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

***Supplementary Material***

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**S1: Supplementary notes**

## ***Note S1.1:* 3D printed filter description**

To create a filter from this sorbent, silica is combined with a binder solution containing 25% methyl cellulose, 10% bentonite, and 25% polyvinyl alcohol (PVA) based on the weight of silica. Water is added until the mixture attains a clay-like consistency, allowing it to be shaped and formed into the desired filter geometry through 3D printing. A post-treatment process is necessary to remove the methyl cellulose and PVA, which is achieved by drying the printed filter in a vacuum dryer, followed by calcination in a nitrogen environment (Middelkoop et al., 2019). Finally, the functionalization of both sorbents with TEPA is performed using the wet impregnation method, which maximizes the sorbent’s CO2 capture capabilities (Surkatti et al., 2025).

## ***Note S1.2:* Delivered, installed and escalated cost estimation for DAC**

Most of the equipment base costs considered are free on board (FOB) costs, apart from the heat exchangers which are delivered (DEL) costs. To account for the delivered (DEL) cost, a factor of 1.1 is multiplied to the FOB cost. Additionally, a factor of 1.4 is multiplied to the DEL cost to estimate the installed (INST) cost of the equipment. Moreover, a cost index of 1518.1, following the Marshall and Swift (M&S) indices, is used to escalate the estimated cost of equipment to the year 2022 as shown in eq. (1) (Jiang et al., 2024; Towler and Sinnott, 2022).

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

# **S2: Supplementary tables**

## ***Table S2.1:* Power requirements for DAC filter production.**

|  |  |  |  |
| --- | --- | --- | --- |
| Equipment | Power (W) | Capacity | Reference |
| Mixer | 4 | 1 L | (Farfly Machinery, n.d.) |
| Vacuum dryer | 57.2 | 1 kg | (Griffin Machinery, n.d.) |
| Calcinator | 18000 | 10 L | (ZKCOMP, n.d.) |
| 3D printer | 22 | 1 cm3 | (PioCreat, n.d.) |

## ***Table S2.2:* Equipment base cost parameters for DAC-HVAC.**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Equipment type | Capacity type | Capacity units | Reference capacity (q1) | Reference cost6  (C1) | Type of cost7 | Capacity range | n |
| Vacuum pump1 | Input flowrate | kW |  | $ 30,000 | ESC |  |  |
| Compressor2 | Fluid power | kW | 224 | $ 133,000 | FOB | 0.75– 1490 | 0.84 |
| Heat exchangers3 | Area | m2 | 93 | $ 21,700 | DEL | 1.9 – 1869 | 0.59 |
| Heat pump4 | Power | kW | 10.55 | $ 4,270 | DEL |  | 0.7 |
| Fan5 | Flowrate | m3/h | 10,800 | $ 13, 000 | FOB |  |  |
| 1 based on an empirical equation of cost with respect to input flowrate (Subraveti et al., 2021).  2 reciprocating compressor.  3 shell tubes - other types of heat exchangers can be assumed to meet the jacketed type needed for this application such as vertical jacketed tank but could incur additional costs related to some integrated equipment components such as agitators – two heat exchangers are considered.  4 cost taken from (US EIA, 2023).  5 based on a cost chart with respect to capacity (Loh et al., 2002).  6 based on a Marshall and Swift index (M&S) of 1000.  7 free on board (FOB), delivered (DEL), installed (INST) cost, and escalated (ESC) cost. | | | | | | | |

## ***Table S2.3:* Material costs for DAC filter.**

|  |  |  |
| --- | --- | --- |
| Material | Cost | Unit |
| Lewatit VP OC 1065 | 7.64 | $/kg |
| Mesoporous silica (SBA-15) | 62 | $/kg |
| Methyl cellulose | 8.95 | $/kg |
| Bentonite | 8.68 | $/kg |
| Polyvinyl alcohol | 5.22 | $/kg |
| [Tetraethylenepentamine](https://www.sciencedirect.com/topics/engineering/tetraethylenepentamine) (TEPA) | 6.12 | $/kg |

