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Prospective Economics of Small Modular Reactors in Vietnam: A Time-Indexed Techno-Economic Assessment

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Abstract

Vietnam's growing electricity demand, net-zero commitment, and renewed consideration of nuclear power motivate a transparent assessment of small modular reactor (SMR) economics. This study applies a harmonized plant-level levelized cost of electricity (LCOE) framework, based primarily on the Viet Nam Technology Catalogue for Power Generation 2026 (DEPP3), to compare SMRs with large pressurized water reactors, coal, LNG combined-cycle generation, solar PV, and onshore and offshore wind in 2030, 2040, and 2050. The analysis combines cost decomposition, construction-financing profile tests, common-rate and differentiated financing cases, normalized sensitivity analysis, multidimensional scenarios, and carbon-price break-even analysis. Under the common 10% real financing-rate assumption, the calculated SMR LCOE changes from 170.3 USD/MWh in 2030 to 103.1 USD/MWh in 2050; this is a DEPP3-conditioned pathway, not an independently forecast cost decline. The 2030 value is 170.3 USD/MWh under the INL S-curve financing formulation, 171.7 USD/MWh under uniform annual mid-year spending, and 233.1 USD/MWh in a bounding prepaid case. Normalized local sensitivities identify the financing rate, capacity factor, overnight capital cost, and construction duration as the largest responses. These plant-level results support conditional technology screening and staged evidence development rather than an immediate deployment or exclusion decision for Vietnam.

Keywords: small modular reactors; techno-economic assessment; levelized cost of electricity; financing conditions; energy transition; Vietnam

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1. Introduction

Vietnam is entering a particularly demanding phase of power-sector development. Sustained economic growth, industrialization, electrification, and urbanization are increasing electricity demand, while the country has committed to achieving net-zero greenhouse-gas emissions by 2050 [1,2]. The revised Power Development Plan VIII (PDP8) reflects this dual challenge through rapid expansion of electricity supply, accelerated renewable-energy deployment, grid and storage development, and renewed consideration of nuclear power in the longer-term generation mix [3]. The planning challenge is therefore not simply to

add capacity, but to expand the electricity system while maintaining affordability, reliability, energy security, and progressive decarbonization.

Solar photovoltaic and wind power are expected to remain central to Vietnam's future electricity expansion, with continuing technology-cost reductions projected in the Viet Nam Technology Catalogue for Power Generation 2026 (hereafter called DEPP3) [4]. At the same time, increasing shares of variable renewable energy raise the importance of grid flexibility, storage, reserves, transmission development, and firm low-carbon capacity. Plant-level generation cost is therefore an important screening metric, but it cannot by itself determine the least-cost configuration or system value of generation technologies in a deeply decarbonized power system [4,5].

Against this background, nuclear energy has regained international attention as a source of firm low-carbon electricity, while small modular reactors (SMRs) have emerged as a major advanced-nuclear development pathway [6–8]. SMRs encompass a diverse group of reactor concepts with smaller unit capacities than conventional large reactors and varying degrees of modularization, factory fabrication, design simplification, passive safety, and incremental deployment [7,8]. Their economic proposition is not based on smaller unit size alone. Smaller modules may reduce individual project exposure, support staged capacity additions, and potentially shorten construction schedules, but they also sacrifice part of the economies of scale available to large nuclear plants. Their plant-level cost position therefore depends on whether standardization, modularization, repeat deployment, supply-chain development, construction performance, and financing can offset this scale penalty [9–16].

This trade-off explains the wide range of SMR cost estimates reported internationally. Published assessments differ substantially in overnight capital cost (OCC), construction duration, financing assumptions, project scope, localization, design maturity, and expectations regarding industrial replication [9–14]. Carelli et al. showed how SMR diseconomies of scale could potentially be offset by multi-unit deployment, replication and learning, shorter schedules, modularization, and design simplification [15]. More recent studies and reviews similarly identify capital cost, weighted average cost of capital (WACC), construction performance, standardization, and industrial delivery as central determinants of SMR economics [9–13,16]. These findings indicate that assessing SMRs solely through a single reference LCOE may obscure the conditions under which their prospective plant-level cost position improves or deteriorates.

The deployment challenge is broader in newcomer or re-entering nuclear-energy countries. An SMR programme requires regulatory readiness, institutional and technical-support capability, siting, financing, nuclear-fuel and waste strategies, supply-chain development, human resources, stakeholder engagement, and long-term programme governance [17–21]. The IAEA and OECD/NEA therefore increasingly treat SMR deployment as a multidimensional readiness challenge rather than a reactor-selection exercise [7,8,17–19]. This perspective is particularly relevant to Vietnam, where any future nuclear programme would need to develop or strengthen regulatory, technical, industrial, financing, and project-delivery capabilities in parallel with technology selection.

A persistent limitation of Vietnam-oriented SMR analysis has been the lack of a harmonized national data basis covering SMRs and the principal competing generation technologies. The *Viet Nam Technology Catalogue for Power Generation 2026*, prepared by the Electricity Authority of Viet Nam, the Institute of Energy, the Danish Energy Agency, and the Danish Embassy in Hanoi, substantially improves this situation by providing Vietnam-contextualized technical and economic projections for SMRs, large nuclear power plants, coal, gas, utility-scale solar PV, onshore wind, and offshore wind on a common monetary basis [4]. This creates an opportunity for a more internally consistent cross-

technology assessment than approaches that combine estimates developed for different national contexts, price years, and cost boundaries.

Despite the expanding international literature, important research gaps remain in the Vietnamese context. Publicly available quantitative assessments of SMR economics tailored to Vietnam remain scarce, and existing preliminary studies have generally not compared SMRs with large nuclear, fossil-fuel, and major renewable technologies using a harmonized Vietnam-oriented dataset for common future milestone years. Moreover, the roles of financing conditions, project-execution performance, and carbon policy in shaping prospective SMR plant-level cost position have not been examined systematically within a consistent analytical framework. A further methodological consideration is the distinction between calendar-year technology projections and assumed learning across successive stages of technology maturity and fleet deployment when interpreting future SMR cost trajectories. In addition, the distinction between plant-level generation cost and broader power-system value has received limited attention in Vietnam-specific SMR assessments.

To address these gaps, this study evaluates the prospective economics of SMRs in Vietnam using a harmonized plant-level framework centred on the DEPP3 projections for 2030, 2040, and 2050. These milestone years are consistent with Vietnam's long-term power-planning horizon under the revised PDP8 and extend to the national net-zero target year of 2050. SMRs are compared with large pressurized water reactors (PWRs), ultra-supercritical (USC) coal, liquefied-natural-gas combined-cycle gas turbines (LNG CCGTs), utility-scale solar photovoltaic (PV), medium-turbine onshore wind, and fixed-bottom offshore wind. Particular emphasis is placed on identifying the economic conditions underlying SMR plant-level cost position, including capital cost, financing, project delivery, and carbon pricing, rather than treating future cost reductions as automatic consequences of technological maturity. The calendar-year projections are therefore treated as conditional technology states rather than as predefined stages of SMR industrial maturity or fleet deployment.

The contribution of this study lies not in developing a new LCOE method, but in providing a reproducible, Vietnam-specific application that harmonizes the principal power-generation technologies on a common real-price and calendar-year basis. It distinguishes source-derived inputs from author assumptions, examines how financing conditions, construction-expenditure timing, utilization, and carbon pricing affect plant-level comparisons, and translates the conditional findings into evidence requirements for future SMR assessment in Vietnam as a nuclear newcomer country.

2. Methodology

2.1. Analytical Scope and Data Basis

The assessment is conducted as a plant-level techno-economic comparison for the milestone years 2030, 2040, and 2050. The framework comprises reference calculations, cost decomposition, range-based one-at-a-time (OAT) stress tests, normalized local sensitivity, construction-spend-profile tests, common-rate and differentiated financing cases, an OCC–financing-rate matrix, explicit fossil-utilization cases, and conditional carbon-price break-even analysis. No probability distributions are imposed because the DEPP3 projections and the adopted analytical bounds do not provide defensible distributions or correlations.

