BACK-END FUEL-CYCLE STRATEGIES IN UNCERTAIN 'GENERATION-IV' FUTURES: EFFECTIVE SCENARIOS TOWARDS SUSTAINABLE NUCLEAR ENERGY FUTURES

L. VAN DEN DURPEL
Nuclear-21
vddurpel@nuclear-21.net

Abstract

With nuclear energy anyhow a necessary part of a sustainable and affordable energy future worldwide, intra-nuclear options to further improve the sustainable performance of nuclear energy have been researched and some developed since the early days of nuclear energy.

These especially address the back-end of the nuclear fuel cycle given the management of spent fuel (SF) being a socio-politically sensitive topic translating into technical-economic challenges for many of the back-end fuel cycle options. Especially in those countries with a large legacy of SF from the past decades of nuclear energy use, these SF-inventories become an increasing challenge. For small(er) nuclear power plant (NPP) parks, such a SF-inventory is even more challenging as the prime option to dispose of this SF in geological disposal facility (GDF) may become overly costly. These situations influence the acceptance of nuclear energy as sustainable energy source while nuclear newcomer countries watch which new SF-management options may become available in due time and well before such challenges may also pose to them.

Though, SF-management does not have to be a 'bottleneck' to nuclear energy use now nor in the future. Various SF-management options have been researched, some developed and some even industrialised. There's been expectations during the last 30 years that so-called "Generation-IV" systems or even more advanced "Generation-X" (partitioning & transmutation (P&T)) systems would become online by around the 2030s and able to resolve many of the challenges of such SF-management. Today, these expectations largely remain prospects for post-2050 with exception for some countries continuously advancing towards such advanced nuclear energy systems.

Though, while the role of nuclear energy and thus its prospects in light of sustainable energy is today high on the agenda and will have to be clarified during the 2020s, a proper solution-oriented and responsible and above-all timely SF-management will need to go along and be realised by mid-century.

This paper overviews which back-end fuel cycle strategies may construe such proper solution-oriented SF-management aligned to nuclear energy's role within the uncertain prospect to evolve soon towards "Generation-IV" systems.

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 till about mid-century. 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. In addition, the regional spread of these SF-inventories being shown in Figure 3.

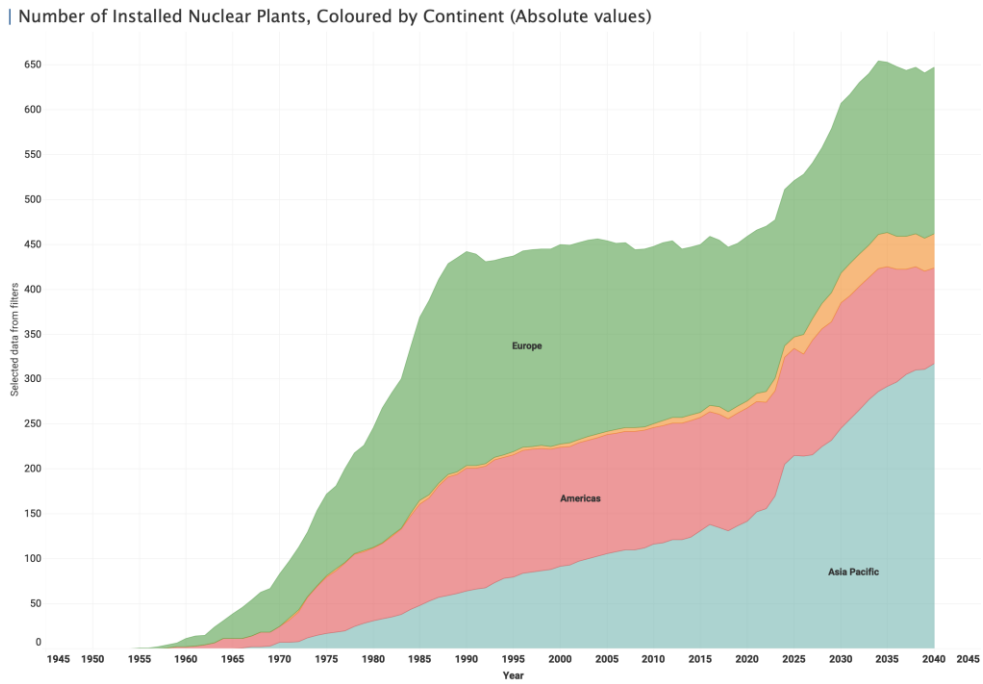

FIG. 1. World's NPP-fleet evolution since mid-last century.

