

Cost-performance analysis and benchmarking of CO₂ capture systems for hard-to-abate industries

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FESC Interim Update
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1. Steel Production [7.2 %]

- Steel manufacturing involves high-temperature processes that release substantial CO₂. Traditional steelmaking methods rely on coal and coke, making emissions reduction difficult. [3]

2. Cement Production [3 %]

- Cement is a fundamental building material, but its production releases substantial CO₂, primarily due to the breakdown of limestone and the use of fossil fuels in kilns. [3]

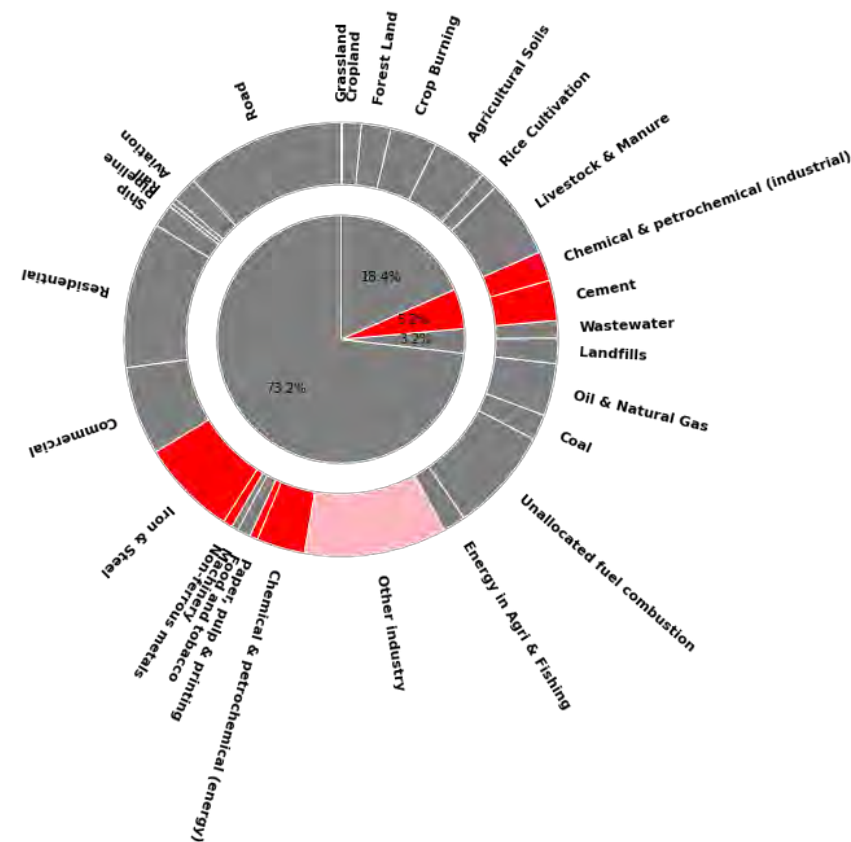
3. Chemical Manufacturing [6.8 %]

- Certain chemical processes require high temperatures and emit CO₂ as a by-product, making emissions reduction complex. [3]

4. Others [13 %]

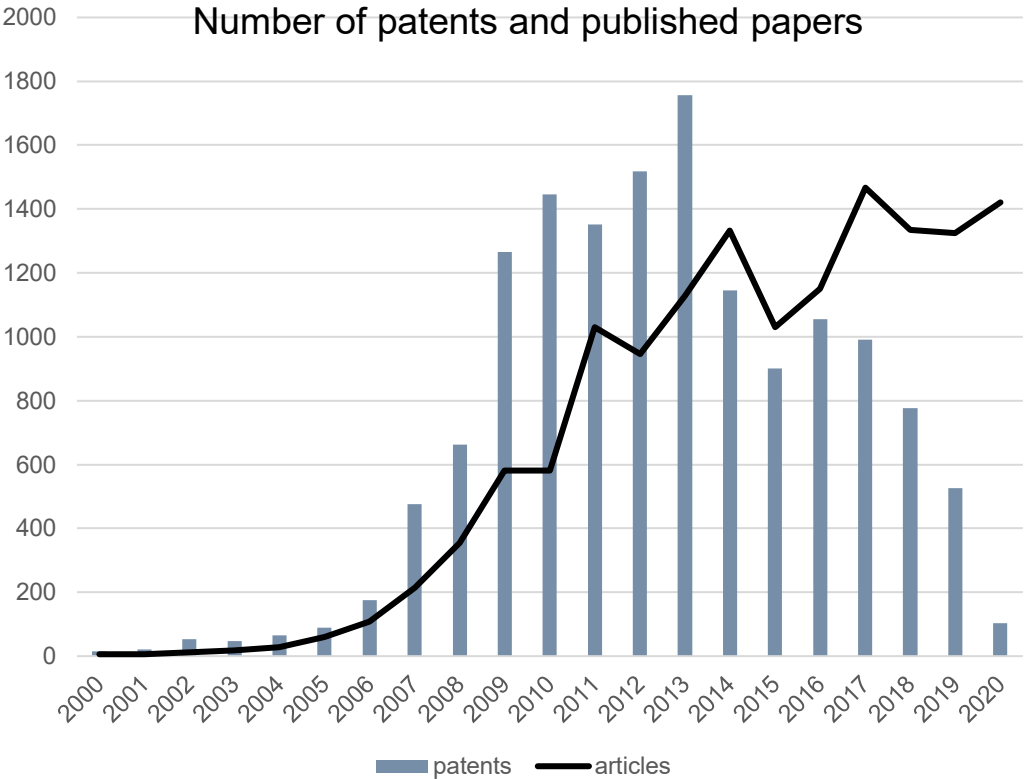
- Small industries, Paper, pulp & printing, non-ferrous metals [3]

Hard to abate industry: $\sum$ 20 %



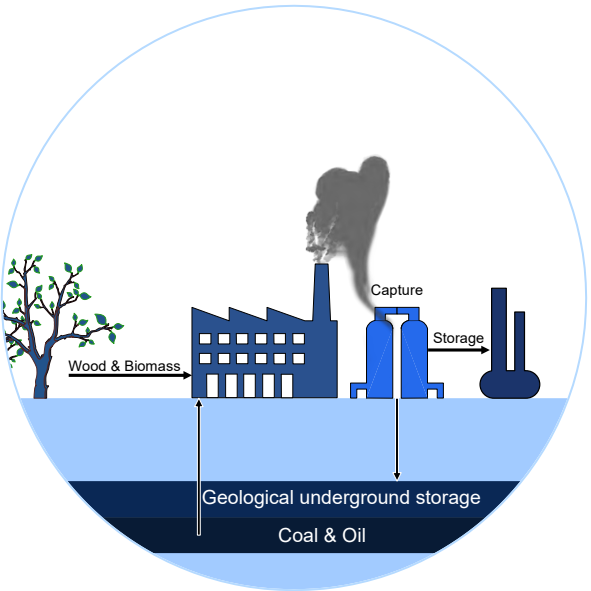
[4] Climate Watch, the World Resource Institute (2020)

[3] Source: European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL). Emission Database for Global Atmospheric Research (EDGAR), release [version 4.tox2_global_gridmaps](#).