The technologies included are nuclear SMRs, conventional large PWRs, USC coal-fired power plants, LNG CCGTs, utility-scale solar PV, medium-turbine onshore wind, and fixed-bottom offshore wind. The *Viet Nam Technology Catalogue for Power Generation 2026* (DEPP3) is used as the primary source of technology-specific parameters [4]. Parameters taken directly from DEPP3 include investment cost, fixed and variable operation and maintenance costs, technical lifetime, net efficiency, construction duration, and other operating characteristics, depending on technology.

The DEPP3 values for 2030, 2040, and 2050 are treated as calendar-year-specific technology projections. They are not assigned to predefined stages of commercial maturity or fleet deployment, and the model does not estimate an endogenous learning rate, cumulative deployment requirement, manufacturing scale-up, or unit-sequence effect. Changes in calculated LCOE across the three milestone years therefore arise from the corresponding input projections adopted for each year and are interpreted as conditional time-based estimates rather than as an independently modelled learning pathway.

The DEPP3 SMR datasheet reports OCC values of 7500, 6000, and 5000 USD/kWe for 2030, 2040, and 2050, respectively, but does not provide a quantitative derivation linking them to cumulative deployment, completed-unit count, localization, factory throughput, design standardization, or construction experience [4]. Although the catalogue qualitatively discusses factory fabrication, modular deployment, supply-chain establishment, licencing, standardization, and limited operating experience, it specifies neither achievement thresholds nor an SMR-specific learning rate; Appendix 2 of Ref. [4] explicitly states that no learning rate was applied to nuclear energy because of high uncertainty and limited supporting literature. Accordingly, the lower-OCC cases are not assigned an implied maturity state. Their interpretation requires future evidence of design stabilization, repeat manufacturing and construction, qualified supply chains, regulatory predictability, and demonstrated reference-project performance. Absent such evidence, the later-year LCOEs are conditional catalogue cases rather than achievable cost forecasts.

All monetary values are expressed in constant 2025 US dollars. Displayed units are written as USD/MWh, USD/kWe, USD/kW-year, and USD/tCO_2; the common 2025 price basis applies to all monetary results unless otherwise stated. Supplementary inputs from earlier price years are converted using the producer-price-index factors reported in the *Vietnam Technology Catalogue 2026* [4].

2.2. LCOE Formulation

LCOE is used as the common metric for comparing lifetime electricity-generation costs across the technologies considered. For technologies with approximately constant annual generation, the model applies the following formulation:

$$LCOE = \frac{[OCC \cdot CRF \cdot (1 + FSIM) + FOM]}{8.76 \cdot CF} + VOM + FC + CC \quad (1)$$

where OCC is overnight capital cost (USD/kWe); CF is capacity factor; FOM is annual fixed operation and maintenance cost (USD/kW-year); VOM is variable operation and maintenance cost (USD/MWh); FC is fuel cost (USD/MWh); and CC is direct operational carbon cost (USD/MWh). All monetary quantities are in constant 2025 US dollars.

The capital-recovery factor is $CRF = r(1 + r)^n/[(1 + r)^n - 1]$, where r is the real financing-rate assumption and n is the economic lifetime. Following Abou-Jaoude et al. [9], the financing-spend impact multiplier is $FSIM = 0.5[1 + \exp(x)]/[1 + (x/\pi)^2] - 1$, where $x = \ln(1 + r)T$ and T is the construction duration. Thus, 1 + FSIM is the OCC-to-commercial-operation multiplier associated with the INL analytical S-curve. For any explicit expenditure schedule with shares s_j incurred at times τ_j, the corresponding multiplier is $M = \Sigma_j s_j(1 + r)\hat{}(T - \tau_j)$, with $\Sigma_j s_j = 1$, and FSIM profile = M − 1. The workbook reports the assumed timing and intermediate multipliers so that every reference LCOE can be reproduced.

For robustness, three expenditure-timing cases are evaluated for the 2030 SMR: the reference INL analytical S-curve; uniform annual spending at each year midpoint, for which $M = (1 + r)\hat{}(1/2)[(1 + r)\hat{}T - 1]/(rT)$; and a prepaid bounding case with all capital committed at the start of construction, for which $M = (1 + r)\hat{}T$. A discrete illustrative S-curve

with annual shares of 5%, 10%, 15%, 20%, 20%, 15%, 10%, and 5% provides an additional numerical check. The prepaid case is a financing bound, not a forecast of project practice.

A 10% common real financing rate is used as a standardized reference convention that holds the financing assumption constant across technologies; it is not claimed to be economically neutral or to estimate a future Vietnamese project-specific WACC. The model parameter is used consistently in both CRF and FSIM. Project-specific WACC would depend on debt and equity shares, debt and equity costs, taxation, guarantees, contractual allocation, and risk premia. Common-rate cases range from 6% to 12%, and an explicitly illustrative differentiated case (6% nuclear, 10% fossil, and 7% renewables) is therefore reported separately and is not treated as a forecast.

For fossil-fuel technologies, fuel expenditure is calculated from fuel price and net efficiency. Carbon cost applies only to direct operational combustion emissions. A separate decommissioning or end-of-life adder is not included in the reference LCOE because DEPP3 does not provide comparable cross-technology values. This exclusion is not assumed to be economically neutral. The "Supplementary File S1" records whether major cost items—including owner's costs, licencing, site infrastructure, initial core, waste management, final disposal, and decommissioning—are included, excluded, or unclear in each source.

2.3. Technology Inputs and Supplementary Assumptions

Table 1 summarizes the principal technology inputs. DEPP3-derived rows are shown without shading, while rows containing author-specified thermal capacity factors are shaded pale yellow. SMR capacity factors are derived from the catalogue's outage assumptions [4]. The source/status and transformation for every input are provided in the "Supplementary File S1".

Table 1. Principal techno-economic inputs used in the reference LCOE calculations.

Technology	Year	Capacity (MWe)	Lifetime (yr)	CF (%)	OCC (USD/kWe)	FOM (USD/kW-Year)	VOM (USD/MWh)	Construction (yr)
Nuclear SMR	2030	300	45	91.0 *	7500	110.0	2.20	8.0
	2040	300	50	91.5 *	6000	105.0	2.15	6.0
	2050	300	55	92.0 *	5000	102.0	2.10	4.0
Large PWR	2030	2400	60	78.0	6000	122.0	2.30	7.4
	2040	2400	60	80.0	5500	118.0	2.20	7.4
	2050	2400	60	83.0	5000	113.0	2.10	7.4
USC coal	2030	1000	30	75.0 *	1990	74.56	1.29	3.0
	2040	1000	30	70.0 *	1950	73.08	1.26	3.0
	2050	1000	30	65.0 *	1910	71.63	1.24	3.0
LNG CCGT	2030	1500	50	60.0 *	1140	41.90	2.46	3.5
	2040	1500	50	55.0 *	1120	41.07	2.41	3.5
	2050	1500	50	50.0 *	1090	40.26	2.36	3.5
Utility solar PV	2030	100	32	20.0	520	8.68	0	0.7
	2040	100	35	20.4	400	7.72	0	0.5
	2050	100	40	21.1	360	7.36	0	0.5
Medium-turbine onshore wind	2030	70	30	35.5	1450	35.90	0	1.5
	2040	80	30	36.0	1400	34.53	0	1.5
	2050	100	30	37.0	1380	34.02	0	1.5
Fixed bottom offshore wind	2030	500	27	44.5	4300	150.50	0	3.0
	2040	1000	30	45.7	3690	133.25	0	3.0
	2050	1500	30	45.7	3450	128.74	0	2.5

* Note: SMR capacity factors are derived from DEPP3 outage assumptions. Pale-yellow rows contain author-specified plant-level capacity factors for coal and LNG. All monetary values are in constant 2025 US dollars.

A limited number of inputs required by the LCOE calculation are not available directly from DEPP3 and are therefore supplied from supplementary sources. Imported coal and LNG prices are based on Vietnamese long-term planning assumptions and converted to the common constant 2025 USD basis [4,22]. Nuclear fuel-cycle costs are taken from the INL advanced-reactor cost database and converted from 2022 to 2025 dollars [9]. Direct CO_2 emission factors for coal and natural gas are based on IPCC stationary-combustion factors and are converted to tCO_2/MWh using the corresponding DEPP3 net plant efficiencies [23].