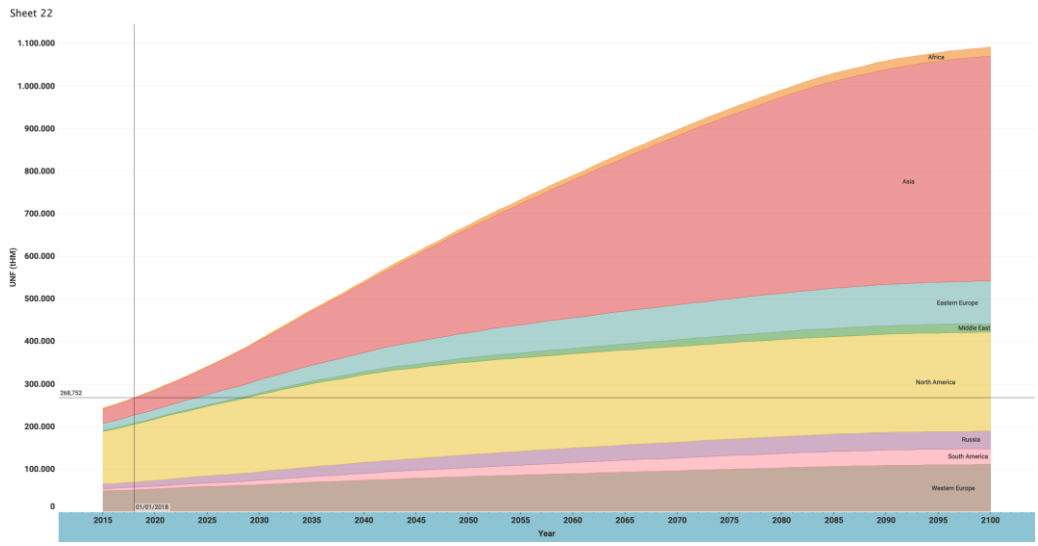

FIG. 2. SF-inventory in Business-as-Usual scenario for the current operating and under-construction NPP-fleet.

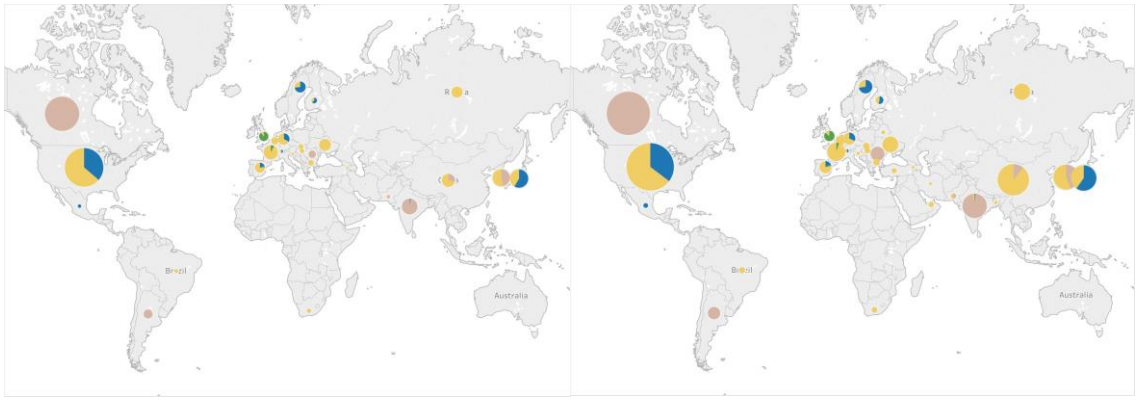

FIG. 3: Regional distribution of SF-inventories today (2019) and by 2040 in Business-as-Usual Scenario [2].

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, at least in most countries. 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).

Figure 4 illustrates today's main nuclear energy system strategies in world regions indicating that most are geared on direct disposal and some nuclear developed and rapidly developing countries within regions transitioning towards mono or even Pu multi-recycling schemes before or by mid-century.

