
Capturing Carbon Dioxide with a Humidity Swing Sorbent

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November 2010

**After initial work at both
Los Alamos and Columbia**

**GRT* demonstrated air
capture in Tucson in 2007****

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Proof of principle

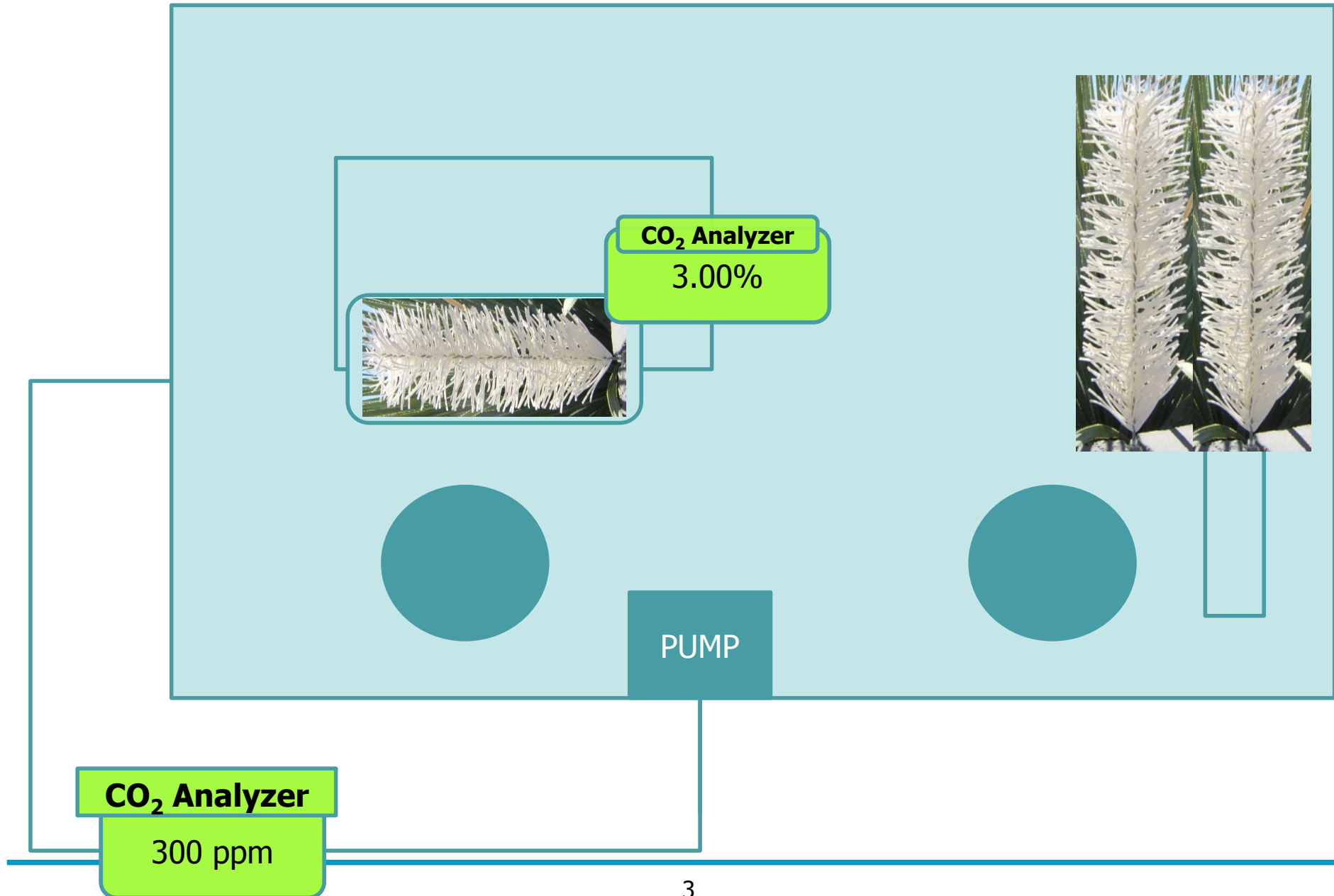


*Now Kilimanjaro Energy, Inc.