The adopted central INL fuel values are 11.0 USD/MWh for SMRs and 10.3 USD/MWh for large PWRs in 2022 dollars (Tables 39 and 38 of Ref. [9], respectively), converted here to 12.66 and 11.85 USD/MWh in constant 2025 dollars. The INL once-through fuel-cost breakdown (Section 6.1 and Tables 34–36 of Ref. [9]) explicitly includes natural uranium, conversion, enrichment, fuel fabrication, depleted-uranium deconversion and disposal, and spent-nuclear-fuel packaging and final disposal. It does not list separate fuel-cost components for interim spent-fuel storage, country-specific institutional arrangements, or treatment and storage of operational radioactive waste. No additional Vietnam-specific allowance for these items is introduced in the present reference case.

Table 2 reports the supplementary inputs and the parameter ranges used in the deterministic sensitivity and policy cases. The bounds are analytical scenarios rather than probability intervals.

Table 2. Supplementary and deterministic sensitivity/scenario assumptions.

Parameter	Reference Value or Range	Unit	Use in the Analysis
Common real financing rate	10% reference; 6%, 8%, 10%, 12% sensitivity cases	%	Reference LCOE and financing sensitivity
Carbon price	0, 50, 100	USD/tCO_2	Carbon-price cases
Imported coal price	5.10	USD/GJ	Coal fuel cost, 2030–2050
Imported LNG price	13.64/13.76/13.76	USD/GJ	LNG fuel cost, 2030/2040/2050
SMR nuclear fuel cost	12.66	USD/MWh	Reference SMR fuel cost
Large-PWR nuclear fuel cost	11.85	USD/MWh	Reference PWR fuel cost
Coal direct CO_2 factor	94.6	kgCO_2/GJ	Direct combustion emissions
Natural-gas direct CO_2 factor	56.1	kgCO_2/GJ	Direct combustion emissions
SMR OCC	5000/7500/15,000	USD/kWe	OAT analysis
SMR construction duration	6–12	yr	OAT analysis
SMR capacity factor	85–93	%	OAT analysis
SMR FOM	88/110/132	USD/kW-year	OAT analysis
SMR nuclear fuel	11.51/12.66/13.93	USD/MWh	OAT analysis
SMR VOM	1.76/2.20/2.64	USD/MWh	OAT analysis

2.4. Comparative, Sensitivity, and Scenario Analyses

The quantitative assessment combines reference-case comparisons with sensitivity, scenario, robustness, and boundary analyses.

First, reference LCOEs are calculated for all seven technologies in 2030, 2040, and 2050 using the year-specific inputs in Table 1, a common real financing rate of 10%, and a zero carbon price. This establishes a consistent plant-level basis for comparing the projected evolution of generation costs over time.

Second, the reference 2030 SMR LCOE is decomposed into capital-related expenditure, fixed O&M, variable O&M, and fuel cost. This decomposition distinguishes the relative contribution of capital and operating components within the adopted cost boundary.

Third, the OAT calculation is performed as a range-based stress test. Its spread combines model responsiveness and the selected interval width and is not interpreted as a probabilistic or statistical importance ranking. To separate local responsiveness from range width, dimensionless central elasticities are calculated using equal ±5% input perturbations: $\varepsilon_x = [(LCOE_+ - LCOE_-)/LCOE_0]/0.10$. Here, $LCOE_+$ and $LCOE_-$ denote the LCOEs obtained when input (x) is increased and decreased by 5%, respectively, while $LCOE_0$ is the reference value.

Fourth, the analysis tests the INL S-curve against uniform annual mid-year and prepaid construction-spending profiles; calculates all technologies at common real financing rates of 6%, 8%, 10%, and 12%; reports an illustrative differentiated financing case; and evaluates the joint effect of OCC and financing rate in a two-dimensional matrix. Table 3 complements the individual sensitivity tests by illustrating the combined LCOE effects of four scenarios: reference planning, improved project delivery, financing support, and upper-corner stress. The compound scenarios vary capital cost, financing rate, construction duration, utilization, and operating-cost assumptions. These compound cases are interpreted as diagnostic scenario corners rather than probability bounds; in particular, the long-duration case represents an analytical construction-duration configuration, not an unplanned project-delay model.

Table 3. Deterministic compound scenarios for the 2030 SMR.

Scenario	OCC (USD/kWe)	Real Financing Rate (%)	Construction (yr)	CF (%)	FOM (USD/kW-Year)	VOM (USD/MWh)
Reference planning	7500	10	8	91	110	2.20
Improved project delivery	6000	10	6	93	99	2.00
Financing support	7500	6	8	91	110	2.20
Upper-corner stress	15,000	12	12	85	132	2.64

Fifth, carbon-price cases of 0, 50, and 100 USD/tCO_2 are applied to direct operational emissions. Rather than reporting only point crossovers, conditional break-even prices are calculated across selected SMR OCC–financing combinations and both reference and Energy Outlook utilization cases for fossil generation [24]. The 2300 full-load-hour coal case corresponds to a 26.3% capacity factor; explicit LNG cases are also calculated. These remain plant-level scenario calculations, not endogenous dispatch simulations.

2.5. Interpretation Boundary

The analysis is intentionally limited to plant-level generation economics. LCOE provides a transparent measure of lifetime electricity-production cost, but it does not quantify all attributes that determine a technology's value within an electricity system [5]. Storage requirements, curtailment, balancing and reserve provision, transmission reinforcement, locational value, market revenues, capacity adequacy, and flexibility are outside the quantitative model boundary.

This distinction is particularly important for comparison between dispatchable generation and variable renewable energy. The solar and wind values represent standalone generation LCOEs and do not include dedicated storage or wider system-integration ex-

penditure. Conversely, no additional system-value credit is assigned to nuclear or fossil generation. Conventional hydropower is excluded because remaining development opportunities in Vietnam are increasingly site-specific, while electricity storage is not treated as a primary generation technology because it shifts electricity across time rather than producing primary electrical energy. The resulting comparisons should therefore be interpreted as plant-level economic screening rather than as a determination of the least-cost future Vietnamese power-system configuration.

Finally, the technology-catalogue values are forward-looking planning projections rather than realized Vietnamese project costs. The representative SMR is an aggregate 300 MWe plant and does not model sequential module commissioning, early revenue from completed modules, inter-unit learning, or shared infrastructure. Separate adders for licencing, localization, newcomer-country capability, site infrastructure, workforce development, and detailed fuel-cycle and waste arrangements are also outside the reference boundary. The resulting values are therefore catalogue-boundary screening estimates and do not represent the full costs of nuclear power deployment in Vietnam.

3. Results and Discussion

The results are presented in terms of reference LCOE evolution, SMR cost structure, parameter sensitivity, compound project and financing scenarios, carbon pricing, and Vietnam-specific thermal-generation utilization. Together, these analyses are used to identify the conditions under which the prospective economics of SMRs improve or deteriorate within the plant-level assessment framework defined in Section 2.

3.1. Reference LCOE and Temporal Evolution to 2050

Applying the year-specific DEPP3 input sets at a common 10% real financing rate and zero carbon price produces an SMR LCOE pathway of 170.3, 129.2, and 103.1 USD/MWh for 2030, 2040, and 2050, respectively (Figure 1 and Table 4). This 39.4% calculated change is driven by exogenous catalogue assumptions, particularly lower OCC and construction duration, and is not an independently estimated forecast or evidence of realized learning.

