Balancing the World's Carbon Emissions

Klaus S. Lackner
Arizona State University
March 2016

the center for negative carbon emissions

ASU IRA A. FULTON SCHOOLS OF engineering

Paris Agreement COP 21

- Hold warming below 1.5°C?
  - How close is this limit? 400 – 450 ppm

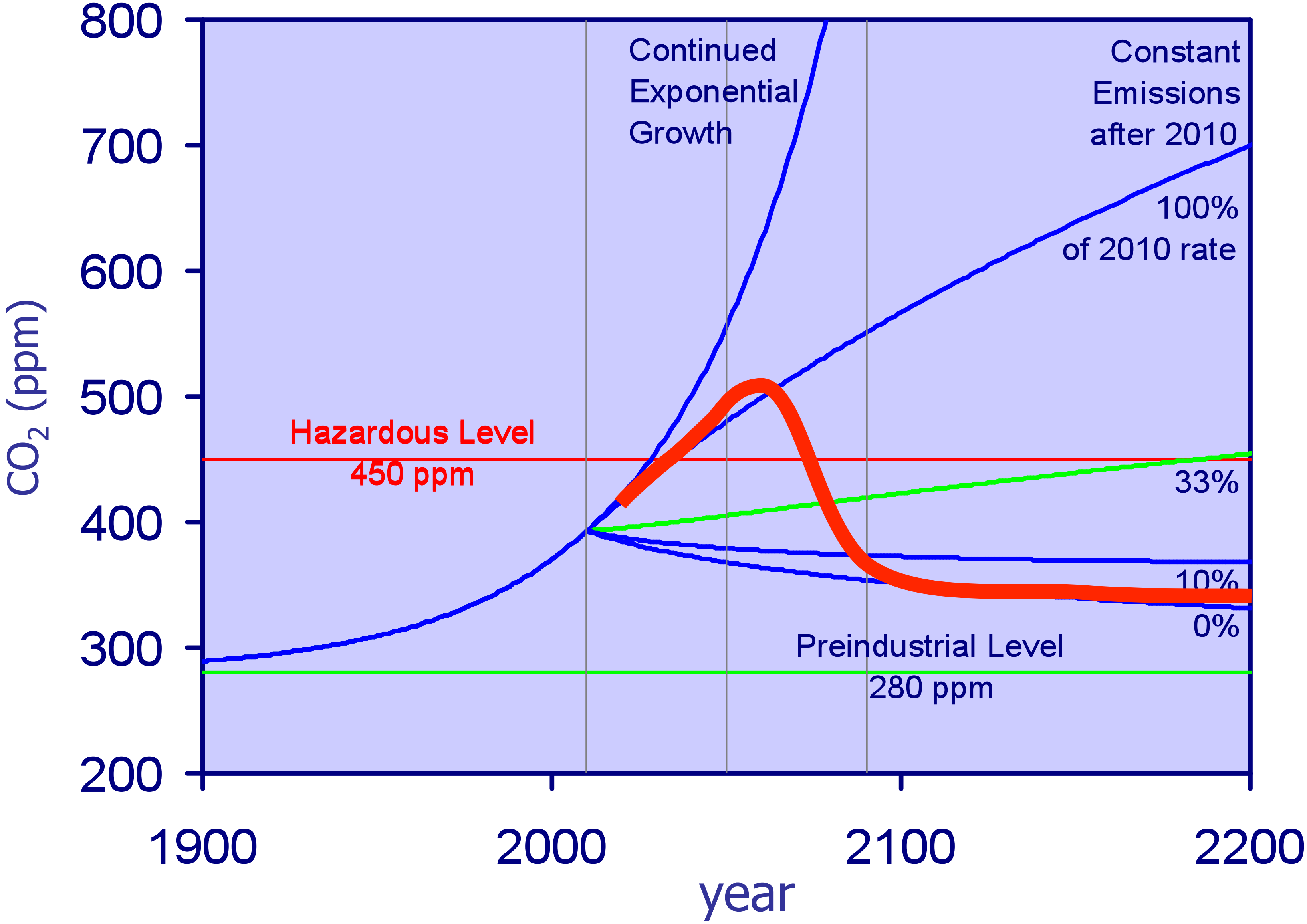
- Hold the line at 2.0°C!
  - IPCC calls for negative emissions 450 – 500 ppm

