Trondheim CCS Conference
CO_2 Capture, Transport and Storage

Universiteit Utrecht

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Evaluation of a Direct Air Capture Process Combining Wet Scrubbing and Bipolar Membrane Electrodialysis

TCCS-10

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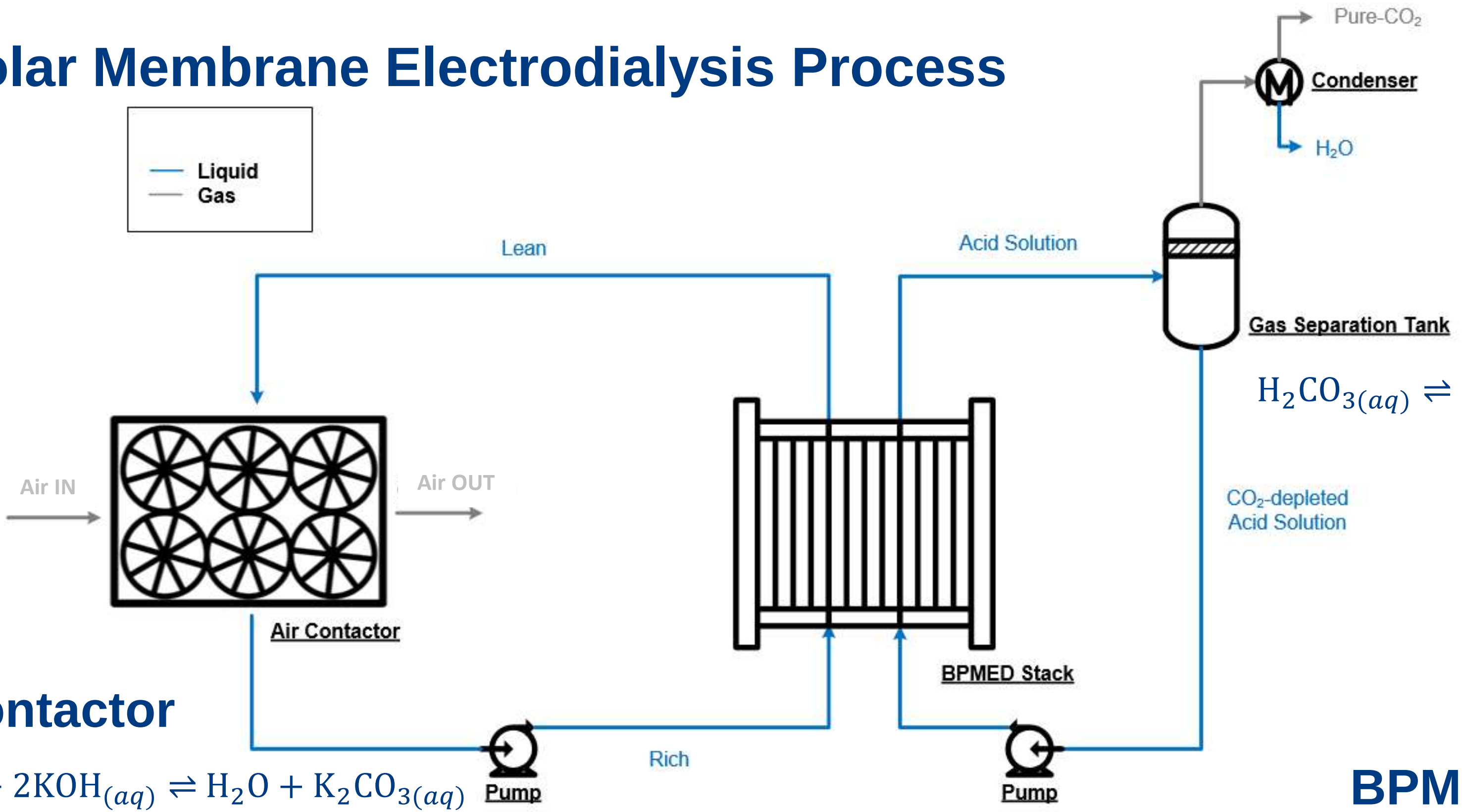
INTRODUCTION

Bipolar Membrane Electrodialysis Process



Tank

$$H_2CO_{3(aq)} \rightleftharpoons CO_{2(g)} + H_2O_{(l)}$$

Air Contactor

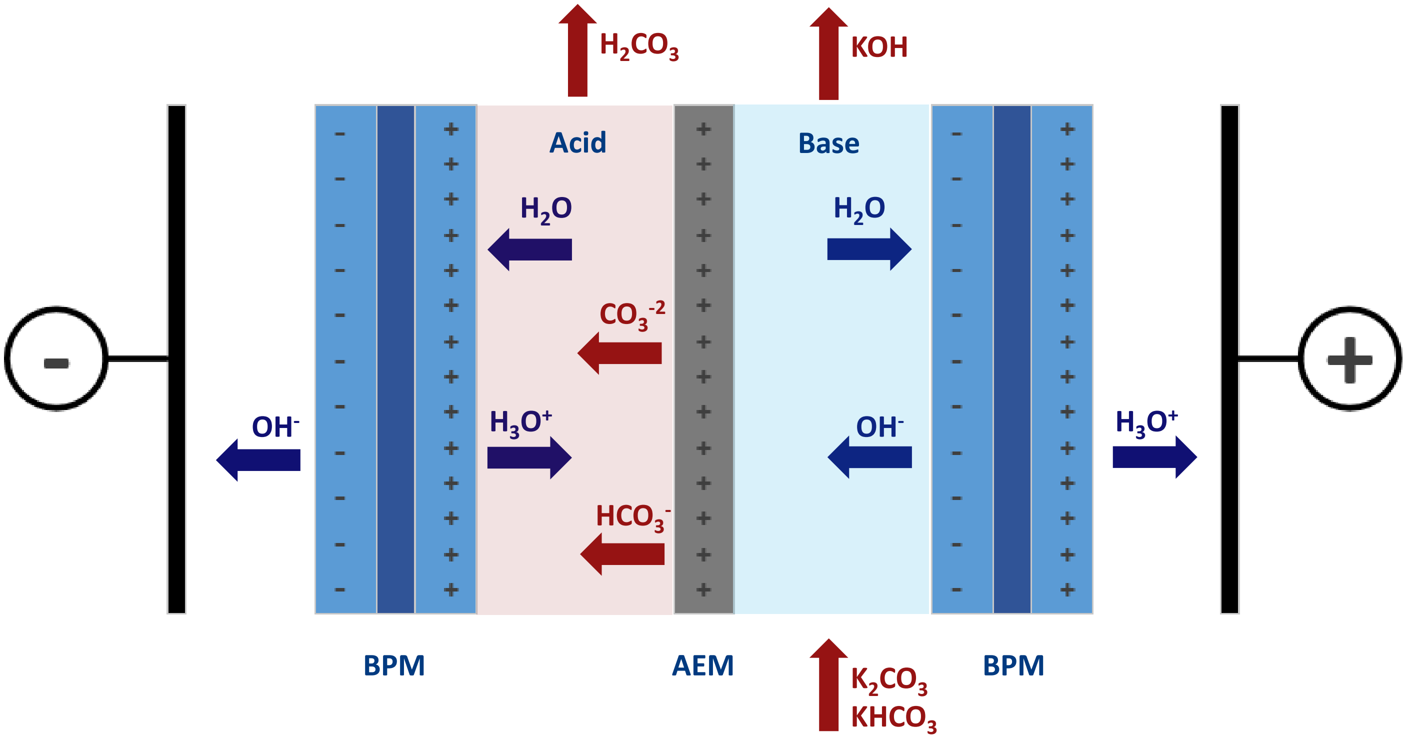
$$CO_{2(aq)} + 2KOH_{(aq)} \rightleftharpoons H_2O + K_2CO_{3(aq)}$$

$$CO_{2(aq)} + KOH_{(aq)} \rightleftharpoons KHCO_{3(aq)}$$

BPMED Stack

$$K_2CO_{3\,(aq)} + 2H^+ + 2OH^- \rightleftharpoons 2KOH_{(aq)} + H_2CO_{3(aq)}$$