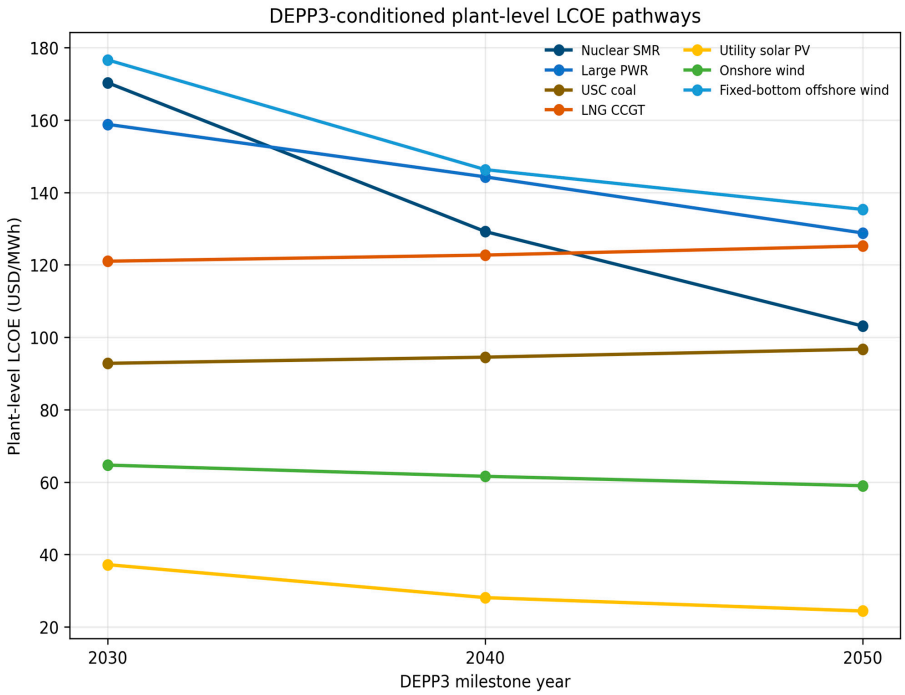


Figure 1. DEPP3-conditioned plant-level LCOE pathways across the selected generation technologies, 2030–2050 (common 10% real financing rate; zero carbon price).

Table 4. Reference plant-level LCOE results (USD/MWh).

Technology	2030	2040	2050
Nuclear SMR	170.3	129.2	103.1
Nuclear PWR	158.8	144.3	128.8
Coal USC	92.8	94.5	96.7
LNG CCGT	121.0	122.7	125.2
Utility Solar PV	37.2	28.1	24.4
Medium-turbine Onshore Wind	64.7	61.6	59.0
Fixed-bottom Offshore Wind	176.6	146.3	135.3

The large PWR pathway changes from 158.8 USD/MWh in 2030 to 144.3 USD/MWh in 2040 and 128.8 USD/MWh in 2050. The later-year SMR–PWR crossover is conditional on the DEPP3 input combination rather than an inherent economic advantage of SMRs. In 2050, both technologies have the same assumed OCC, while the SMR has a shorter construction duration and higher capacity factor; the model does not independently demonstrate that these conditions will occur.

Utility-scale solar PV and medium-turbine onshore wind retain the lowest standalone plant-level LCOEs throughout the modelled period. Solar PV declines from 37.2 USD/MWh in 2030 to 24.4 USD/MWh in 2050, while onshore wind decreases from 64.7 to 59.0 USD/MWh. Fixed-bottom offshore wind remains substantially more capital intensive, although its LCOE falls from 176.6 to 135.3 USD/MWh. The SMR is slightly less costly than offshore wind in 2030, and the difference widens to approximately 32.2 USD/MWh by 2050. These comparisons represent generation-only costs and should not be interpreted as a complete ranking of system value, because storage, curtailment, balancing, transmission, and capacity-value effects are outside the quantitative LCOE boundary.

Under the representative plant-level utilization assumptions adopted in the reference model, USC coal and LNG CCGT exhibit comparatively flat LCOE trajectories. Coal increases from 92.8 USD/MWh in 2030 to 96.7 USD/MWh in 2050, while LNG CCGT rises from 121.0 to 125.2 USD/MWh. At zero carbon price, the SMR remains more expensive than both fossil technologies in 2030 and 2040. By 2050, however, its projected LCOE is approximately 22.1 USD/MWh below LNG CCGT, while remaining about 6.4 USD/MWh above USC coal. These fossil-generation comparisons are conditional on the reference fuel-price and utilization assumptions; the implications of carbon pricing and potentially lower system-level thermal-plant utilization are examined separately in Sections 3.5 and 3.6, respectively.

Overall, Figure 1 is a comparison of catalogue-conditioned plant-level pathways. It does not establish technology forecasts, total system costs, or substitutability between firm generation and variable renewables. The subsequent robustness analyses test how the relative plant-level LCOE positions change when financing, expenditure timing, utilization, and other assumptions vary.

3.2. SMR Cost Composition and Economic Mechanism

The reference 2030 SMR LCOE is strongly dominated by capital-related expenditure. Capital recovery, including the effect of financing during construction, contributes 141.6 USD/MWh, corresponding to 83.2% of the total LCOE of 170.3 USD/MWh (Figure 2). Fixed O&M contributes 13.8 USD/MWh (8.1%), nuclear fuel 12.7 USD/MWh (7.4%), and variable O&M 2.2 USD/MWh (1.3%).

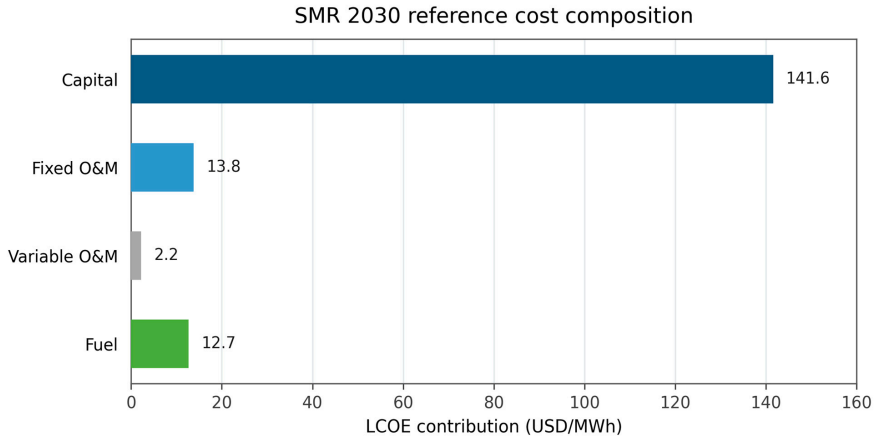


Figure 2. Cost composition of the reference 2030 SMR LCOE at a 10% common real financing rate and zero carbon price.

This cost structure indicates that the prospective economics of the reference SMR are primarily determined by the recovery and financing of upfront investment rather than by recurring operating or fuel expenditure. In particular, the dominant capital share implies that changes in OCC, financing conditions, and construction duration can materially alter the resulting LCOE because these parameters directly affect the annualized capital burden. By contrast, changes in fuel and variable O&M costs act on substantially smaller components of the total generation cost.

The result is consistent with the broader SMR literature, which identifies the balance between diseconomies of scale and potential cost reductions from simplification, modularization, shorter construction schedules, standardization, and repeat deployment as central to SMR economics [6,10,11,25]. Asuega et al. similarly emphasizes the importance of construction duration, modularization, capital structure, and financing in advanced-reactor cost performance, although their numerical estimates are design-specific and are not directly transferred to the Vietnamese case [10]. The present decomposition therefore provides a Vietnam-contextualized illustration of the similar underlying economic mechanism using the DEPP3-based reference assumptions. The capital-dominated cost structure also provides the economic basis for the sensitivity analysis in the following subsection, where the effects of OCC, common real financing rate, construction duration, capacity factor, fixed O&M, nuclear fuel cost, and variable O&M on the reference SMR LCOE are quantified individually.

3.3. Sensitivity of SMR Economics

The range-based OAT stress test gives the largest output spread for OCC (188.8 USD/MWh), followed by the common real financing rate (105.0 USD/MWh) and construction duration (46.3 USD/MWh) over the selected intervals (Figure 3 and Table 5). These spreads do not constitute a rigorous importance ranking because the OCC, rate, duration, and capacity-factor intervals differ materially in relative width.

The normalized ±5% analysis changes the interpretation. The largest absolute central elasticity is the common real financing rate (1.109), followed by capacity factor (0.915), OCC (0.832), construction duration (0.340), FOM (0.081), fuel cost (0.074), and VOM (0.013). Accordingly, both range-based stress and normalized local responsiveness are reported, with neither interpreted as a probabilistic attribution of uncertainty.

The two sensitivity views answer different questions: the OAT spread shows the consequence of the selected analytical bounds, while normalized elasticity shows the local model response to equal proportional changes. Neither provides probabilities, correlations, confidence intervals, or a technology ranking under uncertainty.

