

Economics of the Marginal SMR Module in an Off-Grid 24/7 Carbon-Free Data-Center Microgrid

Sungmun Yoon ^{a*}, Kangwook Cho ^a, Soojin Park ^a

^aKEPCO International Nuclear Graduate School (KINGS), 658-91 Haemaji-ro, Seosaeng-myeon, Ulju-gun, Ulsan 45014, Republic of Korea

*Corresponding author: sungmoon88@naver.com

***Keywords :** Small modular reactor, Data center, 24/7 carbon-free energy, HOMER Pro, Module count

1. Introduction

Gigawatt-scale artificial-intelligence (AI) data-center projects are moving forward in Korea [1–3], and the loads will be served by an isolated power system with expanding carbon-free commitments [4]. A facility drawing about a gigawatt continuously raises a supply question that annual renewable-energy accounting does not answer: which carbon-free portfolio can follow the load hour by hour, and at what cost.

Small modular reactors (SMRs) are often proposed for this application, and the Korean i-SMR program provides a concrete 170-MW module around which the case can be examined [5]. Most techno-economic studies, however, evaluate a plant whose size or module count is fixed before the analysis begins [6,7], and previous work on reactor sizing for data centers has treated the question parametrically, without hourly competition against renewables and storage [8]. Studies on 24/7 carbon-free energy (CFE) have mostly addressed grid-connected procurement [9,10]. In this work the module count is determined endogenously. Up to eight 170-MW module slots compete with photovoltaics (PV), offshore wind, and battery storage for a gigawatt-class Korean data-center load across 24 cost and financing cases, and the full assessment is reported in [11]. This paper examines one question from that assessment in detail, namely, when one more SMR module is worth building. We refer to this as the economics of the marginal module.

2. Model and Scenario Summary

The system is an off-grid, all-carbon-free microgrid dispatched in HOMER Pro over 8,760 hours and a 60-year project horizon. The load represents a hyperscale AI campus. A constant 800-MW IT block scaled by a climate-adjusted monthly power usage effectiveness yields 8,760.6 GWh per year, and stochastic variability of 5% day-to-day and 2% per timestep raises the realized simulation peak to 1,190.7 MW. Solar irradiance and ambient temperature are taken from Korea Meteorological Administration Mokpo ASOS station 165, and offshore wind from a NASA POWER reference point near the Yeonggwang-Nakwol offshore wind area; both are 2016–2025 hour-by-hour mean profiles. Candidate assets are up to eight 170-MW i-SMR module slots, utility-scale PV, 8-MW-class

offshore wind units, lithium-ion battery storage (BESS), and a bidirectional converter, with cost inputs anchored to Korean and U.S. reference sources [12–14]. No grid connection, fossil backup, or demand response is available, so every feasible portfolio must serve the full hourly demand without external support. Dispatch must hold an operating reserve equal to 10% of hourly load plus 80% of PV output and 50% of wind output, and the annual capacity-shortage input is set to 0%, for which HOMER applies an effective evaluation tolerance of about 0.1%.

Twenty-four cases are obtained by crossing six SMR overnight-cost levels with three real discount rates. The cost ladder runs from the i-SMR target cost (4,288 \$/kW) [5], through three intermediate beyond-first-of-a-kind estimates from an INL/GAIN meta-analysis (5,895–10,719 \$/kW) [16], to a U.S. DOE model-based first-of-a-kind estimate (13,000 \$/kW) [15] and a cost derived from the NuScale CFPP demonstration project (17,550 \$/kW) [7]; the DOE-based level serves as the base case. The discount rates of 2.0, 4.5, and 7.0% represent sovereign-backed nuclear financing, the Korean public-appraisal standard, and a private hurdle rate, respectively [12,17]. Two variants additionally apply nth-of-a-kind (NOAK) renewable cost reductions at the base and high-cost anchors; we refer to these as the base and high-cost cases with renewable learning. Two exogenous modeling assumptions deserve explicit mention. First, a staggered planned-maintenance calendar (monthly outage windows arranged to avoid the summer load peak) is imposed on the module slots in order to enforce a 93% capacity-factor anchor; the realized fleet availability under this calendar is 92.0–92.3%. Second, the discount rates are input assumptions rather than observed financing terms. The single SMR operation-and-maintenance input includes fuel cost and an annualized decommissioning provision. Full input documentation and verification records are given in [11].