**KSL is an advisor the company



Experimental Setup



Anionic Exchange Resins

Solid carbonate "solution" Quaternary amines form strong-base resin



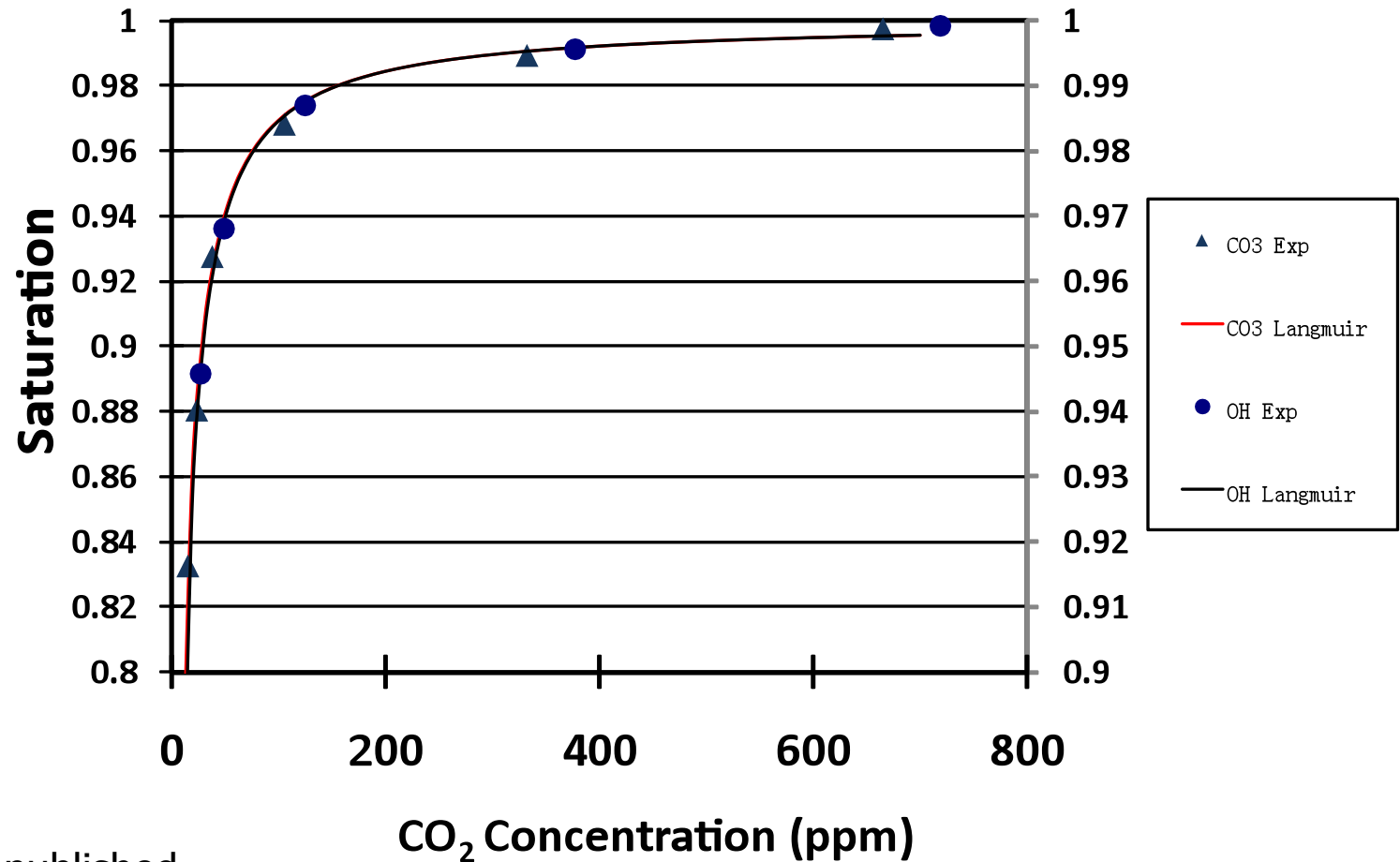
- Positive ions fixed to polymer matrix
 - Negative ions are free to move
 - Negative ions are hydroxides, OH^-
- Dry resin loads up to bicarbonate
 - $\text{OH}^- + \text{CO}_2 \rightarrow \text{HCO}_3^-$ (hydroxide \rightarrow bicarbonate)
- Wet resin releases CO_2 to carbonate
 - $2\text{HCO}_3^- \rightarrow \text{CO}_3^{2-} + \text{CO}_2 + \text{H}_2\text{O}$

