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

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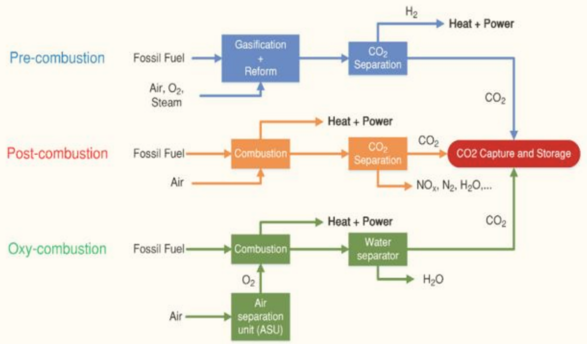
Introduction

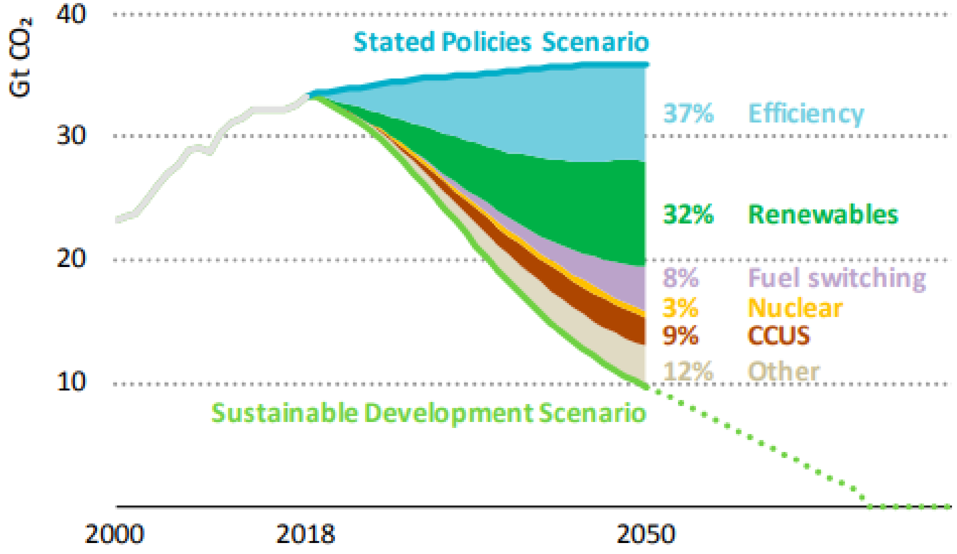
Basic concept of CCS/CCUS

Carbon Sequestration for Carbon Neutrality

CCUS (Carbon Capture, Storage and Utilization, CCUS)
or CCS (Carbon Capture and Sequestration, CCS) Technology

- Technology separates CO_2 from its source
- It is fundamentally derived from gas separation/purification technologies
  → Representative processes: **Adsorption, Absorption,** Cryogenic, Membrane…
  → Energy-intensive processes: Large amount of heat and electricity are required
- It primarily assumes capture from flue gas after fossil fuel combustion.
- Carbon capture technology is broadly divided into pre-combustion, post-combustion, oxy-combustion and **DAC** technologies.





[Source: IEA World Energy Outlook (2019)]

(단위 : 백만톤 CO_2eq)

구분	2018년	2050년 배출량		
		1안	2안	3안
합계(순배출량)*	727.6 (686.3)	25.4	18.7	Net-Zero
전환	269.6	46.2	31.2	0.0
산업	260.5	53.1	53.1	53.1
수송	98.1	11.2 (-9.4)	11.2 (-9.4)	2.8
건물	52.1	7.1	7.1	6.2
농축수산	24.7	17.1	15.4	15.4
폐기물	17.1	4.4	4.4	4.4
탈루 등	5.6	1.2	1.2	0.7
흡수원	-41.3	-24.1	-24.1	-24.7
CCUS	-	-95.0	-85.0	-57.9
수소	-	13.6	13.6	0.0

[표 1] 탄소중립위원회가 지난 8월 발표한 탄소중립 시나리오 3개 안

Introduction

To reach 2050 carbon neutrality

Direct Air Capture for Active Carbon Negative Emission

Reneable

Hydrogen

Absorbent

CCUS

※ 2050 Carbon Neutrality (21.10, S. Korea)

(2018 기준) CCUS contribution : ZERO
→ (2030 Goal) CCUS contribution -10.3 Mton
→ (2050 Goal) [A] CCUS contribution -55.1 Mton
[B] CCUS contribution -84.6 Mton
+ DAC -7.4 Mton

▶ Urgent DAC development needed

※A안: 화력발전 전면중단, 100% 그린수소 생산 등 온실가스 배출을 최대한 줄여 순배출 제로 달성
※B안: 화력발전 중 LNG 일부 잔존 및 내연기관차와 대체연료 (e-Fuel) 사용, 부생/추출 수소 일부 생산 가정 및 추가적인 제거원을 적극 활용하여 순배출 제로 달성

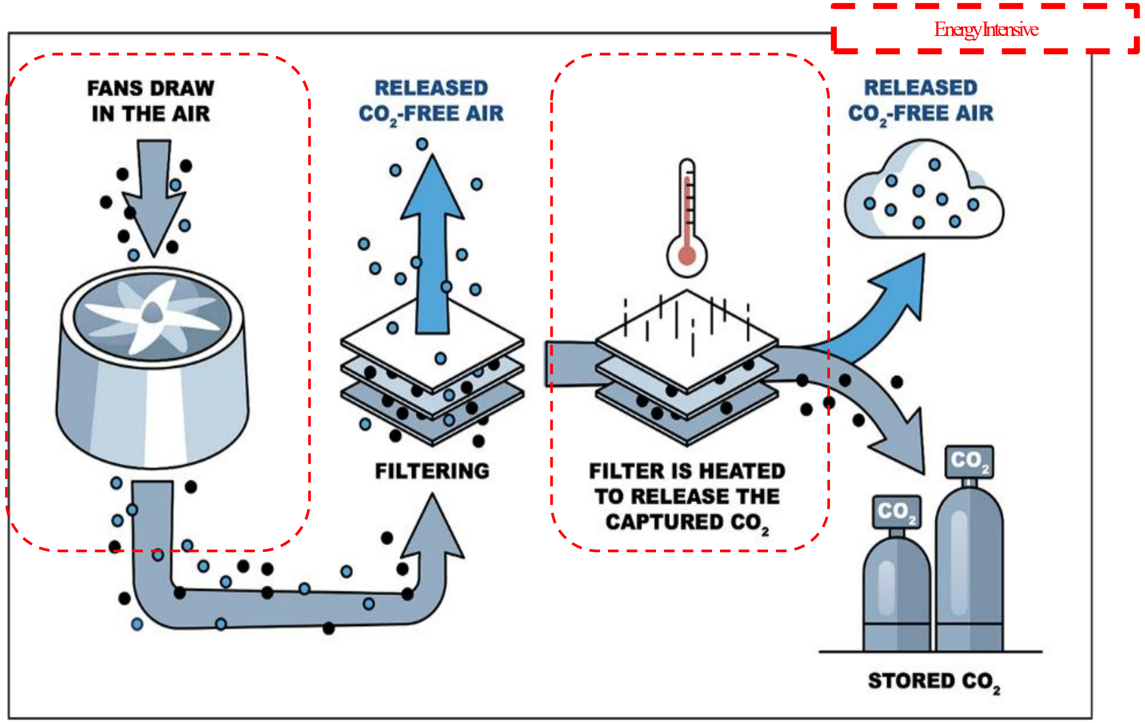
Largest DAC plant
Mammoth (Iceland)

To achieve net-zero emissions by 2050, the use of carbon dioxide removal (CDR) technologies, such as DAC, is essential.

