Columbia Engineering
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# Optimizing Direct Air Capture (DAC) for Profitability and Climate Impact: A Comparative Study in New York and California

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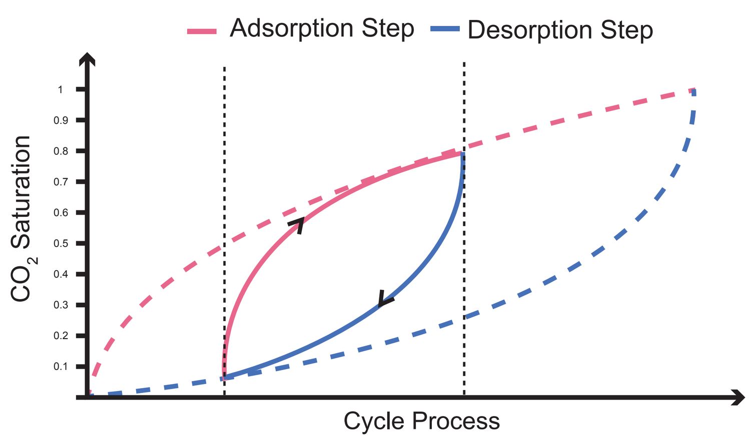
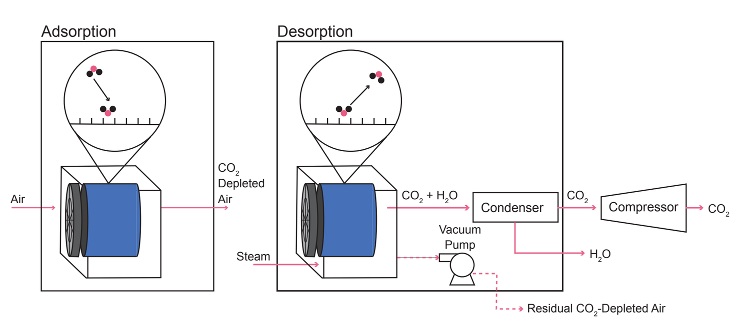
## Motivation: Removing $CO_2$ From the Air

Direct Air Capture (DAC) is crucial in combating climate change. Given rising atmospheric $CO_2$ levels, curbing future emissions is inadequate and net carbon removal technologies are projected to be mandatory to maintain global warming below 1.5 °C [IPCC, 2023]. DAC technologies offer a promising solution to this challenge. The captured $CO_2$ can be stored or sold and utilized in many industries such as synthetic fuel production or supercritical fluid extraction for pharmaceuticals, contributing to a circular carbon economy [Koytsoumpa et al., 2018]. This work exposes DAC to time-varying electricity price fluctuations and emission rates, and applies different optimization methods to maximize DAC's profit, which serves as a critical guidance for DAC technologies improvements and larger scale deployment.

## Background: Low-temperature Solid Sorbents DAC system

1. Air is introduced and $CO_2$ molecules engage with hierarchically porous materials such as amines [McQueen et al., 2021]
2. Materials selectively bind with $CO_2$
3. Captured $CO_2$ is released via heat or pressure, resulting in a pure stream of $CO_2$ to be sold and repurposed
4. While the sorbent can be reused following the desorption process, recycling incurs operational and material costs to account the energy consumption and material life consumption