Moisture driven CO_2 swing

The Moisture Swing



Absorption Isotherm – Dry

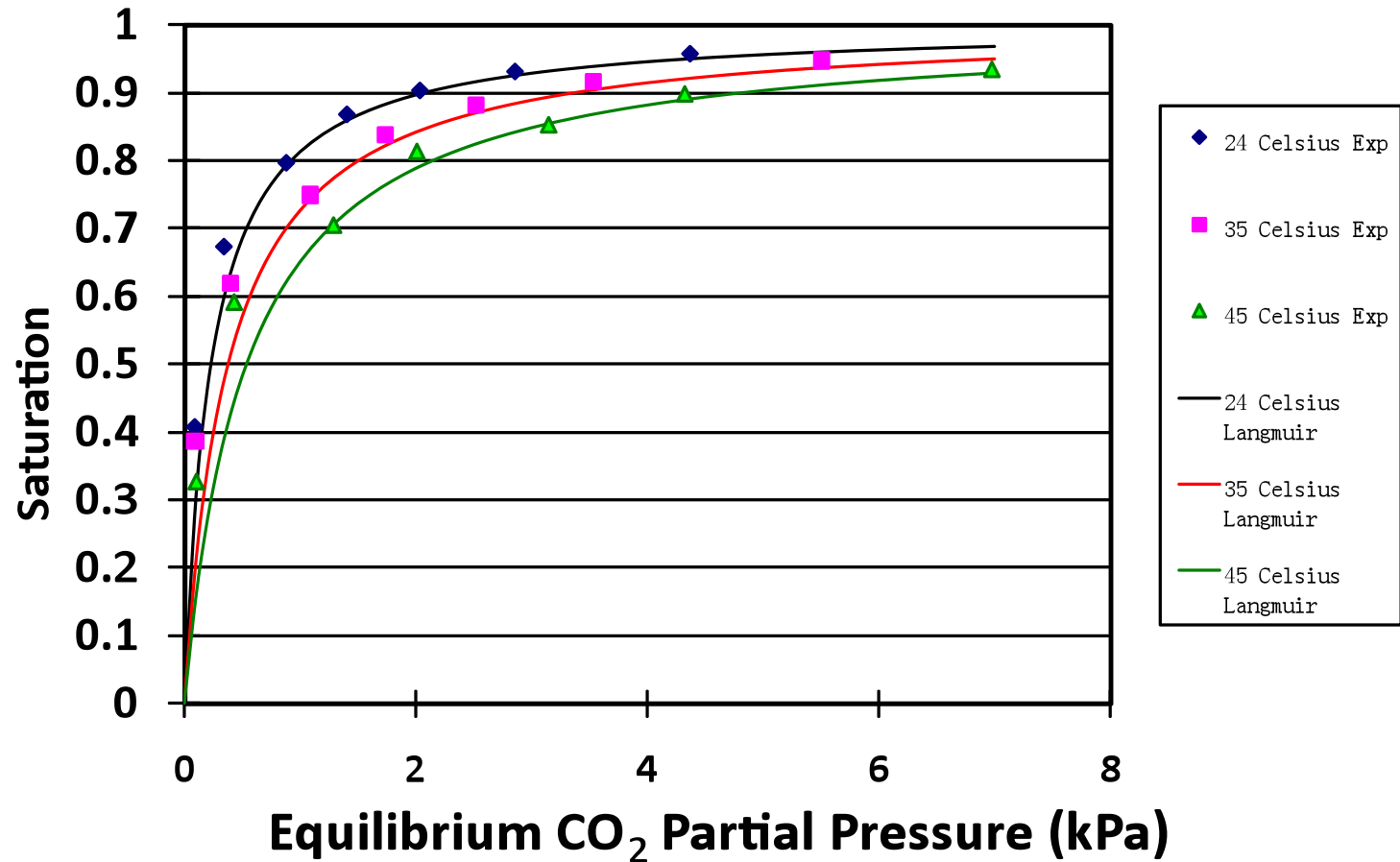


Tao Wang et al, to be published

The Moisture Swing

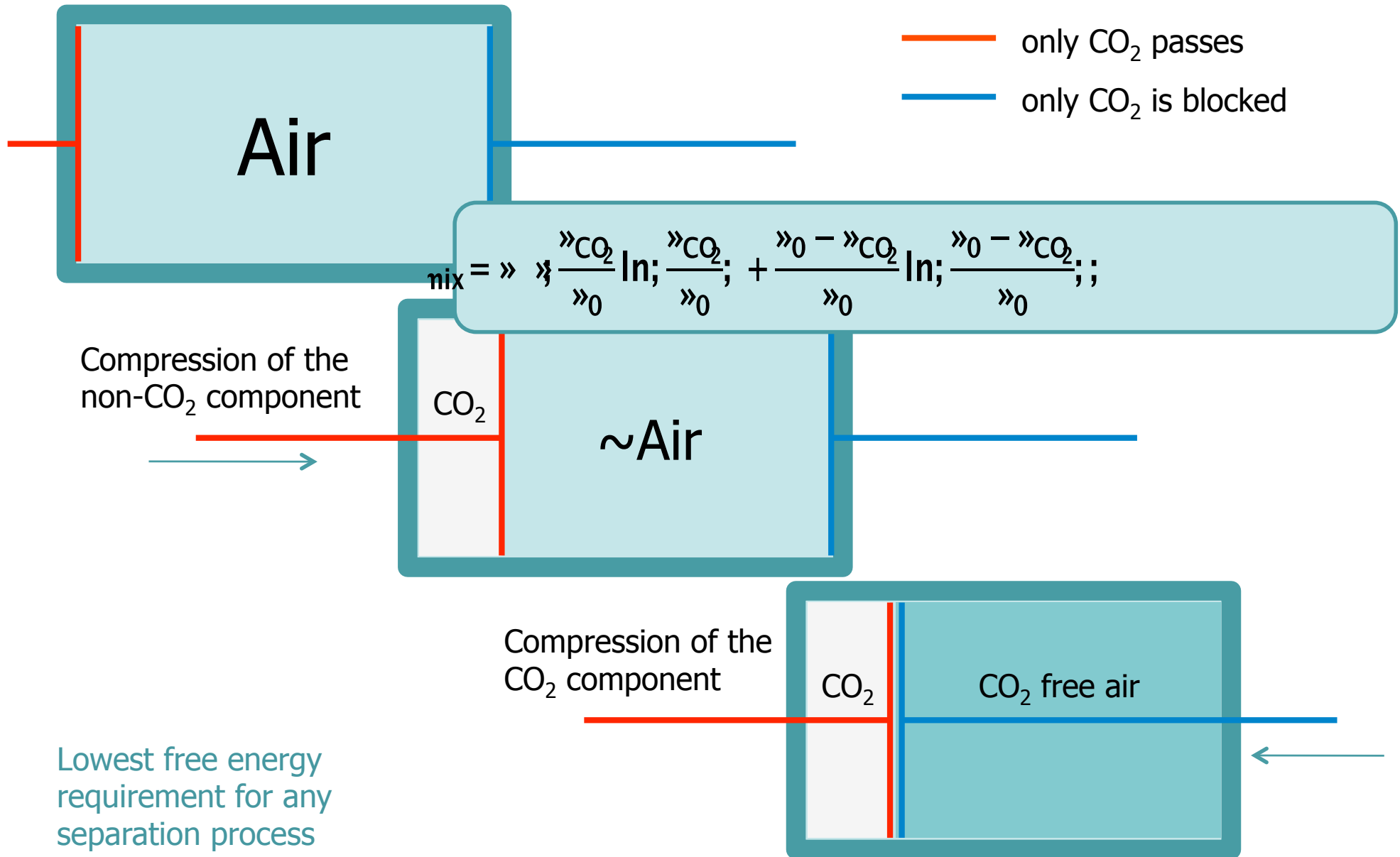


Desorption Isotherm - Wet



Tao Wang et al, to be published

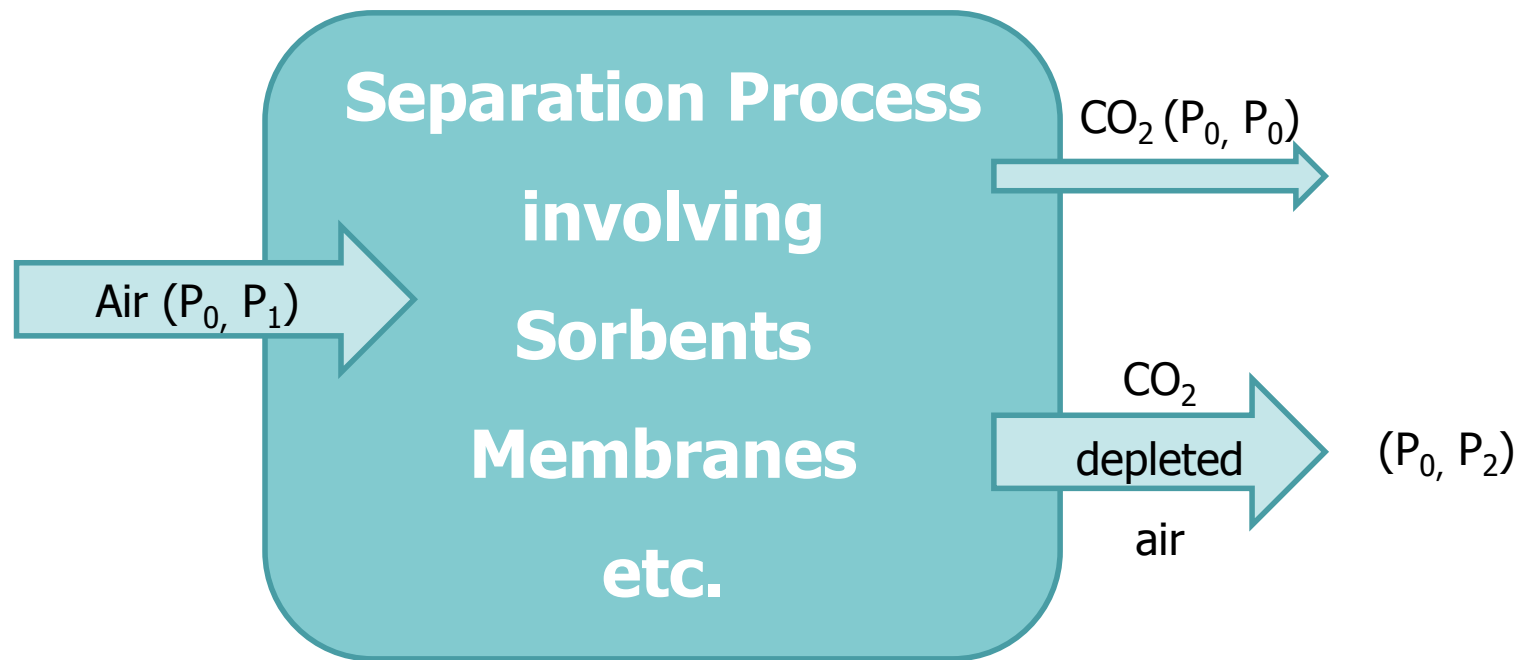
The free energy of mixing



Separation of a gas stream

Theoretical minimum free energy requirement for the regeneration is the free energy of mixing

Gas pressure P_0
