Life Cycle Cost Analysis of Direct Air Capture Integrated with HVAC Systems: Utilization Routes in Formic Acid Production and Agricultural Greenhouses

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ABSTRACT

Integrating direct air capture (DAC) technology into Heating, Ventilation, and Air Conditioning (HVAC) systems offers an innovative approach to improving energy efficiency and indoor air quality in buildings while simultaneously reducing carbon emissions. This study investigates the economic feasibility of DAC integrated with HVAC by evaluating several key economic indicators including life cycle costing. Two adsorbents, Lewatit VP OC 1065 (Lewatit) and SBA-15, are evaluated within the system, for which the results indicate a significant economic advantage for SBA-15 over Lewatit. The levelized cost of the DAC with SBA-15 was found to be $202 per ton of CO_2 captured, demonstrating competitive economics for this carbon capture technology. To enhance the process's economics, the captured CO_2 is utilized in two key utilization pathways: low-carbon fuel and agricultural production. The first pathway explores the electrochemical conversion of CO_2 into formic acid (FA). The system demonstrates strong economic potential, with an NPV of $6.41 million and a levelized cost of $0.499/kg of FA. Critical economic parameters, such as Faradaic efficiency, current density, and electrolyzer stack price, are identified and should be optimized through further research into electrolyzer design. Alternatively, the second pathway considers utilizing the captured CO_2 for greenhouse CO_2 enrichment, enhancing crop growth and reducing water consumption, thus addressing food security concerns. The NPV for the greenhouse system with CO_2 enrichment was calculated to be $226,879, with a levelized cost of $1.13/kg of produce (tomatoes). Sensitivity analyses are performed on key economic variables, including the discount rate, electricity price, and final product selling price, to account for future market fluctuations.

1. Introduction

Atmospheric CO_2 levels are rising rapidly due to increased industrialization and economic development, currently reaching 50 % above pre-industrial levels. The burning of fossil fuels for electricity generation and transportation, deforestation, cement manufacturing, and agriculture are some of the causes of increased CO_2 emissions. According to the Paris Agreement, it is necessary to maintain the global temperature increases below 2 °C compared to pre-industrial levels [1]. There is a need to reduce the amount of CO_2 in the atmosphere, which can be achieved by limiting the amount released and implementing negative emission technologies (NET). Direct air capture (DAC) is a type of NET that removes CO_2 directly from the air. The captured CO_2 can be stored or directly used as a climate-neutral feedstock for other processes. This provides a solution for legacy emissions and a way to balance emissions from non-point sources that are difficult to avoid. In the IEA net zero emissions by 2050 scenario, it is predicted that DAC technologies will capture around 85 and 980 Mt of CO_2 by 2030 and 2050, respectively. Eighteen small-scale DAC plants are currently capturing 0.1 Mt of CO_2 per year worldwide [2]. DAC units can be placed inside a building's heating, ventilation, and air conditioning (HVAC) system and benefit from the higher concentration of CO_2 inside buildings [3]. Click or tap here to enter text.By coupling these two systems, higher energy efficiencies can be achieved for both systems. DAC placement within the HVAC system significantly impacts its efficiency and operational conditions. A recent study by the coauthors identified six potential placements for DAC within the HVAC system and compared their performance. These positions include: (1) after the HVAC filter, where the system is exposed to outside temperature and humidity fluctuations; (2) after the energy recovery wheel, benefiting from cooler air but experiencing variable humidity levels; (3) after the pre-cooler, (4) after

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Nomenclature

AHU	Air handling unit
BCR	Benefits-cost ratio
BEU	Breakeven units
BOP	Balance of plant
CAPEX	Capital expenditures
CC	Climate change
CCS	Carbon capture and storage
CCU	Carbon capture utilization
CEPCI	Chemical engineering plant cost index
CRF	Capital recovery factor
DAC	Direct air capture
DAL	Delivered costs
DPP	Discounted payback period
ECR	Electrochemical reduction
ETS	Emissions Trading Schemes
FA	Formic acid
FE	Faradaic efficiency
FOB	Free on-board costs
FT	Fischer-tropsch
HCOOH	Formic acid
HVAC	Heating, ventilation and air conditioning
INST	Installed cost
IRR	Internal rate of return
KPI	Key performance indicators
LAI	Leaf area index
LC	Levelized cost
LCC	Life cycle cost
LCF	Low carbon fuels
LCOD	Levelized cost of DAC
LCOF	Levelized cost of formic acid
LCOG	Levelized cost of greenhouse produce
NET	Negative emission technology
NPV	Net present value
OPEX	Operating expenditures
OSBL	Offsite battery limit
PAR	Photosynthetic active radiation
PEM	Proton exchange membrane
KPI	Key performance indicator
TEPA	Tetraethylenepentamine
TRL	Technology readiness level
TVSA	Temperature vacuum swing adsorption
VPD	Vapor pressure deficit

the cooler, and (5) after the heater, all of which operate under controlled temperature and humidity conditions; and (6) after the exhaust air (considering recirculation), where CO_2 concentrations, temperature, and humidity are highest. The study found that placing DAC after the exhaust air stream was the most efficient configuration [4]. HVAC systems have a high energy demand, and DAC integration can help lower this energy demand and contribute to building sustainability. Baus and Nehr [5] reported that DAC-HVAC integration led to a decrease in the energy demand by 37 %. Additionally, another advantage is that it improves indoor air quality and leads to benefits to human health by capturing CO_2 from the indoor environment.

This captured CO_2 can either be managed by long-term storage or conversion into a useful product. Long-term storage includes sequestration in geological formations to remove the carbon from the atmosphere entirely. Converting CO_2 into useful chemicals, fuels, and commodities has the dual advantage of mitigating greenhouse gas emissions while simultaneously creating valuable products for energy sectors and industries. Mitigation of emissions is also achieved through the replacement of fossil fuel-based feedstock with recycled CO_2. CO_2 can be converted to a variety of useful products, such as synthetic fuels, chemicals, or minerals [6]. FA can be synthesized from CO_2 via the process of electrochemical reduction (ECR). It is considered a suitable hydrogen carrier or can be directly used as fuel in FA fuel cells and hence generate clean electricity. Furthermore, it can be used as a raw material for synthesizing other fuels and chemicals, or direct applications such as greenhouse CO_2 enrichment. The conventional production of FA relies on fossil fuel feedstocks and involves a high emission process. In contrast, sustainably produced FA using renewable energy sources offers significant potential in further reducing emissions [7].

Captured CO_2 can also be utilized in agricultural greenhouses to enhance the photosynthesis process in crops. Several studies have shown that CO_2 concentrations of 1000–1200 ppm are optimal for increasing crop yields and reducing water consumption in greenhouses [8,9]. Ghiat et al. [9] conducted a techno-economic and environmental analysis of a biomass-based carbon capture and utilization system for greenhouse CO_2 enrichment to enhance crop yield and reduce crop water requirements. When scaled-up, the levelized cost of the system was found to be $0.35/kg of agricultural produce, considering prices of commercial CO_2. Akrami et al. [10] performed a thermodynamic and techno-economic assessment of an integrated system utilizing captured CO_2 in a greenhouse. The overall system energy efficiency, internal rate of return, and payback period were found to be 21.8 %, 28.84 %, and 4.8 years, respectively.

Azarabadi and Lackner [11] developed a model to predict the profitability of different sorbents for DAC by estimating the maximum allowable budget. It was noted that due to the large quantity and fast deterioration of the sorbent, their costs can be higher in comparison to the other capital, operational and maintenance costs. To make the process commercially viable, DAC sorbents need to undergo testing in real life conditions. Sinha and Realff [12] also conducted a sorbent-based economic study, and their modelling results revealed that the cost of DAC is around 86 and 221$ per ton CO_2. Low-cost sorbents with long lifetime and high purity are required for improving the economics of the DAC technology. Fasihi et al. [13] conducted a techno-economic assessment on DAC and considered future scenarios using a 15 % learning curve of capital expenditures and development in renewable energies. The costs of direct capture can be reduced to 89 and 79 €/tCO_2 by 2050 for high-temperature and low-temperature DAC technologies, respectively.

Several studies have explored various utilization routes for direct air captured CO_2 and assessed their economic implications. Daniel et al. [14] evaluated the DAC process with a solid oxide electrolysis unit to produce syngas for the utilization of CO_2. Using the estimates taken in the base case, the obtained cost of capture was high at $383 per ton CO_2. Optimization studies using different future seniors revealed that the capture costs can be negated, and the system can be profitable. Significant improvements in the economics can be obtained if there is an increase in price of final product, decrease in electricity price, increase in carbon tax and reduction in capital expenses. Marchese et al. [15] studied the economics of DAC with carbon utilization by converting CO_2 into syngas, followed by the production of hydrocarbons using the Fischer-Tropsch (FT) process. It was noted that the produced FT wax breakeven can be achieved at 264 €/tCO_2 when electricity from hydropower is utilized. Kiani et al. [16] connected the methanation of CO_2 to the DAC process. It was estimated that when the process is scaled-up to a capture capacity of about 1 MtCO_2/year the costs for capture can be reduced to $114 per ton CO_2.

Ramdin et al. [17] studied the economics of the ECR of CO_2 to FA. It was noted that since the electricity requirement is high, the price of electricity will have a significant impact on the economics of the process.

Improved design of the electrocatalyst is needed to improve the economics of ECR [17]. Rumayor et al. [18] conducted a preliminary economic study on ECR and conventional FA production (carbonylation of methanol). It was shown that ECR has promise and can be profitable when looking at the utility costs, but more detailed studies taking all capital and operational costs are needed. Pérez-Fortes et al. [19] studied the economics of FA from catalytic conversion of CO_2 and H_2 from electrolysis. Expensive catalysts increase the operating cost and the high electricity requirement from the electrolyzer, making it economically unsustainable compared to the conventional FA production process. Further developments are needed in the catalysts to make it favourable. Kim and Han [20] conducted a comparative analysis of two catalyst systems, demonstrating that a more efficient catalyst has the potential to enhance the economic viability of the process.

Since DAC-HVAC integrated systems are still in the early stages of research and development, many technical, economic, and scalability challenges remain to be addressed. In the current literature, detailed economic analyses and life cycle costing of integrated DAC systems for CO_2 utilization are limited. This study addresses this gap by providing a comprehensive techno-economic and life cycle costing (LCC) analysis of a novel integrated DAC-HVAC system, exploring its potential for CO_2 utilization in greenhouse applications and FA production in Qatar. By integrating DAC with HVAC systems, captured CO_2 can be repurposed for both greenhouse enrichment and electrochemical conversion to FA, offering sustainable alternatives to fossil fuel-derived CO_2 sources. These utilization pathways not only support agricultural productivity and industrial applications but also enhance the economic feasibility of DAC deployment by creating value-added products. Through this analysis, the study aims to provide valuable insights into the economic feasibility of integrating DAC with HVAC systems and utilizing CO_2 for electrochemical reduction and CO_2 enrichment in agriculture. The specific objectives of the study include assessing the economics of DAC when integrated with HVAC, followed by an evaluation of two integrated systems: DAC-HVAC with CO_2 conversion for FA production and DAC-HVAC with CO_2 use in agricultural greenhouses. The study also performs thermodynamic modelling of these systems and assesses their economic feasibility in terms of capital expenditures, operating expenditures, and levelized costs of the DAC-HVAC system, electrolyzer, and greenhouse units. A cash flow analysis is conducted, along with an evaluation of key economic performance indicators (KPIs) and life cycle costs (LCC) of the integrated CCU systems. Finally, sensitivity analyses are performed on various economic parameters.

2. System description

This study aims to evaluate the economics of a complete integrated CCU system. The CO_2 is captured by a DAC system integrated within HVAC systems in buildings and then utilized in two distinct processes, as shown in Fig. 1. The first pathway involves CO_2 electrochemical reduction to produce FA, a valuable chemical. The second pathway involves using the captured CO_2 in greenhouses to enhance crop growth and reduce water consumption. The following sections provide a brief description of the subsystems in the CCU process.

