Sizing and Economic Assessment of SMR–Open-Air Brayton Cycles

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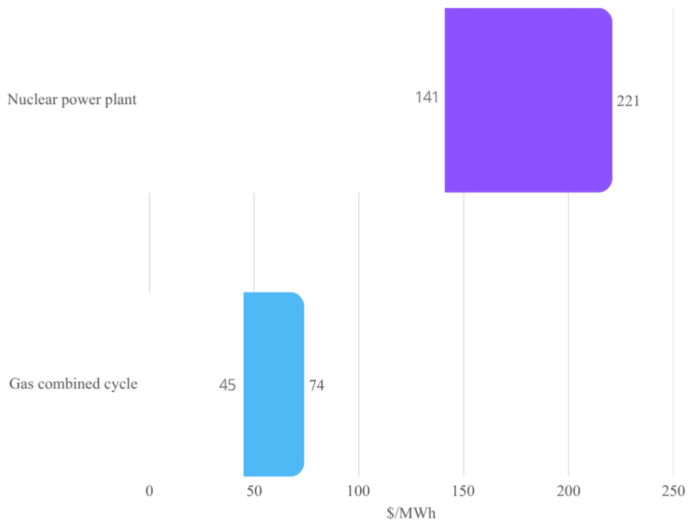
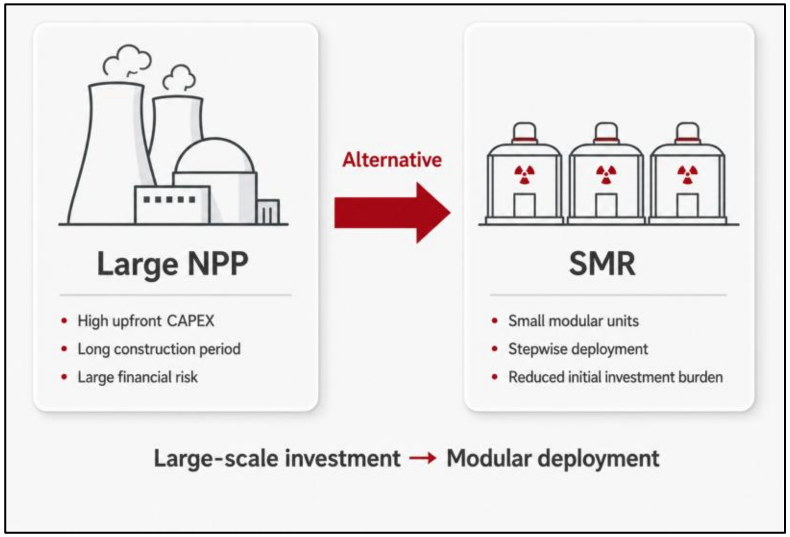
Content

1 Introduction

Cost Challenges of Large NPPs and SMRs





Large NPP

- High upfront CAPEX
- Long construction period
- Large financial risk

Alternative

SMR

- Small modular units
- Stepwise deployment
- Reduced initial investment burden

Large-scale investment → Modular deployment

- Large nuclear power plants (NPPs) face high construction costs and long construction periods, resulting in high Capital Expenditure (CAPEX) and Levelized Cost of Electricity (LCOE) compared with conventional power sources.

- Small modular reactors (SMRs) have been proposed as an alternative that may reduce upfront CAPEX through modularization, shorter construction time, and learning effects.

