COST/RISK-OPTIMISED FUEL CYCLE DECISION-MAKING IN UNCERTAIN MARKET FUTURES

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Abstract

The various options for the management of spent fuel (SF) from nuclear power reactors is a topic that has been debated from multiple dimensions, being it the socio-political concerns with regard to geological disposal, the technical-economic competitiveness of options such as reprocessing and recycling, as well as from the growing discussion on sustainability and international policy.

Many of the discussions relating to SF-management have historically been rather binomial between, on the one hand, the socio-political concerns on the direct disposal of SF and the proliferation concerns regarding reprocessing, and, on the other hand, the uncertain costs of such disposal facilities versus the economics of reprocessing and recycling schemes. Especially since the 1990s, various intergovernmental and national organisations initiated studies on very advanced SF-management schemes such as separation and transmutation also impacting the progress towards a proper solution-oriented and responsible and above-all timely SF-management.

After some decades of - generally - indecisiveness on SF-management, and with nuclear energy increasingly in the spotlight in the context of sustainable energy mixes, a more solution-oriented and responsible SF-management becomes necessary, if not urgent.

Especially as the uncertain costs and timing for such SF-management become increasingly translated into financial risks for the SF-owners, i.e. utilities. Many discussions on SF-management options were in the past coloured by strategic reflections on U_{nat} availability and pricing, sustainable nuclear fuel cycle options (including Generation-IV systems [1]) and political considerations regarding non-proliferation. Today, there is a growing financial risk presented to utilities which becomes a more compelling trigger towards a decision on various SF-management options.

This paper addresses the changing market context for nuclear energy and particularly how SF-management options are increasingly assessed in such uncertain futures. Cost/risk optimising SF-management schemes are crucially important for utilities not to have SF as such remaining a hurdle for the future of nuclear energy's use.

1. CONTEXT

The deployment of the nuclear power plant park (NPP) worldwide goes with the continuously increasing amount of SF to be managed as pictured in figures 1 and 2 [2]. Figure 1 pictures the time-evolving NPP-park since mid-last century and projecting the NPP-park as currently operating and under construction. Figure 2 shows the resulting SF inventory under a business-as-usual scenario (i.e. without modification of today's fuel cycle option). Under such business-as-usual scenario, a doubling of the world's SF-inventory is to be expected during the next 25 years with potentially even a larger growth of SF-inventories assuming additional new build NPPs as increasingly projected in decarbonising energy mix scenarios.

