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# Decarbonizing desert greenhouse crop production with direct air capture–based $CO_2$ enrichment

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## Abstract

### Introduction

Carbon dioxide ($CO_2$) enrichment is one of the key practices to improve crop productivity in greenhouses (Esmeijer, 1999). Elevated $CO_2$ levels positively affect stomatal development, photosynthesis, carbon assimilation, and nutrient acquisition, which contributes to shorter growing periods and has been demonstrated to produce 17–57% yield increase in a range of greenhouse crop types (Kimball & Mitchell, 1979; Pan et al., 2019; Wittwer & Robb, 1964). While $CO_2$ enrichment is a standard practice in cold climates such as Europe and North America, its implementation in hot climates is uncommon. Since the utilization of $CO_2$ by plants for photosynthesis coincides with incident solar radiation, there is a tradeoff in greenhouses between ventilation and maintaining elevated $CO_2$ concentrations. This is particularly problematic for ventilated greenhouses in hot regions which depend on ventilation for cooling for most of the year. However, high-tech greenhouse facilities cooled via mechanical air-conditioning are becoming increasingly common in hot, arid climates due to high water-use efficiencies and control over growing conditions; in this case, $CO_2$ enrichment is not only feasible but techno-economically imperative for greenhouse operators (Hopwood et al., 2024). $CO_2$ must be supplied to the greenhouse externally. The most common methods to transport $CO_2$ from the source to the utilization location are trucks, ships, and pipelines (Svensson et al., 2004), which results in elevated costs for greenhouse operators. The cost of $CO_2$ to the greenhouse grower in Saudi Arabia ranges from \$160/$t_{CO2}$ to \$220/$t_{CO2}$ depending on the greenhouse location, compared to \$80 to 150/$t_{CO2}$ in the Netherlands, a mature greenhouse industry with extensive $CO_2$ transmission infrastructure (Mikunda, et al, 2015). Direct air capture (DAC) technology is increasingly seen as a competitive solution for greenhouse $CO_2$ enrichment supply in regions lacking $CO_2$ distribution infrastructure (Bao et al., 2023; T. Wang et al., 2014; Wu et al., 2024, Wilcox, et al, 2017). The concept of capturing $CO_2$ directly from air to produce a higher concentration stream of $CO_2$ was introduced more than two decades ago by Lackner et al. (1999). Since then, DAC technology has made significant technological advances but faces both technical and economic challenges to scale-up, especially for utility-scale carbon capture and sequestration (CCS) applications. The low concentration of $CO_2$ in the atmosphere compared to concentrated exhaust streams presents a thermodynamic challenge for DAC, raising the energy requirement and reducing the efficiency of the capture process (Keith, 2009). To produce high-purity, concentrated $CO_2$ as the final product, large quantities of air must be processed, requiring high energy input and material resources for air movement, $CO_2$ capture and release, and subsequent compression or purification (Fasihi, 2019). The estimated energy input

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ranges from 600–1400 kJ/mol$CO_2$ to achieve 99% purity, as required in CCS applications (Wilcox, et al, 2017). The associated capital and operating expenses with this process challenge CCS economic feasibility. However, these techno-economic challenges with DAC technology become less significant in greenhouse applications firstly because $CO_2$ is a valuable product to boost plant productivity (versus a waste stream needing disposal in CCS scenarios). Secondly, greenhouses require a relatively lower output $CO_2$ concentration (typically 1–2%), thus reducing the work required for $CO_2$ separation from ambient air to a range of 200–500 kJ/molCO2 (Wilcox, et al, 2017).

**Objective**

The expanding high-tech greenhouse industry in hot regions coupled with the lack of $CO_2$ supply infrastructure creates a compelling market opportunity for sustainable alternatives that leverage DAC. However, wide-scale adoption will depend on a competitive business case for DAC compared to conventional $CO_2$ enrichment systems. This study provides the first assessment of the techno-economic feasibility of DAC-based greenhouse $CO_2$ enrichment in hot regions, identifying the design, operational, and market conditions that enable competitive levelized costs compared to conventional bottled liquid $CO_2$ supplies (ConvE).

**Methodology**

The key metric to evaluate the techno-economic performance of the enrichment systems is the levelized cost of $CO_2$ ($LC_{CO2}$). $LC_{CO2}$ is the average cost of supplying one ton of $CO_2$ to the greenhouse over the system's lifetime, accounting for both capital and operational expenses. A local sensitivity analysis is performed with the economic model to identify how changes in key variables, such as energy prices, cyclic performance, air velocity, materials' cost, liquid $CO_2$ prices, etc., affect CapEx, OpEx and $LC_{CO2}$. A temperature swing adsorption DAC system is selected for the model because it is the most reported system in the literature for greenhouse applications (Araoz et al., 2021; Bao et al., 2018, 2023; Hou et al., 2017; A. Wang et al., 2022; T. Wang et al., 2013, 2014; Wu et al., 2024). The model calculates capital costs (CapEx) and operational costs (OpEx) based on greenhouse and ambient conditions, crop $CO_2$ requirement, daily operation time, system lifetime, cost of equipment, cost of energy, and specific features of each system. All the values and assumptions utilized in this study are theoretical or literature based. CapEx for both DAC and ConvE includes the equipment needed to deliver and monitor the $CO_2$ from its source to the crops, such as piping, flow meters and sensors, while OpEx covers energy consumption and equipment maintenance. For DAC systems, CapEx includes the cost of the fans, columns and the equipment required to induce desorption, while OpEx incorporates the cost of the sorbent material. The cost analysis of the DAC system assumes that the cyclic performance of a single DAC unit is known. For ConvE, OpEx includes the cost of liquid $CO_2$ supply, transportation and tanks rental.