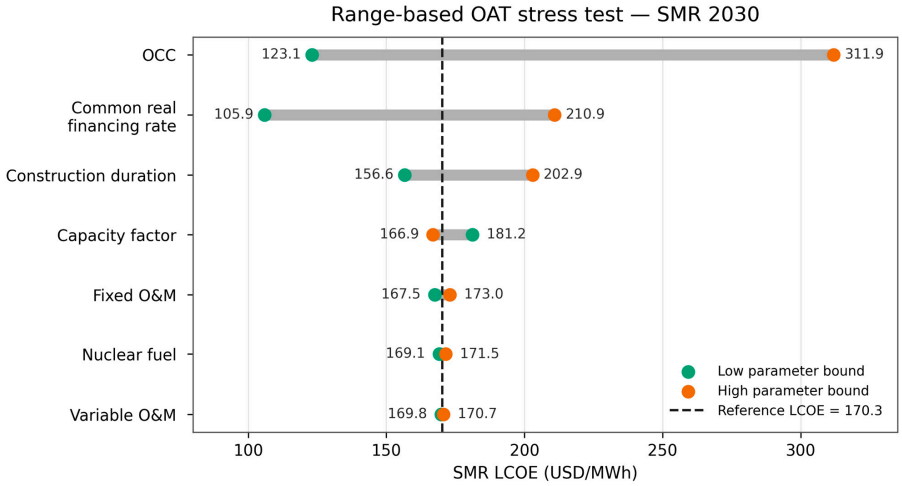


Figure 3. Range-based OAT stress test for the reference 2030 SMR LCOE. End points are analytical bounds, not probability intervals or a statistical importance ranking.

Table 5. Range-based OAT stress-test results and normalized local elasticities for the reference 2030 SMR.

Parameter	LCOE at Low Parameter Bound	Reference LCOE	LCOE at High Parameter Bound	Spread	Normalized Elasticity (±5%)
OCC	123.1	170.3	311.9	188.8	0.832
Common real financing rate	105.9	170.3	210.9	105.0	1.109
Construction duration	156.6	170.3	202.9	46.3	0.340
Capacity factor	181.2	170.3	166.9	14.3	−0.915
FOM	167.5	170.3	173.0	5.5	0.081
Nuclear fuel	169.1	170.3	171.5	2.4	0.074
VOM	169.8	170.3	170.7	0.9	0.013

The financing sensitivity is particularly significant because most nuclear-project expenditure is incurred before electricity generation begins. At the reference 10% common real financing rate, the capital-related contribution to the 2030 SMR LCOE is 141.6 USD/MWh. Reducing the common real financing rate to 6% lowers this contribution to 77.2 USD/MWh and reduces total LCOE from 170.3 to 105.9 USD/MWh. This result illustrates the strong leverage of financing conditions for a capital-intensive SMR project and is consistent with international assessments identifying the cost of capital, project risk, and construction performance as important determinants of nuclear generation cost [6].

3.4. Financing Profiles and Multidimensional Robustness

Figure 4 combines two tests to improve the transparency of construction financing. For the 2030 reference SMR, the INL analytical S-curve gives 170.3 USD/MWh, uniform annual mid-year spending gives 171.7 USD/MWh, and the prepaid bounding case gives 233.1 USD/MWh. The close agreement between the first two profiles supports the reference result under broadly distributed expenditure, whereas the prepaid case demonstrates the material effect of strongly front-loaded financing exposure.

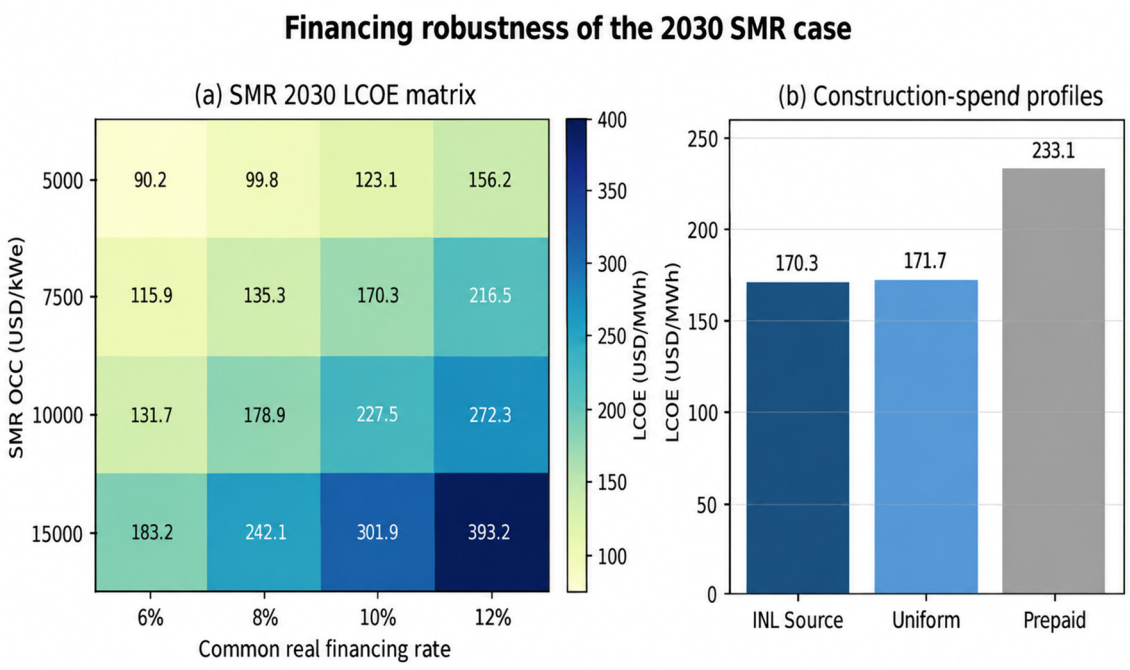


Figure 4. Financing robustness of the 2030 SMR case: (**a**) joint OCC–common-real-financing-rate LCOE matrix; and (**b**) construction-spending-profile comparison. The prepaid case is a bounding financing case, not a project forecast.

The OCC–rate matrix ranges from 80.2 USD/MWh at 5000 USD/kWe and 6% to 393.2 USD/MWh at 15,000 USD/kWe and 12% (Figure 4). At the reference OCC of 7500 USD/kWe, the LCOE ranges from 105.9 to 210.9 USD/MWh across 6–12%. Thus, a single OAT spread cannot describe the joint financing exposure.

Applying common rates of 6%, 8%, 10%, and 12% to every technology preserves a controlled comparison but changes the magnitude of the gaps. In 2030, the SMR remains above the PWR by 6.2–15.8 USD/MWh across these common-rate cases. In the illustrative differentiated case (6% nuclear, 10% fossil, 7% renewables), the LCOEs are 105.9 USD/MWh for SMR, 99.7 for PWR, 92.8 for coal, 121.0 for LNG, 29.0 for solar PV, 51.1 for onshore wind, and 140.6 for fixed-bottom offshore wind. These are transparent scenarios, not estimates of project-specific WACC.

The compound scenarios in Table 3 reinforce the separate sensitivity results. Compared with the reference LCOE of 170.3 USD/MWh, improved project delivery reduces the LCOE to 127.0 USD/MWh, while financing support lowers it to 105.9 USD/MWh. Conversely, the upper-corner stress combination increases the LCOE to 534.5 USD/MWh. These deterministic combinations are diagnostic scenario corners rather than probability bounds. In particular, the 12-year construction case represents an analytical construction-duration assumption, not a four-year project delay, because the model excludes endogenous cost escalation, additional owner's costs, refinancing, contractual consequences, and revenue-delay effects.

Taken together, the profile and matrix results show that both expenditure timing and the financing-rate assumption materially affect capital-intensive generation. They also clarify why the common-rate baseline is analytically standardized but not economically neutral across technologies with different construction periods and risk structures.