Post-Combustion Capture

Captures CO₂ emissions from flue gases after combustion in power plants and industrial facilities



Amine Scrubbing

Ammonia Scrubbing

Membrane Separation

Direct Air Capture (DAC)

Cryogenic Separation (CCC)

Solid Sorbent Capture

Molten Salt Capture

[5] Khosroabadi, F., Aslani, A., Bekhrad, K., & Zolfaghari, Z. (2021). Analysis of Carbon Dioxide Capturing Technologies and their technology developments. *Cleaner Engineering and Technology*, 5(September), 100279. <https://doi.org/10.1016/j.clet.2021.100279>

Current Research Objectives

- Amine-alternatives for mid/high temperatures
- Combine **high working capacity** of solid sorbents with **versatility** of liquid sorbents
 - Calcium looping (CaL)
 - Solid Oxides mediated by molten salts (MgO)
- Combine CCS with electrolysis in molten salts

Do molten salts redefine carbon capture?

-  High CO₂ uptake
-  Excellent cyclic behavior
-  Liquid mid-to-high temperature processes
-  Reduce thermodynamic and economic cost



Kinetics & Stability

- CO₂ Absorption & Desorption
- Cycle stability



CO₂ Uptake

- Key identifier for efficient CCS process
- mmol / g sorbent
- Working capacity vs max. uptake



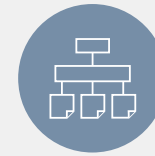
Scale Up

- Depending on empirical system size



Operation Temp.

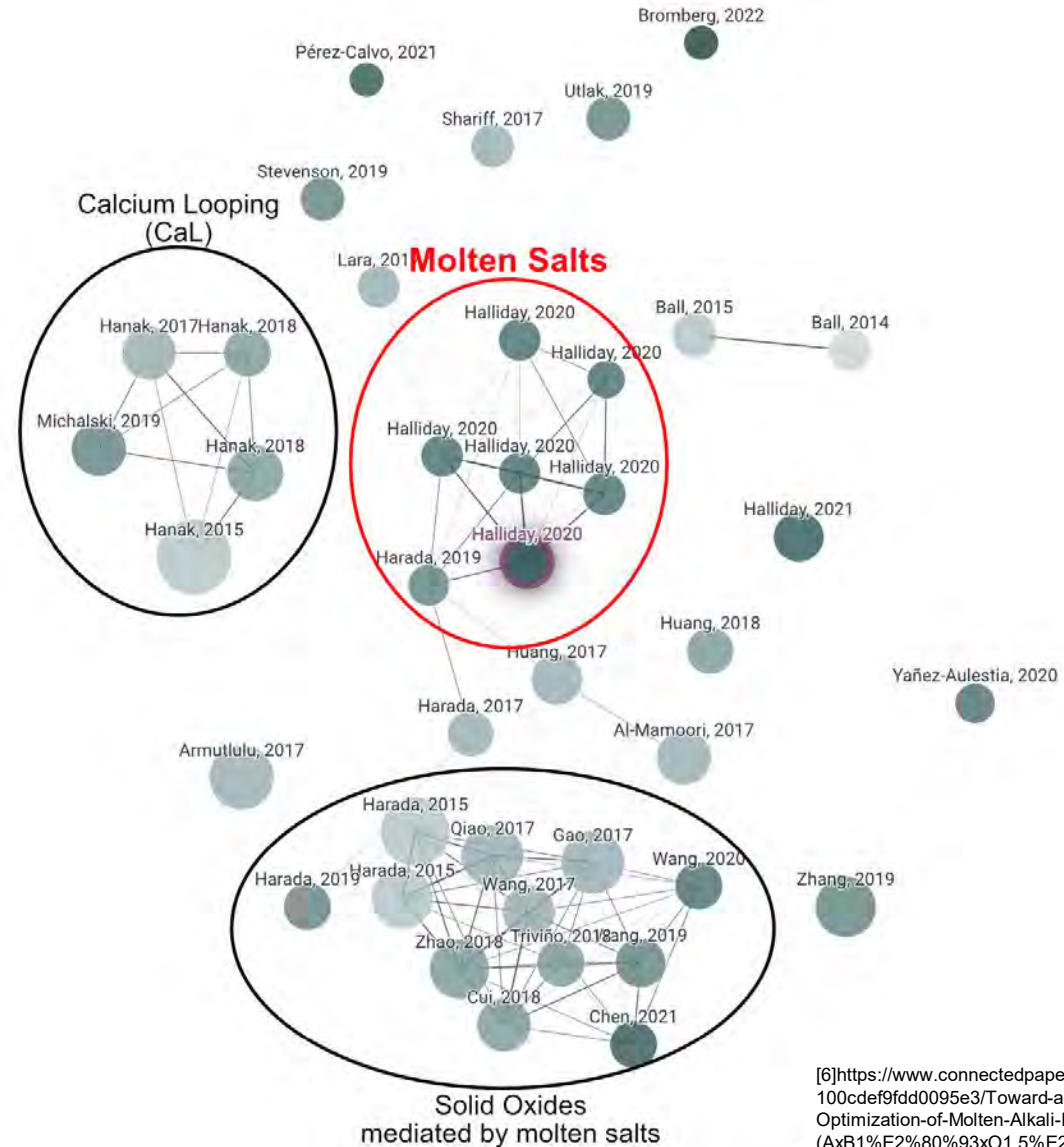
- Matching to process
- 500-800 ° C



Separation System

- Temperature Swing
- Pressure Swing

- **Diverse Sorbent Exploration**
 - Research in carbon capture explores innovative sorbents like Alkali Metal Borates and Solid Oxides mediated by molten salts, striving for high capacity and recyclability
- **Economical Sustainability**
 - These research areas collectively aim for cost-effectiveness, surpassing conventional amine-based sorbents