※IPCC special report (2018)

Introduction

▪ Types of DAC technologies



Conceptual diagram of DAC

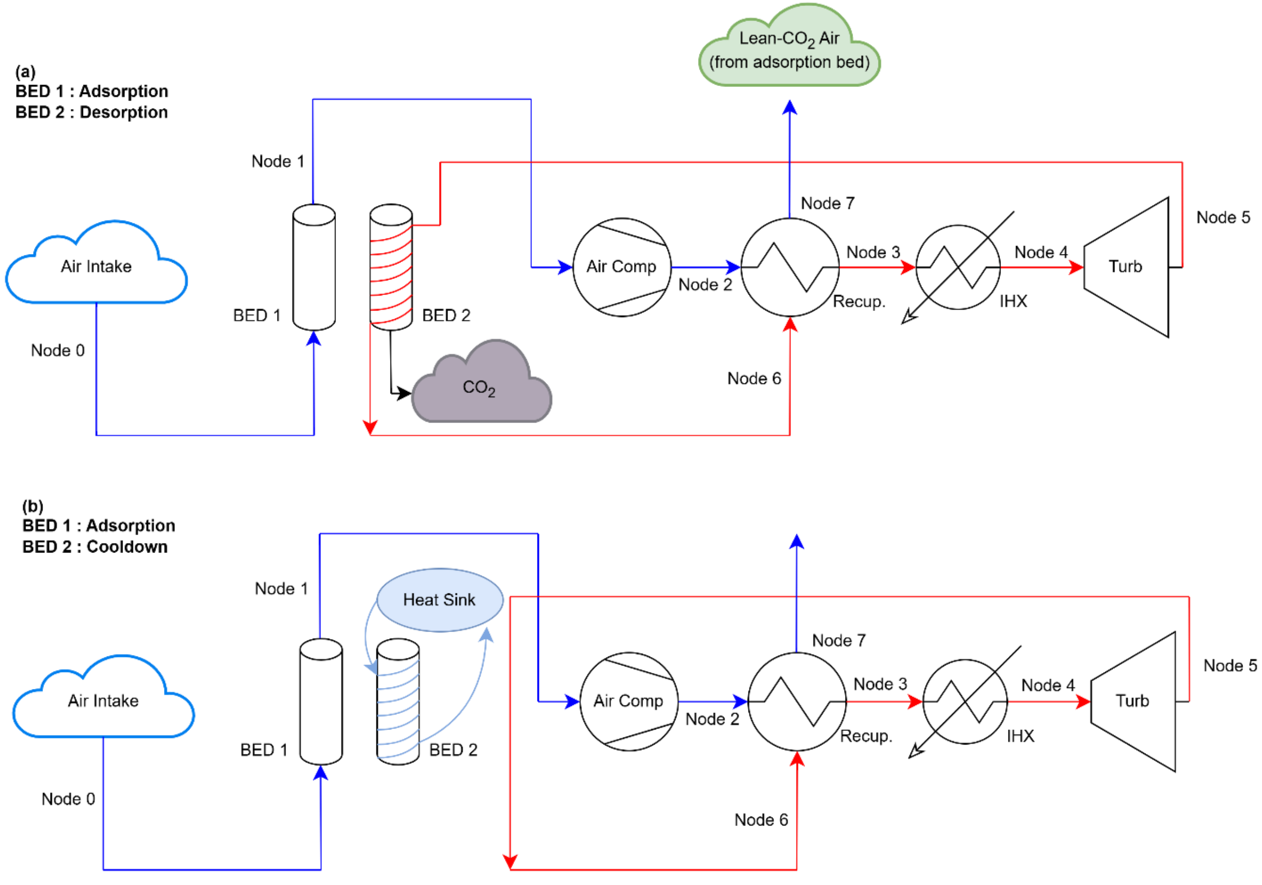
Technical comparison of L-DAC and S-DAC

		L-DAC	S-DAC
Operating flexibility		High	Low
Response time		5–15 min	N/A
CO_2 removal efficiency		90%–98%	80%–95%
Energy required		4–6 MJ/kgCO_2	2–3 MJ/kgCO_2
Characteristics		Capital-intensive; high capture efficiency; high water consumption; potential environmental impact	Energy-intensive; impurity-sensitive; no water requirement; possible water by-product generation
Regeneration temperature		High (~900 °C)	Low (80–120 °C)
Top substantiation level	Company	Carbon Engineering (2015)	Climeworks (2024)
	Scale	365 tCO_2/yr	36000 tCO_2/yr
	Energy required	5.25 GJ/tCO_2	5.76 GJ/tCO_2
	Cost	\$90 (NOAK) to \$232 (FOAK)/tCO_2	\$200 (NOAK) to ~\$500–600/tCO_2 (FOAK)
	Regeneration Temperature	900 °C	80–120 °C

Reference: Song, Yewon, Oh, Sangjin and Oh, Chaewoon (2024). Korea's technological level evaluation compared with global direct air capture (DAC) and reactive capture and conversion (RCC) technologies: Expert surveys using the Delphi method, Journal of Climate Change Research, Vol. 15, No. 4, pp. 489~511
Keith, D. W., Holmes, G., Angelo, D. S., & Heidel, K. (2018). A process for capturing CO2 from the atmosphere. Joule, 2(8), 1573-1594.
Climeworks AG. (2024). Direct air capture technology and Mammoth facility: Integrated technical information (capacity, regeneration temperature, energy requirement, and cost update).Retrieved from https://climeworks.com

System description

- Description of the OABC-DAC system and boundary conditions



Flow chart of the OABC-DAC system

Boundary conditions for the i-SMR

Component	Specification
Thermal power	520 MWth
Electrical capacity	170 MWe
Construction cost	3,500 $/kWe
Power generation cost	65 $/MWh
Core inlet temperature	286 °C
Outlet coolant temperature	321 °C

Boundary conditions for the OABC-DAC system

Component	Specification
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
Atmospheric temperature	298.15 K
Exhaust-to-atmosphere pressure ratio	99%

Reference: i-SMR innovative Small Modular Reactor brochure. KHNP(Korea Hydro and Nuclear Power)
Son, S. (2025). Thermodynamic Assessment of a Direct Air Capture System Integrated with an Open-Air Brayton Cycle for Application in the Secondary System of a Small Modular Reactor

System description

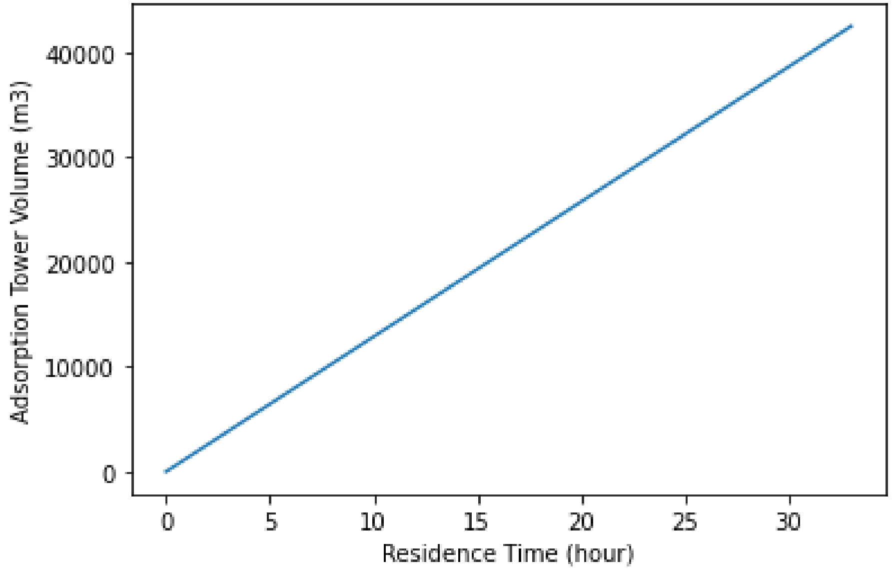
- Method for Determining the Adsorption Tower Capacity

