Back-end cost methodologies: valuing flexibility and integrating risks in used fuel management

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French fuel cycle strategy: used fuel recycling perspectives

Back-end cost methodologies:
integrating risks and valuing flexibility
The French Fuel Cycle consistency

Used MOX and ERU fuel are stored under water pending future use.

- Interim storage
- Multimodal transports
- La Hague reprocessing plant
- Melox MOX plant

22 NPPs fueled with MOX
~ 10% of French nuclear electricity
Up to 25% with RepU recycling from 2023

58 NPPs operating (63 GWe)
72% of French electricity is nuclear
1 EPR in construction

RepU recycling restart decided by EDF:
First loading for 4 Cruas reactors scheduled in 2023
The French Fuel Cycle: key benefits

- 22,000 t of Natural U saved
- Savings of 23,000 tHM of Spent Fuel storage
- Final waste: Volume reduced by 4
  Toxicity reduced by 10
- Standard waste packages licensed by 9 safety authorities for storage & disposal
- IL-HLW in-storage infrastructure licensed for 100 years minimum
  HLW vitrified canister confinement durability in disposal (1000 years +)
- Geological disposal footprint and cost optimization

Energy independence reinforced:
- 2 years of strategic stockpile (RepU)
French Governmental orientation / Multiannual Energy Program (1/2)

Confirmation by the French government that the closed fuel cycle is of strategic importance.

Diversification of the energy mix with the raise of the renewable, up to 14 reactors shut down by 2035 to reach 50% of nuclear energy in power generation, depending on electricity prices, the mix of neighboring countries, the electric system margins.

After a government-led instruction with industrial bodies, a decision is expected to be taken mid-2021 regarding the construction of new EPR reactors

Mono-recycling back-end strategy to continue at least until 2040:
Prepare MOX fueling of part of the 1300 MWe reactors to accommodate for planned shutdowns of some 900 MWe reactors and ensure the robustness of the system

Industrial mastery of reprocessing and recycling technologies: the enabler to move to advanced fuel cycle
French Governmental orientation / Multiannual Energy Program (2/2)

Development of R&D program between CEA, EDF, Framatome and Orano to support closure of the nuclear fuel cycle

- Focusing in the middle term on Multi recycling of plutonium in PWR
  - Allowing to stabilize used fuel inventory and control Pu inventory
  - Experimental programme with loading of one test assembly in reactor around 2025-2028
  - Industrial deployment potentially envisaged in the 2040’s in the renewed nuclear fleet

- Maintaining the perspective of a potential industrial deployment of a fleet of SFRs in the second half of the 21st century considering natural uranium availability

Plutonium Multi recycling in LWR prepares the perspective of a potential industrial deployment of a fleet of Fast Reactors in the second half of the 21st century
Strategic industrial and R&D roadmap for closure of the fuel cycle

Mid-term R&D ambitions:
- **Multi-recycling in PWR**: MOX-2 fuels
  Industrial commissioning deemed feasible by around 2040

Short-term industrial performances:
- **MOX fuel Excellence** program for use in 1,300MWe reactors:
  deployment to start in the late 2020s

Fuel cycle closure and **Gen IV** fast neutron reactors:
- increase natural uranium savings, up to 100%
- decrease waste volume and toxicity
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Used Fuel management
Two main Nuclear Fuel Cycle Options: Open or Closed

For both options, the cost of the back-end of the fuel cycle represents a small portion of the total LCOE.
Used Fuel management
an Overview of Fuel Cycle Elements

All Fuel Cycle stages have to be considered to assess overall technical and economical fuel cycle performance and value... but not only
Used Fuel Management
a Very Long-term Multi-dimensional Strategic Approach

Multi-dimensional criteria
• National & international Policies
• Regulation
• Long-term energy mix plan
• Available Resources incl. financial
• Installed and future Nuclear capacity
• Social Acceptance
• Geology
• Shared infrastructures incl. handling & transport system, reprocessing, consolidated storage, final disposal
• Plant D&D planning– site remediation- asset valorization/sale
• Nuclear Phase-out