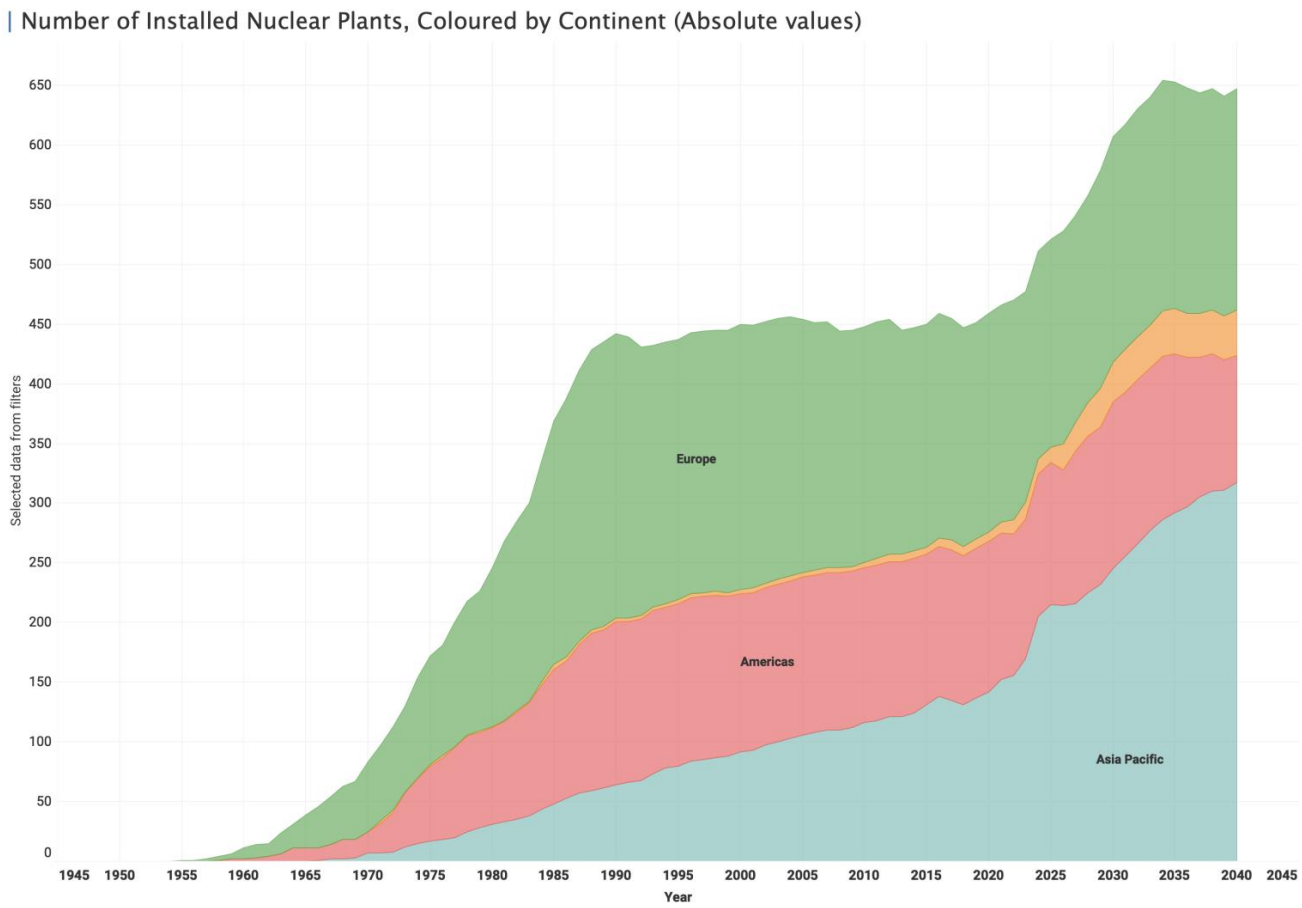


FIG. 1. World's NPP-fleet evolution since mid-last century.

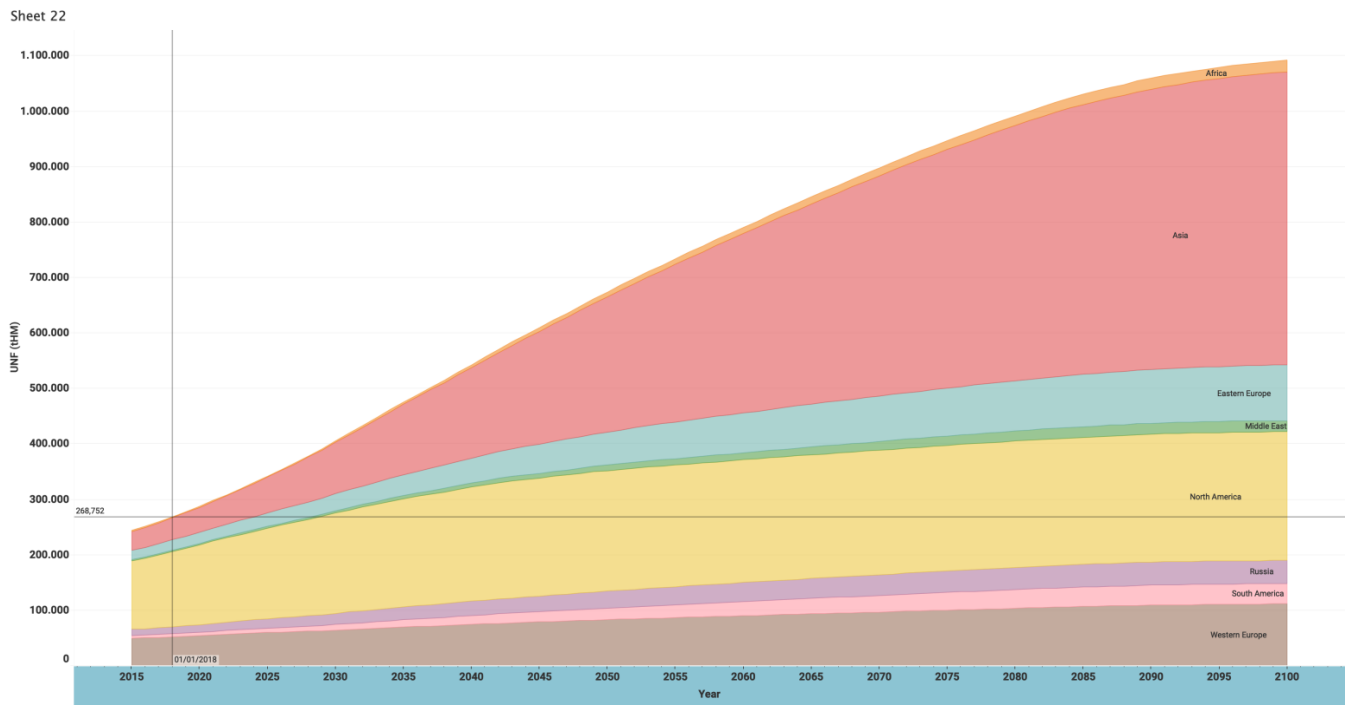


Figure 2. SF-inventory in Business-as-Usual scenario for the current operating and under-construction NPP-fleet.

Awaiting decisions on the final destination of this SF, most of the SF remains interim stored in dry interim storage solutions at reactor sites with the remainder awaiting in at-reactor pools for cooling before being transferred to interim storage. Reprocessing of SF being practiced since the 1970s has resulted into the reduction of the SF-inventory in many countries and for some 30% by now of the SF-inventory worldwide.

The deployment of final geological disposal repositories (GDF), the prime solution for the ultimate management of high-level waste, hasn't yet been following this trend as no GDF for commercial NPP SF is operational today [3]. And even if so, the pace of GDF deployment will probably not match the SF-inventory growth during this century as the first GDF's to become operational foresee accepting conditioned SF from the late 2030s on. Many other countries projecting operational GDFs only from well into the second half of this century or just from the 22nd century on.

The option to reprocess SF and recycle the reprocessed uranium (REPU) and plutonium (Pu) is practiced by some countries since the 1970s and has been industrialised by France, UK, Russia and soon Japan, India and China. The recycled fuel as MOX-fuel and REPU-fuel being a mature fuel option for light water reactors.

