Effect of i-SMR Load-Following Operation on Energy Storage System Requirements under High Renewable Penetration Scenarios in the Korean Power System

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1. Introduction

The share of variable renewable energy (VRE) in the Korean power system is expected to expand rapidly under the 11th Basic Plan for Long-term Electricity Supply and Demand (2024–2038), which targets 77.2 GW of solar and 40.7 GW of wind capacity by 2038, while renewable sources (including non-VRE sources such as by-product gas, hydro, and biomass) supplied only 9.64% of electricity in 2023. This rapid, policy-driven expansion of VRE intermittency requires a corresponding expansion of energy storage system (ESS) capacity to maintain supply–demand balance.

Most existing studies quantify ESS requirements under VRE-only supply scenarios, treating the operational flexibility of dispatchable generation as a fixed assumption rather than an independent variable. The innovative Small Modular Reactor (i-SMR), currently under standard design certification review in Korea (170 MWe per module, 680 MWe per four-module standard plant), is designed as a load-following, carbon-free flexibility resource with a target output range of 20–100% of rated power and a linear ramp rate of 5%/min [2]. However, the quantitative relationship between i-SMR load-following operation and the resulting reduction in ESS requirement—and the number of i-SMR modules needed to reach a given share—has not been established in the literature.

Given the scale of hourly variability in Korean net load, a comparable reduction in ESS requirement could, in principle, be pursued with any sufficiently large dispatchable low-carbon resource, including conventional large-scale nuclear power plants. In practice, however, large PWRs are predominantly operated near baseload, and frequent load-following is generally not their intended mode of operation [6]. i-SMR, by contrast, is explicitly designed for load-following operation, with a boron-free, control-rod-driven design [5] intended to enable rapid and repeated output adjustment. The comparative advantage this study attributes to i-SMR is therefore not generation capacity per se, but its superior output controllability relative to large reactors, which is the specific mechanism through which it reduces ESS requirements.

This study addresses this gap by (i) constructing an hourly time-series dispatch simulation, driven by 2019–2025 Korea Power Exchange (KPX) historical data, in which the i-SMR fleet tracks the residual load in real time ahead of the ESS with zero curtailment, and (ii) extending the methodology to the 11th Basic Plan target years (2030, 2036, 2038) to quantify how i-SMR load-following operation affects ESS requirements under both historical and policy-projected high-VRE-penetration conditions.

2. Methodology

The simulation defines net power as $P_{\mathrm{net}}(t) = P_{\mathrm{VRE}}(t) + P_{\mathrm{SMR}}(t) - P_{\mathrm{D}}(t)$, where P_{VRE}, P_{SMR}, and P_{D} denote hourly VRE generation, i-SMR output, and demand. ESS state of charge (SOC) is accumulated as

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1) + \eta_{\mathrm{c}} P_{\mathrm{ch}}(t) - \frac{P_{\mathrm{dis}}(t)}{\eta_{\mathrm{d}}}$$

where $\eta_{\mathrm{c}} = 0.92$ and $\eta_{\mathrm{d}} = 0.90$ are the charge and discharge efficiencies. The required ESS energy capacity is defined as $\max \mathrm{SOC}(t) - \min \mathrm{SOC}(t)$ for each of seven independent weather-years (2019–2025); the weather-year yielding the maximum requirement is adopted as the representative value, following Ruhnau and Qvist [1], who showed that single-year optimization can underestimate multi-year storage requirements. Because the solar and wind energy produced in the KPX data (4.7–14.7 TWh/yr, 0.9–2.6% of demand) is far below demand (about 565 TWh/yr), the produced solar $S(t)$ and wind $W(t)$ of each year are scaled by one common factor, $P_{\mathrm{VRE}}(t) = k[S(t) + W(t)]$, so that the solar-to-wind ratio of that year is kept; capacities are obtained with capacity factors of 0.14 (solar) and 0.23 (wind), and k is found by bisection so that $\mathrm{SOC}(8760) = \mathrm{SOC}(0)$ in each year. Six scenarios (S0–S5) are defined by the i-SMR share of annual generation, from 0% to 50% in 10-percentage-point steps, with zero curtailment and zero supply deficit enforced in every scenario: every surplus MWh is stored and every deficit is served from storage. Fig. 1 shows the underlying 2019–2025 KPX dataset used to drive the simulation, confirming that measured hourly demand and VRE generation—not synthetic profiles—underlie all reported results.

