An Economic Analysis of the South Korean Nuclear Fuel Cycle Options using Dynamic Mass Flow Model

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1. Introduction

Over the past decade, an average of 28.57% of South Korea's electricity has been generated by nuclear power [1]. This reliance is expected to persist as a mix of renewable and nuclear energy becomes increasingly desirable. With such dependence, South Korea faces growing challenges in managing Spent Nuclear Fuel (SNF). Limited capacity for on-site storage and the absence of operational interim storage or a final repository have made the selection of a sustainable back-end fuel cycle a pressing national policy issue [2]. As part of the efforts made in this cause, South Korea has actively considered closing the fuel cycle with pyroprocessing (also known as electrochemical reprocessing) and Sodium-cooled Fast Reactors (SFRs). Repurposing the SNF from Pressurized Water Reactors (PWRs), by means of pyroprocessing, has also been a major focus of research at several national research institutes, such as the Korea Atomic Energy Research Institute (KAERI) [3].

The South Korean Government has expressed a desire to continue pursuing nuclear energy as a carbon-free energy source. This desire is reflected in the 11th Basic Plan on Electricity Demand and Supply (11th Basic Plan) released in early 2025, that plans seven new APR-1400 reactors in the next fourteen years [4]. Alongside this the High-Level Radioactive Waste Special Act was enacted in early 2025, mandating that high-level radioactive waste interim storage and the disposal facilities start operation by 2050 and 2060, respectively [5]. While these policy changes are necessary, more nuclear reactors generate more SNF hence accelerating and exacerbating the existing limited storage problem; thus, a fundamental and concrete decision in back-end fuel cycle policy is required. Especially with recent advancements in the discussion regarding the U.S.-South Korean 123 agreement, a comparison of the available back-end fuel cycle options is necessary to make the best decision. A comparison between options for an open or closed fuel cycle should be made by considering many aspects such as the mass flow between each stage of the Nuclear Fuel Cycle (NFC), economics, and social acceptance of the reprocessing policy, etc. This is because each aspect intertwines with the other, especially for the mass flow and economics since fuel cycle expenses are predominately proportional to the fuel material mass.

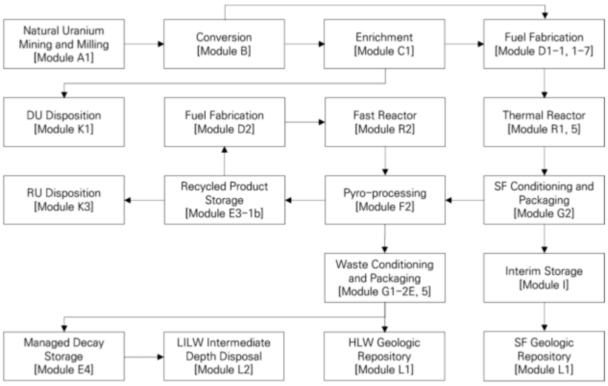

Figure 1. Module based approach, developed by Idaho National Laboratory. [6]

This study aims to evaluate the economics of different fuel cycle options for South Korea: (1) Once-Through (OT) and (2) pyro-SFR fuel cycle (pyroprocessing and SFRs). By calculating the mass flow of each fuel cycle implemented in four different scenarios tailored to South Korea, the Levelized Cost Of Electricity (LCOE) of each scenario will be calculated for comparison. The mass flow will be evaluated using a mass flow and economic evaluation model developed in-house. Based on the results of the analysis, this study aims to provide policy recommendations for the future of South Korean NFC. This individual paper focuses on the methodology used to calculate the mass flow and assess the economics of future NFC scenarios.

2. Method and input parameters

2.1. Mass flow model

This research follows a module-based approach, referencing the modules provided in Figure 1. To calculate the mass of nuclear fuel materials flowing in between modules, calculation formula shown in Table 1 are used. The calculation interval was one year. The electricity demand outlook including the nuclear generation share was created by extrapolating the 11th Basic Plan. Then, the nuclear electricity demand was converted to a total nuclear reactor capacity required. The required fuel materials were calculated according to this reactor capacity.

Table 1. Mass flow calculation formula.

