Assessment of an SMR–Renewable Energy Hybrid System for Stable Power Supply to the Saemangeum Industrial Complex

Kyung Jin Park[a,b,*], Keung Koo Kim[a], Hak-kyu Lim[a]
[a] KEPCO International Nuclear Graduate School (KINGS), [b] SUNG IL CO., LTD. (SIM),
*Corresponding author: pcpkj@naver.com
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1. Introduction

Carbon neutrality and the expansion of large electricity-consuming facilities, including AI data centers, hydrogen production by electrolysis,require industrial complexes to secure a stable 24-hour electricity supply. Saemangeum is being developed as a renewable-energy-based industrial complex; however, hourly and seasonal variations in solar and wind generation can cause supply–demand mismatches even when annual generation is sufficient. This study therefore investigates a combined power-supply system using SMRs and ESSs. Three scenarios integrating renewable energy, small modular reactors (SMRs), and energy storage systems (ESSs) were analyzed for the Saemangeum Industrial Complex using 2025 renewable-generation data, with a focus on supply reliability, required ESS capacity, and economic performance.

2. Methodology

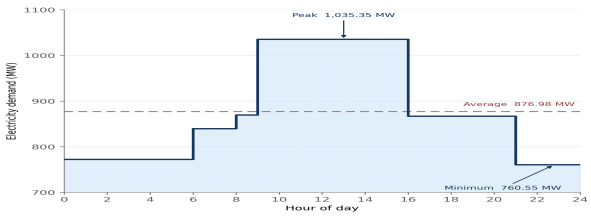


Fig. 1. Hourly Electricity Demand of the Saemangeum Industrial Complex

The hourly load profile was constructed based on projected electricity demand from a 500 MW AI data center, a 200 MW hydrogen electrolysis facility, robotics and component manufacturing and chemical materials facilities. The annual electricity demand was estimated at 7,682 GWh, with a peak demand of 1,035 MW. For the hourly renewable generation profiles, the 2025 hourly generation data from Korea Southern Power's 893-kW Iksan Dasong-ri solar PV plant were scaled proportionally to the installed capacity, while nationwide hourly onshore wind generation data were used for wind power. Therefore, the results of this study should be interpreted as a system-level comparative assessment rather than a site-specific generation forecast. The ESS charging and discharging efficiencies were each set to 90%, and the depth of discharge (DoD) was set to 80%. Electricity imports from the external grid were excluded.

Scenario A meets demand using renewable energy and ESS alone. Scenario B operates a 680 MW SMR continuously at fixed baseload output, while the ESS balances residual surpluses and deficits. Scenario C absorbs all available solar and wind generation without curtailment, jointly dispatching a load-following SMR (170–680 MW) and the ESS. To maintain zero curtailment, ESS discharge may precede an increase in SMR output.

Table I: Power Mix and Operating Principles by Scenario

Scenario	Power mix	SMR operation	Variability response
Scenario A	Solar + Wind + ESS	-	ESS only
Scenario B	SMR + Solar + Wind + ESS	Fixed at 680 MW	ESS only
Scenario C	Solar + Wind + SMR + ESS	170–680 MW	SMR + ESS

3. Power Balance Analysis and Required ESS Capacity

All scenarios met hourly electricity demand over the 8,760-hour simulation with zero grid imports. The required ESS size was obtained by tracking hourly charging and discharging with 90% efficiencies and 80% DoD. For the Scenario C, zero renewable curtailment and equal initial and final ESS energy were imposed, and a minimum-capacity dispatch was selected.

In Scenario A, 5,220 MW of solar PV and 522 MW of wind generated about 8,498 GWh per year, requiring 733.2 GWh of ESS storage. Scenario B combined a 680 MW fixed-baseload SMR (5,957 GWh) with 1,857 GWh of renewables and required 162.3 GWh of storage. In Scenario C, renewable generation remained 4,249 GWh, but SMR generation fell to 3,691 GWh (capacity factor: 62.0%), and the ESS capacity was 12.9 GWh. Zero curtailment was achieved through increased ESS cycling. Scenario A's unusually large storage reflects long-duration and seasonal energy shifting under zero grid import rather than a conventional short-duration battery application.

