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Techno-Economic Assessment (TEA) of CO2 Direct Air Capture Technologies (DAC)

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Important Terminology

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Term	Definition
TEA	Techno-Economic Assessment refers to conducting a cost assessment of an industrial process or product under development.
DAC	Direct Air Capture of CO2 is the process by which CO2 is captured directly from the air. It differs from conventional point-source carbon capture where CO2 is captured directly from the emitting source.
LCOD	Levelized cost of Capture, which is the cost per unit of CO2 captured.
Capex	Capital expenditures refer to the one time capital investments required to develop the project.
Opex	Operational expenditures refer to the annual expenses to be able to operate the plant.
ISBL	In Side Battery Limit refers to the area where the process plant and equipment are located.
OSBL	Out Side Battery Limit refers to the structure of the plant outside the plant boundary limit.

The urgency to deploy DAC

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- To mitigate climate change, it is urgent to develop and deploy Direct Air Capture of CO_2 at scale.
- Even under a wide-economy decarbonization, the IPCC has outlined 10 Gt of CO_2 need to be sequestered from air by 2050 and twice that by the end of the century to maintain global temperatures below +2ºC.
- Various sorbents and process configurations have been presented in literature for DAC, most of them still at the lab scale.
- Some technologies have slowly moved to pilot and commercial scale, but further analysis is necessary to understand at-scale costs and other implications.
- This analysis attempts to provide a cost assessment of three DAC technologies, with regional sensitivity across the US and outline cost-reduction pathways for their implementation through 2050.

Processes for DAC

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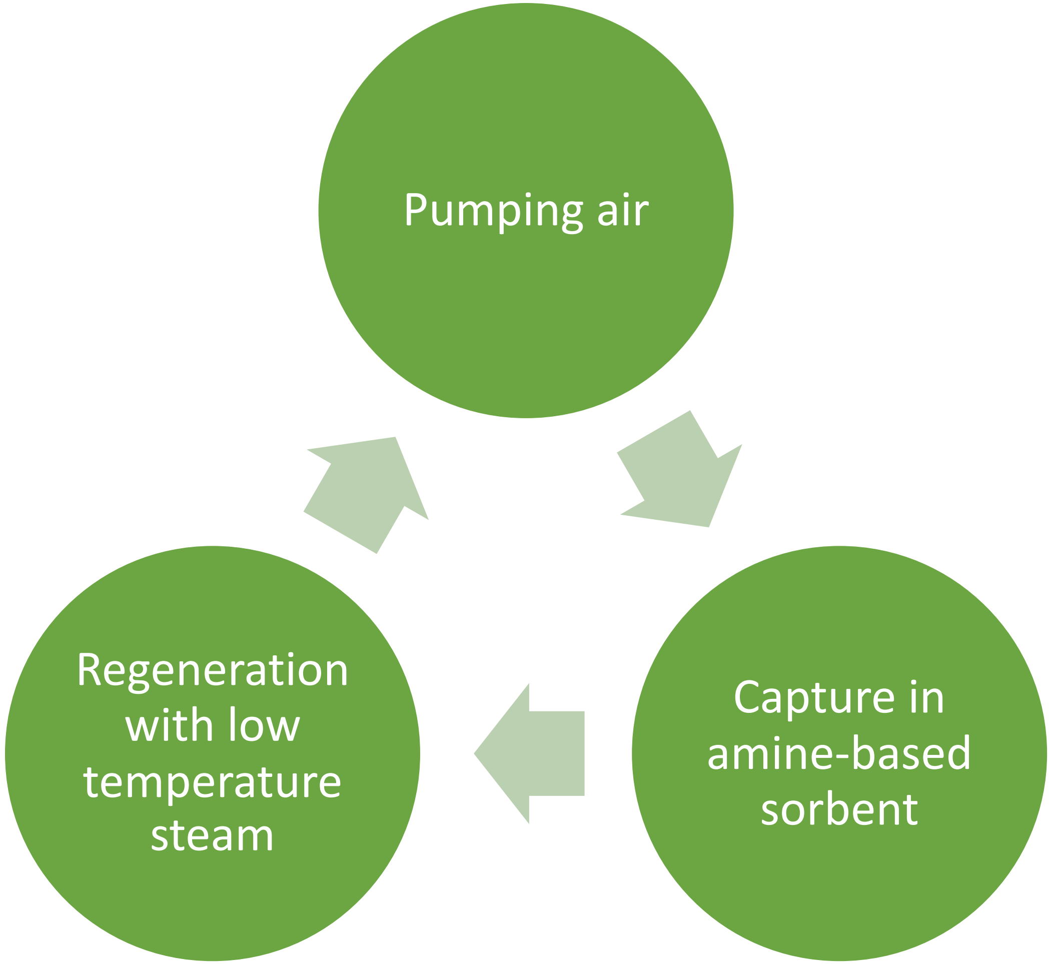
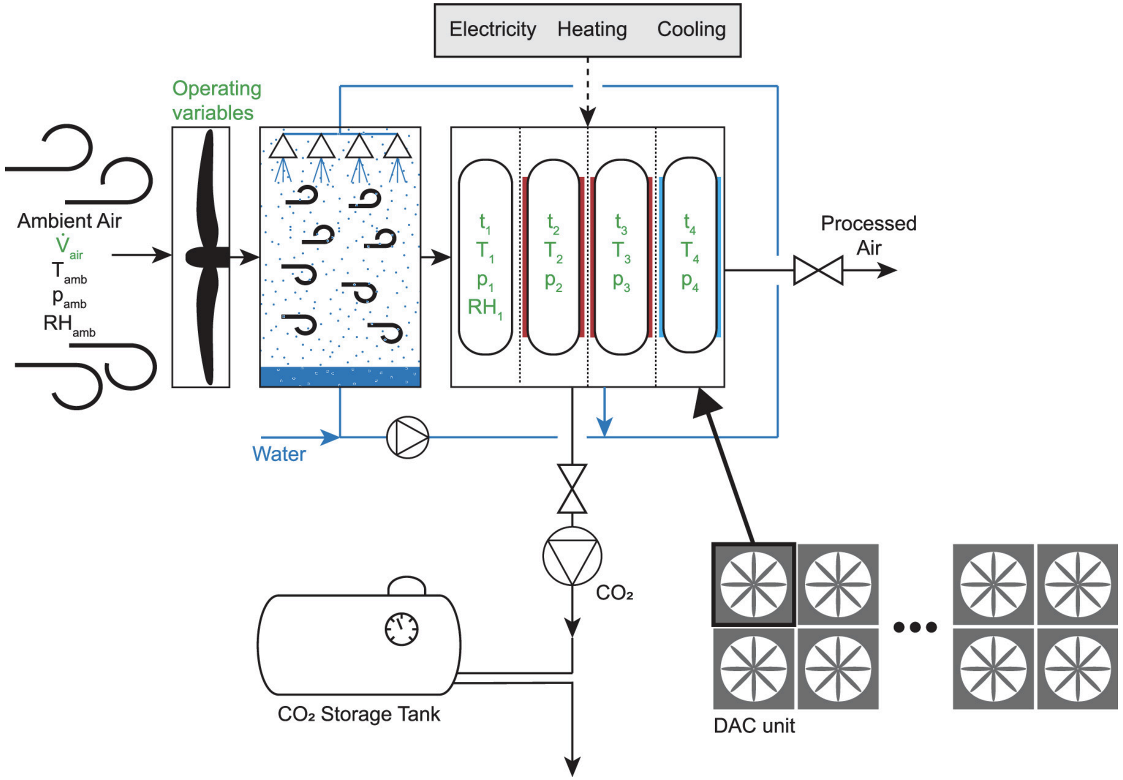
1. Low Temperature Solid Sorbents (LT)
2. High Temperature Aqueous Solvents (HT)
3. Moisture Swing Sorbents (MS)