Step 1: Rate Calculation Using Equilibrium Theory

To simplify the governing equations using equilibrium theory, the following two assumptions are introduced

1. Equilibrium is reached instantaneously.
2. Axial dispersion can be neglected.

$$w = \frac{u_g/\varepsilon}{1 + \left(\frac{1-\varepsilon}{\varepsilon}\right)\rho_p \frac{\Delta q}{\Delta c}}$$



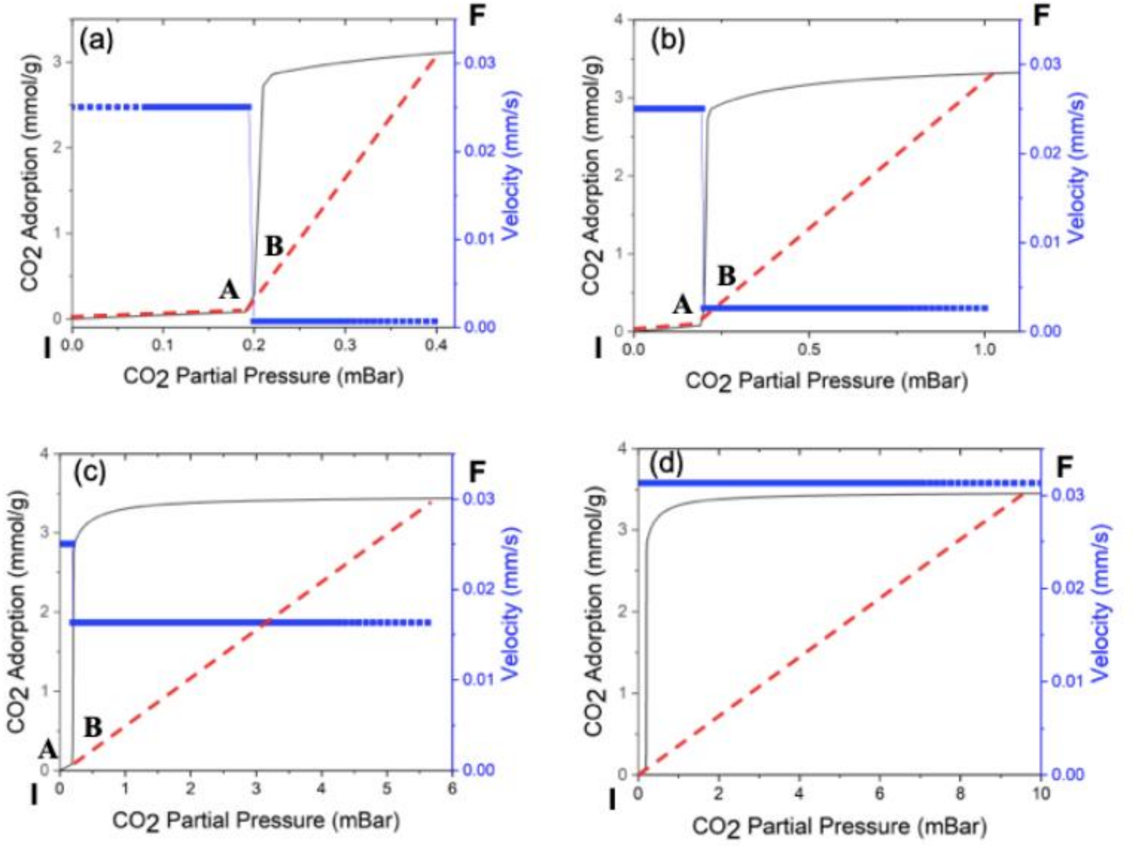


***Figure S1**. Application of Golden's string analysis to predict breakthrough times resulting for the CO_2 isotherm in MMEN-Mg_2(dobpdc) at 23 °C for the feed (F) with CO_2 partial pressures of 0.4 mBar (a), 1 mBar (b), 5.6 mBar(c), and 10 mBar(d). The bed was completely regenerated indicating zero CO_2 loading at the start of adsorption (I).The velocities were calculated for the adsorption experiment at 23 °C at the gas flowrate of 17.2 NmL/min.*

Methodology

- 0D Turbomachinery off-design model (Stodola / Stage37)

- Reference to previous studies on open-cycle air refrigeration cycles conducted within a similar pressure ratio range

: Park, S. K., Ahn, J. H., & Kim, T. S. (2012). Off-design operating characteristics of an open-cycle air refrigeration system. *International journal of refrigeration*, *35*(8), 2311-2320.
Reid, L., & Moore, R. D. (1978). *Design and overall performance of four highly loaded, high speed inlet stages for an advanced high-pressure-ratio core compressor* (No. NASA-TP-1337).

Fig.3. Compressor performance map with examples of running lines.

The turbine swallowing capacity versus pressure ratio relation was modeled using the Stodola equation (Dixon, 1978), described by Eq. (6), and a semi-theoretical efficiency correlation (Dugan, 1965), described by Eq. (7), was used to simulate the turbine efficiency variation:

$$\frac{\dot{m}_{\rm in}\sqrt{T_{\rm in}}/P_{\rm in}}{(\dot{m}_{\rm in}\sqrt{T_{\rm in}}/P_{\rm in})_{\rm d}} = \frac{\sqrt{1-(P_{\rm out}/P_{\rm in})^2}}{\sqrt{1-(P_{\rm out}/P_{\rm in})^2_{\rm d}}} \qquad (6)$$

$$\frac{\eta}{\eta_{\rm d}} = 1 - \left[1 - \frac{(N/\sqrt{T_{\rm in}})}{(N/\sqrt{T_{\rm in}})_{\rm d}}\sqrt{\frac{\left(1-(P_{\rm out}/P_{\rm in})^{(\gamma-1)/\gamma}\right)_{\rm d}}{\left(1-(P_{\rm out}/P_{\rm in})^{(\gamma-1)/\gamma}\right)}}\right]^2 \qquad (7)$$

The heat exchanger effectiveness also varied according to a change in the operating conditions, especially the flow rate. The heat transfer capacity (UA) from Eq. (8) was