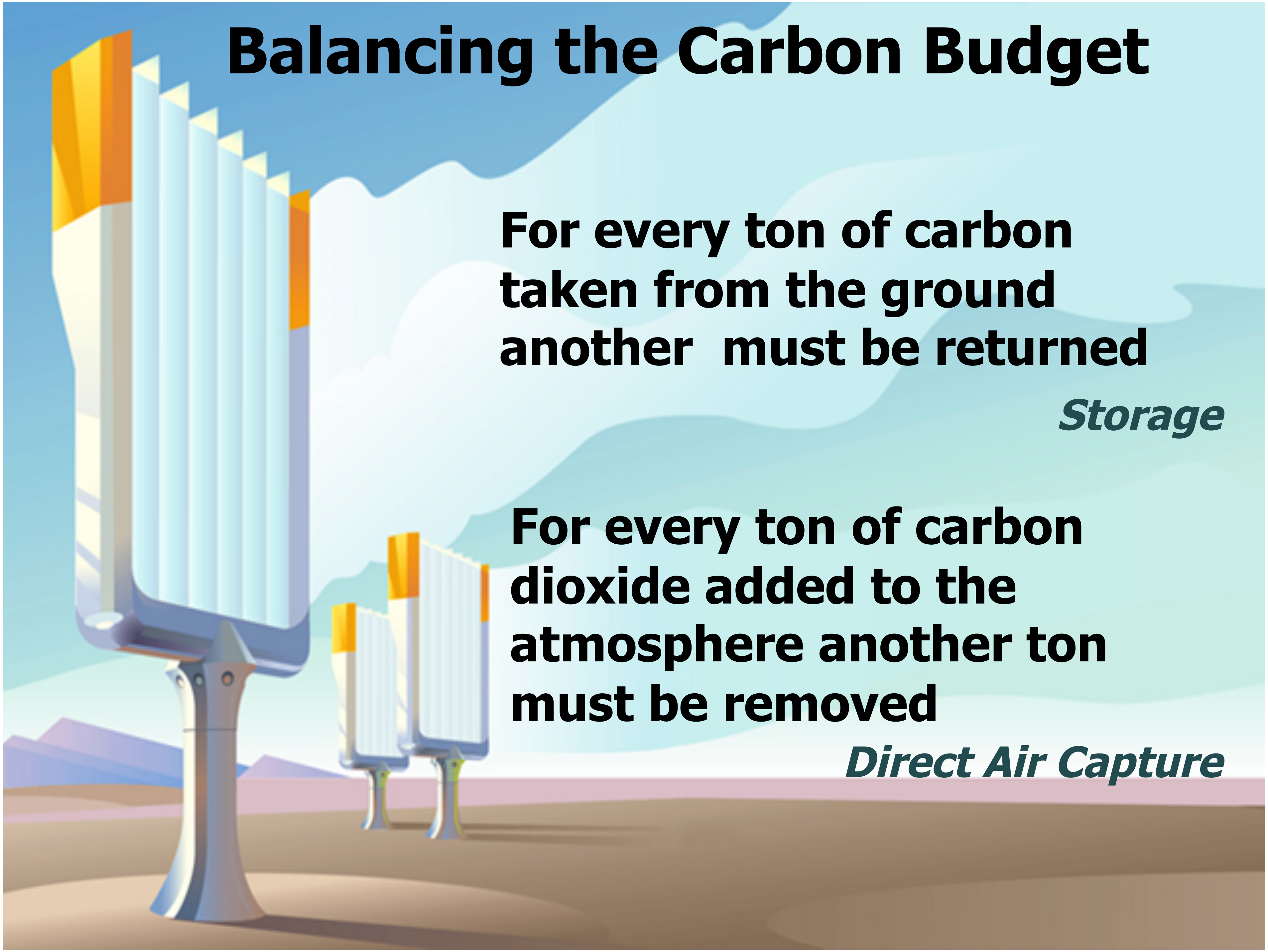
Promised actions do not match ambitions

Safely changing energy infrastructures takes time

Public domain image taken from the internet

IPCC calls for negative emissions




Balancing the Carbon Budget
For every ton of carbon taken from the ground another must be returned
Storage
For every ton of carbon dioxide added to the atmosphere another ton must be removed
Direct Air Capture