Low Temperature Solid Sorbents (LT)

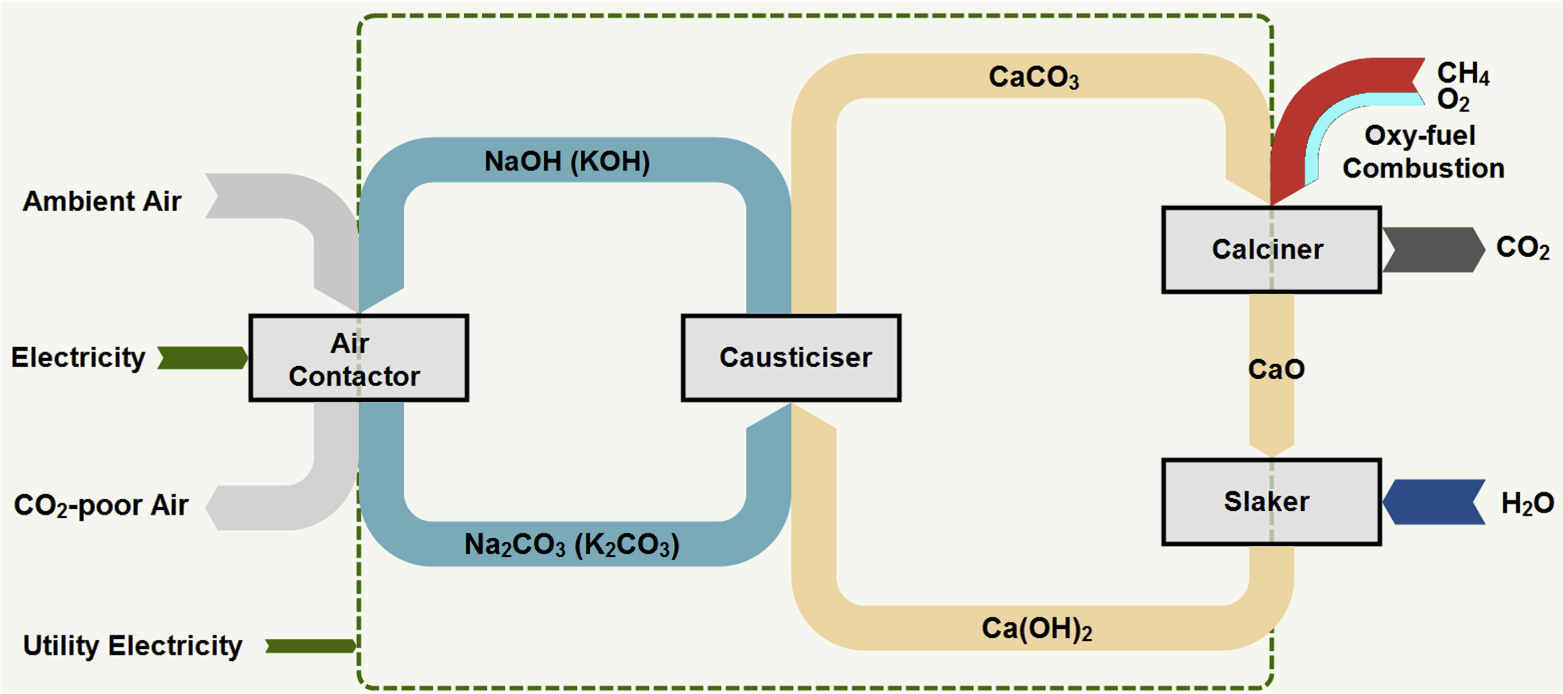




https://pubs.acs.org/doi/10.1021/acs.iecr.2c00681

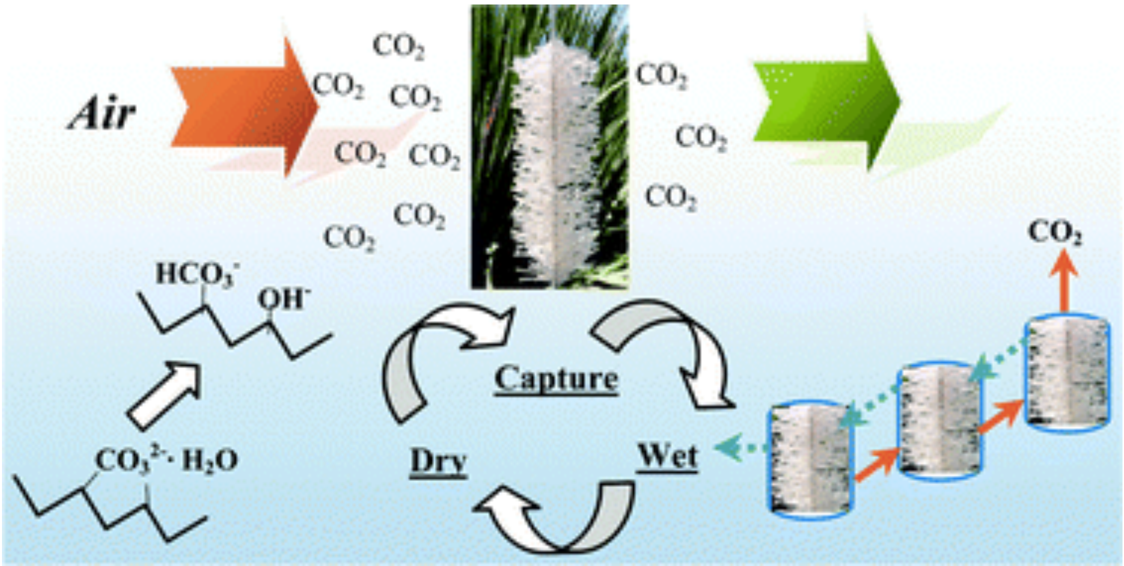
High Temperature Aqueous Solvents (HT)

Pumping of air into air contactor → Looping of strong liquid hydroxide solvent → Regeneration of liquid solvent via looping of calcium oxide → Regeneration of calcium oxide in calciner unit (High temp)



https://www.sciencedirect.com/science/article/pii/S0959652619307772

Moisture Swing Sorbents (MS)



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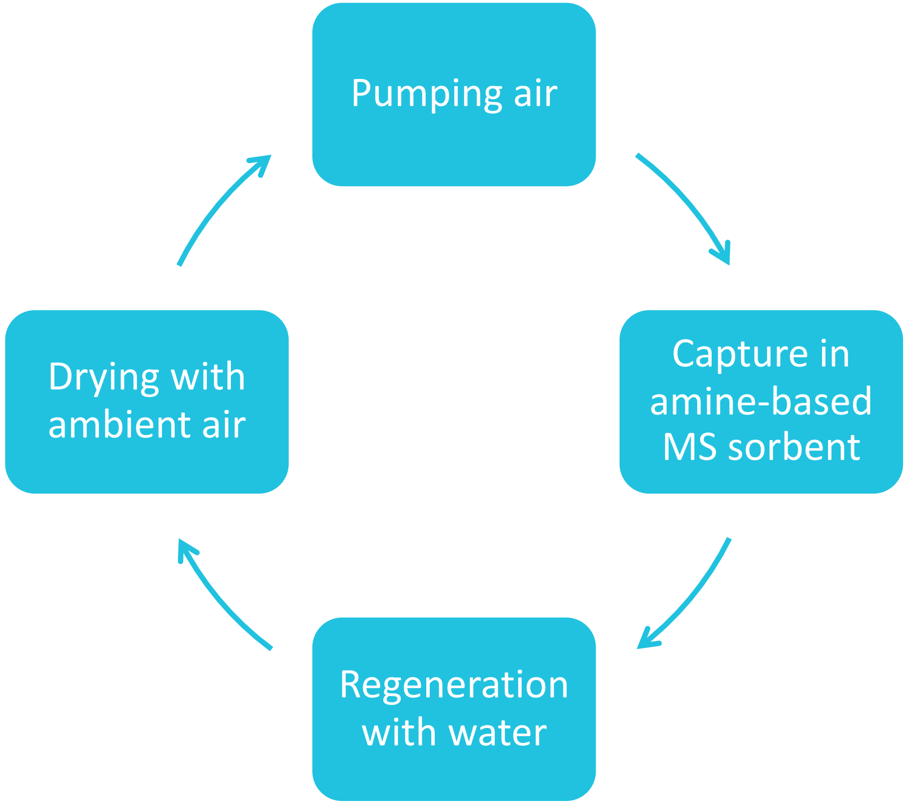

Procedure to conduct a TEA

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1. Scope & Functional Unit
2. Inventory Analysis
3. Indicators & Sensitivity Analysis
4. Reporting

Scope and Functional Unit

Scope → Assessment based on a DAC plant with 1 Mt CO2/year target capacity → 3 DAC plant configurations for 3 class sorbents mentioned → Geographical sensitivity for every US state

Functional unit → $USD/tCO2 → Or Levelized cost of CO2 capture (LCOD)

Inventory Analysis

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Capex
- Price and erection of equipment
- Inside & Outside Battery Limit Cost (ISBL & OSBL)
- Land cost (variable in each state)

$Opex_{fix}$
- Labor, maintenance and taxes.
- Estimated as 4% of Capex

$Opex_{var}$
- Raw materials (considering sorbent degradation rate)
- Utilities (heat, electricity, water).

Annuity factor
- Calculated based on a weighted average cost of capital (WACC) of 7%

Method to Calculate the Levelized Cost of Capture (LCOD)

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- Inventory of Purchase of Equipment Costs (PEC) from commercially available data, or estimated based on size (S) and other process engineering constants.
- Calculating Inside Battery Limit cost (ISBL) by adding PECs multiplied by a factor to account for piping, equipment erection, electrical work, instrumentation and process control, civil engineering work, structures and buildings.
- Calculating Outside Battery Limit Cost (OSBL) by multiplying ISBL by a factor to account for offsites, design & engineering and contingency factors.
- Adding ISBL and OSBL weighted by a 10% working capital to find Capital Expenditures (Capex).
- Calculate Operational Expenditures (Opex) based on inventory data. Add Capex and Opex and divide by total CO_2 captured by plant to obtain LCOD.