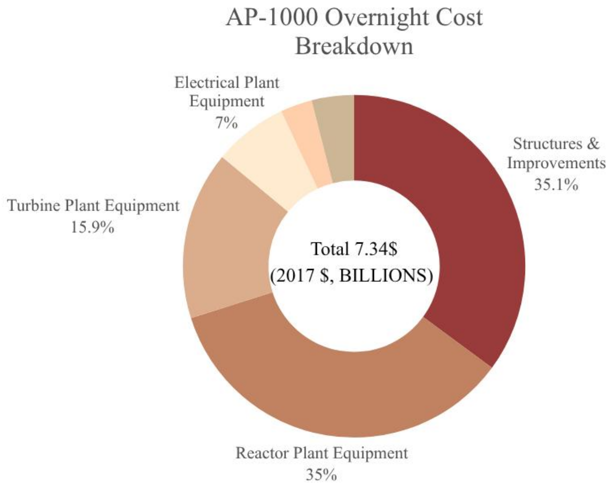
- However, first-of-a-kind (FOAK) SMRs may still face high unit costs, CAPEX burden, and deployment uncertainty due to diseconomies of scale, construction delays, and uncertain learning effects.

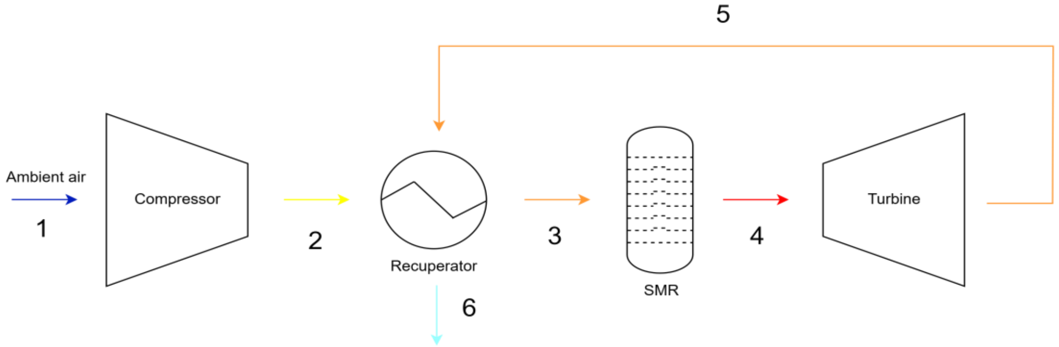
Kim, P., & Macfarlane, A. (2026). Challenges of small modular reactors: A comprehensive exploration of economic and waste uncertainties associated with US small modular reactor designs. Progress in Nuclear Energy, 190, 105989.
Lazard Ltd, 2023. Lazard's levelized cost of energy analysis - version 16.0 [WWW Document]. URL. https://www.lazard.com/media/typdgxmm/lazards-lcoeplus-a pril-2023.pdf.

1

Introduction

Why Evaluate the OABC Power Conversion System?





- The power conversion system is a non-negligible cost component in nuclear power plants.
- Turbine plant equipment accounts for approximately 15.9% of the AP-1000 overnight cost in both FOAK and nth-of-a-kind(NOAK) cases.
- Open-air brayton cycle(OABC) may provide power conversion advantages for high-temperature nuclear applications due to its simple configuration and operational flexibility.

Stewart, W. R., Velez, E., Wiser, R., & Shirvan, K. (2020). Pathways to Cost-effective Advanced Nuclear Technology. Energy Proceedings, 8(6).
Song, M., Qian, Y., Leng, Y., Liu, T., Yu, L., & Chen, W. (2024). Multi-objective optimization research of open and closed air Brayton cycle. International Journal of Advanced Nuclear Reactor Design and Technology, 6(1), 21-31.

1 Introduction

Selection of Xe-100 as the Reference SMR Heat Source

	BXRX – 300	Nuscale power module	Xe – 100	AFR – 100
Type	BWR	i-PWR	HTGR	SFR
(Power(Thermal/ Electrical)	870/300	255/77	200/80 (or 82.5)	250/100
Turbine inlet temperature(°C)	285.3	343	565.6	517
OABC Efficiency / Pressure ratio	18.35 / 1.65	24.46 / 1.74	39.40/2.16	36.64/2.08