Negative carbon emissions

- **Retrieval of carbon from environment**
  - Direct removal of CO_2 from air or ocean, BECCS, etc.
- **Large demand for carbon dioxide disposal**
  - Euphemistically called storage
  - 100 ppm reduction implies ~ 400 Gt C or ~1500 Gt CO_2
    - Ocean will return its carbon
- **CCS proven reserve needs to be built up from scratch**
  - Negative emissions create enormous demand stress
  - Biggest argument against continued use of fossil fuels
  - Coal use will be eliminated or postponed?

Ask when – not if – CCS is needed

Waste Disposal Paradigm

- **CO_2 dumping in the atmosphere needs to stop**
  - Reuse, reduce, recycle alone cannot achieve goal
- **Analogy to other waste management**
  - sewage systems - health imperative
  - garbage collection – environmental/health imperative
  - highway litter removal – aesthetic/environmental
- **Less litter generation does not permit littering**
  - Emissions must stop
  - Reuse, reduce recycle will follow

Collect and dispose of waste

Disposal is the bigger challenge

- **But research is more advanced and more accepted**
  - Geological sequestration removes the objection that there is no option
  - Mineral sequestration offers a large long-term storage reservoir
  - Exotic options might be added later

**Capacity, Permancence,
Physical and Environmental Safety,
Public Acceptance**


Image courtesy Stonehaven production

Focus on air air capture

- **Air capture eliminates exceptions**
  - No emission source can be exempt
  - Separates sources from sinks
  - Carbon democratization
- **Air capture for drawing down CO_2**
  - Negative emissions are already unavoidable
  - Requires vast CO_2 storage capacity
  - Negative carbon emissions
- **Air capture with non-fossil liquid fuels**
  - Synthetic fuel production from CO_2 and H_2O
  - Provides energy storage & liquid fuels
  - Requires cheap non-fossil energy
  - Carbon recycling
- **Air capture with fossil liquid fuels**
  - Carbon balanced by sequestration
  - Requires cheap CO_2 storage
  - Carbon balancing

Difficulties in gaining acceptance for direct air capture

- **No need**
  - Climate skeptics: no need to spend resources
- **Moral hazard**
  - Social Engineer: DAC delays necessary life style changes
  - Renewable Advocate: DAC delays renewables
- **Forces unwanted action**
  - Oil companies: Focus on CO2 from coal
- **Not economically feasible**
  - Chemical Engineers: Sherwood's Rule implies too high a cost
    - After challenging the thermodynamics of the process

Responses

- **Climate Skeptic:**

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

- **Social Engineer:**

  Withholding a solution to a potentially catastrophic change in climate is irresponsible.

- **Renewable Energy:**

  Air capture enables renewable energy via synthetic fuels.

- **Oil companies:**

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

- **Traditional Engineering:**

  Technology demonstration, active research, and reasoned arguments. Sherwood's Rule does not always apply.

Three Rules for Technological Fixes

D. Sarewitz and Richard Nelson:

Three rules for technological fixes, *Nature,* 2008*, 456*, 871-872

I. The technology must largely embody the cause-effect relationship connecting problem to solution.

II. The effects of the technological fix must be assessable using relatively unambiguous or uncontroversial criteria.

III. Research and development is most likely to contribute decisively to solving a social problem when it focuses on improving a standardized technical core that already exists.

In contrast, direct removal of CO_2 from the atmosphere — air capture — satisfies the rules for technological fixes. Most importantly, air capture embodies the essential cause–effect relations — the basic go — of the climate change problem, by acting directly to reduce CO_2 concentrations, independent of the complexities of the global energy system (Rule I). There is a criterion of effectiveness that can be directly and unambiguously assessed: the amount of CO_2 removed (Rule II). And although air-capture technologies have been remarkably neglected in both R&D and policy discussions, they nevertheless seem technically feasible (Rule III).

Feasibility & Affordability?