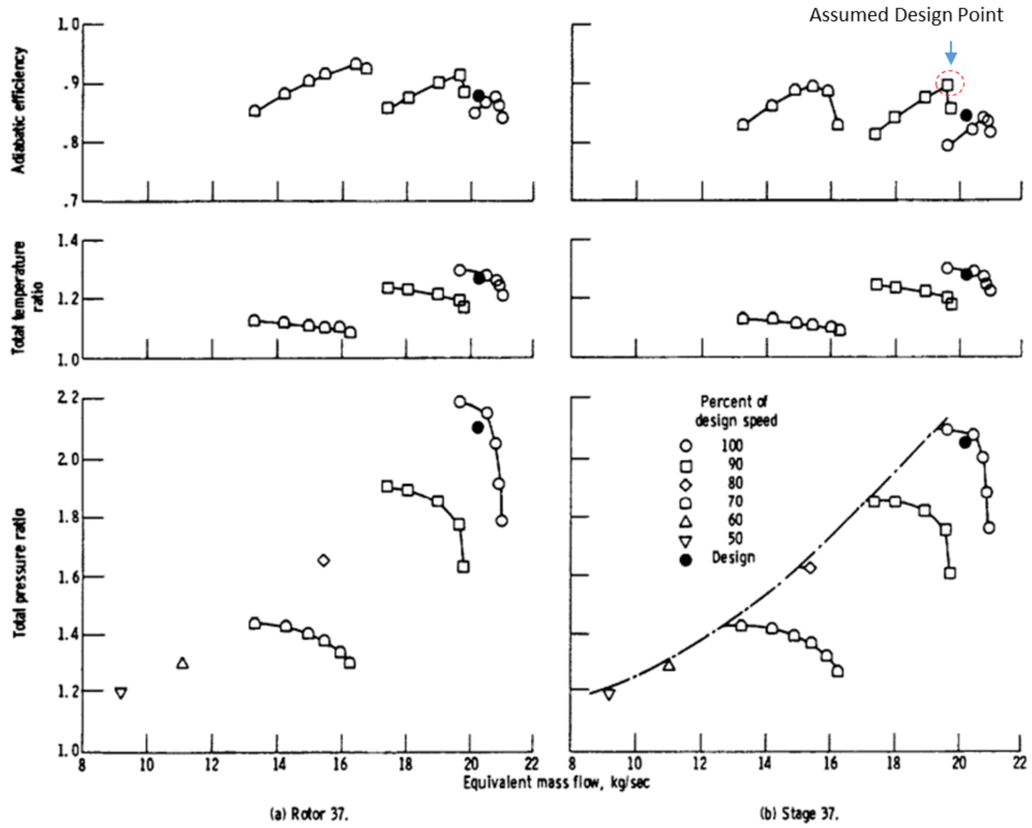
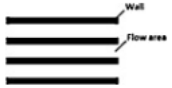
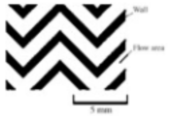
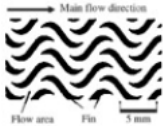
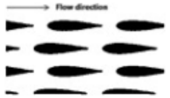


Figure 23. - Overall performance for configuration 37.

Methodology

- 1D Heat Exchanger model

Table 1. Current status of the correlations for the different PCHEs.

Channel shape	Description	Laminar	Turbulent
Straight		$f{\cdot}Re=15.78$ $Nu=4.089$	$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{e/D}{3.7}+\frac{2.51}{Re\sqrt{f}}\right)$ $Nu=0.023Re^{0.8}Pr^{n}$
Zigzag		$f{\cdot}Re=15.78+0.004868{\cdot}Re^{0.8416}$ (15°) $Nu=4.089+0.00365RePr^{0.58}$ (15°)	$f=0.1942Re^{-0.091}$ (40°) $Nu=0.1696Re^{0.629}Pr^{0.317}$ (40°)
S-shape		Not exist	$f=0.4545Re^{-0.34}$ $Nu=0.174Re^{0.593}Pr^{0.43}$
Airfoil		Not exist	Not exist

Yoon, S. H., No, H. C., & Kang, G. B. (2014). Assessment of straight, zigzag, S-shape, and airfoil PCHEs for intermediate heat exchangers of HTGRs and SFRs. *Nuclear Engineering and Design*, *270*, 334-343.

