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Integrating Direct Air Capture and HVAC Systems: An Economic Perspective on Cost Savings

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ABSTRACT

Direct Air Capture (DAC) technology has gained significant attention as a promising solution for mitigating CO_2 emissions and meeting climate goals. However, the current challenges of high energy demand, capital costs, and scalability present critical challenges to the widespread deployment of DAC systems. Integrating DAC with Heating, Ventilation, and Air Conditioning (HVAC) systems in buildings offers a potential solution by enhancing indoor air quality while capturing CO_2, thus lowering energy consumption and capital investment compared to standalone DAC systems. This study evaluates the techno-economic performance of an integrated DAC-HVAC system against a standalone DAC system. This analysis combines thermodynamic estimation of CO_2 and H_2O loadings and energy requirements with an economic evaluation of capital and operating costs to calculate the levelized cost of CO_2 capture (LCOD) for both DAC-HVAC and DAC-standalone. A sensitivity analysis explores the effects of varying climatic conditions, specifically temperature and humidity, on the economic performance of the DAC-standalone system. Further sensitivity analysis examines the impact of discount rates and electricity prices on both systems' economic viability. Results show that the DAC-HVAC integration achieves lower energy consumption and capital costs, with an LCOD of approximately 219 $/ton CO_2, compared to the DAC-standalone system, which ranges from 349–429 $/ton CO_2 depending on climatic conditions. In addition to offering a lower levelized cost, the DAC-HVAC system also provides resilience against climate and cost fluctuations. This study demonstrates the significant economic benefits and scalability potential of integrating DAC technologies within existing building infrastructures.

Keywords: DAC, CO2 capture, HVAC, Energy efficiency, Techno-economics.

INTRODUCTION

As the global climate crisis intensifies, the need for effective negative emission technologies (NETs) to remove CO_2 from hard-to-abate industries and address historical emissions has become increasingly urgent [1]. Among the various NETs, Direct Air Capture (DAC) with carbon storage is considered a promising complementary solution to meet climate goals, with the potential to significantly reduce atmospheric CO_2 levels [2]. However, despite the significant promise of DAC, the energy and economic costs of its implementation remain uncertain, with estimates ranging between $100 and $1000 per ton of CO_2 captured. Furthermore, DAC is projected to require substantial energy resources if deployed at scale, potentially consuming around 50 EJ annually by 2100 which is more than half of the current global electricity production [2]. This highlights the critical need to explore innovative solutions to reduce the energy requirements associated with DAC systems.

One promising approach is the integration of DAC into existing Heating, Ventilation, and Air Conditioning (HVAC) infrastructures. This coupling offers dual benefits; it not only reduces the energy demands of DAC systems but also enhances the efficiency of HVAC systems by enabling air recirculation and CO_2 recycling. Additionally, the integration provides an opportunity to maintain high indoor air quality (IAQ), which is crucial for the well-being of building occupants. Research has shown that CO_2 concentrations above 1000 ppm can lead to adverse health effects, such as the Sick Building Syndrome (SBS), while concentrations below 1000 ppm are generally considered acceptable for IAQ, provided that appropriate ventilation measures are in place [3,4]. Moreover, elevated CO_2 levels have been associated with reduced cognitive performance, further emphasizing the importance of maintaining optimal air quality [4].

Although limited studies have examined the integration of DAC with HVAC systems, few have addressed the fluctuations in CO_2 and H_2O loadings with varying outside temperatures and humidity, which directly impact the energy requirements of DAC standalone systems [5]. Other studies explored DAC-standalone economics without consideration of varying climatic conditions [6].

The goal of this study is to evaluate the techno-economics of integrating DAC with HVAC systems and compare it with the performance of standalone DAC systems. In standalone DAC, the energy requirements for the Temperature-Vacuum Swing Adsorption (TVSA) process vary with changes in external climate condition such as temperature and humidity, as these factors influence the CO_2 and H_2O adsorption capacities. This study aims to assess the fluctuations in CO_2 and H_2O loadings in response to changes in outside temperature and pressure and examine how these fluctuations affect energy requirements, and consequently, the operating expenses of the DAC standalone system. This will provide a comprehensive comparison with the proposed DAC-HVAC integration, which remains unaffected by external temperature and humidity conditions.