So-called 'Generation-IV' nuclear energy systems have been presented during the last 20 years without a real industrial deployment of such systems expected before mid-century. The prime Generation-IV NPP-type being sodium-cooled fast reactor (FR) has been designed and operated by France, UK and Russia and continues so by Russia with, soon to be, also India and China and possibly US. The reprocessing of the LWR-origin SF being anyhow a central requirement by any of these Generation-IV nuclear energy systems and even more so for advanced nuclear energy systems that have been researched for the last decades, e.g. molten salt reactors (MSR) and accelerator-driven systems (ADS).

A central challenge remains how such more advanced nuclear energy systems developed within essentially a governmental-strategic approach may be fitted within an economic driven energy market future? And this especially for economic decision-making which span multiple decennia, and which is typically way beyond a utility's decisional horizon? The answer to these questions relates to financial risk management as the rest of this paper will document.

2. WHAT ARE THE TANGIBLE OPTIONS FOR SF-MANAGEMENT BY MID-CENTURY?

With nuclear energy potentially becoming a substantial contributor to sustainable energy mix futures worldwide, the question arises which SF-management options are truly tangible solutions today and within the coming decades?

While the growing SF-inventory worldwide is pictured in figure 2, figure 3 shows this same SF-inventory from the perspective of age of the growing dry interim stored SF. Ageing interim stored SF is one of the issues to be addressed given the constantly delayed GDF deployment calendar. Interim storage of SF is a safe and economically attractive option awaiting future reprocessing or disposal of the SF though the potential degradation of the, especially dry, interim stored SF may be very problematic if this SF needs to be reconditioned after (very) long periods of interim storage. As much of this interim stored SF still resides on NPP-sites, with possibly already many sites without operational NPP, this reconditioning can be a very substantial cost exposure. Dedicated hot cell construction may be required to recondition into, at least, dual purpose containers for continued interim storage or transport to other storage or reprocessing or disposal facilities.

Figure 3 shows the SF-inventory for only the current operational and under-construction NPPs the amount of interim stored SF indicating the 'frontier' of 60 and 80 years of interim stored SF. There will be a significant amount of SF reaching the 60-years interim storage duration by mid-century with an increasingly important amount of SF that has been stored for more than 80 years from mid-century on. According international studies on ageing dry interim stored spent fuel, significant investments may be expected to recondition this ageing SF especially beyond the 80 years interim storage time as most of this SF may be still residing on shut-down NPP-sites and thus requiring a transfer to centralised interim storage sites or sites allowing further processing of this SF, being it for disposal or for reprocessing.

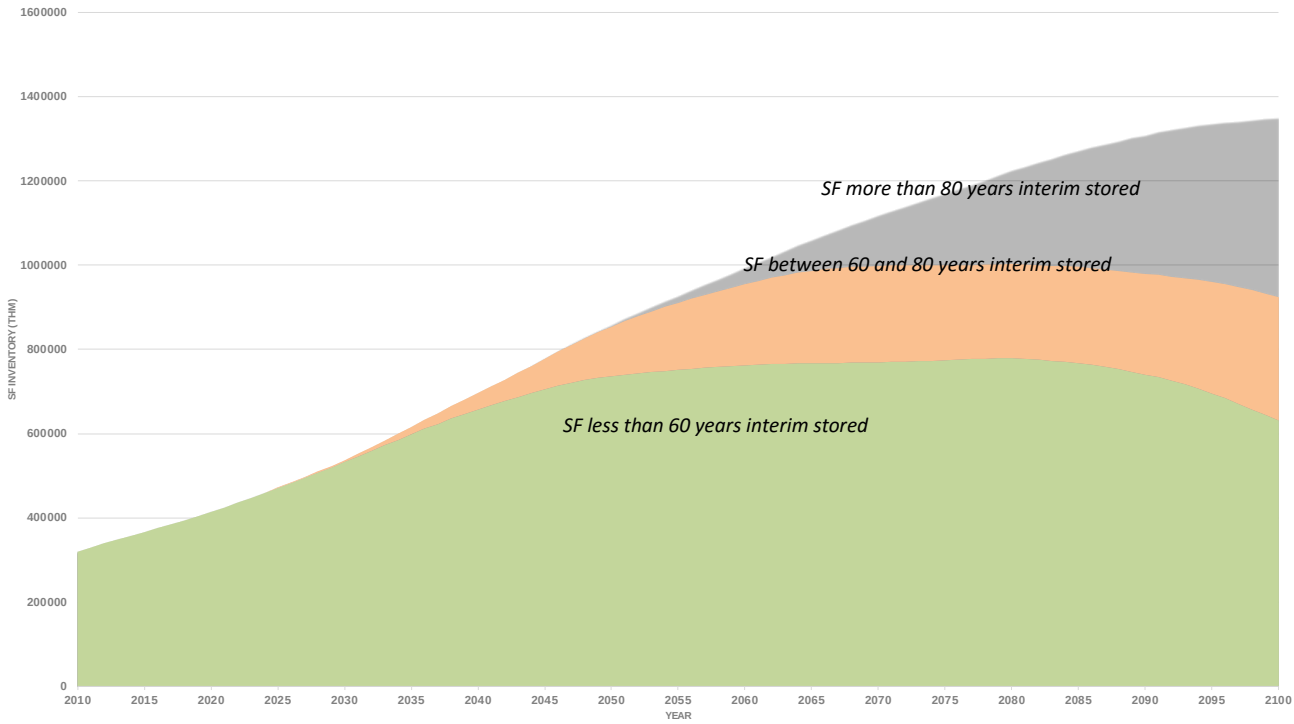


FIG.3. Evolution of SF: Inventory for the foreseeable NPP-fleet with distinction for interim storage duration of SF.