	Recuperator Design	
Hot	Diameter (mm)	9
	Length (m)	8.641293
	Mult	5000000
Cold	Diameter (mm)	9
	Length (m)	8.641293
	Mult	5000000
Plate	Thickness (mm)	0.6
	Material	SS-316L
	THK (W/mK)	14.6

```
0.24229807859163696
0.6627776125886171
527.314168681300５
523.7889999851426
er 1 :  1.4857391761324834e-08
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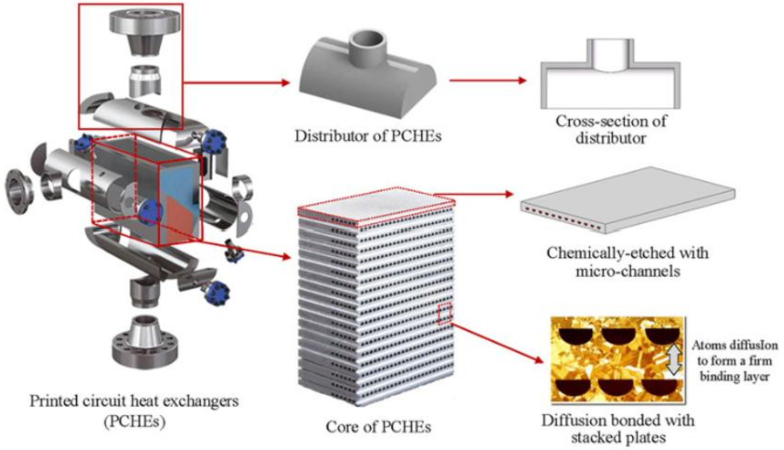


출처 : Alfa Laval

Methodology

- 0D Adsorption tower thermodynamic short-cut model

$$q^*_{CO_2} = q_{low}(P,T)\big(1-\omega(P,T)\big) + q_{high}(P,T)\,\omega(P,T) \qquad q_{low} = \frac{q_L (b_L P)^n}{1+(b_L P)^n}$$

$$\omega = \left(\frac{\exp\left(\frac{\ln(P/P_{step})}{\sigma}\right)}{1+\exp\left(\frac{\ln(P/P_{step})}{\sigma}\right)} \right)$$

$$q^*_{N_2} = \frac{q_{N_2} b_{N_2} P}{1+b_{N_2} P} \qquad q_{high} = \frac{q_H b_H P}{1+b_H P} + q_U P$$

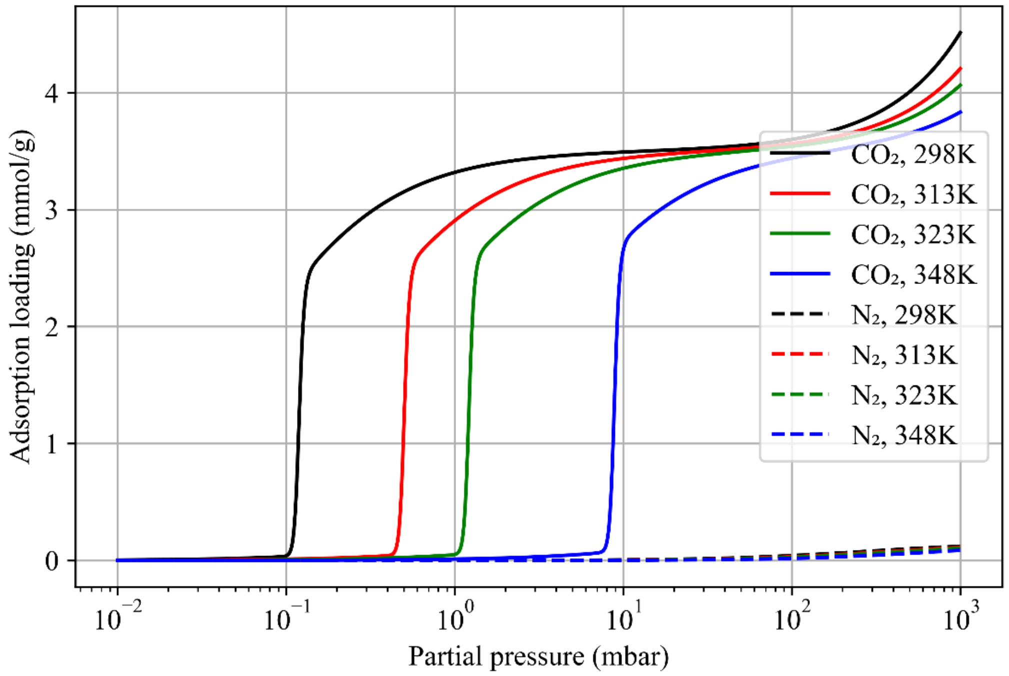
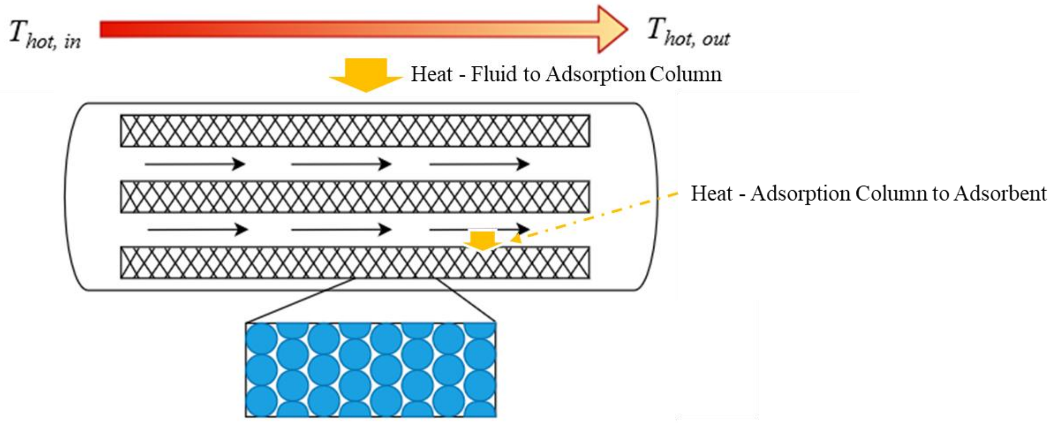


Fig. Adsorption isotherm fits of *mmen*-Mg_2(dobpdc) for CO_2 and N_2 at different temperatures



Energy Balance

$$\dot{Q} = (mCp)_{tot}\frac{dT_{BED}}{dt} - \frac{dm_{ADS}\sum_i \Delta H_{ads} q^*(T_{BED}, P_{BED}, y_i)}{dt} = (\dot{m}C_p)_{fluid}(T_{hot,in} - T_{hot,out})$$

$$\dot{Q} = UA\left(\frac{T_{hot,in} + T_{hot,out}}{2} - T_{BED}\right)$$

Species Mass Balance

$$q_i^{k+1} = q^*(T_{BED}^{k+1}, P_{BED}, y_i^{k+1})$$

$$y_i^{k+1} = \frac{q_i^k - q_i^{k+1}}{\sum_i (q_i^k - q_i^{k+1})}$$

Methodology

- Methodology and Explanation for CAPEX and OPEX Calculation

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

Item	Equation	REF
Adsorption tower	$\frac{\Gamma_s \cdot n_{contactors} \cdot \pi l(d_2^2 - d_1^2)\rho_s \left(\frac{w_1}{d_3}\right)\left(\frac{w_2}{d_3}\right) t_l}{t_s}$	McQueen et al., *Environ. Sci. Technol.*, 2020
Compressor	$\left(\frac{k_{c1} \cdot \dot{m}_{air}}{k_{c2} - \eta_{isen,C}}\right) \cdot (r_p) \cdot ln(r_p)$	Mondal & Ghosh, *Clean Technol. Environ. Policy*, 2017
Turbine	$\left(\frac{k_{AT1} \cdot \dot{m}_{air}}{k_{AT2} - \eta_{isen,AT}}\right) \cdot (r_p) \cdot (1 + \exp(k_{AT3} T_{in} - k_{AT4}))$	Mondal & Ghosh, *Clean Technol. Environ. Policy*, 2017
IHX	$1700 \times UA$	Marchionni et al., *SN Applied Sciences*, 2020
Recuperator	$1700 \times UA$	Marchionni et al., *SN Applied Sciences*, 2020

Total Cost of CAPEX :