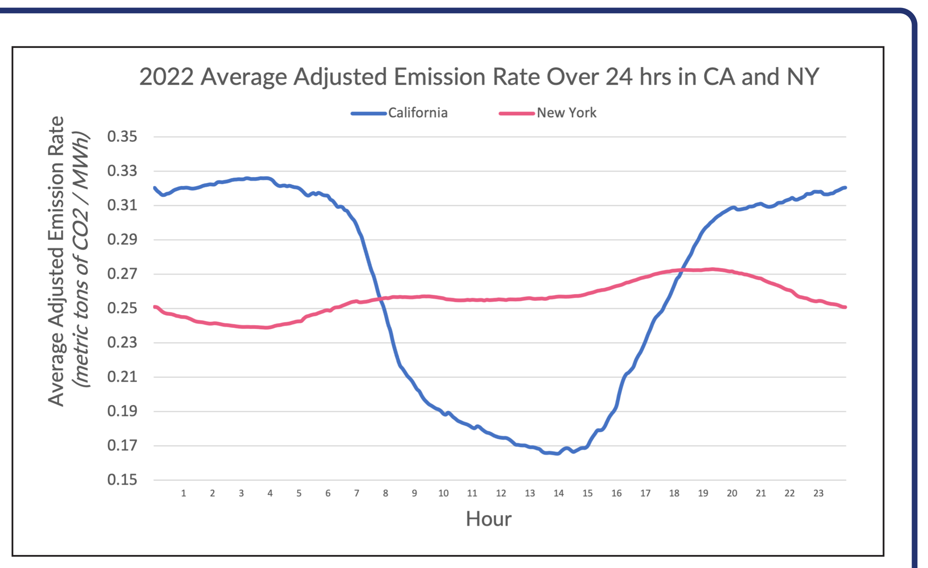



The adsorption and desorption phases exhibit patterns that resemble logarithmic curves, characterized by sharp initial changes leveling off towards plateaus after saturation for adsorption and depletion for desorption. To maximize the system's efficiency, we optimize it to operate the DAC only between ~5-80% saturation to maximize its operation value per unit time, e.g., performing 75% of adsorption and desorption with only 50% of full-cycling time. This allows the DAC to consistently adsorb or desorb at high speeds.

## Background: Power Systems in CA and NY

**California:**
- Lower emission rates during midday due to solar energy integration
- 'Duck curve' describes low net electricity demand (or dispatchable power generation) at midday, with surplus solar energy production leading to an energy supply overabundance
- DAC technology can capitalize on lower prices during this period




**New York:**
- Heavily relies on fossil fuels and hydropower, resulting in a relatively constant emission rate
- Electricity prices fluctuate primarily in response to shifts in demand due to industrial facilities and other factors

## Methods: Modeling the DAC System for Optimization

The objective function maximizes the total profit of the DAC operation

$$max \sum_t \pi d_t - \lambda_t(P^a u_t + P^d v_t) - S z_t$$

- $\pi$: CO2 rewarding constant including selling price, subsidies, etc.
- $d_t$: desorption amount of DAC system at time period t
- $\lambda_t$: electricity price at time period t, can subjected to modification of $CO_2$
- $P^a$: electricity consumption for absorption phase per unit time period
- $P^d$: electricity consumption for desorption phase per unit time period
- $u_t$: 1 if DAC is during the absorption phase at time period t, otherwise zero.
- $v_t$: 1 if DAC is during the desorption phase at time period t, otherwise zero.
- $S$: switching cycle cost for consumption of sorbent materials
- $z_t$: 1 if DAC is switched to a new cycle at time period t, otherwise zero

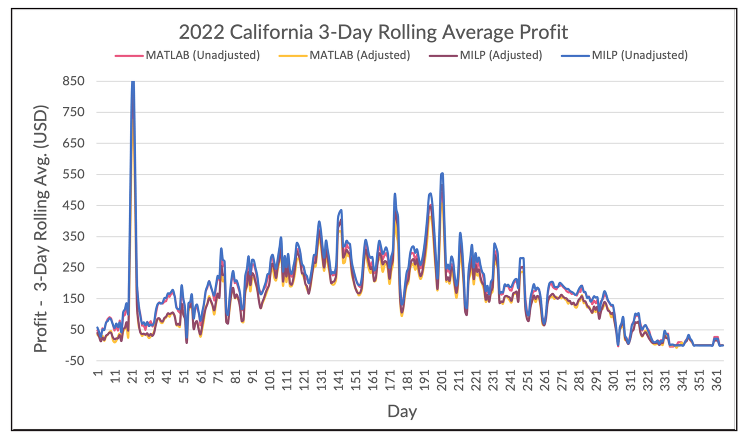
Comparison of Optimization Methods for DAC Operation

1. Mixed-integer linear programming (MILP) benchmark code implemented in Julia by Zhiyuan Fan
   - Gurobi solver optimizes multiple decision variables simultaneously to maximize the objective function derived by the Xu Lab
2. New, custom in-house MATLAB open-source algorithm designed to handle nonlinear processes
   - Finds optimal price threshold (lambda) for each day which determines whether or not the DAC system operates at that 5 min time step
   - Can be implemented in any other language