SYSTEM DESCRIPTION

The proposed system integrates a direct air capture (DAC) unit into the Heating, Ventilation, and Air Conditioning (HVAC) infrastructure of buildings to optimize energy use during adsorption and desorption while also improving indoor air quality. The DAC-HVAC system is strategically positioned at the exhaust stream, where CO_2 concentrations are highest, to maximize the CO_2 capture efficiency. This placement within the HVAC system has been shown to optimize CO_2 capture for DAC-HVAC integration, when air recirculation is considered [7]. A target CO_2 concentration of 400 ppm is assumed for CO_2 capture in this study.

Both the DAC-HVAC and DAC-standalone systems operate through temperature vacuum swing adsorption (TVSA) process, which includes vacuum application, heating for desorption, cooling, pressurization, and adsorption. The DAC system operates continuously with two parallel adsorbent filters, one in adsorption mode while the other undergoes desorption. A cooling jacket-type heat exchanger is used to meet the thermal needs of the TVSA process, providing heating and cooling as required.

Lewatit VP OC 1065 is used as the sorbent material in both configurations. While the DAC-HVAC system benefits from utilizing existing HVAC blowers, reducing capital expenditures, the DAC-standalone system requires additional blowers, increasing its capex. The consistent filter design and TVSA process across both systems allow for a direct techno-economic comparison of DAC-HVAC integration versus the standalone DAC system.

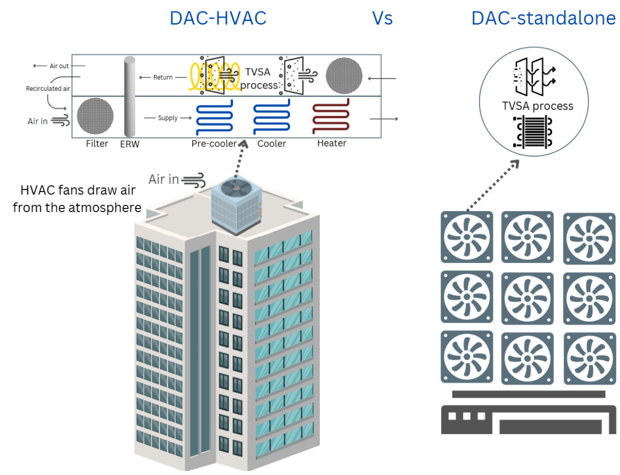

Figure 1. Schematic of DAC-HVAC and DAC-standalone systems.

METHODOLOGY

This study is structured into two key components; a thermodynamic analysis to estimate CO_2 and H_2O loadings and assess the energy requirements of the TVSA process and an economic analysis to evaluate capital and operational costs and determine the levelized cost of CO_2 capture (LCOD).

Thermodynamic analysis

This study entails a thermodynamic analysis of the DAC system to evaluate its energy requirements, which include operating the vacuum pump, heating the sorbent during desorption and cooling the sorbent before adsorption. Additionally, blower power is considered to account for the pressure drop from the filters in the system. Equations 1–6 quantify these energy demands, detailing the heating load for desorption (Equations 1–3), the cooling load before adsorption (Equation 4), the vacuum pump work (Equation 5), and the additional blower power required to compensate for pressure drop from the filters (Equation 6). These calculations are essential for estimating the system's variable operational costs in terms of electricity consumption and for determining the appropriate sizing of equipment required. Table 1 presents the various thermodynamic variables utilized in the analysis.

$$\dot{Q}_{heating} = Q_{sens} + Q_{latent} \quad (1)$$

$$\dot{Q}_{sens} = \dot{m}\left(\frac{c_{p,ads}}{\Delta_{qCO2}} + c_{p,CO2} + c_{p,H20}\frac{\Delta_{qH2O}}{\Delta_{qCO2}}\right)(T_{des} - T_{ads}) \quad (2)$$

$$\dot{Q}_{latent} = \dot{m}\left(\Delta H_{H2O}\left(\frac{\Delta_{qH2O}}{\Delta_{qCO2}}\right) + \Delta H_{CO2}\right) \quad (3)$$

$$\dot{Q}_{cooling} = \dot{m}\frac{c_{p,ads}}{\Delta_{qCO2}}(T_{des} - T_{ads}) \quad (4)$$

$$\dot{W}_{pump} = \dot{m}\frac{R.T_{pump}}{\eta_{pump}}\ln\left(\frac{P_{amb}}{P_{des}}\right) \quad (5)$$

$$\dot{W}_{blower} = 2.72 \text{ x } 10^{-5}\frac{\dot{V}_{air}\Delta P}{\eta_{fan}} \quad (6)$$

