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System-level techno-economic evaluation of Open-Air Brayton Cycle–based Direct Air Capture integrated with Innovative Small Modular Reactors

Taejun Song[a], Joohyung Jung[a], Seongmin Son[a*]
[a]*Department of Convergence & Fusion System Engineering, Kyungpook National University*
[a] *80, Daehak-ro, Buk-gu, Daegu, Republic of Korea*
[*]*Corresponding author: seongminson@knu.ac.kr*

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1. Introduction

Direct Air Capture (DAC) is a negative-emission technology that selectively captures carbon dioxide (CO_2) from ambient air at very low concentrations (~400 ppm). Unlike conventional post-combustion carbon capture technologies that must be deployed at specific emission sources, DAC can remove CO_2 independently of source location and has therefore attracted significant attention as a key option for achieving carbon neutrality. According to the Intergovernmental Panel on Climate Change (IPCC) [1] and Goldman Sachs [2], large-scale deployment of DAC is essential to achieve net-zero emissions by 2050; however, the current cost of direct air carbon capture and storage (DACCS) remains high, typically in the range of over 400 $\$_{2021}/tCO_2$ [2].

DAC technologies are broadly classified into liquid solvent-based systems (L-DAC) and solid sorbent-based systems (S-DAC). Among these, S-DAC is particularly attractive for integration with energy systems due to its relatively low regeneration temperature requirements (80–120°C). Nevertheless, high capital expenditure (CAPEX) and operating expenditure (OPEX), mainly associated with large air-handling equipment and thermal energy demand for sorbent regeneration, remain significant challenges. Although several studies have explored the coupling of DAC systems with nuclear energy to address these issues [3][4][5], most existing work remains conceptual, with limited quantitative evaluation of system-level thermodynamic behavior and power losses. In this study, a sector-coupled system integrating an open-air Brayton cycle (OABC) with a temperature swing adsorption (TSA)-based S-DAC, powered by an innovative small modular reactor (i-SMR), is proposed and evaluated through a system-level techno-economic analysis.

2. Methods and Results

2.1 System description

As illustrated in the flow diagram in Fig 1, the OABC–DAC system is configured as a thermally integrated system that combines an open-air Brayton cycle (OABC) with a direct air capture (DAC) unit, enabling the simultaneous production of electricity and removal of CO_2. The system operates under two representative modes, where one bed undergoes adsorption while the other alternates between desorption and cooldown stages.

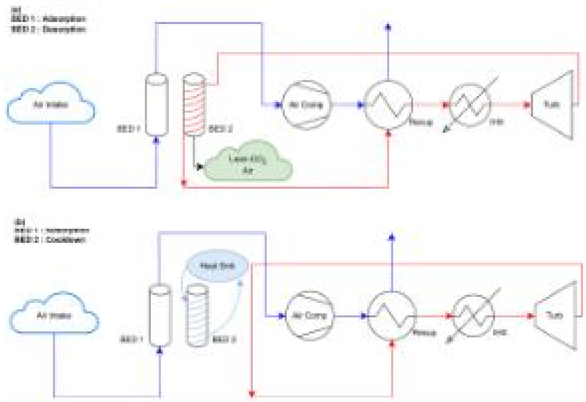

Fig 1. Flow chart of the OABC-DAC system

The OABC–DAC system consists of an adsorption bed, a desorption bed, a compressor, a recuperator, an intermediate heat exchanger (IHX), and a turbine. The system boundary conditions are defined based on the reactor thermal power, turbine inlet and outlet conditions, and the air mass flow rate and pressure. Table 1 presents the boundary conditions of the OABC–DAC system.

Table 1. Boundary conditions for the OABC-DAC system [6]

Component	Specification	Note
IHX effectiveness	98%	
IHX pressure ratio	99%	
Recuperator effectiveness	98%	
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%	

2.2 Adsorption column off-design model

The size of the adsorption column was determined based on the operating conditions of the temperature swing adsorption (TSA) cycle. The thermodynamic behavior of the adsorption bed under off-design conditions was evaluated using a simplified heat transfer model represented by an overall heat transfer coefficient (UA), while accounting for the endothermic nature of the desorption process. Fig 2 illustrates the heat transfer and adsorption–desorption behavior during regeneration.

