Is Korea's Spent Fuel Policy Ready for the AI Era? A System Dynamics Assessment under Surging Electricity Demand and Reactor Policy Scenarios

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1. Introduction

Korea's electricity demand is projected to rise substantially, driven by the expansion of AI data centers and semiconductor manufacturing facilities. This trend is expected to be further strengthened by the government's three mega-projects targeting semiconductors, physical AI, and nationwide AI data center expansion [1]. The government finalized new nuclear build plans through 2038 under the 11th Basic Plan for Long-term Electricity Supply and Demand (BPLE), with the 12th BPLE currently under revision to reflect higher demand projections and expanded nuclear targets.

Nuclear expansion inevitably increases spent nuclear fuel (SNF) generation and affects the entire back-end fuel cycle — from at-reactor storage through interim storage to the final disposal facility. Quantitative advance planning of high-level radioactive waste management infrastructure is therefore essential.

While the BPLE is revised on a two-year cycle with a 15-year planning horizon, securing or expanding nuclear facilities, interim storage buildings, and disposal repositories takes several decades. Unless a long-term integrated plan is maintained in parallel with each BPLE revision, infrastructure scale and cost requirements will be underestimated.

This study applies an enhanced SNUCYCLE (Seoul National University Nuclear Fuel CYCLe Evaluator), a system dynamics (SD) simulation model developed at Seoul National University based on Powersim Studio 10 [2]. The enhanced model quantifies SNF management requirements from 2026 to 2100 across seven scenarios: four electricity demand levels (S0–S3) and three reactor-supply sub-scenarios (S3-A, S3-B, S3-C). Model outputs under the S0 baseline were cross-checked against KHNP's published saturation projections, confirming model fidelity before scenario analysis.

2. Scenario Design

Seven scenarios were designed based on electricity demand trajectory, nuclear supply strategy, and lifetime extension (LTO) policy, as summarized in Table I. S0 represents the current policy baseline; S1–S3 reflect escalating demand levels.

Table I: Scenario Description

Scenario	Electricity Demand	Supply / LTO Condition
S0	11th BPLE baseline (current policy basis)	35-unit maintained with LTO (+20 years)
S1	11th BPLE target demand	gap-based NPPs with LTO (+20 years)
S2	S1 × 1.034 + Mega-projects	gap-based NPPs with LTO (+20 years)
S3	S2 × IEA AI acceleration	gap-based NPPs with LTO (+20 years)
S3-A	Same as S3	+6 units at existing sites with LTO (+20 years)
S3-B	Same as S3	gap-based NPPs + 12 i-SMRs with LTO (+20 years)
S3-C	Same as S3	gap-based NPPs without LTO

S2 applies a mega-project multiplier (×1.034) with demand increasing linearly from 2028 to 2040 (peak +253 TWh), while S3 S3 applies an additional AI-driven acceleration to S2 demand, resulting in approximately +2.4%p/yr above S1 during 2027–2028 and +4.75%p/yr above S1 during 2031–2040, consistent with IEA high-case projections for AI data centre-led electricity demand growth in Korea [1]. Nuclear share is fixed at 35.2% after 2038, as specified in the 11th BPLE.

S3-A restricts supply to two additional units each at Hanbit, Saeul, and Shin-Hanul (total +6 units). Use of existing sites eliminates site-selection margin and shortens licensing by one year and construction by one year, reducing the total construction lead time from 9 to 6 years. S3-B reflects the joint policy recommendation of three energy societies and introduces 12 i-SMR units (including 1 predefined) between 2034 and 2050 [3]. S3-C models operation without any lifetime extension, applying original licensed lifetimes.

3. Model Structure

3.1. Reactor and Electricity Module

The model represents ten reactor groups (index i = 1–10): Kori, Hanbit, Hanul, Saeul, Wolsong PWR, Wolsong CANDU, and three new-site APR1400 groups (NEW-1 and NEW-2 capped at 10 units each; NEW-3 uncapped) and one SMR group. New reactor orders are triggered automatically when a demand-supply gap is projected 9 years ahead (the construction lead time for new sites).

Reactors with confirmed construction plans — Shin-Hanul Units 3 and 4 (2032–2033), Yeongdeok Units 1 and 2 (2037–2038), and the Gijang i-SMR (2034) — are modeled as predefined reactors, assigned directly to their commissioning years independently of the gap-based ordering mechanism. In S3-A, the lead time for existing-site units (i = 2, 3, 4) is set to 6 years (2-year licensing + 4-year construction, no margin). In S3-B, the SMR group (i = 10) is capped at 12 units, including 1 predefined unit at Gijang. In S3-C, lifetime extension is not applied; all reactors operate only for their original licensed lifetimes.