3.5. Carbon Pricing and Plant-Level Comparison with Fossil Generation

Carbon pricing affects fossil generation through direct operational emissions, a mechanism distinct from SMR financing. In the 2030 reference case, USC coal and LNG CCGT have

LCOEs of 92.8 and 121.0 USD/MWh, respectively, compared with 170.3 USD/MWh for the SMR. At 50 USD/tCO_2, the coal and LNG values increase to 132.6 and 138.4 USD/MWh; at 100 USD/tCO_2, they increase to 172.5 and 155.9 USD/MWh, respectively (Figure 5).

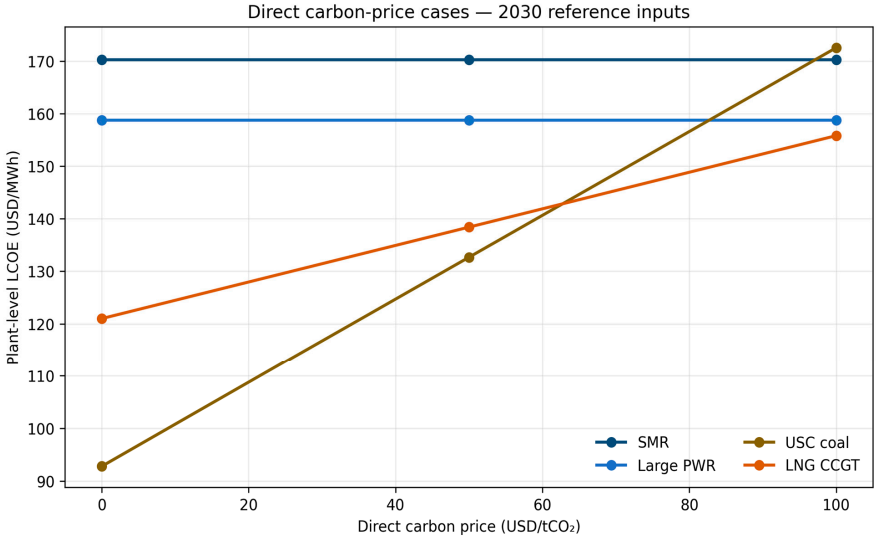


Figure 5. Effect of direct carbon pricing on the 2030 plant-level LCOE of SMR, large PWR, USC coal, and LNG CCGT. Nuclear LCOEs remain unchanged because only direct operational CO_2 emissions are priced.

Under the reference assumptions, the 2030 break-even carbon prices remain approximately 97 USD/tCO_2 for USC coal and 141 USD/tCO_2 for LNG CCGT. Across selected SMR cases, however, the corresponding reference-utilization break-even values range from zero to 377 USD/tCO_2 for coal and from zero to 781 USD/tCO_2 for LNG. For the central and intermediate cases (SMR OCC 7500–10,000 USD/kWe and financing rates 6–10%), coal values range from 16 to 156 USD/tCO_2 and LNG values from zero to 277 USD/tCO_2. These are conditional analytical break-even values, not policy recommendations or general technology thresholds.

The low-utilization fossil cases frequently produce zero carbon-price break-even values because fixed capital and O&M costs are already spread over substantially fewer MWh. This result does not imply that low utilization is desirable; it shows that utilization, fuel price, efficiency, emissions, and SMR financing jointly determine the comparison. The full matrix is reported in the "Supplementary File S1".

This pattern is consistent with previous SMR techno-economic studies showing that carbon constraints can improve the relative economic position of nuclear generation compared with unabated fossil-fuel technologies [10,26]. The crossover values obtained here are nevertheless specific to the fuel prices, efficiencies, emission factors, financing assumptions, and cost inputs adopted in the present Vietnam-oriented model and should therefore be interpreted as scenario-dependent results rather than general technology thresholds.

3.6. Vietnam System-Utilization Context for Fossil Generation

The reference LCOE calculations for USC coal and LNG CCGT use representative plant-level capacity factors to maintain a consistent basis for cross-technology comparison. Actual thermal-plant utilization in Vietnam, however, may differ substantially as the power system evolves toward higher shares of renewable energy and tighter decarbonization constraints.

The *Viet Nam Energy Outlook 2024* [24] illustrates this distinction. Coal generation around 2040 in NZ/NZ+ (NZ: Net Zero) corresponds to approximately 2300 full-load hours, or 26.3% utilization, compared with 70% in the reference plant case. Substituting this explicit

utilization value increases the calculated 2040 coal LCOE from 94.5 to 179.3 USD/MWh. The 3000 h coal case gives 147.6 USD/MWh.

For LNG CCGT, the Energy Outlook ranges produce similarly material effects: the 2030 LCOE is 265.3 USD/MWh at 1000 h and 168.1 USD/MWh at 2200 h, compared with 121.0 USD/MWh in the reference case. For 2050, 1700–1900 h gives approximately 186.6–176.1 USD/MWh, compared with 125.2 USD/MWh at the reference 50% capacity factor. These are explicit plant-level what-if calculations using system-model utilization outcomes; they are not endogenous dispatch results of the present model.

The alternative-utilization calculations demonstrate sensitivity to dispatch but do not convert LCOE into a system-cost metric. A consistent system assessment would require endogenous capacity expansion, hourly dispatch, renewable variability, storage, transmission, reserve requirements, and reliability constraints. The reference and low-utilization cases are therefore presented separately as alternative utilization scenarios.

3.7. Integrated Interpretation of Plant-Level Cost Positions

Taken together, the results show that the prospective economic position of SMRs in Vietnam is shaped by several interacting mechanisms rather than by a single cost parameter or by calendar-year progression alone. The projected decline in SMR LCOE toward 2050 is primarily associated with lower capital cost and shorter construction duration in the DEPP3 projections, while financing conditions strongly influence the extent to which these improvements translate into lower generation cost. Project execution and financing therefore act as complementary determinants of the economic outcome rather than as independent considerations.

The comparison with fossil generation introduces a different set of drivers. Carbon pricing increases the plant-level cost of coal and LNG through their direct operational emissions, whereas lower system-level utilization can further weaken their economics by spreading fixed costs over fewer generated megawatt-hours. These mechanisms are distinct from the capital and financing factors that dominate SMR economics. As a result, the relative position of nuclear and fossil generation may evolve through both changes in SMR project performance and changes in the operating and policy environment faced by thermal generation.

The comparison with renewable technologies requires a different interpretation. Utility-scale solar PV and onshore wind retain substantially lower standalone plant-level LCOEs than the SMR throughout the assessment period. However, these values do not incorporate dedicated storage, curtailment, balancing, transmission reinforcement, or capacity-value effects. The results therefore do not support a conclusion that SMRs should substitute for low-cost renewable generation. Rather, they indicate that any future role for SMRs should be assessed within a broader portfolio of low-carbon technologies with different cost structures, operating characteristics, and system functions.

Overall, the plant-level results identify conditions under which the relative LCOE position of SMRs improves or deteriorates; they do not establish technological substitutability or total-system plant-level cost position. Lower OCC, shorter and predictable schedules, broadly distributed construction spending, and lower financing rates improve the SMR result. Fossil utilization and carbon treatment materially alter nuclear–fossil comparisons, while standalone renewable LCOEs omit system integration and capacity-value effects.

3.8. Limitations and Directions for Further Work

The principal limitations arise from forward-looking catalogue inputs, a generic aggregate SMR representation, plant-level rather than system-level scope, and incomplete project boundaries. The model does not quantify endogenous learning, cumulative deploy-

ment, design-specific modularization, sequential module commissioning, early revenue, inter-unit learning, owner's costs, newcomer capability, site infrastructure, localization, decommissioning, or unresolved nuclear back-end items. These exclusions can act in different directions and should not be interpreted as economically neutral.

Although the excluded newcomer-related items cannot be estimated as Vietnam-specific costs from the available evidence, the LCOE consequences of assumed overnight-equivalent capital adders can be quantified transparently. Under the 2030 SMR reference assumptions, treating each adder as part of OCC and applying the same construction-financing multiplier, an additional 1000 USD/kWe increases LCOE by 18.9 USD/MWh. Illustrative adders of 500, 1000, and 2000 USD/kWe would increase total LCOE from 170.3 to 179.7, 189.1, and 208.0 USD/MWh, respectively. These are sensitivity thresholds, not estimates of Vietnam's licencing, regulatory-capacity, infrastructure, workforce-training, or supply-chain costs. Programme-wide costs would also depend on their allocation across sites and units.

