Direct Air Capture Advances and Context

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the center for negative carbon emissions

ASU IRA A. FULTON SCHOOLS OF engineering

CO_2 piles up like garbage

Carbon stays in the air

- No single lifetime for CO_2
- Half of the CO_2 will be around for centuries
- A quarter will last for millennia
- Ocean warming balances ocean absorption for a millennium

Need a balanced carbon budget

- Uptake by natural sinks depend on rising atmospheric CO_2


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WHAT GOES UP DOESN'T COME DOWN.
CO2 EMISSIONS STAY IN THE ATMOSPHERE FOR CENTURIES.
Scientists are normally a very conservative bunch. So why are almost all climate scientists so alarmed by our current course of rising fossil fuel emissions?
Here's why: carbon emissions from fossil fuels will stay in our atmosphere, warming the planet for many centuries. While most pollutants go up and come back down or dissipate in a short time, on the human time frame, carbon is forever.
There is already so much excess carbon trapping heat that polar ice and mountain glaciers worldwide are melting. Rainstorms and droughts are intensifying. Oceans are acidifying, threatening the food chain. Each year we add more, and it doesn't come out of the system for a very long time. We are rapidly running out of room for it.
Meanwhile, scientists have created a "carbon budget" to estimate how much more CO2 the atmosphere can tolerate before temperatures threaten civilization, freedom and prosperity. At the current rate of fossil fuel use, PricewaterhouseCoopers has calculated that budget (to keep the world below 2 degrees Celsius of warming) will be used up in just 20 years.
If we bust this budget to burn more of earth's known fossil fuel reserves, the climate will become intolerable. If this sounds like things are becoming serious, it's because they are. There is a conservative, market-based, pro-growth solution to this. More on that soon and at pricecarbon.org.
PARTNERSHIP FOR RESPONSIBLE GROWTH
www.pricecarbon.org | For a Free Market Solution to Climate Change
*Sourcing can be found at www.pricecarbon.org

Waste Disposal Paradigm

- No contradiction with utilization, efficiency and reliance on renewable energy
- Reduce, Reuse, Recycle
- Value derives from disposal requirement

Need same association for CO_2

Is the world's carbon credit card in overdraft ?

- **Stop at 2°C warming**
  - 450 ppm or 450 ppm_e
  - Currently ~440 ppm_e 400 ppm
  - Annual increase 2.0 … 2.5 ppm/yr
- **Current emissions:**

  ~ 36 billion tons of CO2 per year

  15 billions tons = 1 ppm

  i.e., half of the CO_2 stays

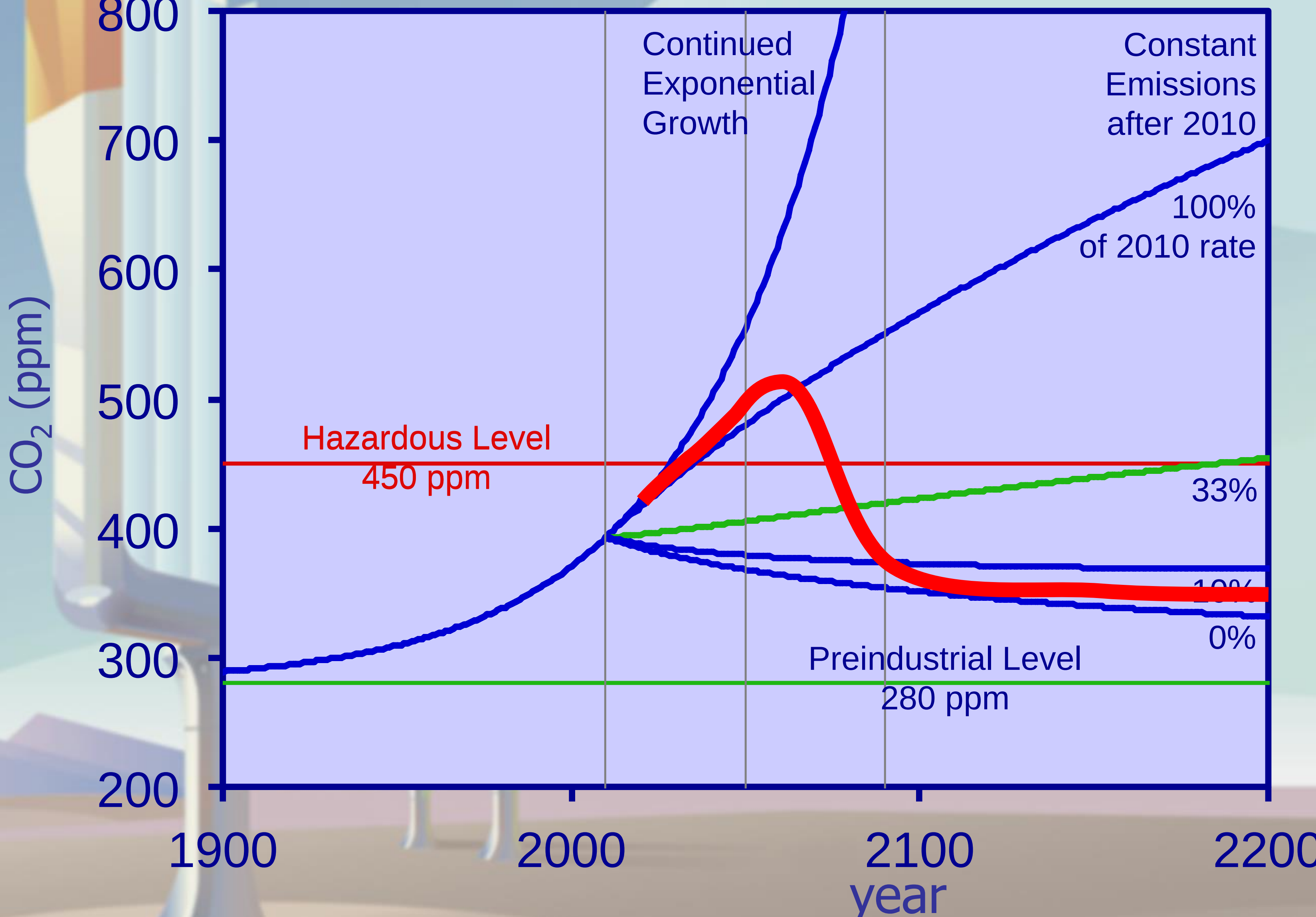
The personal carbon allowance

~ 30 tons C for every person will lead to 450 ppm

Total permanent allotment

Picture from emercedes online blog: http://www.emercedesbenz.com/Aug08/08_001327_Mercedes_Benz_Econic_Semi_Trailer_Tanker_Trucks_Enter_Service_At_London_Farnborough_Airport.html

IPCC calls for negative emissions



Air Capture of CO_2

- **Air capture eliminates exceptions**
  - No emission source need remain exempt
  - Separates sources from sinks
  - Carbon democratization
- **Air capture can draw down CO_2**
  - Paying back carbon overdraft
  - Requires vast CO_2 storage capacity for sequestration
- **Air capture central for non-fossil liquid fuels**
  - Synthetic fuel production from CO_2 and H_2O
  - Provides energy storage & liquid fuels
  - Requires cheap non-fossil energy
- **Air capture with fossil liquid fuels**
  - Carbon use balanced by sequestration
  - Requires cheap CO_2 storage

Markets will determine the balance between these options

Difficulty of gaining acceptance for air capture

- **No need for air capture**
  - Climate skeptics: no need to spend resources
  - CO_2 short lifetime perspective: CO_2 levels will drop without help

CO_2 accumulates in the air, therefore, there is a limit on CO_2 emissions even if the exact number may still be debatable.

- **Moral hazard of air capture**
  - Social Engineer: technology delays necessary life style changes
  - Renewable Advocate: DAC delays renewables

Withholding a solution to a potentially catastrophic change in climate is irresponsible. Moreover, air capture enables renewable energy.

- **Forces unwanted attention or action on current business practice**
  - Oil companies: Focus on CO_2 from coal

Regulations should treat all CO_2 emissions equal.
No reason to make an exception for transportation fuels.