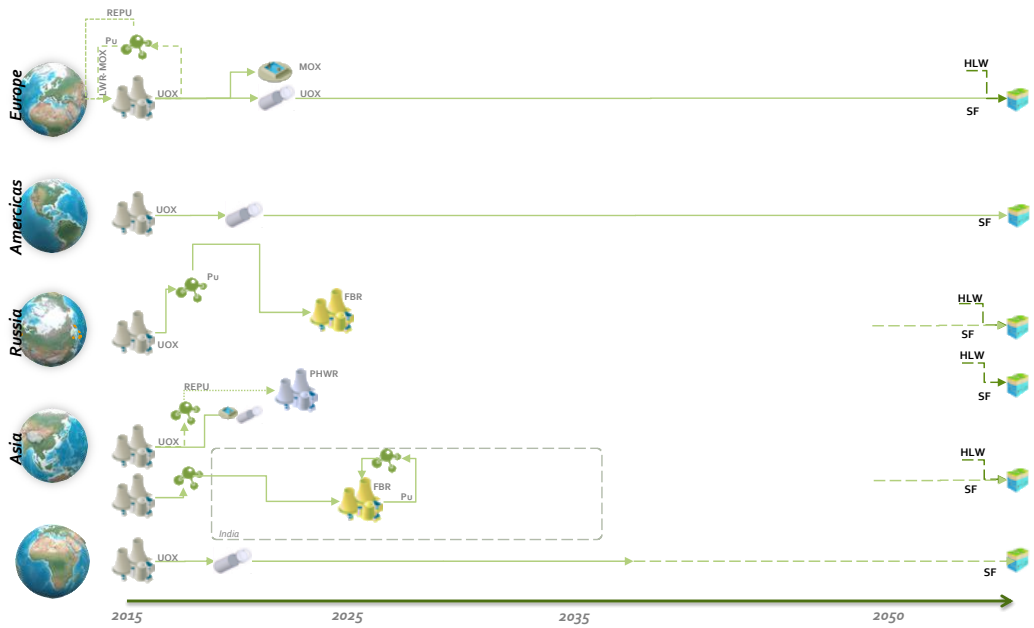

FIG. 4. Today's mainly direct disposal strategy in most regions around the world.

2. THE BASIC NUCLEAR ENERGY SYSTEM OPTIONS

Figure 5 summarises the main strategic objectives, i.e. Stage 1 and 2, and the options one may consider for nuclear energy systems, i.e.:

– Above all, nuclear energy systems have to and remain to deliver safe, secure, economic/affordable and publicly acceptable energy with security of supply and of deliverance. Irrespective SF, nuclear energy is among the most sustainable energy solutions and we may not jeopardise this first stage objective;

– The safe disposal of all nuclear waste with retrievability not to limit future generation's options is the undeniable second stage irrespective if this involves SF, technical waste and/or any waste arising from (SF) fuel cycle operations and NPPs;

Three main strategic options can be considered:

– Today's industrialised option, reprocessed uranium (REPU) and Plutonium (Pu) recycling, providing the Option A of limited recycling with net benefit to the natural resource needs and overall reduction of the waste arising;
– The "Generation-IV" systems mainly focusing the Option B where complete or multi-recycling of, especially, the Pu is envisaged leading to virtually unlimited fuel resource while significantly improving the waste management;
– Option C focusing on the further reduction of the radiotoxicity of all waste as presented by partitioning and transmutation (P&T) systems. Remark that this Option C may be combined with Option B systems.