Where $\dot{Q}_{heating}$ is the total heating load including sensible heat (Q_{sens}) and latent heat (Q_{latent}). $\dot{Q}_{cooling}$ is the cooling load, $\dot{W}_{pump}$ is the work of the pump, $\dot{W}_{blower}$ is the fan power, $\dot{V}_{air}$ is the incoming air flowrate, ΔP is the pressure drop, η_{fan} is the fan efficiency, and $\dot{m}$ is the CO_2 mass flowrate.

Moreover, the water and CO_2 adsorption capacities are determined using mechanistic co-adsorption models, which describe the isotherm behavior as outlined in Equations 7 and 8. These models provide a detailed understanding of how the sorbent interacts with both CO_2 and H_2O, enabling the calculation of adsorption capacities under varying conditions [5].

$$q_{CO2} = \frac{\phi}{\phi_{dry}}\text{ f}(p_{CO2}, T, \Delta H) \quad (7)$$

$$q_{H2O} = \frac{q_m kcx}{(1 - kx)(1 + (c - 1)kx)} \quad (8)$$

Where q_{CO2} is the CO_2 loading, ϕ, and ϕ_{dry} are amine efficiencies under actual and dry conditions, f is the partial pressure (p_{CO2}) and temperature dependent isotherm function, and ΔH is the average heat of adsorption of wet and dry states. q_{H2O} is the H_2O loading, q_m is the monolayer loading, x is the humidity and k and c are affinity parameters taken from Young et al. [5].

Table 1: Thermodynamic analysis variables.

Variable	Description	Value
$c_{p,ads}$	Specific heat of adsorbent	1.58 kJ/kg/K
$c_{p,CO2}$	Specific heat of CO_2	0.03868 kJ/mol/K
$c_{p,H20}$	Specific heat of H_2O	0.07528 kJ/mol/K
T_{ads}	Adsorption temperature	23.7 °C
T_{des}	Desorption temperature	90 °C
P_{des}	Desorption pressure	25 kPa
ΔH_{CO2}	CO_2 heat of desorption	70 kJ/mol CO_2
ΔH_{H2O}	H_2O heat of desorption	44.2 kJ/mol CO_2

Economic analysis

To evaluate the overall economic performance, the levelized cost of direct air capture (LCOD) is calculated using equation 9. LCOD is a crucial metric for comparing the costs of different DAC technologies. In this study, it is used to compare the DAC-HVAC and DAC-standalone systems by consolidating both fixed and variable operating costs, as well as capital expenditures providing an overall cost comparison between the two systems based on the amount of CO_2 captured. The economic analysis of the DAC system involves estimating both capital expenditures (CAPEX) and operating expenditures (OPEX) of both the DAC-HVAC and DAC-standalone systems. Equipment base costs are determined using an exponential method that incorporates capacity-ratio exponents to calculate equipment costs based on their capacity, as previously estimated in the thermodynamic analysis. These equipment costs are then estimated in terms of delivered, installed, and escalated cost projections. The variable operating costs include electricity for heating and cooling, pumping, and additional fan power requirements. The fixed operating cost includes ongoing costs such as maintenance, insurance, labor, and other administrative expenses that remain constant regardless of the system's operation.

$$LCOD = \frac{Capex\,.CRF + Opex_{fix}}{CO2} + Opex_{var} \quad (9)$$

Where CAPEX represents the capital expenditures, CRF is the capital recovery factor, CO_2 is the annual amount of CO_2 captured, and $Opex_{fix}$ and $opex_{var}$ denote fixed and variable operating expenditures, respectively. The CRF is calculated using equation 10.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (10)$$

In this equation, i is the annual discount rate (7%), and n is the system's lifetime (20 years). The CRF is used to calculate the annualized capital cost, enabling the distribution of CAPEX over the system's lifespan.