2.1. CO_2 capture using DAC-HVAC

This work entails a temperature vacuum swing adsorption (TVSA) based DAC-HVAC system integrating direct CO_2 capture technology within a comprehensive HVAC framework. The DAC system operates through a TVSA process, which consists of six essential phases designed to optimize CO_2 capture efficiency including vacuum, heating, desorption, cooling, pressurization and adsorption. The vacuum phase lowers the pressure within the system, reducing the partial pressure of CO_2 and thus aiding its desorption from the sorbent material. The heating phase consists of heating the sorbent material, which aids in the detachment of CO_2 from the sorbent surface. Following heating, the desorption phase encompasses the actual release of CO_2 from the sorbent material. Subsequently, during the cooling phase, additional cooling is applied to lower the temperature of the sorbent material. This step is crucial to prevent sorbent saturation and to prepare the material for the next adsorption cycle.

This study involves integrating a DAC system into the HVAC infrastructure of the Doha Tower, standing 46 floors tall with a total volume of 138,000 m^3 . The HVAC system complies with ASHRAE air change standards of 0.69 – 1.38 Mm^3 /h. To accommodate the building's substantial air handling needs, an Air Handling Unit (AHU) size has been carefully selected. The chosen AHU measures 2.73 × 4.10 m (LxW) and is capable of handling an airflow of 75,000 m^3 /h. Operating at velocities between 2 and 2.5 m/s, this AHU size is specifically chosen to minimize the pressure drop during CO_2 capture, utilizing specifications aligned with commercial AHU standards, specifically from the York AHU series [21]. Based on these specifications, it is estimated that 14 AHUs will be required for the Doha Tower, with each AHU system serving approximately 3–4 floors. With a flowrate of 75,000 m^3/h per AHU, the total available CO_2 per DAC system is 59.4 kg/h, which amounts to 831.6 kg/h for the entire building with 14 AHUs.

Equipment specifications are carefully designed around AHU parameters, leveraging existing HVAC infrastructure such as fans to reduce initial capital expenditures. Ensuring continuous operation, the DAC system incorporates two parallel 3D-printed adsorbents for both adsorption and desorption, enhanced by cooling jacket-type heat exchangers to meet the heating and cooling needs of the TVSA process. The economic feasibility of the DAC-HVAC system is evaluated through a comparative analysis between the performance and cost-effectiveness of Lewatit VP OC 1065 and SBA-15 + tetraethylenepentamine (TEPA) sorbents, aiming to identify the most efficient and economically viable solution for sustainable CO_2 capture in urban environments like Doha.

Moreover, this study investigates the development of 3D-printed filters for the DAC system, using Lewatit VP OC 1065 as a baseline sorbent for comparison against SBA-15, with both sorbents

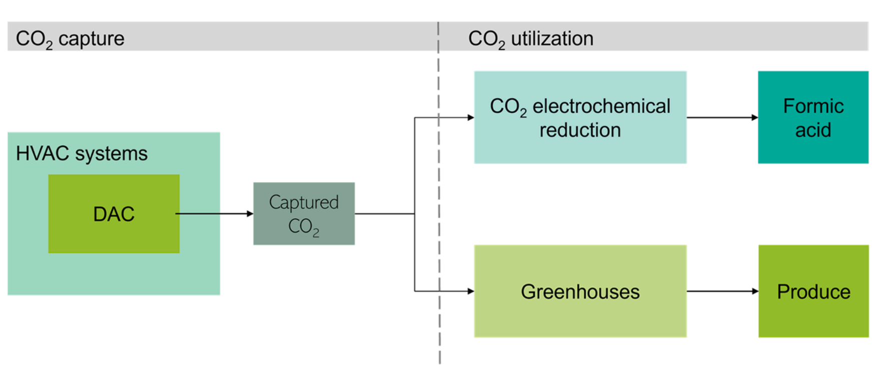

Fig. 1. System diagram of DAC-HVAC integration and the two CO_2 utilization routes.

functionalized with TEPA for enhanced performance. The use of SBA-15 functionalized with TEPA as a sorbent for DAC is attracting significant interest due to its enhanced CO_2 uptake capacity, which rivals that of traditional point source capture systems [22]. Additional details about filter fabrication are given in Supplementary Note S1.1.

2.2. CO_2 utilization in ECR

In this scenario, it is assumed that all of the pure CO_2 captured from the DAC-HVAC is converted to FA via electrochemical reduction. The electrochemical reduction of CO_2 takes place at ambient temperature and pressure in an electrolyzer cell. Typically, the cell features two electrodes (anode and cathode), electrocatalyst coating on the electrodes and electrolytes that facilitate the flow of ions. The CO_2 is fed to the electrolyzer along with water and the main reactions that take place for the formation of FA are shown in Eqs. (1) and (2).

$$CO_2 + H_2O + 2e^- \rightarrow HCOO^- + OH^- \tag{1}$$

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \tag{2}$$

Achieving high selectivity for the desired product, FA, is essential, as the electrochemical reduction of CO_2 can yield various other products. This selectivity is influenced by both reactor design and operating conditions [23]. Moreover, the electrocatalyst material and its characteristics play a decisive role in the selectivity of the desired product [24].

Faradaic efficiency (FE) and current density are two important parameters that need to be optimized to reduce the required electrolyzer area and thereby improve overall process economics. FA production using this method is still in its early stages, with significant progress needed before large-scale industrial use. Therefore, this study utilizes reported parameters from the electrolyzer cell in laboratory-scale studies performed by Yang et al. [25]. As these parameters can significantly vary for a given cell design, a sensitivity analysis will be performed to guide research and provide insights on the economic feasibility of the process.

This study also considers the transportation cost of CO_2 from the capture location to the conversion site. The conversion of CO_2 is carried out in a small plant with an electrolyzer cell stack, which is located 58 km away from the Doha Tower building in Mesaieed Industrial City, Doha-Qatar, and is transported in liquid form via trucks.

2.3. CO_2 utilization in greenhouses

The greenhouse system in this work is a high-tech, cooling-based facility located in Qatar, a region characterized by high levels of solar radiation that necessitate the use of advanced cooling systems. The greenhouse is of Venlo design, covering an area of 800 m^2, and utilizes tempered glass as its covering material. It is equipped with an HVAC system for temperature and humidity control. Tomatoes are grown in the greenhouse using a hydroponic system with drip irrigation.

The CO_2 enrichment practice in greenhouses entails concentrations between 1000 and 1200 ppm, traditionally achieved using LPG-based burners [8]. However, to explore more sustainable options, this study proposes using CO_2 captured from an integrated DAC-HVAC system in buildings. The captured CO_2 is transported from the DAC system, proposed in this study, located in the Doha Tower to the greenhouse via trucks for enrichment purposes, presenting a cleaner alternative to conventional CO_2 enrichment methods. The amount of CO_2 transported from the DAC system in Doha Tower is determined based on the specific CO_2 requirements of the greenhouse, ensuring an optimal concentration of 1000 ppm for efficient crop growth and productivity [8].

3. System modelling

The subsystems of the CCU pathways, DAC, CO_2 electrolyzer and greenhouse, are modelled to obtain the energy, water and CO_2 requirements and the feed flowrates. The following sections outline the modelling of the subsystems to obtain data for the economic analysis.

3.1. DAC-HVAC

The energy requirements of the DAC system are estimated and used to size the different equipment used in the system for economic analysis. The energy requirements of the DAC system include the energy needed for operating the vacuum pump, heating the sorbent during the desorption process, cooling the sorbent before adsorption, and CO_2 compression. Additional blower power is considered to account for the pressure drop in the DAC system. Moreover, fan power is required to compensate for the pressure drop in the fan used for water condensation.

The vacuum pump plays a crucial role in the TVSA process by lowering the CO_2 partial pressure and thus facilitating the desorption of CO_2 from the sorbent material. The work required for the vacuum pump is calculated using Eq. (3)

$$\dot{W}_{pump} = \dot{m}_{CO_2} \frac{R.T_{pump}}{\eta_{pump}} \ln\left(\frac{P_{amb}}{P_{des}}\right) \tag{3}$$

Where $\dot{W}_{pump}$ (kW) is the work of the pump, $\dot{m}_{CO2}$ is the CO_2 mass flowrate, P_{amb} and P_{des} are the ambient and desorption pressures, respectively.

The heating requirements for desorption include the sensible heat to raise the temperature to the required desorption temperature and latent heat required for the phase change of CO_2 as presented in Eqs.(4)-(6).

$$\dot{Q}_{HE} = Q_{sens} + Q_{latent} \tag{4}$$

$$\dot{Q}_{sens} = \dot{m}_{CO_2} \left(\frac{c_{p,adsorbent}}{\Delta_{qCO_2}} + c_{p,CO_2} + c_{p,H_20} \frac{\Delta_{qH_2O}}{\Delta_{qCO_2}} \right) (T_{des} - T_{ads}) \tag{5}$$

$$\dot{Q}_{latent} = \dot{m}_{CO_2} \left(\Delta H_{H_2O} \left(\frac{\Delta_{qH_2O}}{\Delta_{qCO_2}} \right) + \Delta H_{CO_2} \right) \tag{6}$$

The total heat is then used to size the heat exchanger by calculating the required heat transfer area using Eq. (7)

$$A_{HE} = \frac{\dot{Q}_{HE}}{U_{HE,LMTD}.\Delta T_m} \tag{7}$$

Where A_{HE} is surface heating area (m^2), $\dot{Q}_{HE}$ (W) is the heating duty, $U_{HE,LMTD}$ is the heat transfer coefficient and ΔT_m is the log mean difference temperature.

Similarly, the cooling load before adsorption is needed to prevent the saturation of the adsorbent. Eq. (8) estimates the sensible cooling required to lower the temperature after desorption, preparing the system for the adsorption phase.

$$\dot{Q}_L = \dot{m}_{CO_2} \frac{c_{p,adsorbent}}{\Delta_{qCO_2}} (T_{des} - T_{ads}) \tag{8}$$

The work required for CO_2 compression is calculated using Eq. (9).

$$\dot{W}_{comp} = \dot{m}_{CO_2} \frac{R.T_{comp}}{\eta_{comp}} \ln\left(\frac{P_{out}}{P_{in}}\right) \tag{9}$$

Where P_{out} is the desired CO_2 pressure for truck transportation in liquid form, taken as 73.8 bar and P_{in} is the inlet pressure [8].

The additional blower power required to compensate for the increased pressure drop is calculated using Eq.(10) [26]. The pressure drop arises from the resistance added by the DAC filters, which makes the existing HVAC blowers work harder to maintain the desired airflow. In the proposed configuration, 80 % of the time, the system is adsorbing with two filters at a lower velocity of 2 m/s and a pressure drop of 1645 Pa/m, while 20 % of the time, the system uses one filter for adsorption at a higher velocity of 4 m/s and a pressure drop of 2105 Pa/m, while the other filter is at the desorption phase [27].

Table 1
Thermodynamic variables of the DAC system.

Variable	Value		Unit
	SBA-15	LEWATIT VP OC 1065	
Specific heat of adsorbent ($c_{p,adsorbent}$)	1.08	1.58	kJ/kg/K
Specific heat of CO_2 (c_{p,CO_2})	0.03868		kJ/mol/K
Specific heat of H_2O (c_{p,H_2O})	0.07528		kJ/mol/K
CO_2 loading (Δ_{qCO_2})	3.17	1.1	mol/kg
H_2O loading (Δ_{qH_2O})	11.34	3.586	mol/kg
Adsorption temperature (T_{ads})	23.7		°C
Desorption temperature (T_{des})	90		°C
CO_2 heat of desorption (ΔH_{CO_2})	104	70	kJ/mol CO_2
H_2O heat of desorption (ΔH_{H_2O})	44.2	44.2	kJ/mol CO_2
Pump temperature (T_{pump})	76.85		°C
Pump efficiency (η_{pump})	70		%

$$\dot{W}_{fan} = 2.72\,x\,10^{-5}\frac{\dot{V}_{air}\Delta P}{\eta_{fan}} \tag{10}$$

Where $\dot{V}_{air}$ is the incoming air flowrate (m^3/h), ΔP is the pressure drop (cm), and η_{fan} is the fan efficiency.

