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Techno-economic Assessment for Applying Open-Air Brayton Cycle to i-SMR secondary system

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1. Introduction

This study examines the feasibility of applying an OABC (Open-Air Brayton Cycle)-based secondary system for i-SMR. When operated within the output temperature range of the i-SMR (approximately 320 °C), the OABC has a relatively low thermodynamic efficiency due to the inherent characteristics of the Brayton cycle, which limits its advantages in terms of power generation. Consequently, converting the conventional Rankine-based secondary system to OABC leads to a reduction in power output, resulting in an economic penalty in the form of increased electricity production costs. These factors can serve as significant barriers to the economic viability of such a system transition. Nevertheless, OABC offers notable advantages. Because air is used as the working fluid, large volumes can be easily supplied, and its simple configuration allows sector coupling with other process and operating easier than with the Rankine system.

Accordingly, this study analyzes the economic feasibility of an OABC-based secondary system integrated with an i-SMR, focusing on the Levelized Cost of Electricity (LCOE), capital expenditure (CAPEX), and annual operating expenditure (OPEX). Furthermore, it estimates the changes in power generation and electricity production costs when replacing the conventional Rankine-based system with OABC. Through this analysis, the study aims to evaluate the integration potential and economic viability of i-SMR–OABC systems and to establish a foundation for designing next-generation nuclear-based energy systems.

2. Methods and Results

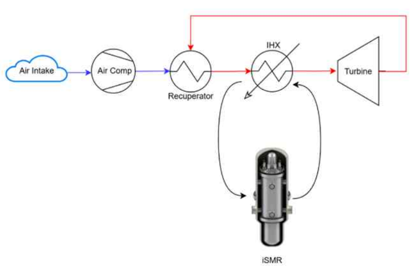

Figure 1. i-SMR OABC system flow diagram

Figure 1 provides a simplified visualization of the flow diagram of the OABC system utilizing the i-SMR as a heat source. The OABC system is an open Brayton cycle that uses air as the working fluid: air is drawn in and compressed, then heated using the heat source, after which the heated air expands through the turbine and is discharged into the atmosphere. The main components consist of a compressor, recuperator, IHX, and turbine.

Table 1. Boundary conditions of OABC system [1][2]

Component	Specification	Note
IHX effectiveness	95%	
IHX pressure ratio	99%	
Recuperator effectiveness	95%	
Recuperator pressure ratio	99%	
Turbine isentropic efficiency	90%	
Compressor isentropic efficiency	90%	
Compressor pressure ratio	Calculated	
Atmospheric pressure	1 atm	Boundary condition
Atmospheric temperature	298.15 K	Boundary condition
Exhaust-to-atmosphere pressure ratio	99%	

Table 1 summarizes the boundary conditions applied for the thermodynamic analysis of the main equipment in the OABC system, including the efficiency and pressure loss of each component, as well as atmospheric conditions.

Table 2. OABC system design values [1]

	T (°C)	P(bar)	h (kJ/kg)	s (kJ/kg/K)
Turbine inlet	316.24	1.6371	722.267	4.4380
Turbine outlet	253.10	1.0338	656.492	4.4519
Compressor inlet	25.000	1.0133	424.436	3.8805
Compressor outlet	75.81	1.6703	475.522	3.8952
IHX inlet (air side)	244.28	1.6536	648.345	4.2995
Waste air	74.269	1.0236	484.668	4.0617
Heat input (MWth)	26.000			
Thermal efficiency (%)	19.606			

Network output (MWe)	4.1290
Mass flow rate (kg/s)	347.03
Recuperator UA (kW/K)	6709.49
IHX UA (kW/K)	1630.409

Table 2 summarizes the design values for the base scenario of the OABC system, including the thermodynamic states of each component (temperature, pressure, enthalpy, and entropy) as well as the system's heat input, thermal efficiency, network output, mass flow rate, and the UA values of the heat exchangers.

Table 3 summarizes the calculation formulas used to estimate the installation costs of the main equipment in the OABC system. The costs of the compressor and turbine were calculated using thermodynamic variable-based equations, while those of the IHX and recuperator were determined based on heat transfer performance (UA values). The costs for Civil Works and the Distribution Network were set at $70,577 and $99,095, respectively, and incorporated into the calculations.

Table 3. Costing formula for calculating the total capital cost (CAPEX) of the OABC system [3][4]

Item	Equation	Ref
C_{comp}	$C_{comp} = (\frac{k_{c1} \cdot \dot{m}_{ar}}{k_{c2} - \eta_{isen,C}}) \cdot (r_p) \cdot \ln(r_p)$	[3]
C_{AT}	$C_{AT} = (\frac{k_{AT1} \cdot \dot{m}_{ar}}{k_{AT2} - \eta_{isen,AT}}) \cdot (r_p) \cdot (1 + \exp(k_{AT3} T_{in} - k_{AT4})$	[3]
C_{IHX}	IHX Cost = 1700 × UA	[4]
C_{Recup}	Recuperator Cost = 1700 × UA	[4]
C_{CW}	$ 70,577	[3]
C_{DN}	$ 99,095	[3]

Table 4 presents the calculated costs of each component of the OABC system and, based on these values, summarizes the total capital expenditure (CAPEX) and annual operating expenditure (OPEX).