Bipolar Membrane Electrodialysis (BPMED)



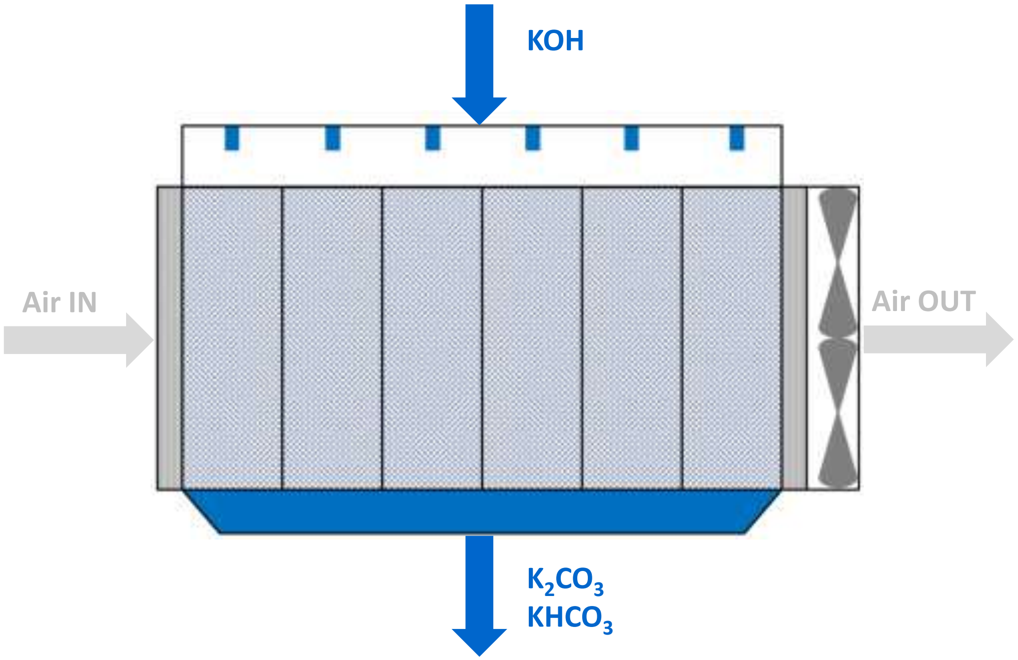
- BPM splits water after a threshold potential is reached;

$$2H_2O \rightleftharpoons H_3O^+ + OH^-$$
$$(E^0 = -0.83\ V)$$

- Anions diffuse trough AEM to the Acid compartment;

$$CO_3^{2-} + H^+ \rightleftharpoons HCO_3^-$$
$$HCO_3^- + H^+ \rightleftharpoons H_2CO_3$$

Air Contactor

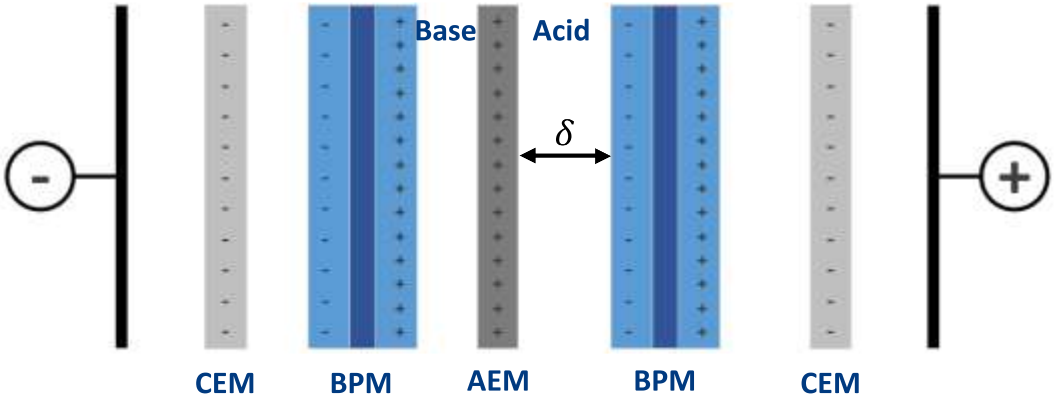


- Designed by Carbon Engineering, pilot contactor in operation;
- Based on commercial cooling tower technology;
- Open, cross-flow configuration;
- Modular design;
- A factor 4 less expensive than conventional absorption towers [1];

[1] *An air-liquid contactor for large-scale capture of CO_2 from air,* Keith et al. (2011)

METHODOLOGY

BPMED Stack Model (I)



Resistance (Ωm²)

$$R_{cell} = R_{base} + R_{AEM} + R_{acid}$$

$$R_i = \frac{\delta}{k_i}$$

$$k_{base} = f(J_{CO_2})$$

- Steady-state, 0D model;
- Base compartment is assumed to be comprised of two phases: base solution and gaseous CO_2;
- Main equations reported below:

Specific Energy Demand (kJ/mol_{CO2})

$$SPEND = \frac{N_{STACK}F}{\eta}\left[N_{CELL}(iR_{CELL} + E_{BP}) + E_{EC}\right]$$

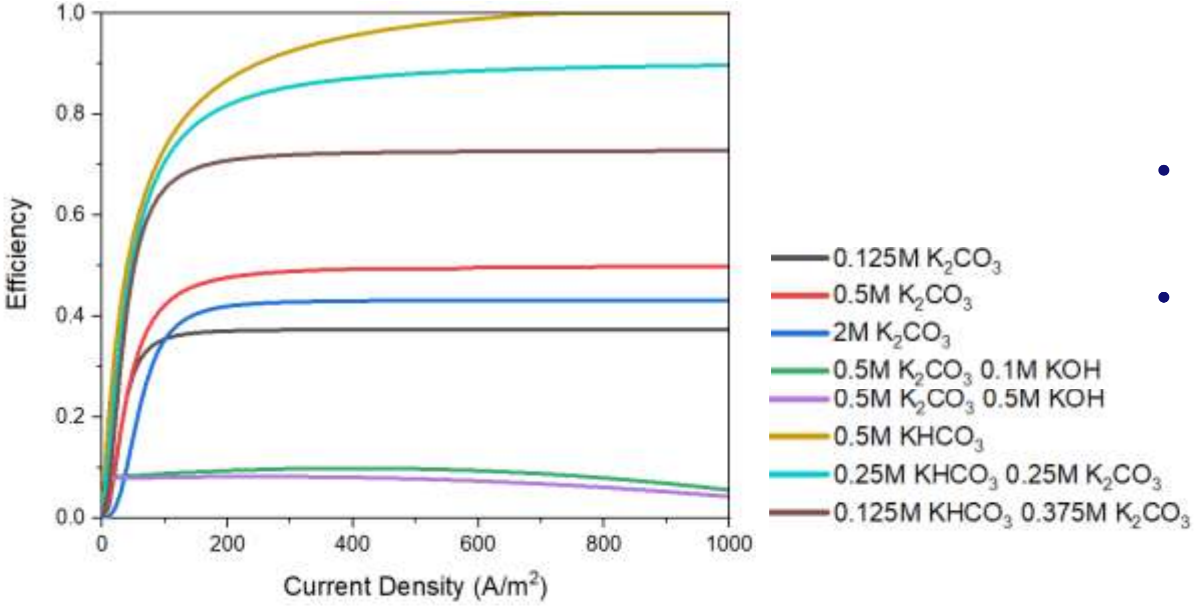
CO_2 Production Rate (mol_{CO2}/s)

$$J_{CO_2} = \frac{i}{F}\eta$$

Electrical efficiency

$$\eta = \frac{moles\ of\ CO_2\ produced}{charge\ transported}$$

BPMED Stack Model (II)