- **Not economically feasible**
  - Chemical Engineers: Sherwood's Rule implies too high a cost

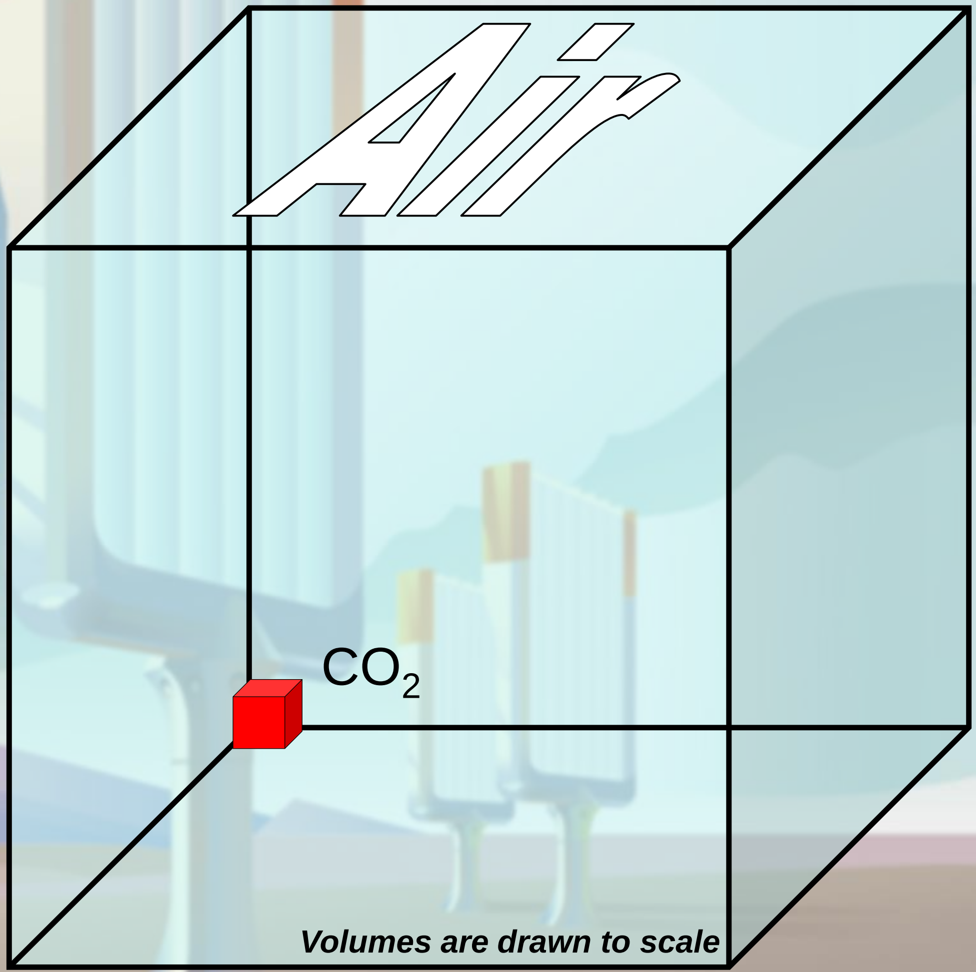
Technology demonstration, active research, and reasoned arguments. Sherwood's Rule is not a LAW. Public demonstration!

Air capture is sorbent based

- **Sorbents bind CO_2 without spending energy on the air**
  - Concentration ratio is 1 : 2500
    - Sorbents postpone work to the regeneration step
    - Only do work on CO_2
- **All air capture sorbents are chemical sorbents**
  - At 400 ppm only chemical bonds are strong enough
  - Minimum free energy of binding: $\Delta G > 22$ kJ/mol
- **All air capture sorbents exploit carbonate chemistry**
  - Alkali hydroxides
  - Weak and strong based amines
  - Thermal, vacuum and reaction based recovery
  - Humidity swing takes advantage of H_2O – CO_2 – sorbent reactions

CO_2 Content of Air

1 m^3 of air contains CO_2 and wind energy



40 moles of gas, 1.16 kg
wind speed 6 m/s

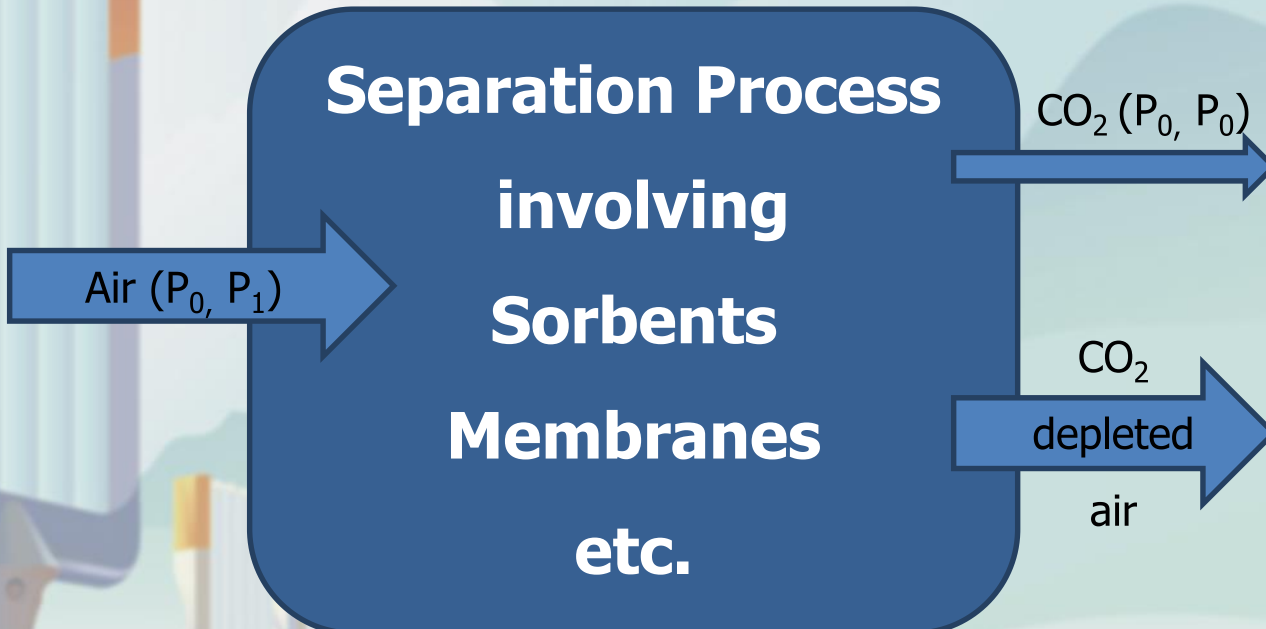
$$\frac{mv^2}{2} = 20\ \text{J}$$

0.016 moles of CO_2
produced by
10,000 J of gasoline

Thermodynamics checks out

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

Gas pressure P_0
CO_2 partial pressure P_x
Denoted as (P_0, P_x)



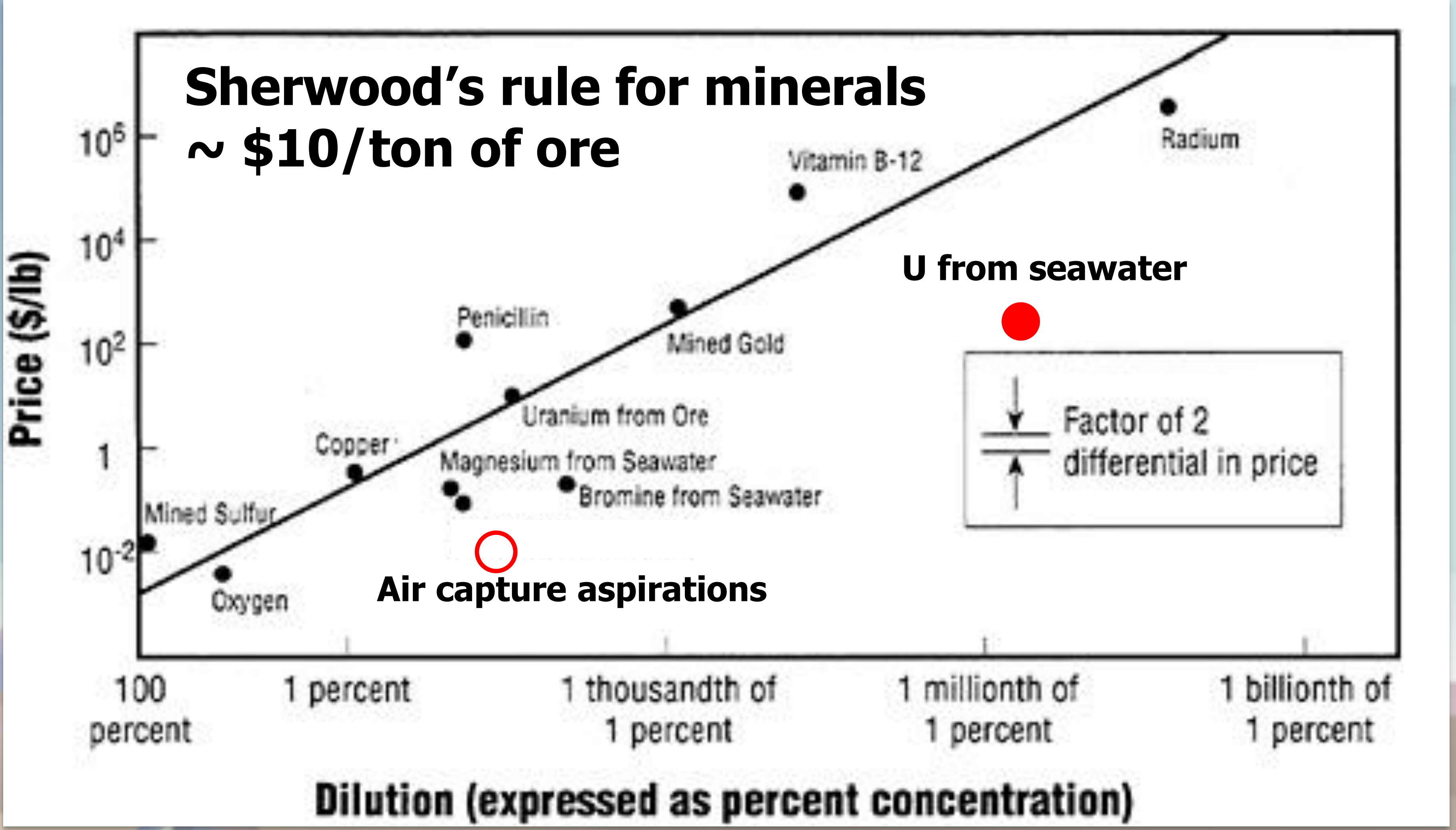
$$\Delta G = RT\left(\left(\frac{P_0 - P_2}{P_1 - P_2}\right)\frac{P_1}{P_0}\ln\frac{P_1}{P_0} - \left(\frac{P_0 - P_1}{P_1 - P_2}\right)\frac{P_2}{P_0}\ln\frac{P_2}{P_0} + \left(\frac{P_0 - P_1}{P_0}\right)\left(\frac{P_0 - P_2}{P_0}\right)\frac{P_0}{P_1 - P_2}\ln\frac{P_0 - P_1}{P_0 - P_2}\right)$$