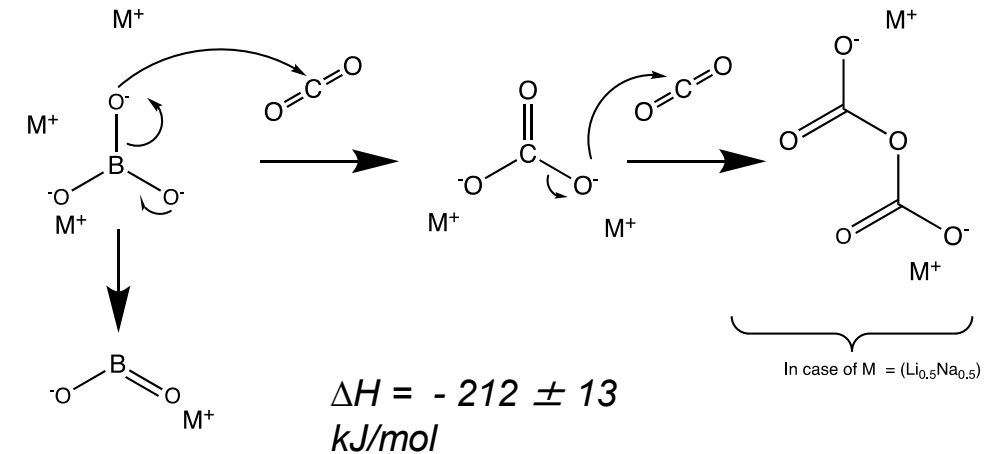


[6][https://www.connectedpapers.com/main/e4d0cd1c5d4ce61f41ecc08100cdef9fdd0095e3/Toward-a-Mechanistic-Understanding-and-Optimization-of-Molten-Alkali-Metal-Borates-\(AxB1%E2%80%931.5%E2%80%93xO1.5%E2%80%93x\)-for-High-Temperature-CO2-Capture/graph](https://www.connectedpapers.com/main/e4d0cd1c5d4ce61f41ecc08100cdef9fdd0095e3/Toward-a-Mechanistic-Understanding-and-Optimization-of-Molten-Alkali-Metal-Borates-(AxB1%E2%80%931.5%E2%80%93xO1.5%E2%80%93x)-for-High-Temperature-CO2-Capture/graph)

- Newly discovered class of **molten salt acid gas sorbents**
- Tunable** working range from 550 ° C - 700 ° C
- Near-isothermal operation possible
 - Absorption/desorption mechanism depends on partial pressure of CO₂
- Capacity for other acidic gases (NO_x, SO_x and H₂S) enables all-in-one gas sweetening

Molten Salt	$(\text{Li}_{0.5}\text{Na}_{0.5})_x\text{B}_{1-x}\text{O}_{1.5-x}$	[12]
MW	26.81-(11.84)x g/mol	
Melting Point	~539°C	
Main Products	LiNaCO ₃ , α-Na ₂ CO ₃ , (Li-Na)C ₂ O ₅	
Absorption	550 ° C, p(CO ₂) = 100% 590 ° C	
Desorption	550 ° C, p(CO ₂) = 0% 650 ° C	
CO ₂ Capacity	4.2 mmol/g ~5 mmol/g (7.27 mmol/g (max.))	
Kinetics Enthalpy	fast ~10min 212 ± 13 kJ/mol	
Cycle Stability	excellent behaviour, 1000 cycles w/out performance loss	
System Size	~5mg	
System combability	temperature swing, pressure swing	

Reaction Mechanism of Capture & Release

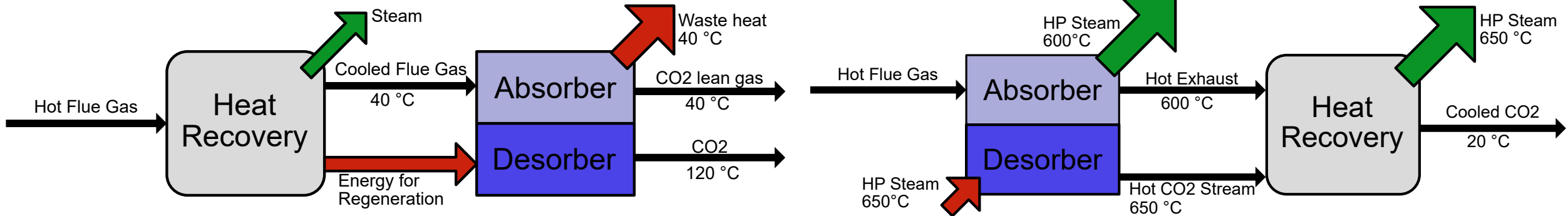


[12] Nitzsche, M. P., & Nitzsche, M. P. (2021). *Molten Alkali Metal Borate / Carbonate Salts for High Temperature CO₂ Capture and Electrochemical Conversion By Electrochemically Mediated Molten Salt Processes for High Temperature CO₂ Capture and Conversion*. Harada, T., & Hatton, T. A. (2017). Tri-lithium borate (Li₃BO₃): A new highly regenerable high capacity CO₂ adsorbent at intermediate temperature. *Journal of Materials Chemistry A*, 5(42), 22224–22233. <https://doi.org/10.1039/c7ta06167f>

Comparative Analysis | Process Enhancements

From...

...To



- Conventional processes cannot use **excess energy from absorber**
 - Waste energy at low temperature
- Heat recovery from flue gas is limited
 - CAPEX intensive equipment needed

- Energy from flue gas can **be used** in absorber
 - No heat recycling recovery
- Balancing excess energy from absorber (heat release) with desorber (heat consumption)
- Excess energy can be used in form of **high-pressure steam**