A sensitivity analysis is conducted to evaluate the effect of varying temperature and humidity on CO_2 and H_2O adsorption capacities, and the resulting changes in LCOD for the DAC-standalone system. This analysis considers humidity ranges between 20-90% and temperatures between 25-45°C. Additionally, actual data points for temperature and humidity from Qatar, based on hourly data collected over four months (May to August), are studied to assess the range of LCOD changes for this case study. This sensitivity analysis, however, is not applicable to the DAC-HVAC system, as it maintains a constant temperature and humidity within the HVAC infrastructure, which helps stabilize conditions and mitigate the fluctuations observed in the standalone system.

Moreover, a sensitivity analysis is performed to evaluate the impact of varying discount rates (5-15%) and electricity prices ($0.30-$0.14/kWh) on the levelized cost of direct air capture (LCOD) for both the DAC-HVAC and DAC-standalone systems. This analysis allows for an assessment of how fluctuations in these key economic factors influence the overall cost-effectiveness of the systems.

RESULTS AND DISCUSSION

At a discount rate of 7% and an electricity price of 0.0351 \$/kWh, the levelized cost of direct air capture (LCOD) for the DAC-HVAC system is 219 \$/ton CO_2, while the DAC-standalone system has a significantly higher LCOD of \$374/ton CO_2. This disparity highlights the cost advantages of integrating DAC with HVAC systems.

The DAC-HVAC system benefits from the synergy between the two processes. By utilizing the heating and cooling capabilities of the HVAC system to enhance the CO_2 loading and reduce the H_2O loading, the DAC-HVAC system can capture CO_2 more cost-effectively. This integration results in improved energy efficiency, reducing the energy consumption per ton of CO_2 captured, which is a key driver of its lower LCOD. On the other hand, the DAC-standalone system operates independently and is subject to fluctuations in climate conditions, which influence CO_2 and H_2O adsorption capacities, thereby affecting energy requirements and operational expenses. Additionally, the DAC-HVAC system can leverage existing HVAC blowers, while the DAC-standalone system incurs additional capital expenditure due to the need for separate blowers.

The LCOD of the DAC-standalone system is highly sensitive to variations in temperature and humidity due to their impact on CO_2 and H_2O adsorption capacities. A contour plot was generated to visualize the fluctuations in LCOD across a range of temperature (4–25°C) and humidity (20–90%) conditions as presented in Figure 2. Additionally, actual hourly temperature and humidity data over four months in Qatar were plotted on the contour map to assess variations in LCOD.

The results indicate that LCOD fluctuates between 349–429 \$/ton CO_2, with the highest LCOD observed at high temperatures and high humidity levels. This can be attributed to the increased presence of H_2O in the air under these conditions, which competes with CO_2 for adsorption on the sorbent material. As a result, CO_2 capture efficiency declines, leading to higher energy requirements for desorption and subsequently increasing LCOD. The lowest LCOD values occur at low temperatures and low humidity levels, where CO_2 adsorption is more favorable, and less energy is required for regeneration.

For the Qatar case study, the results indicate that when temperature is high, humidity is relatively lower, leading to a maximum LCOD of approximately 405 \$/ton CO_2. Notably, there are no data points corresponding to conditions where both temperature and humidity are high for the studied dataset of three months, which means the LCOD does not reach the maximum value of 429 \$/ton CO_2.

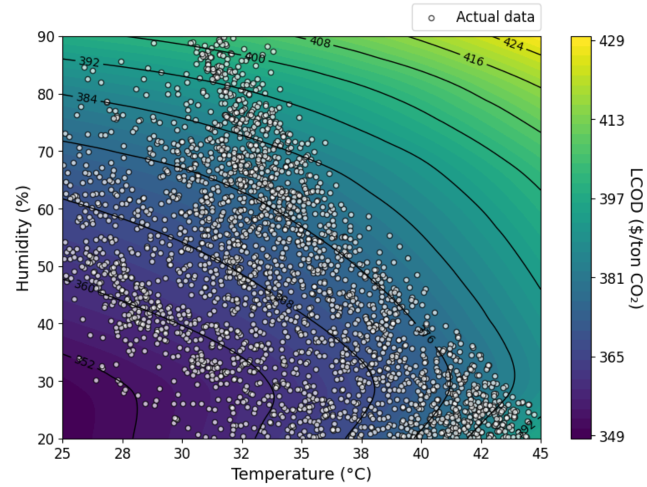

Figure 2. Contour plot of LCOD with respect to temperature and humidity for DAC-standalone system.

