

Comparative Economic Assessment of an Open-Air Brayton Cycle-Based Direct Air Capture System Considering the Heat Source Characteristics of Different Reactor Types

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1. Introduction

Direct Air Capture (DAC) is a negative emissions technology that directly separates and removes carbon dioxide from ambient air, where CO_2 is present at a concentration of approximately 420 ppm, and has attracted attention as one of the key technologies for achieving carbon neutrality. However, because of the low atmospheric concentration of CO_2 , large volumes of air must be processed, which consumes substantial amounts of electricity and thermal energy.

In a previous study, an Open-Air Brayton Cycle-based Direct Air Capture (OABC-DAC) system was integrated with an innovative Small Modular Reactor (i-SMR), which is a Pressurized Water Reactor type SMR, and its system-level thermodynamic performance and economic feasibility were evaluated [1]. The effects of adsorption time and recuperator effectiveness on the Levelized Cost of Direct Air Capture (LCOD) were also investigated. However, the previous analysis considered only the i-SMR, and the effects of reactor-specific thermal output, process heat supply temperature, and energy cost characteristics on the economic performance of the OABC-DAC system were not comparatively evaluated.

In this study, the existing OABC-DAC system model was updated to incorporate the characteristics of the $K_2CO_3@ \gamma-Al_2O_3$ sorbent, which is a cost-efficient DAC adsorbent candidate, and the scope of application was extended beyond the i-SMR to include High-Temperature Gas-Cooled Reactor (HTGR), Sodium-cooled Fast Reactor (SFR), and Molten Salt Reactor (MSR) concepts. The thermal and electrical outputs, temperature conditions, and energy costs of each reactor were considered as major heat-source characteristics. Based on these conditions, the LCOD and captured CO_2 purity were compared according to reactor type and recuperator effectiveness to evaluate the impact of reactor heat-source characteristics on the economic performance of the OABC-DAC system.

2. Methods and Results

2.1. OABC-DAC System and Adsorbent Model

In this study, a comparative analysis of different reactor types was performed using the thermodynamic

and economic assessment model of the OABC-DAC system developed in the previous study.

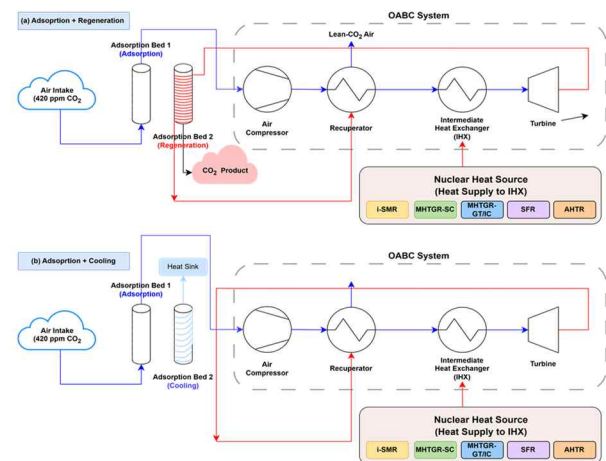


Figure 1. Schematic configuration and operating modes of the OABC-DAC system coupled with different nuclear heat sources

Figure 1 shows the schematic configuration and operating modes of the OABC-DAC system. The system consists of an adsorption bed, air compressor, recuperator, intermediate heat exchanger (IHx), and turbine. Ambient air containing approximately 420 ppm CO_2 is introduced into the adsorption bed, where CO_2 is selectively captured by the adsorbent. The CO_2 -depleted air is subsequently compressed and preheated in the recuperator before receiving additional thermal energy from the nuclear heat source through the IHx. The heated air is then expanded through the turbine to generate electricity. During the regeneration period, the hot turbine exhaust is supplied to the adsorption bed to provide the thermal energy required for CO_2 desorption, and the remaining thermal energy is subsequently recovered in the recuperator. During the cooling period, the regenerated adsorption bed is cooled before the subsequent adsorption cycle, while the turbine exhaust is directed to the recuperator.

In the previous study, mmen- $Mg_2(dobpdc)$ was employed as the reference sorbent, whereas in this study, the sorbent model was updated to incorporate the characteristics of $K_2CO_3@ \gamma-Al_2O_3$. The CO_2 adsorption

equilibrium of $K_2CO_3@ \gamma\text{-}Al_2O_3$ was calculated using the Dual-site Langmuir (DSL) model. The model parameters were fitted to in-house experimental data. The regeneration process considered in this analysis consisted of a 3 h heating and desorption period followed by a 1 h cooling period. The key analysis conditions are summarized in Table 1.