Additionally, a fan is incorporated to supply cooled air for water condensation after the desorption process. This step is necessary to remove any water before CO_2 compression. The fan power required to overcome the pressure drop in the fan is calculated using Eq.(11). For this, the volumetric flowrate of air required to supply the cooling load is calculated using the sensible heat of both CO_2 and H_2O and the latent heat of H_2O as presented in eq.(12). Moreover, the cooling load for condensation is also used to size the heat exchanger, which transfers the cooling load from the fan to the hot stream exiting the desorption phase, ensuring effective water condensation.

$$\dot{Q}_{fan} = \frac{\dot{V}_{air}\Delta P}{\eta_{fan}} \tag{11}$$

$$\dot{V}_{air} = \frac{Q_{sens,CO_2} + Q_{sens,H_2O} + Q_{sens,H_2O}}{c_{p,air}.\Delta T_{air}.time}\frac{1}{\rho_{air}} \tag{12}$$

Where $\dot{Q}_{fan}$ is the fan power, $\dot{V}_{air}$ is the volumetric flowrate of air and η_{fan} is the fan efficiency, Q_{cond} is the cooling load, $c_{p,air}$ is the specific heat capacity of air, ΔT_{air} is the temperature difference of air and time is the time for cooling. Table 1 summarizes the parameter values used in this assessment, taken from Surkatti et al. [22].

The energy requirements to create the SBA-15 and Lewatit filters are assessed based on the power requirements, capacities and time of operation of the different equipment used, including a mixer, vacuum dryer, calcinator, and 3D printer. Detailed information on the power requirements for DAC filter production is provided in Supplementary Material Table S2.1. Moreover, the filter is designed to fit within the selected AHU with dimensions of 1.22 m in height, 4 m in width. Based on the adsorption capacities of the selected material, SBA-15 and Lewatit, presented in Table 1, the filter can achieve a maximum CO_2 capture rate of 100 with filter thicknesses of 1.46 m for SBA-15 and 0.46 m for Lewatit.

3.2. DAC-FA

The energy requirements and flowrates of the ECR system are estimated and used to size the different equipment of the system for the economic analysis. The DAC-HVAC system captures a total of 832 kg/h from the 14 AHUs. Based on these flowrates, the ECR system is scaled. The flowrates of the products from ECR are calculated using their Faradaic efficiency, $\varepsilon_{Faradic}$, by using Eq. (13).

$$\varepsilon_{Faradaic} = \frac{zn_iF}{Q} \tag{13}$$

Where Q is the total charge passed, z is the number of electrons per molecule of the product i, F is the Faraday's constant, and n_i is the molar production rate of the product. The Faradaic efficiency of FA is 94 % and the FE of the by-products, hydrogen and carbon monoxide are 2 % and 4 %, respectively [25]. The current density is taken as 0.14 A/m^2 [25] and the voltage as 3 V. For the calculation of the total charge passed, Eq. (13) was used which was then converted to the power needed in watts using the assumed voltage of 3 V. The main parameters of the electrolyzer are shown in Table 2. Based on these assumptions, 3.2 MW of electricity is required for producing 17.77 kmol/h of FA. The electrolyzer requires an area of 770 m^2 based on the current density assumption for the given CO_2 flowrate. As the assumed parameters can significantly vary for a given cell design, a sensitivity analysis will be performed on cell parameters.

The mole balance on the ECR system is shown in Fig. 2 for the mixing, electrolyzer and separating units. A 50 % CO_2 conversion rate is assumed for the electrolyzer [28]. The electrolyzer is scaled based on the current requirements using the reference flow rate of 4.4 × 10^6 mol/h. Moreover, it is assumed that 97 % of the CO_2 is recycled back after the separator which uses the pressure swing adsorption technology [29].

3.3. DAC-Greenhouse

The CO_2 supplied from the DAC to the greenhouse is considered pure, as water has been removed after the desorption process, ensuring a controlled CO_2 source that prevents humidity fluctuations inside the greenhouse. The desired level of CO_2 enrichment is set at 1000 ppm to optimize plant growth and photosynthetic efficiency.

3.3.1. CO_2 requirements

To estimate the amount of CO_2 required in the greenhouse, it is essential to first evaluate the assimilation rate of CO_2 by the plants, which is influenced by several microclimate and biophysical factors. This assimilation rate determines how much CO_2 the plants will consume for their photosynthesis. Additionally, CO_2 loss to the ambient should be considered, as it can reduce the concentration available for plant uptake, necessitating additional CO_2 supplementation to maintain desired levels. Although the greenhouse is a closed system, an air exchange every 2 h was considered due to leaks. Thus, the rate of CO_2 supply can be estimated by the mass balance of CO_2 following Eq. (14) [30].

$$S_{CO_2} = ACH(CO_{2in} - CO_{2out})\rho_{CO_2} + A \tag{14}$$

Where ACH is the air change rate (m^3/m^2/h), CO_{2in} and CO_{2out} are the CO_2 concentrations inside and outside the greenhouse respectively, ρ_{CO2} is the density of CO_2 and A is the net CO_2 assimilation rate (g/m^2/h).

The net assimilation can be estimated by the following regression model presented in Eq. (15) [30,31].

Table 2
Main parameters of the electrolyzer base case.

Parameter	Value	Unit
Cell Voltage	3	V
No. electrons/mole CO_2	2	e
Faraday's constant (F)	96480	C/mol
Current density	0.14	A/cm^2
Total current (E)	1077702	A
Electrolyzer area	770	m^2
Power needed	3.2	MW
FA production rate	17.77	kmol/h

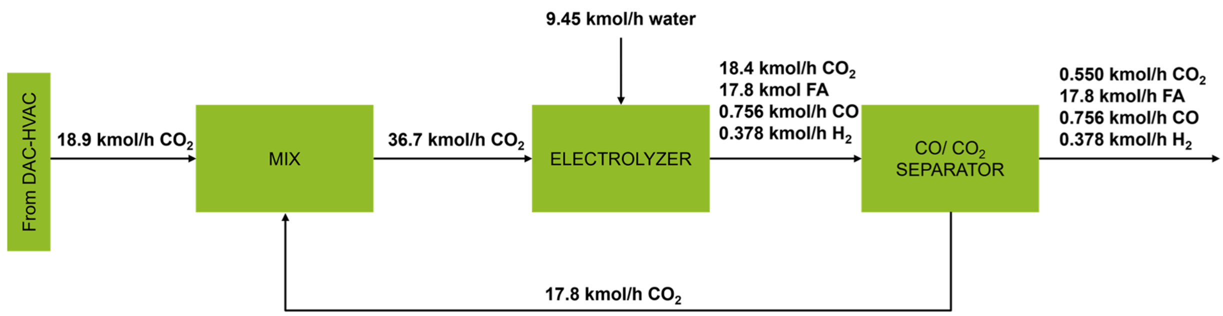

Fig. 2. Calculated results of the flowrates of the DAC-FA system.

$$A = \frac{2.2}{1 + \frac{230}{CO_2}}[1 - \exp(-0.001I)] \quad (15)$$

Where CO_2 is the CO_2 concentration inside the greenhouse taken as 100 ppm, and I denotes the photon flux density in the photosynthetic active radiation (PAR) spectrum and can be approximated as twice the net solar radiation (W/m^2).

The calculated average CO_2 assimilation rates are 3.5 kg/h in winter and 4.05 kg/h in summer, resulting in a total daily CO_2 assimilation of 31.7 kg/day in winter and 36.4 kg/day in summer, without accounting for air change.

3.3.2. Water requirements

The water requirements are estimated using the Penman Monteith modified Stanghellini model, which incorporates CO_2 concentration as a parameter in calculating evapotranspiration for greenhouse plants as presented in Eq. (16) [9,31]. Given an irrigation efficiency (η) of 90 % for drippers, the crop water requirements are determined using Eq. (17).

$$ET_0\lambda = \frac{\delta R_n + \left(\frac{2LAI\rho_A C_A}{r_e}\right)VPD}{\gamma(1 + \frac{\delta}{\gamma} + \frac{r_i}{r_e})} \quad (16)$$

$$W_{req} = \frac{ET_c}{\eta} \quad (17)$$

Where R_n is the net solar radiation, LAI is the leaf area index, ρ_A and C_A are the air density and specific heat capacity respectively, VPD is the vapor pressure deficit, γ is the psychometric constant, δ is the slope of the saturation curve and r_i and r_e are the internal and external crop resistances respectively. r_i is estimated using microclimate parameters in the greenhouse, including CO_2 concentrations, which affect the minimum canopy resistance through empirical functions. Detailed calculations and parameter values can be found in Ghiat et al. [9].

3.3.3. Energy requirements

The cooling requirements for the high-tech greenhouse are calculated by summing the heat loads from solar radiation, cover material and plant transpiration as presented in Eq. (18).

$$\dot{Q}_{total} = \dot{Q}_{solar} + \dot{Q}_{cover} + \dot{Q}_{trans} \quad (18)$$

Where $\dot{Q}_{solar}$, $\dot{Q}_{cover}$, and $\dot{Q}_{trans}$ represent the heat transfer through solar radiation, greenhouse cover and transpiration respectively, which are estimated following Eqs. (19)-(21).

$$\dot{Q}_{solar} = \tau_{cover} I_s A_{gh} \quad (19)$$

Where τ_{cover} is the transmissivity of the greenhouse cover material taken as 90 % for glass, I_s is the solar radiation and A_{gh} is the greenhouse floor area.

$$\dot{Q}_{cover} = U_{cover} A_{cover} \Delta T \quad (20)$$

Where U_{cover} is taken as 6 $W/m^2/K$, representing the heat transfer coefficient of the glass cover material, A_{cover} is surface area, and ΔT is the temperature difference between the inside and outside of the greenhouse.

$$\dot{Q}_{trans} = ET\ \lambda \quad (21)$$

Where λ is the latent heat of vaporization, taken as 2450 kJ/kg.

4. Economic analysis

4.1. DAC-HVAC

For the economics analysis of the DAC system, the capital expenditures (CAPEX) and operating expenditures (OPEX) were estimated. Equipment base costs are estimated using the exponential method that considers capacity-ratio exponents to draw equipment costs based on their capacity as shown in Eq. (22) [32]. The different parameters used in estimating the unit capital cost for each equipment of the DAC system are found in Supplementary Material Table S2.2 and the delivered, installed and escalated cost estimations are provided in Supplementary Material Note S1.2. Other equipment costs were determined using different methods; the vacuum pump was primarily estimated using an empirical method, while the fan's cost was derived from a capacity-based cost chart (Supplementary Material Table S2.2).

$$C_2 = C_1\left(\frac{q_2}{q_1}\right)^n \quad (22)$$

Where C_2 is the new cost of the equipment with capacity q_2 and C_1 is the reference equipment cost at capacity q_1, and n is the cost exponent.

The capital costs of the filters are assessed differently from those of the other DAC equipment. These costs entail the expenses associated with fabricating the filters from the sorbents, including material, energy, and water costs.

The filters are considered to have an expected lifetime of 5 years and require re-functionalization with TEPA when saturated. A stability reduction of 5.47 % is considered over 180 cycles, necessitating re-functionalization when efficiency falls below 50 % [33]. The initial cost of each filter is incorporated into the CAPEX, while replacement costs at years 5, 10, and 15 are calculated as present values, annualized, and included as a fixed OPEX. The costs associated with re-functionalization are categorized under variable OPEX.