Table 4. Calculation of each model of the OABC system

Item	Value ($)
Compressor	962,659.3606 ($)
Turbine	19,732,800.74 ($)
IHX	3,732,232.87 ($)
Recuperator	15,358,971.425 ($)
Civil Works	70,577 ($)
Distribution Network	99,095 ($)
Labor	359,607 ($) [5]
Fuel Cost	0.02125 ($/kW(t))
Total CPAEX	39,956,336.716 ($)
Total OPEX	3,307,599.682 ($)

The total capital expenditure (CAPEX) includes the costs of the compressor, turbine, IHX, recuperator, civil works, and distribution network. The annual operating expenditure (OPEX) was calculated based on Figure 2 by adding the labor cost to the maintenance cost, which corresponds to a certain percentage of the CAPEX-derived value. The labor cost was determined using the formula "Maintenance × 0.3" from McQueen, N [5].

Input parameter	Fraction value of capital cost-BFCC plant
Annual O & M cost of compressor	0.05
Annual O & M cost of combustor of BCHX unit	0.2
Annual O & M cost of HX of BCHX unit	0.1
Annual O & M cost of air turbine	0.05
Annual O & M cost of HRSG	0.1
Annual O & M cost of steam turbine	0.05
Annual O & M cost of condenser	0.1
Annual O & M cost of pump	0.05
Annual O & M cost of civil works	0.03
Annual O & M cost of distribution network	0.02

Figure 2. Equipment-specific ratio information for calculating the annual operating expenses (OPEX) of the OABC system [3]

The annualized capital expenditure (Annualized CAPEX, ACC) represents the total capital expenditure (CAPEX) converted to an annual value and is calculated using the following equation, which incorporates the discount rate d (%) and the plant lifetime T (years).

$$R = \frac{d(1+d)^T}{(1+d)^T - 1} \quad (1)$$

Assuming a discount rate (d) of 2% and a system lifetime (T) of 20 years, the calculation yielded an annualized capital recovery factor (R) of approximately 0.0612.

Table 5. Parameters for calculating Annualized CAPEX [3]

Item	Value
d	0.02 (%)
T	20 (year)
R	0.061156

In this study, the Levelized Cost of Electricity (LCOE) for evaluating the economic feasibility of the OABC system was calculated using the following equation.

$$LCOE\ Cost = \frac{Annualized\ \ CAPEX(ACC) + Annual\ OPEX + fuel\ cost}{Annual\ Electricity\ \ Generation}$$

Here, the Annualized CAPEX (ACC) represents the annual capital cost reflecting the discount rate and system lifetime, while the Annual OPEX refers to the annual cost required for system operation and maintenance. The Fuel Cost Total, as shown in Table 7, was determined based on the opportunity cost of thermal output of the i-SMR by calculating the fuel cost per unit of thermal output.

Table 6. Item-by-item input values and results for LCOE Cost calculation [3]

Item	Value
Annualized CAPEX (ACC)	2,443,598.422 ($)
Annual OPEX	3,307,599.682 ($)
Fuel Cost Total	0.02125 ($/kW(t))
Operation rate	90%
Annual Electricity Generation	40,189,516.087 ($/kWh)
LCOE	0.164352 ($/kWh)

Table 7. Key design values for fuel cost calculation [3]

Item	Value
Thermal	520 MW(t)
Electrical Capacity	170 MW(e)
Efficiency	0.3269
Fuel Cost	0.02125 $/kW(t)

By applying the values for each item, the LCOE of the OABC system was calculated to be 0.164352 $/kWh. The LCOE of the OABC system (164 $/MWh) remains higher than that of solar PV (38–78 $/MWh), wind power (37–86 $/MWh), and coal (71–173 $/MWh) [6], indicating limited economic competitiveness as a stand-alone power source. In particular, the current efficiency level may not be sufficient for application to SMRs. However, utilizing higher-temperature heat sources, improving heat exchanger efficiency, or optimizing the process could enhance system efficiency and thereby reduce the LCOE. In addition, rather than operating OABC alone, coupling it with additional processes such as DAC can generate further added value, which in turn could improve overall economic competitiveness. This result can be used to evaluate the economic feasibility of the system and to perform comparative analyses with other power generation methods. The methodology applied in this study is significant not only for calculating the economic feasibility but also for identifying the major contributing factors to the overall system cost through sensitivity analysis. Accordingly, it plays an important role in quantitatively validating the economic feasibility of the OABC system while simultaneously suggesting directions for future technological development.

3. Sensitivity Analysis

After estimating the LCOE for the base scenario, a sensitivity analysis was conducted to examine which variables, and to what extent, influence the economic feasibility of the OABC system. In this sensitivity analysis, a total of nine parameters were selected, including the thermodynamic performance of the recuperator and IHX (pressure drop and efficiency), the efficiencies of the turbine and compressor, the discount rate, and the system lifetime. The impact on LCOE was then evaluated by introducing small variations from the baseline values of each parameter.