Process Development

Standard process setup for a carbon capture process in Aspen HYSYS

Comparable to amine-based CCS processes



Absorber and desorber operating in temperature- and pressure swing operation

Absorber 600° C, 1 bar

Desorber 650 ° C, 11 bar

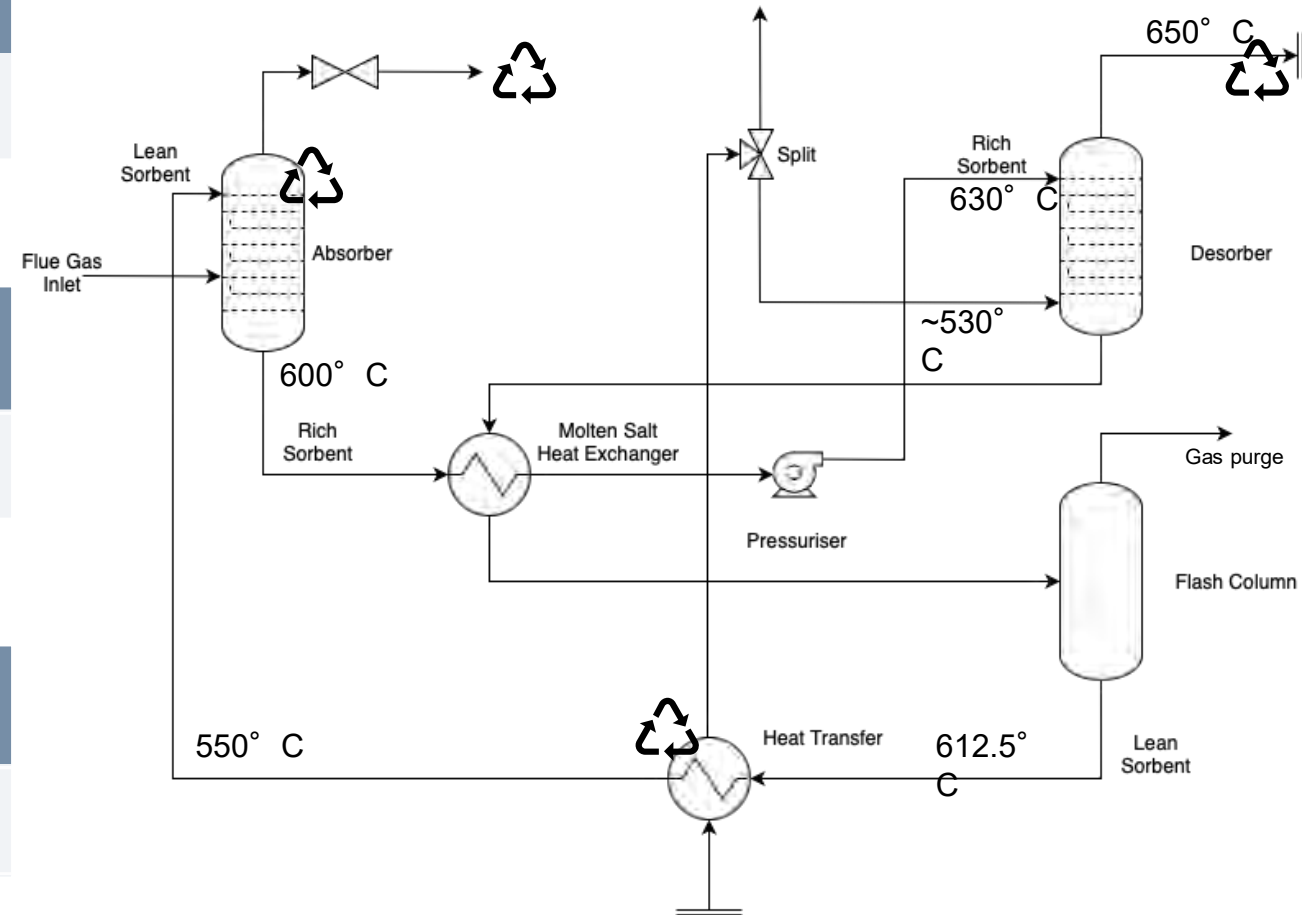


Heat recycling through heat exchanger

$\Delta H = -212 \text{ kJ/mol}$
(forward reaction)

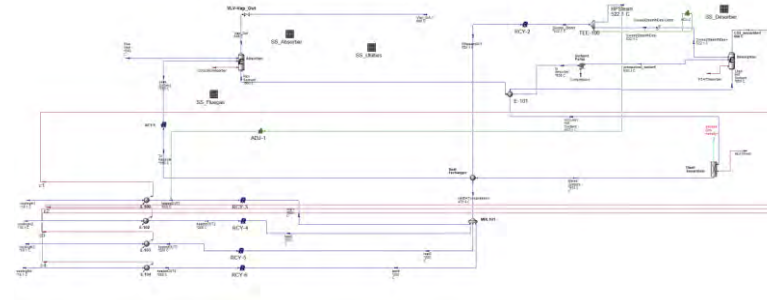
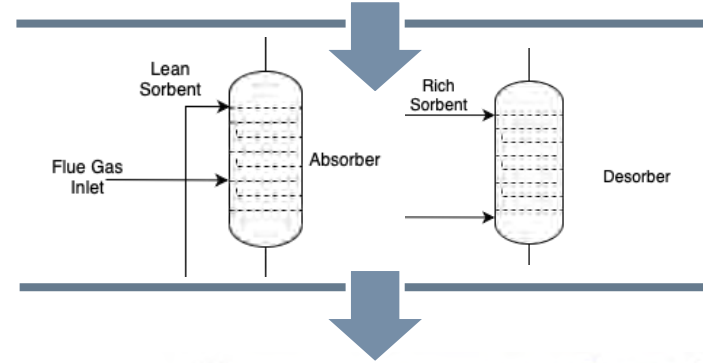
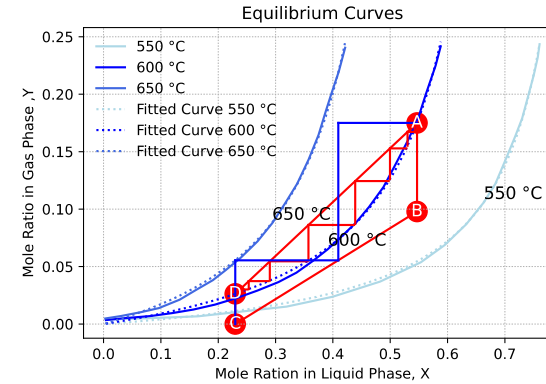
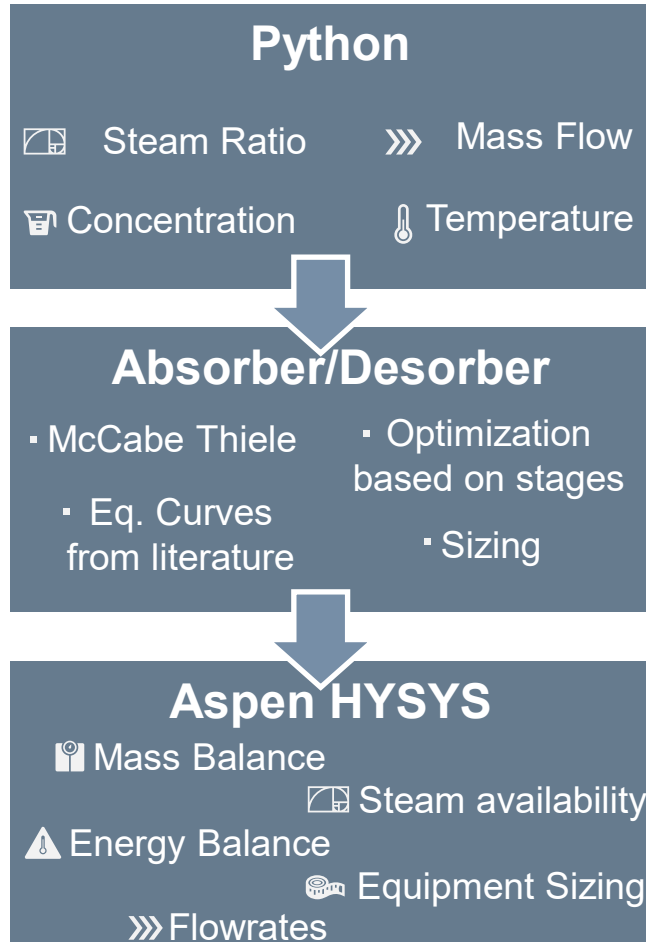
Balancing of reaction energy
of absorber and desorber