The sensitivity analysis of LCOD with respect to varying electricity prices and discount rates further illustrates the cost dynamics of both systems. As electricity prices increase, the LCOD for both DAC-HVAC and DAC-standalone systems rises (Figure 3). For example, at an electricity price of 0.14 \$/kWh, the LCOD for the DAC-standalone system increases to 536 \$/ton CO_2, while the DAC-HVAC system reaches 381 \$/ton CO_2. This significant difference highlights that in regions where electricity prices are volatile or high, DAC-HVAC systems may offer a more cost-effective solution.

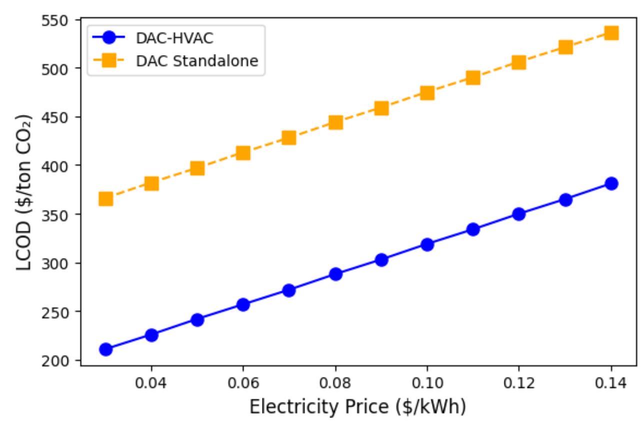

Figure 3. Effect of electricity price on LCOD.

Similarly, the LCOD values for both systems are sensitive to changes in the discount rate. While both systems experience a rise in LCOD with higher discount rates, the DAC-HVAC system consistently maintains a lower cost compared to the DAC-standalone system (Figure 4). This suggests that the DAC-HVAC system is more resilient to long-term financial considerations, owing to its lower operational and capital costs, making it a more attractive option for long-term projects.

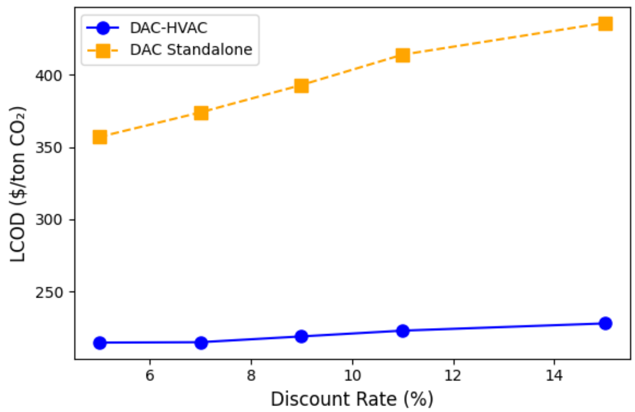

Figure 4. Effect of discount rate on LCOD.

The DAC-HVAC integration mitigates several technical and financial barriers of standalone DAC. However, key technical challenges remain, including managing pressure drop from the filters and ensuring efficient adsorbent regeneration, both of which are considered in this study. Financially, DAC-HVAC integration reduces capital and operational costs by leveraging existing HVAC infrastructure, as demonstrated by its economic advantage over standalone DAC.

CONCLUSION

This study highlights the techno-economic benefits of integrating direct air capture (DAC) with Heating, Ventilation, and Air Conditioning (HVAC) systems compared to standalone DAC. The results show that the levelized cost of direct air capture (LCOD) for the DAC-HVAC system is significantly lower (219 \$/ton CO_2) than that of the DAC-standalone system (374 \$/ton CO_2) at an electricity price of 0.0351 \$/kWh and a 7% discount rate. This cost reduction is attributed to the synergy between DAC and HVAC, which improves energy efficiency by leveraging existing heating, cooling, and ventilation infrastructure. Additionally, the DAC-HVAC system benefits from more stable operating conditions, avoiding the fluctuations in CO_2 and H_2O adsorption capacities that significantly impact the energy requirements of standalone DAC. A sensitivity analysis of the DAC-standalone system further reveals that LCOD is highly dependent on external climate conditions. Temperature and humidity variations influence CO_2 and H_2O loadings, leading to LCOD fluctuations between 349 and 429 \$/ton CO_2.

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