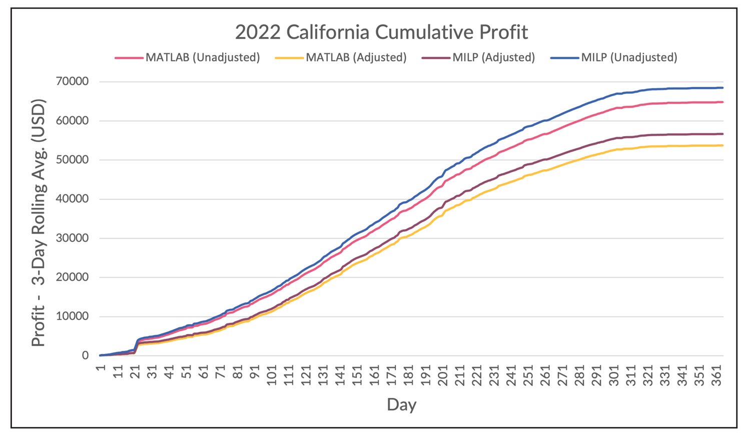
Both methods incorporate the following:
- 5-min resolution electricity price data (raw and adjusted for CO2)
- 5-min resolution emission data from NYISO and CAISO
- A look-ahead parameter for potential profit opportunities a few hours ahead of the current day

## Results: MILP vs. New MATLAB Algorithm

| Case | Model | Execution Time (HH:MM:SS) | Profit (USD) | Gross CO2 Captured (Metric Tons) |
|---|---|---|---|---|
| CA Adjusted Price | MILP | 05:41:53 | 56,710.65 | 2,331.02 |
| | MATLAB | 00:00:47 | 53,777.99 | 2,079.08 |
| | Comparison | **439 x faster** | **5.45% different** | 12.12% |
| CA Unadjusted Price | MILP | 05:57:39 | 68,499.61 | 2,902.30 |
| | MATLAB | 00:00:35 | 64,828.25 | 2,610.85 |
| | Comparison | **620 x faster** | **5.66% different** | 11.16% |
| NY Adjusted Price | MILP | 07:24:24 | 22,476.45 | 2724.07 |
| | MATLAB | 00:00:36 | 21,632.19 | 2414.94 |
| | Comparison | **745 x faster** | **3.90% different** | 12.80% |
| NY Unadjusted Price | MILP | 07:59:18 | 35,384.55 | 3606.64 |
| | MATLAB | 00:00:45 | 34,090.96 | 3248.18 |
| | Comparison | **633 x faster** | **3.79% different** | 11.04% |

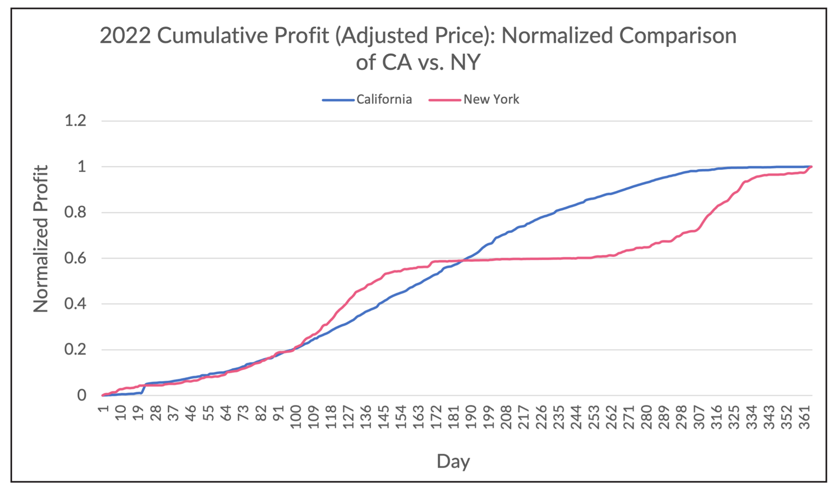


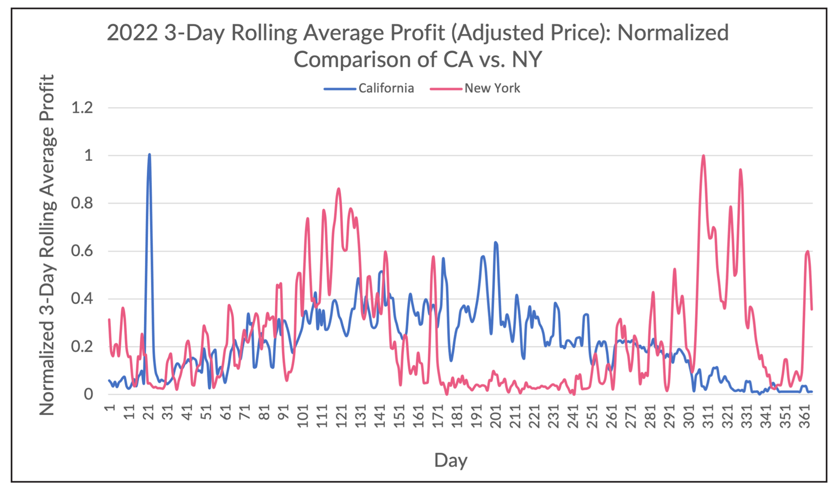

**Profit vs. Execution Time:** When comparing simulations with similar $CO_2$ adjustments (adjusted or unadjusted), MATLAB is up to 745 times faster with a <5% difference in profit from the benchmark, making it useful for generating electricity demand bids.