Table 1. Key analysis conditions for the OABC-DAC system

Parameter	Value/assumption
Adsorbent	$K_2CO_3@ \gamma\text{-}Al_2O_3$
CO ₂ equilibrium model	Dual-site Langmuir
CO ₂ isotherm temperatures	283.15, 298.15, 313.15 K
N ₂ isotherm temperature	298.15 K
Initial condition	Adsorbed equilibrium state at ambient conditions
Heating and desorption period	3 h
Cooling period	1 h
Total regeneration period	4 h
Time step	400 s

2.2 Heat Source and Economic Conditions for Different Reactor Types

To compare the effects of reactor-specific heat-source characteristics on the economic performance of the OABC-DAC system, i-SMR, HTGR (MHTGR-SC and MHTGR-GT/IC), SFR, and MSR (AHTR) were selected for evaluation. The power output, temperature characteristics, and energy costs of each reactor were incorporated into the analysis. LCOE values reported for different reference years were converted to 2024 USD and applied consistently.

In addition, the thermal energy cost supplied to the OABC-DAC system was estimated based on the LCOE and cost structure of each reactor. The steam cost for each reactor was calculated by applying a cost fraction that excludes secondary-system costs. The major reactor characteristics and economic input conditions are summarized in Table 2.

Table 2. Reactor heat-source and economic conditions

Reactor concept	Thermal power (MW _{th})	LCOE* (\$/MWh _e)	Steam cost (\$/MWh _{th})	Ref
i-SMR	520	65.00	17.6375	[2]
MHTGR-SC	1,800	111.7767	33.2739	[3][4]
MHTGR-GT/IC	1,800	107.3056	37.1515	[3][4]
SFR	3,360	152.1590	45.9135	[3][5]
AHTR	3,000	154.7950	55.2386	[3][5]

*Note: LCOE values were converted to 2024 USD.

2.3 Economic Assessment Method for the OABC-DAC System

The economic assessment of the OABC-DAC system was performed by considering the capital cost (CAPEX) of the major components, the annual operating cost (OPEX), the thermal energy cost supplied by the reactor,

and the economic benefit associated with electricity generation from the OABC. The capital costs of the adsorption system, compressor, turbine, IHX, and recuperator were estimated based on their respective design variables and thermodynamic performance. The major capital cost correlations are summarized in Table 3.

Table 3. Capital cost correlations for the major components of the OABC-DAC system

Item	Equation	Ref
Adsorption system	$C_{\text{adsorbent}} + C_{HX,ADS}$	[6][7]
Compressor	$\left(\frac{k_{c1} \cdot \dot{m}_{air}}{k_{c2} - \eta_{ben,c}} \right) \cdot (r_p) \cdot h(r_p)$	[8]
Turbine	$\left(\frac{k_{AT1} \cdot \dot{m}_{air}}{k_{AT2} - \eta_{ben,AT}} \right) \cdot (r_p) \cdot (1 + \exp(k_{AT3} T_h - k_{AT4}))$	[8]
IHX	$1700 \times UA_{IHX}$	[7]
Recuperator	$1700 \times UA_{Recup}$	[7]

The economic performance of the system was evaluated using the Levelized Cost of Direct Air Capture (LCOD), which was calculated as follows:

$$LCOD = \frac{C_{CAPEX,annual} + OPEX_{total} + C_{thermal} - R_{electricity}}{m_{CO_2,annual}} \quad (1)$$

where $C_{CAPEX,annual}$ is the annualized capital cost, $OPEX_{total}$ is the total annual operating cost, $C_{thermal}$ is the annual thermal energy cost supplied by the reactor, $R_{electricity}$ is the annual revenue from electricity generated by the OABC, and $m_{CO_2,annual}$ is the annual amount of captured CO₂. The steam cost listed in Table 2 was applied in the calculation of $C_{thermal}$ for each reactor.