 CO₂ partial pressure P_x
 Denoted as (P_0, P_x)



$$\Delta G = RT \left[\frac{y_0 - y_2}{y_1 - y_2} \frac{y_1}{y_0} \ln \frac{y_1}{y_0} - \frac{y_0 - y_1}{y_1 - y_2} \frac{y_2}{y_0} \ln \frac{y_2}{y_0} + \frac{y_0 - y_1}{y_0} \frac{y_0 - y_2}{y_0} \ln \frac{y_0 - y_1}{y_0 - y_2} \right]$$

Specific irreversible processes have higher free energy demands

The limit of skimming

In this limit:

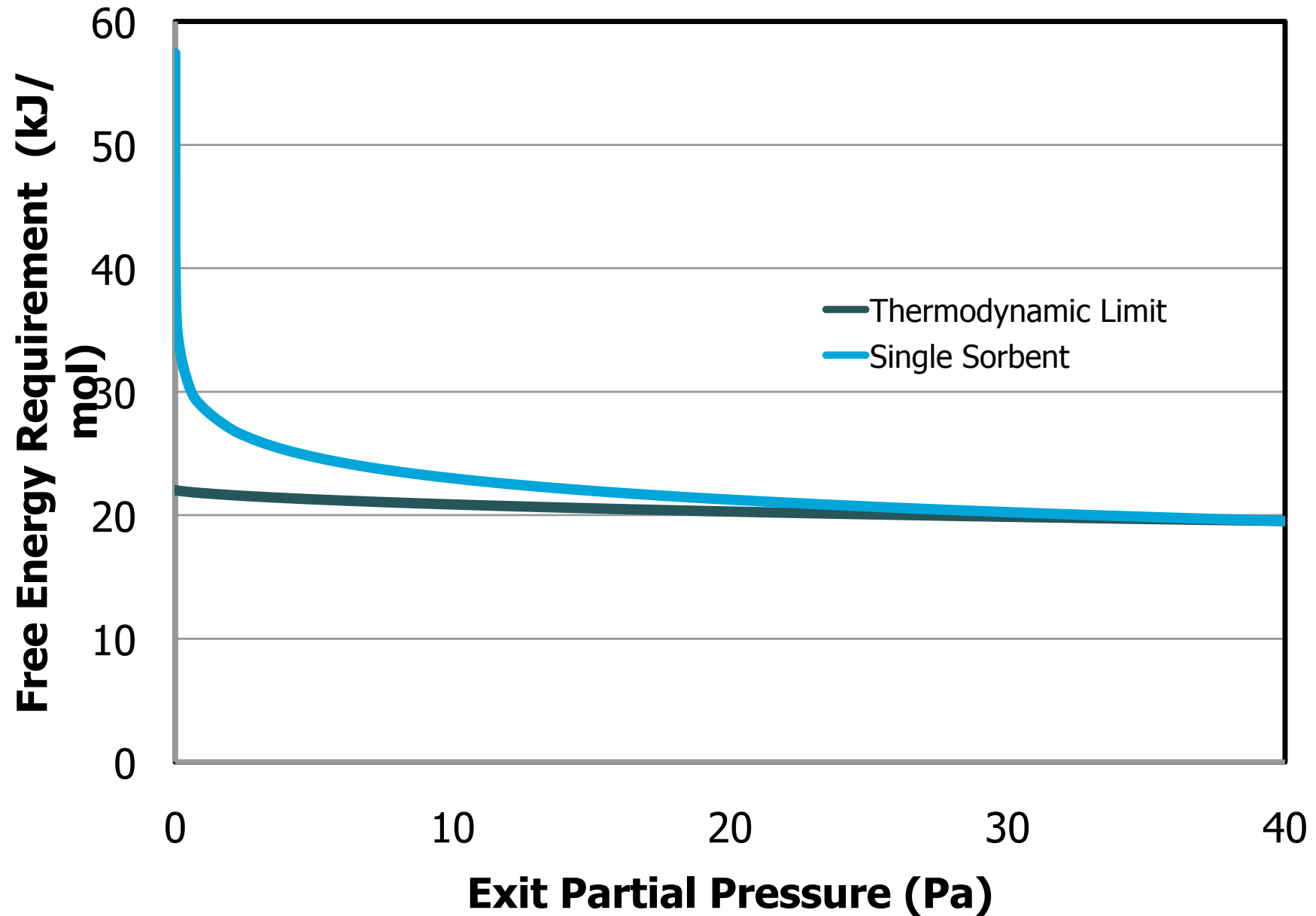
Simplify the general expression by expanding logarithms