The various materials used in the fabrication of the filters and their corresponding costs are detailed in Supplementary Material Table S2.3. The material costs are calculated from scaling the Sigma Aldrich laboratory prices to bulk prices using the method suggested by Hart and Sommerfeld [34]. Additionally, the energy costs are estimated based on the power requirements of the different equipment utilized in the filter manufacturing process. The filters are assumed to have a lifetime of 5 years and need to be re-functionalized with amines when saturated.

Moreover, since modifications and improvements to the current HVAC infrastructure are necessary to integrate the DAC system, an offsite battery limit (OSBL) cost needs to be added to the installed equipment cost. This can be estimated as 10 % of the installed cost (INST). In addition, engineering and contingency charges are also added to the INST and OSBL costs, each estimated as 10 % of the combined INST and OSBL costs. Eq. (23) presents the total fixed capital cost [35].

$$CAPEX = INST + OSBL + engineering\ costs + contingency\ charges \tag{23}$$

The fixed operating cost consists of maintenance, insurance, labour, and administrative costs. The maintenance and insurance costs are estimated as 3 % and 1 % of the escalated INST cost respectively [35]. The labour costs are estimated as 3 % of the escalated INST cost [36] and the administrative costs as 65 % of the labour cost [35]. The variable operating cost includes electricity for heating and cooling, pumping and compression, as well as filter re-functionalization costs. The electricity price is set at \$0.0351/kWh [37]. For the cost-benefit analysis of the DAC-HVAC, a price of CO_2 of \$261 per ton CO_2 is considered, corresponding to the maximum credit price in the year 2024 under California's Low Carbon Fuel (LCF) credit trading system. This system recognizes DAC as an eligible technology for receiving CO_2 credits [38]. The choice of the LCF system is driven by the lack of recognition of DAC in the compliance markets of existing Emissions Trading Schemes (ETS), which do not formally acknowledge carbon capture through DAC as an eligible mitigation activity for earning credits or offsets [39].

4.2. DAC-FA

The economic analysis of the FA production via ECR entailed estimating both CAPEX and OPEX for the process. There is a lack of large-scale CO_2 electrolyzers; therefore, several studies have used water electrolyzers to estimate the costs [40]. This is because most current CO_2 electrolyzers are at a bench scale and there is a lack of standard design for a CO_2 electrolyzer cell. In CO_2 electrolysis, non-precious metal catalysts are used. Additionally, most CO_2 electrolysis is carried out in alkaline conditions. Therefore, alkaline water electrolysis is a similar process that can be used to conduct the economic modelling [41].

The cost for the proton exchange membrane (PEM) water electrolyzer is taken and converted for use in the CO_2 electrolyzer model. A cost of \$250.25/kW [41,42] derived from the DOE H2A analysis for central water electrolysis [42]. The total capital cost of the PEM electrolyzer is converted to the capital cost per area for the stack using the parameters of the water electrolysis cell: 1.75 V and current density of 175 mA/m^2. The calculated cost in year 2010 is \$766/m^2 for the CO_2 electrolyzer and cost for year 2022 is calculated using the Chemical engineering plant cost index (CEPCI) [43]. For 2022, the stack cost was found to be \$1117.2/m^2, and the balance of plant (BOP) cost is assumed to be 35 % of the total electrolyzer cost [42]. The parameters for the cost calculation are reported in Supplementary Material Table S2.4. It should be noted that although water electrolyzers and CO_2 electrolyzers have similarities, the materials and design can result in varying costs per electrode area. This limitation will be addressed by carrying out a sensitivity analysis on the stack cost of the CO_2 electrolyzer.

The installation cost is taken as 20 % of the total capital cost of the electrolyzer, contingency cost at 15 % of the installed capital cost, site preparation cost is 2 % of the installed capital cost, engineering and design is taken as 8 % of the installed capital cost, and up-front permitting 15 % of the installed capital cost. Additionally, a replacement cost is considered every 7 years equal to 15 % of the installed capital cost [28]. To calculate the operating cost of the electrochemical cell, the electricity price is taken as \$0.0351/kW and water price is taken as \$1.458/m^3 [37]. Operating and maintenance cost is taken as 3.2 % of the installed capital cost.

The costs for the separation of the product are taken from Li et al. [29]. The CEPCI is used to estimate the cost in year 2022 [43]. As this cost is based on the flowrate, the reference flowrate is used with a scaling factor of 0.65 to obtain the cost for this system using Eq. (22) [28]. The electricity required for the reference separator is 10 kW, scaled accordingly based on the system flowrate. Operating and maintenance cost is taken as 3 % of the installed capital cost. For the overall DAC-FA system, other operating costs include an insurance cost taken as 1 % of installed capital cost, The labour costs are taken as 3 % of the installed capital costs and the administrative costs are taken as 65 % of the labour costs.

The CO_2 captured via DAC-HVAC is transported 58 km from the Doha Tower to Mesaieed Industrial City in Doha, Qatar. The CO_2 is stored in cylinders with a capacity of 10 kg CO_2 per cylinder and transported via truck with a capacity of 50 cylinders per truck. The price of diesel is taken to be 0.5\$/L and the diesel consumption of the truck is 0.5 L/km. The calculated cost for CO_2 transport comes to be \$0.0201 per kg of FA produced [9].

4.3. DAC-Greenhouse

The economic analysis of the greenhouse subsystem entailed estimating both CAPEX and OPEX, with detailed cost components summarized in Supplementary Material Tables S2.5 and S2.6 for the CAPEX and OPEX respectively. The variable OPEX was calculated in \$/kg of tomato produce, assuming a yield of 65 kg/m^2, achieved through CO_2 enrichment. The fixed OPEX encompasses costs related to maintenance, insurance, labor, and administration. Maintenance and insurance are estimated at 3 % and 1 % of the CAPEX, respectively, while administrative costs are set at 65 % of the labor cost. Electricity and water costs for the greenhouse application are factored in at \$0.0189/kWh and \$0.1404/m^3, respectively [37].

4.4. Metrics

The following selected metrics or KPIs will be used in the economic analysis for assessing the feasibility of the systems. The levelized cost (LC) is the average cost per unit of the final product over the project's lifetime, incorporating capital and operating expenditures. The formula presented in Eq. (24) is used to calculate the levelized cost (LCOD) for the DAC-HVAC system.

$$LCOD = \frac{CAPEX.CRF + OPEX_{fix}}{CO_{2,captured}} + OPEX_{var} \tag{24}$$

Where CAPEX is the total fixed capital cost, $OPEX_{fix}$ is the fixed operating cost, and $OPEX_{var}$ is the variable operating cost, and $CO_{2,captured}$ is the total amount of captured CO_2 in tons. CRF is the capital recovery factor, i is the interest rate taken as 7 % and n is the project lifetime taken as 20 years for a typical DAC system [13,44]. The CRF is calculated using Eq. (25).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{25}$$

Where i is the discount rate and n is the total lifetime.

Similarly, the levelized cost of FA (LCOF) for the DAC-FA system is calculated using Eq. (26).

$$LCOF = \frac{Capex.CRF + Opex_{fix}}{FA_{produced}} + Opex_{var} \tag{26}$$

Where $FA_{produced}$ is the amount of FA produced in kg.

The levelized cost of the greenhouse tomato produce (LCOG) for the DAC-Greenhouse system is calculated using the formula shown in Eq. (27).

$$LCOG = \frac{Capex.CRF + Opex_{fix}}{produce} + Opex_{var} \tag{27}$$

where the produce is taken in kg.

The net present value (NPV) considers the time value of money and measures the difference between present values of cash inflows and outflows. The NPV is calculated using Eq. (28) [45].

$$NPV = -CAPEX + \sum_{t=1}^{t=20} \frac{CF_t}{(1+i)^t} \tag{28}$$

Where t is the time period, CF is the cash flow which is the net profit at t, i is the discount rate.

The internal rate of return (IRR) is the discount rate at which the present value of future cash flows equals the initial investments (when NPV is zero) and is calculated using Eq. (29) [46].

$$0 = NPV = -CAPEX + \sum_{t=1}^{t=20} \frac{CF_t}{(1+IRR)^t} \tag{29}$$

The discounted payback period (DPP) is the time it takes for the discounted cash flows to recover the initial investment and is calculated using equation Eq. (30) [47].

$$DPP = (\frac{\ln\left(1 + \left(\frac{CAPEX}{CF_1}\right)\cdot\left(-\frac{i}{1+i}\right)\right)}{\ln\left(\frac{1}{1+i}\right)} \tag{30}$$

Where t is the time period and i is the discount rate.

The benefit-cost-ratio (BCR) is the ratio of total profit generated over the lifetime of the project and the total costs including capital and operating costs; it is calculated using Eq. (31) [48]

$$BCR = \frac{\sum_{t=1}^{t=20} \frac{Profit_t}{(1+i)^t}}{CAPEX + \sum_{t=1}^{t=20} \frac{OPEX_t}{(1+i)^t}} \tag{31}$$

Where the yearly profit is the revenue generated from selling the final product, t is the time period, and i is the discount rate.

The Break-even units (BEU) is the number of units that need to be sold to cover the costs, both fixed and variable. BEU is calculated using Eq. (32).

$$BEU = \left(\frac{FC}{SP - VC}\right) \tag{32}$$

Where FC is the fixed costs, SP is the selling price per kg and VC is the variable cost per kg of product.

The LCC can be determined by considering all costs that occurred during the lifetime of the project, including end-of-life costs as presented in Eq. (33) [49].

$$LCC = C_C + C_{O\&M} + C_F + C_R + C_D - C_{SV} \tag{33}$$

In the above formula, C_C is the total capital cost, $C_{O\&M}$ is the operating and maintenance costs, C_F is the total feedstock costs, C_R is the replacement costs, C_D is the total decommissioning costs, C_{SV} is the total salvage value costs. As the cash flows occur at different times during the plant lifetime, they are adjusted to their present values using Eq. (24).

$$LCC = C_C + \sum_{t=1}^{t=20} \frac{C_{O\&M}}{(1+i)^t} + \sum_{t=1}^{t=20} \frac{C_{F_{total}}}{(1+i)^t} + \frac{C_R}{(1+i)^t} + \frac{C_D}{(1+i)^t} - \frac{C_{SV}}{(1+i)^t} \tag{34}$$

Where t is the time period, and i is the discount rate. The salvage value and decommission costs occur at the end of the project lifetime and hence t is taken as 20. For ECR, the replacement occurs every seven years, therefore, t will be taken as 7 and 14. The salvage value is taken as 10 % of the total capital investment and the decommissioning costs are taken as 10 % of the depreciable capital investment [50,51].

Moreover, several sensitivity analyses are conducted to study the impact of key financial and technical parameters on the economic metrics. The parameters studied and their respective ranges for the sensitivity analyses of DAC-HVAC, DAC-FA, and DAC-Greenhouse are reported in Supplementary Material Tables S2.7, S2.8, and S2.9, respectively.

5. Results and discussion

The results of the DAC-HVAC, DAC-FA, and DAC-Greenhouse are presented, encompassing both base case scenarios and sensitivity analyses to illustrate their economic performance across varying parameters.

5.1. DAC-HVAC

5.1.1. Base case

Table 3 summarizes the base costs for the equipment associated with SBA-15 and the share of each piece of equipment relative to the total cost. This breakdown highlights the most significant cost drivers, emphasizing that the 3D printed filters have the most dominant share, while the vacuum pump contributes the least to the total expenses.

The results indicate that the CO_2 capture rates for SBA-15 and the baseline sorbent Lewatit are largely influenced by the filter size, specifically the width and height, which are constrained by the dimensions of the AHU. A filter thickness of 1.46 m and 0.46 m were chosen to achieve 100 % capture for SBA15 and Lewatit, respectively. The filter thickness also impacts the system's economics; while increased thickness can reduce the frequency of re-functionalization, it may also lead to a higher pressure drop, requiring additional blower power.