3. Overview of Optimization Outcomes

Every case returns a valid least-cost portfolio, and the winning module counts are not uniform: eight modules win in four cases, seven in fifteen, six in two, five in two, and zero in one. Table 1 organizes the outcomes as a base case with four perturbations. The base case is structurally stable, selecting seven modules plus 363–401 MW of PV and roughly one gigawatt-hour of BESS

at every discount rate, with the reactors supplying about 95% of annual energy. When the SMR is cheap enough, the portfolio becomes an all-nuclear corner. At the i-SMR target cost, eight modules win at all three rates, and the only remaining asset is 0.21–0.25 GWh of battery. When the SMR is expensive, the portfolio shifts toward renewable–storage hybrids, but only under financing stress; the high-cost case keeps the seven-module architecture at 2.0 and 4.5% and drops to six modules with 29 wind units at 7.0%. Renewable cost learning matters mainly where the reactors are already expensive. It improves NPC by only 0.9–2.1% at the base anchor, but removes modules at every rate at the high-cost anchor and, at 7.0%, eliminates nuclear entirely. This zero-SMR case should be interpreted carefully, since it outperforms the best SMR-retaining candidate by \$70.6M, a 0.31% margin, under three simultaneous stresses. Raising the real discount rate from 2.0 to 7.0% leaves the base-case architecture unchanged but moves the two headline metrics in opposite directions: NPC falls from \$26.54B to \$20.58B, while LCOE rises from 0.0872 to 0.1674 \$/kWh through the higher capital-recovery factor, so the two metrics must be read separately [11]. Hourly CFE matching stays between 99.968% and 100.000% in every case and does not discriminate among the portfolios; the meaningful differences appear in cost and over-generation [11].

Table I: Base case and four perturbations
(winning architectures; NPC in \$B at 2.0 / 4.5 / 7.0% real discount rates).

Perturbation	Winning architecture	NPC [\$B]
Base case (DOE FOAK, 13,000 \$/kW)	7 modules + PV 363–401 MW + BESS 0.96–1.05 GWh; no wind	26.54 / 22.57 / 20.58
i-SMR target (4,288 \$/kW)	8 modules + BESS 0.21– 0.25 GWh only	15.97 / 12.00 / 10.08
High cost (NuScale FOAK, 17,550 \$/kW)	7-module bridge at 2.0/4.5%; at 7.0%: 6 modules + PV 549 MW + 29 wind + BESS 3.1 GWh	32.04 / 28.10 / 25.74
Renewable learning (Base / High anchor)	Base: 7/7/5 modules High: 6/5/0	Base : 26.16 /22.36/20.15 High :31.08 /26.60/22.58
Financing: 2.0% → 7.0% (base case)	Architecture unchanged	NPC : 26.54 → 20.58 LCOE(\$/kWh) : 0.0872 → 0.1674

4. The Economics of the Marginal Module

Module-level utilization explains most of what Table 1 shows. In the eight-module winner at the target cost

and a 4.5% rate, the first six modules run at capacity factors of 85.6–92.3%, the seventh at 41.6%, and the eighth at only 3.0%, or about 532 hours per year. The last module in the stack therefore functions as availability capacity for reserve provision and planned-outage coverage rather than as a baseload asset, and whether it is justified is essentially a question of capital utilization. An eighth module costs \$1.00B at an overnight cost of 5,895 \$/kW and \$2.98B at 17,550 \$/kW. The competing bundle, a few hundred megawatts of PV plus about a gigawatt-hour of storage, supplies the same marginal functions at a much lower capital cost once the overnight cost rises above the low-cost corner. Nor is the comparison biased toward the battery. The BESS is assigned a 15-year life, so the bridge carries three replacement events (years 15, 30, and 45) within the 60-year horizon and still remains cheaper than the eighth module.

Figure 1 plots the lowest candidate NPC at each module count for four representative cases. The curve shapes differ considerably among the cases. At the target cost (at a 4.5% rate) the curve falls monotonically all the way to eight modules. At the base and high-cost anchors (same rate) it reaches a shallow minimum at seven modules and bends upward at eight. The region around the optimum is flat but not symmetric: in the base case at 4.5%, adding the eighth module raises NPC by \$1.31B, whereas reducing the fleet to six modules raises it by \$1.07B. In the zero-SMR stress case (high cost with renewable learning, at 7.0%) the interior minimum disappears and the curve declines to zero modules. Figure 2 summarizes the same comparison across the whole cost ladder. $\Delta NPC(8-7)$ increases monotonically with overnight cost at every discount rate, and its sign change, that is, the cost level at which the eighth module ceases to be economical, lies between 5,895 and 8,575 \$/kW at a 2.0% rate and between 4,288 and 5,895 \$/kW at 4.5 and 7.0%. Linear interpolation places the crossing near 6,984, 5,056, and 4,340 \$/kW, respectively. These values are interpolated between simulated cost points and should not be read as simulated thresholds.