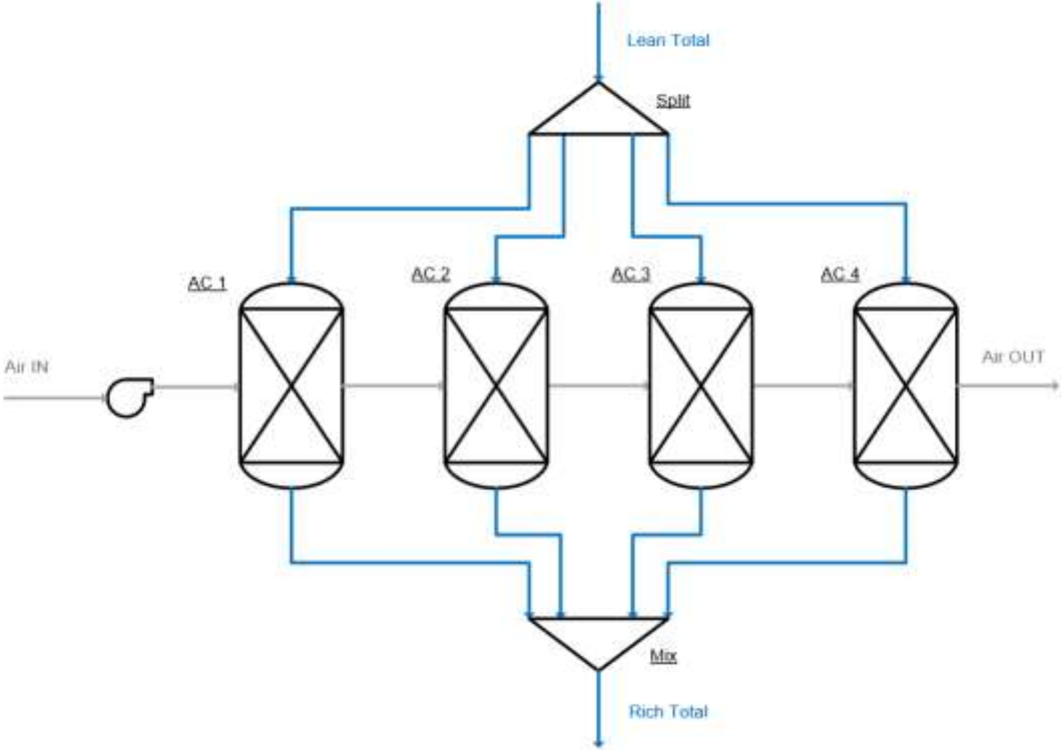


- Values of η published in literature for different Rich compositions [2];
- η increases with i until a plateau value is reached;
- The experimental points have been fitted with the following equation:

$$\eta = \frac{\eta_{max} k i^{1/m}}{1 + k i^{1/m}}$$

[2] *CO_2 separation using bipolar membrane electrodialysis,* Eisaman et al. (2011)

Air Contactor Model



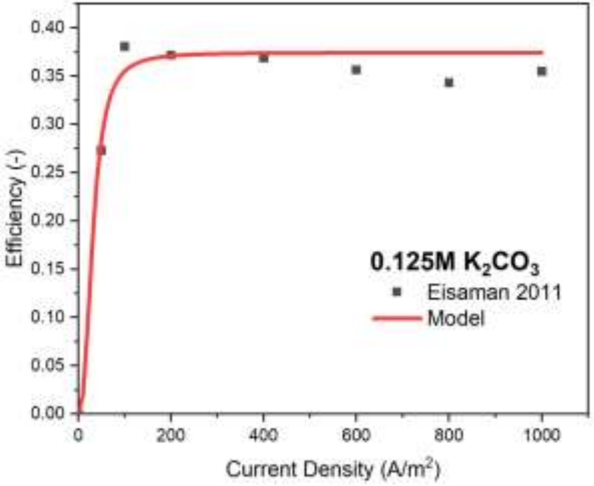
- Parallel blocks to simulate cross-flow;
- Detailed, rate-based units;
- Parameters used are reported in the Table below:

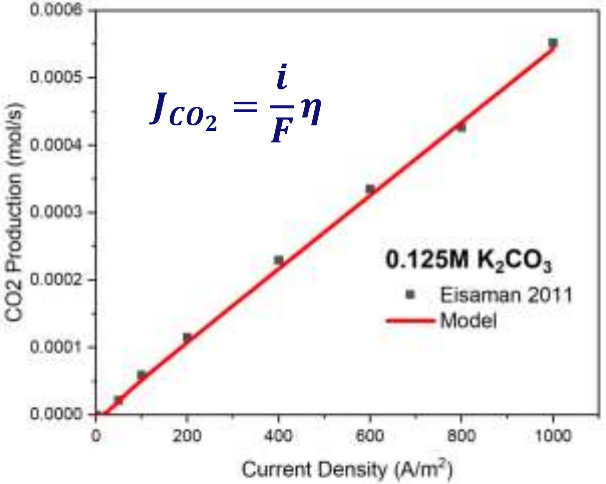
Description	Value [3]
Block	RadFrac
Thermodynamic model	ELECNRTL
Inlet Area [m^2]	25
Width [m]	7
Number of Units	6
Packing	Sulzer Mellapak 250.Y
Flow model	VPlug

[3] *A Process for Capturing CO_2 from the Atmosphere,* Keith et al. (2018)

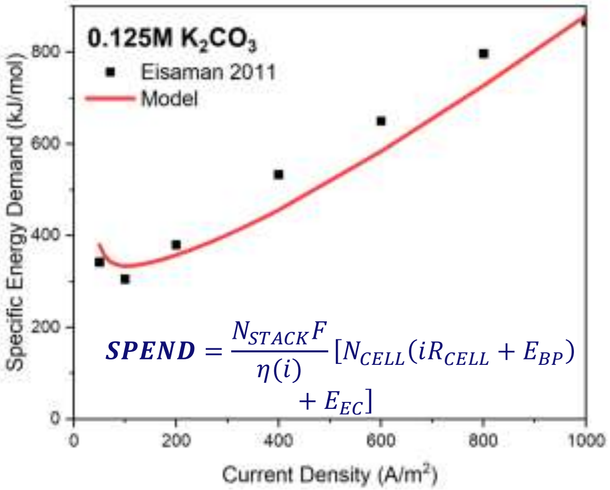
RESULTS

Model Validation (I)