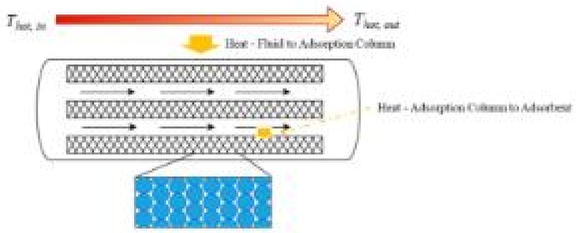

Fig 2. Schematic of the thermal analysis during regeneration in the adsorption column [6]

Fig 3 illustrates the three-step TSA operating cycle consisting of adsorption, regeneration, and cooling. CO_2 is captured during adsorption, released during thermal regeneration, and the bed is subsequently cooled for reuse, enabling continuous DAC operation through alternating adsorption columns.

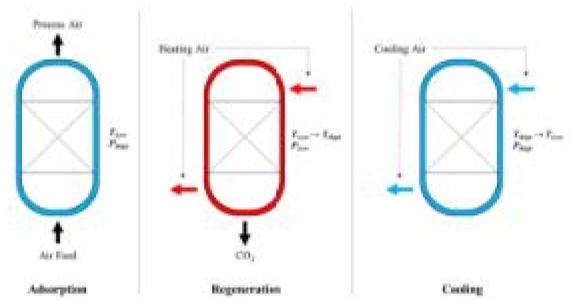

Fig 3. Conceptual diagram of the three-step TSA process [7]

2.3 Turbomachinery off-design model

The off-design performance of the turbomachinery was evaluated using established models from the literature for air turbines and axial-flow compressors operating under similar pressure ratio conditions [8]. A representative axial-flow compressor based on the NASA Stage 37 configuration was adopted and the turbine was modeled using a simplified Stodola model to simulate off-design conditions.

2.4 Off-design model for the heat exchanger

The heat transfer correlations employed in this study were adopted from the work of Yoon et al. [9], who investigated various channel configurations. Among these, the correlation corresponding to the zigzag channel configuration was selected for the present analysis.

2.5 Econmic evaluation of the OABC-DAC system

All cost data were converted to 2024 U.S. dollars for consistency. Table 2 summarizes the cost correlations used to estimate the installation costs of major OABC–DAC components. Turbomachinery costs were evaluated using thermodynamic-variable-based correlations [10], while IHX and recuperator costs were estimated based on heat transfer performance (UA) [11]. Civil works and distribution network costs were adopted from Ref [10].

Table 2. Costing formula for calculating the total capital cost (CAPEX) of the OABC-DAC system

Item	Equation	Ref
Adsorption tower	$\frac{\Gamma_s \cdot n_{contactors} \cdot \pi l (d_2^2 - d_1^2) \rho_s \left(\frac{w_1}{d_3}\right)\left(\frac{w_2}{d_3}\right) t_l}{t_s}$	[4]
Compressor	$\left(\frac{k_{c1} \cdot \dot{m}_{air}}{k_{c2} - \eta_{isen,C}}\right) \cdot (r_p) \cdot \ln(r_p)$	[10]
Turbine	$\left(\frac{k_{AT1} \cdot \dot{m}_{air}}{k_{AT2} - \eta_{isen,AT}}\right) \cdot (r_p) \cdot (1 + \exp(k_{AT3} T_{in} - k_{AT4}))$	[10]
IHX	$1700 \times UA$	[11]
Recuperator	$1700 \times UA$	[11]

The steam cost was estimated based on Ref. [12], in which the cost breakdown of the primary and secondary systems was analyzed using the AP1000 reactor as a reference. In this study, the cost components associated with the secondary system (i.e., the reactor and turbine plant) were excluded. The remaining cost fractions, excluding the secondary system, were then assumed to be applicable to the i-SMR with the same proportional structure and were used for the steam cost calculation.

Table 3. Capital cost breakdown of an AP1000 nuclear power plant used for steam cost estimation [12]

	Direct (%)	Indirect/ Direct	Indirect (%)	Total (%)
21-Structures & Improvements	26%	1.43	33%	30%
22-Reactor Plant Equipment	31%	1.43	39%	35%
23-Turbine Plant Equipment	22%	0.61	12%	17%
24-Electrical Plant Equipment	10%	0.61	5%	8%
25-Misc. Plant Equipment	6%	1.43	8%	7%
26-Condensing Heat Rejection	5%	0.61	3%	4%

The levelized cost of direct air capture (LCOD) represents the net cost of capturing one tonne of CO_2 and is calculated from the annualized CAPEX and

OPEX, accounting for electricity revenue and annual CO_2 capture.

$$\mathrm{LCOD} = \frac{\mathrm{CAPE}}{} \quad (1)$$

**ann = annualized, elec = electricity*

2.6 Results of the case study and sensitivity analysis

An operating-condition optimization was performed to improve the economic performance of the system. The adsorption time t_ADS and recuperator effectiveness were identified as the key variables affecting the LCOD. The analysis shows that a recuperator effectiveness of 92% and t_ADS of 4 h result in an LCOD of approximately 306.76 $/t$CO_2$, representing a reduction of about 37% compared to the baseline case, while satisfying the CO_2 purity requirement for CCS applications (≥95%).