$$\ln \frac{N_1}{N_2} = \ln \left(1 + \frac{N_1 - N_2}{N_2} \right) \approx \frac{N_1 - N_2}{N_2} - \frac{(N_1 - N_2)^2}{2N_2^2}$$

$$\ln \frac{N_0 - N_1}{N_0 - N_2} = -\ln \frac{N_0 - N_2}{N_0 - N_1} = -\ln \left(1 + \frac{N_1 - N_2}{N_0 - N_1} \right) \approx -\frac{N_1 - N_2}{N_0 - N_1} + \frac{1}{2} \left(\frac{N_1 - N_2}{N_0 - N_1} \right)^2$$

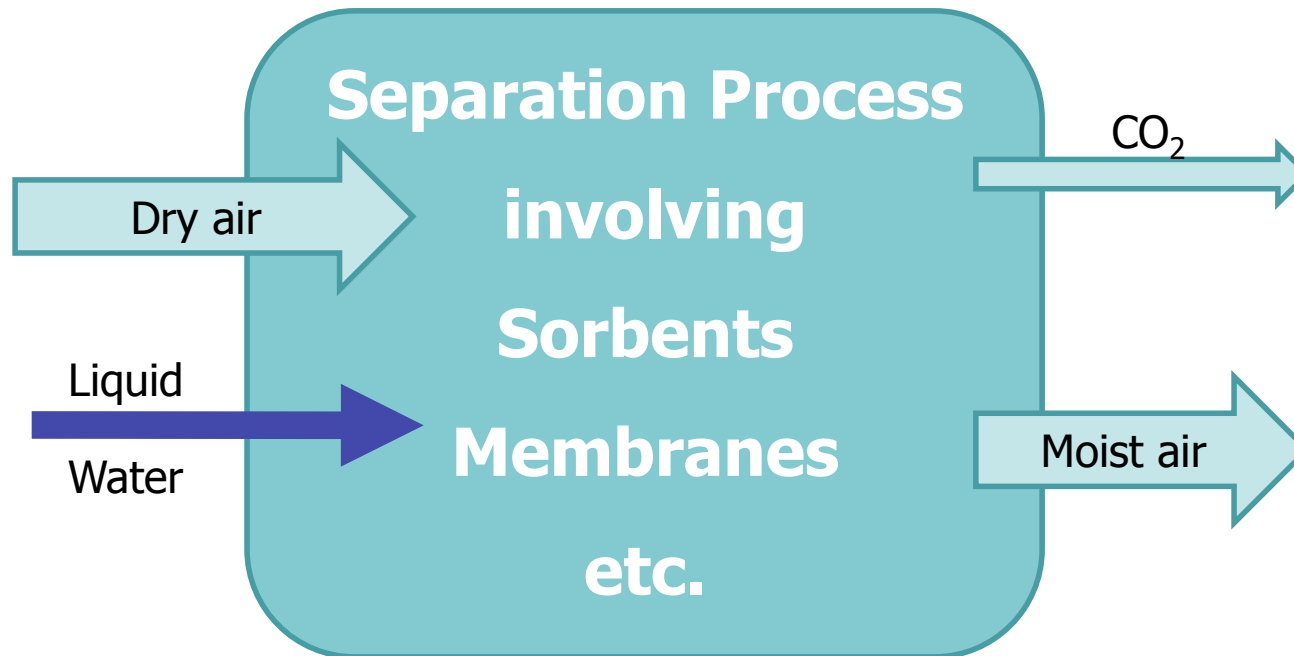
$$\ln \frac{N_1}{N_0} - \frac{N_1 - N_2}{2N_1}$$

Air Capture Free Energy



Free energy from water evaporation

Water evaporation can drive CO₂ capture



Free energy of water evaporation
at a relative humidity RH :

$$\Delta G = RT \ln(P/P_{\text{sat}}) = RT \ln(RH)$$

Ball park estimate: 2.5 kJ/mol
140 MJ/m³
@ 20¢/m³ 0.5¢/kWh

Four steps in the moisture swing

- **Dry resin absorbs CO₂ from air**
 - Lowers free energy
- **Wetting the resin**
 - no free energy change in water transfer
 - water interaction with resin may change state
- **Wet resin releases CO₂ at higher pressure**
 - Total system lowers free energy
 - CO₂ has increased free energy (paid internally)
- **Resin dries**
 - Releases latent free energy available in the liquid water
 - This is the only source of free energy to drive the cycle

Two Stages of Air Capture

- Contacting the air and CO₂ absorption
 - Processes air
 - costs scale with dilution ($1/C$)
- Sorbent regeneration and CO₂ compression
 - Processes sorbent
 - Costs scale with log of CO₂ concentration ($\log C$)