Table II: Installed Capacities and Power-Balance Results

Item	Scenario A	Scenario B	Scenario C
Solar PV capacity (MW)	5,220	1,141	2,610
Wind capacity (MW)	522	114	261
SMR capacity (MW)	-	680	680
Required ESS capacity (GWh)	733.2	162.3	12.9
Annual solar generation (GWh)	7,109	1,554	3,554
Annual wind generation(GWh)	1,389	304	694
Annual SMR generation(GWh)	-	5,957	3,691
Annual ESS charging (GWh)	4,290	693	1,353
Annual ESS discharging(GWh)	3,475	562	1,096
Capacity factor (%) Solar/Wind/SMR	15/30/-	15/30/100	15/30/62
Final supply (GWh)	7,682	7,682	7,682
Unmet demand / curtailment (GWh)	0 / 0	0 / 0	0 / 0

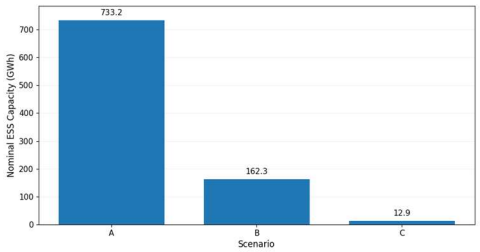


Fig. 2. Comparison of Nominal ESS Capacity by Scenario

Fig. 2 compares minimum ESS energy capacities across the three scenarios. With no firm generation in Scenario A, ESS must manage all renewable variability. In Scenario B, the fixed-baseload SMR reduces the net balancing requirement, but ESS still manages large seasonal mismatches. In Scenario C, load-following SMR output and actively managed ESS charging/discharging jointly maintain the power balance without renewable curtailment; ESS may discharge even when additional SMR output is available, preserving room for subsequent renewable surpluses. Consequently, the required nominal ESS capacity is 12.9 GWh. The installed solar-plus-wind capacity is about 5.74 GW (5.55 times peak demand) for A, 1.26 GW (1.21 times peak demand) for B, and 2.87 GW (2.77 times peak demand) for C.

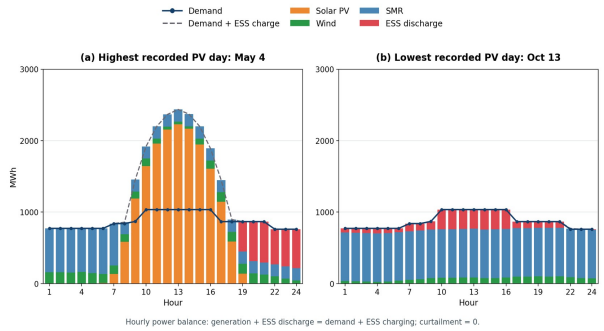


Fig. 3. Scenario C Hourly Dispatch on Maximum and Minimum Recorded PV Days

Fig. 3 illustrates Scenario C hourly operation on the highest and lowest recorded PV days. On May 4, surplus renewable energy is absorbed by ESS charging rather than curtailed. On October 13, zero recorded PV output is offset by SMR generation and ESS discharge. Over the year, renewable output was fully utilized with zero unmet demand, while coordinated SMR–ESS dispatch limited the nominal ESS energy capacity to approximately 12.9 GWh.