2.4 Economic Assessment Results for Different Reactor Types

In the previous study [1], sensitivity analyses showed that recuperator effectiveness had a significant influence on the economic performance of the OABC-DAC system. Therefore, recuperator effectiveness was selected as the primary component-performance variable in the present study, while other component performance parameters, such as compressor and turbine efficiencies, were kept fixed to isolate the effects of reactor-specific heat-source characteristics.

To compare the economic performance of the OABC-DAC system among different reactor types, the LCOD was calculated by varying the adsorption bed volume for each reactor and recuperator effectiveness condition. The effects of adsorption bed size on both capital cost and CO₂ processing capacity were considered, and the bed volume yielding the minimum LCOD under each condition was selected for comparison across reactor types. Figure 2 shows the minimum LCOD for each

reactor over the investigated recuperator effectiveness range of 91–96%.

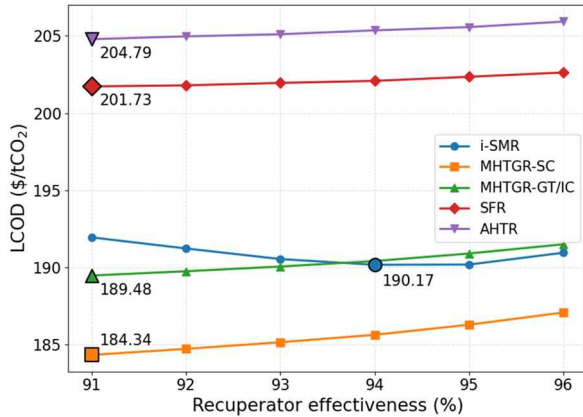


Figure 2. Minimum LCOD as a function of recuperator effectiveness for different reactor concepts.

The LCOD of MHTGR-SC, MHTGR-GT/IC, SFR, and AHTR decreased with decreasing recuperator effectiveness, reaching the lowest values at 91% within the investigated range of 91–96%. In contrast, the LCOD of the i-SMR decreased as the recuperator effectiveness increased from 91% to 94%, and then increased again, resulting in a minimum value at 94%.

Among the reactor concepts considered, MHTGR-SC exhibited the lowest LCOD, followed by MHTGR-GT/IC and i-SMR. In contrast, SFR and AHTR showed relatively higher LCOD values. These differences are attributed to the combined effects of reactor-specific heat-source characteristics and energy cost conditions, including the LCOE and steam cost. Meanwhile, the CO₂ purity remained at approximately 98 mol% under all evaluated conditions, indicating that the differences in CO₂ purity among reactor types and recuperator effectiveness conditions were relatively small.

3. Conclusions

In this study, the economic performance of an OABC-DAC system employing K₂CO₃@ γ -Al₂O₃ was compared across different reactor types, including i-SMR, MHTGR-SC, MHTGR-GT/IC, SFR, and AHTR, by incorporating their respective heat-source and economic conditions. For each reactor and recuperator effectiveness condition, the LCOD was evaluated by varying the adsorption bed volume, and the economic performance of the reactor types was compared using the lowest LCOD obtained within the investigated range.

Table 4. Minimum LCOD for different reactor types within the investigated range

Reactor concept	Recuperator effectiveness (%)	LCOD (\$/tCO ₂)
i-SMR	94	190.17
MHTGR-SC	91	184.34

MHTGR-GT/IC	91	189.48
SFR	91	201.73
AHTR	91	204.79

The results showed that MHTGR-SC exhibited the lowest LCOD of 184.34 \$/tCO₂, while MHTGR-GT/IC and i-SMR showed similar values of 189.48 \$/tCO₂ and 190.17 \$/tCO₂, respectively. In contrast, SFR and AHTR exhibited relatively higher LCOD values of 201.73 \$/tCO₂ and 204.79 \$/tCO₂, respectively. The i-SMR showed its minimum LCOD at a recuperator effectiveness of 94%, whereas MHTGR-SC, MHTGR-GT/IC, SFR, and AHTR showed their lowest LCOD values at 91% within the investigated range of 91–96%. In addition, the CO₂ purity remained at approximately 98 mol% under all evaluated conditions.

These results demonstrate that the economic performance of the OABC-DAC system can vary depending on reactor-specific heat-source characteristics and energy supply costs, even when the same OABC-DAC system configuration is applied. Under the conditions evaluated in this study, MHTGR-SC exhibited the lowest LCOD, indicating relatively favorable economic performance for integration with the OABC-DAC system.

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