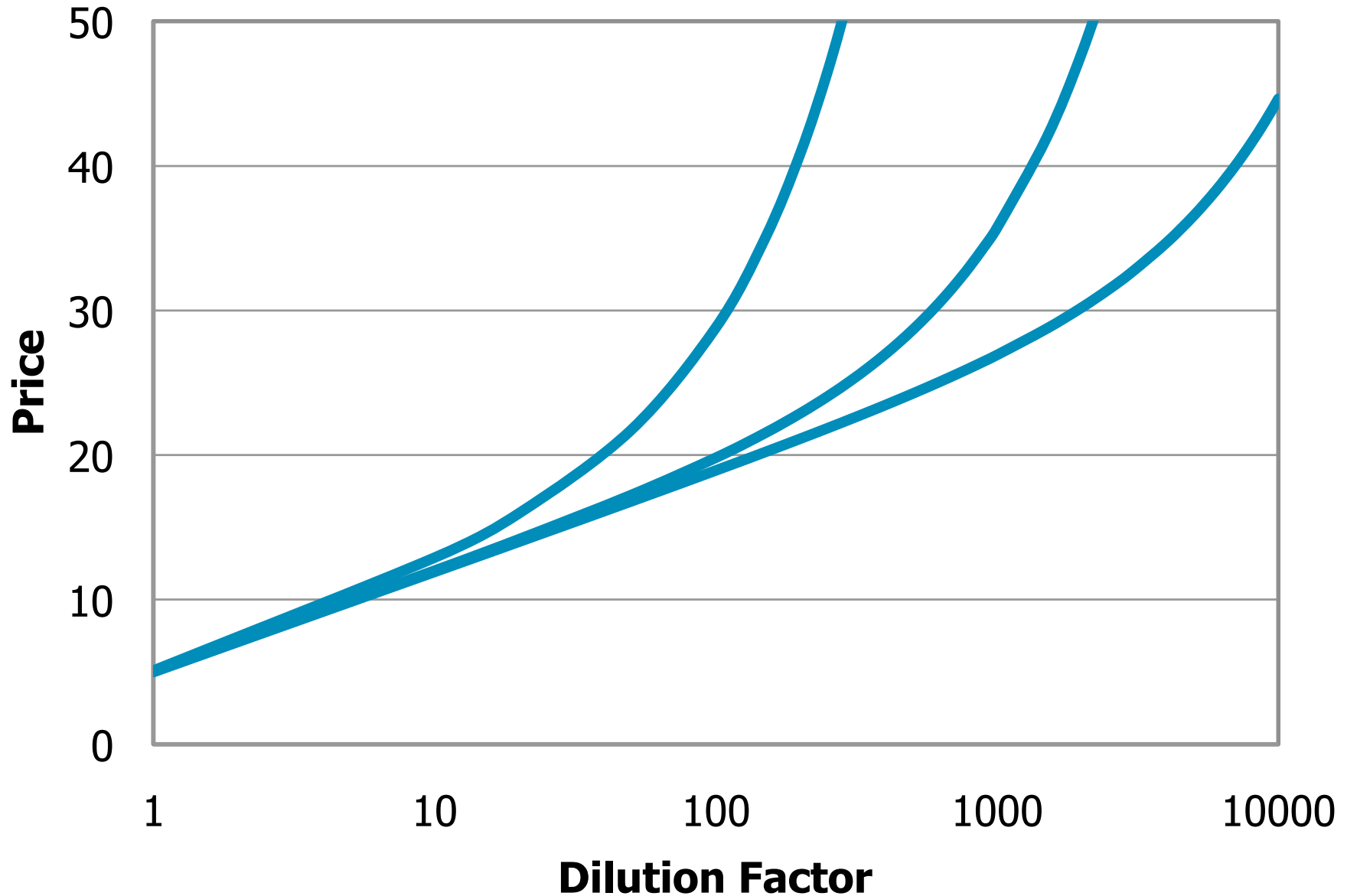
Cost Scale with Dilution

- Cost C as function of dilution $D = 1/P$

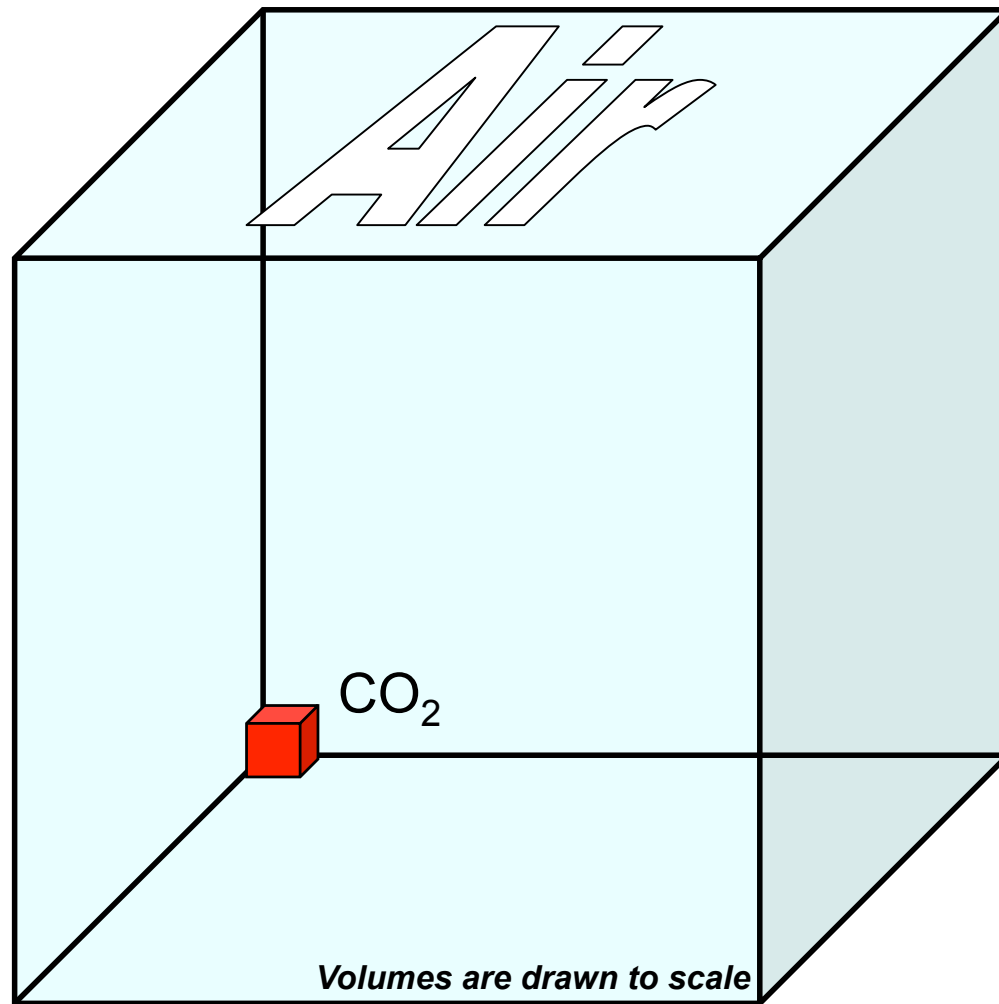
$$C = C_1 D + C_2 + C_3 \log D$$

- Constants depend on technology choice
 - C_1 : contacting the air stream
 - Passive system sitting in the wind
 - C_2 : handling of sorbent material (transport etc.)
 - Likely small, can be very much limited
 - C_3 : sorbent regeneration
 - Not much different from flue gas scrubbing
-