4. Economic Analysis

For the economic comparison, solar PV, onshore wind, and i-SMR reference costs of KRW 129, 165, and 105/kWh, respectively, were applied [1,2]. Because commercial SMR costs remain uncertain, the SMR unit cost was used for relative comparison rather than as a definitive commercial estimate. Annual source costs were calculated as generation multiplied by the applicable unit cost. ESS costs were separated into capital and fixed O&M components instead of applying a single LCOS. Domestic LFP ESS reference values of KRW 369,936/kWh for energy capacity, KRW 245,295/kW for PCS and grid connection, and KRW 10,770/kW·yr for O&M were applied [3]. ESS capital cost was calculated from nominal battery capacity and the sum of maximum hourly charging and discharging PCS ratings, and annualized over 10 years at 5% (CRF = 0.1295). Fixed O&M was calculated from the combined PCS rating, yielding about KRW 25.4 billion/yr for Scenario C. With a 62.0% capacity factor in Scenario C, the SMR reference unit cost was scaled from 105 to approximately KRW 169.5/kWh, holding annual SMR cost constant.

Table III: Comparison of Costs and LCOE by Scenario

Cost item	Scenario A	Scenario B	Scenario C
Solar PV (100 million KRW/yr)	9,170	2,004	4,585
Wind (100 million KRW/yr)	2,292	501	1,146
SMR (100 million KRW/yr)	-	6,255	6,255
Total ESS installation cost (100 million KRW)	2,724,364	603,073	53,422
Annualized ESS installation cost (100 million KRW/yr)	352,818	78,101	6,918
ESS O&M cost (100 million KRW/yr)	527	115	254
Total annual ESS cost (100 million KRW/yr)	353,344	78,216	7,173
Total annual cost (100 million KRW/yr)	364,806	86,976	19,158
LCOE (KRW/kWh)	4,749	1,132	249

The adjusted system-level cost per unit of delivered electricity was approximately KRW 4,749/kWh for Scenario A, KRW 1,132/kWh for Scenario B, and KRW 249/kWh for Scenario C, ranking C, B, and A from lowest to highest under the stated assumptions. In Scenario C, the lower SMR capacity factor raises the assumed unit SMR cost to approximately KRW 169.5/kWh. Nevertheless, coordinated no-curtailment operation limits nominal ESS energy capacity to 12.9 GWh, substantially reducing storage capital cost relative to A and B. Compared with the earlier dispatch, Scenario C requires more ESS cycling and PCS capacity, increasing annual ESS expense. The main result remains the reduced long-duration energy-storage requirement, not a definitive commercial cost ranking. These results compare simplified system configurations rather than predict absolute commercial generation costs; Table III values are individually rounded. The LFP ESS benchmarks describe mainly six-hour systems, so applying the same costs to very long-duration storage may overstate expenditures. Scenario B assumes a 100% SMR capacity factor with no maintenance or outages. Scenario C neglects reactor ramp-rate and minimum operating-time constraints, storage degradation, and reserve requirements. Its no-curtailment dispatch includes ESS discharge before fully utilizing SMR output, and the zero-PV records on October 12–13 may reflect source-data anomalies. SMR cost adjustment assumes annual cost fixed and scales inversely with capacity factor rather than separating fixed and variable operating costs.

5. Conclusion

This study evaluated the efficiency of an SMR–renewable energy–ESS hybrid system for the Saemangeum Industrial Complex, considering the growing demand for carbon neutrality and reliable electricity supply driven by climate change and the expansion of energy-intensive industries, including AI data centers. The 8,760-hour simulation demonstrated that all three scenarios met the annual electricity demand of 7,682 GWh without grid imports or unmet demand. The required nominal ESS capacity was 733.2 GWh in Scenario A and 162.3 GWh in Scenario B with fixed SMR baseload operation, whereas Scenario C, integrating renewable energy with load-following SMR operation, reduced the required capacity to approximately 12.9 GWh. This represents reductions of 98.2% and 92.1% compared with Scenarios A and B, respectively, while achieving the lowest adjusted LCOE of approximately KRW 249/kWh. These findings suggest that flexible SMR load-following operation can mitigate renewable energy intermittency and minimize ESS dependence, providing a potentially reliable and cost-effective power supply strategy that supports carbon neutrality. However, further validation of practical operating constraints, generation-data uncertainties, and commercial costs is required.

※ Affiliation
KEPCO International Nuclear Graduate School (KINGS)

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