Table 8. Sensitivity analysis results

Item	Range of changes	LCOE change per 1% change	Ranking
Recup_P_ratio pressure drops	0.99 → 0.991	2.008	1
Recuperator Effectiveness	0.95 → 0.951	1.316	2
Turbine Efficiency	0.9 → 0.91	0.7555	3
Compressor Efficiency	0.9 → 0.91	0.6022	4
Discount rate	0.02 → 0.021	0.588	5
IHX_P_ratio pressure drops	0.99 → 0.991	0.544	6
Operating rate	0.9 → 0.91	0.159	7
IHX Effectiveness	0.95 → 0.951	0.039	8
Plant Lifetime	20 → 21	0.002397	9

The analysis results are summarized in Table 8 and Figure 3, showing that the pressure drop and effectiveness of the recuperator were identified as the variables exerting the greatest influence on the LCOE, followed by turbine efficiency, compressor efficiency, and the discount rate in order of sensitivity. In contrast, factors such as system lifetime and IHX effectiveness exhibited relatively low sensitivity, indicating that heat exchange performance has a more direct impact on economic feasibility than the initial system cost. These findings can be utilized to identify key factors that should be prioritized in future system optimization and design efforts.

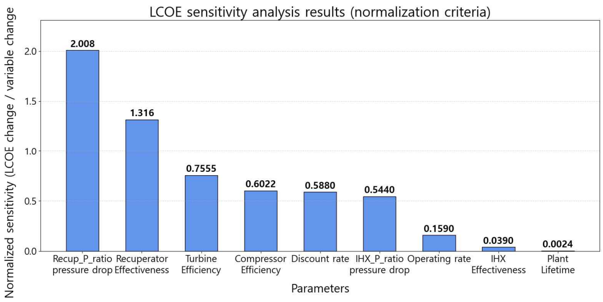

Figure 3. Sensitivity analysis results

To improve the cost efficiency of the OABC system, it is necessary to analyze the extent to which adjustable design variables influence system performance. Among the various factors affecting system performance, some can be modified through operational conditions or design adjustments, while others are difficult to alter due to mechanical or structural limitations. For example, although lower pressure drops in the recuperator and IHX improve the system's thermal efficiency, the range of adjustment is limited by mechanical constraints such as the internal structure of the equipment. In contrast, factors such as the effectiveness of the recuperator and IHX can be adjusted through design modifications or operational condition changes. Therefore, in this study, the recuperator effectiveness was set as an adjustable variable, and the resulting changes in thermal efficiency were analyzed to identify the optimal LCOE point. The results of this analysis are summarized in Figure 4.

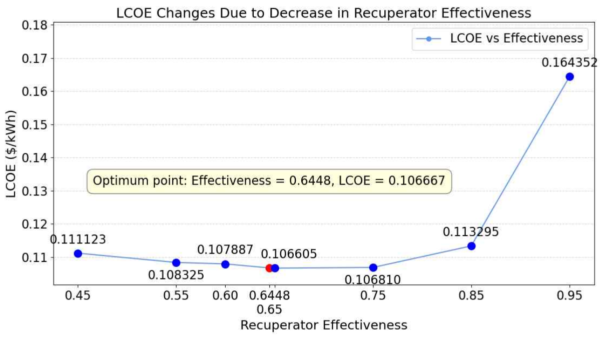

Figure 4. LCOE change and optimal point derivation results according to changes in Recuperator effectiveness

4. Conclusion and Suggestions

In this study, the LCOE of the OABC system utilizing the i-SMR heat source was calculated based on the boundary conditions, design values, CAPEX, and OPEX of the base scenario, and a sensitivity analysis was conducted on the key variables affecting economic feasibility. The results indicated that recuperator pressure drop and effectiveness, turbine and compressor efficiencies, and the discount rate were the variables with the highest impact on LCOE. Among these, focusing on the recuperator effectiveness an adjustable parameter under actual operating conditions the optimal point was derived, showing an LCOE of 0.106667 $/kWh at an effectiveness of 0.6448. This figure is high compared to the previously known Rankine cycle-based electricity prices. This study tends to overestimate fuel costs due to the hidden CAPEX of the Rankine cycle, which is calculated as opportunity cost. Nevertheless, it is significant as it can serve as a foundation for related research. Based on the results of this study, we plan to expand our research to include economic evaluations of multipurpose systems, such as sector coupling with direct air capture. In addition, if the waste heat generated during the operation of the OABC system cycle is utilized in conjunction with DAC for the regeneration stage of the adsorption column, the amount of heat required from external sources can be reduced. Such waste heat utilization not only improves the overall energy efficiency of the system but also decreases auxiliary power consumption, thereby reducing operating costs (OPEX). The reduction in operating costs leads to a decrease in the levelized cost of electricity (LCOE), ultimately contributing to the enhancement of the system's economic feasibility.

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