Sketching the cost function



CO₂ Content of Air



1 m³ of Air

40 moles of gas, 1.16 kg

wind speed 6 m/s

$$\frac{mv^2}{2} = 20\text{J}$$

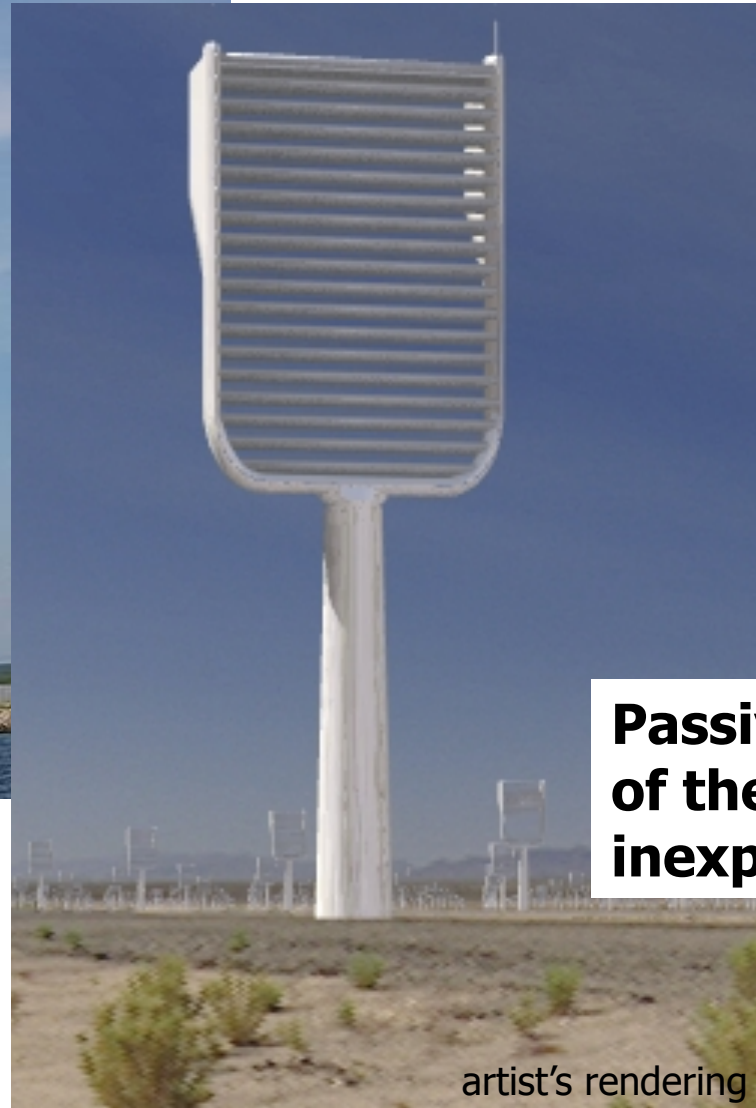
0.016 moles of CO₂

produced by **10,000 J** of gasoline

C_1 can be small: wind energy – air capture



Air collector reduces net CO₂ emissions much more than equally sized windmill



**Wind energy
~20 J/m³**

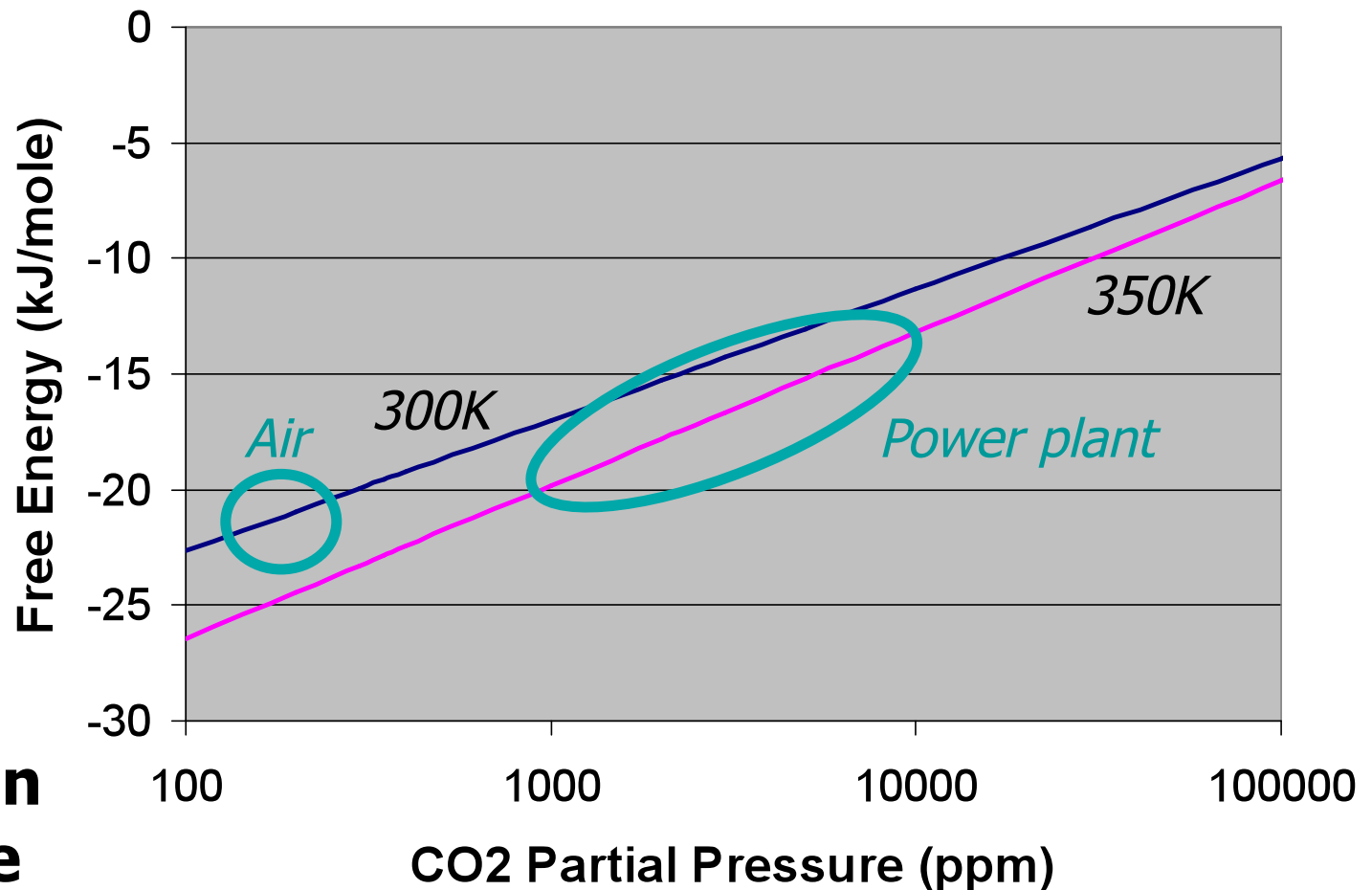
**CO₂ combustion
equivalent in air
10,000 J/m³**

**Passive contacting
of the air is
inexpensive**

Sorbent Strength

