Direct Air Capture (DAC) is crucial in combating climate change. Given rising atmospheric CO₂ levels, curtailing 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 CO₂ 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 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 CO₂ molecules engage with hierarchically porous materials such as amines (McQueen et al., 2021).
2. Materials selectively bind with CO₂.
3. Captured CO₂ is released via heat or pressure, resulting in a pure stream of CO₂ to be sold and repurposed.
4. The sorbent can be reused following the desorption process, recycling incurs operational and material costs to account for the energy consumption and material life expectancy.

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 -50% 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.

**Methods: Modeling the DAC System for Optimization**

The objective function maximizes the total profit of the DAC operation

\[
\text{maximize} \sum_{t} n(t)(P_d(t) + P_u(t)) - C_{\text{op}}(t)
\]

- \( n(t) \): CO₂ recharging cost including selling price, subsidies, etc.
- \( P_d(t) \): desorption amount of DAC system at time period \( t \)
- \( P_u(t) \): electricity consumption for adsorption phase per unit time period
- \( C_{\text{op}}(t) \): electricity consumption for desorption phase per unit time period
- \( \lambda(t) \): electricity price threshold (lambda) for each day which determines whether or not the DAC system operates at that 5 min time step.
- \( \lambda(t) \) 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**

<table>
<thead>
<tr>
<th>Case</th>
<th>Model</th>
<th>Execution Time (HH:MM:SS)</th>
<th>Profit (USD)</th>
<th>Gross CO₂ Captured (Metric Tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA Adjusted Price</td>
<td>MATLAB</td>
<td>00:00:35</td>
<td>64,828.25</td>
<td>2,610.85</td>
</tr>
<tr>
<td>NY Adjusted Price</td>
<td>MATLAB</td>
<td>00:00:36</td>
<td>21,632.19</td>
<td>2414.94</td>
</tr>
<tr>
<td>NY/Fixed &amp; 35%</td>
<td>MATLAB</td>
<td>00:00:36</td>
<td>21,632.19</td>
<td>2414.94</td>
</tr>
<tr>
<td>NY/Fixed &amp; 37%</td>
<td>MATLAB</td>
<td>00:00:47</td>
<td>53,777.99</td>
<td>2,079.08</td>
</tr>
<tr>
<td>CA Adjusted Price</td>
<td>MATLAB</td>
<td>00:00:45</td>
<td>34,090.96</td>
<td>3248.18</td>
</tr>
</tbody>
</table>

**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, 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 across various 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.

**References & Acknowledgments**

California: - Lower emission rates during midday due to solar energy integration - "Quick curve" describes low net electricity demand (or dispatchable power generation) at midday, with surplus solar energy production leading to an energy surplus over abundance - 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

- 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 A/C heat)

- 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) vs. activated carbon (AC))

- NYISO Real-Time Fuel Mix.