Method to Calculate the Levelized Cost of Capture (LCOD)

$$\frac{Capex \cdot crf + Opfix + Opvar}{TotalCO2\ captured}$$

$$(ISBL + 1.1 * (OSBL))$$

$$ISBL = \sum PEC\ (1 + f_p + f_{er} + f_{el} + f_i + f_c + f_s + f_l) = 3.2 * \sum PEC$$

$$OSBL = ISBL\ (1 + OS)(1 + D\&E + X) = 1.89 * ISBL$$

$$PEC = a + bS^n$$

Levelized cost of capture (LCOD)

Capital expenditures

Inside battery limit & outside battery limit costs

Purchase of equipment cost

LCOD Results for 2023

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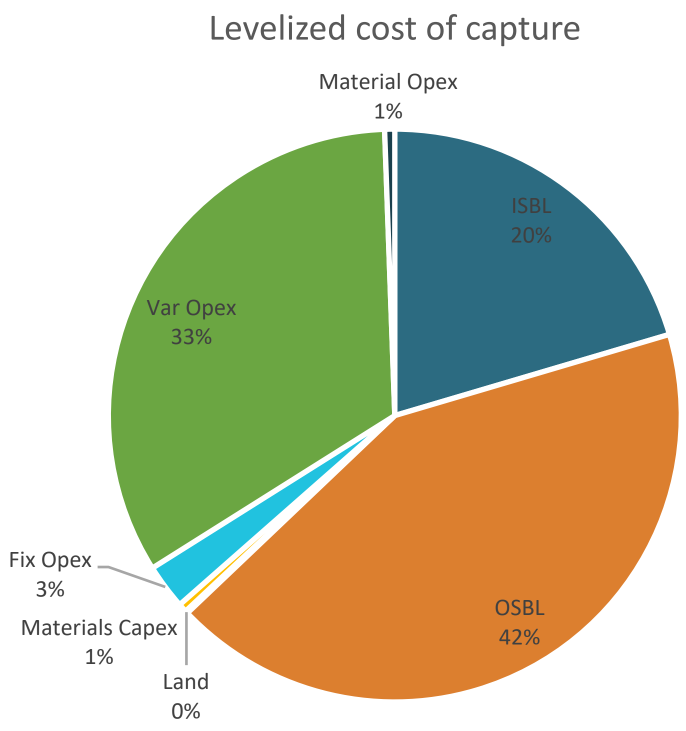
- **HT**
  - 533 USD/tCO_2
- **LT**
  - 474 USD/tCO_2
- **MS**
  - 428 USD/tCO_2

*Assume plant operating at full capacity of 1 Mt CO_2/year

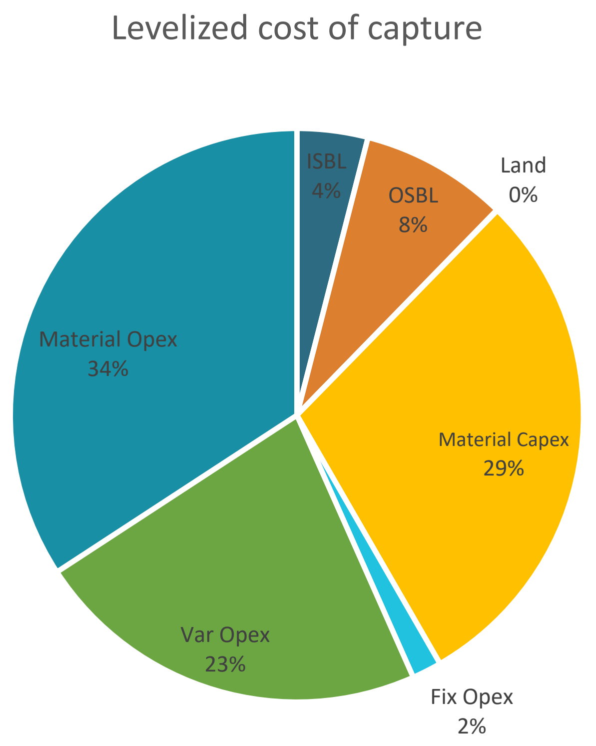
HT DAC cost break down

- OSBL and ISBL occupy largest percentage of cost given the large number of units employed in process.
- Variable expenses are the second largest percentage due to high heat usage for regeneration of sorbent.



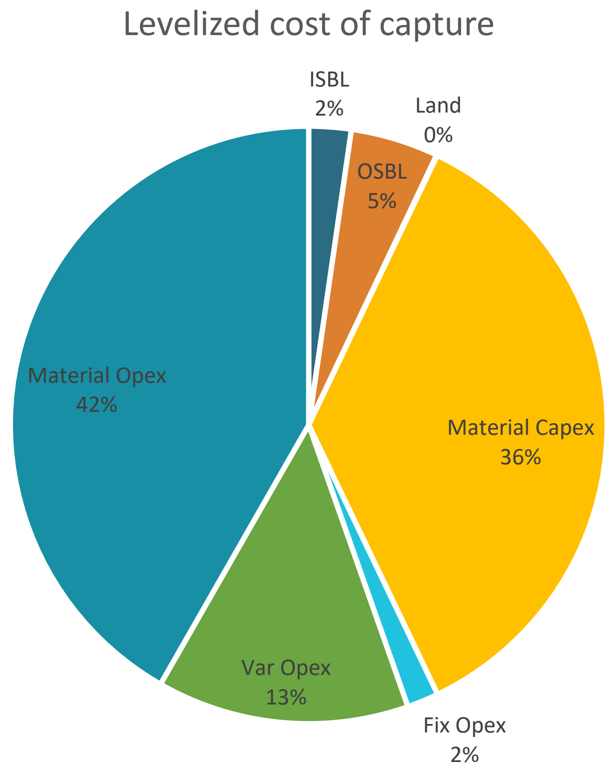
LT DAC cost break down

- Materials capital expenditures and replenishment (material opex) dominate cost due to short sorbent lifetime (2 years) and rapid degradation with continuous heat operation.
- Variable expenses are the second largest percentage due to heat and water usage to operate facility.
- Equipment expenditures occupy smaller percentage due to simple unit design.



MS DAC cost break down

- Materials capital expenditures and replenishment (material opex) dominate cost due to short sorbent lifetime (5 years).
- Variable expenses are the second largest percentage due to high water usage to operate facility.
- Equipment expenditures occupy smaller percentage due to simple unit design.