depends logarithmically on CO₂ concentration at collector exit

$$\Delta G = RT \log P$$



Sorbent regeneration is expensive

C₃ comparison: flue gas scrubbing – air capture

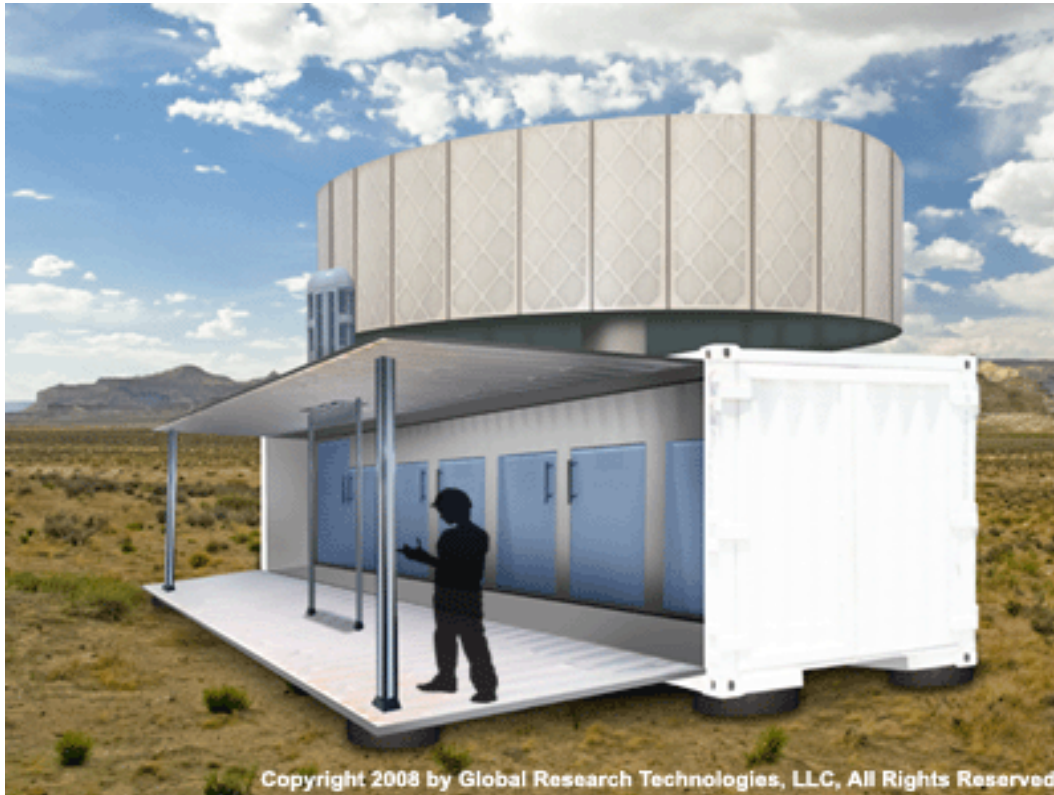


Sorbent regeneration slightly more difficult for air capture than for flue gas scrubbers



Dominant costs are similar for air capture and flue gas scrubbing

Setting the scale for 1 ton/day



- 2 × 30 panels
 - 2.5m × 1m × 0.3m
- 2 × 2500 kg of resin
 - 10,000m² of surface
- 6 × Chambers
 - 4m³ each
- One Container
 - 86m³
 - can hold all panels

Assembly line based automation