$$C_{CAPEX} = C_{Adsorption\ tower} + C_{Comp} + C_{Turbine} + C_{IHX} + C_{Recup} + C_{CW} + C_{DN}$$

Cost of the civil works (C_{cw}) is considered as USD 4665,0. Cost of distribution network (C_{DN}) is considered as USD 6250,0 in the present study (Nouni et al. 2007).

Total capital cost (C_{BFCC}) of the BIGCC plant is given by

$$C_{BFCC} = C_{Comp} + C_{AT} + C_{BC} + C_{HX} + C_{HRSG} + C_{ST} + C_P + C_{Cond} + C_{CW} + C_{DN}.$$

Total Cost of OPEX :

$$OPEX_{total} = OPEX_{DAC} + OPEX_{OABC}$$

*Note: The operating expenditures (OPEX) were calculated separately for the DAC and OABC subsystems and then aggregated to obtain the total OPEX.

Reference: 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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Methodology

Methodology and Explanation for CAPEX and OPEX Calculation

- OPEX of the DAC system

$$OPEX_{DAC} = C_{Transport} + C_{Storage} + C_{Maintenance} + C_{Labor}$$

DAC-related OPEX components and calculation method

Item	Calculation method
Transport cost	11(fixed value) · Annual capture volume
Storage cost	10(fixed value) · Annual capture volume
Maintenance	$CAPEX_{Adsorption\ tower} \cdot 0.03$
Labor	$CAPEX_{Adsorption\ tower} \cdot 0.03 \cdot 0.3$

- OPEX of the OABC system

$$OPEX_{OABC} = C_{Comp} + C_{Turbine} + C_{IHX} + C_{Recup} + C_{CW} + C_{DN} + C_{Labor}$$

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
Manpower cost	0.25 USD/man-h
Manpower required	Twenty

O&M cost ratio applied to the CAPEX for each component

Labor and Maintenance

Labor and maintenance are determined as fixed fractions of the total CAPEX, wherein maintenance equals 0.03[CAPEX] and labor is 0.30[0.03[CAPEX]]. However, the labor fraction is subject to change as global labor rates are highly variable. While a small component in this study (labor amounts to a fraction of one percent of the total cost of capture), this component could become more dominant in under-developed areas.

Reference: McQueen, Noah; Psarras, Peter; Pilorgé, Hélène; Liguori, Simona; He, Jiajun; Yuan, Mengyao; et al. (2020). Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States. ACS Publications. Collection. https://doi.org/10.1021/acs.est.0c00476
Berwick, M. D., & Farooq, M. (2003). *Truck costing model for transportation managers* (No. MPC Report No. 03-152). Mountain-Plains Consortium.