**CO2 Emission Adjustment Effect:** Incorporating $CO_2$ emission adjustments significantly impacts the DAC's profit and overall behavior, emphasizing the importance of considering environmental factors in economic simulations.

## Results: California vs. New York




- Due to MATLAB's short execution time and comparable results, subsequent trials are conducted using MATLAB
- CA case is more profitable during summer with lower energy costs from solar energy, as shown by the steeper slope
- NY case is more profitable during spring and fall due to electricity price fluctuations driven by seasonal demand (summer & winter consume more AC/heat)

## Discussion

DAC offers advantages like carbon removal and minimal land area requirement, but faces challenges in initial costs and energy intensity, particularly in fossil fuel-dominant grids. As DAC gains popularity and technology improves, initial costs are expected to decrease. Incorporating real electricity prices into DAC simulations through optimization becomes crucial, as it significantly influences both profitability and overall success.

Optimizing the DAC system to align with real-time pricing is essential for ensuring profitable incorporation into electricity markets. The use of MATLAB proves advantageous due to its faster processing, making it suitable for DAC integration, where operators must submit hourly bids to determine the electricity price they are willing to accept for its operation. On the other hand, while Julia has the potential to yield greater profit overall, its longer processing time may limit operators' ability to make timely operation decisions and account for the price variation. By participating in electricity markets through this bidding process, DAC operators can consume excess electricity during periods of lower demand and lower price, potentially generating revenue at market price valleys. Incorporating electricity and carbon costs becomes increasingly vital, given the potential impact of wind and solar on electricity price fluctuations in the envisioned renewable-focused energy grid.

## Future Work

- Investigate different DAC technologies like pressure swing adsorption (PSA) and temperature swing adsorption (TSA)
- Explore and compare various DAC sorbent materials (ex. metal-organic framework (MOF) physisorbents) [Leonzio et al., 2022]
- Include data from different states or countries

## References & Acknowledgments

- *California ISO - Today's Outlook.* (2022). Retrieved July 24, 2023, from https://www.caiso.com/TodaysOutlook/Pages/default.aspx
- *Interval Locational Marginal Prices—OASIS Prod—PUBLIC - 0.* (2022). Retrieved July 24, 2023, from http://oasis.caiso.com/mrioasis/logon.do
- IPCC. (2023). *Global Warming of 1.5 oC* —. Retrieved July 25, 2023, from https://www.ipcc.ch/sr15/
- Koytsoumpa, E. I., Bergins, C., & Kakaras, E. (2018). The CO2 economy: Review of CO2 capture and reuse technologies. *The Journal of Supercritical Fluids*, 132, 3–16. https://doi.org/10.1016/j.supflu.2017.07.029
- Leonzio, G., Fennell, P. S., & Shah, N. (2022). A Comparative Study of Different Sorbents in the Context of Direct Air Capture (DAC): Evaluation of Key Performance Indicators and Comparisons. *Applied Sciences*, 12(5), Article 5. https://doi.org/10.3390/app12052618
- McQueen, N., Gomes, K. V., McCormick, C., Blumanthal, K., Pisciotta, M., & Wilcox, J. (2021). A review of direct air capture (DAC): Scaling up commercial technologies and innovating for the future. *Progress in Energy*, 3(3), 032001. https://doi.org/10.1088/2516-1083/abf1ce
- *NYISO Real-Time Fuel Mix.* (2022). Retrieved July 24, 2023, from http://mis.nyiso.com/public/P-63list.htm
- *NYISO Real-Time Market LBMP - Zonal.* (2022). Retrieved July 24, 2023, from http://mis.nyiso.com/public/P-24Alist.htm
- Wiegner, J. F., Grimm, A., Weimann, L., & Gazzani, M. (2022). Optimal Design and Operation of Solid Sorbent Direct Air Capture Processes at Varying Ambient Conditions. *Industrial & Engineering Chemistry Research*, 61(34), 12649–12667. https://doi.org/10.1021/acs.iecr.2c00681

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