All these criteria contribute to the choice of an option for the Fuel Cycle but also impact it throughout its course with potential changes over time
The Economics of the Back End of the Nuclear Fuel Cycle
High level analysis for idealized systems (an OECD/NEA No. 7061, © OECD 2013)

LCOE_{Fuel cycle} for different reactor fleets and back-end strategies
(3% discount rate)

Notes:
- The central values represent the results from the REFERENCE cost scenario, and the error bars correspond to the LOW and HIGH cost scenarios.
- For small nuclear fleet, Reprocessing/recycling cost are based on service cost from shared infrastructure.

- Comparisons should be drawn on the basis of the comprehensive fuel cycle costs beyond the sole BE costs
- Differences among the three options in the total fuel cycle component of the LCOE (Levelized Costs Of Electricity) are within the uncertainty margin, given the uncertainties around some input data.
- Such assessment cannot be implemented into a specific national context, it requires a detailed and adapted analysis to each specific country context.

On the long run, Spent Fuel Management system involves multidimensional criteria that may lead to multiple decisions
- Uncertain factors conditioning the decisional options in future times
- No fixed scenario
Spent Fuel Management has a growing impact on Utilities’ financial performance and their market value.

**Spent fuel inventories**

- 2018: 100 KHM
- 2030: 250 KHM

**Shutdown reactors**

- 2018: 50 reactors
- 2030: 150 reactors

**Risks & Challenges**

- Spent Fuel Pool Saturation
- Extended interim storage period beyond design basis and assumptions
- End of life (EoL) Management at shutdown reactors (including early or premature shutdowns, stranded sites)
- Deep Geological Repository (DGR or GDF) delays and cost overrun

**Environment**

- Regulatory requirements
- Technical – economic
- Security concerns
- Public acceptance
- Environmental impact
- Financial accountability
Solutions for Storage, Handling and Transportation as well as Final Repository Program are needed independently of the selected option

- Long-term Interim Storage is an industrial reality
  - Continued safety and security of “existing” systems
  - Long term performance of “new” systems

- Transportation is a vital brick in any Nuclear Program
  - Consolidated storage and/or Reprocessing/Recycling
  - Future Final Disposal
  - Strong safety records of the industry in countries actively shipping spent fuel (France, UK, Japan, Sweden,...)
  - In many other countries, transportation will occur after many years of interim storage, transportability requirement is a must
  - Transport programs face political and public acceptance challenges
  - Need to continue education of public and main stakeholders

- Final Disposal is Mandatory
  - Implementation of domestic DGR
  - Multi-national Shared Final Disposal infrastructure
Recycling schemes and processes to minimize risks and increase flexibility

- Orano recycling platform: a strategic asset with 40 years of experience, shared worldwide

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  - Continuous enlarging industrial scope and capacities
    - Wide range of LWR fuel including high Burn up, RTR, RNR, MOX fuels and specific types
    - Cold Crucible induction melting to enlarge products’ range and reduce waste
    - Research centers to enhance the robustness of MOX Fuel Fabrication Plant
    - Beaumont (La Hague) test facility: development & qualification in inactive operating conditions

- A path to the future multi-Recycling of Pu in LWR and FR

Recycling is a key asset to reduce risks, increase flexibility and financial predictability
Used fuel management: a very long-term strategic matter with risks and uncertainties to mitigate

Illustrative uncertainty/risk evolution with time

Reprocessing/Recycling

Demonstrated safe
Long term storage of vitrified canisters

Confinement durability,
no safeguards, limited footprint

Interim Storage

UNF

Industrialized Operations

- Fuel and storage system integrity after extended storage period
- Security of fuel not self protecting
- Damaged UNF

Extended Storage Period

Transport

Encapsulation

- Safety requirements for transportation after long-term interim storage
- Requirements for reconditioning prior to transportation
- Handling

- Fuel characterisation requirements
- Handling
- No standardisation

Open cycle

Closed cycle

Final Disposal

Waste optimization
Volume & radiotoxicity reduction
No safeguarding of UVC
Standardisation of package

Very long term Safeguards regime

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From a utility’s / policy maker’s perspective: how to decide in uncertain future environments?