Specific irreversible implementations have higher free energy demands

22 kJ/mol for capture vs. 700 kJ/mol from release

Sherwood's Rule

A challenge for dilute values



SOURCE: National Research Council (1987)

Wind energy – Air capture

Wikipedia picture

artist's rendering

Image courtesy Stonehaven production

Wind energy
~20 J/m^3

CO_2 combustion equivalent in air

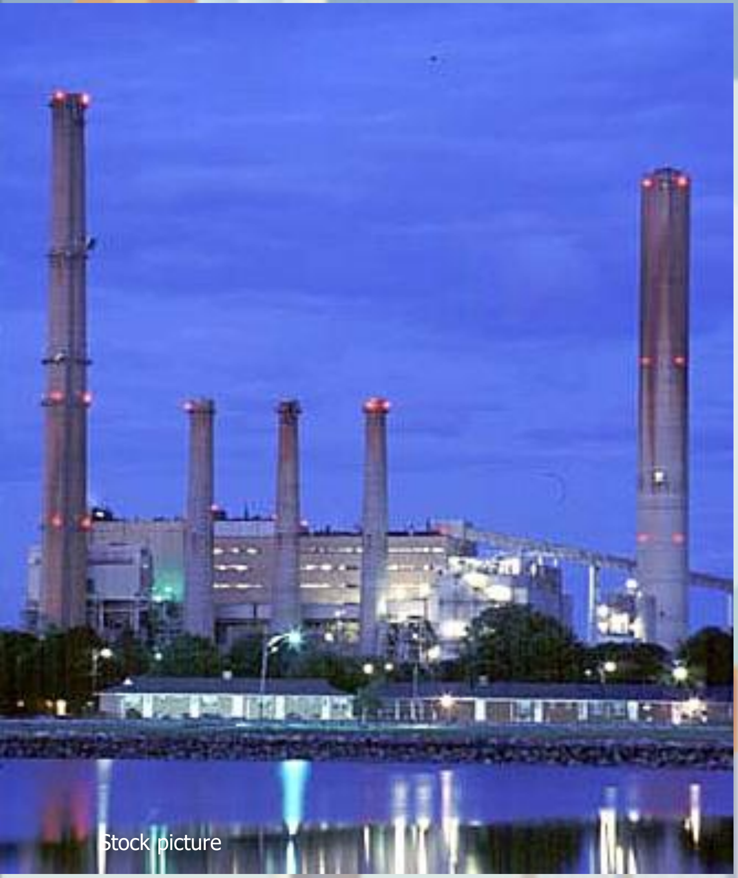
10,000 J/m^3

<u>Passive</u> contacting of air is inexpensive

Air collector reduces net CO_2 emissions much more than equally sized windmill

Extracting 20 J/m^3 seems feasible

Regenerator: Flue Gas Scrubbing – Air Capture



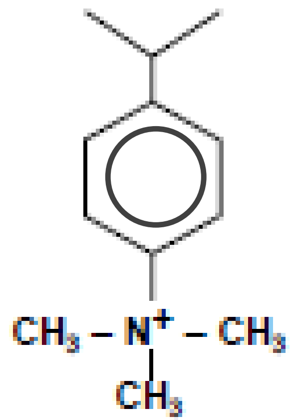
Sorbent regeneration slightly more difficult for air capture than for flue gas scrubbers

Dominant costs are similar for air capture and flue gas scrubbing

artist's rendering
Image courtesy Stonehaven production

Our Sorbent Choice: Anionic Exchange Resins

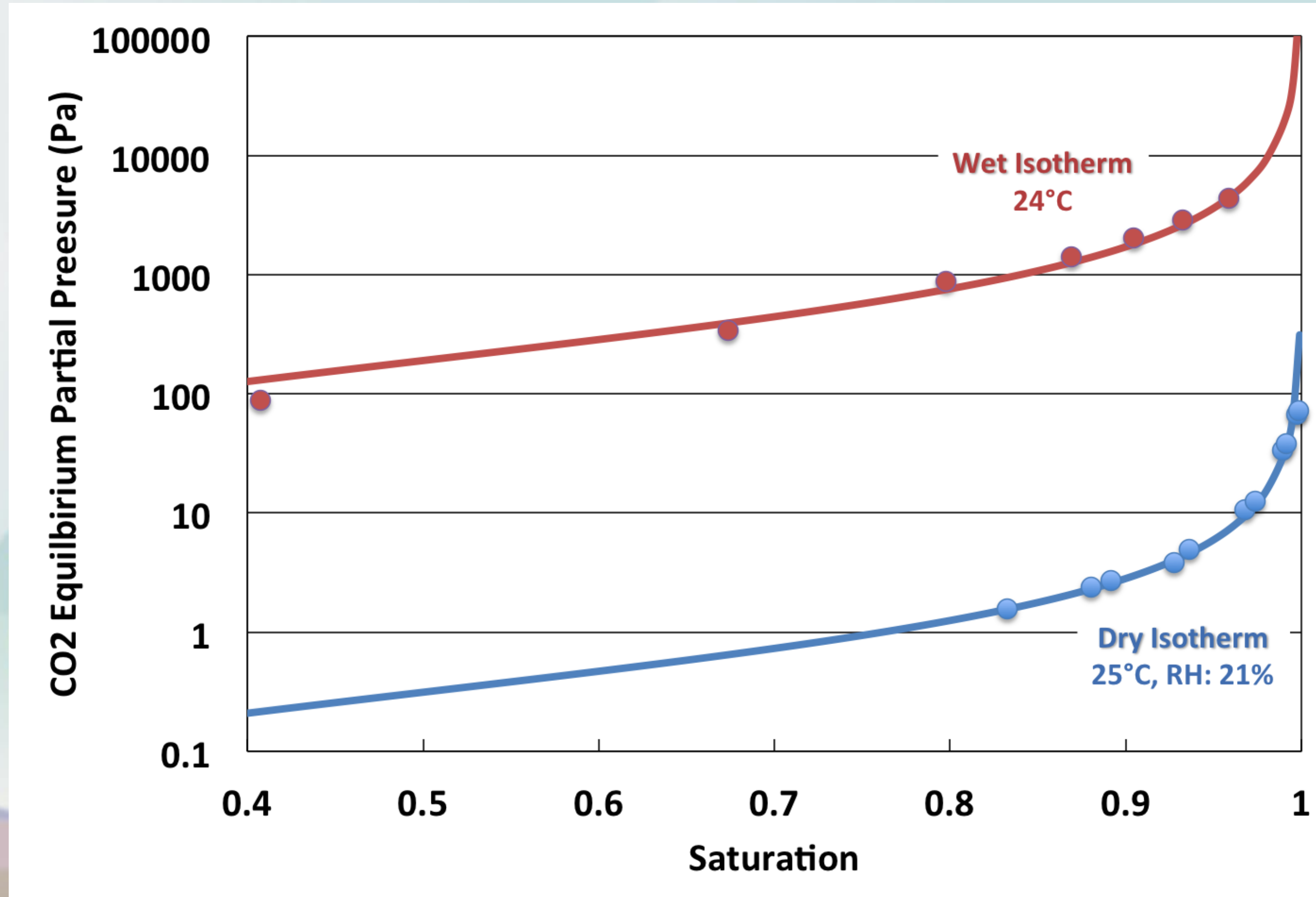
Solid carbonate "solution"
Quaternary ammonium ions form strong-base resin



- Positive ions fixed to polymer matrix
  - Negative ions are free to move
  - Negative ions are hydroxides, OH^-
- Dry resin loads up to bicarbonate
  - $OH^- + CO_2 \rightarrow HCO_3^-$ (hydroxide → bicarbonate)
- Wet resin releases CO_2 to carbonate
  - $2HCO_3^- \rightarrow CO_3^{--} + CO_2 + H_2O$