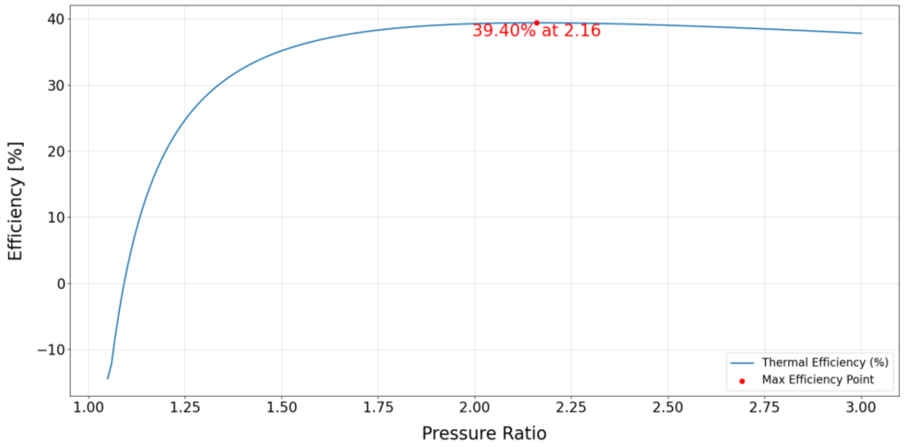
Component	Spec
Recuperator effectiveness	95%
Recuperator P ratio	99%
Turbine Eff	90%
Turbine inlet temperature(K)	838.75
Compressor Eff	90%
Compressor P ratio	Calculated
Atmosphere pressure	1 atm
Atmosphere temperature(K)	288
Ratio of exhaust pressure to atmosphere	98%
Reactor power (MWth / Mwe)	200 / 80

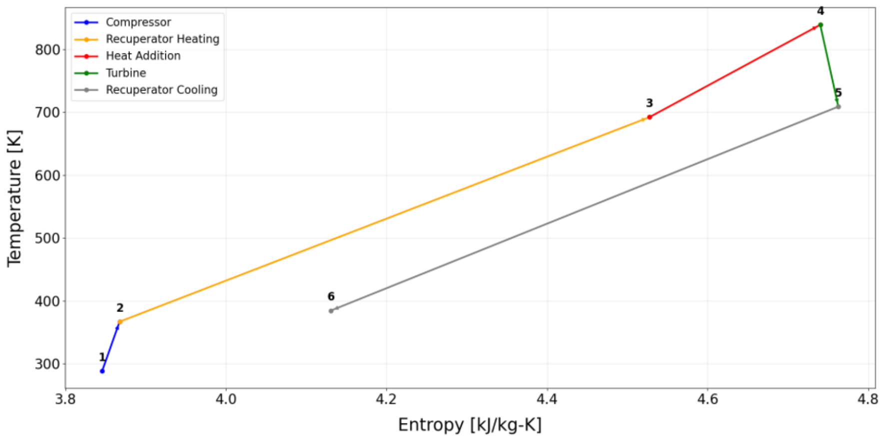
- However, because OABC operates at a relatively low pressure ratio, its economic benefit must be evaluated together with turbomachinery diameter and RPM limitations.
- Four representative SMR concepts were compared based on reactor type, power output, turbine inlet temperature, and OABC performance.
- Xe-100 was selected as the reference case because its high-temperature gas reactor (HTGR) design provides a high-temperature heat source, resulting in the most favorable OABC performance among the compared SMR options.

Zohuri, B., McDaniel, P. J., & De Oliveira, C. R. (2015). Advanced nuclear open air-Brayton cycles for highly efficient power conversion. Nuclear Technology, 192(1), 48-60.
Olaru, D., Cuciumita, C. F., & Vilag, V. A. (2017). Test bench configuration to facilitate gas turbine in-situ combustion experimentation. Energy Procedia, 112, 306-313.
Wang, H., Ponciroli, R., & Vilim, R. B. (2024). Assessments of advanced reactor heat supply to high temperature industrial unit operations: Heat Engines and Heat Pumps (No. ANL/NSE-23/91). Argonne National Laboratory (ANL), Argonne, IL (United States).
BWRX-300 General Description
Banaszkiewicz, M., & Skwarło, M. (2023). Numerical investigations of transient thermal loading of steam turbines for SMR plants. Archives of Thermodynamics, 44(4), 197-220.
Nuscale power module technical specifications
Edwards, G., & Leung, L. (2022). GIF Supercritical Water Cooled Reactor: Proliferation Resistance and Physical Protection White Paper (No. SAND2022-3624R; GIF/PRPPWG/2022/001). Sandia National Laboratories (SNL-NM), Albuquerque, NM (United States); Canadian Nuclear Laboratories, Chalk River, ON (Canada).