The different CO_2 adsorption capacities of the sorbents result in different energy requirements and equipment capacities, which in turn contribute to the variation in equipment capital costs. Additionally, the costs of the 3D-printed filters vary due to differences in material characteristics and associated costs. The total equipment cost for Lewatit is $205,996.61, compared to $230,619.72 for SBA-15. This increased total cost is particularly evident in specific component base costs, mainly the filters. The heat exchanger base cost for SBA-15 is lower ($5,328.19) compared to Lewatit (5,561.97), as SBA-15 has lower heating requirements per mole of CO_2 due to its high CO_2 loading. The filter costs differ, with Lewatit having a lower cost per filter ($35,246.64) than SBA-15 ($48,455.04), primarily due to the higher material cost of SBA-15.

Table 4 presents the breakdown of the total fixed CAPEX, fixed OPEX, and variable OPEX for the SBA-15 case, showing costs for a single DAC unit and scaling up to 14 units to accommodate the Doha Tower. The fixed OPEX is estimated at $28,314.69, whereas Lewatit had a lower fixed OPEX of $24,018.99. This cost difference is primarily due to the lower initial cost of Lewatit's 3D-printed filter and its attributed fixed costs, particularly the filter's replacement cost every five years, which is largely attributed to the lower purchasing price of Lewatit compared to SBA-15 material. The variable OPEX for SBA-15 is $ 0.093 per kg of CO_2, which is lower than the $ 0.128. per kg of CO_2 for Lewatit. This difference is primarily due to variations in electricity and filter re-functionalization costs per unit of CO_2 adsorbed. Lewatit and SBA-15 differ in technical performance based on their adsorption capacities for both CO_2 and H_2O, as well as key thermodynamic variables such as the heat of desorption for CO_2 and H_2O, as presented in Table 1. SBA-15 exhibits higher CO_2 and H_2O loadings compared to Lewatit. Additionally, the CO_2 heat of desorption for SBA-15 is higher than that of Lewatit, while the H_2O heat of desorption remains the same for both materials. This results in lower heating and cooling requirements for SBA-15 mainly due to its higher CO_2 loading. However, the total energy requirement for SBA-15 is higher than for Lewatit, primarily due to the additional blower power needed. This can be attributed to the lower density of SBA-15, which necessitates a greater filter thickness to achieve 100 % efficiency. The increased thickness leads to a higher pressure drop, requiring more blower power compared to Lewatit. From an economic perspective, the higher electricity demand for SBA-15 increases operational costs relative to Lewatit. However, Lewatit has a higher re-functionalization cost, leading to a greater overall variable OPEX than SBA-15. This has a significant impact on the final levelized cost of CO_2 capture.

The results summarized in Table 5 highlight the economic metrics for

Table 3
Equipment base costs for the DAC-HVAC system with SBA-15.

Equipment type	Unit capital cost - FOB	Unit capital cost - DEL	Unit capital cost – INST	Escalated cost to 2022	Share from total cost
Vacuum pump	$ 38,006.30	$ 38,006.30	$ 38,006.30	$ 38,006.30	16 %
Compressor	$ 7,007.27	$ 7,708.00	$ 10,791.20	$ 16,382.12	7 %
Filters[a]	$ 34,610.75	$ 34,610.75	$ 48, 455.04	$ 48,455.04	42 %
Heat exchangers[b]	$ 2,506.98	$ 2506.98	$ 3,509.77	$ 5,328	5 %
Heat exchanger[c]	$ 3,088.82	$ 3,088.82	$ 4,324.34	$ 6,564.78	3 %
Fan	$ 13,000.00	$ 14, 300.00	$ 20,020.00	$ 30,392.36	13 %
Heat pump	$ 22,648.34	$ 22,648.34	$ 31,707.68	$ 31,707.68	14 %
Total capital cost				**$ 230,619.72**	

[a] Cost per unit - two filters are considered.
[b] Heat exchangers of adsorption and desorption phases - cost per unit - two heat exchangers are considered.
[c] Heat exchanger for water condensation phase.

Table 4
Capital and operating cost breakdown for the DAC-HVAC system for SBA-15.

Cost type	Cost for 1 DAC system	Cost for 14 DAC systems	Unit
Fixed capital cost ($CAPEX_{fix}$)	**299,805.63**	**4,197,278.86**	**$**
INST cost	230,619.72	3228,676.04	$
OSBL cost	23,061.97	322,867.60	$
Engineering costs	23,061.97	322,867.60	$
Contingency charges	23,061.97	322,867.60	$
Fixed operating cost ($OPEX_{fix}$)	**28,314.69**	**396,405.59**	**$**
Maintenance cost	6918.59	96,860.28	$
Insurance cost	2306.20	32,286.76	$
Labor cost	6918.59	96,860.28	$
Administrative costs	4497.08	62,959.18	$
Filter replacement costs	7674.22	107,439.08	$
Variable operation cost ($OPEX_{var}$)	**0.093**		**$/kg CO_2**
Electricity cost	6.28×10^{-2}		$/kg CO_2
Filter re-functionalization cost	3.02×10^{-2}		$/kg CO_2

Table 5
Evaluated economic KPIs for DAC-HVAC system for different adsorbents.

KPI	SBA-15	LEWATIT VP OC 1065	Unit
LCOD	202	223	$/ton CO_2
NPV	326,281	208,382	$
DPP	6	7.3	years
BCR	1.293	1.17	-
IRR	17	14	%
BEU	5156	5645	ton CO_2

the DAC-HVAC system, indicating a significant advantage for the SBA-15 based system over Lewatit. The levelized cost of DAC-HVAC integration for SBA-15 is $202 per ton of CO_2, which is lower than Lewatit's estimated cost of $223 per ton. This is further reflected in the NPV, which stands $326,281 for SBA-15, compared to $208,382 for Lewatit. Additionally, the discounted payback period for SBA-15 is 6 years, significantly shorter than Lewatit (7.3 years), indicating a quicker return on investment. The benefit-cost ratio of 1.29 for SBA-15 also surpasses Lewatit's ratio of 1.17, suggesting a more favourable financial outcome. Moreover, the IRR for SBA-15 is 17 %, which is higher than Lewatit's 14 %. This difference indicates that investments in the SBA-15 based DAC yield a higher rate of return over the project's lifespan, which makes it a more attractive option with a faster profitability. The high IRR of 17 % suggests that SBA-15 not only covers the cost of capital but also generates additional returns, considering a CO_2 market price of $261 ton CO_2 from California's LCFs credit trading system. Lastly, the break-even point for SBA-15 is at 5,156tons of CO_2, which is lower than Lewatit' break-even point of 5,645 tons, emphasizing SBA-15's greater economic viability for DAC applications over Lewatit.

The levelized cost of the SBA-15 based DAC-HVAC system in this study is $202 per ton CO_2, which lies within the range estimated by the National Academy of Sciences (NAS), which projects a potential cost of $88–$228 per ton CO_2 for solid adsorption-based DAC systems within the next decade [11]. Additionally, for TVSA with a solid MOF sorbent, the cost is estimated to be $60–$190 per ton CO_2 [11]. The slight difference in costs can be explained by the different sorbent types. Compared to other systems, the levelized cost of DAC is reported as $197.16 and $200.29 per ton of CO_2 for a solid desiccant dehumidification and condensation dehumidification systems respectively [28]. Climeworks, another prominent player in the DAC field, has claimed a target cost of less than approximately $81 per ton CO_2 for large-scale plants [13].

The LCC analysis for the DAC system reveals a cost of $0.10 per kg of CO_2 captured for the SBA-15 based DAC system, compared to $0.11 per kg of CO_2 for Lewatit. This indicates a more economical opportunity with SBA-15, due to its higher performance in capturing CO_2. Fig. 3 illustrates the breakdown of costs incurred during the LCC analysis, highlighting a total capital cost of $299,806. The salvage value is approximated at 10 % of the capital cost, amounting to $7,748 while the decommissioning cost, estimated at 10 % of the total depreciable capital cost, comes to approximately $6,556. Notably, the most significant expenses in the LCC analysis arise from electricity as the highest expense followed by the fixed operational and initial capital costs for SBA-15. For Lewatit, the highest expenses originate from the filter re-functionalization cost followed. The high electricity cost for the SBA-15 case, although having a high CO_2 capacity, highlights the need to optimize resource consumption for this application. Therefore, integrating DAC with HVAC systems is essential, as it helps reduce overall energy consumption.

5.1.2. Sensitivity analysis

A sensitivity analysis is conducted on key financial variables including discount rate, CO_2 price, and electricity price, to further assess the economic viability of the DAC system with SBA-15 under different scenarios. The selected parameters for the sensitivity analyses and their ranges for the DAC-HVAC are found in Supplementary Material Table S2.7. The analysis reveals that as the discount rate increases, both the NPV and the BCR decline, indicating that higher discount rates reduce the attractiveness of the investment over time (Fig. 4). The NPV positively correlates with the CO_2 price, demonstrating that increased CO_2 prices enhance the economic benefits of capturing CO_2. Specifically, the analysis indicates that if the CO_2 price falls below approximately $200 per ton, the NPV becomes negative, indicating a potential financial risk under low CO_2 market prices (Fig. 5). Furthermore, as electricity prices rise, particularly when they are unsubsidized, the NPV decreases, and the levelized cost of capturing CO_2 increases. Notably, the levelized cost peaks at $390 per ton of CO_2 if electricity costs are unsubsidized. The NPV also becomes negative once electricity costs surpass the subsidized rates, starting at 0.07$/kWh, emphasizing the critical role of energy costs in DAC overall cost (Fig. 6).

These findings highlight how market fluctuations influence the scalability and adoption of DAC- HVAC systems. A lower discount rate can improve investment viability by reducing capital recovery costs,

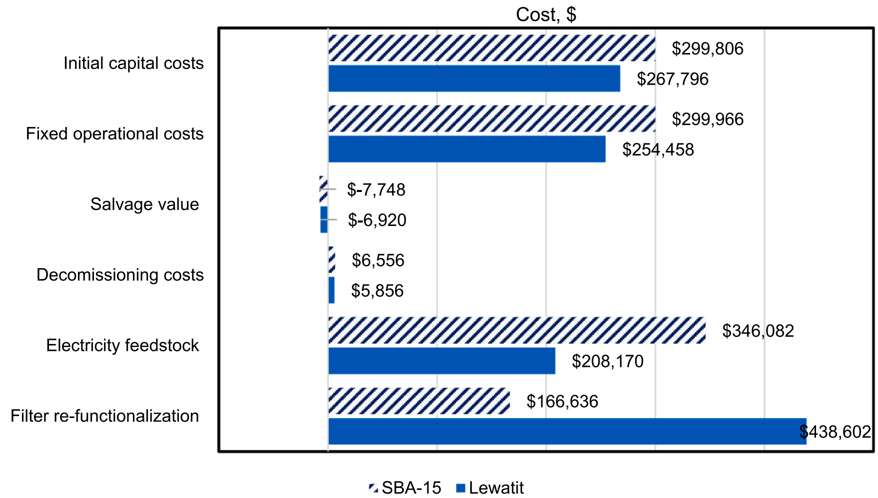

Fig. 3. Life cycle cost breakdown of the DAC-HVAC system using different adsorbents.