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Impact of weather on LCOD of DAC

Low temperature solid sorbents (LT DAC)	• Works better at lower temperatures • Works better at higher relative humidity
High temperature aqueous solutions (HT DAC)	• Works better at higher temperatures • Works better at higher relative humidity
Moisture Swing Sorbents(MS DAC)	• Humidity is main driver. Works better at lower relative humidity • Works better at lower temperatures

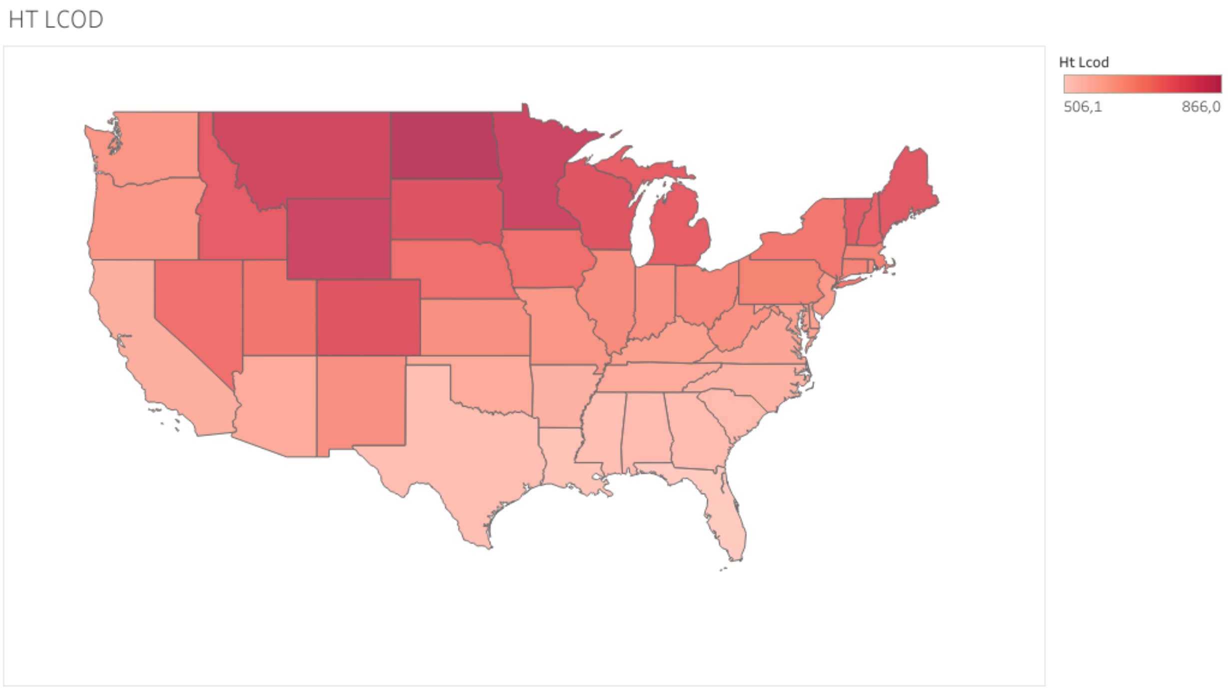
*Ultimately weather conditions will reduce plant throughput increasing the levelized cost of capture

Regional Sensitivity

- To assess the impact of regional weather conditions on plant operating capacity, performance data of all three sorbents under different temperatures and relative humidity was obtained.
- The performance was then ran against historical weather data obtained from NOAA for the past 15 years.
- This yielded a total operating capacity for all 3 technologies for every site with available data. This data was then averaged to state-level performance.

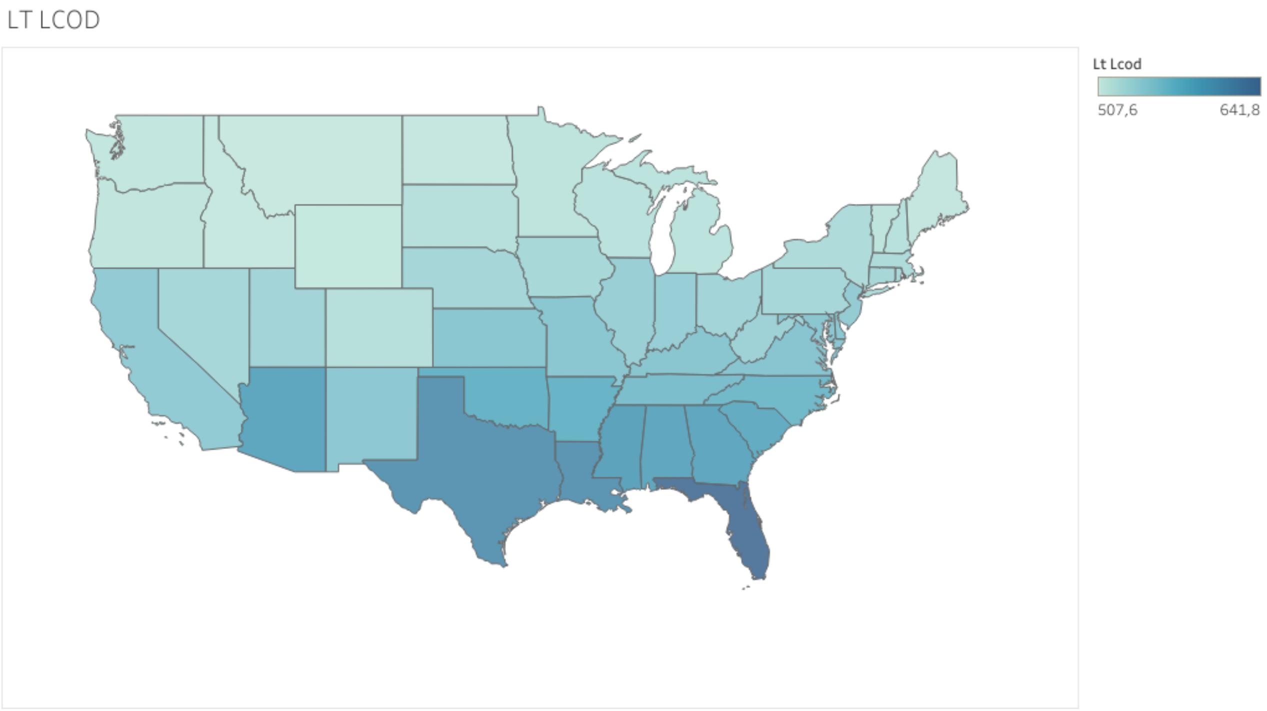
HT DAC Regional Sensitivity

- Better operations in southern states, thus lower levelized costs in these locations.
- This due to higher average temperatures and relative humidity.
- Higher temperatures favor the kinetics and higher humidity favor sorbent capacity, leading to better sorbent performance.