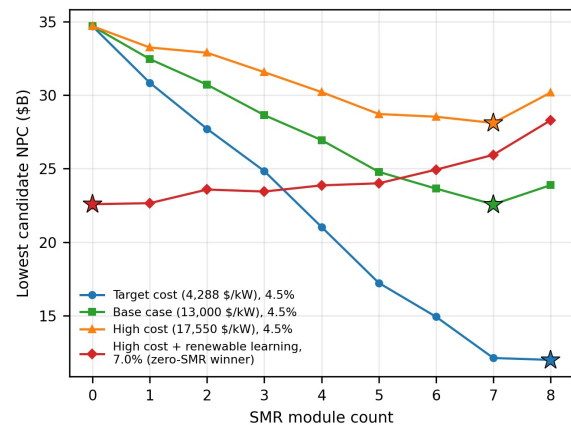


Fig. 1. Lowest candidate NPC by SMR module count for four

representative cases (stars mark winners). All values are taken directly from the HOMER optimization result files of [11].

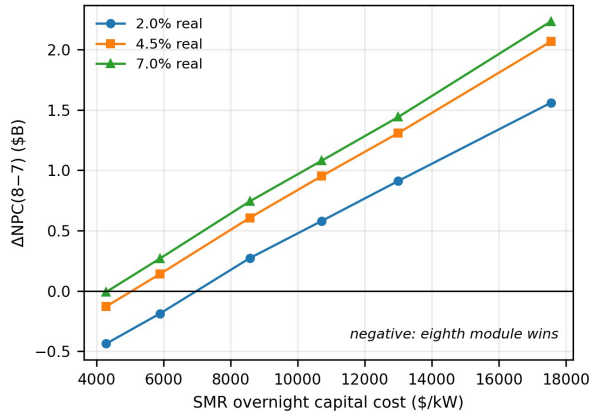


Fig. 2. NPC difference between the best eight-module and best seven-module candidates along the SMR cost ladder, by discount rate. All values are taken directly from the HOMER optimization result files of [11].

Two portfolio details support this interpretation. Storage appears in every winner, including the all-nuclear corners, which keep 212–247 MWh of battery while carrying no PV at all. This indicates that the BESS is selected to meet the operating-reserve requirement described in Section 2 rather than for bulk energy storage. In the seven-module winners the battery grows to roughly a gigawatt-hour and additionally covers planned-outage backfill, and only in the renewable-heavy cases does it become bulk storage, reaching 20.8 GWh in the zero-SMR stress case. Wind behaves as a strictly marginal resource at business-as-usual costs. It enters only where high overnight cost and high financing cost coincide (29 units in the high-cost case at 7.0%) and expands with renewable learning. Keeping seven modules also imposes little over-generation burden. The CFE over-generation gap is 0.52 percentage points in the base case at 4.5% and 0.1–0.7 points across the SMR-dominant winners, against 46.0 points in the zero-SMR stress case [11].

These results have a practical implication for module-count planning. The redundancy margin that a dedicated nuclear campus would conventionally hold as an extra unit is allocated, in this setting, to a small PV-plus-storage bridge, because the functions of the marginal module can be replicated at a much lower capital cost. The curve in Fig. 1 is flat enough near its optimum that the choice between seven and eight modules remains a genuine design decision. As the overnight cost rises, however, the balance shifts steadily against the eighth module, and this tendency holds at all three discount rates.

5. Conclusions

Treating the SMR module count as an optimization outcome rather than a design input yields information that fixed-configuration studies cannot provide. Across

the 24 cases the winning architectures span eight-, seven-, six-, five-, and zero-module portfolios. The seven-module configuration with a small PV and BESS complement is the dominant pattern, an all-nuclear corner appears at target-level SMR costs, and complete nuclear displacement occurs only under the combination of high SMR cost, renewable cost learning, and high financing cost, and even then by a margin of 0.31%. The marginal-module analysis suggests that fleet sizing for nuclear-powered data centers comes down to capital utilization. The reactors carry the load in nearly every case, and the remaining question is which asset supplies the last increment of availability at the lowest cost. The results are bounded by the study design, which assumes a single Korean site, 2016–2025 mean weather profiles, and a deliberately off-grid configuration serving as a diagnostic boundary; grid-connected variants remain future work. The full assessment, including sustainability indicators and diagnostic sensitivities, is given in [11].

ACKNOWLEDGMENT

This research was supported by the 2026 Research Fund of the KEPSCO International Nuclear Graduate School (KINGS), the Republic of Korea.