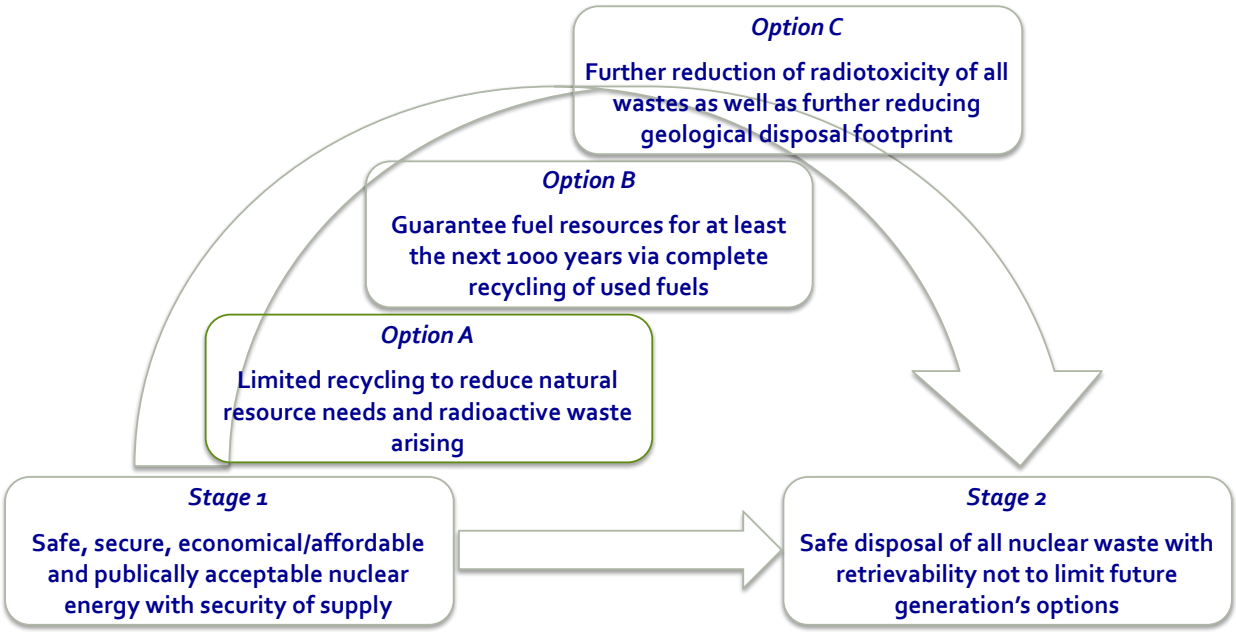

FIG. 5: Main strategic objectives and options for nuclear energy system.

Figure 6 summarising the results of various back-end fuel cycle studies addressing the three options of figure 5. While the REPU and Pu are already well-managed and geared towards improved management before mid-century, the management of the minor actinides can be diverse depending on the nuclear energy system legacy and envisaged future. Americium (Am) hereby the central minor actinide to be managed with regard to GDF footprint as well as long-term radiotoxicity despite hardly apparent in the radiological risk from the envisaged GDF's. The Fission Products (FP) and Activation Products (AP) are embedded in the high-level waste where further separation, before vitrification, of some valuable FPs is performed.

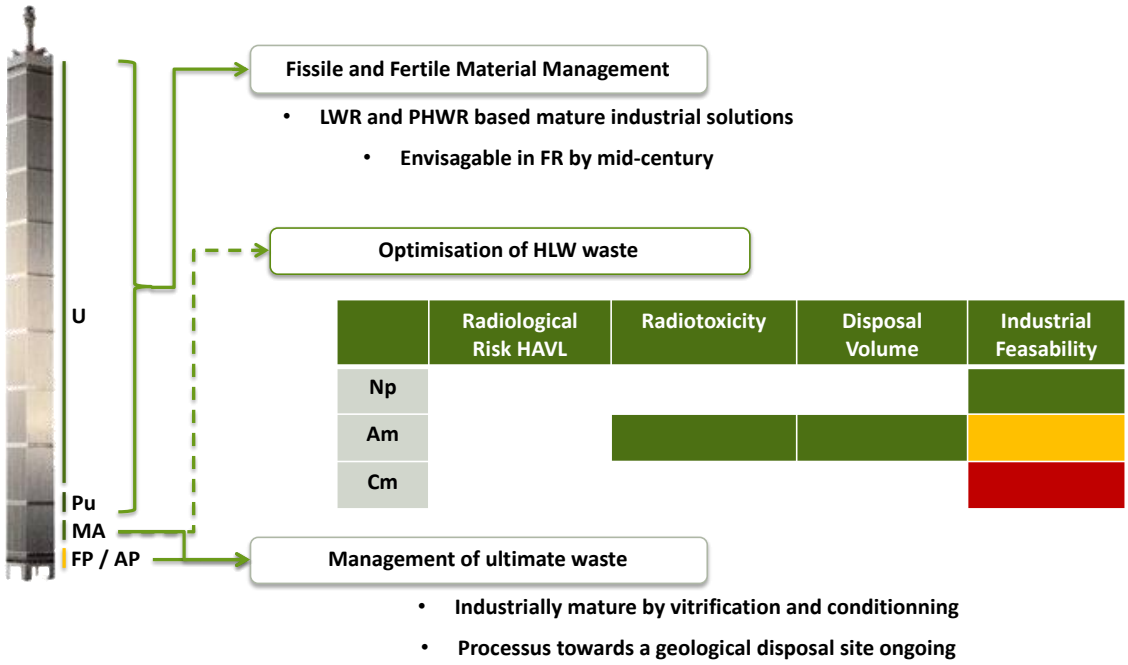

FIG. 6: Main strategic objectives and options for nuclear energy system.