LT DAC Regional Sensitivity

- Better operations in northern states.
- This due to lower average temperatures primarily.
- Amines tend to degrade at higher average temperatures. Thus, sorbent stability increases with average lower temperatures leading to better performance.



MS DAC Regional Sensitivity

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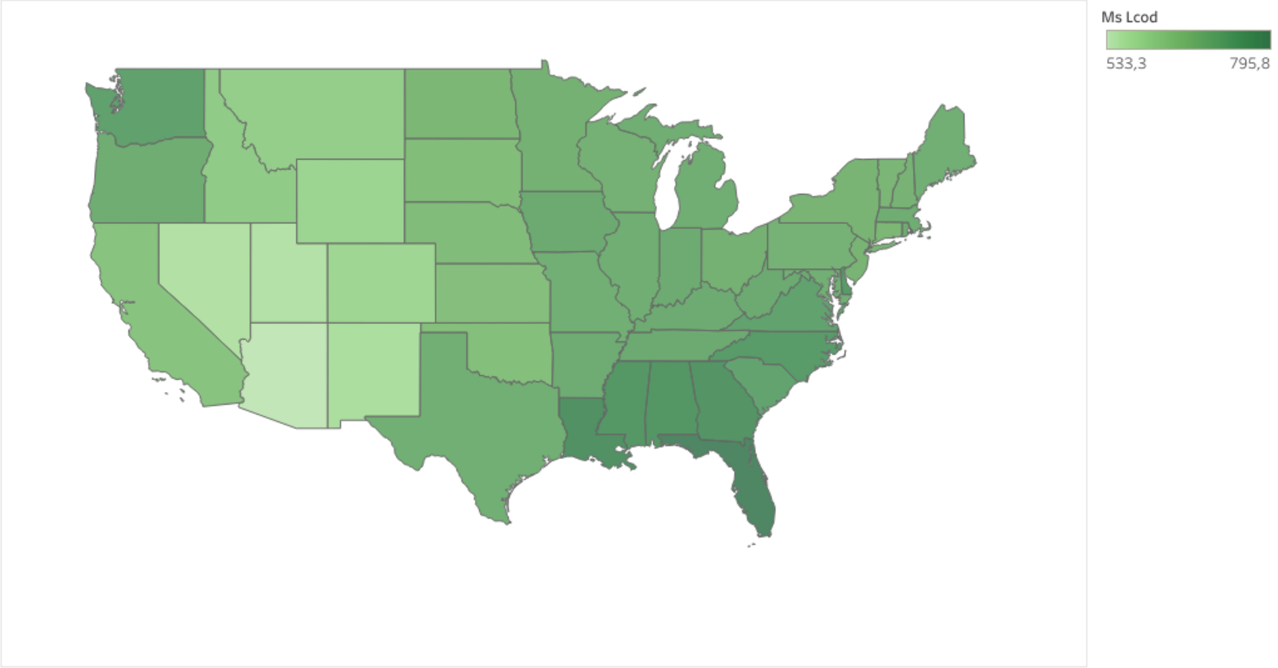
- Better operations in drier states, since humidity is the main driver for sorption-desorption.
- Technology most impacted by weather conditions. Operation can be significantly reduced at high relative humidity.

MS LCOD



Impact of desalinization on LCOD

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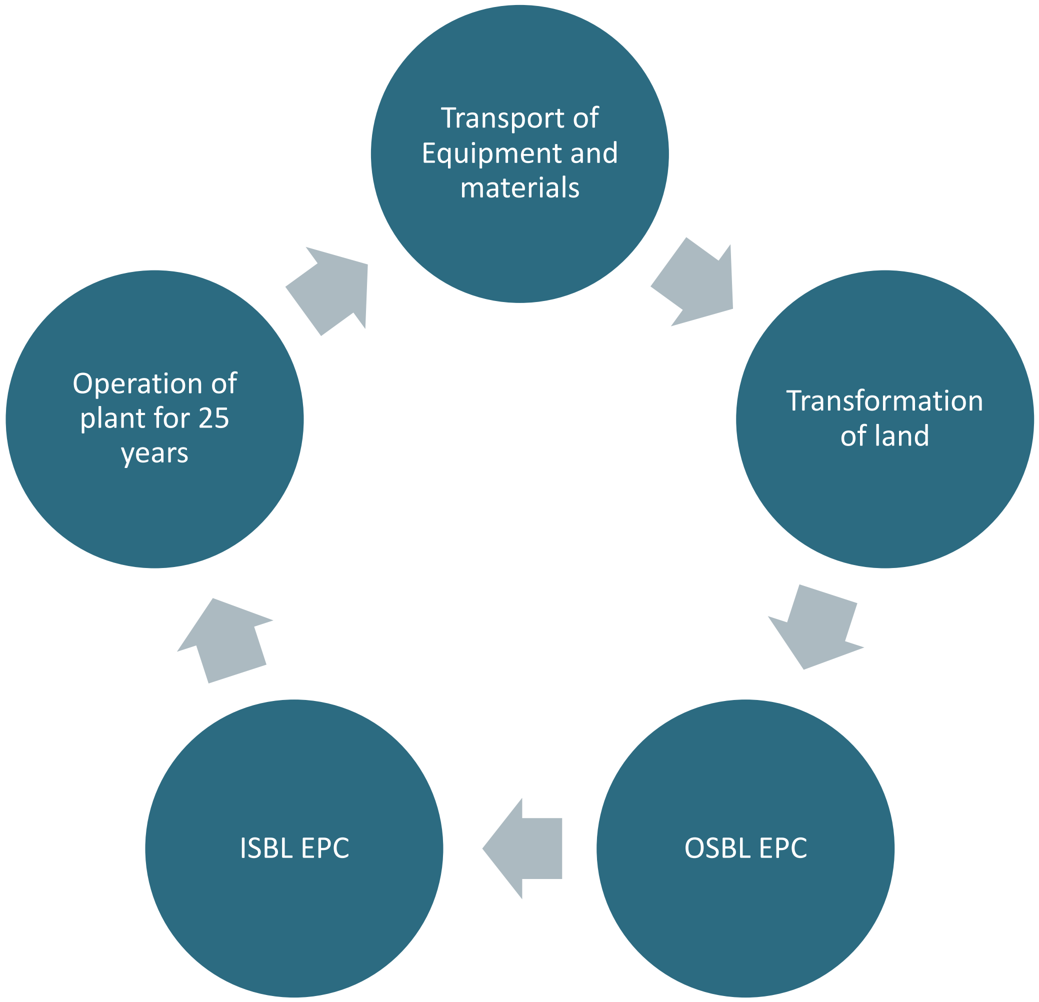
- Each of the technologies under study requires water for operation.
- However, Moisture Swing DAC requires much more water for operation since it is the only driver for sorbent regeneration.
- As such, an analysis was carried out to assess the impact of using desalinization for water in the Levelized cost of capture (LCOD).
- While there is a small increase of 1 dollar/tCO2 for HT and LT technologies, the cost can increase by up to 100 dollars/tCO2 for MS DAC if desalinization is used.
- As such, MS DAC deployment should be limited in drought prone areas.