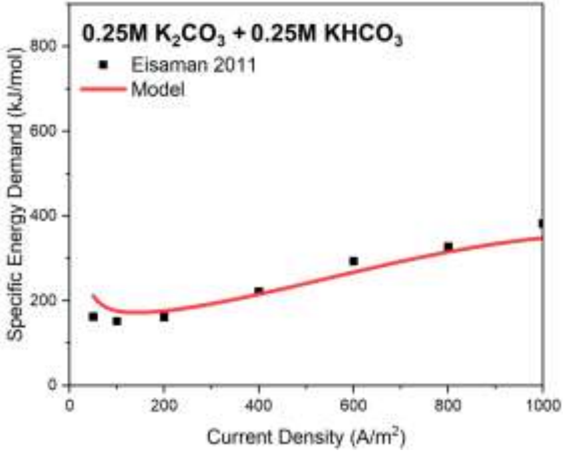
$$J_{CO_2} = \frac{i}{F}\eta$$

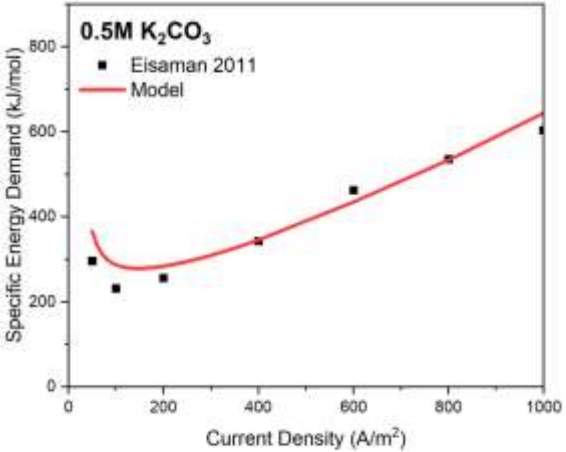


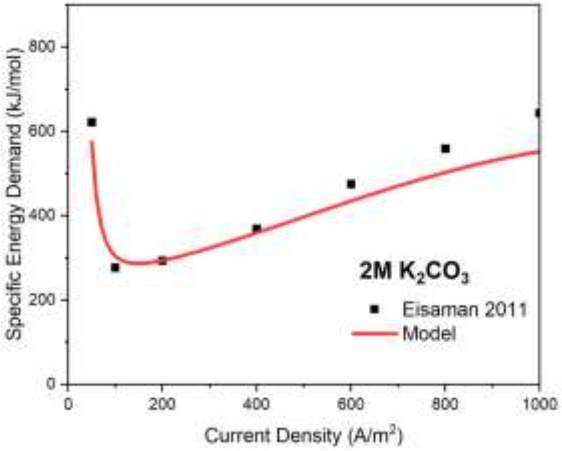
$$\boldsymbol{SPEND} = \frac{N_{STACK}F}{\eta(i)}\left[N_{CELL}(iR_{CELL} + E_{BP}) + E_{EC}\right]$$

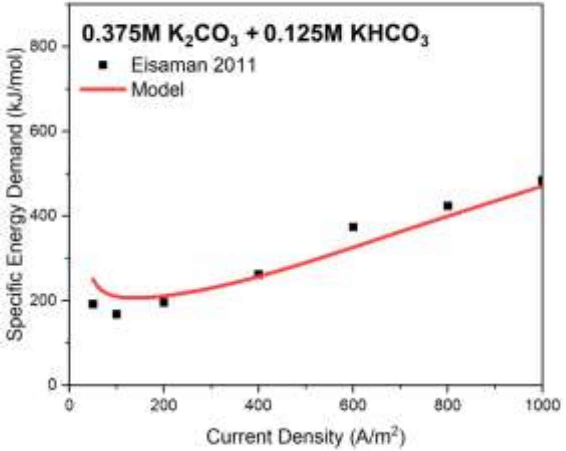
1. Fitting Electrical Efficiency.
2. Calculation of CO_2 Production Rate.
3. Calculation of Specific Energy Demand.

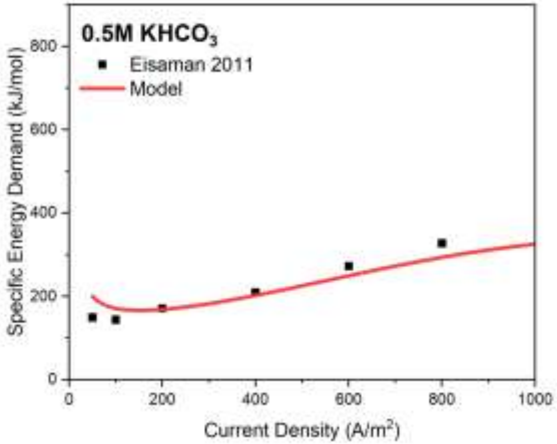
Model Validation (II)



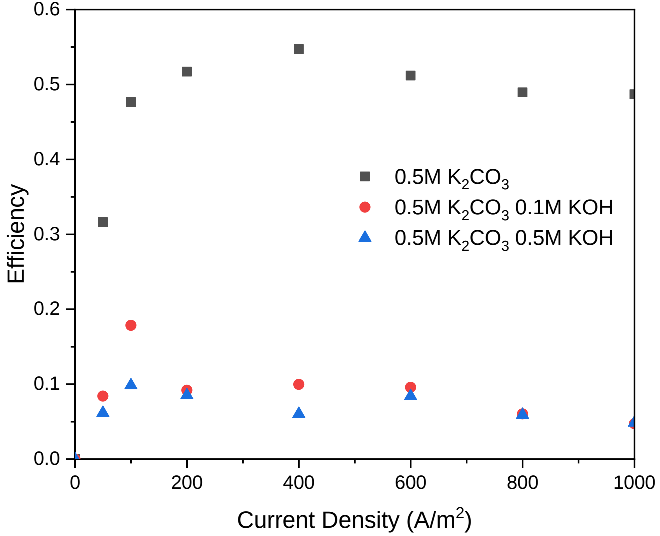


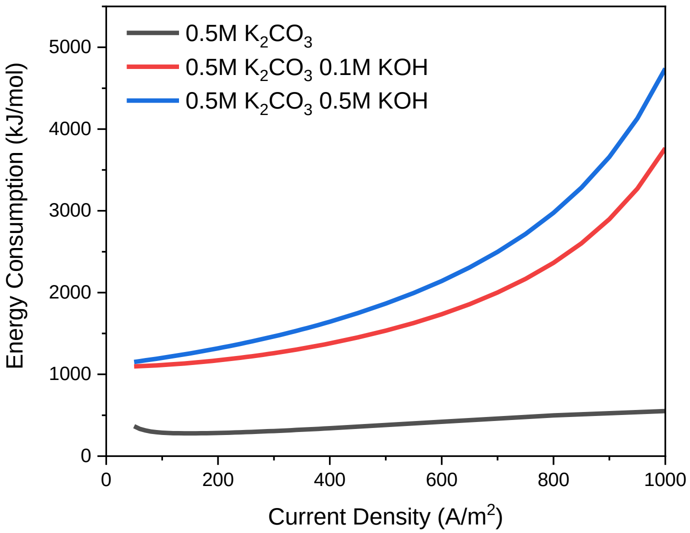






Air Contactor Operating Conditions (I)