Some countries having such aged SF will not yet have geological disposal sites in operation when an increasing SF-amount reaches the 80-years frontier with thus an increasing technological and above-all financial risk arising.

A variety of other SF-management options are or may become industrially available during the coming decades (see Fig. 4), i.e.

- Reprocessing of UOX-fuels and recycling of uranium and plutonium is an industrial practice in LWRs today with progress being made allowing for additional reprocessing and recycling of the MOX-fuel with multi-recycling of Pu in (TOP)MOX, CORAIL, MIX or REMIX fuels;
- So-called Generation-IV nuclear energy systems essentially using fast reactors (FR) may become industrially available by mid-century with some demonstration plants currently under operation, construction or consideration in Russia, India, China and possibly France and USA later-on;
    - Though, the pace of deployment of such FRs will not match the possible urgency to manage the aged SF-inventory from mid-century on;
    - HTGRs may deploy earlier as part of more sustainable energy mix policies including the use of HTGRs for non-electric applications. Such HTGRs may serve, in parallel, a Pu-burning mission contributing to the SF-management essentially from LWRs;
    - Molten Salt Reactors (MSRs) are currently again subject if increased interest though industrial deployment is not to be expected well before 2050. Even if their deployment would come significantly earlier, the deployment of associated fuel cycle services will not signify a real contribution to LWR's SF-management soon.
- Finally, very advanced options as Accelerator-Driven Systems (ADS) are to be projected well into the second half of this century, if ever required to be realised, in furthering closed nuclear energy systems. Their prime motivation being the transmutation of minor actinides being an option beyond the management of Pu. Such Pu-management remains the prime objective with secondly the management of reprocessed uranium amounts towards a true SF-management before such minor actinide management could further improve waste management.

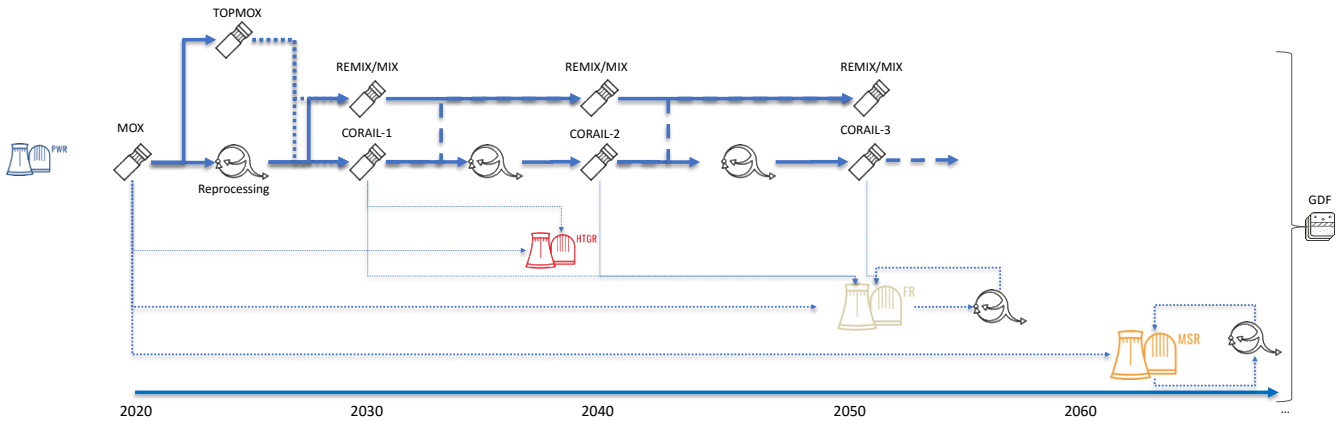


FIG. 4. Projected deployment of nuclear energy systems towards more advances SF-management.

The next two decades will be crucial to demonstrate the proper deployment of ultimate SF management options beyond the continued (dry) interim storage of this SF.

3. THE DRIVERS FOR SF-MANAGEMENT DECISION-MAKING BEING THE COST/RISK EXPOSURE FOR THE VARIOUS STAKEHOLDERS

Past discussions on SF-management and particularly the choice between direct disposal and reprocessing/recycling were mostly governed by two prime considerations:

- Since the early days of nuclear energy use, the availability of deemed scarce natural uranium resources were considered as a clear driver towards closed fuel cycles minimising the amount of Unat to be mined. The introduction of FRs and, as intermediate step, LWR-MOX were considered prime options towards such reduction in Unat-requirements while also reducing the amount of SF;
- Since the early 1990's, given the continuous delay in geological disposal facilities deployment, the 'clean waste, dirty fuel' idea got traction in various countries seeking to minimise the amount and radiotoxicity of resulting waste to be disposed of. The thought being to reduce this amount and radiotoxicity as being considered the prime socio-political objections against nuclear energy. More than 2 decades of significant R&D hasn't yet resulted in progress towards the industrial deployment of such very advanced nuclear energy systems and multiple decades are still required before this may become reality.

During this period, the SF-owner i.e. utilities hands-in-hand with fuel cycle service companies have continued to further evolutionary progress towards the safe and economic management of SF by deployment of interim SF storage solutions. However, such interim SF storage solutions are not ultimate SF management solutions and need, in due time, to transition towards such final solutions.