3.2 Spent Fuel Management Module

The SNF management module comprises three stages: at-reactor wet storage → interim storage (IS; opening 2050) → disposal facility (DF; opening 2060). Transport from wet pools to the IS facility is allocated dynamically using a priority index based on the reciprocal of remaining years to saturation (pre-saturation) or pool utilization ratio (post-saturation). Transport parameters are assumed as 6 trips/yr at 185 tHM/trip for PWR and SMR, and 6 trips/yr at 96 tHM/trip for CANDU, consistent with nuclear industry cost references, to allow quantitative comparison of interim storage costs across scenarios.

Transport from IS to DF uses a PWR+SMR disposal rate of 400 tHM/yr and a CANDU rate of 380.16 tHM/yr, prorated by reactor-type inventory share. IS building capacity is set at 1,440 tHM per building (equivalent to 2,880 PWR fuel assemblies) based on the KHNP Kori dry-storage facility plan [4]. IS building cost and CANDU MACSTOR cost are assumed at KRW 150 billion per building and KRW 5 billion per unit, respectively, consistent with nuclear industry cost references, to allow quantitative comparison of interim storage costs across scenarios. CANDU MACSTOR KN-400 capacity is 480 tHM per unit.

Disposal area is calculated using the existing KRS disposal concept [5]: 147.5 m²/tHM for PWR (295 m²/canister ÷ (4 assemblies × 0.5 tHM/assembly)) and 21.7 m²/tHM for CANDU (208 m²/canister ÷ (480 bundles × 0.02 tHM/bundle)).

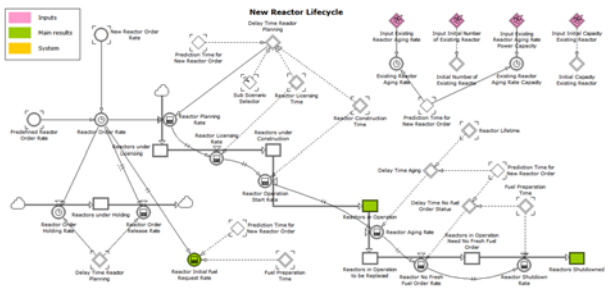


Fig. 1. New Reactor Lifecycle Module of SNUCYCLE

4. Results and Discussion

4.1 Nuclear Power Capacity and SNF Generation

Fig. 2 shows the simulated nuclear electricity demand targets (dashed lines) and supply (solid lines) from 2026 to 2100. Identical colors correspond to the same scenario.

Under the current policy baseline (S0), existing units retire sequentially without replacement, so supply declines continuously and falls below demand from 2047 onward. This confirms that nuclear electricity demand cannot be met from the mid-2040s without new construction — underscoring the need to reassess mid-to-long-term nuclear policy.

In S1–S3, the gap-based ordering mechanism keeps supply above demand throughout most of the simulation. However, owing to the 9-year construction lead time, S3 exhibits a temporary supply shortfall during 2031–2037 even when orders are placed immediately in 2026. This structural delay highlights the urgency of timely policy decisions in high-demand scenarios. S3-A was designed to examine whether the shorter 6-year lead time at existing sites can alleviate this shortfall.

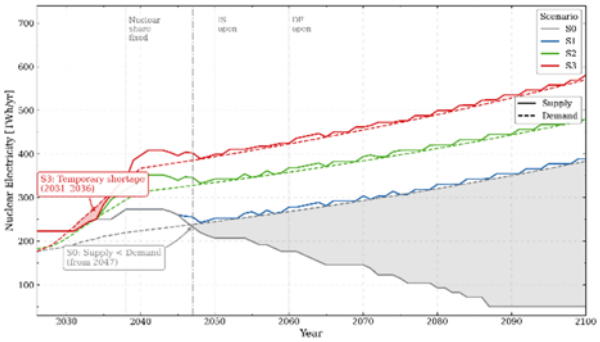


Fig. 2. Nuclear Electricity Supply and Demand by Scenario (2026-2100)

Table II summarizes cumulative reactors in operation by scenario. S0 peaks at 32 NPPs (33 including the predefined SMR) after 2038, whereas S1 requires up to 60 NPPs, S2 up to 68 NPPs, and S3 up to 77 NPPs, as most existing reactors retire before 2100 and must be replaced by new builds. The reactor count directly drives SNF generation and thereby the scale and cost of interim storage and disposal infrastructure analyzed in the following sections.