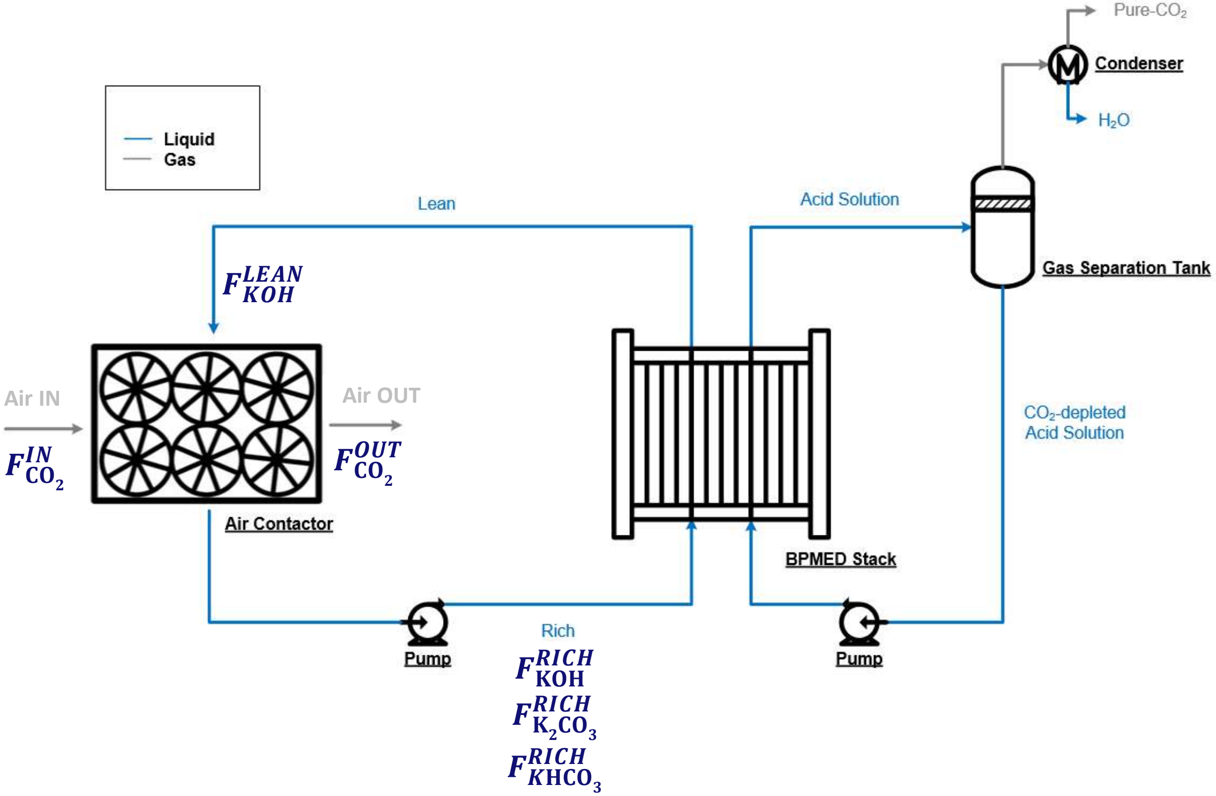




- The presence of KOH has a great impact on the Electrical Efficiency, due to competitive transport of OH^-.

- This, in turn, determines a considerable increase in the Specific Energy Demand.

Air Contactor Operating Conditions (II)



- KOH concentration affects both CO_2 capture and sorbent regeneration;
- To assess its effect on the performance of the process, these indicators will be used:

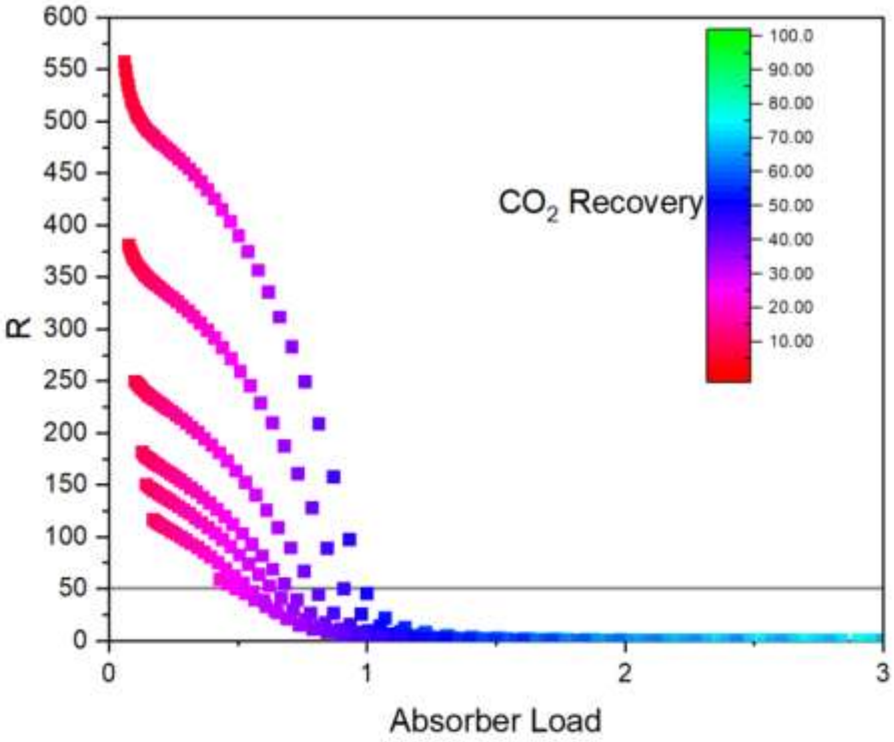
$$\text{Absorber Load} = \frac{F_{\text{KOH}}^{LEAN}}{F_{\text{CO}_2}^{IN}}$$

$$\text{R} = \frac{F_{\text{K}_2\text{CO}_3}^{RICH} + F_{\text{KHCO}_3}^{RICH}}{F_{\text{KOH}}^{RICH}}$$

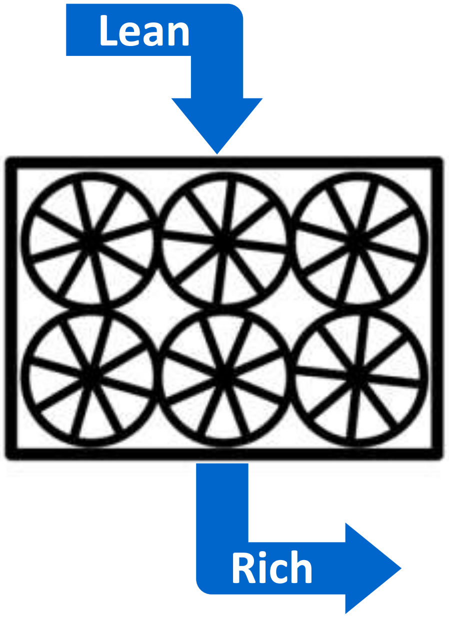
$$\text{CO}_2\text{ Recovery} = \frac{F_{\text{CO}_2}^{IN} + F_{\text{CO}_2}^{OUT}}{F_{\text{CO}_2}^{IN}}$$

Air Contactor Operating Conditions (III)

- Based on experimental data, we assume that for R > 50 the influence of KOH on BPMED is negligible;
- CO_2 capture is favored at high Absorber Loads;
- On the other hand, sufficient values of R are only achieved with diluted Lean solutions;
- A greater number of Air Contactor units is required, thus increasing capture costs.



Air Contactor Operating Conditions (III)

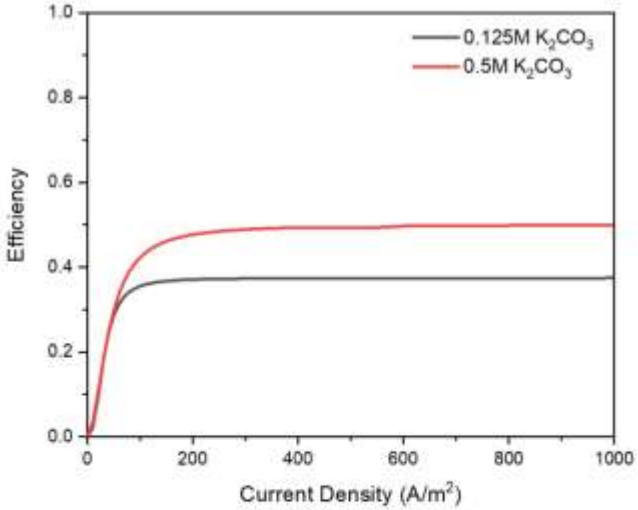


Component	Concentration (mol/L)
KOH	0.3
K_2CO_3	0
$KHCO_3$	0

Parameter	Value
L/G	0.05
CO_2 Recovery (%)	50
Number of Units	2720

Component	Concentration (mol/L)
KOH	0.0032
K_2CO_3	0.17
$KHCO_3$	0.002

- Compared to CE, roughly 1.7 times more Air Contactor units are needed;
- We will assume that η lies in the range of 40% - 50%.