2 SMR–OABC Cycle Optimization

Optimized Operating Condition of the SMR–OABC Cycle

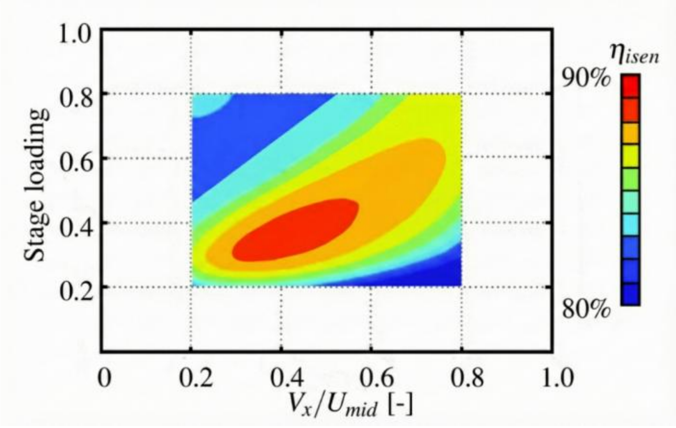


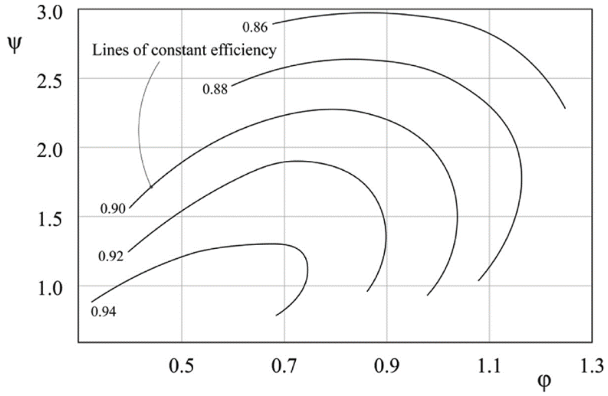


- The compressor pressure ratio was optimized based on the maximum thermal efficiency of the SMR–OABC cycle.
- The optimized operating point was calculated as 39.40% efficiency at a pressure ratio of 2.16.
- The optimized cycle state was used as the thermodynamic basis for subsequent turbomachinery sizing and economic evaluation.

3 Sizing methodology

Smith Chart-Based Turbomachinery Design Framework





$$D = \left[\frac{4\dot{m}}{\pi\rho\phi} \cdot \left(\frac{\psi}{\Delta h}\right)^{1/2}\right]^{1/2}$$

$$N = \frac{1}{\pi D}\sqrt{\frac{\Delta h}{\psi}}$$

- The Smith chart is used as a turbomachinery sizing framework to determine the feasible design region by relating the flow coefficient (φ) and loading coefficient (ψ) to efficiency characteristics.

- The selected point was arbitrarily chosen at the 0.9-efficiency region within contour line.

Gambini, M., & Vellini, M. (2020). Preliminary design of axial flow turbines. In Turbomachinery: Fundamentals, Selection and Preliminary Design (pp. 109-153). Cham: Springer International Publishing.
Schreiber, J. (2016). Investigation of experimental and numerical methods, and analysis of stator clocking and instabilities in a high-speed multistage compressor (Doctoral dissertation, Université de Lyon).