REFERENCES

- [1] 산업통상자원부 신산업분산에너지과 (Ministry of Trade, Industry and Energy of the Republic of Korea [MOTIE], New Industries and Distributed Energy Division), "전남 해남에 대규모 데이터센터 집적화단지 조성 — 솔라시도 데이터센터 파크 조성사업 업무협약(MOU) 체결 (Establishment of a Large-Scale Data Center Cluster in Haenam, Jeollanam-do — Solaseado Data Center Park MOU Signed)," 보도자료 0823(24 석간) [press release 0823, embargoed for the 24 August evening edition], 세종, 한국 (Sejong, Republic of Korea), 23 August 2023.
- [2] 관계부처합동 (Inter-Ministerial Joint, Republic of Korea), "국가 AI 컴퓨팅 센터 구축(SPC 설립) 실행계획 (안) (National AI Computing Center [KAIC] Construction and SPC Establishment Implementation Plan, draft)," 국정현안관계장관회의 겸 경제관계장관회의 25-4-4 (공개) [State Affairs Coordination Meeting jointly with Economic Affairs Coordination Meeting, document 25-4-4, public], Sejong, Republic of Korea, 22 January 2025.
- [3] 과학기술정보통신부 (Ministry of Science and ICT of the Republic of Korea [MSIT]), "국가 인공지능 컴퓨팅 센터 구축 사업, 우선협상대상자로 삼성 SDS 연합체(권소시업) 선정 (National Artificial Intelligence Computing Center Construction Project — Samsung SDS Consortium Selected as Preferred Bidder)," 보도자료 [press release], 세종, 한국 (Sejong, Republic of Korea), 10 March 2026.[4] International Energy Agency, Korea 2025: Energy Policy Review. Paris, France: IEA Publications, 2025.
- [5] S. J. Chang and S. J. Lee, "Economic feasibility analysis of innovative small modular reactor (i-SMR) applications in South Korea," in Trans. Korean Nuclear Society Spring Meeting, Jeju, Korea, May 22–23, 2025. Korea Hydro & Nuclear Power Co., Ltd., SMR Development Group.

- [6] A. Asuega, B. J. Limb, and J. C. Quinn, "Techno-economic analysis of advanced small modular nuclear reactors," *Applied Energy*, vol. 334, p. 120669, 2023, doi: 10.1016/j.apenergy.2023.120669.
- [7] P. Kim and A. Macfarlane, "Challenges of small modular reactors: A comprehensive exploration of economic and waste uncertainties associated with U.S. small modular reactor designs," *Progress in Nuclear Energy*, vol. 190, p. 105989, Aug. 2026, doi: 10.1016/j.pnucene.2025.105989.
- [8] B. N. Hanna, A. Abou-Jaoude, N. Guaita, P. Talbot, and C. Lohse, "Navigating economics of scale and multiples for nuclear-powered data centers and other applications with high service availability needs," *Energies*, vol. 17, no. 20, 5073, 2024, doi: 10.3390/en17205073.
- [9] Q. Xu, W. Ricks, A. Manocha, N. Patankar, and J. D. Jenkins, "System-level impacts of voluntary carbon-free electricity procurement strategies," *Joule*, vol. 8, no. 2, pp. 374–400, Feb. 2024, doi: 10.1016/j.joule.2023.12.007.
- [10] I. Riepin and T. Brown, "On the means, costs, and system-level impacts of 24/7 carbon-free energy procurement," *Energy Strategy Reviews*, vol. 54, p. 101488, Jul. 2024, doi: 10.1016/j.esr.2024.101488.
- [11] S. M. Yoon, K. W. Cho, S. J. Park, "SMR–renewable hybrid microgrids for 24/7 carbon-free data-center power: a techno-economic and sustainability assessment," manuscript under review, 2026.
- [12] H. S. Moon, S. Baik, and W. Y. Park, "Assessing the levelized cost of energy in South Korea," *Energy Strategy Reviews*, vol. 62, p. 101897, 2025, doi: 10.1016/j.esr.2025.101897.
- [13] W. Cole, J. Ramasamy, and T. Turan, "Cost projections for utility-scale battery storage: 2025 update," National Renewable Energy Laboratory, Golden, CO, USA, Tech. Rep. NREL/TP-6A40-93281, 2025. [Online]. Available: <https://docs.nrel.gov/docs/fy25osti/93281.pdf>
- [14] National Renewable Energy Laboratory (NREL), "2024 Annual Technology Baseline (ATB)," Golden, CO, USA, 2024. [Online].
- [15] U.S. Department of Energy (DOE), "Pathways to commercial liftoff: Advanced nuclear," Washington, DC, USA, DOE Liftoff Report, 2024.
- [16] Idaho National Laboratory (INL) / Gateway for Accelerated Innovation in Nuclear (GAIN), "Advanced reactor cost estimation: A meta-analysis," (Abou-Jaoude et al.), Idaho Falls, ID, USA, 2024.
- [17] 한국개발연구원(KDI) 공공투자관리센터 PIMAC, "공기업·준정부기관 사업 예비타당성조사 수행을 위한 일반지침 수정·보완 연구(제 4 판)," 2023 년도 공공기관 사업 예비타당성조사 연구보고서, 세종, 한국, 2023 년 12 월.