McCollum, D. L., & Ogden, J. M. (2006). Techno-economic models for carbon dioxide compression, transport, and storage & correlations for estimating carbon dioxide density and viscosity.
GHG, I. (2009). CO2 storage in depleted oilfields: global application criteria for carbon dioxide enhanced oil recovery. Cheltenham Glos, UK: Prepared by Advanced Resources International and Melzer Consulting, 12.

Techno-Economic Assessment

- Optimization of the operating conditions and the capture unit cost based on the LCOD

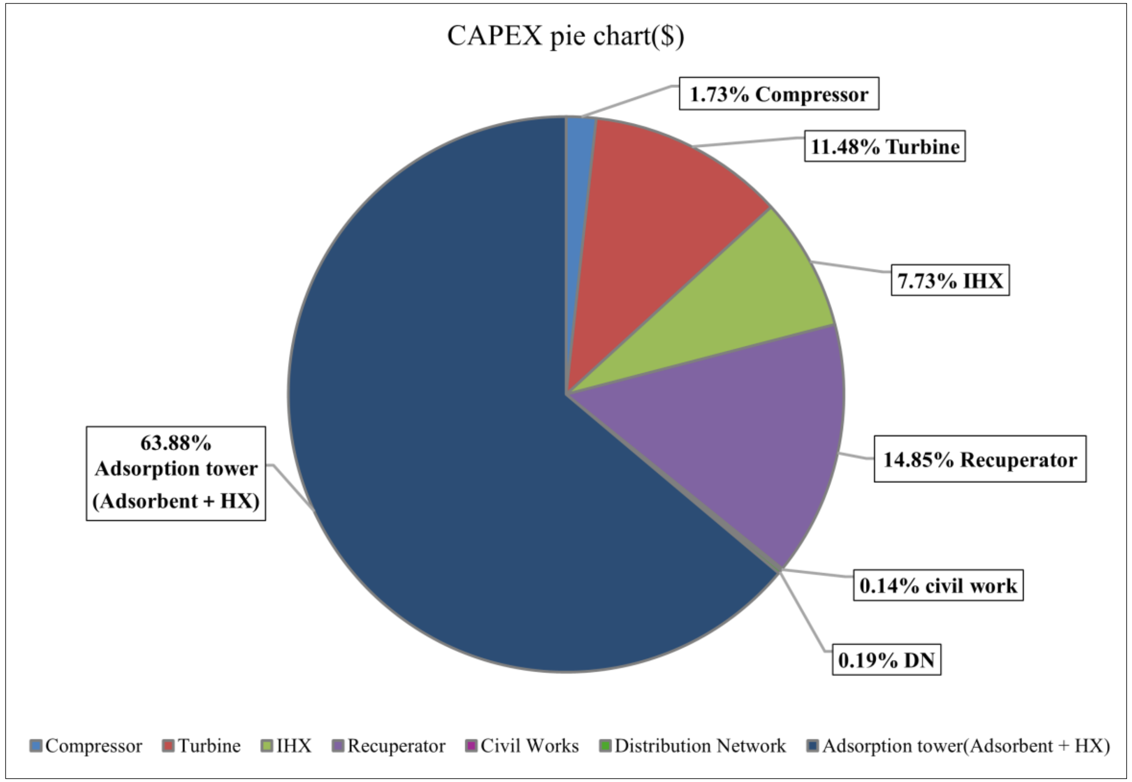
Purity and price according to changes in recuperator effectiveness and adsorption time

Cost ($\$/tCO_2$)		Recuperator effectiveness								
		98%	96%	94%	92%	91%	90%	84%	78%	76%
Cycle time (h)	3	961.702	738.019	669.185	645.242	646.897	638.567	657.366	678.863	687.375
	4	413.886	329.149	309.455	306.758	307.598	310.281	336.363	370.179	382.438
	5	436.589	353.423	334.210	331.704	332.553	335.294	361.288	394.951	407.149
	6	462.704	380.279	361.352	358.993	359.874	362.671	388.787	422.507	434.716
	7	490.137	408.060	389.283	387.012	387.917	390.750	416.972	450.756	462.979
	8	517.984	436.102	417.416	415.203	416.125	418.982	445.287	479.123	491.361
	9	545.938	464.141	445.475	443.273	444.196	447.055	473.349	507.162	519.392
	10	573.983	492.270	473.652	471.481	472.415	475.288	501.637	535.488	547.728
Purity (mol%)		Recuperator effectiveness								
		98%	96%	94%	92%	91%	90%	84%	78%	76%
Cycle time (h)	3	90.365	90.403	90.637	90.865	90.868	91.067	91.595	92.195	92.376
	4	96.056	96.056	96.059	96.061	96.061	96.064	96.070	96.077	96.079
	5	96.122	96.122	96.123	96.124	96.124	96.125	96.128	96.132	96.133
	6	96.150	96.150	96.151	96.151	96.151	96.152	96.154	96.156	96.156
	7	96.162	96.162	96.163	96.163	96.163	96.164	96.165	96.166	96.166
	8	96.168	96.169	96.169	96.169	96.169	96.170	96.170	96.171	96.172
	9	96.172	96.172	96.172	96.172	96.172	96.173	96.173	96.174	96.174
	10	96.174	96.174	96.174	96.175	96.175	96.175	96.175	96.176	96.176

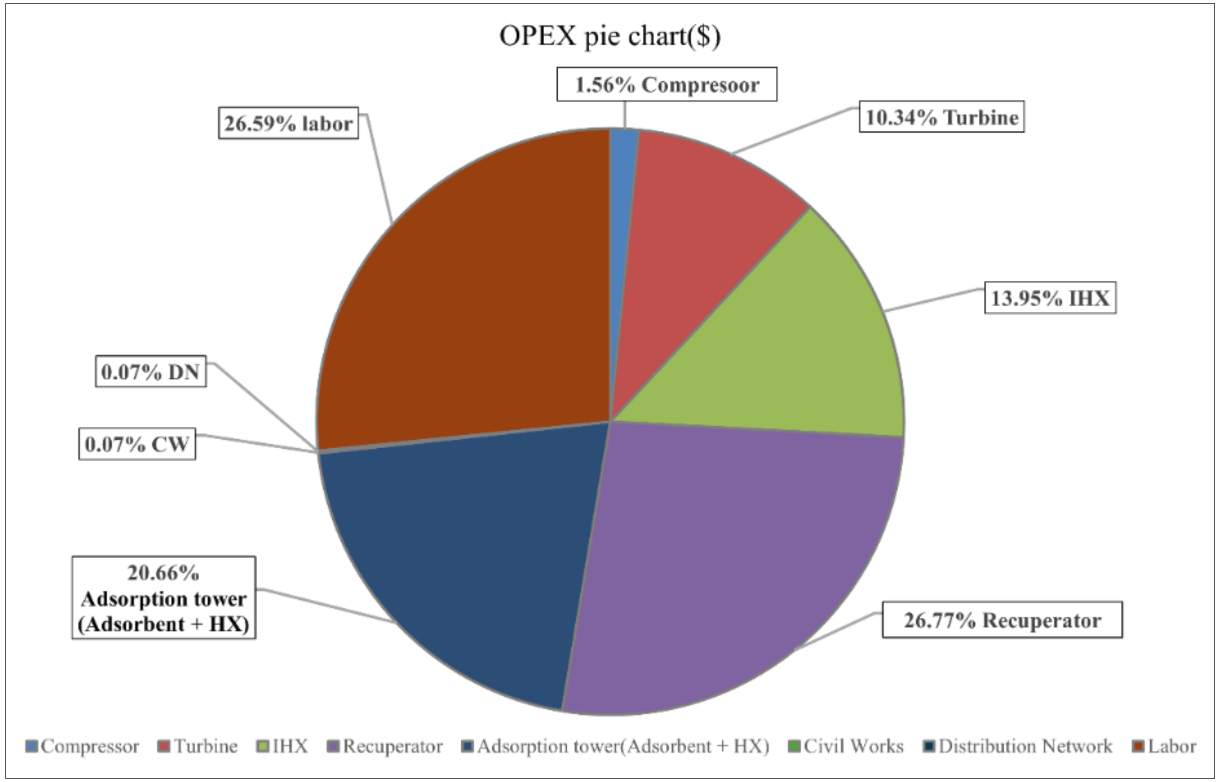
**The values in red represent the optimal cost point.*

Techno-Economic Assessment

- CAPEX and OPEX Breakdown (Pie Charts)



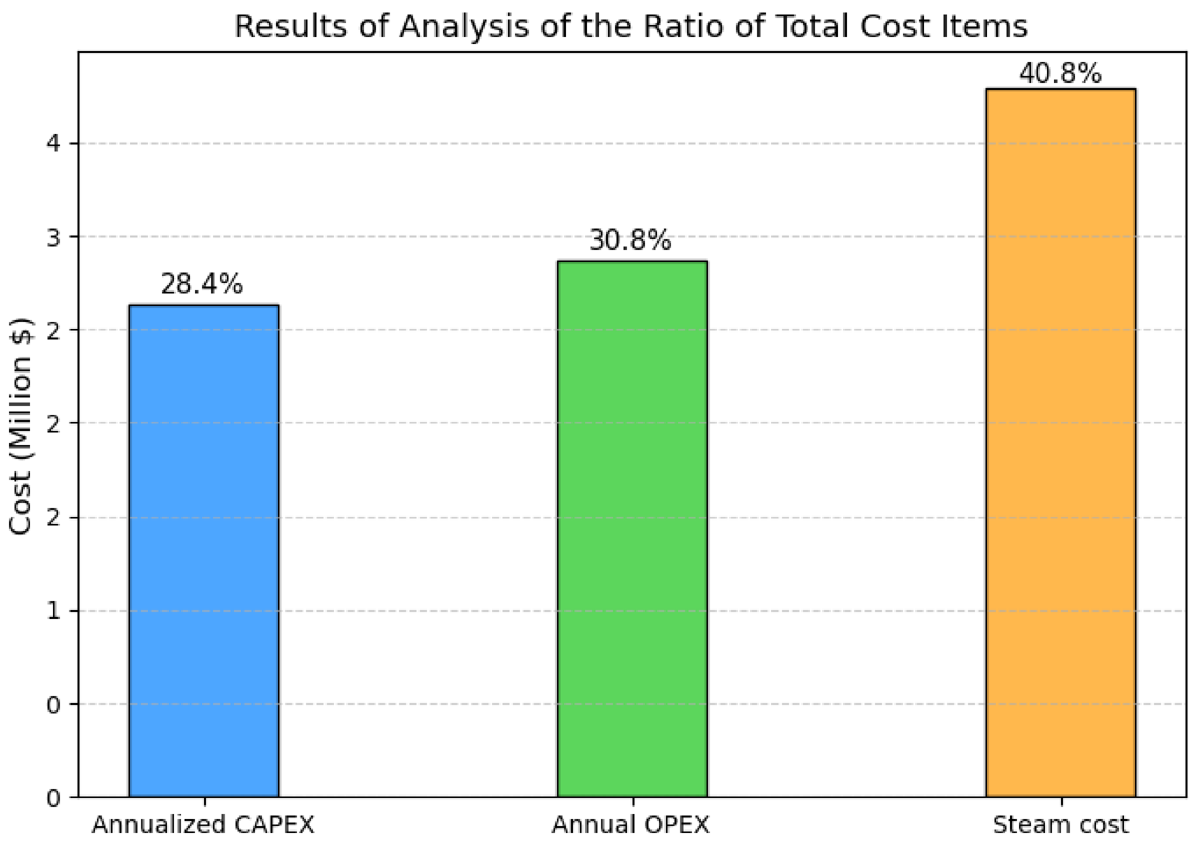
Pie chart illustrating the composition ratios of the CAPEX



Pie chart illustrating the composition ratios of the OPEX

Techno-Economic Assessment

