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Direct air capture for cheaper carbon dioxide enrichment in greenhouse agriculture in hot climates

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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/molCO_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

First, the economic performance of ConvE and DAC-based CO_2 enrichment is evaluated under a baseline scenario, defined by median values reported in literature and realistic assumptions. Figure 1 a) and b) show the comparison of CapEx, Opex and levelized cost of CO_2 of ConvE vs DAC-based CO_2 enrichment for the baseline scenario. ConvE is more cost-effective than DAC with a levelized cost of \$281/t_{CO2} vs \$607/t_{CO2} respectively. Figure 1 c), d), e), f) presents the breakdown of CapEx and OpEx for both CO_2 enrichment systems. The OpEx of the ConvE system depends 69% on the cost of the liquid CO_2, and 28% on the cost of the tanks' rental, highlighting the importance of exploring scenarios with higher liquid CO_2 prices. In the DAC-based system, CapEx is primarily driven by the cost of the column (58%), followed by installation (20%), while OpEx is driven by energy consumption (54%), maintenance (27%), and sorbent costs (19%). Therefore, on the design side, efforts should focus on reducing the number of required columns and optimizing column size. For operations, priority should go to enabling high productivity at low are velocities to reduce energy consumption, and reducing the amount of sorbent used and/or utilizing cost-effective sorbents.

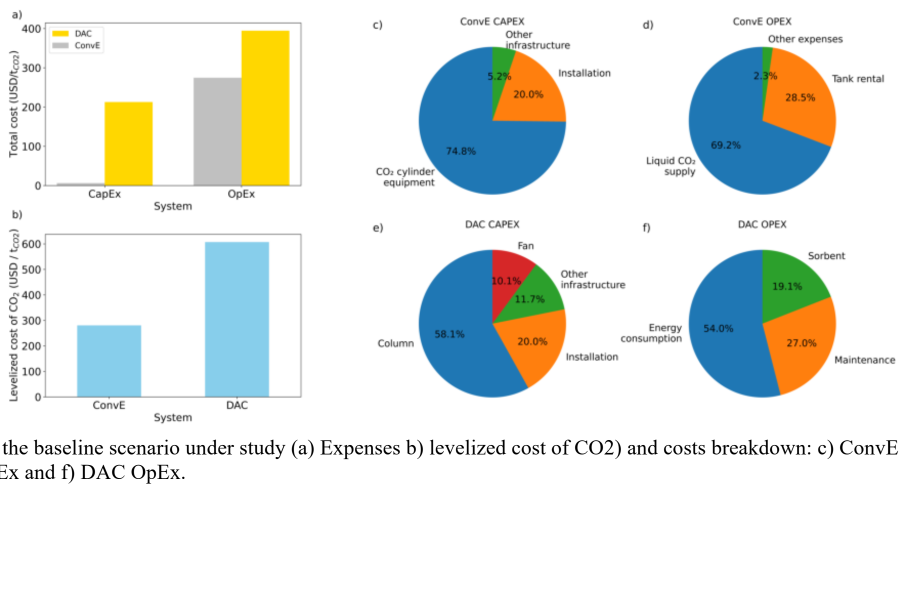

Figure 1. Results of the baseline scenario under study (a) Expenses b) levelized cost of CO2) and costs breakdown: c) ConvE CapEx d) ConvE OpEx, e) DAC CapEx and f) DAC OpEx.

These dominant cost parameters identified in the baseline scenario are investigated in the sensitivity analysis (Figure 2 a)), which shows LC_{CO2} to be most sensitive to adsorption/desorption velocities, column material cost, energy cost, cyclic productivity, and adsorption/desorption times. Estimating conservative, realistic, and optimistic values of each parameter, we observe that the fan consistently accounts for the highest energy consumption, followed by the heater. As a result, the energy use is particularly sensitive to adsorption/desorption air velocity and cyclic productivity.
The sensitivity analysis evidences that multiple parameters must be optimized for DAC-based enrichment systems to be economically viable. A scenario with favourable conditions for DAC is proposed, including lower costs of the DAC system, a more efficient sorbent, and challenging conditions for ConvE. For the DAC system, quicker cycles (40-minute adsorption and 15-minute desorption per cycle), low column material cost ($1.5/kg) and a high cyclic productivity (30 $g_{CO2}/kg_{sorbent}$/cycle) are achievable targets (Low et al., 2023; Sabatino et al., 2021). Regarding challenging conditions for ConvE, the transportation costs for liquid CO_2 increase for greenhouses located further from liquid CO_2 sources, making DAC more cost-effective. A distance of 450 km between the CO_2 supplier and the greenhouse is considered. Additionally, as carbon taxes become more common, greenhouse companies must consider their CO_2 emissions and tax implications to remain competitive and sustainable. To reflect moderate regulatory conditions, a carbon tax of $50 per ton is applied for the conventional system (Statista, 2024). Figure 2 b) and c) show the comparison of CapEx, Opex and levelized cost of CO_2 of ConvE vs DAC-based CO_2 enrichment for the optimistic scenario. DAC is more cost-effective than DAC with a levelized cost of \$255/t_{CO2} vs \$336/t_{CO2} respectively.

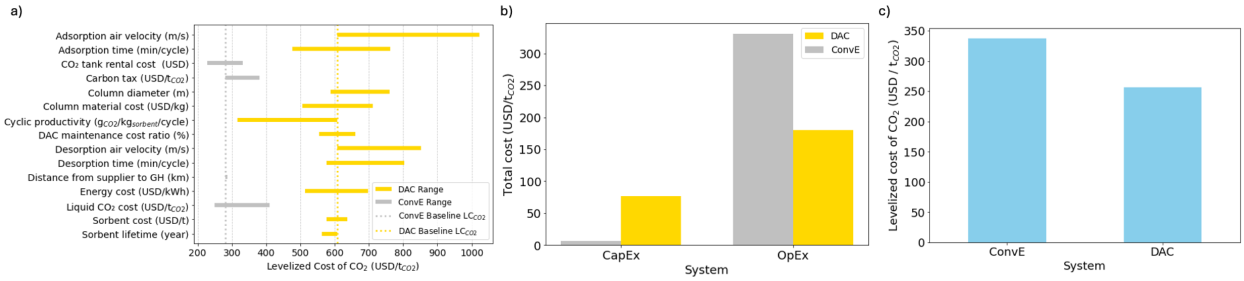

Figure 2. a) Sensitivity analysis of the levelized cost of CO_2. b) CapEx and OpEx of an optimistic scenario c) levelized cost of CO_2 of an optimistic scenario

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 (>30 g/kg), cycle time (< 55 min), sorbent cost (<\$5000 / t_{CO2}), and column's material cost (< \$ 1.5/ kg). These findings highlight that DAC-based enrichment systems are a clear opportunity to capitalize on the CO_2 from the atmosphere. 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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