Simplified Process Setup



 = Potential for heat recycling

Process Development



Analysis

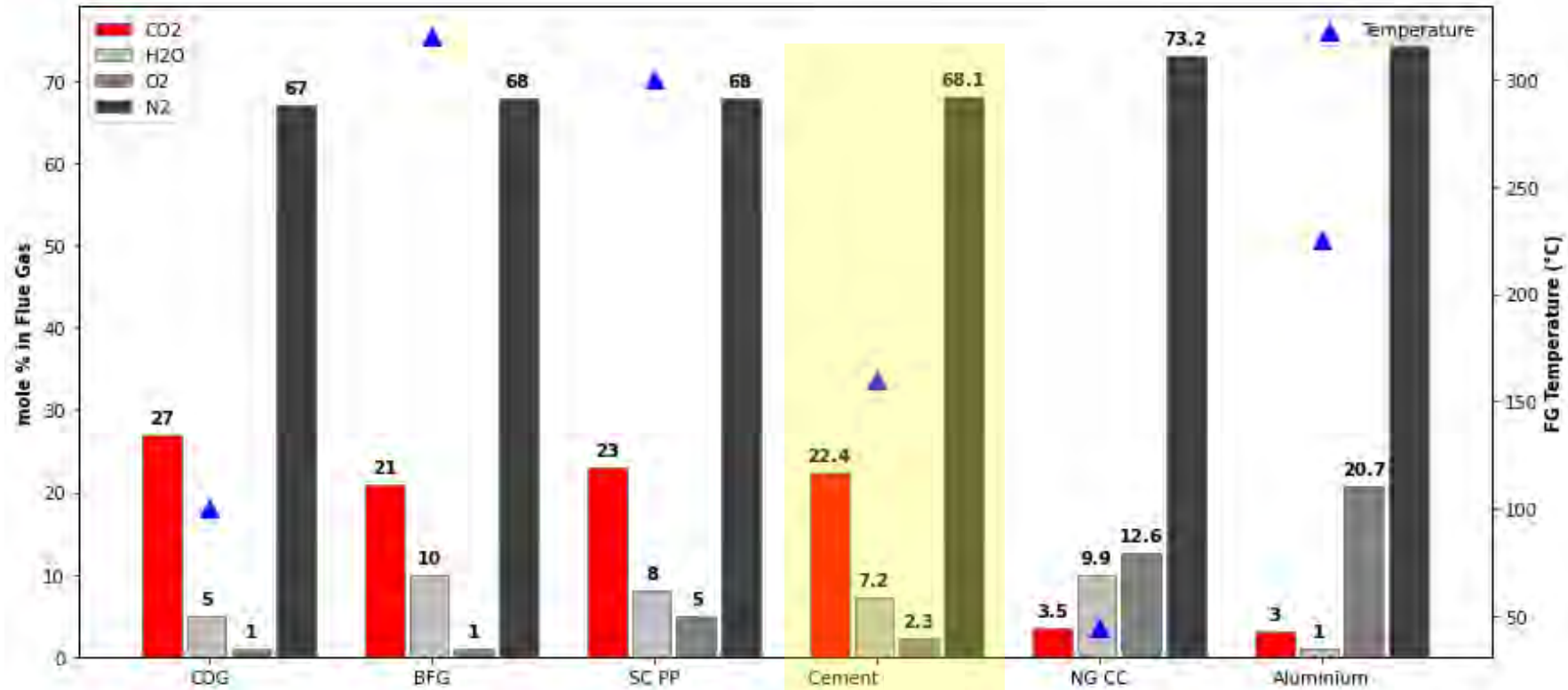
Base case for comparison of influencing factors

CO₂
concentration
22 mole %

Flowrate
305'070 kg/h

Temperature
160 ° C

- Homogenous FG conditions
- Increasing demand
- High CO₂ emissions



[16]. NETL: Cost of Capturing CO₂ from Industrial Sources_011014, 2014, p.92

[17]. Source NETL: p.106, Cost of Capturing CO₂ from Industrial Sources_011014, 2014

[18]. Light metals 2014. Grandfield online monitoring of aluminum primary production gas composition by use of Fourier-transform infrared spectrometry

[19]. Scala, Fabrizio & Lancia, Amedeo et.al. (2005). Spray-Dry Desulfurization of Flue Gas from Heavy Oil Combustion. Journal of the Air & Waste Management Association (1995)

[20]. Arachchige, Udara & Mohsin, Muhammad & Melaaen, Morten. (2023). Optimization of post combustion carbon capture process- solvent selection.

[21]. Folkedahl, Bruce C., G. Weber and Michael E. Collings. "Water Extraction from Coal-Fired Power Plant Flue Gas." (2006).