Module	Formula	
Natural Uranium (A1)	$M_{NU}^{t} = M_{EU}^{t+t_{lag,feed}} \frac{x_{EU} - x_{DU}}{x_{NU} - x_{DU}}$	(1)
Conversion (B)	$M_{Conv}^{t} = M_{NU}^{t-t_{lag,conv}}$	(2)
Enrichment (C1)	$M_{SWU}^{t} = M_{EU}^{t} X_{EU} + M_{DU}^{t} X_{DU} - M_{NU}^{t} X_{NU},$ $X_i = (2x_i - 1)\, ln\left(\frac{x_i}{1 - x_i}\right)$	(3)
PWR Fresh Fuel Loading (D1-1)	$M_{\mathrm{PWR},FF}^{t} = \frac{365\, CF_{\mathrm{PWR}}}{Bu_{\mathrm{PWR}}\, \varepsilon_{\mathrm{PWR}}} \cdot \left[\left(P_{\mathrm{PWR}}^{t} - P_{\mathrm{PWR,decom}}^{t}\right) + N_{\mathrm{batch}}\, P_{\mathrm{PWR,decom}}^{t}\right]$	(4)
PWR SNF generation (G2)	$M_{PWR,SF}^{t} = M_{PWR,FF}^{t}$	(5)
Interim Storage (I)	$M_{PWR,IS}^{t} = \frac{1}{t_f - t_{0,IS}} \sum_{t_{0,IS}}^{t_f} M_{\mathrm{PWR},FF}^{t}$ $\left(\text{for } t \geq t_{0,IS}, \text{ constant}\right)$	(6)
SNF Final Disposal (L1)	$M_{FD}^{t} = \frac{1}{t_f - t_{0,FD}} \sum_{t_{0,FD}}^{t_f} M_{\mathrm{PWR},FF}^{t}$ $\left(\text{for } t \geq t_{0,FD}, \text{ constant}\right)$	(7)
Pyroprocessed SNF (F2)	$M_{Pyro}^{t} = C_{Pyro} \times CF_{Pyro}$	(8)
Reprocessed TRU (E3-1b, D2)	$M_{TRU}^{t} = M_{Pyro}^{t} \left(1 - l_{pyro} - l_{fuel\, fab}\right)$	(9)
Pyro HLW Disposal (L1)	$V_{HLW}^{t} = M_{Pyro}^{t} \times R_{Pyro,HLW}$	(10)

M_i^t: Mass flow in process *i* on year *t*
EU: Enriched Uranium, NU: Natural Uranium, DU: Depleted Uranium
$t_{lag,i}$: Lag time for process *i*
x_j: Ratio of U-235 in substance *j*
CF_i: Capacity factor of reactor type *i*, ε: Thermal efficiency of reactor
P_i^t: Power capacity of reactor type *i* at time *t*.
$t_{0,IS}$: Interim storage facility first operation year
$t_{0,FD}$: Final disposal facility first operation year
l_i: Loss of TRU in process *i*
C_{Pyro}: Total capacity of pyroprocessing plant [tHM/yr]
CF_{Pyro}: Capacity factor of pyroprocessing plant
$R_{Pyro,HLW}$: HLW generated per 1 ton of pyroprocessed SF

Table 2. Cost calculation formula.

Costs	Formula	
Natural Uranium	$C_{NU} = \sum_{t_0}^{t_f} \left(M_{NU}^{t} \cdot c_{NU}\right) \cdot (1+r)^{t_0 - t}$	(11)
Conversion	$C_{Conv} = \sum_{t_0}^{t_f} \left(M_{Conv}^{t} \cdot c_{Conv}\right) \cdot (1+r)^{t_0 - t}$	(12)
Enrichment	$C_{Enr} = \sum_{t_0}^{t_f} \left(M_{SWU}^{t} \cdot c_{SWU}\right) \cdot (1+r)^{t_0 - t}$	(13)
PWR Fuel Fabrication	$C_{PWR,FF} = \sum_{t_0}^{t_f} \left(M_{PWR,FF}^{t} \cdot c_{PWR,FF}\right) \cdot (1+r)^{t_0 - t}$	(14)
Interim Storage	$C_{IS} = \sum_{t_{0,IS}}^{t_f} \left(M_{PWR,IS}^{t} \cdot c_{IS}\right) \cdot (1+r)^{t_0 - t}$	(15)
PWR SNF Final Disposal	$C_{FD} = \sum_{t_{0,FD}}^{t_f} \left(M_{FD}^{t} \cdot c_{FD}\right) \cdot (1+r)^{t_0 - t}$	(16)
TRU Fuel Fabrication	$C_{TRU,FF} = \sum_{t_0}^{t_f} \left(M_{TRU}^{t} \cdot c_{TRU,FF}\right) \cdot (1+r)^{t_0 - t}$	(17)
Pyro HLW Disposal	$C_{HLWdis} = \sum_{t_{0,FD}}^{t_f} \left(V_{HLW}^{t} \cdot c_{HLWdis}\right) \cdot (1+r)^{t_0 - t}$	(18)
Capital Cost	$C_{Cap} = \sum_{t_0}^{t_f} \left(\left(P_{PWR}^{t} \cdot OCC_{PWR} \cdot \kappa_{IDC} \cdot CRF\right) + \left(P_{SFR}^{t} \cdot OCC_{SFR} \cdot \kappa_{IDC} \cdot CRF\right)\right) \cdot (1+r)^{t_0 - t}$ $CRF = \frac{i(i+1)^N}{(1+i)^N - 1}, \kappa_{IDC} = \frac{(1+i)^n - 1}{n * i}$	(19)
Fixed O&M Cost	$C_{OM} = \sum_{t_0}^{t_f} \left(\left(P_{PWR}^{t} \cdot c_{PWR,fix} + E_{PWR}^{t} \cdot c_{PWR,var}\right) + \left(P_{SFR}^{t} \cdot c_{SFR,fix} + E_{SFR}^{t} \cdot c_{SFR,var}\right)\right) \cdot (1+r)^{t_0 - t}$	(20)