Decisions on UNF-management by governments and utilities are essentially “wait-and-see”, implementing storage, which leave options opened: this does require to value them along time in order to trigger responsible, complete industrial programme implementation.

Development of specific customized analysis considering the dynamic nature of fuel cycle rather than non-representative idealized evaluation based on Current UNF inventory and its evolution, Evolution of installed nuclear capacity, Regulation demand, NPP-operator’s specific financial cost/risk objectives, Potential multi-clients schemes,…

A utility and/or UNF-fund manager regularly needs to revisit the question of the optimal UNF-management policy (with respect to the available funds) addressing two main questions:

- What is the most affordable portfolio management strategy for UNF’s inventory and potential future issues?
- Which portfolio-management options are most attractive, when and under which conditions to execute those?

The decisional times \( t_d \) are not continuum but should be decided upon such that maximal flexibility is provided in light of uncertain future developments in all UNF-management options.

The “UNF-Provision Fund” manager has a limited set of strategic decisional moments \( t_d \), however can decide when to trigger these.
Used Fuel Management path is paved with uncertainties
BE options flexibility offers possibilities to mitigate risks and uncertainties

When to decide which options to secure future risk-mitigating strategy?

- Costs and risks for each option
- Option(s) and timing to secure minimal cost/risk-exposure
- Value for an option to keep future decisional flexibility
- Financial risk exposure for a stakeholder across the options

SF Management involve multiple decisions.
No fixed scenario: alternatives arise as the market conditions of options evolve

Uncertainties Impacting overall SF Management programme

- Environmental impact
- Technical-economic
  - Evolution of SF-management service costs
  - Timing of industrial maturity of UNF-management options: encapsulation and GDF, FR technology
  - Integrity of both used fuel and storage systems with extended storage period
  - Transportability of SF following extended storage period
  - Evolution of Unat prices
- Financial
  - Discounting policies for the different SF Management activities and options
  - Impact on NPP Operator competitiveness
- Socio-political
  - Security of SF-management options
  - Regulatory changes impacting SF Management options
  - Societal acceptance of SF-management options
Back-end cost methodologies: take-aways

- Used Fuel interim Storage Solutions are needed independently of used fuel management option
- All used fuel management schemes require a handling and transport program and implementation or access to geological disposal capacity
- Recycling is a key asset to reduce risks, increase flexibility and financial predictability: Adaptable schemes providing flexibility and a road to future multi-Recycling in LWR and FR
- Nuclear’s competitiveness in changing markets requires continuous innovations in fuel cycle services
- Assessments of the overall costs and associated uncertainties are essential to size liabilities
- Beyond classical NPV/DCF, the use of innovative assessment methodologies integrating Cost, Risks, Time and Options, such as Real Alternative Valuations is key to develop optimal Used Fuel Mgt. implementation program
  - To match the uncertain socio-political-economic environment
  - To minimize deployment costs and risks through phased development, valuing flexibility to accommodate future development
  - To value longer-term objectives in shorter-term decisions
  - To consider sharing fuel cycle/disposal facilities and infrastructures that would especially benefit countries with smaller nuclear programs

Potential Issues
- Approach avoiding early cash-out that doesn’t value uncertainties nor account for future risks
- Wait & See approach without regular assessment of the options yet left open
- Only use of static Model in high level analysis of idealized options

Challenges
- Avoid Spent Fuel Pool saturation and safely and timely manage interim storage
- Safe and optimal DGR development
- Minimize environmental impact & footprint
- Ensure Robustness of retained Funding
- Public acceptance

Drivers
- Preserve natural resources
- Increase energy independence
- Contribute to security of supply
- Minimize waste generated for disposal
- Optimize cost of safe and secure Spent Fuel management

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Giving nuclear energy its full value