Today, the situation on SF-management is changing with the cost and financial risks for utilities as SF-owners being the prime drivers in decision-making on SF, e.g.:

- GDF-programmes remain delayed with increasing needs for utilities to provision for ever growing budgetary projections for GDF-programmes;
- Utilities may need to provision as well for extended (dry) interim storage even beyond the operational lifetime of the NPPs;
- In addition to the transfer of the SF from such 'sunk' NPP-sites towards centralised interim storage options awaiting the final destination for the SF;
- Changing regulatory framework may add to a changing context and particularly economics of longer-term interim storage options, and
- Many other influencing factors as there are national programmes, safety/security and safeguards, etc.

The decisional framework is not as such the Unat-availability or any very far future radiological risk but the financial risks associated to uncertain SF-management deployment. Cost/risk-reducing scenarios for SF-management become hereby central in the decision-making on SF as pictured in Fig. 5.

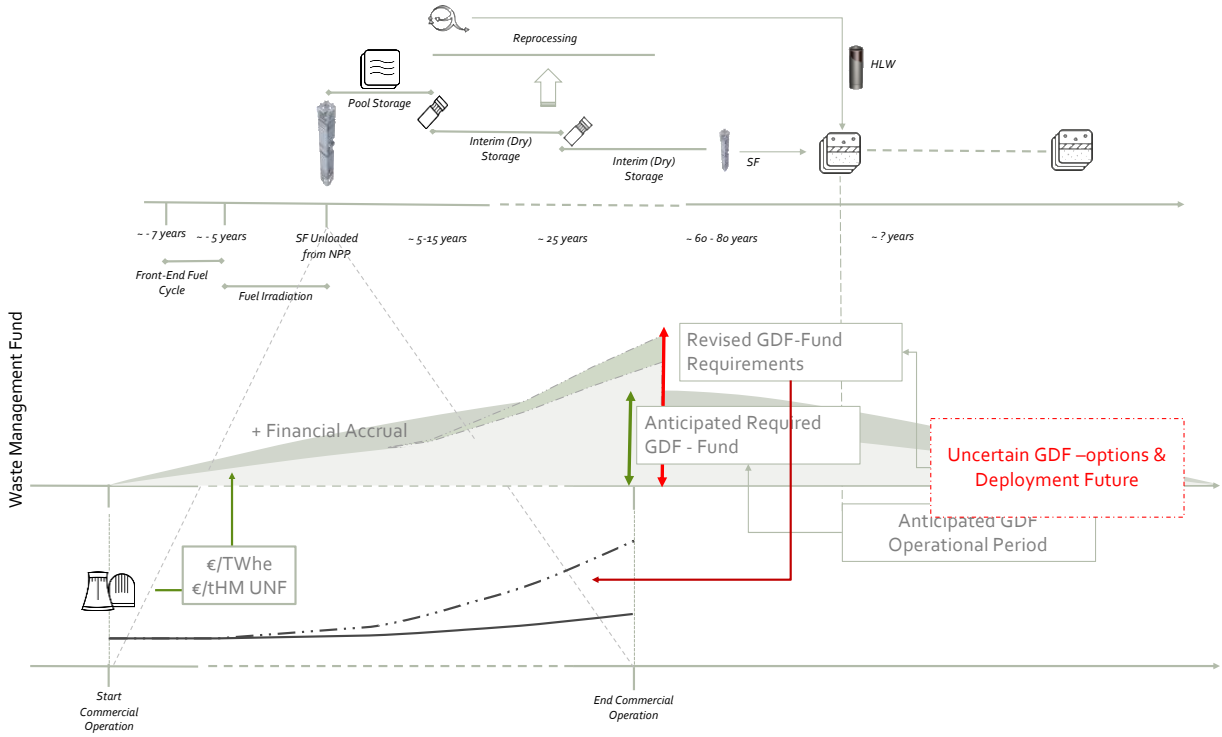


FIG. 5. Financial risks from uncertain SF-management futures.

An increasing number of utilities are being faced with increasing waste provision tariffications due to the uncertain timing and costing of SF-management programmes particularly the GDF-deployment. Especially for utilities with eldering NPP-fleet, i.e. beyond half of the expected lifetime of the NPPs, these higher tariffs for GDF may be impacting the market rating and overall economic competitiveness of the NPPs and NPP-owner.

4. COST/RISK REDUCING SCENARIOS FOR SF-MANAGEMENT

A cost/risk reducing decisional framework is therefore increasingly central in utilities' SF-management decision-making. Such a cost/risk-reducing decisional framework seeks:

- To assess the expected and uncertainty distributions for the future costs related to various SF-management options;
- To define and assess the decisional moments when one may switch between SF-management options;
- To value the decisional flexibility at these (also uncertain) decisional moments;
- Allowing to design decisional scenarios minimising costs and risks over time such that the overall financial cost/risk exposure from SF-management is minimised and matched to the stakeholder/utility's financial risk appetite.

Such a cost/risk reducing decisional framework model (i.e. NROM developed by Nuclear-21 as part of the NESSAT toolbox) on SF-management is demonstrated in what follows on a generic SF-management case where SF-management options of direct disposal, partial recycling with MOX-fuel and closed fuel cycles with FRs was considered for a large and eldering NPP-fleet with significant amount of SF in dry interim storage.

Figure 6 summarises the various decisional options a utility may take starting from the management of spent UOX-fuel. A utility may decide to extend the pool interim storage or the dry interim storage awaiting progress in GDF or may decide to switch to early or delayed reprocessing during the interim storage of SF. The reprocessed materials as reprocessed uranium and plutonium may be recycled once or multi-recycled as (TOP)MOX/CORAIL/REMIX/MIX-fuel.