r: Discount rate, *i*: Interest rate
c_i: Unit cost of procedure *i* [$/kg]
C_i: Total discounted cost of procedure *i*
N: Operational lifetime, *n*: construction time
CRF: Capital Recovery Factor
κ_{IDC}: Ratio between OCC with IDC and OCC

It should be noted for multiple specific modules such as fresh fuel fabrication and SNF conditioning and packaging, the mass balance will be maintained.

2.2. Economic evaluation model

The LCOE approach was used to evaluate the economics of fuel cycle scenarios. To achieve this calculation, the cost of each module was calculated. The basic principle of the economic evaluation model was using the unit cost per mass: multiplying it against the mass calculated in the mass flow model and discounting the cost according to the base year to convert future values to present values. The LCOE formula is as below, where C_{PV}^{t} is the total discounted cost of electricity generation including front-end, back-end, and reactor cost components in year *t* and E_{PV}^{t} is the total discounted electricity generated by the nuclear reactor fleet in year *t*:

$$LCOE = \frac{\sum_t C_{PV}^{t}}{\sum_t E_{PV}^{t}} \qquad (21)$$

C_{PV}^{t} also corresponds to the sum of total module costs. An excerpt of the formula used for each module can be seen in Table 2.

It is notable that the capital cost of the reactors deployed in this research considers Interest During Construction (IDC) and Capital Recovery Factor (CRF). With IDC, the interest rising on the investment divided by the duration of the construction is factored in, which provides a more realistic calculation of the capital cost compared to the Overnight Construction Cost (OCC), which assumes that the capital payment is made at once. Additionally, as large-scale nuclear reactors' construction costs are very large and the recovery of the costs will only start after the reactors start operation (i.e. make profit by selling electricity), using CRF that will divide the capital cost for an amount of time after the construction provide a basis for a more reasonable calculation.

2.3. Scenarios and input parameters

The four scenarios designed in this study can be classified into two classes regarding the electricity demand outlook, and two categories regarding the applied back-end fuel cycle, as shown in Table 3. The electricity demand outlook from 2025 to 2100 was created based on the outlook provided by the 11th Basic Plan, with a yearly growth rate of 0.9%. The nuclear share of electricity varied according to the type of scenario, fixed at 35.2% for the reference demand, and rose linearly to 50% until 2100 for the high demand. For the back-end fuel cycle, OT and pyro-SFR scenarios were each designed so that the SNF is either completely disposed of or reprocessed. Pressurized heavy water reactors were not considered.

Table 3. Matrix table of the scenarios used in this study.

		Back-end Fuel Cycle	
		OT	Pyro-SFR
Electricity Demand	Reference		
	High		

Input parameters consist of two types: cost information for the economic analysis, and NFC operation information, like burnup of the PWR fuels and TRU/SNF ratio within pyroprocessing plants. The unit cost information used in this research was sourced from various sources including the Advanced Fuel Cycle Cost Basis Report published by the Idaho National Lab [7], with the mode values converted to year 2024 USD. Major costs such as the SFR overnight capital cost, pyroprocessing costs, and disposal costs were calculated in this study to tailor to the circumstances of South Korea. The discount rate was set to 3%, as recommended for long-term public benefit projects by the OECD/NEA [8].

As key input parameters, the capacity of the reactors built after 2038 -- the year that the outlook of 11th Basic Plan ends -- is set to 1.4 GWe for PWRs, and 1.5 GWe for SFRs. Reactor design life is fixed at 60 years. Parameters regarding the operation of SFRs were cited from or interpolated based on previous designs created by KAERI [9]. The capacity of a unit pyroprocessing facility was set to 100 tHM/year each and deployed to keep the TRU inventory as low as possible. The capacity of the on-site SNF storage facility was assumed to be 29,429 tHM, the amount of SNF produced by all reactors listed in the 11th Basic Plan during their design lives. Reactor deployment was controlled to utilize on-site SNF storage facilities as much as possible.