Life Cycle Assessment (LCA)

- In order to understand the true impact of DAC operations it is important to account for the emissions associated with the erection of the plant and energy usage in the operation.
- As such, a cradle-to-gate LCA was conducted to assess the carbon emissions of all three plant configurations as well as energy use.
- Results show upstream emissions associated with plant erection are minimal compared to energy usage under a carbon intensive grid scenario.
- This highlights the importance of pairing DAC operations with renewable electricity.



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Future Scenarios

Method to Develop a Learning Curve tailored to DAC

- With future deployment, DAC operations are expected to improve significantly and thus reduce their costs.
- Improvements include increasing sorbent capacity and cycle kinetics, improving sorbent lifetime and performance under different weather conditions, developing systems with reduced pressure drop and reduce regeneration energy use.
- Given the different process configurations, a component based Learning Rate (LR) system was developed based on four criteria.
- Later, the individual component learning rates were weighted on their percentage contribution to the cost and added to yield a system level learning rate.

DAC Capacity

- In order to reach a global, wide-economy decarbonization and meet the IPCC's ambitious climate goals, DAC capacity may need to increase from 3 Mt/year (2020) to as much as 10000 Mt/year by 2050.
- The biggest applications for the captured CO2 are Fischer Tropsch fuels for transportation and the chemical industry, carbon-based chemicals, removal and permanent storage.
- Two scenarios, conservative and optimistic, were developed for the learning curve, based on full DAC projected capacity implementation and half of it for the conservative scenario.

Component Learning Rates

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- Individual components of all three systems were graded based on four criteria
  - Whether they are a novel development or previously used in the chemical industry
  - Whether the cost of producing such component is expected to reduce.
  - Whether the component's throughput is expected to increase
  - Whether the kinetics of that portion of the process is expected to increase.
- If fulfilled, each criteria would give the component a 5% LR on the conservative scenario and 10% on the optimistic scenario

System Learning Rates

- Once individual component learning rates were obtained, they were weighted on their percentage contribution to the levelized cost and added to yield the System Learning Rate.
- A conservative learning rate of 5% and optimistic learning rate of 10% was assumed for both fixed and variable operational expenditures.
- The formula below was used to calculate the cumulative learning rate:

$$LR_{system} = \sum LR_{component} * \frac{Cost_{component}}{Cost_{system}}$$

System Learning Rates

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HT
- 5.7 % (Conservative)
- 11.4 % (Optimistic)

LT
- 10.0 % (Conservative)
- 20.0 % (Optimistic)

MS
- 11.0 % (Conservative)
- 22.0 % (Optimistic)

Divergence in Learning Rates

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- HT DAC employs processes and reactors previously used in the chemical industry. Additionally, units are less modular with a pilot being built at about 100 kt CO2/year capacity.
- LT DAC and MS DAC employ novel sorbents and reactor systems which are expected to undergo much higher improvement with deployment. Additionally, the units are highly modular since they are single units at capacity of 50 kg/year which are just replicated to achieve desired plant capacity.
- As such, HT DAC has a much reduced LR on a system basis compared to LT and MS technologies.

Applying the Learning Curve

Using systems LR, calculate learning index

Calculate projected DAC units based on estimated capacity

Calculate future cost using logarithmic learning curve

$$\mathrm{LR} = 1 - 2^{-\alpha}$$

$$N = \frac{Capacity_{Total}}{Capacity_{Unit}}$$

$$LCOD_{Projected} = LCOD_{Initial} * \log(N)^{-\alpha}$$

Future Scenarios

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Conservative				Optimistic			
Year	Cost of Capture (USD/tCO2)			Year	Cost of Capture (USD/tCO2)		
	HT	LT	MS		HT	LT	MS
2030	435	311	269	2030	345	191	156
2040	425	302	261	2040	330	180	146
2050	421	299	257	2050	325	175	142