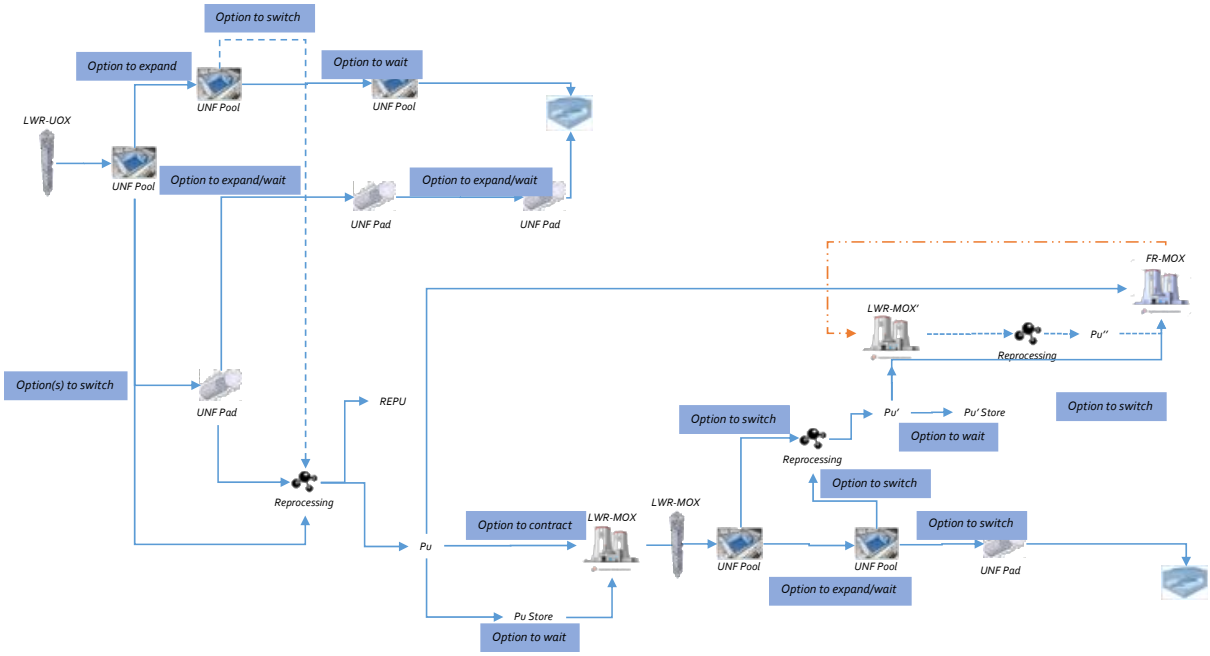


FIG. 6. Schematics of decisional options in SF-management.

Such a more complex decisional framework covering multiple decades as well as many stakeholders having influence on the decisional options and timing of decisions can be analysed with appropriate risk assessment methodologies such as real options analysis.

Applying such methodology, i.e. NROM Nuclear Real Options Model, figure 7 generalises the outcome of such assessment with figures 8 and 9 picturing the results of a real (though generalised) case example.

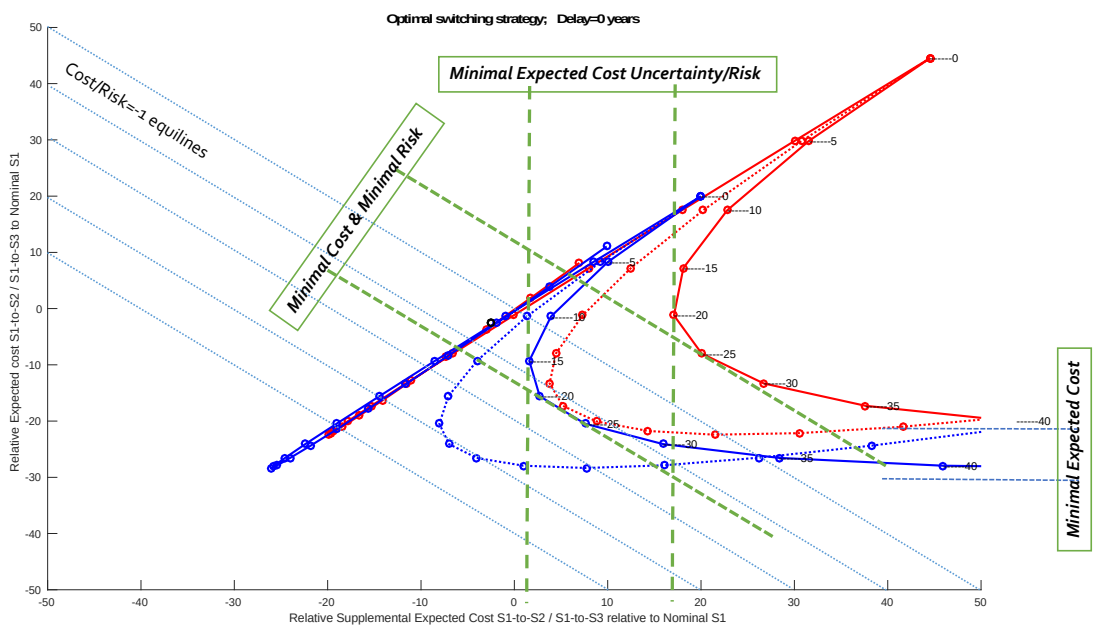


FIG. 7. Cost/risk decisional framework on SF-management comparing direct disposal and partial recycling option.