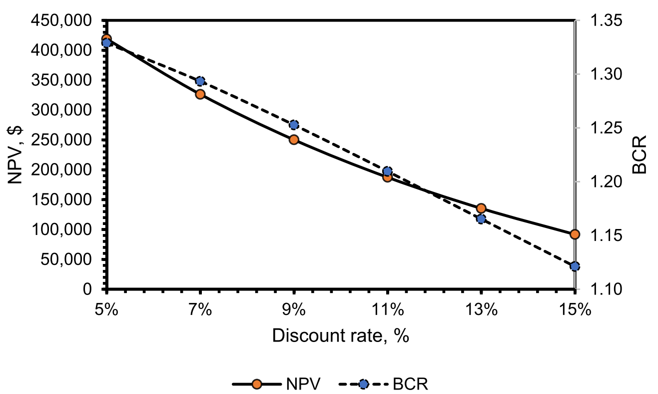

Fig. 4. Effect of discount rate on NPV and BCR for the DAC-HVAC system with SBA-15.

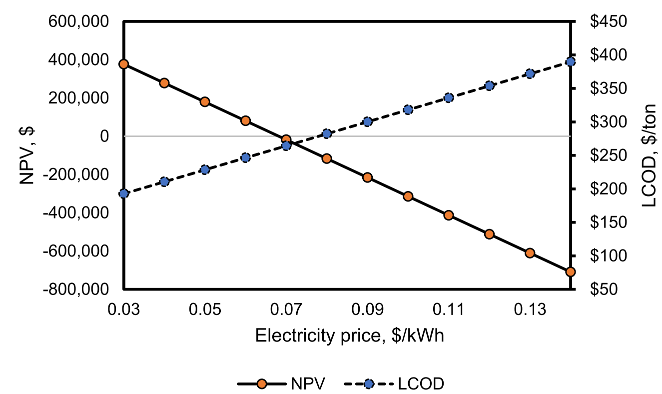

Fig. 6. Effect of electricity price on NPV and LCOD for the DAC-HVAC system with SBA-15.

making DAC more attractive for long-term implementation. The CO_2 price plays a crucial role in determining financial feasibility, with higher credit values or DAC-specific incentives enhancing profitability. Additionally, the dependency on electricity prices underscores the need for access to low-cost renewable or subsidized energy to ensure cost-competitiveness.

5.2. DAC-FA

5.2.1. Base case

The CO_2 captured from 14 AHUs, modelled using both SBA-15 and Lewatit in the Doha Tower, will be utilized for FA production through electrochemical reduction. Table 6 presents the summary of the fixed CAPEX, fixed OPEX and variable OPEX for this process. The total fixed CAPEX and OPEX is $3.4 million and $0.21 million, respectively. The variable OPEX for Lewatit is higher at $0.4389 per kg of FA compared to $0.4140 for SBA-15. This is mainly due to do the overall cost of CO_2 input with the use of Lewatit being 11 % higher than SBA-15 at $0.2596 per kg of FA. The separator makes up the lowest percentage of the total CAPEX at 21 % while majority of the costs are from the electrolyzer. The stack and BOP cost make up 39 % of the CAPEX and the other electrolyzer associated costs make up 40 %. For the fixed OPEX, the electrolyzer and separator maintenance costs account for 32 % of the total, while labor costs contribute 33 % of the total.

A cash flow analysis was performed with a discount rate of 7 % based on the Qatar Bank lending rate [52]. The selling price for the product FA was set to be $0.596 per kg of FA based on the middle east (MEA) region market price in the second quarter of 2024 [53]. When using 100 % of the CO_2 captured from DAC-HVAC, the production rate of FA via ECR is 6.26 kton FA/year. Table 7 lists the various KPIs that were evaluated to understand the economic feasibility of the integrated DAC-FA process. When CO_2 is captured using SBA-15 in comparison to Lewatit, the LCOF is 4 % lower at $0.499 per kg of FA; therefore, more economically favourable. It was noted that Lewatit gives a higher LCOD in the DAC-HVAC system which further contributes to the higher LCOF. The FA production with CO_2 from SBA-15 has a significantly higher NPV, at $6.41 million, compared to $4.76 million for Lewatit. This means the SBA-15 adsorbent yields a much more profitable project. Electrochemical reduction with CO_2 from the SBA-15 based DAC has a shorter payback period of 4.1 years, showing that the initial investment is

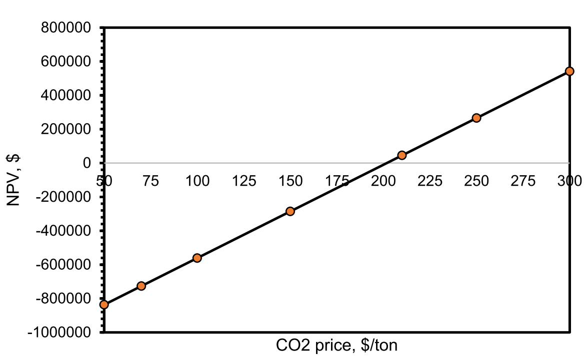

Fig. 5. Effect of CO_2 selling price on NPV for the DAC-HVAC system with SBA-15.

Table 6
Capital and operating cost breakdown for the DAC-FA system using different adsorbents.

Cost type	SBA-15	LEWATIT VP OC 1065	Unit
Fixed capital cost ($CAPEX_{fix}$)		**3412,044**	**$**
Stack cost		859,980	**$**
BOP cost		463,066	$
Installation cost		264,609	$
Contingency cost		238,148	$
Site preparation cost		31,753	$
Engineering and design		127,012	$
Up front permitting		238,148	$
Replacement cost		476,297	$
Separator capital cost		713,030	$
Fixed operating cost ($OPEX_{fix}$)		**213,042**	**$**
Insurance cost		30,137	$
Labour cost		69,021	$
Administrative cost		44,863	$
Electrolyzer maintenance cost		47,630	$
Separator maintenance cost		21,391	$
Variable operation cost ($OPEX_{var}$)	**0.4104**	**0.4389**	**$/kg/FA**
Electrolyzer electricity		0.1587	$/kg FA
Water		0.0003	$/kg FA
Separator electricity		0.0001	$/kg FA
CO_2 cost (from DAC)	0.2347	0.2596	$/kg FA
CO_2 transportation		0.0201	$/kg FA

recovered faster compared to the 5 years for the case of Lewatit. While the FA production with CO_2 captured with both adsorbents have a BCR above 1, SBA-15 yields higher benefits compared to Lewatit for this application. Moreover, the IRR for the DAC-FA system with SBA-15 is 27 %, which is higher than Lewatit'11 %. Lastly, the break-even point for the DAC-FA system with SBA-15 is at 42 kton FA, which is lower than the break-even point of 49 kton FA for Lewatit. These results indicate that the integrated DAC-HVAC and the utilization of capture CO_2 for FA production is an economically feasible project with SBA-15 as a more favourable option. Rumayor et al. [45] compared the KPIs for producing FA via electrochemical reduction with the conventional process requiring heavy fuel oil and natural gas. The NPV for the electrochemical reduction of CO_2 to FA was $32.81 million with a BCR of 1.68 without taking into account the electrode lifetimes. With an electrode lifetime of 4.45 years, their base case plant was economically unfeasible with a negative NPV.

The LCC of the DAC-FA system reveals a life cycle cost of $0.474 per kg of FA produced for the SBA-15 sorbent case, compared to $0.499 per kg of FA produced using Lewatit. Showing that SBA-15 is more favourable option. Fig. 7 shows a breakdown of the LCC analysis for both adsorbents. The most significant costs are associated with CO_2 feedstock (from DAC) amounting to $15.57 million and $17.23 million, respectively for SBA-15 and Lewatit. The salvage value based on 10 % of the capital costs was found to be $0.09 million, implying that there is some residual value recovered at the end of the project's life, which can help slightly offset the overall costs. Capital costs of $2.94 million indicate the initial investment required to set up the system, which, while substantial, is not the largest contributor to the total life cycle costs. As electricity is one of the most significant expenses, optimizing the electrolyzer's performance is essential.

Table 7
Evaluated economic KPIs for DAC-FA system for different adsorbents.

KPI	**SBA-15**	**LEWATIT VP OC 1065**	**Unit**
LCOF	0.499	0.524	$/kg FA
NPV	6,409,290	4,758,696	$
DPP	4.1	5.0	years
BCR	1.19	1.14	-
IRR	27	22	%
BEU	42	49	kton FA

5.2.2. *Sensitivity analysis*

A sensitivity analysis is conducted by varying several economic and technical parameters on the DAC-FA system. The base case using SBA-15 adsorbent is used for this analysis as it is more profitable. The sensitivity analysis' parameters and their ranges for the DAC-FA are found in Supplementary Material Table S2.8.

Fig. 8 shows the sensitivity of the NPV and BCR to changes in the discount rate. A range of 5–15 % has been selected for the sensitivity analysis to account for any future changes in the discount rate due to economic fluctuations. As the discount rate rises, the NPV declines significantly but remains positive, indicating that the project still generates value across the entire discount rate range. The NPV is the highest at 5 %, around $8.14 million and decreases to $2.39 million at 15 %. The BCR, does not go below 1 when the discount rate is increased till 15 %. At 15 % the BCR reduced to 1.11 from 1.21 at 5 %. The plant becomes economically more unfavourable but remains viable across the discount range considered. The DAC-FA system's profitability is sensitive to the discount rate, highlighting the need for favourable economic conditions.

The base case FA selling price was set to be $0.596 per kg of FA based on the 2024 Q2 prices of the middle east region [53]. The market for FA in the middle east region saw a decline in prices in the second quarter of 2024 due to weak demands and oversupply conditions [53]. According to Fig. 9, the selling price of FA needs to be above ~$0.45 per kg of FA to have a positive NPV. The BCR increases with increasing market selling price of FA as the profits from the process increase. However, it can be noted that the BCR goes below 1 when the FA price falls below $0.5 per kg; showing that the costs outweigh the benefits at these lower prices. Currently the market for FA in the middle east is down. Nevertheless, the global FA market is steadily growing at a growth rate (CAGR) of 2.97 % and is expected to reach a demand of 1,202 ktons by 2032 [54]. These results suggest that a competitive FA selling price is crucial for the economic viability of the DAC-FA system.

As electricity is a major input into the process for powering the electrochemical reaction, a sensitivity analysis is conducted on the price of electricity. The effect on the performance indicators NPV and LCOF is evaluated. Understanding how these economic indicators respond to changes in electricity price is essential for assessing the viability of the process under different market conditions. Moreover, these results can guide the selection of alternative electricity sources, especially when considering renewable options to achieve a lower environmental impact. The base case uses an electricity price of $0.0351/kWh for Qatar, the range for the sensitivity analysis selected is $0.03–0.14/kWh. From Fig. 10, it can be noted that as the electricity price increases from $0.03 to $0.14/kWh, the LCOF increases from $0.466 to $1.192 per kg of FA. Higher electricity prices lead to higher costs per unit of FA produced, thus increasing the LCOF significantly. A high LCOF effects the competitiveness of the ECR process for FA production compared to alternative and traditional routes. The NPV becomes negative at an electricity price above $0.06/kWh making the process economically unfeasible. These results suggest that low-cost renewable electricity is crucial for the economic success of the ECR process.