CO_2 in air is dilute and air is full of water

- **Sherwood's Rule suggests that costs scale linearly in dilution**
- **The air carries 10 to 100 times as much H_2O as CO_2**
- **First-of-a-kind apparatus is expensive (APS study: $600/t)**

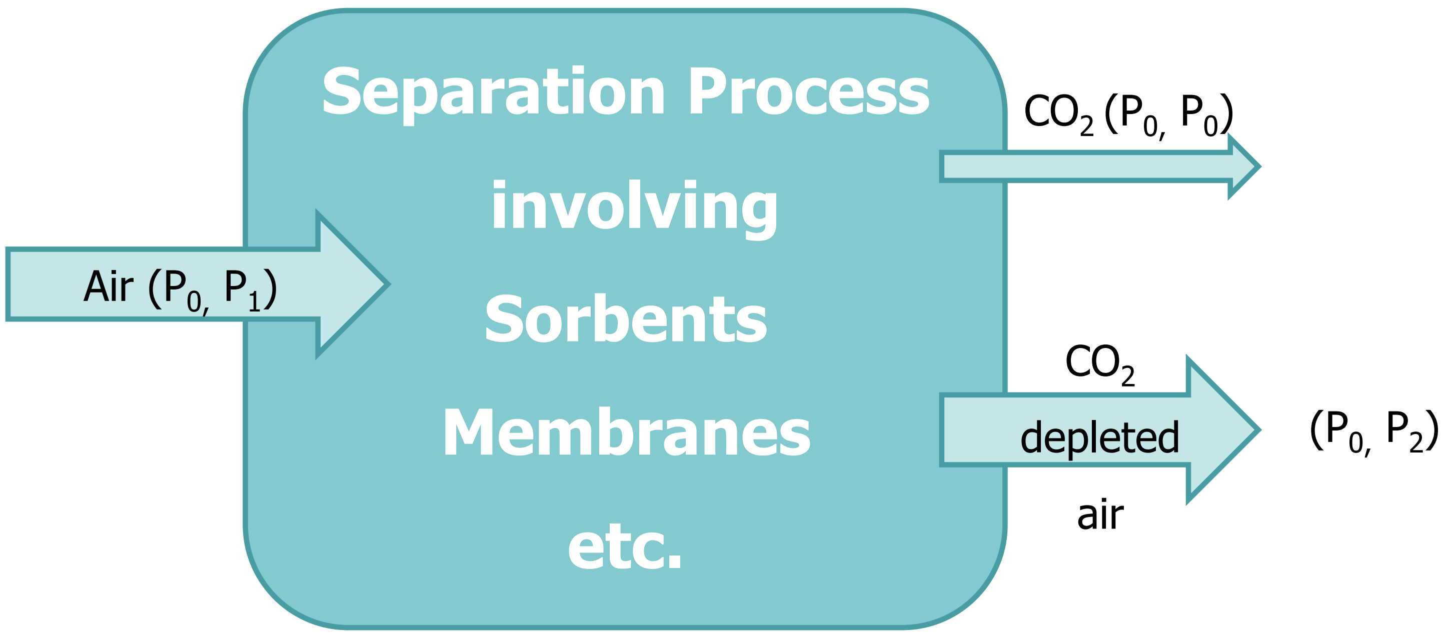
Air capture is sorbent based

- **Sorbent based separation of CO_2 from air**
  - Concentration ratio is 1 : 2500
    - Eliminates all options that perform significant work on the air
    - Sorbents postpone work to the regeneration step
- **All sorbents are chemical sorbents**
  - At 400 ppm physisorption is too weak
  - Minimum free energy of binding: $\Delta G > 22$ kJ/mol
- **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

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)



$$\Delta » = » \; » ; \frac{»_0 - »_2}{»_1 - »_2} ; \frac{»_1}{»_0} \ln \frac{»_1}{»_0} - ; \frac{»_0 - »_1}{»_1 - »_2} ; \frac{»_2}{»_0} \ln \frac{»_2}{»_0} + ; \frac{»_0 - »_1}{»_0} ; ; \frac{»_0 - »_2}{»_0} ; \frac{»_0}{»_1 - »_2} \ln \frac{»_0 - »_1}{»_0 - »_2} ;$$