From the method explained above, calculated outputs include the mass flow of each step of the fuel cycle, and the corresponding costs calculated by multiplying the unit costs by the mass flow, in USD. The key mass flow results are the enrichment needs, SNF inventory, and pyroprocessed SNF. With the calculated costs, the overnight cost, net present value, and the LCOE can be calculated for each scenario.

3. Results and discussion

3.1. Calculated mass flow

Preliminary calculations were performed to validate the methodology. The results of these preliminary calculations are summarized in figure 2 and table 4. These show that pyro-SFR back-end fuel cycle has reduced significant portions of the accumulated SNF, especially in the pyro-SFR scenario, compared to the OT scenarios. Both 2100 SNF masses of the pyro-SFR scenario are below the assumed full capacity of on-site SNF storage, which reduces pressure on away-from-site SNF storage limits and utilizes resources to the fullest.

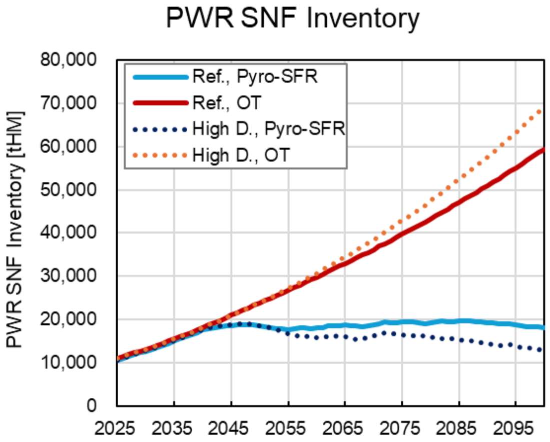

Figure 2. PWR SNF inventory for scenarios.

Table 4. Accumulated PWR spent fuel in 2100.

[tHM]	**OT (A)**	**Pyro-SFR (B)**	**(1-B/A)**
Ref.	59,458	20,832	64.96%
High D.	69,237	15,243	77.98%

3.2. *Economic analysis*

The calculated LCOE are between 45 and 48 $/MWh in 2024$ (Figure 2), and high demand scenarios share the same trend. Pyro-SFR scenarios are generally costlier than OT by 5.806% (reference) and 7.751% (high demand). Across all scenarios, it is notable that the reactor capital cost and O&M costs make up a large fraction of LCOE, a trend commonly seen in NFC economic evaluation studies. However, it should be noted that the individual unit costs' range is very large, as the uncertainty of pyroprocessing and SFRs' costs are very large.

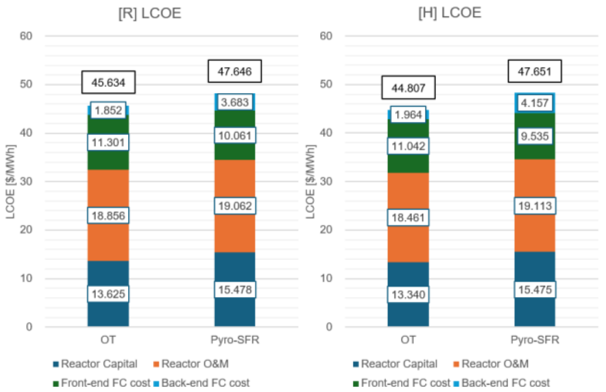

Figure 3. LCOE of reference demand scenario (left), LCOE of high demand scenario (right).

3.3. *Future Work*

With the methodology established, the next step for this study is to conduct analysis on the results and draw policy implications. Possible implications may include those pertaining to the siting of various NFC facilities and long-term infrastructure deployment plan. Furthermore, sensitivity analysis on the cost variables used in this study will be conducted to precisely assess the uncertainty margins of the LCOE. Additionally, new scenarios that utilize pyroprocessing as a fuel supplier for advanced reactors may be designed and assessed to reflect the rise of innovative reactor types.

4. Conclusion

This study provides an updated economic comparison of South Korea's OT and pyro-SFR fuel cycle options using dynamic mass-flow model. According to the preliminary results, the pyro-SFR cycle reduces accumulated SNF significantly across both demand scenarios but remains more expensive than the OT option. As this is a trend commonly seen for pyro-SFR fuel cycle studies, it can be concluded that the methodology presented in this paper aligns with previous studies. This study is significant in that it utilizes individual cost information that was determined tailoring to South Korean circumstances, and from said cost information provides an updated economic assessment to shed light on the ongoing discussions about closing the South Korean NFC. Further analyses of LCOE will be provided in the future to refine the conclusions calculated using the methodology discussed in this paper.

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