To further examine the cost structure under this optimal operating condition, the CAPEX and OPEX compositions of the system were analyzed. The adsorption tower dominates the CAPEX, accounting for approximately 63.9%, while labor represents the largest share of the OPEX (26.6%) due to contributions from both the DAC and OABC subsystems. The cost breakdown ratios are shown in Fig 4 and Fig 5.

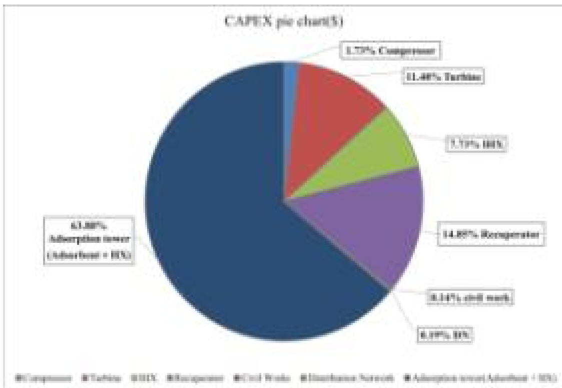

Fig 4. Pie chart illustrating the composition ratios of the CAPEX

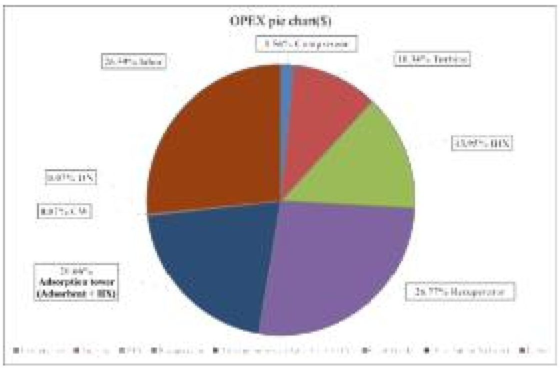

Fig 5. Pie chart illustrating the composition ratios of the OPEX

Additionally, a sensitivity analysis was conducted under the optimal operating condition (t_ADS = 4 h, recuperator effectiveness = 92%). The results indicate that the recuperator pressure drop, adsorption pressure ratio, turbine efficiency, operating rate, and adsorbent lifetime are the dominant factors influencing the LCOD, with variations causing LCOD changes of approximately 2.2–3.8 $/t$CO_2$. The discount rate was also found to have a significant impact through its effect on annualized capital costs. Adsorbent lifetime, in particular, is associated with sorbent degradation under repeated TSA cycling, which reduces CO_2 capacity and increases replacement frequency, ultimately leading to higher LCOD over the project lifetime.

3. Conclusions

The LCOD estimated for the OABC–DAC system under the optimal operating condition is approximately 306.76 $/t$CO_2$. To assess the economic competitiveness of this value, the estimated LCOD was compared with the reported CO_2 capture cost ranges of other DAC and CCS-related technologies.

Table 4. Comparison of CO_2 removal costs across major CCS and DAC technologies

Technology	Cost range ($/t$CO_2$) (based on 2024 CPI)	Ref
L-DAC + nuclear	175–268	[13]
S-DAC + nuclear	669–700	[13]
Renewable energy-based DAC	307–736	[5]
This work (i-SMR + OABC + S-DAC)	186.3–306.8	-

When compared with the CO_2 capture cost ranges of nuclear- and renewable energy–based DAC technologies presented in Table 4, the i-SMR+OABC+S-DAC system exhibits competitive CO_2 removal costs within a similar range even under the baseline operating conditions. In particular, as the electricity selling price increases, the LCOD can be reduced to below 200 $/t$CO_2$, demonstrating substantial economic potential. These results indicate that the OABC–DAC system coupled with nuclear thermal energy from an i-SMR can achieve strong economic performance for CO_2 removal.

Acknowledgement

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