*Assume plant operating at full capacity of 1 Mt CO2/year

Impact of weather

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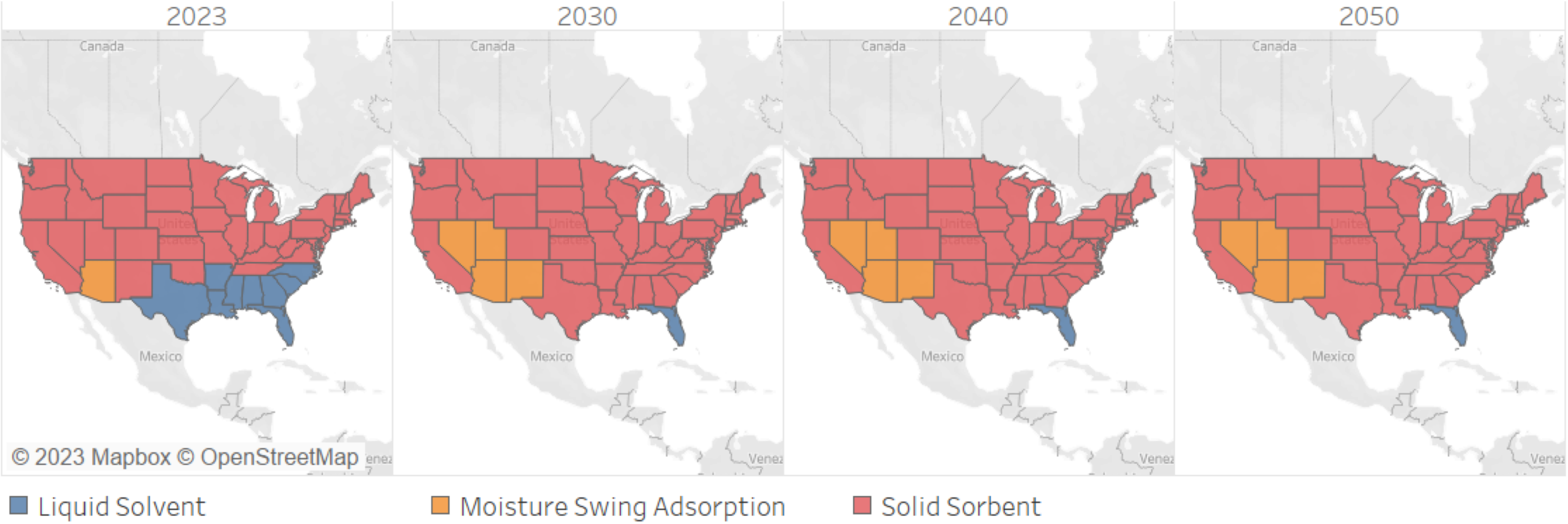
- The impact of weather on plant operation was also assessed for future cost scenarios.
- This allowed determining the most economically optimal sorbent per state now and in future scenarios, to guide deployment of the three studied technologies.

Economically Optimal Technology by State (2023-2050)



Findings

- Under conservative scenarios, LT and MS DAC can reach costs below 300 dollars/t CO2 by 2050. Under optimistic scenarios, LT DAC can be below 200 USD/tCO2 and MS DAC can be below 150 USD/tCO2.
- Due to the reduced Learning Rate of HT Aqueous Solvents, in the future it is expected for it to have higher costs across all geographies compared to LT and MS DAC, except in Florida.
- Deployment of HT Solvent systems should be reduced to areas with high humidity and high average temperatures such as Florida.
- LT solid sorbents have lower levelized costs across most states, particularly in future projections.

Findings

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- Deployment of MS sorbents should be limited to areas with low relative humidity.
- MS sorbents should not be deployed in drought prone areas, as use of desalinization can increase cost by about 100 USD/t CO2 captured.
- MS Sorbents have so far been given little attention. This analysis shows they have great potential for future deployment of DAC in the US due to their reduced energy use under a current-carbon intense grid and their high Learning Rates.
- DAC needs to be paired with renewables to allow feasible net removal costs.

Selected references

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- An, Farooqui, & McCoy. (2022, September 6). *The impact of climate on solvent-based direct air capture systems*. Applied Energy. https://www.sciencedirect.com/science/article/pii/S0306261922011588
- Faber, G., Ruttinger, A., Strunge, T., Langhorst, T., Zimmermann, A., van der Hulst, M., Bensebaa, F., Moni, S., & Tao, L. (2022, March 14). *Adapting technology learning curves for prospective techno-economic and life cycle assessments of emerging carbon capture and utilization pathways*. Frontiers. https://www.frontiersin.org/articles/10.3389/fclim.2022.820261/full
- Fasihi et al. (2019, March 14). *Techno-Economic Assessment of CO2 Direct Air Capture plants*. Journal of Cleaner Production. https://www.sciencedirect.com/science/article/pii/S0959652619307772
- National Academies Press. (n.d.). *"negative emissions technologies and reliable sequestration: A research agenda."* 5 Direct Air Capture | Negative Emissions Technologies and Reliable Sequestration: A Research Agenda | The National Academies Press. https://nap.nationalacademies.org/read/25259/chapter/7
- Terlouw, Treyer, Bauer, & Mazzotti. (2021, August 5). *Life cycle assessment of direct air carbon capture and storage with low-carbon energy sources*. Environmental science & technology. https://pubmed.ncbi.nlm.nih.gov/34351133/
- Thorin et al. (2021, December 20). *Techno-economic analysis of Direct Air Carbon Capture with CO2 Utilisation*. Carbon Capture Science & Technology. https://www.sciencedirect.com/science/article/pii/S2772656821000257#bib0012
- Wiegner et al. (2022, August 9). Optimal design and operation of solid sorbent direct air capture ... https://pubs.acs.org/doi/10.1021/acs.iecr.2c00681

About the author

- Federico de Lima is a rising Senior at Columbia University majoring in Earth and Environmental Engineering.
- He is originally from Colombia and having witnessed the impact of climate change on various local ecosystems while growing up, he decided to pursue a career to help the energy transition and mitigate climate change.
- While at Columbia, he developed an early passion for Carbon Capture and Direct Air Capture by having the opportunity to work under the guidance of Dr. Ah-Hyung (Alissa) Park at the Lenfest Center for Sustainable Energy developing sorbents and process engineering for DAC.
- Apart from researching DAC technologies, Federico also joined the Carbon Tech Development Initiative at the Center for Global Energy Policy as part of their operations team, to help early-stage founders and researchers take their carbon removal technologies from lab scale to commercialization.
- He had the opportunity to work at Evolved this summer, where he was able to broaden his understanding of energy systems modeling and dive deep into assessing the future deployment of DAC at scale.

THANK YOU

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