## ***Table S2.4:* Calculated stack and BOP cost for the ECR process.**

|  |  |  |
| --- | --- | --- |
| Parameter | Cost | Unit |
| H2A Base Cost (PEM Water electrolysis) | 250.25 | $/kW |
| Electrolyzer Voltage (PEM Water electrolysis) | 1.75 | V |
| Electrolyzer Current Density (PEM Water electrolysis) | 175 | mA/cm2 |
| Stack Cost | 1117.2 | $/m2 |
| BOP cost | 601.6 | $/m2 |
| Total cost | 1718.7 | $/m2 |

## ***Table S2.5:* Capital cost components for the greenhouse.**

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Cost | Unit | Reference |
| Greenhouse structure | 25 | $/m2 | (Mahmood et al., 2024) |
| Greenhouse cover material | 16.5 | $/m2 | (Harnois, n.d.) |
| HVAC system | 145 | $/kW | (Sajid et al., 2024) |
| Fertigation system | 44.7 | $/m2 | (Yara International, 2019) |
| Gutter system | 14.18 | $/m2 | (Yara International, 2019) |
| CO2 pressure regulator, flow meter, and solenoid valve | 98 | $ | (CO2Meter, n.d.) |
| CO2 sensor and controller | 150 | $ | (CO2Meter, n.d.) |

## ***Table S2.6:* Operating cost components for the greenhouse.**

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Cost | Unit | Reference |
| Substrate | 1.86 | $/m2 | (Benis et al., 2018) |
| Fertilizers | 3.5 | $/m2 | (Mahmood et al., 2024) |
| Pesticides | 1.42 | $/m2 | (Benis et al., 2018) |
| CO2 transportation | 0.15 | $/km/truck | (Ghiat et al., 2021) |
| CO2 storage | 9.5 | $/ton | (Svensson et al., 2004) |
| Labor cost | 8 | $/m2 | (Yara International, 2019) |

## ***Table S2.7*: Parameters selected for the sensitivity analysis on DAC-HVAC system.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Base case | Unit | Reference | Variance |
| Discount rate | 7 | % | (CEIC, n.d.) | 0.05-0.15 |
| Selling price of CO2 | 261 | $/ton CO2 | (Rennert et al., 2022),(California Air Resources Board, n.d.) | 50-300 |
| Electricity price1 | 0.0351 | $/kWh | (Qatar General Electricity & water Corporation, n.d.) | 0.01-1 |

## ***Table S2.8:* Parameters selected for the sensitivity analysis on DAC-Formic acid system.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Base case | Unit | Reference | Variance |
| Discount rate | 7 | **%** | (Yang et al., 2017) | 0.05-0.15 |
| Selling price of FA | 0.596 | $/kg FA | (Yang et al., 2017) | 0.25-1.5 |
| Electricity price1 | 0.0351 | $/kWh | (Qatar General Electricity & water Corporation, n.d.) | 0.01-1 |
| Electrolyzer stack price | 1113 | $/m2 | (NREL, n.d.) | 300-2100 |
| Faradic efficiency | 94 | % | (NREL, n.d.) | 0.6-1 |
| Current density | 0.14 | A/cm2 | (Yang et al., 2017) | 0.05-0.2 |

## ***Table S2.9:* Parameters selected for the sensitivity analysis on DAC-Greenhouse system.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Base case | Unit | Reference | Variance |
| Discount rate | 7 | % | (CEIC, n.d.) | 0.05-0.15 |
| Selling price of produce | 1.5 | $/kg produce | (MOCI, n.d.) | 0.5-1.5 |
| Electricity price1 | 0.0351 | $/kWh | (Qatar General Electricity & water Corporation, n.d.) | 0.0189-0.1289 |

1The electricity price sensitivity range is based on the current subsidized price and the unsubsidized price, with the subsidy amount being 0.11 $/kWh (Sanfilippo et al., 2024).

# **S3: Supplementary figures**

## ***Figure S3.1:* Effect of FE and current density on the NPV for DAC-Formic acid system.**

## ***Figure S3.2:* Effect of FE and current density on the LCOF for DAC-Formic acid system.**

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