The uncertainty analyses are deterministic. The OAT bounds, normalized elasticities, financing profiles, differentiated-rate case, OCC–rate matrix, and break-even ranges characterize model response but do not assign likelihoods. Monte Carlo analysis is not introduced because defensible probability distributions and correlations cannot be inferred from DEPP3 projections or analytical stress bounds. Future probabilistic work should use empirically supported project data and explicitly model dependence between OCC, construction duration, financing, and utilization.

A further limitation is that plant-level LCOE cannot measure hourly dispatch, storage, curtailment, balancing, transmission, capacity adequacy, flexibility, market revenue, locational value, or fuel-security benefits. Accordingly, the results are interpreted as plant-level LCOE comparisons rather than as comprehensive measures of system-level competitiveness, particularly when firm generation is compared with variable renewable energy.

Future work should therefore extend the present harmonized cost framework in two directions. First, Vietnam-specific capacity-expansion and production-cost modelling should be used to evaluate SMRs, variable renewables, storage, transmission, and thermal generation on a common system basis, including hourly operation, capacity adequacy, curtailment, fuel-import exposure, and carbon constraints. Second, as more mature project information becomes available, vendor- and site-specific assessments should examine financing structures, construction schedules, licencing requirements, localization, nuclear-fuel supply, decommissioning, and radioactive-waste-management arrangements. These extensions would allow the plant-level findings reported here to be tested against progressively more realistic project and system conditions.

4. Policy Implications for Vietnam

The quantitative results do not support a deployment decision based on plant-level LCOE alone. They identify evidence requirements for further assessment: cost and scope reconciliation, financing structure, construction-spend timing, project delivery, utilization, regulatory readiness, fuel and waste arrangements, and system value. The implications below are conditional guidance rather than a recommendation for immediate deployment.

4.1. SMRs as a Conditional Long-Term Strategic Option

Under the reference assumptions, the projected SMR LCOE declines substantially between 2030 and 2050 and becomes lower than the corresponding large-PWR and fixed-bottom offshore-wind values in the later milestone cases. However, this trajectory is conditional on the future technical and economic characteristics reported in the Viet Nam Technology Catalogue 2026, particularly the assumed reductions in OCC and construction

duration. The results therefore do not imply that SMRs become competitive automatically with the passage of time.

For Vietnam, the more defensible near-term policy interpretation is to preserve the SMR option while progressively reducing the major uncertainties that determine its economic viability. Candidate technologies could be periodically reassessed against observable international evidence, including licencing progress, completed reference projects, realized construction schedules and capital costs, operating performance, supply-chain development, and financing terms. Such evidence would provide a stronger basis for future decisions than assuming that projected 2040–2050 technology characteristics will necessarily be achieved.

This approach is consistent with international SMR deployment experience and guidance, which emphasize the importance of successful reference projects, regulatory readiness, credible economics, supply-chain capability, and institutional preparedness before large-scale deployment [5–7,18,25,27]. For a newcomer or re-entering nuclear country, maintaining the option therefore involves more than monitoring reactor technology itself; it also requires gradual development of regulatory, technical, financing, siting, fuel-cycle, waste-management, and project-management capabilities.

This conditional approach is also compatible with Vietnam's emerging nuclear-energy policy framework. Recent national policy documents identify energy security, nuclear-energy development, and advanced technologies, including SMRs, as strategic long-term priorities [28–31]. These policy directions provide a basis for capability building and systematic technology assessment, but they do not remove the need for project-specific technical, economic, regulatory, and financial due diligence before major investment commitments are made.

4.2. Capital-Cost Reduction and Financing as Coupled Priorities

Capital cost, financing rate, construction duration, and expenditure timing should be treated as coupled assessment variables. The normalized results identify financing rate and capacity factor as at least as consequential locally as OCC, while the two-dimensional matrix shows that adverse OCC and financing conditions compound. Future due diligence should therefore evaluate project-specific construction-expenditure schedules and financing cash flows rather than relying solely on quoted OCC estimates.

For Vietnam, this implies that financing strategy should be developed in parallel with technology selection, project preparation, and measures to reduce delivery risk. Lower-cost financing is most credible when supported by evidence of design maturity, licencing progress, realistic construction schedules, qualified suppliers, clear contractual allocation of risk, and sufficiently mature reference-project experience. International guidance similarly emphasizes that reduced financing costs depend on credible risk reduction, regulatory clarity, project maturity, and confidence in delivery performance [6,7,25,27]. Financing support should therefore be viewed as part of an integrated project-risk-reduction framework rather than as an independent means of compensating for weak project fundamentals.

Potential financing arrangements may include state-supported or blended finance, sovereign or partial credit support, export-credit or multilateral financing, long-term power-purchase arrangements, regulated-asset mechanisms, or other forms of risk sharing. Such mechanisms have been discussed internationally as possible approaches for reducing the financing burden of capital-intensive nuclear projects, although their suitability depends strongly on national institutional, regulatory, market, and fiscal conditions [6,25]. The present analysis does not identify an optimal financing instrument for Vietnam, nor does it assume that the 6% sensitivity case represents an achievable future project-specific WACC. Instead, the financing results illustrate the economic leverage of a lower cost of capital for a

highly capital-intensive technology and the importance of evaluating financing conditions explicitly during project development.

A practical implication is that future SMR due diligence should assess not only the vendor's stated OCC but also the financing structure required to realize the corresponding generation cost. This assessment should include the cost and maturity of debt and equity financing, sovereign exposure, construction-risk allocation, contingency provisions, schedule-related financing escalation, and the conditions attached to any public support. In this sense, credible cost reduction and credible financing are mutually reinforcing: stronger project fundamentals can reduce perceived investment risk, while more favourable financing can improve the economic viability of a well-prepared project [5–7,23,26].

4.3. Project Delivery, Regulatory Readiness, and Industrial Capability

Project execution performance directly affects LCOE; however, the long-duration case (Table 3) represents an analytical construction-duration scenario rather than an unplanned project delay. Future project-specific analysis should separately represent cost escalation, owner's costs, refinancing, contractual consequences, and delayed revenue. Regulatory readiness, design maturity, site engineering, supplier qualification, fuel arrangements, and financing closure should be evaluated through explicit decision gates.

For Vietnam, major capital commitments should be preceded by explicit project-readiness gates covering design maturity, licencing progress, site-specific engineering, construction planning, supplier qualification, financing closure, nuclear-fuel arrangements, and relevant reference-project evidence. International SMR guidance likewise emphasizes technology demonstration, regulatory preparedness, realistic construction planning, vendor-customer coordination, and supply-chain capability as important conditions for successful deployment [6,18,25,27]. A staged readiness process would help reduce the risk that unresolved technical or institutional issues are transferred into the construction phase, where their economic consequences may be amplified through delay and financing escalation.

Regulatory capability is particularly important because licencing uncertainty can translate directly into project risk. Unresolved requirements, late design changes, prolonged technical review, or insufficient independent assessment capability may extend project schedules and increase financing costs. Vietnam should therefore develop SMR-related regulatory and technical-support capacity in parallel with technology evaluation, including competence for staged design review, site and safety assessment, multi-module configurations, emergency preparedness, safeguards, security, radioactive-waste management, and decommissioning. This capability development should precede, rather than follow, any decision to commit to a specific commercial deployment schedule.

Industrial and supply-chain readiness should be assessed with the same caution. Localization may offer long-term economic and strategic benefits, but premature localization targets can introduce quality, schedule, and qualification risks if domestic suppliers have not yet demonstrated the required nuclear-grade capabilities. A more robust approach would be to define localization progressively, beginning with a realistic assessment of domestic manufacturing, engineering, construction, quality-assurance, and inspection capability and expanding participation only as qualified capacity is demonstrated.

Overall, the economic results support a milestone-based approach in which progress toward deployment is conditional on demonstrated readiness in design, regulation, supply chain, project management, and financing. Such sequencing would not eliminate project risk, but it could reduce the likelihood that unresolved institutional or technical deficiencies translate into the schedule delay and cost escalation identified as major drivers in the present analysis.