In S3-A, the total large NPP count (79 units) closely tracks S3 (77 units), indicating that the primary benefit of the existing-site strategy is faster deployment — delaying pool saturation — rather than a reduction in total unit count. In S3-B, introducing 11 gap-based i-SMR units reduces gap-based large NPP orders by 6 units (45→39) relative to S3, demonstrating partial substitution. In S3-C, the absence of LTO requires 13 additional gap-based NPPs (45→58) relative to S3, reinforcing the importance of LTO as a tool for limiting new build requirements.

Table II: Total Reactors in Operation by Scenario

	Existing+ Predefined		Gap-Based		Total	
	NPP	SMR	NPP	SMR	NPP	SMR
S0	28+4	0+1	0	0	32	1
S1	28+4	0+1	28	0	60	1
S2	28+4	0+1	36	0	68	1
S3	28+4	0+1	45	0	77	1
S3-A	28+4	0+1	47	0	79	1
S3-B	28+4	0+1	39	11	71	12
S3-C	28+4	0+1	58	0	90	1

Fig. 3 presents the annual reactor count by site for the S1 scenario. Hanul and Hanbit dominate the early period; their unit counts decline sequentially from the 2030s as reactors reach end of license. NEW-1 reaches its 10-unit ceiling in the 2050s to compensate for retiring legacy units, while NEW-2 and NEW-3 ramp up from the 2070s and 2090s, respectively.

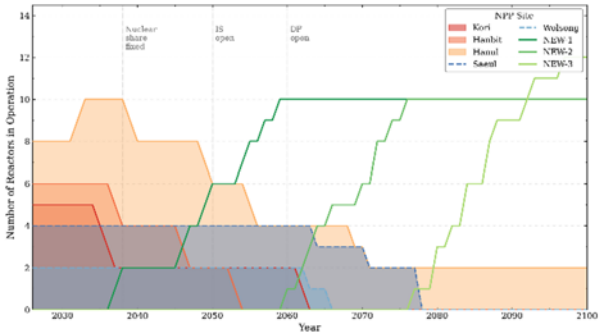


Fig. 3. Number of Reactors in Operation by Site – S1 Scenario (2026~2100)

4.2 At-Reactor Storage Saturation

Pool saturation sequences differ distinctly across scenarios. Under S0 and S3, saturation at existing sites occurs in the same order — Hanbit (2030), Hanul (2031), and Kori (2032) — because both scenarios share identical existing-reactor configurations. Table III lists saturation years for the three main scenarios.

Table III: At-Reactor Storage Saturation Year by Scenario

	Kori	Hanbit	Hanul	Saeul	Wolsong	CANDU
S0, S3	2032	2030	2031	2064	2042	2034
S3-A	2032	2030	**2054**	**2074**	2042	2034

In S3-A, adding two units each at Hanul and Saeul delays saturation from 2031 to 2054 and from 2064 to 2074, respectively. Hanbit saturation remains unchanged (2030) because the 6-year lead time is still insufficient to commission units before pool saturation occurs.

The planned at-reactor dry storage facilities at Kori, Hanbit, and Hanul can provide additional short-term buffer capacity beyond wet pool saturation, potentially deferring transport to the IS facility until after its opening in 2050. When combined with existing-site NPP deployment (S3-A), dry storage provides a dual buffer of wet pool and dry storage capacity, serving as an effective short-term mitigation strategy prior to IS facility opening in 2050.

Fig. 4 shows the at-reactor SNF inventory by site for S1. All existing sites accumulate SNF continuously until IS opening in 2050, when inventories decline sharply. Hanul reaches its peak of ~10,837 tHM at IS opening. NEW-1 reaches its peak of approximately 8,454 tHM in 2092 before declining as DF transports commence.