**Results**

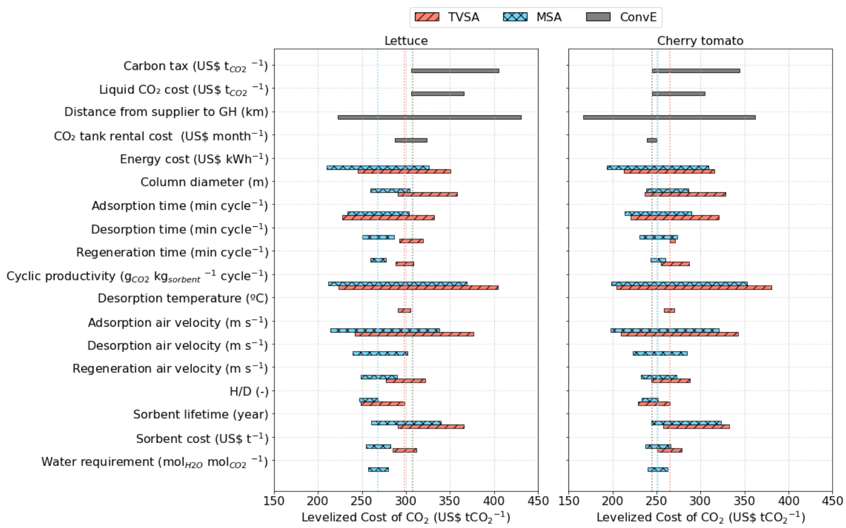


**Fig. 1. Levelized cost sensitivity in DAC-E and ConvE systems**. Sensitivity of levelized cost to key process and economic parameters for TVSA, MSA and ConvE. Bars represent the cost variation resulting from high and low parameter values. Dotted vertical lines represent the levelized cost at the baseline scenario of each technology.

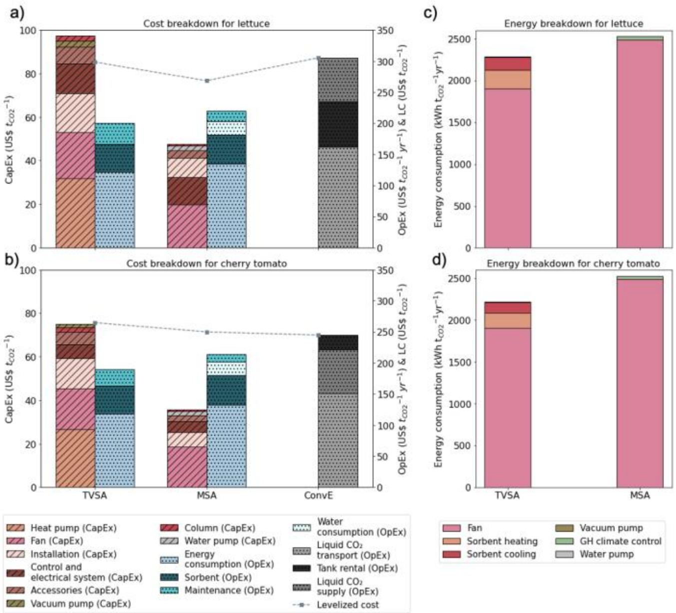


**Fig. 2. Breakdown of CapEx, OpEx, levelized cost, and energy consumptions.** a) Disaggregated CapEx (left axis), OpEx and levelized costs (right axis) for TVSA, MSA, and ConvE systems for a high-tech greenhouse facility (HTGH) producing lettuce and b) cherry tomato. c) Disaggregated annual energy consumption for lettuce-HTGH and d) cherry tomato-HTGH.

## Conclusion

This work presents a techno-economic assessment to determine the conditions under which DAC-based enrichment is more cost-effective than conventional bottled liquid $CO_2$ supplies (ConvE). A model that calculates the capital and operation expenses, and the levelized cost of $CO_2$ of both enrichment systems is developed, followed by a sensitivity analysis to identify the key factors that make DAC-based $CO_2$ enrichment competitive with ConvE. Scenarios with elevated costs of liquid $CO_2$ supply due to carbon taxes and transportation costs are discussed as well. The results reveal that to minimize the levelized cost of $CO_2$ of a DAC-based enrichment system, the key factors are cyclic productivity, cycle time, and energy cost. These findings highlight that DAC could be a reliable and affordable option for supplying $CO_2$ to greenhouses, especially if climate regulations and carbon taxes become stricter.

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