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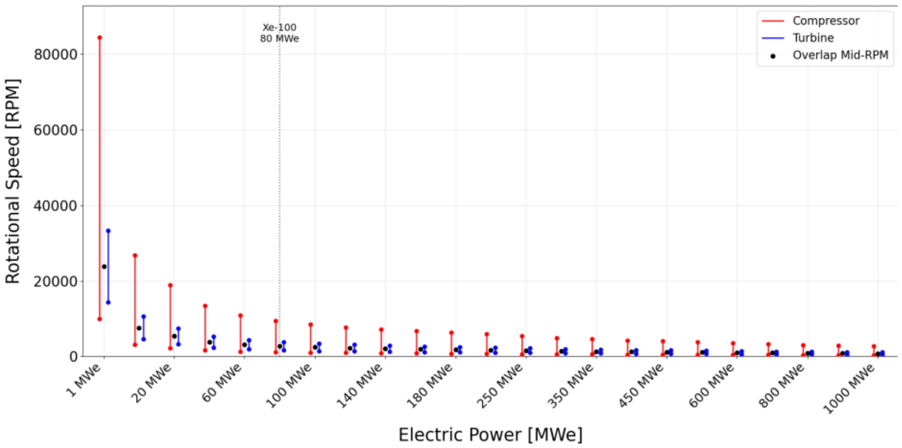
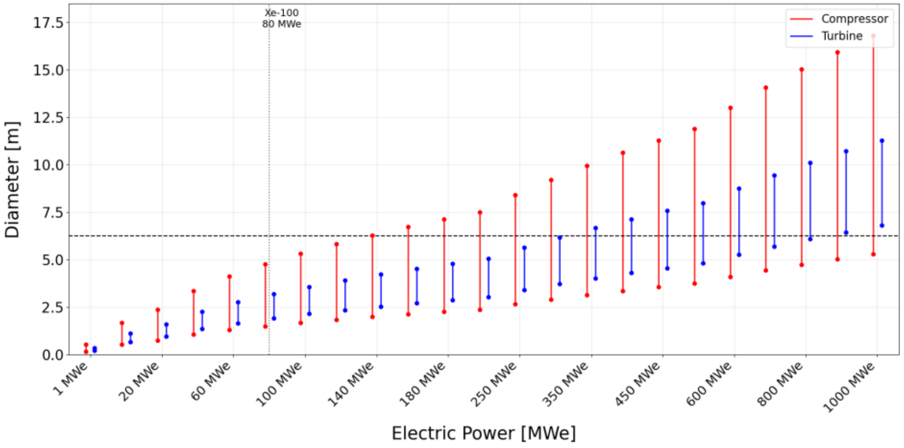
Sizing methodology

Smith Chart-Based Turbomachinery Design Framework





MWe	RPM range	Diameter range [m]	Mid-RPM based Diameter [m]
1	Comp. 9,909–84,426 / Turb. 14,310–33,266	Comp. 0.17–0.53 / Turb. 0.21–0.36	Comp. 0.35 / Turb. 0.24
10	Comp. 3,133–26,698 / Turb. 4,525–10,520	Comp. 0.53–1.68 / Turb. 0.68–1.13	Comp. 1.11 / Turb. 0.77
20	Comp. 2,216–18,878 / Turb. 3,200–7,439	Comp. 0.75–2.37 / Turb. 0.96–1.60	Comp. 1.57 / Turb. 1.09
40	Comp. 1,567–13,349 / Turb. 2,263–5,260	Comp. 1.06–3.36 / Turb. 1.36–2.26	Comp. 2.21 / Turb. 1.55
60	Comp. 1,279–10,899 / Turb. 1,847–4,295	Comp. 1.30–4.11 / Turb. 1.66–2.76	Comp. 2.71 / Turb. 1.90
80	Comp. 1,108–9,439 / Turb. 1,600–3,719	Comp. 1.50–4.75 / Turb. 1.92–3.19	Comp. 3.13 / Turb. 2.19