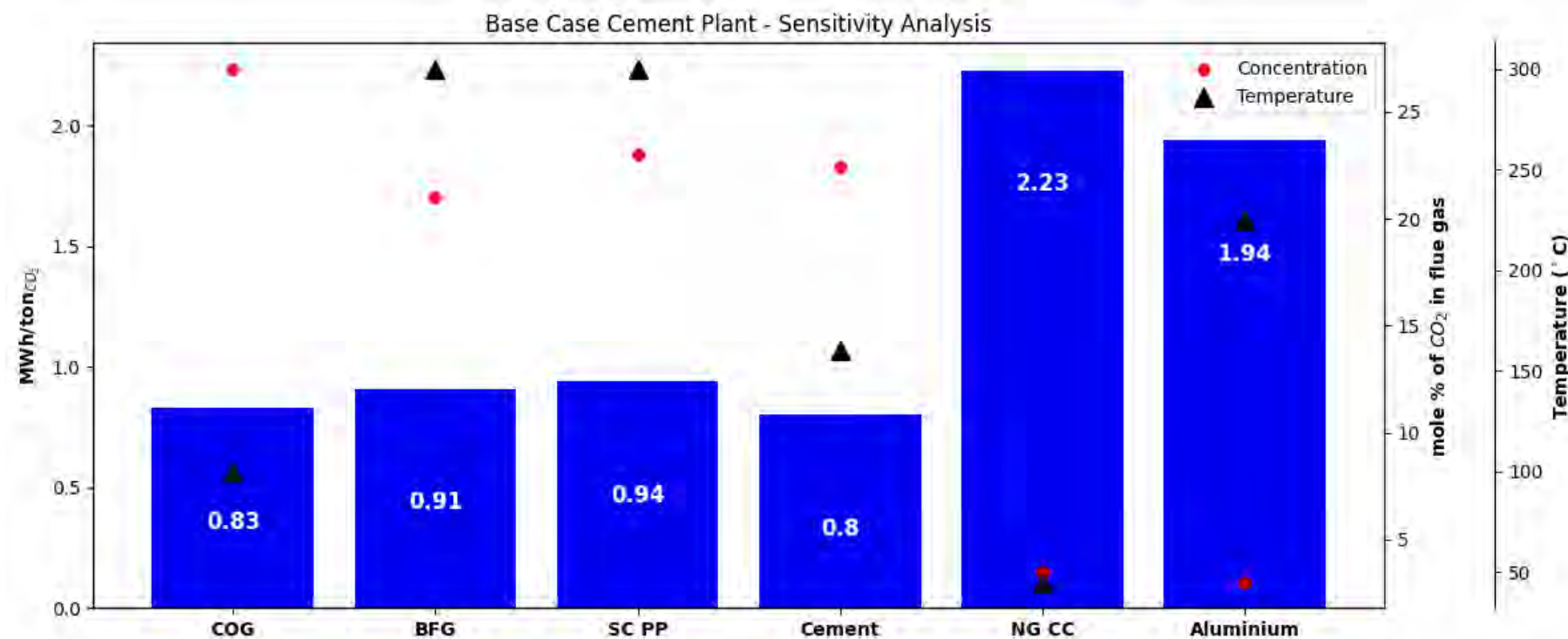
[22]. Date, P. (2021). UC San Diego UC San Diego Electronic Theses and Dissertations.

COG = Coke Oven Gas
BFG = Blast Furnace Gas
SC PP = Supercritical Power Plant

Cement = Cement Plant
NG CC = Natural Gas Combined Cycle
Aluminum = Aluminum Plant

Energy Cost | Comparison

Technology	CCS MS BC	CCS MS lit. ^[25]	CCS Amine ^[26]	CCS Ammonia ^[27]	CCS CaL ^[28]
MJ/ton _{CO2}	2880	1800 - 2200	2800 - 3610	14300	2110 - 2340
MWh/ton _{CO2}	0.8	0.56 - 0.61	0.78 - 1.0	3.97	0.59 - 0.65



[25] Halliday, C., & Hatton, T. A. (2020). The potential of molten metal oxide sorbents for carbon capture at high temperature: Conceptual design. *Applied Energy*, 280(August), 116016. <https://doi.org/10.1016/j.apenergy.2020.116016>

[26] Plomp, T. dkk. (2007). SLIPSTREAM PILOT-SCALE DEMONSTRATION OF A NOVEL AMINE-BASED POST-COMBUSTION TECHNOLOGY FOR CARBON DIOXIDE CAPTURE FROM COAL-FIRED POWER PLANT FLUE GAS. *Angewandte Chemie International Edition*, 6(11), 951–952.