The base case uninstalled stack price has been taken as $1,117/m^2. As there is currently no specific data available for the cost of CO_2 electrolyzers, the price is estimated using reported costs for PEM water electrolyzers. The final cost of the electrochemical cell may vary significantly based on its design and materials. Therefore, it is crucial to conduct a sensitivity analysis on the stack cost to understand its impact on various economic indicators for the DAC-FA process. In the literature, the costs for a CO_2 electrolyzer, estimated based on a PEM water electrolyzer, range from $5,000 to $15,000 per m^2 [40]. Fig. 11 illustrates the effect of the stack price on the NPV and LCOF. It reveals that the plant becomes economically unfeasible if the total uninstalled stack price exceeds $3,500/m^2 as the NPV becomes negative. The LCOF increases to $0.805 per kg of FA at a stack price of $6,500/m^2. Therefore, the plant is very sensitive to uninstalled stack costs and it is necessary to

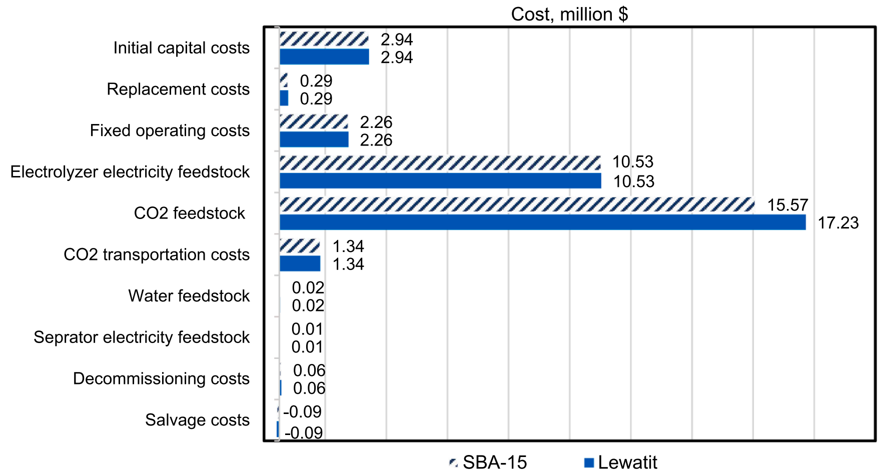

Fig. 7. Life cycle cost breakdown of the DAC-FA system using different adsorbents.

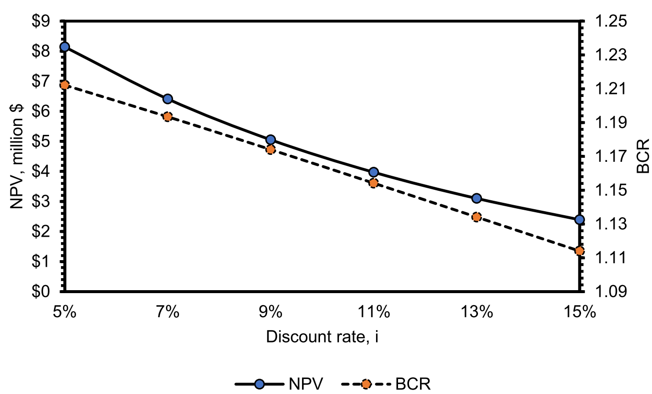

Fig. 8. Effect of discount rate on NPV and BCR for the DAC-FA system.

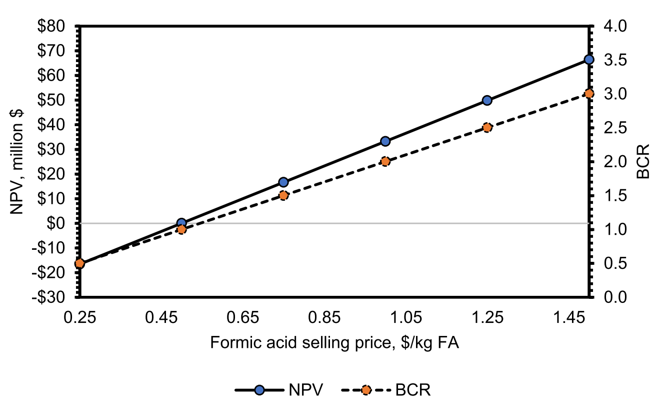

Fig. 9. Effect of selling price on NPV and BCR for DAC-FA system.

lower this cost to have greater profits. Optimizing the stack price of the electrolyzer is challenging due to the high cost of the advanced materials such as electrocatalysts and membranes. The performance of these materials such as the efficiency and selectivity towards the product over time are essential for lowering the costs for replacement. The stack costs can be lowered by optimizing the design and materials used in electrochemical cells, as well as by conducting research to identify more cost-effective alternatives and improve the performance.

As the ECR process for FA production is currently at a low TRL level, the base case analysis relies on experimental results from laboratory-scale studies. It has been established in the literature that improvements in the electrode and the reactor design can significantly enhance

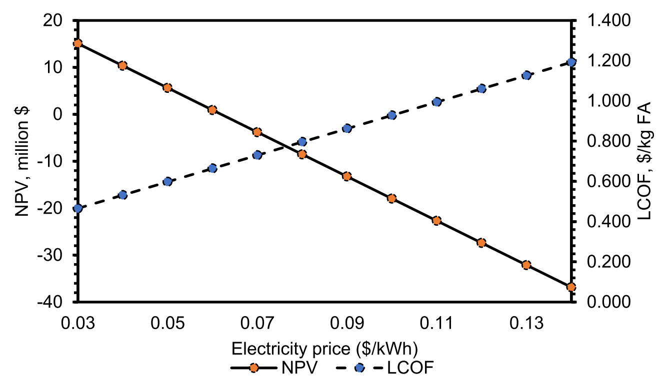

Fig. 10. Effect of electricity price on NPV and LCOF for the DAC-FA system.

key performance metrics, such as FE and current density [55]. These improvements are critical because they directly affect the amount of energy consumed, the rate of FA production, and the overall selectivity of the product. The current density needs to be optimized according to the selectivity of the desired product, while also maintaining low energy consumption and reducing overall efficiency. To understand the economic implications of these improvements, a sensitivity analysis is conducted on these parameters. A 3D surface plot of the effect of FE and current density on the NPV can be found in Supplementary Material Figure S3.1. At higher Faradaic efficiencies, above 90 %, and higher current densities closer to 0.25 A/cm^2, the NPV tends to be higher, reaching positive values between $6 and $12 million. As FE decreases

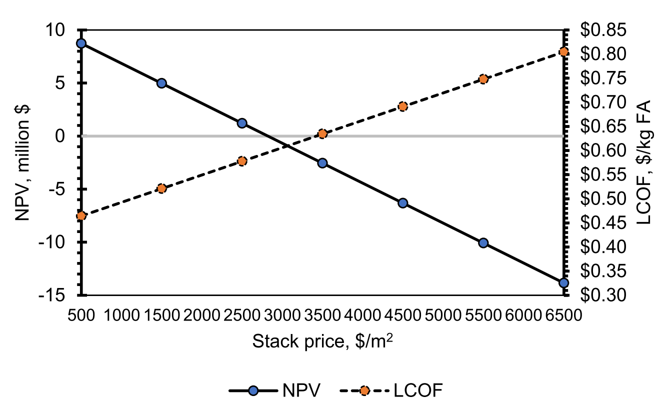

Fig. 11. Effect of electrolyzer stack cost on NPV and LCOF for the DAC-FA system.

Table 8
Capital and operating cost breakdown for the DAC-Greenhouse system using different adsorbents.

Cost type	SBA-15	LEWATIT VP OC 1065	Unit
Fixed capital cost ($CAPEX_{fix}$)	**130,223**		**$**
Greenhouse structure	43,200		$
Cooling system	17,969		$
Water system	47,102		$
CO_2 system	248		$
Installation cost	10,852		$
Contingency charges	10,852		$
Fixed operating cost ($OPEX_{fix}$)	**14,901**		**$**
Maintenance cost	3,256		$
Insurance cost	1,085		$
Labor cost	6,400		$
Administrative costs	4,160		$
Variable operation cost ($OPEX_{var}$)	**0.60**	**0.61**	**$/kg produce**
Electricity cost	3.94×10^{-1}		$/kg produce
Water cost	1.86×10^{-2}		$/kg produce
Substrate cost	2.86×10^{-2}		$/kg produce
Fertilizers cost	5.38×10^{-2}		$/kg produce
Pesticides cost	2.18×10^{-2}		$/kg produce
Transportation cost	3.37×10^{-2}		$/kg produce
Storage cost	2.40×10^{-3}		$/kg produce
CO_2 usage fraction of DAC levelized cost	0.05	0.06	$/kg produce

below 80 % and current density decreases (around 0.20–0.05 A/cm^2), the NPV becomes negative, making the process unfeasible. To maximize the NPV, the FE and current density need to be improved.

A 3D surface plot illustrating the effect of current density and FE on LCOF is provided in Supplementary Material Figure S3.2. At high FE of 100 % and high current density 0.25 A/cm^2, the LCOF is the lowest at $0.432 per kg of FA. As the FE decreases to 60 %, the LCOF at the same current density increases to $0.911 per kg of FA. Additionally, as the current density decrease to 0.05 A/cm^2 (at 60 % FE), the LCOF increases to $1.259 per kg of FA. Reducing costs is crucial to maintaining competitiveness with other fuels and alternative FA production methods. It can be noted that the NPV and LCOF do not change as sharply with current density as they do with FE (for the selected ranges based on literature reports). The results from this sensitivity analysis can guide the research and development of electrolyzer designs that achieve higher current densities and faradaic efficiencies. This is essential for improving the overall economics and scalability of CO_2 electrochemical reduction technologies.

5.3. DAC-Greenhouse

5.3.1. Base case

The economic results of the CO_2 utilization in greenhouses, including fixed CAPEX, fixed OPEX and variable OPEX are presented in Table 8. The fixed total CAPEX for the greenhouse is estimated at $130,223, with fixed operational expenditure standing at $14,901. Additionally, the variable OPEX is $0.59 per kg of produce for the greenhouse using CO_2 from the DAC with SBA-15. The DAC cost is factored into the variable OPEX by multiplying the levelized cost of the DAC by the amount of CO_2 required per kilogram of produce. In comparison, the greenhouse utilizing CO_2 from the DAC system with Lewatit has a slightly higher variable OPEX of $0.61 per kg, owing to the higher levelized cost of the corresponding DAC system.

Table 9 presents the assessed economic metrics for the DAC-Greenhouse pathway. The levelized cost for CO_2 from the DAC system with SBA-15 is $1.128 per kg of produce (tomatoes), demonstrating a competitive market cost that can be attributed to the high achievable yields from CO_2 enrichment. The NPV of $226,879 indicates a positive return on investment, while the DPP of 3.7 years suggests a reasonable timeframe for recovering initial investments. Additionally, a BCR of 1.38 and an IRR of 29 % confirm the financial viability of this investment, with a BEU of 454 tons of tomato produce.

Table 9
Evaluated economic KPIs for DAC-Greenhouse system for different adsorbents.

KPI	SBA-15	LEWATIT VP OC 1065	Unit
LCOG	1.128	1.133	$/kg produce
NPV	226,879	223,902	$
DPP	3.7	3.8	years
BCR	1.38	1.37	-
IRR	29	28	%
BEU	454	457	ton produce

The CO_2 captured from the DAC system using Lewatit as a sorbent serves as a baseline, with a slightly higher levelized cost of $1.133 per kg of produce for the greenhouse application. Notably, Mahmood et al. [56] found a higher levelized cost for greenhouses at $2.70 per kg, assuming a purchase price of $6 per kg for CO_2. This underscores the importance of carbon capture technologies that can lower CO_2 market prices, thereby reducing the cost of CO_2 for utilization routes such as CO_2 enrichment in greenhouses. The DAC-HVAC integration presented in this study demonstrates how such technologies can help decrease CO_2 costs and, in turn, lower the cost of value-added products, making CO_2 enrichment in agricultural greenhouses more feasible.

The LCC for the DAC-Greenhouse system reveals a cost of $0.64 per kg of produce for CO_2 captured using SBA-15 and $0.65 per kg for CO_2 from DAC with Lewatit. The most significant contributor to these costs is energy consumption of the high-tech greenhouse which is equipped with an HVAC system. This highlights the energy-intensive nature of controlled-environments which are essential in arid regions like Qatar and emphasizes the need to use more sustainable practices such as CO_2 enrichment to optimize resources and enhance crop yields. Fixed operating costs and initial capital expenditures also contribute notably to the overall LCC. Fertilizer, water, transportation, and other operational costs are substantial but less significant compared to energy, fixed operational costs and capital expenses. The CO_2 feedstock cost is the second highest variable operational cost for the case of CO_2 sourced from SBA-15, amounting to $30,745, and the highest variable operational cost for the case of CO_2 captured with Lewatit, amounting to $34,003. The salvage value, calculated as 10 % of the capital cost, amounts to $13,022, representing a potential recovery of investment at the end of the project's lifecycle. This could potentially help offset the decommissioning costs which total to $11,937 (Fig. 12).