As figure 7 summarises the impact of some of the SF-management options on the GDF' footprint (applicable for the French programme as published by CEA [5], Pu-management is the first objective to be achieved where the management of minor actinides can be optional to achieve the reduced footprint objective as well as reduced radiotoxicity content in the disposed waste.

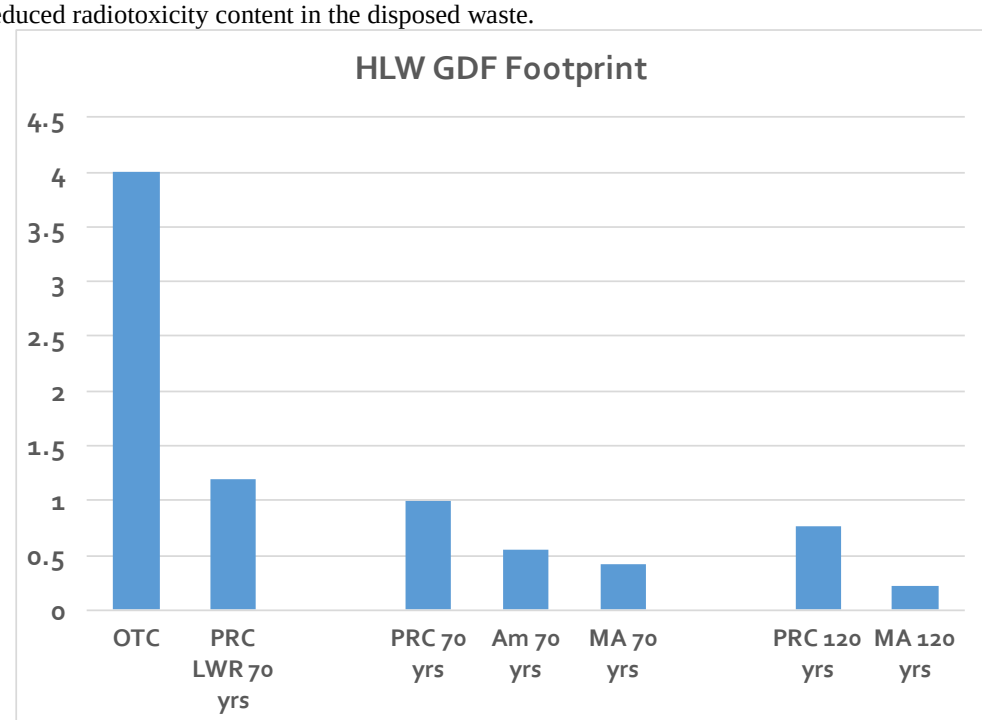

FIG. 7: Impact on GDF footprint from Pu-management (Partial Recycling Cycle PRC) and Am-transmutation or Minor Actinide (MA) transmutation with different cooling times of vitrified High Level Waste (HLW) before disposal. Based on CEA's reports on French SF-management studies [4].

3. 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 6 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. Figure 6 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. 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.