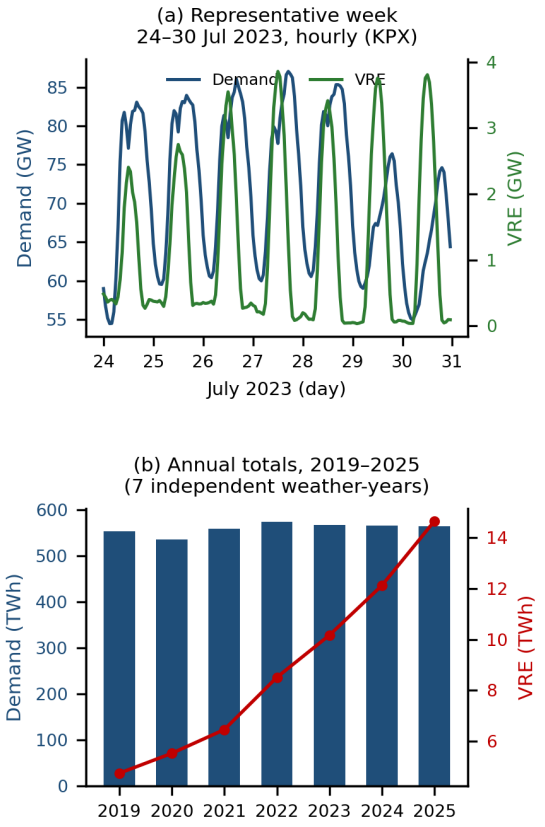


Fig. 1. Measured 2019–2025 KPX input data: (a) hourly demand and VRE generation for a representative week; (b) annual demand and VRE generation totals for the seven independent weather-years used in the simulation.

2.1 i-SMR dispatch formula

Because i-SMR has not yet been constructed or operated, no historical load-following dispatch data exist for calibration. The dispatch rule below is therefore a model-based idealization consistent with published i-SMR design targets [2] and a conservative ramp-rate assumption. At each hour t, the i-SMR fleet tracks the residual load in real time and is dispatched before the ESS,

$$P_{\mathrm{SMR}}(t) = \mathrm{clip}[P_{\mathrm{D}}(t) - P_{\mathrm{VRE}}(t), 0.2C_{\mathrm{inst}}, C_{\mathrm{inst}}]$$

$$|P_{\mathrm{SMR}}(t) - P_{\mathrm{SMR}}(t-1)| \le 0.5C_{\mathrm{inst}}$$

where $C_{\mathrm{inst}} = 170\,\mathrm{MWe} \times N_{\mathrm{module}}$ is the installed fleet capacity. When VRE is short (night and cloudy hours), the fleet rises to full output first and the ESS discharges only the remaining deficit; when VRE is in surplus, the fleet falls to 20% of rated power, consistent with the 20–100% design range of each module, and all surplus is stored. The ramp limit of 50% of rated power per hour is conservative relative to the 5%/min design value. No annual energy target is imposed on the hourly dispatch; the i-SMR share is the outcome of this rule for a given fleet.

The fleet size (an integer number of 170 MWe modules, identical for all seven weather-years) is then found iteratively so that the seven-year i-SMR share equals the scenario target s^*,

$$s(N_{\mathrm{module}}) = \frac{\sum_y E_{\mathrm{SMR},y}}{\sum_y (E_{\mathrm{SMR},y} + E_{\mathrm{VRE},y})} = s^*$$

Because s increases monotonically with N_{module}, N_{module} is obtained by bisection, and the VRE scale factors are re-solved for each weather-year at every trial N_{module}. The model uses an hourly energy balance and assumes that all modules are available; forced outages, refuelling, and maintenance are not modelled.

The methodology is further extended to 2030, 2036, and 2038 using 11th Basic Plan target demand and capacity data [4]. The hourly demand shape is projected using an affine transform, $D_{\mathrm{fut}}(t) = aD_{\mathrm{hist}}(t) + b$, that simultaneously matches annual energy and summer peak demand. Solar and wind profiles are built from the planned capacities of each target year (capacity factors 14% and 23%) and the measured hourly shapes, and both are multiplied by a common factor k so that the Plan mix is preserved; k is therefore the multiple of the Plan VRE capacity needed for zero annual SOC drift. The Plan mix is adopted as stated, although the planned offshore wind expansion may be constrained by port infrastructure [3].

3. Results and Discussion

Table 1 summarizes the validation results (2019–2025). With VRE alone (S0), supplying the demand requires 367 GW of solar, 81 GW of wind, and 42.6 TWh of ESS. As the i-SMR share rises to 50% (S5, 43.5 GW, 256 modules), the solar and wind capacities fall to 175 GW and 38 GW, and the ESS requirement falls to 20.5 TWh, a 51.9% reduction, with zero curtailment and zero supply deficit in all scenarios; 2025 is the binding weather-year in every scenario. Each 10-percentage-point step adds about 8.7 GW of i-SMR and lowers the ESS requirement by 4.1–4.7 TWh, about 10% of S0.