5.3.2. Sensitivity analysis

A sensitivity analysis is conducted for the greenhouse CO_2 utilization, focusing on key financial variables, including the discount rate, selling price of produce, and electricity price. The ranges of the sensitivity parameters for the DAC-Greenhouse system are found in Supplementary Material Table S2.9. The analysis is based on CO_2 captured from the SBA-15-based DAC system. The results indicate that both the NPV and BCR decline as interest rates rise, resulting in an NPV $89,646 and BCR of 1.22 at 15 % discount rate (Fig. 13). Conversely, an increase in the selling price of produce positively impacts the NPV and BCR. NPV is negative if the selling price falls below $1.1/kg. The NPV reaches $226,879 and the BCR improves to 1.38 when the selling price is set at $1.50 per kg, which is similar to import prices in Qatar (Fig. 14). Additionally, an increase in electricity prices adversely impacts the greenhouse system, resulting in a decline in NPV values, which become negative when electricity prices exceed $0.03/kWh. It also leads to an increase in the levelized cost of greenhouse applications (LCOG), which rises to $3.47 per kg when electricity prices are unsubsidized ($0.1289/kWh) (Fig. 15).

5.4. Overall discussion

Achieving a levelized cost of $202 per ton of CO_2 captured suggests

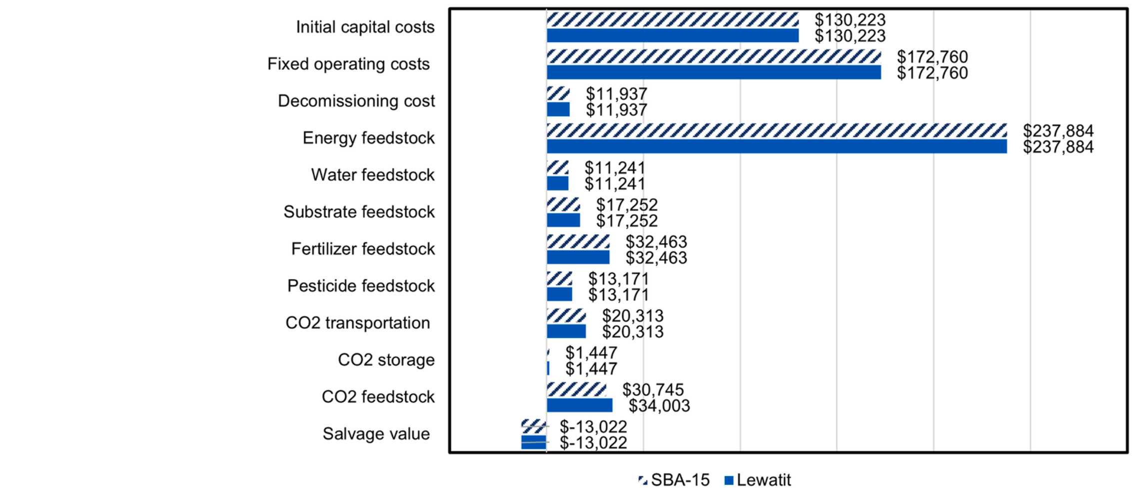

Fig. 12. Life cycle cost breakdown of the DAC-Greenhouse system using different adsorbents.

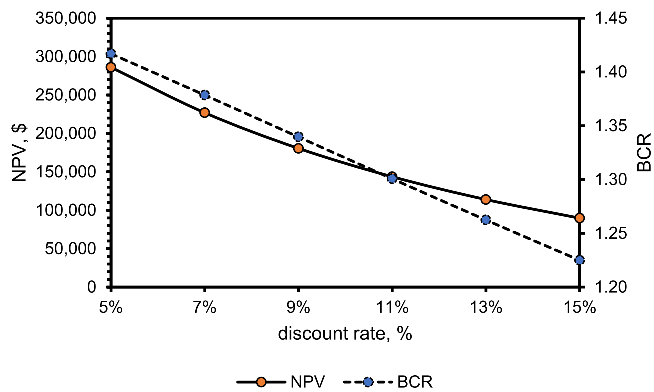

Fig. 13. Effect of discount rate on NPV and BCR for the DAC-Greenhouse system.

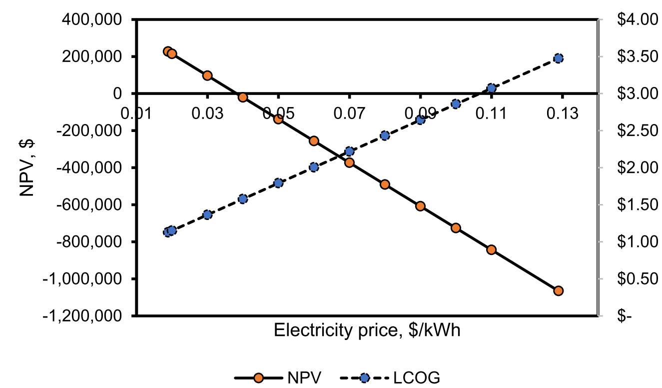

Fig. 15. Effect of electricity price on NPV and LCOG for the DAC-Greenhouse system.

that further optimization is needed for DAC to be competitive under typical carbon credit and tax schemes, which range from $50–150/ton CO_2 and are primarily designed for lower-cost, mature CO_2 emission reduction technologies such as point-source carbon capture. However, under higher credit prices, such as the $261/ton CO_2 maximum observed in 2024 within California's Low Carbon Fuel (LCF) credit trading system, DAC could be economically viable. Additionally, if dedicated trading systems or incentives specifically for DAC technologies emerge, the financial feasibility of this technology could significantly improve, supporting its wider adoption.

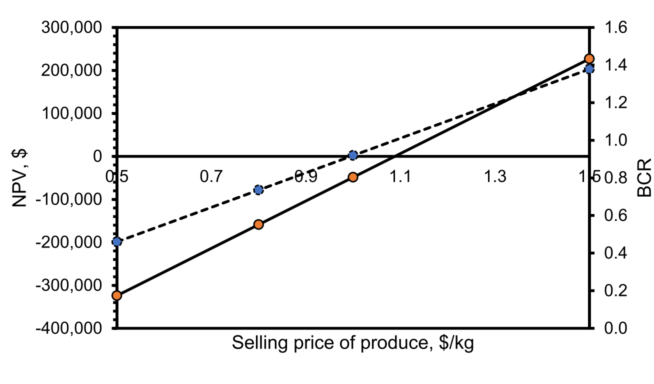

Fig. 14. Effect of selling price of produce on NPV and BCR for the DAC-Greenhouse system.

The economics of the DAC-HVAC process significantly improves when it is connected to the FA production process. The NPV increases from $326,281 to $6.41 million as a higher value product is synthesized from the captured CO_2. This also due to the larger scale of FA production compared to the greenhouse application, where the system was sized to utilize all the captured CO_2 for FA production, while for the greenhouse, only the CO_2 requirements of a single greenhouse were considered. The DAC-FA process has a shorter payback period and higher internal rate of return for CO_2 captured with SBA-15 as compared to the Lewatit case, showing faster recovery of initial investment. When comparing DAC-Greenhouse utilization with DAC-FA, the NPV for the DAC-Greenhouse is lower ($226,879) because the revenue generated from agricultural produce is less than what can be achieved from a high-value fuel like FA. Moreover, the scale of profits from greenhouse use is limited by the lower demands for CO_2 in agriculture compared to the chemical industry. Additionally, the utilization of CO_2 captured from DAC in greenhouses can be scaled up to supply more greenhouses and avail more economic profits from this application. However, this utilization route is limited to meeting the specific crop requirements for plant growth. In contrast, FA production can utilize 100 % of the captured CO_2. FA production has higher potential for large-scale application. As DAC integration into the built environment is more widely adopted, the production of FA can be scaled-up to meet the growing energy demands. It should be noted that the two utilization routes considered serve distinct goals. While the FA production addresses energy security by producing a sustainable energy carrier from CO_2. On the other hand,

CO_2 use in agricultural greenhouses addresses food security goals by enhancing crop yields and optimizing resource use. Therefore, both CO_2 utilization routes can be deployed simultaneously, as each plays a crucial role in addressing distinct goals. This creates opportunities for future research on the utilization of CO_2 from DAC-HVAC systems and the various possible CO_2 allocation scenarios between the two routes.

6. Conclusions

This study investigates the economic feasibility of integrating DAC into HVAC to capture CO_2 from the indoor environment in Qatar. Two adsorbents are evaluated: Lewatit VP OC 1065, a commercial adsorbent, and SBA-15, both functionalized with TEPA, and used in the form of 3D-printed filters. A detailed model is developed to determine the energy and material requirements for the process and size the equipment based on an HVAC's AHU. To enhance the economics of the CO_2 capture process, two utilization routes are explored. CO_2 can be converted into FA via electrochemical reduction to produce a sustainable fuel. For this pathway, experimental data from the literature is used to determine system performance metrics to model the process. Alternatively, CO_2 is also considered to be used in agricultural greenhouses to enhance crop growth and reduce water consumption. A high-tech agricultural greenhouse with CO_2 enrichment is assessed in terms of its CO_2, energy, and water requirements. A comprehensive economic analysis is conducted for these three subsystems – DAC-HVAC, DAC-FA, and DAC-Greenhouse. Various KPIs and life cycle costs are calculated to assess the feasibility of each system. Moreover, a sensitivity analysis is conducted on the discount rate, selling price of the final product and the electricity price.

The following are the key findings for the DAC-HVAC system:

- Using SBA-15 as the adsorbent is more economically favourable and gives an NPV of $326,281 and an LCOD of $202 per ton of CO_2. On the other hand, Lewatit gives an NPV of $208,382 and LCOD of $223 per ton of CO_2.
- For the SBA-15 case, the DPP, BCR, IRR and BEU for this system were found to be 6years, 1.29, 17 %, and 5156 ton CO_2, respectively.
- For the Lewatit case, the DPP, BCR, IRR and BEU for this system were found to be 7.3 years, 1.17, 14 %, and 5645 ton CO_2, respectively.
- The economic advantage of SBA-15 is primarily attributed to its higher CO_2 capture capacity, highlighting that the adsorbent's properties are critical to the success of the DAC-HVAC integrated system.

The following are the key findings for the DAC-FA system:

- At an FE and current density of 94 % and 0.14 A/m^2, and 100 % utilization of captured CO_2 the system produced 17.77 kmol/h of FA.
- Using SBA-15 as the adsorbent is more economically favourable and gives an NPV of $6.41 million and an LCOF of $0.499 per kg of FA.
- The DPP, BCR, IRR and BEU for this system were found to be 4.1 years, 1.19, 27 %, and 42 kton FA, respectively.
- The economic success of the ECR process is highly dependent on the electrolyzer design, which can be improved by optimizing key parameters such as FE, current density and stack cost.

The following are the key findings for the DAC-Greenhouse system:

- Using SBA-15 as the adsorbent is more economically favourable and gives an NPV of $226,879 and levelized cost of $1.128 per kg of produce.
- The DPP, BCR, IRR and BEU for this system were found to be 3.7 years, 1.38, 29 %, and 454 ton produce, respectively.
- This process demonstrated a competitive market cost that can be attributed to the high achievable yields and reduced crop water requirements from CO_2 enrichment.

CRediT authorship contribution statement

Amhamed Abdulkarem I: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Al-Ansari Tareq:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Bicer Yusuf:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Ghiat Ikhlas:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abdullatif Yasser M:** Formal analysis, Data curation. **Mir Namra:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Banu Aliya:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jece.2025.116201.

Data Availability

The authors are unable or have chosen not to specify which data has been used.

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