- Cost Breakdown and Sensitivity Analysis Results of the Economic Evaluation

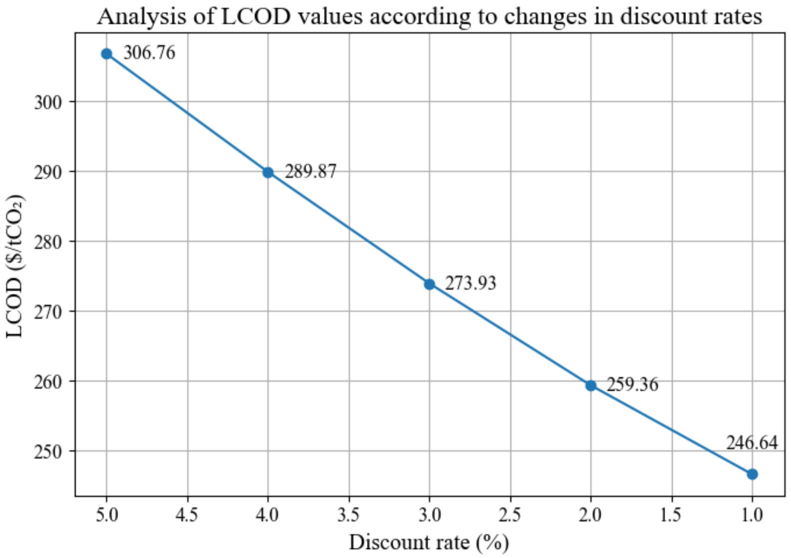


Sensitivity analysis results obtained under the optimal operating conditions

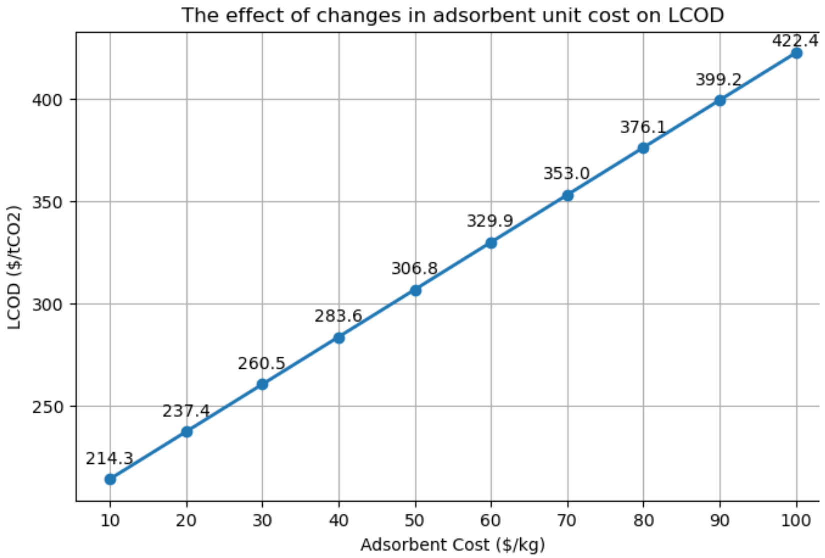
Item	Baseline value	LCOD change per 1%p change ($/%p)	Ranking
Recuperator pressure drop	1%	3.719537	1
ADS pressure ratio	0.99	3.845061	2
Turbine efficiency	90%	3.181014	3
Operating rate	90%	2.299817	4
Adsorbent lifetime	5 years	2.266605	5
IHX pressure drop	1%	1.900758	6
Discount rate	5%	1.726311	7
Compressor efficiency	90%	1.440622	8
Recuperator Effectiveness	92%	0.768059	9
Exhaust pressure ratio	0.99	0.610340	10
IHX Effectiveness	98%	0.496689	11
Adsorption time	4 h	0.718231	12
Unit cost of electricity	65 $/MWh	0.160025	13
Adsorbent unit price	50 $/kg	0.231194	14
Volumetric heat-transfer coefficient	100 (UA/V, W/m^{3}k)	0.029479	15
Plant life	80 years	0.009371	16

Techno-Economic Assessment

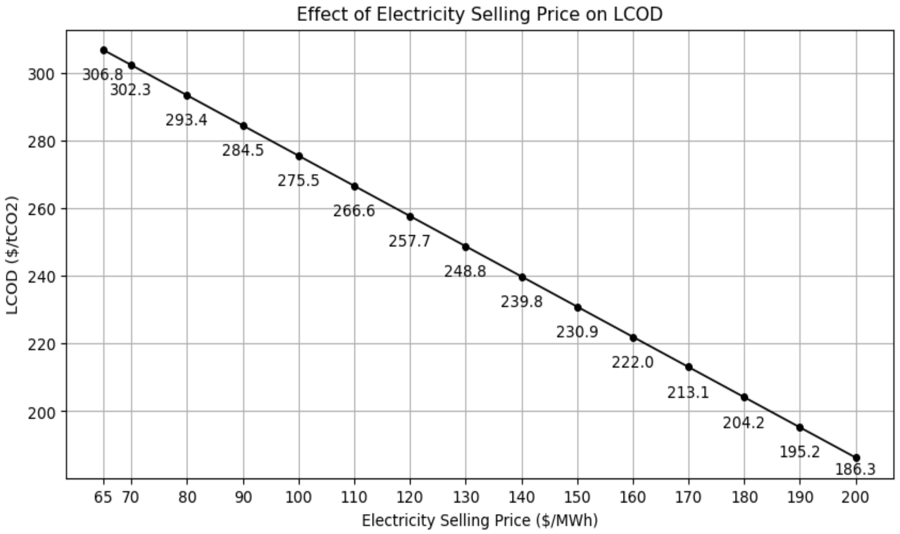
- Analysis of LCOD variation with discount rate, adsorbent price and electricity selling price around the optimal operating point



Analysis results for the LCOD value based on discount rate variations

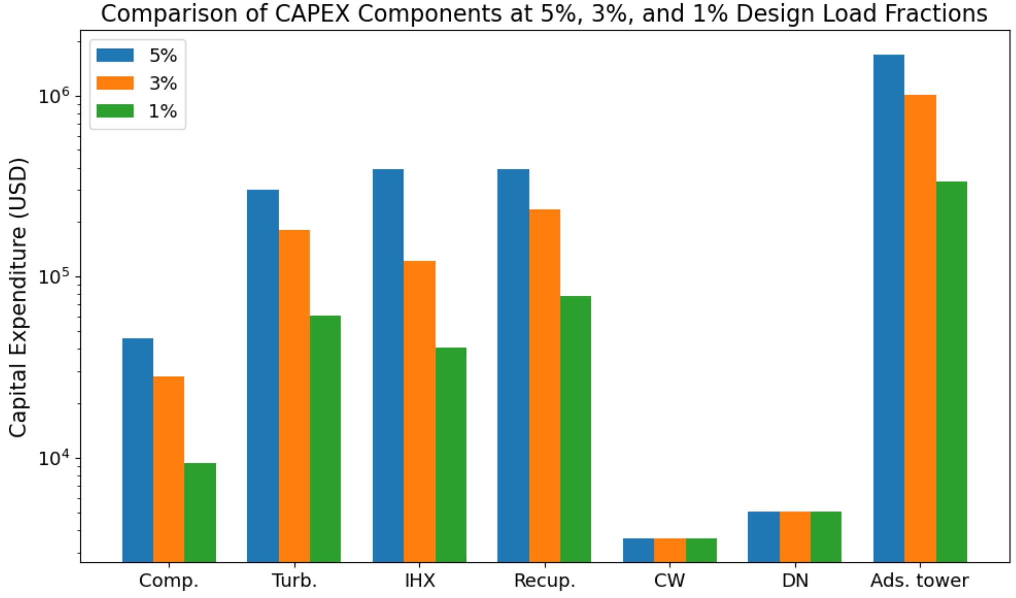


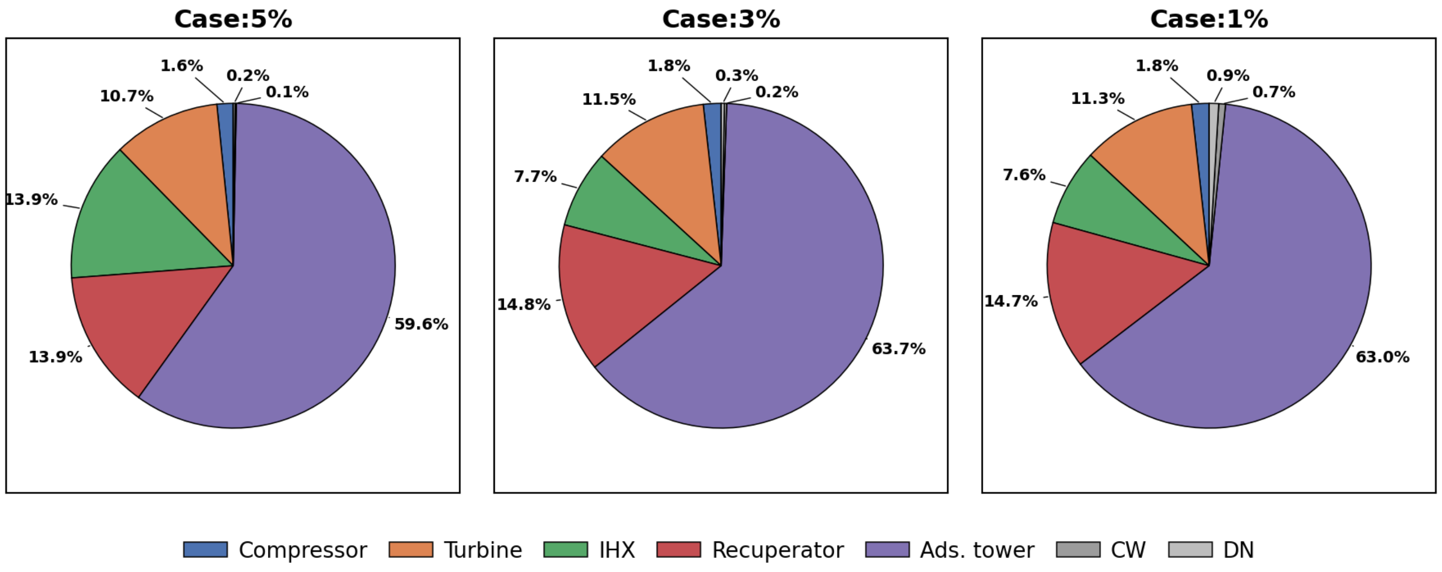
Effect of adsorbent unit cost on LCOD



Analysis results for the impact of electricity sale prices on LCOD

Conclusion and Summary





- Across the entire output range (1–5%), a decrease in heat capacity led to an overall reduction in CAPEX, while the total LCOD remained largely unchanged.
- The cost of the heat exchanger and the sorbent in the adsorption tower was identified as the component with the greatest potential for optimization.
- Improving the power generation efficiency is expected to significantly reduce the LCOD; therefore, the effect is anticipated to be more pronounced when applied to higher-temperature systems compared to light water reactors.
- The capture cost derived in this study is considered to be competitive with that of existing S-DAC integrated systems.

Technology	Cost range ($/t$CO_2$) (based on 2024 CPI)
L-DAC + nuclear	175–268
S-DAC + nuclear	669–700
Renewable energy-based DAC	307–736
This work (i-SMR + OABC + S-DAC)	246–306.8

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Q&A

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