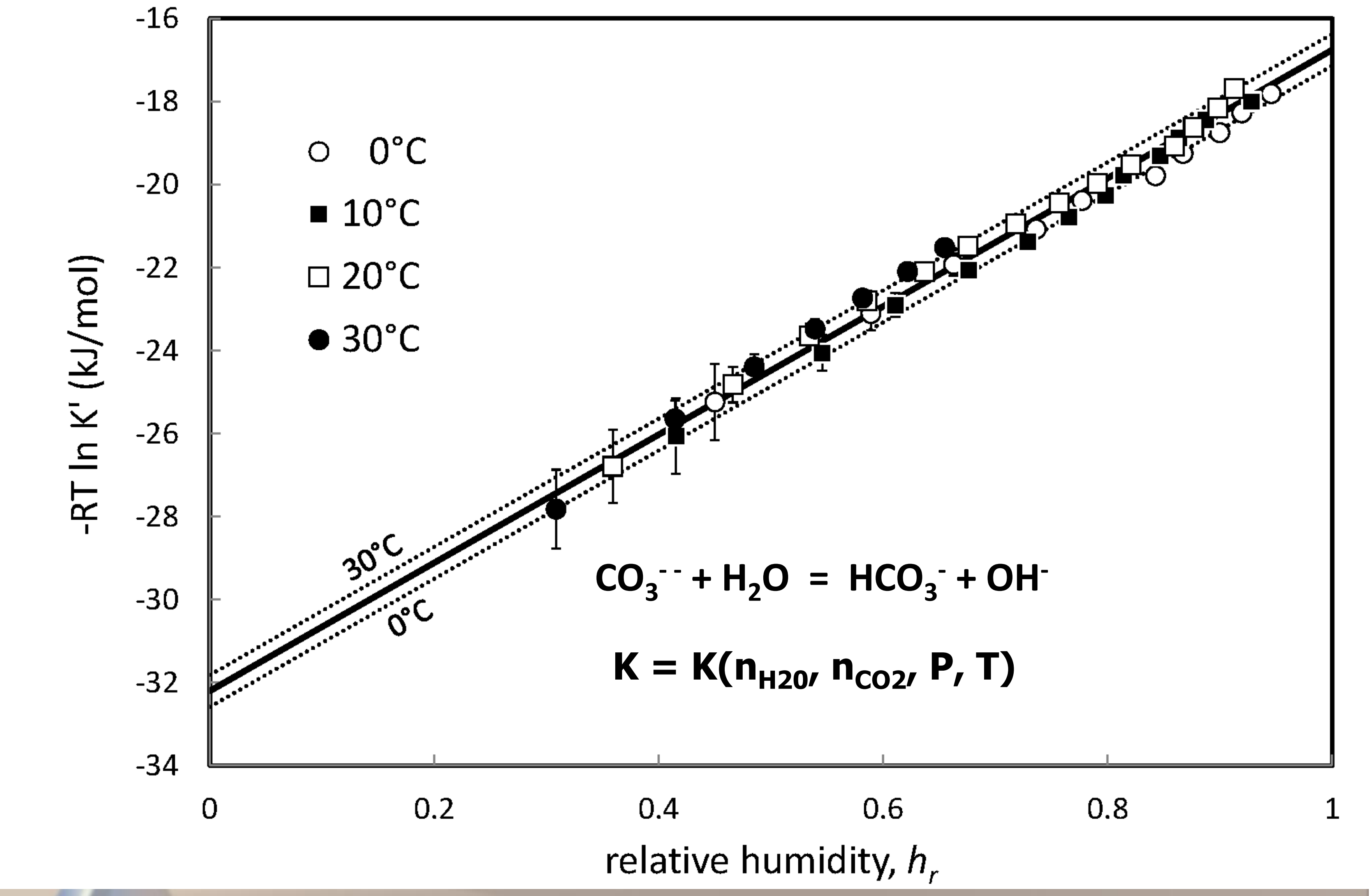
Moisture driven CO_2 swing

The Moisture Swing



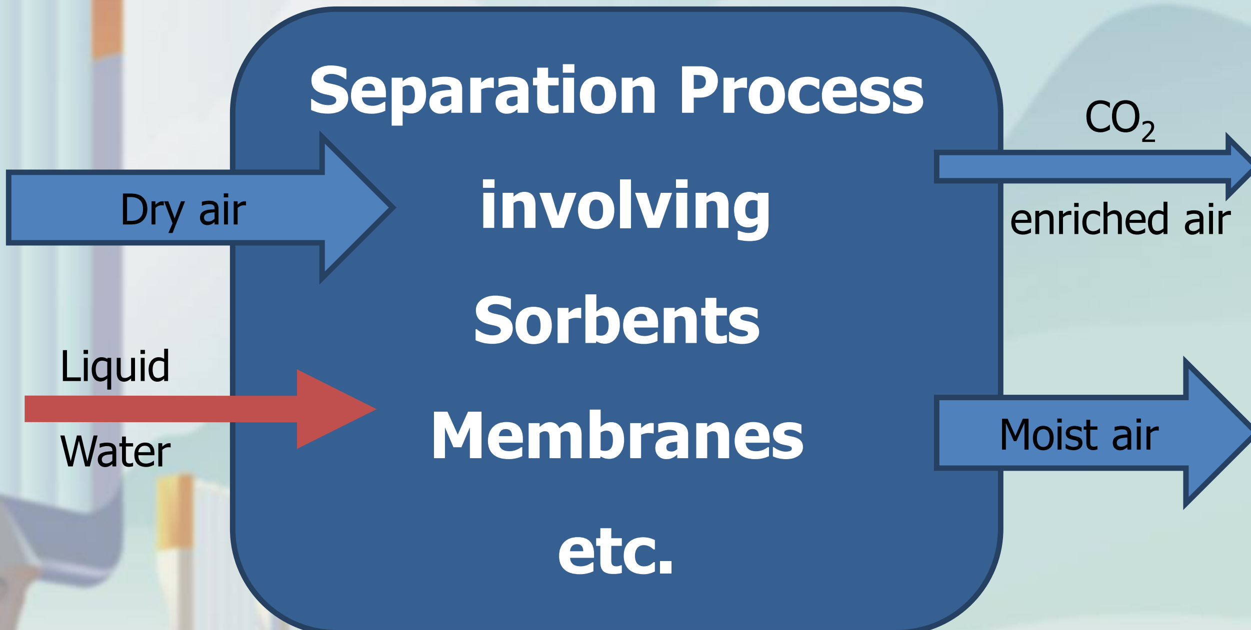
Tao Wang, Lackner & Wright

The standard free energy change



Free energy from water evaporation

Water evaporation can drive CO_2 capture



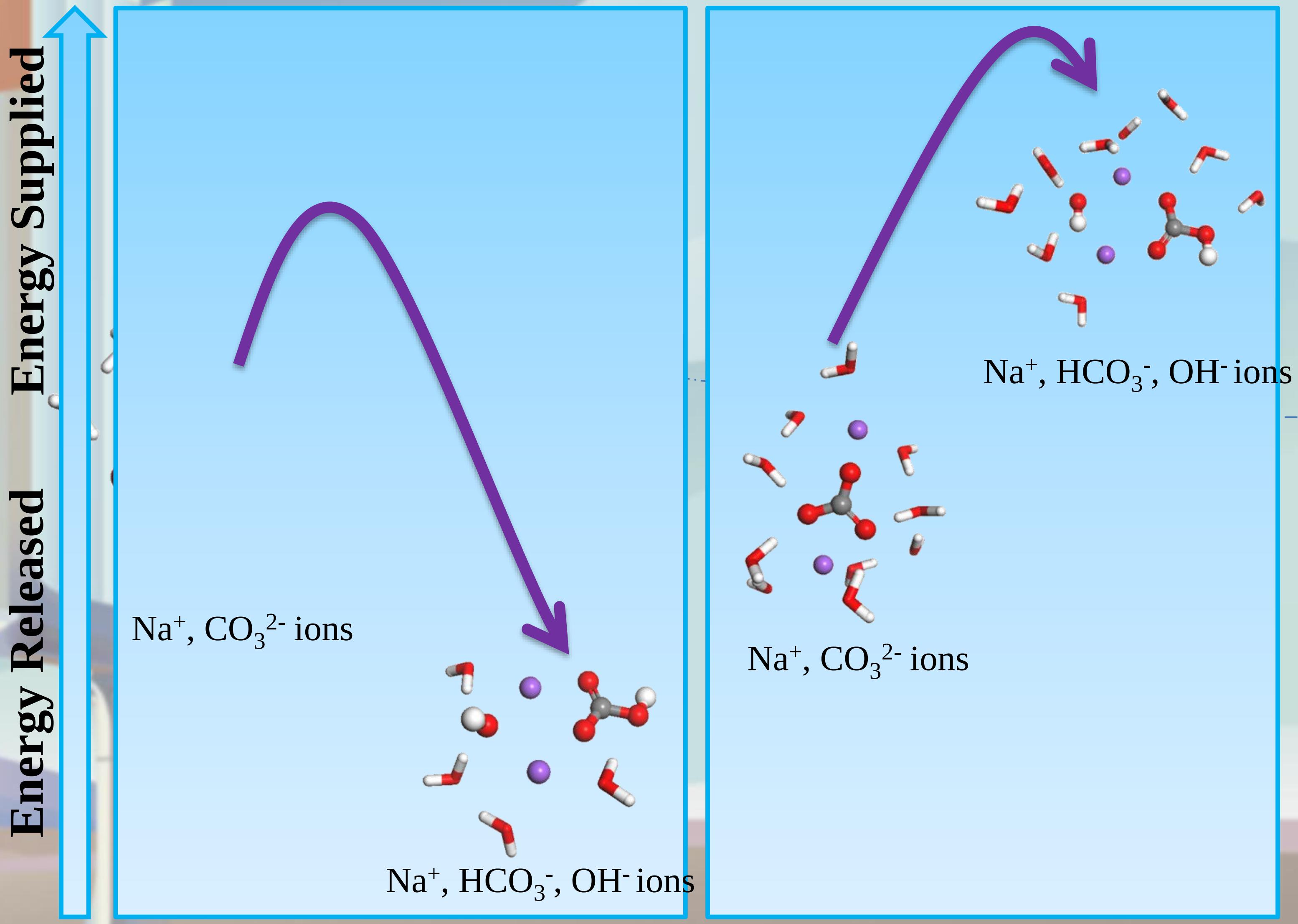
Free energy of water evaporation
at a relative humidity *RH:*
$\Delta G = RT \ln(P/P_{sat}) = RT\, ln(RH)$