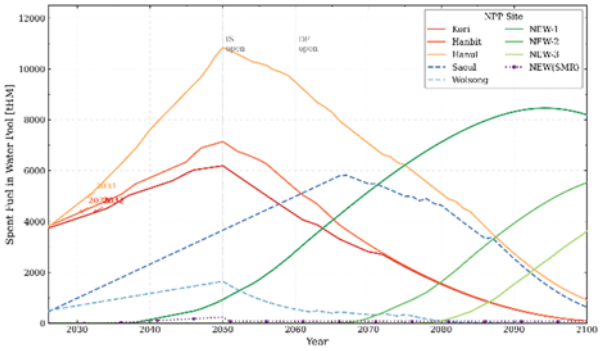


Fig. 4. Spent Fuel Inventory in Water Pool by Site – S1

4.3 Interim Storage Requirements

Table IV presents IS requirements by scenario. Transport from wet pools to the IS facility uses the dynamic priority algorithm described in Section 3.2. IS-to-DF transport applies 400 tHM/yr (PWR+SMR) and 380.16 tHM/yr (CANDU), allocated in proportion to IS inventory share. Relative to S0, PWR+SMR IS buildings increase from 25 to 29 under S3 — a 16% increase — indicating that the current national high-level waste management plan, based on S0, may underestimate facility needs if demand grows as projected. Among sub-scenarios, S3-A yields the same building count as S3 (29), suggesting that existing-site deployment primarily affects pool saturation timing rather than IS building requirements. In S3-B, the building count increases by five relative to S3 (29→34): i-SMR SNF accumulates in the shared PWR+SMR IS inventory, reducing the PWR disposal allocation and causing greater PWR IS buildup, highlighting the need for a dedicated i-SMR disposal pathway. S3-C yields the same building count as S3 (29), confirming that the absence of LTO amplifies disposal area requirements more than IS building needs.

Table IV: Interim Storage Requirements by Scenario

	PWR+SMR Casks	IS Buildings	CANDU MACS-TOR	Storage & Cask Cost (100M KRW)
S0	2,724	25	20	147,460
S1	4,046	29	20	206,340
S2	4,806	29	20	236,740
S3	5,400	29	20	260,500
S3-A	5,504	29	20	264,660
S3-B	5,019	34	20	252,760
S3-C	5,624	29	20	269,460

Fig. 5 shows total PWR+SMR SNF generation (bars) and combined cask-and-storage cost (line) by scenario. Both increase proportionally with demand from S0 to S3. Under S3, cumulative generation reaches ~100,866 tHM and total cost reaches approximately KRW 26.1 trillion — 96% and 77% above S0, respectively. S3-B total cost (KRW 25.3 trillion) is lower than S3 and S3-A despite more IS buildings, because fewer large-NPP casks are required. S3-C records the highest generation (104,997 tHM) and cost (KRW 26.9 trillion) of all scenarios.

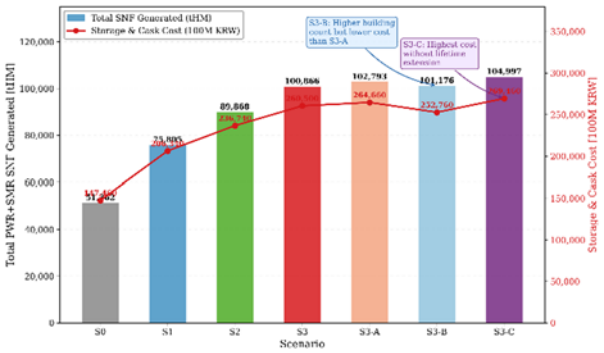


Fig. 5. PWR+SMR Total SNF Generation and Interim Storage & Cask Cost by Scenario

4.4 Disposal Site Requirements

Fig. 6 shows disposal area requirements. Disposal areas are calculated using the existing KRS disposal concept [5]: 147.5 m²/tHM for PWR and 21.7 m²/tHM for CANDU, derived from unit disposal areas of 295 m²/canister (4 assemblies per canister) for PWR and 208 m²/canister (480 bundles per canister) for CANDU. As no dedicated disposal standard for i-SMR SNF has been established, the same unit area as PWR (147.5 m²/tHM) is applied conservatively. CANDU disposal area is constant across all scenarios because no additional CANDU units are built.

Total disposal area grows from 7.92 km² (S0) to 15.22 km² (S3), a 92% increase attributable entirely to PWR SNF accumulation. S3-B slightly reduces PWR disposal area (13.69 km²) through large-NPP substitution, but SMR disposal area grows from 0.14 to 1.23 km², yielding a net total of 15.27 km². S3-C reaches the largest total area (15.83 km²), confirming that the absence of LTO amplifies long-term disposal burden most severely.