ECONOMIC ANALYSIS

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Base Case (I)

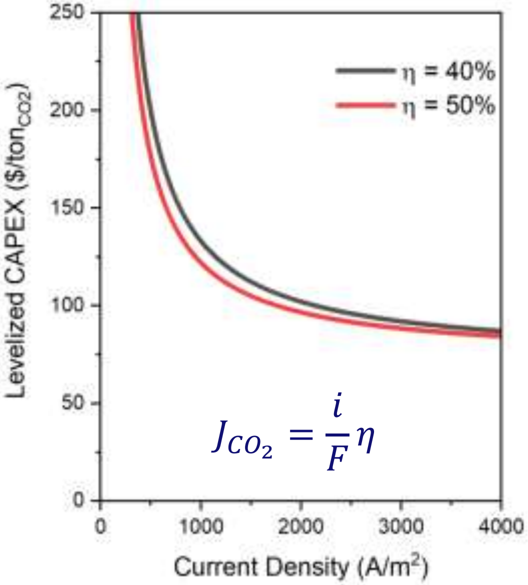
Parameter	Value [4],[5]
N_{cells}	2400
$A_{membrane}$ [m²]	1.785
δ [mm]	1.5
R_{AEM} [Ωm2]	0.00041
Membrane Lifetime [yr]	5

- DAC plant with capacity of 1 $Mton_{CO2}$/year;
- Calculation of required number of Air Contactor units and BPMED stacks and estimation of total costs;
- Base Case assumptions are reported in the Table below:

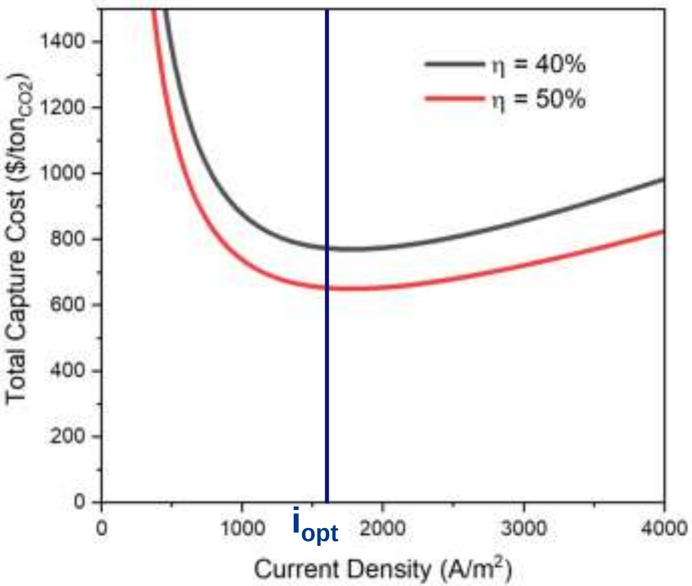
Cost	Value [6]
Electricity [$/kWh]	0.06
Stack [M$/unit]	0.75
AEM [$/m²]	70
BPM [$/m²]	750

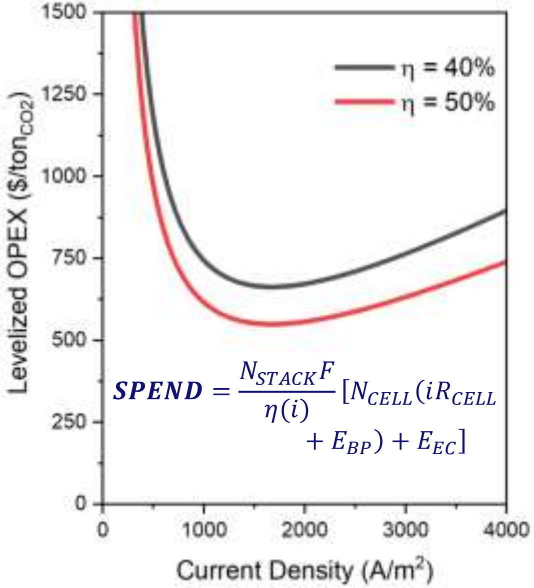
[4] *SELEMION Products Catalogue*
[5] *ASTOM Products Catalogue*
[6] *Carbon dioxide recovery from carbonate solutions using bipolar membrane electrodialysis,* Iizuka et al. (2012).

Base Case (II)



$$J_{CO_2} = \frac{i}{F}\eta$$

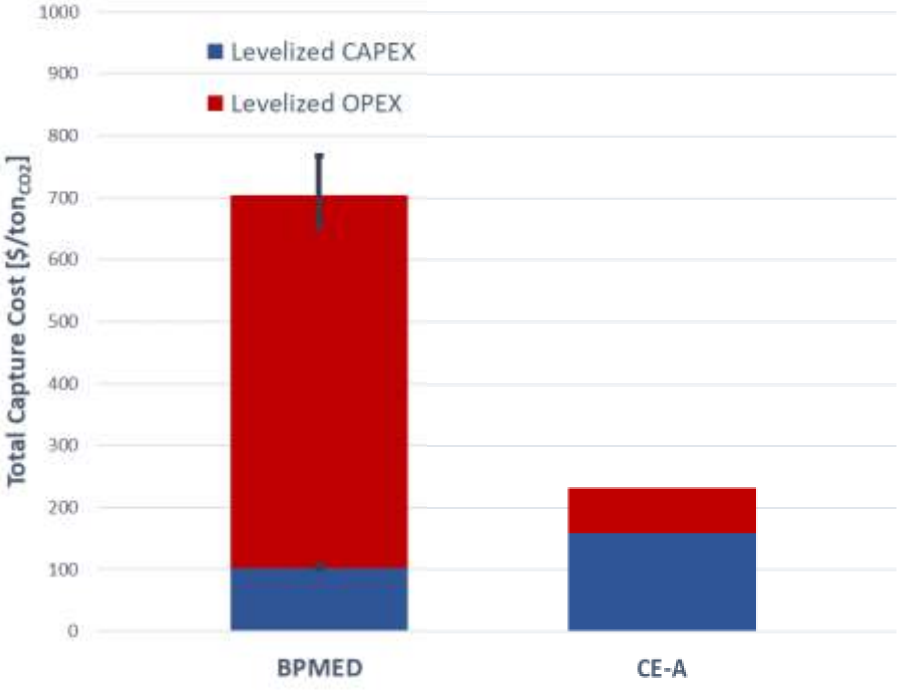




$$\boldsymbol{SPEND} = \frac{N_{STACK}F}{\eta(i)}[N_{CELL}(iR_{CELL} + E_{BP}) + E_{EC}]$$

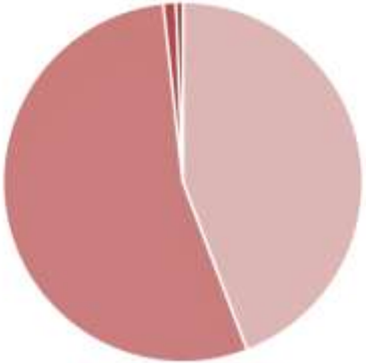
- With increasing i, less BPMED stacks are needed, therefore CAPEX decreases.
- Optimal operating conditions are identified.
- Voltage drop across the stack increases with i and with it the OPEX.