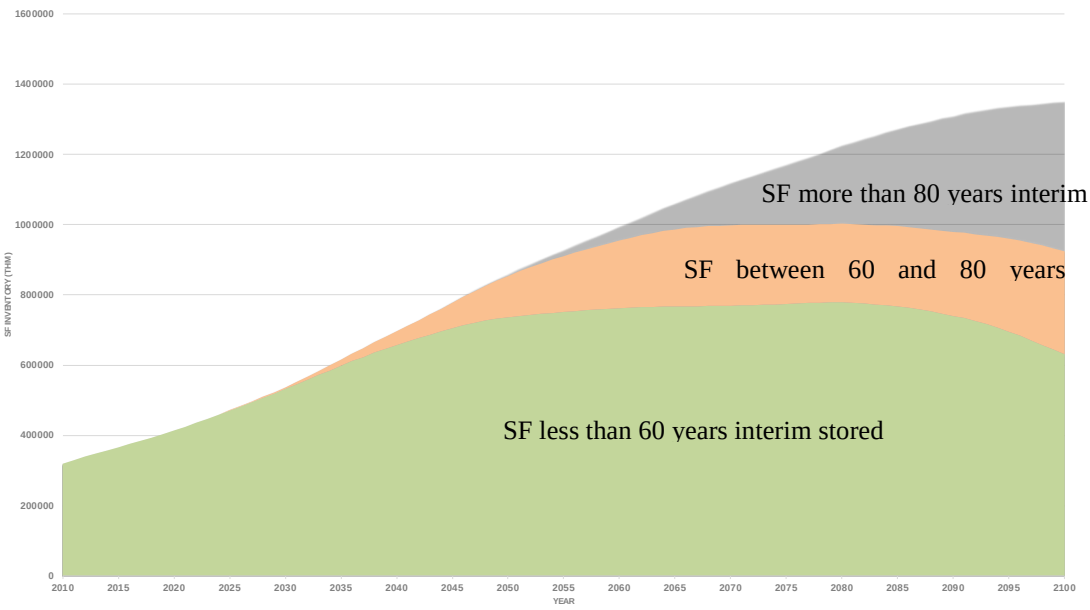

FIG. 6. Evolution of SF: Inventory for the foreseeable NPP-fleet with distinction for interim storage duration of SF.

A variety of other SF-management options are or may become industrially available during the coming decades (see Figure 7), 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 worldwide industrial deployment, including associated multi-recycling fuel cycle, 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.

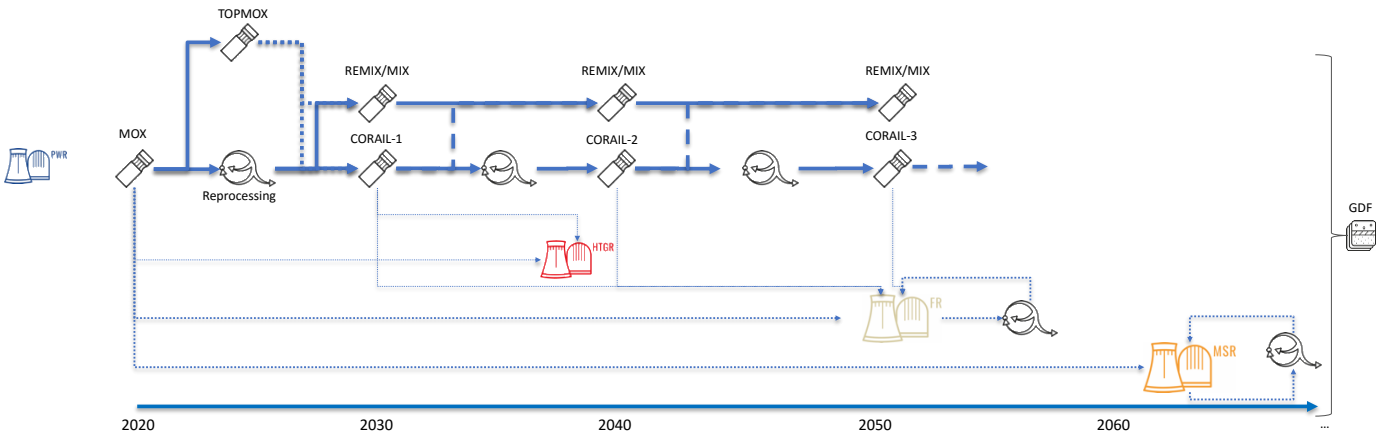

FIG. 7. Projected world deployment of nuclear energy systems towards more advanced SF-management from UOX and/or MOX fuel.

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.

The projected world fuel cycle developments in figure 8 sketches the projection of what could become the more internationally connected fuel cycle where SF is interim stored, disposed of but also reprocessed with the recycling options being across countries and across NPP-types, e.g. LWR and PHWR synergy for REPU-management, LWR + HTGR and/or FR for Pu-management, or MOX/CORAIL/(RE)MIX synergies between different NPP-parks.