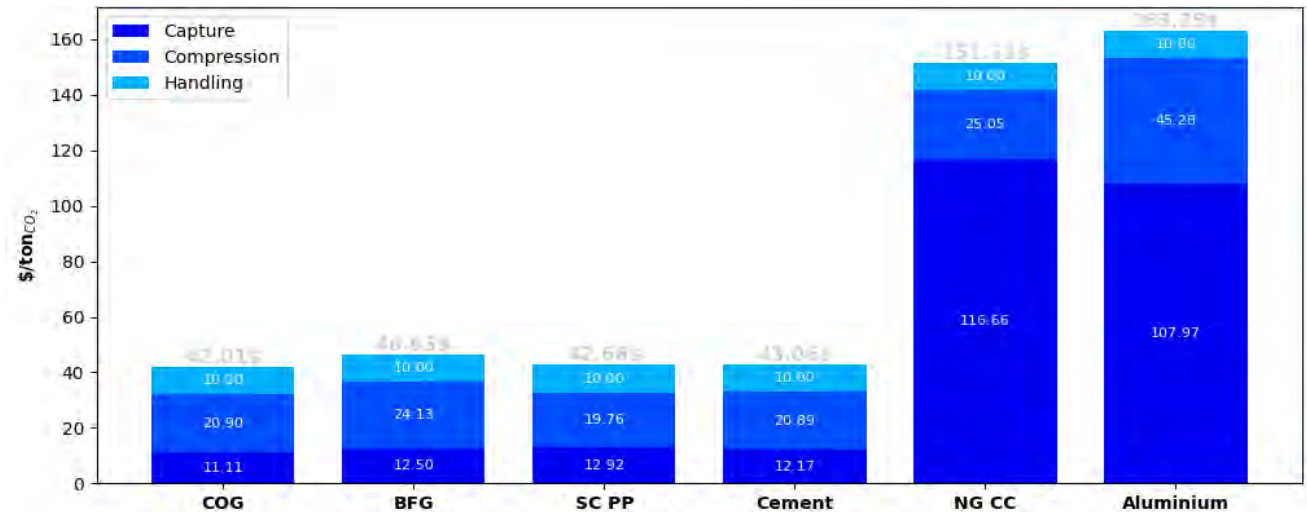
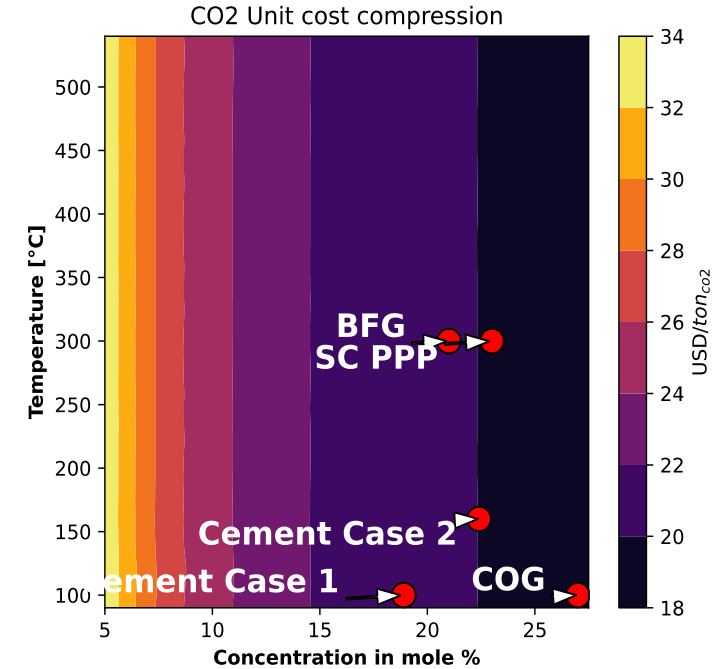
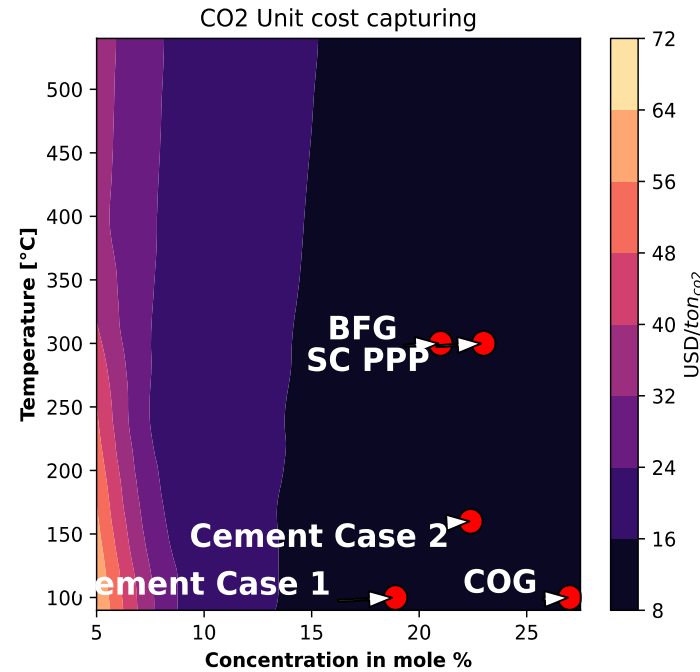
[27] Al-Hamed, K. H. M., & Dincer, I. (2022). Analysis and economic evaluation of a unique carbon capturing system with ammonia for producing ammonium bicarbonate. *Energy Conversion and Management*, 252(September 2021), 115062. <https://doi.org/10.1016/j.enconman.2021.115062>

[28] Astolfi, M., De Lena, E., Casella, F., & Romano, M. C. (2021). Calcium looping for power generation with CO₂ capture: The potential of sorbent storage for improved economic performance and flexibility. *Applied Thermal Engineering*, 194, 117048. <https://doi.org/10.1016/j.applthermaleng.2021.117048>

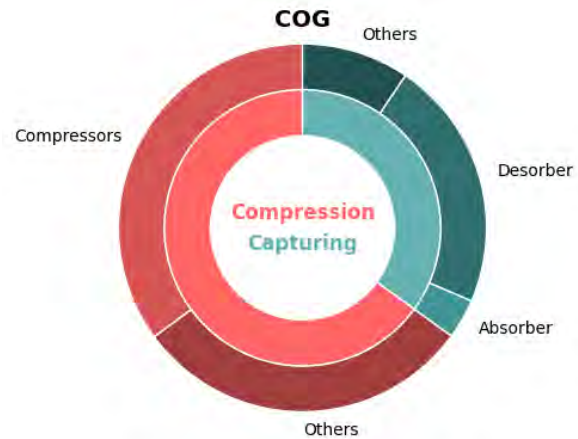
Economic Assessment Temperature/Concentration

- Flue gas temperature itself has little impact on the CO₂-costs
- Steam Ratio itself has high impact on the costs since its influencing the efficiency and therefore the total CO₂ capture rate