Ball park estimate: 2.5 kJ/mol
140 MJ/m^3
@ 20¢/m^3 0.5¢/kWh

Transport Model

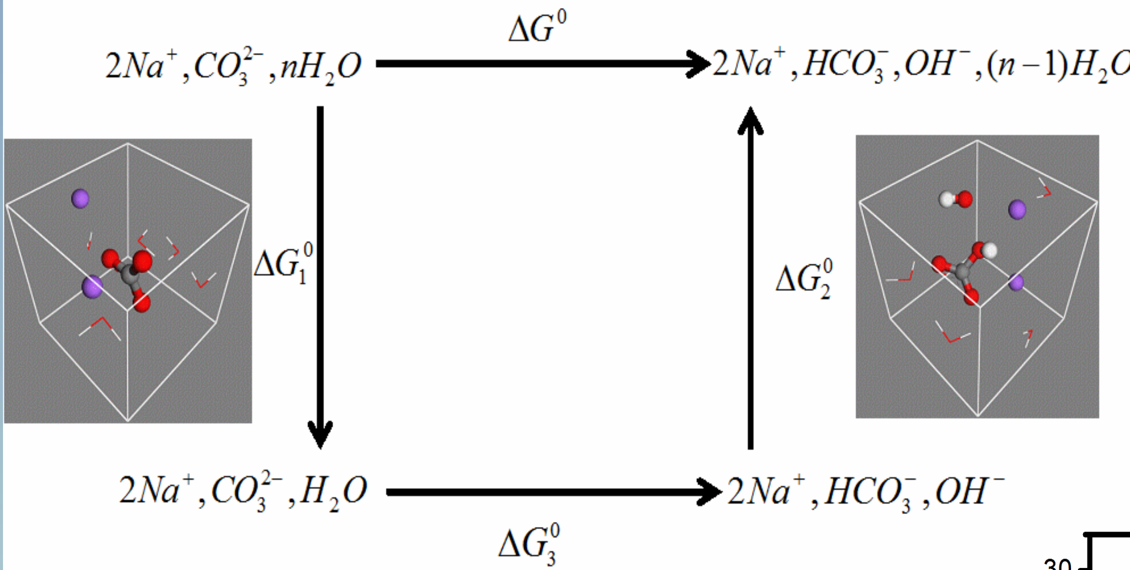
- **Numerical calculations reproduce moisture sensitivity**

Molecular Dynamics & Quantum Modeling

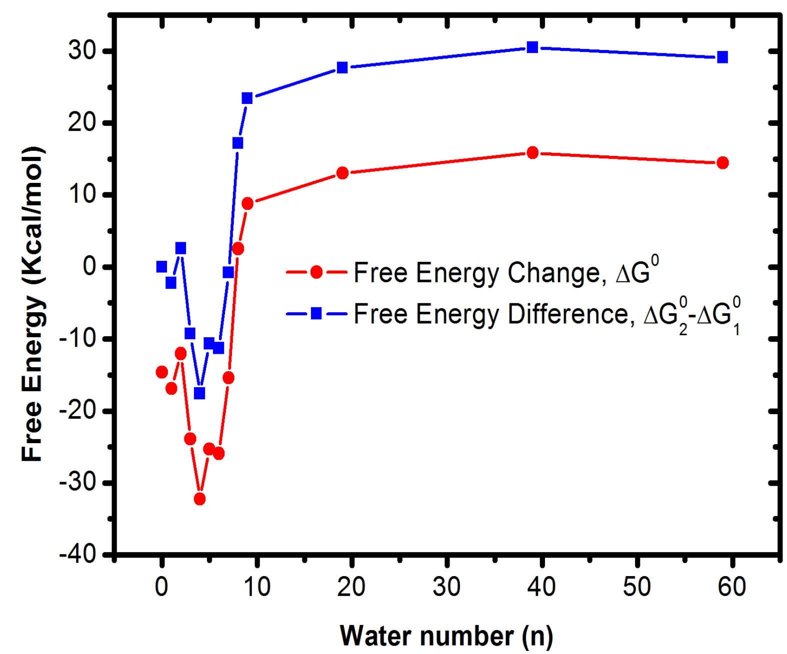


(a) Low Humidity **(b) High Humidity**

Xiaoyang Shi



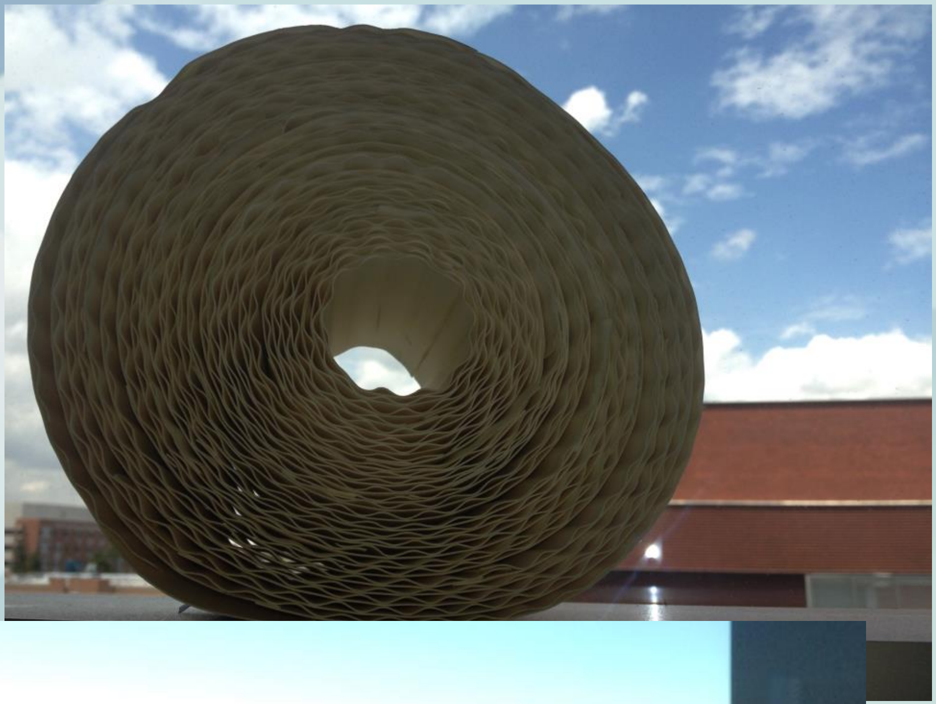
$$\Delta G^0 = \Delta G_1^0 + \Delta G_2^0 + \Delta G_3^0$$



- Moisture swing is not limited to ion exchange resins
  - Hydrophobic cell with ions
  - Water mobility
  - Anion mobility
- Moisture swing is not limited to carbonate ions

