuel as it is a technically challenging, expensive and consumes a lot of energy in its own right. Only countries with significant demand (such as France, Russia and the UK) find it worthwhile, although of course changes in technology could change this outlook over the next few decades. Also the reprocessing process is not a never-ending option and can only be done 2-3 times until ultimately the used fuel needs to be disposed of. Current global recycling capacity is 5,370 tons annually, which is only around 8.7% of the global uranium demand (World Nuclear Association, 2014a).

The vast majorities of used nuclear fuel rods are not reprocessed, however, and go through the open cycle. After removal from the reactor, three phases of fuel deposition follow. In the first phase, fuel cassettes are actively cooled in a pool next to a reactor. After at least 5 years, they are moved into dry containers and then passively cooled in interim storage facilities. These interim facilities are built with a capacity to last for several decades, and at least for a period exceeding the lifespan of the power plant itself. The second phase covers safe transport to the location of final waste deposition. The third phase, deposition, is the final operation, and the depository needs impenetrable protection shields (Marek, 2007, p.4).

Constructing a deep geological repository is a very complicated process which requires detailed data about the location of the store. In terms of its radioactivity, spent fuel becomes safe at least 300 years after its removal from a reactor, and this is therefore the period for which a government must be confident that any selected repository can function without difficulty. However, this storage process, although carrying its own risks, does not really create a security of supply problem for a country as it is usually managed by the home nation, unless the contract specifies otherwise.[25] In the latter case a country could find itself dependent on another state which hosts nuclear waste storage facilities, and this could become more of an issue in future as the disposal of used rods becomes prevalent. In a domestic context, though, the key issues are generally to do with protection of the site in order to prevent any chance of theft, which could lead to the stored residue being used to create some form of weapon or explosive device. These risks are generally low thanks to strict security measures imposed by respective national nuclear safety authorities, the Non-Proliferation Treaty and regulations established by the International Atomic Energy Agency, but nevertheless must be acknowledged and addressed by countries using nuclear energy.

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[25] Currently, this is for example a part of the contract between Russian Federation and Hungary (Digges, 2014). But the so-called Commercial Nuclear Fuel Leasing might become an interesting future´s option as it might very positively relate with non-proliferation efforts and spent fuel management.

6. CONCLUSIONS

Nuclear power still plays an important role in European energy mixes and will probably continue to do so in foreseeable future as several European countries plan to build-up their capacity by building new units. It is, of course, not without its own problems, with perceptions of safety issues being high among them following the accident at Fukushima. From a security of supply perspective, nuclear energy can provide a regular source of base-load domestic energy, although certain dependency issues to need to be recognized. Most of these occur in the initial stages of development, when the high capital costs of building a reactor can lead to deals being struck with contractors that leave countries exposed to possible political risk. This can particularly be the case when BOO contracts are signed, when a country effectively hands over its nuclear plant to an outside operator, but any level of financial dependence on loans from an outside government creates a future risk.

Furthermore, the history of nuclear plant construction demonstrates a litany of delays and cost overruns, which can be very problematic for any country that has committed a large share of its future energy mix to one source. Our analysis suggests that there is very little likelihood of these delays being politically motivated, but nevertheless they do represent a security of supply risk that must be anticipated as almost inevitable. Once a plant has been completed the risks reduce sharply, as the market for uranium is a global one with active price competition, and the provision of fuel rods is also competitive. There is a risk that plant operators try to build unique features into their reactors in order to create bargaining power from their intellectual property, with the hexagonal shape of the fuel rods in VVER reactors being one example of this. However, not only is this specific issue being addressed by the EU, but in reality any dependence can be mitigated by increased fuel storage or by consumers encouraging alternative suppliers to invest in production capacity. There will of course be a cost to this strategy, but the price of security of supply is one that needs to be addressed across all fuels in the European energy mix, not just nuclear power. However, as things stand in the nuclear sector the present balance of market and regulatory forces would appear to be functioning adequately from the perspective of energy security.

Importantly, it is also vital for countries that adopt nuclear energy to establish a core group of domestic staff who understand the industry and its key processes, in order to protect against over-reliance on a specific contractor. This has been one argument in favor of the use of Russian VVER reactors in CEE countries, but it is equally valid if other forms of power plant were to be considered. Having said this, our analysis suggests that there is little security of supply risk in the service period, as any contractor who was seen to be heavily influenced by political considerations would soon find itself with no future contracts. Of course in extremis this argument would not necessarily prevent short term disruptions in electricity output, but this can be addressed through greater interconnection between EU grids that can provide both security of supply and export opportunities.

As a result, it would certainly seem that nuclear power can have a significant role to play in the EU energy mix, despite the antipathy towards it in some countries. It creates no carbon emissions and offers security of supply benefits if certain precautions are taken. Once built it has low variable operating costs, which can ultimately offset the high costs of construction. The market for uranium fuel is competitive, and during the operating phase countries can reduce their dependence on any operator through proactive participation in the process. Overall, as with all the fuels in the energy mix, nuclear power does not provide all the answers to the Trilemma, but it can certainly form one element of the balance that is required to optimize Europe's energy economy.

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