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Economic Evaluation

Specific CAPEX Calculation Framework

$$CAPEX_{OABC} = C_{COMP} + C_{TURB} + C_{REC} + C_{DN} + C_{CW}$$

Component	Equation
C_{COMP}	$\alpha_{2013}\cdot\left(\frac{k_{c1}\cdot\dot{m}_{air}}{k_{c2}-\eta_{isen,C}}\right)\cdot(r_p)\cdot\ln(r_p)$
C_{TURB}	$\alpha_{2013}\cdot(\frac{k_{AT1}\cdot\dot{m}_{air}}{k_{AT2}-\eta_{isen,AT}})\cdot(r_p)\cdot(1+\exp(k_{AT}T_{in}-k_{AT4}))$
C_{REC}	α_{2013} ·UA· $Standard\ unit\ price$
C_{DN}	$\alpha_{2007}\cdot C_{dn}$
C_{CW}	$\alpha_{2007}\cdot C_{cw}$

Component	Term	Value
k_{c1}	Constant for capacity-based cost conversion	75(kg/s)
k_{c2}	Constant for efficiency correction	0.93
$\eta_{isen,C}$	Compressor isentropic efficiency	90(%)
$\dot{m}_{air}$	Air mass flow rate	Calculated
r_p	Pressure ratio	2.16
k_{AT1}	Capacity-based unit cost constant	800(kg/s)
k_{AT2}	Efficiency constant	0.93
k_{AT3}	Temperature sensitivity constant	0.036(K^{-1})
k_{AT4}	Temperature correction constant	54.5
$\eta_{isen,AT}$	Turbine isentropic efficiency	90(%)
T_{in}	Turbine inlet temperature	838.75
UA	Heat transfer capacity per 1 K temperature difference	1,630.409(kW/K)
Standard unit price	Standard unit price	1,700(kw/K)
C_{dn}	Distribution network	62,500(USD)
C_{cw}	Civil work	46,650(USD)
α_{2013}	Dollar conversion factor	1.3465
α_{2007}	Dollar conversion factor	1.5129

Mondal, P., & Ghosh, S. (2017). Techno-economic performance evaluation of a direct biomass-fired combined cycle plant employing air turbine. Clean Technologies and Environmental Policy, 19(2), 427-436.
Hinze, J. F., Nellis, G. F., & Anderson, M. H. (2017). Cost comparison of printed circuit heat exchanger to low cost periodic flow regenerator for use as recuperator in a s-CO2 Brayton cycle. Applied energy, 208, 1150-1161.

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Economic Evaluation

OPEX and LCOE Calculation Framework

$$LCOE = \frac{C_{annual} + OPEX_{OABC} + C_{fuel}}{E_{annual}}$$

Component	Equation
C_{annual}	$CAPEX_{OABC} \cdot CRF$
CRF	$\frac{i(1+i)^n}{(1+i)^n - 1}$
E_{annual}	$P_e \cdot 8760 \cdot CF$
$OPEX_{OABC}$	$C_{COMP} \cdot O\&M_{COMP} + C_{TURB} \cdot O\&M_{TURB} + C_{REC} \cdot O\&M_{REC} + C_{DN} \cdot O\&M_{DN} + C_{CW} \cdot O\&M_{CW}$

Component	Term	Value
i	Discount rate	0.02
n	Plant lifetime	20 years
P_e	Electric power output	1–1000 MWe
CF	Capacity factor	0.90
CRF	Capital recovery factor	0.06116
$O\&M_{COMP}$	Compressor O&M ratio	0.05
$O\&M_{TURB}$	Turbine O&M ratio	0.05
$O\&M_{REC}$	Recuperator O&M ratio	0.10
$O\&M_{DN}$	Distribution network O&M ratio	0.02
$O\&M_{CW}$	Civil work O&M ratio	0.03
C_{LABOR}	Labor cost	$0.3 \cdot C_{labor}$
C_{labor}	Maintenance cost basis	1,198,690 USD