Base Case (III)



[3]*A Process for Capturing CO_2 from the Atmosphere,* Keith et al. (2018)

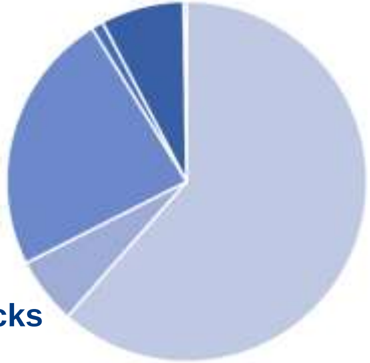
Ventilation and CO_2 Compression



Energy Consumption BPMED

Membrane Replacement

Pump and Compressor

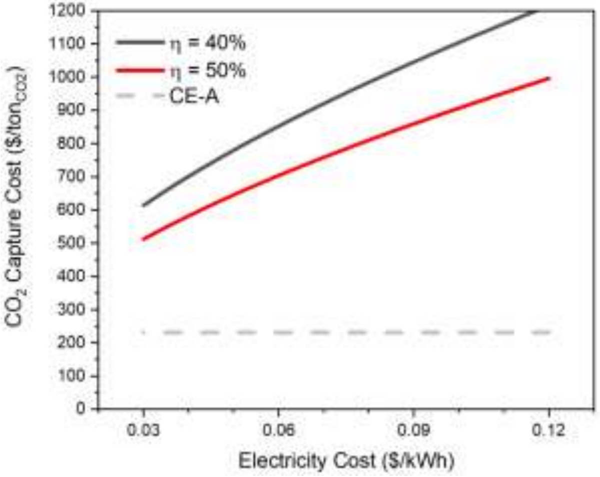


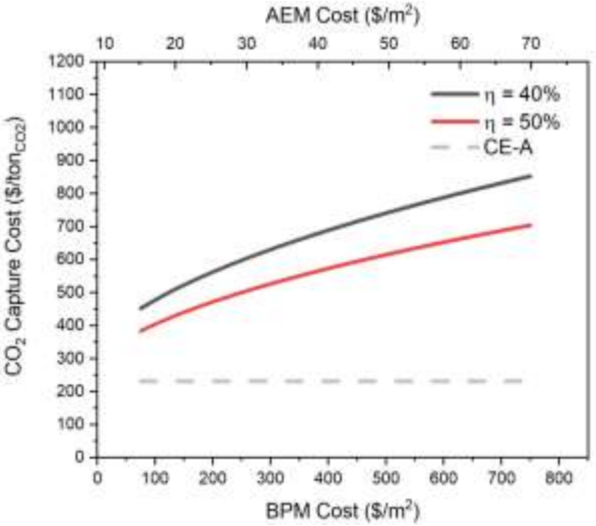
Membranes

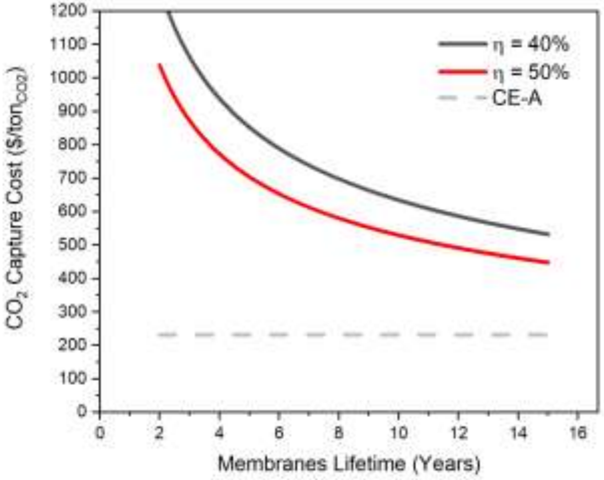
Stacks

Air Contactor

Sensitivity Analysis (I)





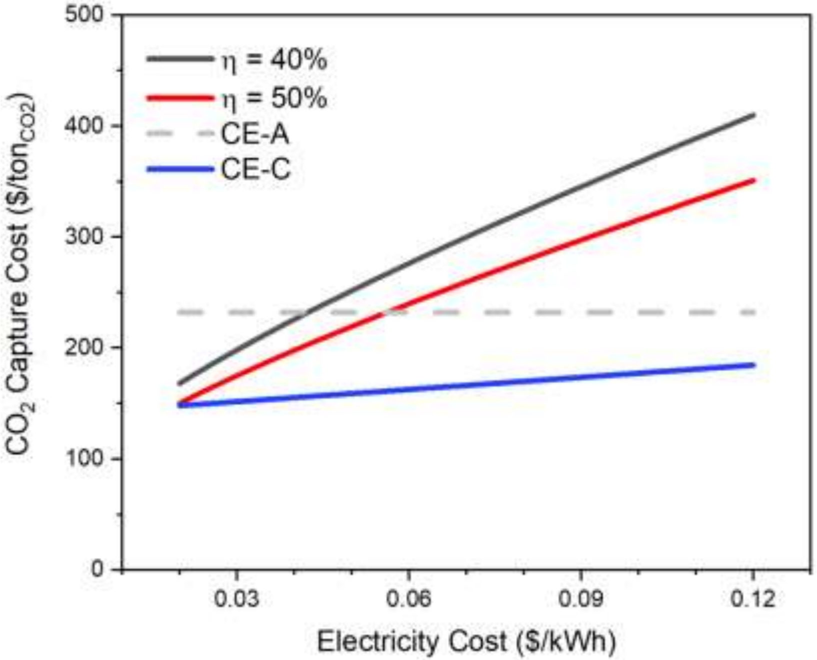


- Conventional CE Process (CE-A) is more cost effective in every condition;
- In order for the BPMED process to become the better option, cheap renewable energy and a reduction in membrane cost is needed;

Sensitivity Analysis (II)

- We assume lowest cost for the membrane to assess if BPMED process could ever be competitive;
- Alternative CE process (CE-C) is also considered. In this process part of the energy input is provided in the form of electricity[6];
- Assumptions are reported in the table below:

Cost	Value
Stack [M$/unit]	0.25
AEM [$/m^2]	15
BPM [$/m^2]	75



[6] *A Process for Capturing CO_2 from the Atmosphere,* Keith et al. (2018)

CONCLUSIONS

Conclusions

- BPMED model provided an adequate description of the performances of a lab-scale setup through implementation of experimentally measured efficiency;
- A fine tuning of Air Contactor operating conditions is needed to make sure an acceptable efficiency is achieved for BPMED;
- With the current electricity and membranes cost, BPMED process cannot compete against CE process;
- BPMED process is very energy-intensive. Cheap, renewable electricity is a fundamental requirement for this process;
- Other DAC processes would also benefit from low energy cost. From our results, it seems unlikely that the BPMED process will ever be the most cost effective.

THANK YOU FOR YOUR ATTENTION

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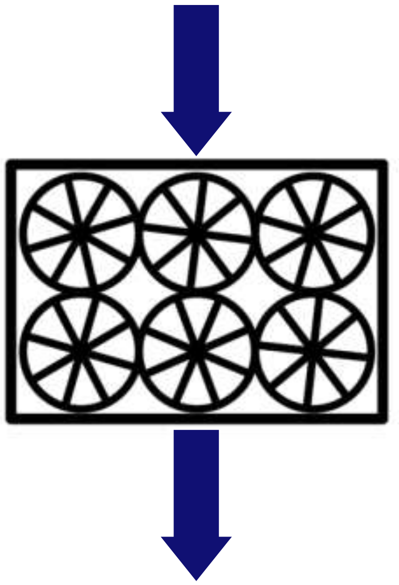
Direct Air Capture