Figure 7 pictures the relative cost (vertical axis) with the risk for relative additional cost exposure (horizontal axis) for a partial (MOX) recycling scenario compared to the direct disposal route and this for two cases depending on historic/nominal (red) GDF-costing and updated higher (blue) GDF-costing. At time = 0

(upper right), the equivalent NPV-analysis indicates that there's no immediate interest to perform partial recycling though, as time progresses and uncertainties from SF interim storage performance and the need for expensive reconditioning and uncertain GDF timing and costing become more apparent or closer-by, partial recycling may lead to a significant reduction in both cost and risk exposure as shown around t = 15 – 25. This would indicate that the optimal time to execute partial recycling strategy would be some 2 decades into the future for this case as it would then minimise both cost and risk exposure compared to the direct disposal route. The dotted variants of the two curves show the impact from larger uncertainty distributions on the SF interim storage and GDF costing and timing. Such cost/risk-optimised scenarios therefore do not lead to a classis 'yes/no'-decision but values the time towards decision during which changing exposure to uncertainties may develop. This also allows to mitigate such future options and to value the mitigation options matching a stakeholder/utility's cost/risk-appetite and financial performance.

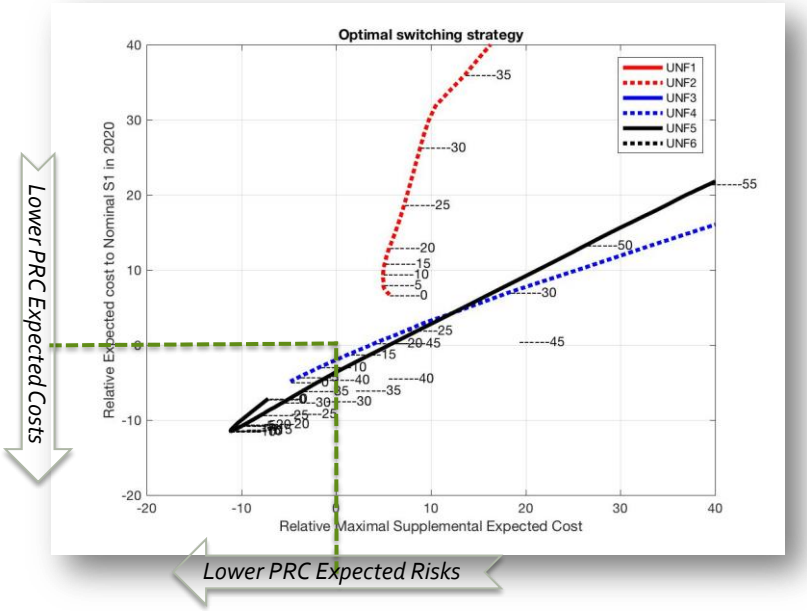
A real case though generalised example in Figs. 8 and 9 shows how such a cost/risk assessment allows to perform portfolio analysis on the amount of SF interim stored to decide when which amount of SF would be ideally switched to other then direct disposal SF-management routes. Figure 8 summarises a portfolio analysis for an amount of SF in a country covering both lower burn-up (BU) longer-cooled SF (UNF2), intermediate BU and dry stored SF (UNF4) up to higher BU pool stored SF (UNF5). Where typical assessments of SF management options address the SF inventory as a whole, this cost/risk portfolio analysis investigates the various SF types and their corresponding cost/risk-exposure allowing to:

- Segment the SF inventory according the cost/risk-exposure and priorisation for SF-management decision-making;
- Minimise the overall cost/risk-exposure over time by optimising the investment and operational costs while optimising the hedging or mitigation of future financial risks;

This example in Fig. 8 indicates that the UNF1 SF wouldn't rank for reprocessing scenarios where the UNF4 would need prompt decision towards reprocessing while the UNF5 SF-inventory remains attractive for reprocessing scenarios until some 35 years into the future though with minimal cost/risk exposure in 15-15 years, i.e. deciding now. The expected cost savings from optimal switching for the different SF-inventories being shown in the lower part of figure 8 indicating a potential expected cost saving of about 25 B$ by 2050 for the considered scenarios of switching from direct disposal towards reprocessing scenarios for some of the SF inventory (UNF4 and UNF5) while other destined for geological disposal (UNF2).

Given that UNF4 represents a significant fraction of the total SF inventory, a sensitivity analysis of decisional factors is presented in Fig. 9, i.e. the relative cost (vertical axis) and relative risk (horizontal axis) for various SF-management routes for the UNF4-category of SF are pictured for:

- S2 = partial LWR-MOX recycling scheme
- S3 = closed fuel cycle scenario with transition of LWR towards FR
- S4 = symbiotic LWR-UOX + LWR-MOX + FR scenario mitigating the development risks for FR with mature technology such as partial recycling using MOX.