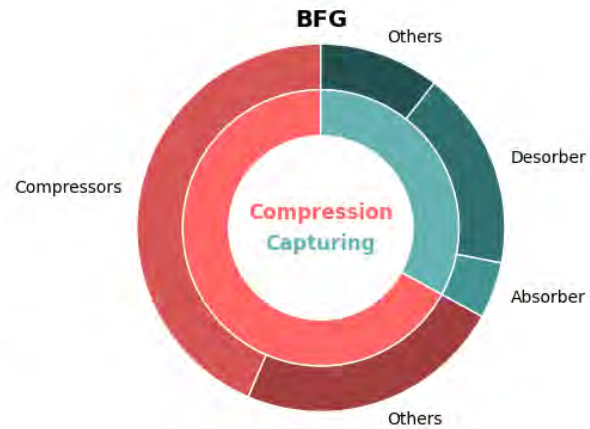
Temperature Sensitivity Analysis



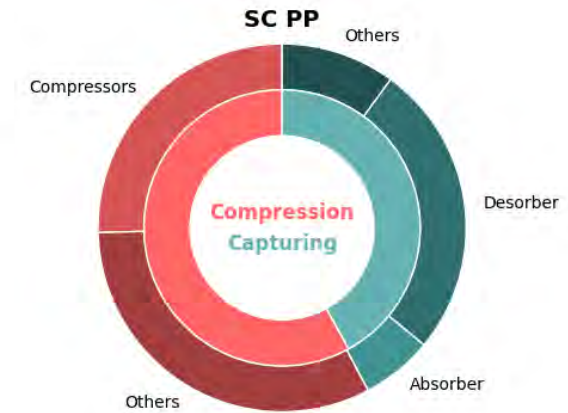
Cost distribution of equipment



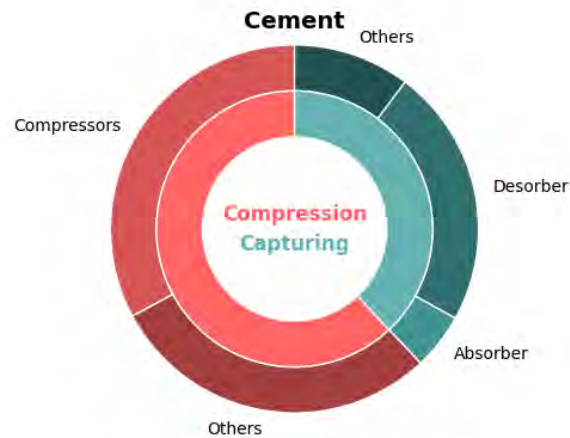
TAC Capturing: 8.0 mio. USD
TAC Compression: 15.0 mio. USD



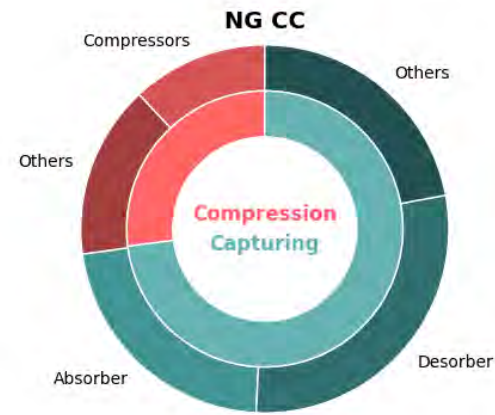
TAC Capturing: 4.8 mio. USD
TAC Compression: 9.3 mio. USD



TAC Capturing: 16.0 mio. USD
TAC Compression: 24.0 mio. USD



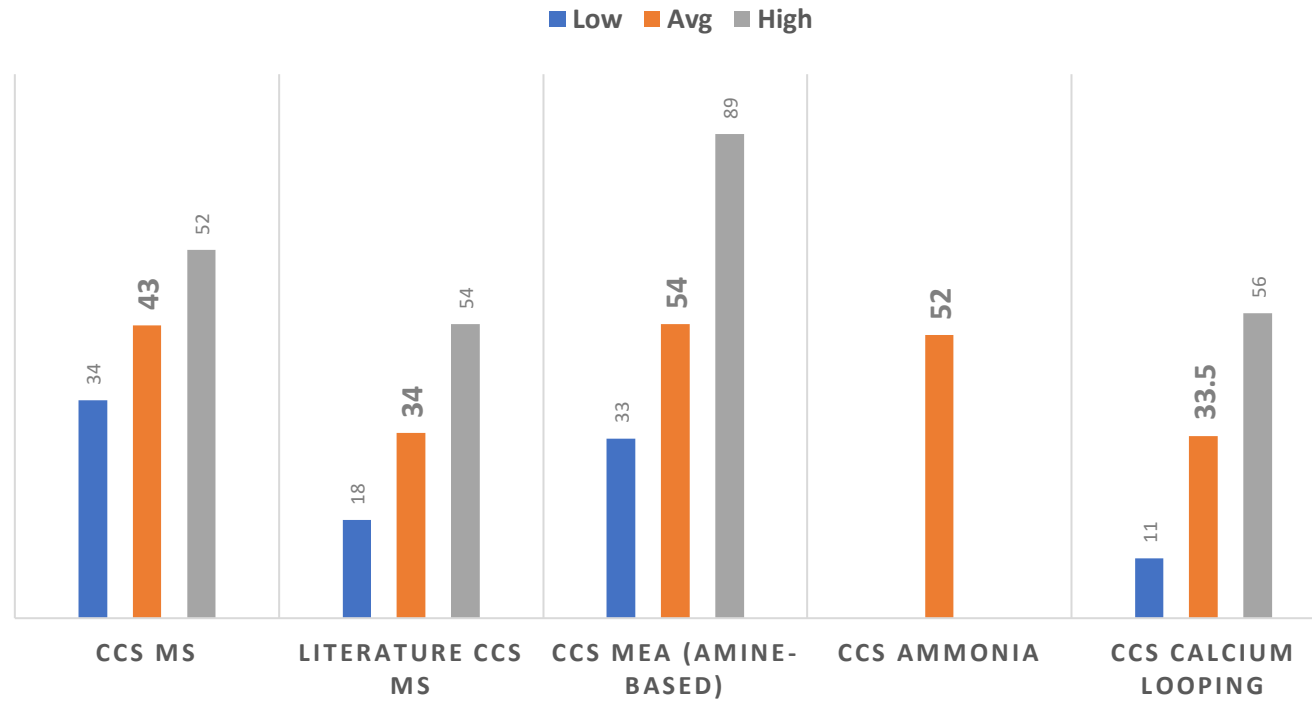
TAC Capturing: 9.0 mio. USD
TAC Compression: 15.0 mio. USD



TAC Capturing: 80.0 mio. USD
TAC Compression: 17.0 mio. USD



TAC Capturing: 11.0 mio. USD
TAC Compression: 4.7 mio. USD



[29] Halliday, C., & Hatton, T. A. (2020). The potential of molten metal oxide sorbents for carbon capture at high temperature: Conceptual design. *Applied Energy*, 280(August), 116016. <https://doi.org/10.1016/j.apenergy.2020.116016>

[30] Shirdel, S., Valand, S., Fazli, F., Winther-Sørensen, B., Aromada, S. A., Karunaratne, S., & Øi, L. E. (2022). Sensitivity Analysis and Cost Estimation of a CO₂ Capture Plant in Aspen HYSYS. *ChemEngineering*, 6(2). <https://doi.org/10.3390/chemengineering6020028>

Main Takeaways

- Unit cost of CO₂ based on preliminary results is competitive to competitors
- Fine tuning of process conditions and process matching can reduce
- Difficult to compare due to several factors

Major influencing factors

- Concentration of CO₂ in Flue Gas
- Process size (industry of scale)