Xiaoyang Shi, Xi Chen

Filter Units



Approximation of a monolith

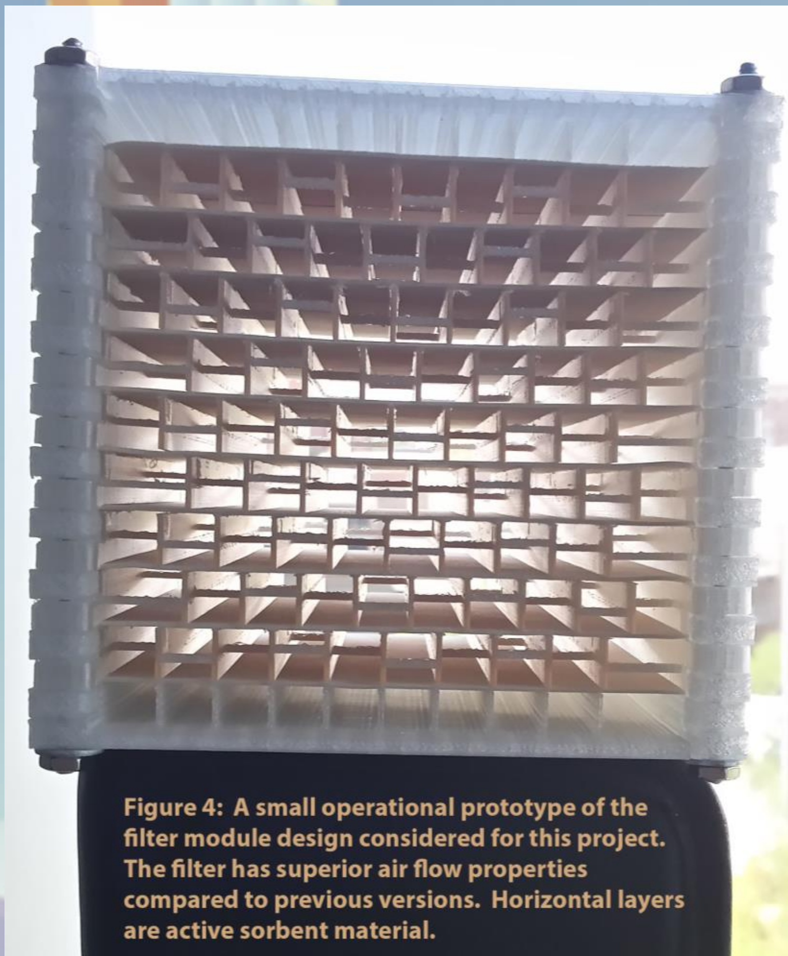
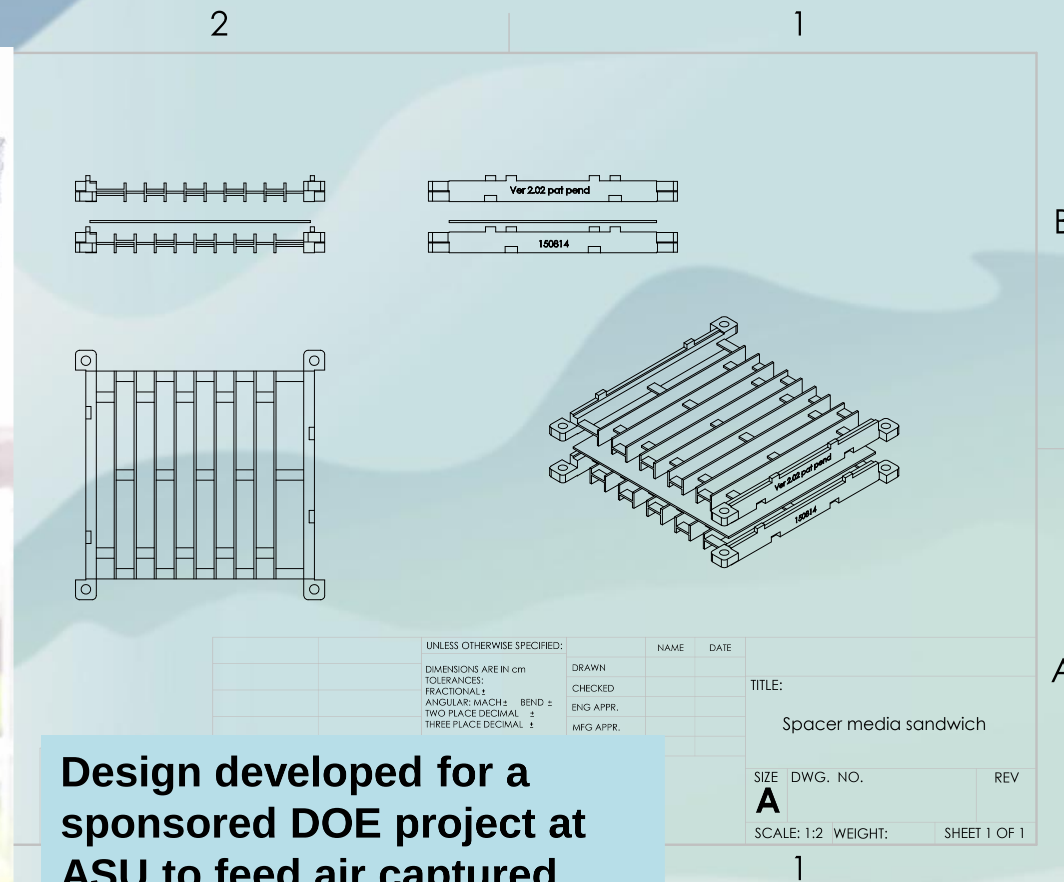


Figure 4: A small operational prototype of the filter module design considered for this project. The filter has superior air flow properties compared to previous versions. Horizontal layers are active sorbent material.



Design developed for a sponsored DOE project at ASU to feed air captured CO_2 to micro algae

Rittmann & Lackner

Slowing down the air

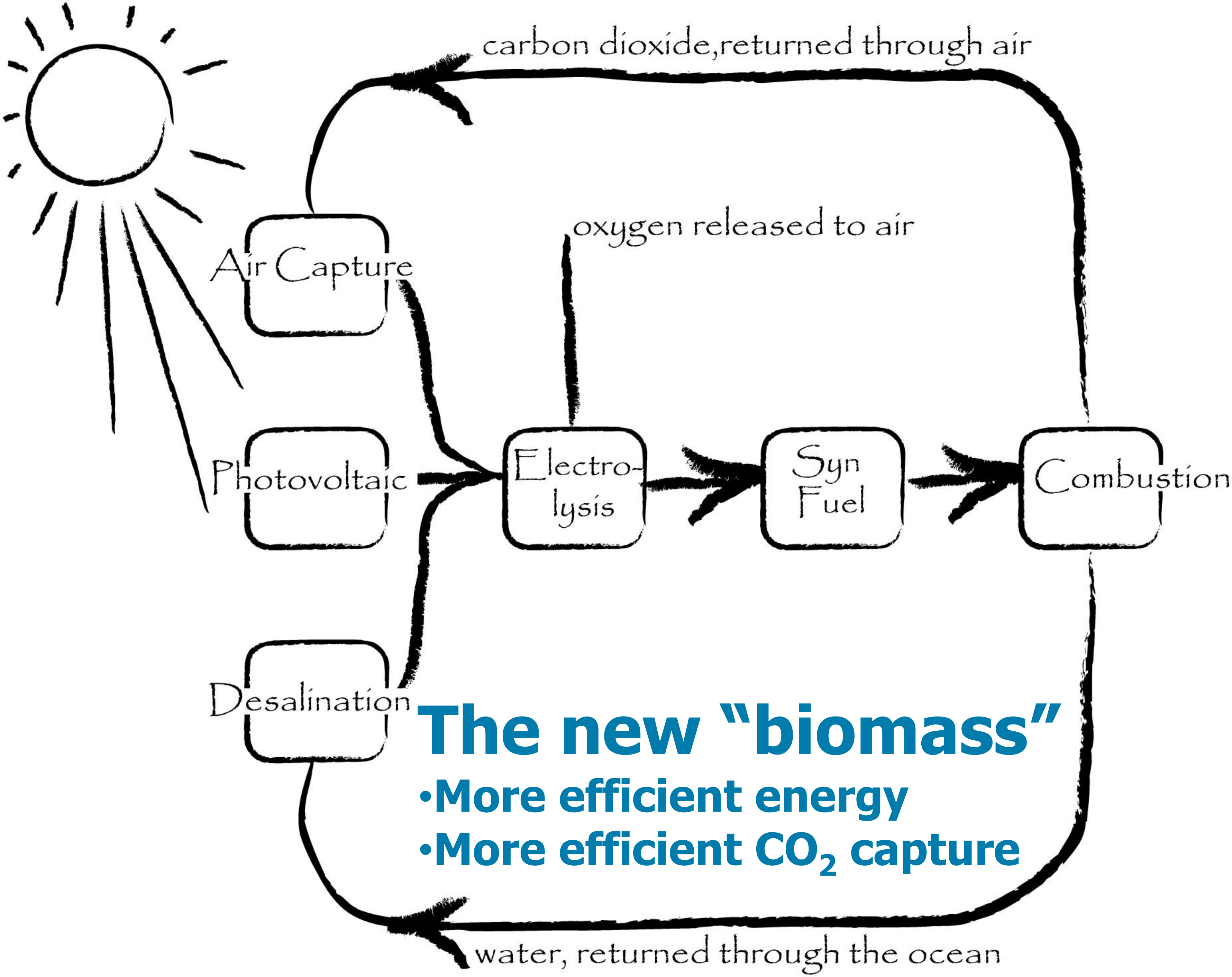
- **Air delivers momentum to the filter wall**
  - Momentum is transported by convection, turbulence, or shear viscosity
  - Viscosity = Molecular diffusion of momentum
  - Lost momentum is made up by pressure drop
  - In narrow passage, momentum loss is linear with distance
- **Air delivers CO_2 to the filter wall**
  - CO_2 is transported by convection, turbulence, or molecular diffusion
  - Lost CO_2 is not made up
  - In narrow passage, CO_2 loss is exponential