McQueen, N., Psarras, P., Pilorgé, H., Liguori, S., He, J., Yuan, M., ... & Wilcox, J. (2020). Cost analysis of direct air capture and sequestration coupled to low-carbon thermal energy in the United States. *Environmental science & technology*, *54*(12), 7542-7551.
Tripathi, A. K., Iyer, P. V. R., & Kandpal, T. C. (1997). A financial evaluation of biomass-gasifier-based power generation in India. Bioresource technology, 61(1), 53-59.
Nouni, M. R., Mullick, S. C., & Kandpal, T. C. (2007). Biomass gasifier projects for decentralized power supply in India: A financial evaluation. Energy Policy, 35(2), 1373-1385.

4 Economic Evaluation

Turbine-Equivalent Baselines for AP-1000 and MIGHTR

		AP-1000	MIGHTR
FOAK	Specific CAPEX	6671 $/kWe	7346 $/kWe
	LCOE	40.97 $/MWh	16.56 $/MWh
	Turbine Cost Fraction	15.9%	21.2%
NOAK	Specific CAPEX	3838 $/kWe	3585 $/kWe
	LCOE	11.59 $/MWh	12.37 $/MWh
	Turbine Cost Fraction	15.9%	25.3%

- AP-1000 represents a conventional large-scale pressurized water reactor(PWR) baseline, while MIGHTR represents an HTGR-based SMR baseline.

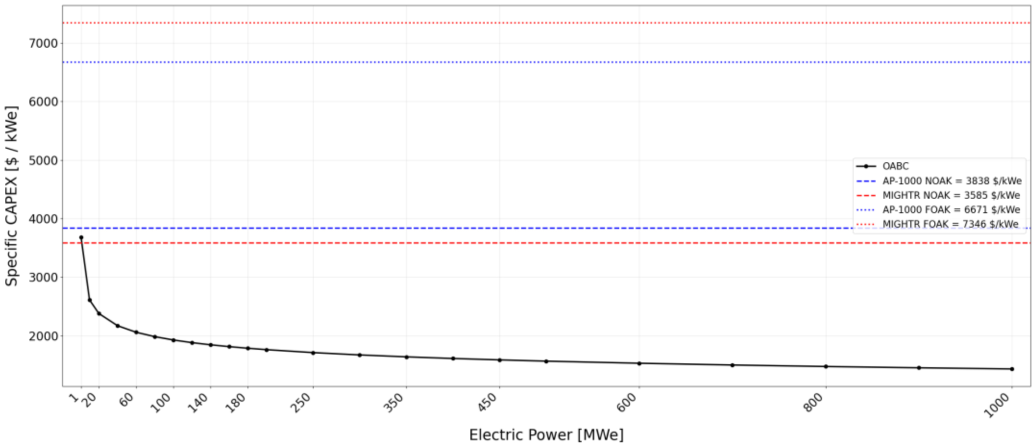
- The reference values were converted into comparable Specific CAPEX and LCOE baselines using the available cost data for each reactor.

- These baselines are used as turbine-equivalent indicators for comparison with the SMR–OABC power block, not as direct whole-plant cost comparisons.

Stewart, W. R., Velez, E., Wiser, R., & Shirvan, K. (2020). Pathways to Cost-effective Advanced Nuclear Technology. Energy Proceedings, 8(6)