Table 1. i-SMR, solar, wind, and ESS requirements by i-SMR share, validation scenarios (2019–2025)

Scenario	i-SMR (%)	i-SMR (GW)	Solar / Wind (GW)	ESS (TWh)
S0	0	0.0	367 / 81	42.6
S1	10	9.4	327 / 72	37.9 (−11%)
S2	20	18.4	287 / 63	33.3 (−22%)
S3	30	27.2	248 / 54	29.0 (−32%)
S4	40	35.5	211 / 46	25.0 (−41%)
S5	50	43.5	175 / 38	20.5 (−52%)

Because the fleet runs at full output whenever VRE is short (4,626 h in 2025 for S5), it directly supplies the night-time and winter deficits that the ESS would otherwise carry, and the annual ESS charge falls by 74% (276.5 → 71.6 TWh). The energy balance confirms that no energy is curtailed: total generation exceeds demand only by the ESS round-trip loss (47.6 TWh in S0 and 12.3 TWh in S5). Fig. 3 illustrates this hourly operation over three winter days.

For the 11th Basic Plan target years, the solar-to-wind ratio of each year's Plan is used (Fig. 2). The VRE-only requirement rises to 48.6, 52.5, and 55.9 TWh in 2030, 2036, and 2038, and falls by 54.0%, 55.9%, and 57.3% at 50% i-SMR share (46.8, 51.3, and 52.7 GW of i-SMR).

The larger reduction in later years comes from the change in the solar-to-wind mix rather than from demand growth: the Plan raises the wind share (solar : wind capacity ≈ 4.5 : 1 in the 2025 production versus 1.9 : 1 in 2038), and wind, which is relatively stronger in winter and at night, reduces the long-term seasonal storage that the ESS must carry once i-SMR runs at full output during VRE shortfalls. With 2025 demand and weather held fixed and only the mix changed to the 2038 Plan ratio, the reduction at 50% i-SMR share rises from 51.9% to 61.1%. In 2038, supplying the demand with VRE alone requires 290 GW of solar and 153 GW of wind, 3.8 times the Plan targets of 77.2 GW and 40.7 GW; with 50% i-SMR share, 139 GW and 73 GW (1.8 times the targets) suffice, underscoring the structural role of a flexible, dispatchable resource such as i-SMR in a renewable-dominated system.

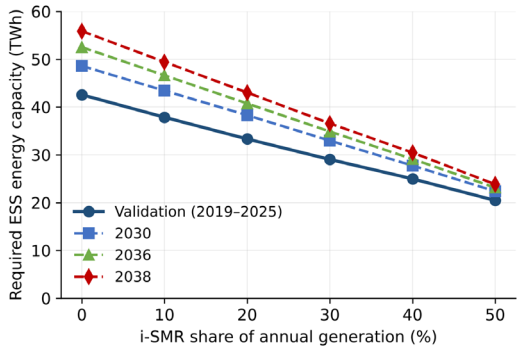


Fig. 2. Required ESS energy capacity (TWh) vs. i-SMR share of annual generation (%): validation (2019–2025) and future scenarios (2030/2036/2038).

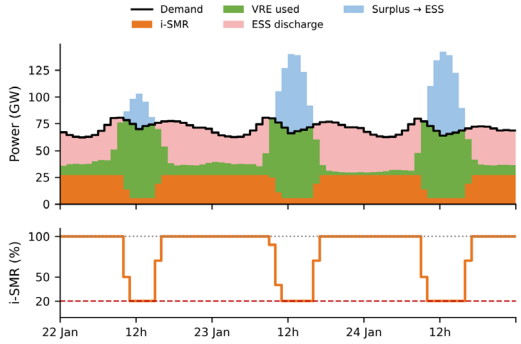


Fig. 3. Simulated hourly operation over three winter days (2025 weather-year): i-SMR runs at 100% when VRE is short and at 20% at midday; all surplus is stored in the ESS.

4. Conclusion

This study quantified the effect of i-SMR load-following operation on ESS requirements using an hourly time-series simulation in which the i-SMR fleet follows the residual load ahead of the ESS with zero curtailment, extended to the 11th Basic Plan target years. Supplying the demand with VRE alone requires 42.6 TWh of ESS for 2019–2025 and 55.9 TWh in 2038. When i-SMR supplies 50% of electricity, the required ESS falls by 51.9% in historical validation and by 54.0–57.3% under future policy scenarios, while the required solar and wind capacity falls from 448 GW to 213 GW; in 2038, the VRE capacity needed falls from 3.8 to 1.8 times the Plan targets. For carbon neutrality, overcoming daily and seasonal renewable intermittency with VRE alone would require ESS of very large capacity, whereas introducing i-SMR with its superior load-following capability was confirmed to substantially reduce the required ESS and VRE capacity. The results support i-SMR specifically—rather than large-scale nuclear power operated at baseload—as the more effective choice, owing to its superior output controllability. These results provide a quantitative reference for ESS capacity planning as i-SMR standard design certification and demonstration progress toward commercial deployment in the mid-2030s.

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