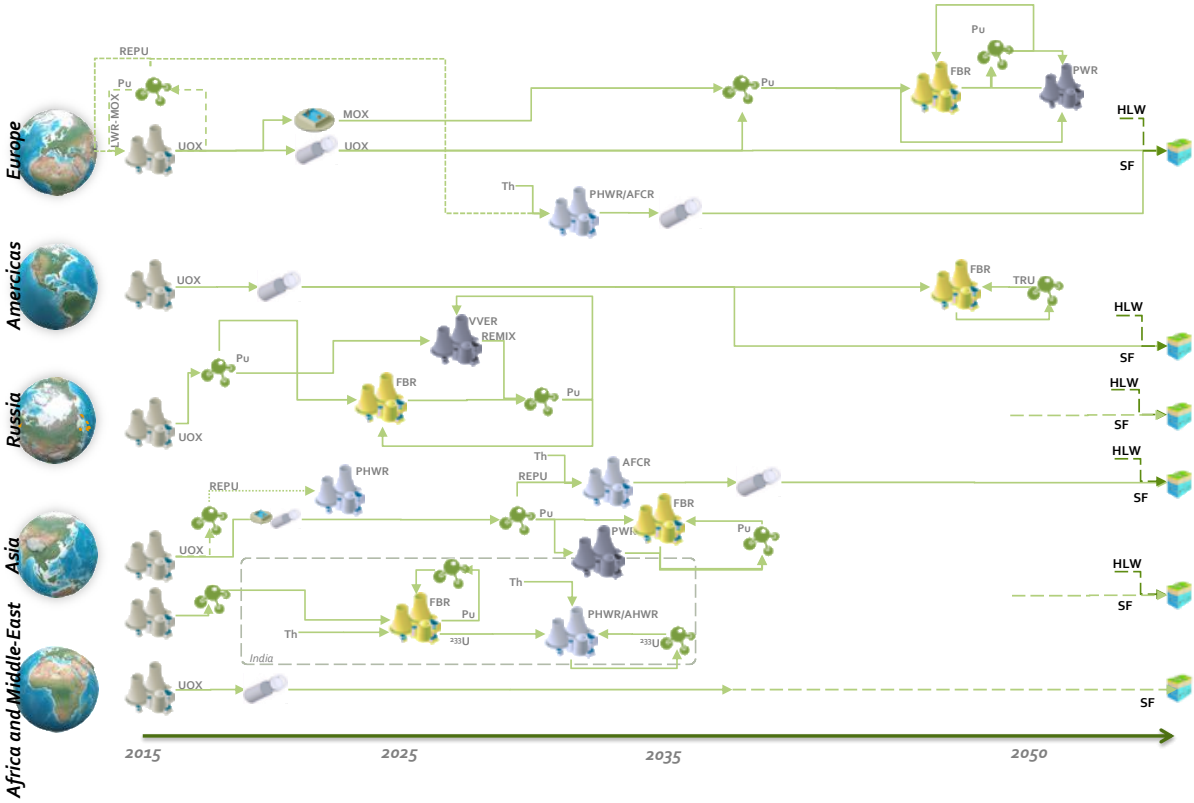

FIG. 8. Evolution of SF: Inventory for the foreseeable NPP-fleet with distinction for interim storage duration of SF

4. CONCLUSIONS

SF-management should not be a challenge as options are and will remain available though a solutions-oriented SF-management approach is increasingly critical to match the anticipated growth in nuclear energy use worldwide.

There's no reason for any national programme to undertake a 'wait-and-see' approach awaiting (very) advanced nuclear energy systems as today's interim storage of SF, despite not a final solution, is performing well and industrially mature and under-development fuel options are available to perform an active SF and Pu-management till well into the second half of this century. More advanced nuclear energy systems, such as "Generation-IV", may make the market scene by then though not being the 'excuse' anymore not to decide on today's and tomorrow's SF-management policies.

REFERENCES

[1] Generation-IV, https://www.gen-4.org/gif/jcms/c_9260/public, OECD-NEA, Paris, France

[2] NucInfo, Nuclear-21, https://nuclear-21.net/nessatitems/nucinfo/

[3] OECD-NEA, Source Book of International Activities Related to the Development of Safety Cases for Deep Geological Repositories, http://www.oecd-nea.org/rwm/pubs/2017/7341-sourcebook-safety-cases.pdf, 2017, Paris, France

[4] CEA, http://www.cea.fr/presse/Pages/actualites-communiques/institutionnel/rapport-gestion-durable-matieres-nucleaires.aspx, France, 2013

[5] IAEA, INPRO, Collaborative Project "Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability – SYNERGIES", 2018, Vienna, Austria