5 Result

Scale-Dependent Cost Trends and Reference Comparison: Specific CAPEX

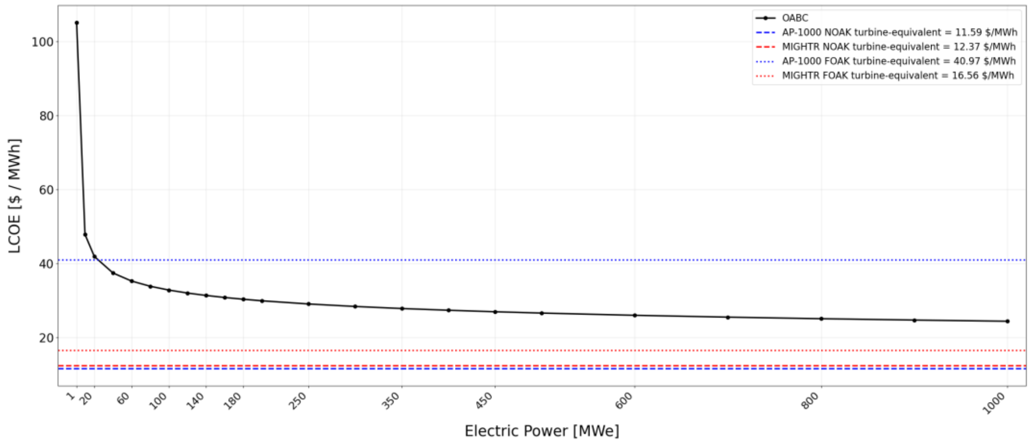


	AP-1000	MIGHTR
Type	PWR	HTGR
FOAK	6671 $ / kWe	7346 $ / kWe
NOAK	3838 $ / kWe	3585 $ / kWe

Power (MWe)	Compressor [$]	Turbine [$]	Recuperator [$]	Civil [$]	Distribution [$]	Total CAPEX [$]	Specific CAPEX [$ / kWe]
1	156,705.05	2,063,914.11	1,289,160.66	70,577.03	99,095.29	3,679,452.14	3,679.45
10	1,109,386.80	14,611,392.90	10,240,167.13	70,577.03	99,095.29	26,130,619.15	2,613.06
20	1,999,670.74	26,337,049.22	19,108,827.54	70,577.03	99,095.29	47,615,219.82	2,380.76
40	3,604,408.36	47,472,555.59	35,658,333.04	70,577.03	99,095.29	86,904,969.32	2,172.62
60	5,087,583.60	67,007,001.16	51,362,147.06	70,577.03	99,095.29	123,626,404.15	2,060.44
80	6,496,949.41	85,569,325.37	66,540,802.30	70,577.03	99,095.29	158,776,749.40	1,984.71

5 Result

Scale-Dependent Cost Trends and Reference Comparison: LCOE



	AP-1000	MIGHTR
Type	PWR	HTGR
FOAK	40.97 / MWh	16.56 $ / MWh
NOAK	11.59 $ / MWh	12.37 $ / MWh

Power (MWe)	Annualized CAPEX [$]	OPEX [$]	Annual Energy [MWh]	LCOE [$ / MWh]
1	225,023.22	603,653.24	7,884.00	105.11
10	1,598,062.91	2,173,761.91	78,840.00	47.84
20	2,911,990.58	3,691,424.97	157,680.00	41.88
40	5,314,822.71	6,483,387.72	315,360.00	37.41
60	7,560,585.15	9,104,650.16	473,040.00	35.23
80	9,710,264.91	11,621,100.19	630,720.00	33.82

6 Conclusion

- The SMR–coupled OABC system showed a maximum thermal efficiency of 39.40% at a pressure ratio of 2.16. This operating point was used as the reference condition for turbomachinery sizing and economic evaluation.

- From the sizing results, the design point of 80 MWe appears to remain within an acceptable range in terms of turbomachinery diameter and RPM. However, the required diameter increases as the electric output increases, indicating that physical sizing constraints become more important at larger scales.

- From the economic perspective, the OABC system showed a relatively low Specific CAPEX, suggesting a potential advantage in terms of initial capital cost for the power conversion system. This may be meaningful for nuclear newcomer countries, where reducing upfront investment burden is an important consideration.

- However, from the LCOE perspective, economic limitations still remain. Therefore, the advantages of OABC should not be interpreted only in terms of initial cost. Instead, LCOE, turbomachinery diameter, RPM, and system-level design constraints such as multistage turbomachinery design, piping constraints, pressure losses, installation space, O&M costs, and fuel cost assumptions should be considered together.