4.4. Carbon Policy, Fossil-Fuel Exposure and Energy Security

The carbon-price analysis shows that nuclear–fossil break-even values are conditional on both sides of the comparison. Across the tested SMR OCC–financing combinations and fossil utilization cases, break-even values vary widely and may be zero when low fossil utilization already raises plant-level LCOE above the SMR case. No single crossover value should therefore be interpreted as a recommended carbon price for Vietnam.

For Vietnam, this also implies that SMR economics should not be assessed only against fossil generation under a permanently zero-carbon-cost assumption. The country's net-zero objective and long-term power-sector decarbonization pathway imply that future fossil generation may face increasing carbon constraints, whether through explicit carbon pricing, emissions limits, or other policy instruments [3,24]. At the same time, the results also show that stronger carbon constraints do not remove the need to control SMR capital cost, construction duration, and financing. Carbon policy and nuclear-project economics therefore operate through different mechanisms and should be assessed jointly rather than treated as substitutes.

Fuel-price exposure introduces a further strategic consideration. LNG generation remains dependent on fuel costs throughout operation, while the SMR cost structure identified in this study is dominated by upfront capital and financing. This difference implies contrasting risk profiles: fossil generation is more exposed to future fuel-market conditions and import-price volatility, whereas SMR economics are more exposed to capital cost, financing terms, and project-delivery performance. The present LCOE framework does not quantify the economic value of reduced fossil-fuel import exposure, but the distinction is relevant to Vietnam's broader energy-security assessment.

Accordingly, potential energy-security benefits of nuclear power should be evaluated explicitly rather than assumed as an inherent advantage. Future system-level analysis should examine how alternative SMR deployment pathways affect fuel-import dependence, exposure to international LNG and coal prices, reserve adequacy, system resilience, and the diversity of the generation portfolio. Such analysis would provide a more robust basis for determining whether the strategic value of firm nuclear generation justifies any additional plant-level cost under specific Vietnamese power-system conditions.

4.5. SMRs in a Renewable- and Storage-Intensive Power System

Utility-scale solar PV and onshore wind retain substantially lower standalone plant-level LCOEs than the reference SMR. This does not answer whether one technology produces lower total system cost or can substitute directly for firm capacity. Vietnam-specific capacity-expansion and dispatch modelling is required to evaluate SMRs together with variable renewables, storage, transmission, demand flexibility, and other firm low-carbon options.

At the same time, plant-level LCOE is not sufficient to determine the least-cost technology mix in a deeply decarbonized power system. High shares of variable renewable energy can increase the importance of storage, transmission expansion, balancing resources, curtailment management, reserve provision, and firm capacity, while the economic value of these services depends on the composition and operation of the power system [5,6,24]. The present analysis does not quantify these system-level effects and therefore does not assign an additional system-value credit to SMRs or an integration-cost adder to solar and wind.

For Vietnam, the relevant policy question is consequently not whether SMRs are cheaper than solar or wind on a standalone LCOE basis, but whether firm low-carbon nuclear generation could provide sufficient system value under high-renewable pathways to justify its higher plant-level generation cost. This value could arise, for example, through contributions to adequacy, reduced dependence on fossil-fuel generation, lower exposure

to prolonged periods of low variable-renewable output, or reduced requirements for other forms of firm capacity. These potential benefits remain hypotheses within the present study and should not be treated as quantified results.

Future Vietnam-specific capacity-expansion and dispatch modelling should therefore evaluate SMRs together with variable renewables, storage, transmission, demand-side flexibility, and other firm low-carbon options. Such analysis should compare total system cost, capacity adequacy, curtailment, storage requirements, transmission needs, fuel-import exposure, and operational interactions across alternative technology portfolios. Until this system-level evidence is available, the appropriate policy position is to regard SMRs as a potential component of a diversified firm low-carbon portfolio rather than as either a substitute for renewable energy or a demonstrated least-cost complement to it.

4.6. A Staged Approach to Future SMR Consideration in Vietnam

Taken together, the results support a cautious and evidence-based approach to the future consideration of SMRs in Vietnam. The analysis does not provide a basis for either immediate large-scale deployment or early exclusion of the technology. Instead, it indicates that future decisions would be better informed by progressively stronger evidence on technology maturity, project delivery, financing conditions, regulatory readiness, and power-system needs.

In the near term, this would imply preserving the option while improving the information and institutional basis for future assessment. Relevant activities may include monitoring international SMR licencing, construction, and operating experience; strengthening regulatory and technical-support capability; undertaking preliminary site and infrastructure assessments; developing expertise in nuclear project finance; and conducting independent technical and economic due diligence. These activities would reduce uncertainty without requiring premature commitment to a specific reactor design or commercial deployment schedule [25,27–31].

As additional international evidence becomes available, candidate technologies could be reassessed against observable indicators such as licencing progress, realized construction schedules and capital costs, operating performance, supply-chain maturity, fuel-supply arrangements, and financing terms. More detailed feasibility studies could then examine site-specific costs, grid integration, project financing, localization potential, nuclear-fuel and waste-management arrangements, and institutional readiness. The timing and scope of such studies should depend on the quality of available evidence rather than on a predetermined calendar.

If a future SMR project is considered technically, economically, and institutionally justified, any initial deployment would warrant separate project-specific evaluation and risk management. Its performance should not be assumed to represent mature fleet economics. Decisions on subsequent deployment would therefore need to consider demonstrated performance in cost, schedule, safety, availability, licencing, supply chain, and financing, together with the evolving requirements of the Vietnamese power system [18,25,27].

This staged interpretation is intentionally non-prescriptive. It does not imply that SMRs should ultimately be deployed, nor that the projected cost reductions for 2040–2050 will necessarily be realized. Equally, the relatively high 2030 plant-level LCOE does not by itself establish that SMRs should be excluded from future consideration. The principal implication of the present analysis is therefore that SMR-related decisions should remain conditional on verified technical, economic, regulatory, and system-level evidence as it becomes available.

5. Conclusions

This study presents a reproducible Vietnam-contextualized application of a harmonized plant-level LCOE framework. It compares SMRs with large PWRs, USC coal, LNG CCGT, utility solar PV, medium-turbine onshore wind, and fixed-bottom offshore wind using DEPP3 as the primary source and supplementary inputs only where required. The 2030, 2040, and 2050 cases are calendar-year input sets, not predefined maturity stages or an endogenous learning model.

Under the common 10% real financing-rate assumption and zero carbon price, the DEPP3-conditioned SMR LCOE pathway is 170.3 USD/MWh in 2030, 129.2 USD/MWh in 2040, and 103.1 USD/MWh in 2050. The later-year SMR–PWR crossover is generated by the catalogue input combination, including equal OCC in 2050 together with shorter SMR construction duration and higher capacity factor, and is not evidence of an inherent SMR cost advantage.

The main economic finding is the dependence of SMR LCOE on interacting capital and utilization assumptions. For the 2030 case, the INL S-curve gives 170.3 USD/MWh, uniform annual mid-year spending gives 171.7 USD/MWh, and a prepaid bound gives 233.1 USD/MWh. Normalized $\pm 5\%$ elasticities are 1.109 for the financing rate, -0.915 for capacity factor, 0.832 for OCC, and 0.340 for construction duration. The OCC–rate matrix spans 80.2–393.2 USD/MWh across the tested bounds; these are conditional responses, not probability intervals.

Fossil utilization materially changes the comparison. The 2040 coal LCOE increases from 94.5 USD/MWh at the reference 70% capacity factor to 179.3 USD/MWh at 2300 full-load hours, while the 2030 LNG value ranges from 168.1 to 265.3 USD/MWh at 2200–1000 h. Carbon-price break-even values consequently form scenario-dependent ranges rather than universal thresholds. Plant-level LCOE remains insufficient to determine total system cost or firm-versus-variable technology substitution.

The results support staged evidence development rather than immediate deployment or exclusion of SMRs. Future decisions require progressively stronger project-specific evidence on cost boundaries, financing structure, construction delivery, licencing, fuel and waste arrangements, multi-module cash flows, and power-system value.

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Data Availability Statement: The accompanying workbook provides the input sources, formulas, intermediate calculations, financing profiles, sensitivity and scenario analyses, and reported results. External data are available from the cited public sources.

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