Same transport law, different boundary conditions

CO_2 uptake

- **If the pressure drop is ρv^2 one can collect the CO_2**
- **First step toward a design**
- **Monoliths, and slow flows**

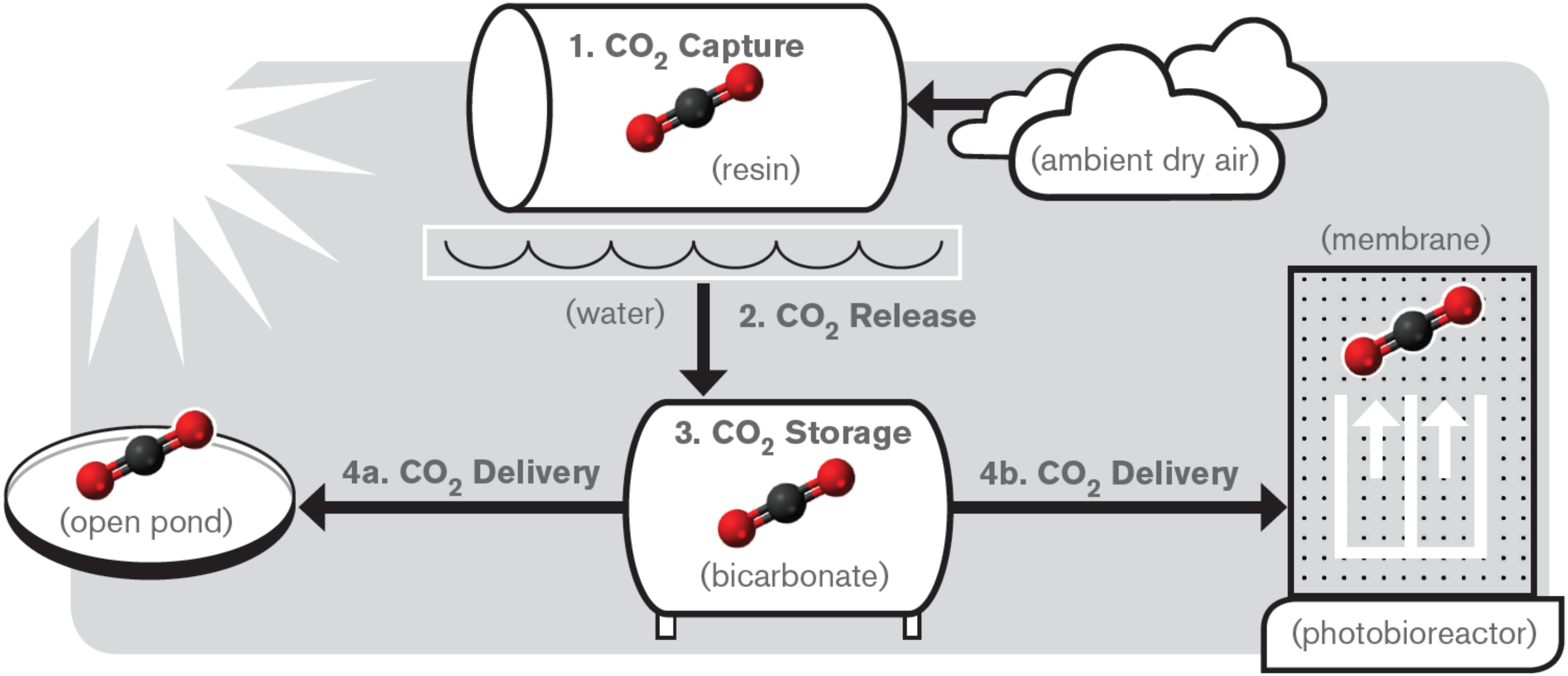
First Outdoor Operation



The new “biomass”

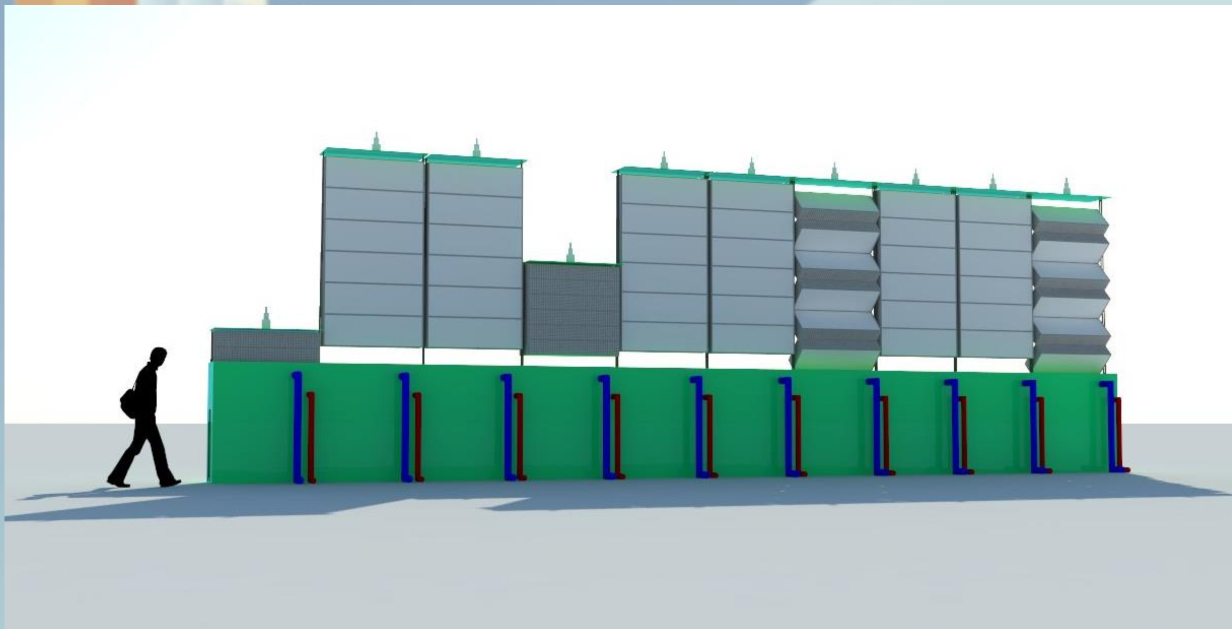
- More efficient energy
- More efficient CO_2 capture

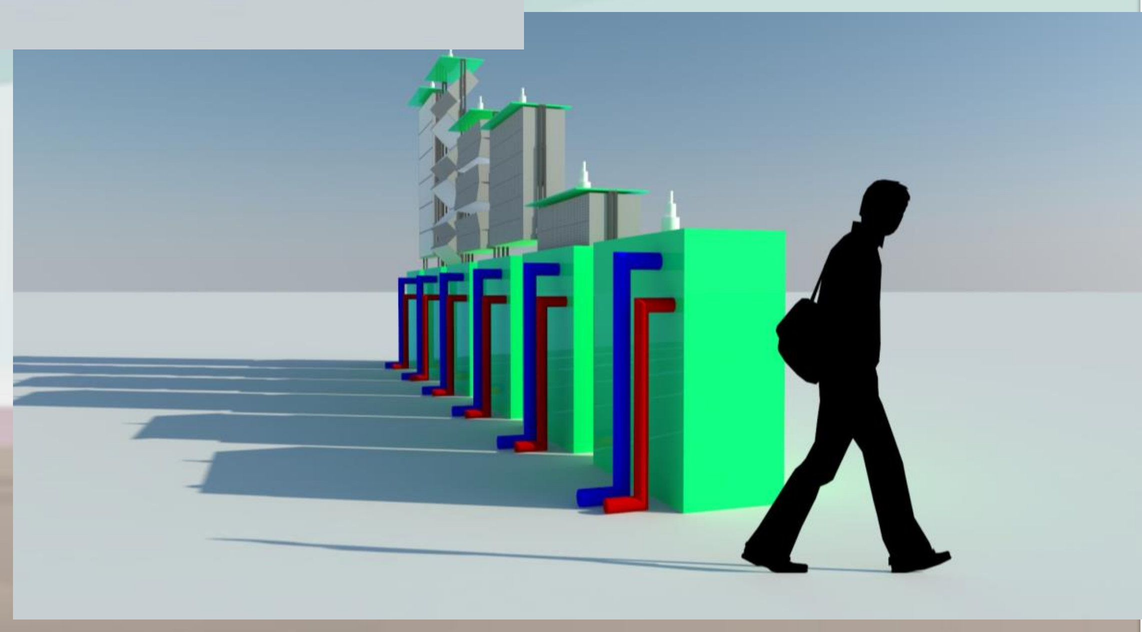
Atmospheric CO_2 Enrichment and Delivery for Algae Bioreactors