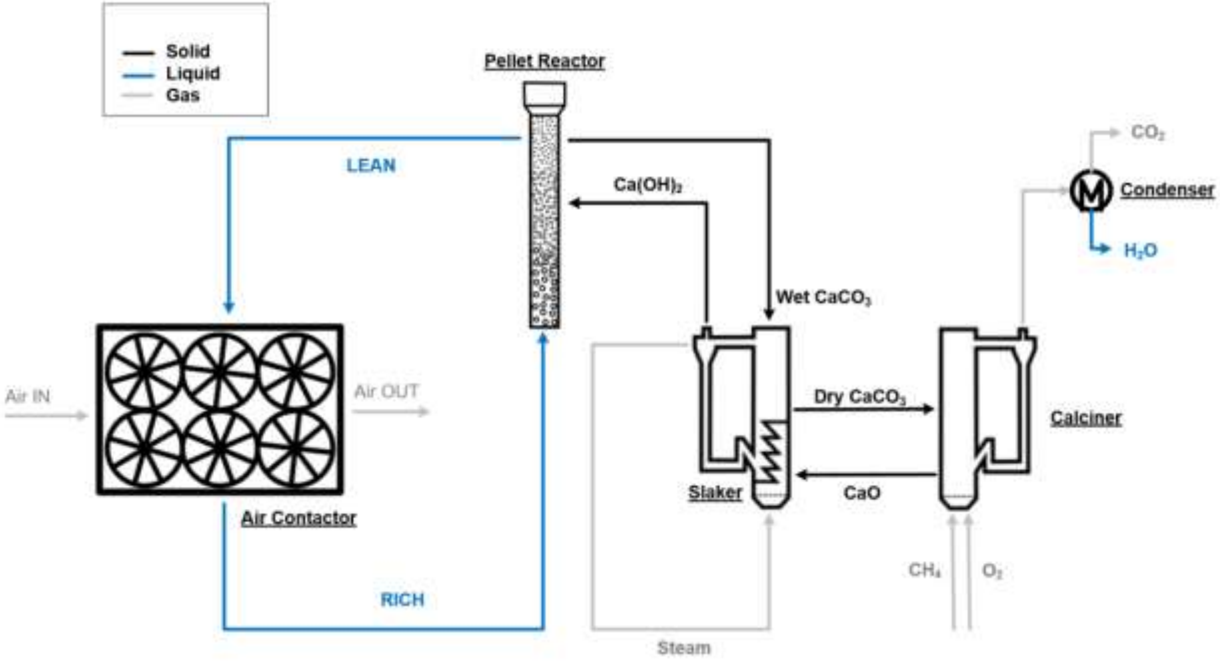
- DAC is a process for separating CO_2 from atmospheric air;
- Huge volumes of air must be processed to capture a meaningful amount of CO_2;
- Physical separation processes are out of the question, leaving absorption and adsorption;
- Air and sorbent should be put in contact in the most efficient way;



$$46000\ \frac{\mathrm{m}^3_{\mathrm{Air}}}{s}$$

$$1\ \frac{\mathrm{Mton}_{\mathrm{CO_2}}}{\mathrm{year}}$$

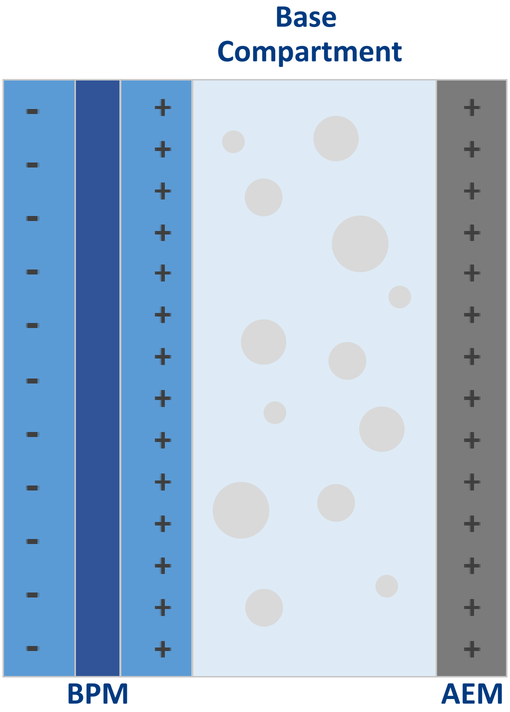
Carbon Engineering's DAC Process



- Regeneration of sorbent carried out through Ca-based thermochemical cycle;
- Natural gas is required;
- CE estimates that CO_2 captured through this process would cost 232 \$/ton [1];
- CE is also developing other process based on the same Air Contactor.

[1] *A Process for Capturing CO_2 from the Atmosphere,* Keith et al. (2018)

Effect of CO_2 Bubbles



- The conductivity of the base compartment accounts for gaseous CO_2:

$$\frac{k_{corr}}{k_{base}} = \frac{1 + AB\varphi_{CO2}}{1 - B\gamma\varphi_{CO2}}$$

- Where:

$$\varphi_{CO2} = \frac{Volume\ of\ gas\ \mathrm{CO_2}}{Volume\ of\ base\ solution}$$

- CO_2 bubbles are assumed to be spherical and randomly packed.

The Thermal and Electrical Conductivity of Two-Phase Systems, Nielsen et al. (1974)

Economic Analysis

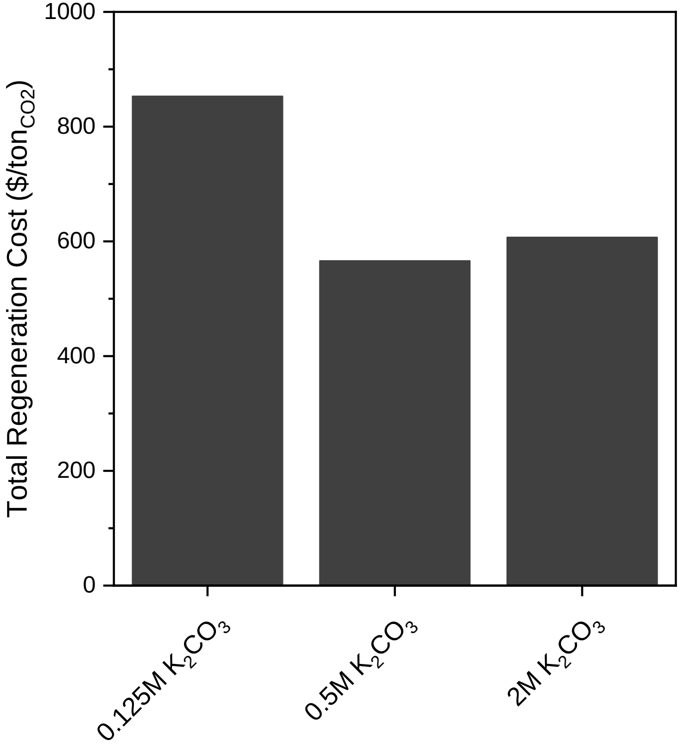
- The process performance has been assessed with the Capture Cost ($/ton$_{CO2}$):

$$Capture\ Cost = \frac{(\mathrm{TOC} \cdot \mathrm{CCF}) + \mathrm{C}^{\mathrm{fix}}_{\mathrm{O\&M}} + (\mathrm{C}^{\mathrm{var}}_{\mathrm{O\&M}} \cdot \mathrm{h_{eq}})}{\mathrm{F}^{\mathrm{BPMED}}_{\mathrm{CO_2}} \cdot \mathrm{h_{eq}}}$$

- Where TOC is the Total Overnight Cost and CCF is Capital Charge rate Factor.

Parameter	Value
CCF	0.125
Bare Erected Cost (BEC)	[Calculated for all the units]
Total Installation Cost (TIC)	80% BEC
Total Direct Plant Cost (TDPC)	BEC + TIC
Indirect Cost (IC)	13% TDPC
Engineering, Procurement and Construction (EPC)	TDPC + IC
Contingency & Other (C&O)	30% EPC
Total Overnight Cost (TOC)	EPC + C&O

Effect of Composition



- Rich solution composition has multiple effects on the regeneration process;
- Diluted solutions are more expensive to regenerate because of lower CO_2 production rate and higher electrical resistance;
- KOH is both an indispensable element and the biggest obstacle to the efficient operation of this process;
- Further development of membrane technology, allowing for selective transport of ions, would tremendously benefit the BPMED process;