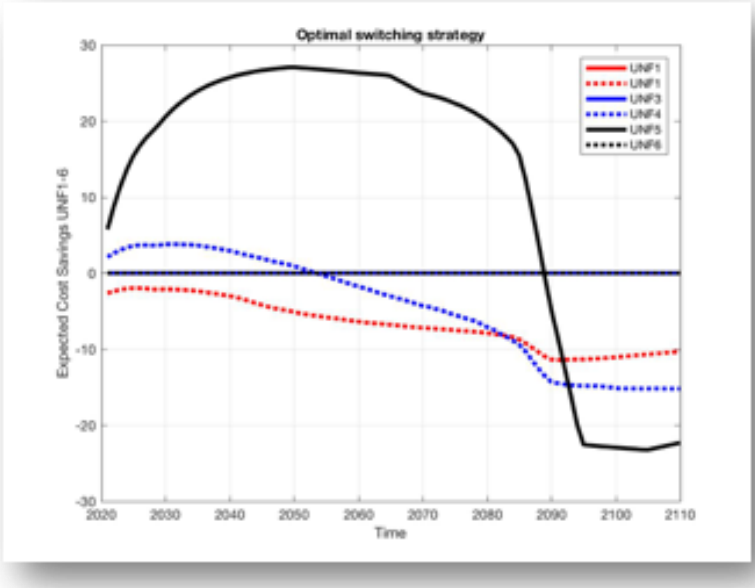


FIG.8. Portfolio analysis of a country's SF inventory.

For various assumptions on GDF-costing and timing and uncertainty, as well as for FR cost/timing uncertainty, the optimal SF-management schemes differ significantly between the SF-management options and the ideal timing of execution of these options. In this real case example, partial recycling options were recommendable by around 2035 where fully closed fuel cycles following LWR-UOX use didn't rank as optimal given the high cost and risks from insufficient FR maturity not compensating yet for the GDF cost/timing uncertainties.

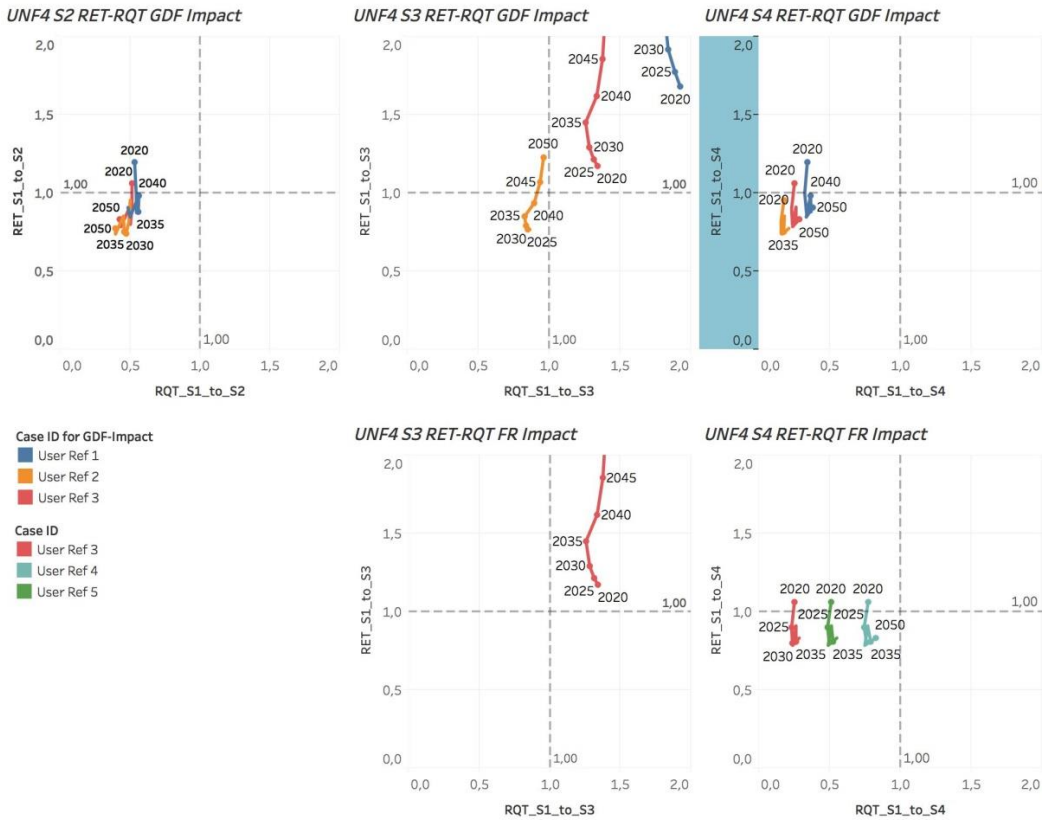


FIG. 9. Generalised though real case application of cost/risk optimised decision-making on SF-management.

5. CONCLUSIONS

Decision-making on SF-management doesn't relate exclusively on strategic reflections on Unat availability and radiological risk reductions in the long term but increasingly on the cost/risk exposure for the SF-owner, i.e. utilities. The decision-making is now geared towards the reduction of cost and financial risks in uncertain energy markets and still uncertain timing and costing for GDF deployment next to uncertainties occurring in long-term interim storage of SF. Other uncertainties relating to the development roadmap for more advanced nuclear energy system options where the past 20 years have shown a rather continuous delay on development and deployment.

Cost/risk-decisioneering methodologies allow to assess the optimal timing when which SF-management options could be executed minimising the cost and risk exposure of utilities to SF-management. Such methodologies allow, among others:

- SF-owners/utilities to assess their cost/risk exposure from SF-management;
- To support decision-making on SF-management and providing a more informative decisional framework on when what option to consider for investment/execution;
- Portfolio management;
- Fuel service company development and commercial offer analysis;
- R&D investment analysis on cost/risk-reduction impact.

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