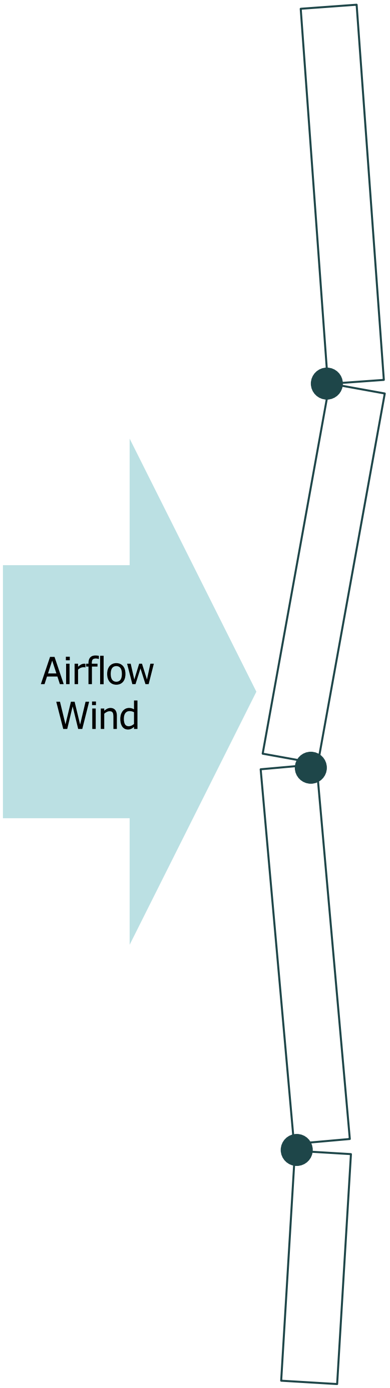
- **Capture atmospheric CO_2; concentrate into stream of 3 – 10% CO_2**
- **CO_2 storage buffer to ensure adequate supply at any time**
- **Bubble-less CO_2 delivery: >90% to media, >70% to biomass**

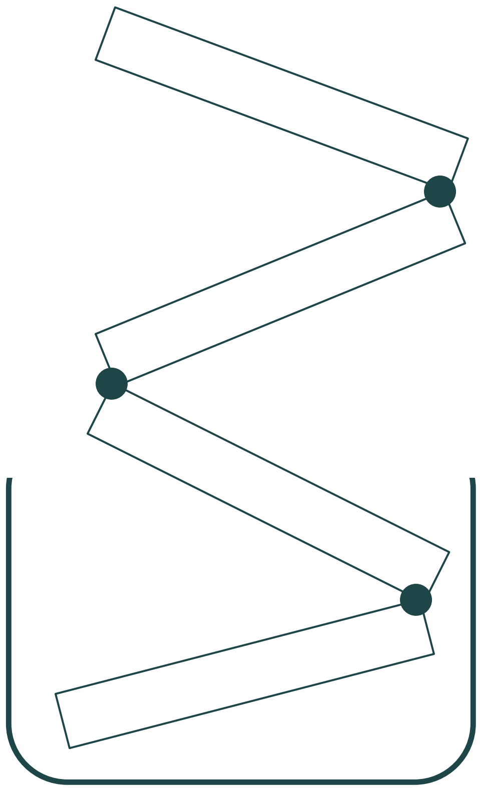
Sail-like structures

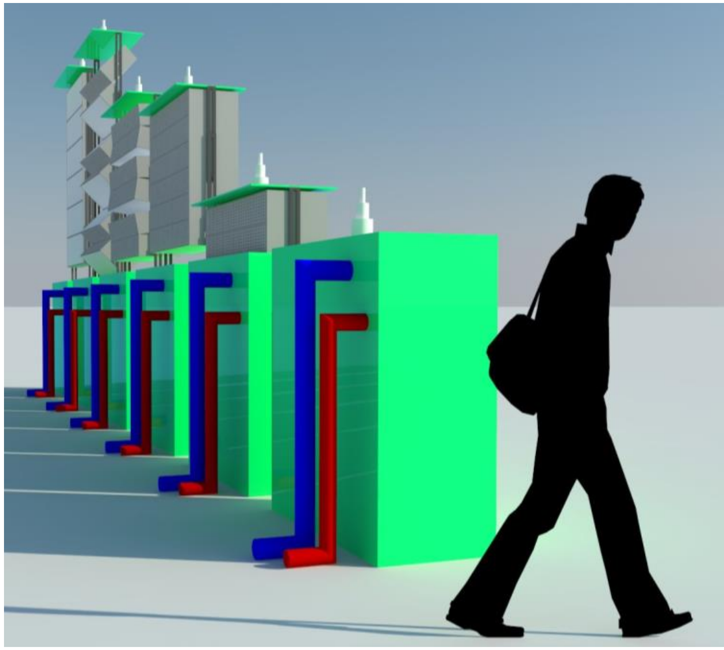


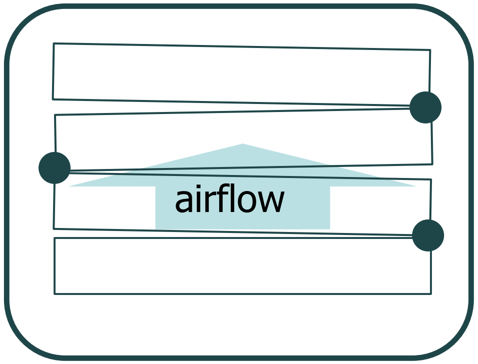


Accordion shape of the collector unit

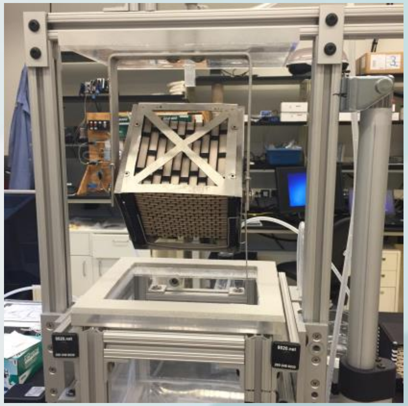








Working on hardware



How to move to scale?

- **Rely on learning**
  - Mass production approach
- **Find markets**
  - Small commercial niches
- **Create value proposition**
  - Value is ultimately derived from cleanup
    - Waste management paradigm

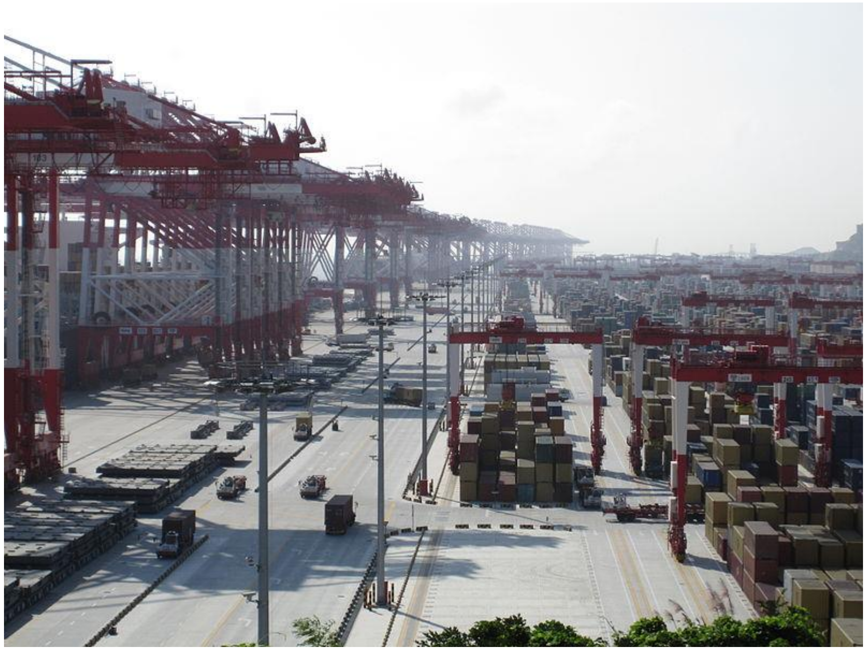
Technology can reach global scales with proper market incentives

Mass-produced factory-built one-ton-per-day units

100 million units would eliminate current world emissions

Production capacity needed: 10 million per year

Required production capacity common on world scale



Shanghai harbor processes
30 million full containers a year

World car and light truck production:
80 million per year

wikipedia pictures

Low cost comes with experience

$600
Per ton CO_2

APS (low tech, first-of-a-kind)

$500

$400

$300

GRT (first-of-a-kind)

$200

$100

Practical interest

Raw material and energy limit (frictionless cost)

$0

The Power of the Learning Curve

Ingredient costs are already small – small units: low startup cost

Wikipedia pictures

A Balanced Carbon Budget

- **Negative emissions take CO_2 back from the environment**
  - Paying back old carbon debts
  - Large-scale air capture with sequestration
- **Fossil carbon extraction is balanced by sequestration**
  - Maintaining access to vast energy resources
- **A circular carbon economy produces carbon-based synthetic fuels and infrastructure materials from CO_2**
  - Tying together intermittent renewable energy, fuels and material resources

Air capture is the common technology gap of all three components of this vision

Value in keeping carbon out of the environment

Public Demonstration Of Technology Fix

- **Open public/private effort**
  - Transparency helps convince policymakers
  - Accelerates market formation
- **One ton per day device demonstration**
  - Open and visible
- **Three year - $20 million concerted effort**

Just like renewable energy, direct air capture needs advocates and a coherent vision

We owe our children not only continued access to energy but also an atmosphere free of garbage

There is more than one air capture technology