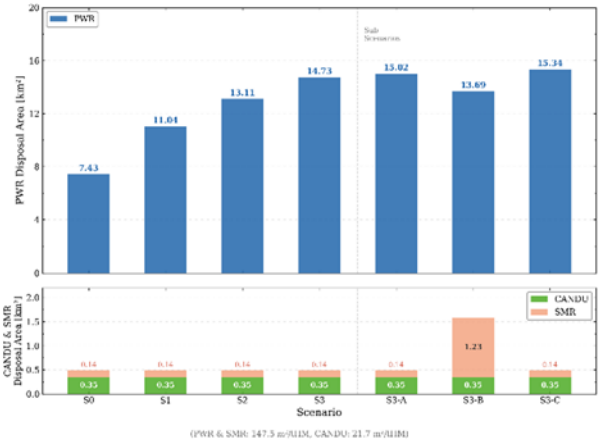


Fig. 6. Disposal Area Requirements by Reactor Type and Scenario

4.5 Impact of Sub-Scenarios

S3-A (Existing-Site Utilization): Shortening the lead time from 9 to 6 years enables faster supply and delays pool saturation at Hanul and Saeul. However, +6 units alone cannot meet S3 demand; new-site development must proceed in parallel.

S3-B (SMR Expansion to 12 Units): Twelve i-SMR units (~8.4 GWe) reduce gap-based large NPP orders by 6 units and lower PWR disposal area by ~1.05 km² relative to S3. However, SMR disposal area grows by ~1.10 km², resulting in a marginally higher net total disposal area (+0.05 km²) than S3. The absence of a dedicated i-SMR disposal standard and dispersed siting increase SNF management complexity.

S3-C (No Lifetime Extension): Eliminating LTO requires approximately 13 additional large NPPs relative to S3, increasing SNF generation and disposal burden substantially. LTO is thus a significant policy lever not only for electricity security but also for containing back-end fuel cycle costs.

4.6 Policy Implications

Fig. 7 compares the percentage increase in PWR+SMR IS buildings and total disposal area relative to S0. CANDU MACSTOR shows 0% change across all scenarios. IS building count increases 16% from S0 under S1–S3 and S3-A, while disposal area increases 46–96%, consistently outpacing IS growth. In S3-B, the IS building count increases by 36% due to SMR SNF accumulation, while disposal area (+93%) remains comparable to S3. Under S3-C, disposal area grows by 100% — the highest of all scenarios — reflecting the compounding effect of high demand and absent LTO.

The current national high-level waste management plan assumes S0-level operation. Should S3 demand and no-LTO conditions materialize simultaneously, disposal area could expand to twice the current plan estimate, while IS facility requirements increase by approximately 16%. Periodic revision of the SNF management plan

synchronized with each BPLE cycle is therefore essential, alongside technologies that reduce disposal inventory — high-burnup fuel, reprocessing and transmutation, and i-SMR fuel efficiency improvements.

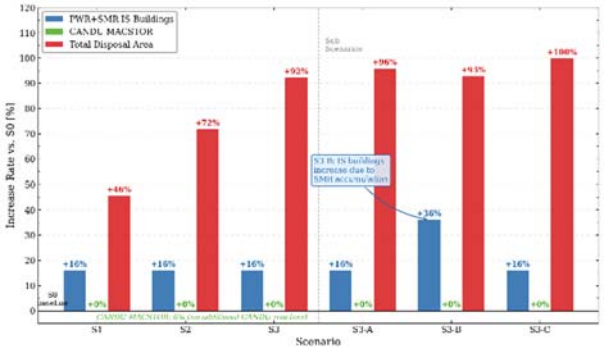


Fig. 7. SNF Management Requirements Increase Rate Relative to S0 by Scenario (%)

5. Conclusions

This study applied an enhanced SNUCYCLE SD model to quantify SNF management requirements across seven scenarios from 2026 to 2100.

First, under the AI/mega-project demand scenario (S3), IS buildings increase by 16% and disposal area grows by 92% relative to S0. Second, existing-site utilization (S3-A) shortens the lead time from 9 to 6 years and extends pool capacity at Hanul and Saeul, but must be paired with new-site development. Third, i-SMR expansion (S3-B) reduces large-NPP orders but marginally increases net disposal area due to SMR footprint growth, and the absence of a dedicated disposal standard and dispersed siting create new SNF management challenges. Fourth, the absence of LTO (S3-C) mandates approximately 13 additional large NPPs versus S3, raising both generation and disposal burden significantly. Fifth, the structural mismatch between the 2-year BPLE cycle and the multi-decade horizon for SNF facility development necessitates institutionalizing a long-term SNF management planning framework.

The quantitative results of this study make clear that long-term policy planning alone is insufficient. Korea is approaching a point at which active R&D investment in technologies that physically reduce SNF volume and disposal area — including optimized canister loading, high-efficiency repository design, canister lid cutting technology to accelerate disposal throughput, and dedicated i-SMR disposal concepts — must be pursued in parallel with policy frameworks. The SNUCYCLE model provides a flexible quantitative platform for evaluating diverse demand, supply, policy, and technology scenarios as they evolve.

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