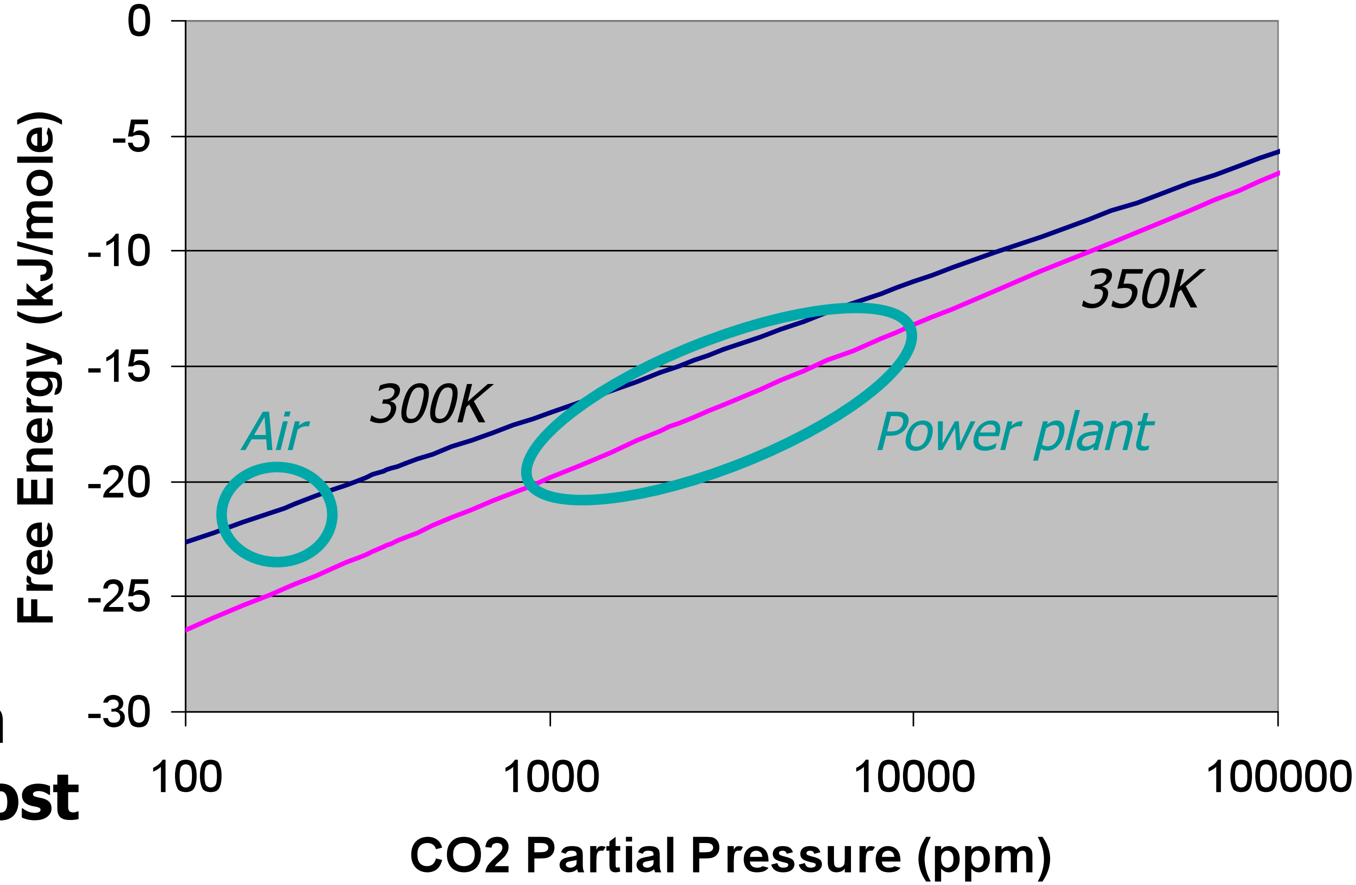
22 kJ/mol

Specific irreversible processes have higher free energy demands

Sorbent Strength

depends logarithmically on CO_2 concentration at collector exit

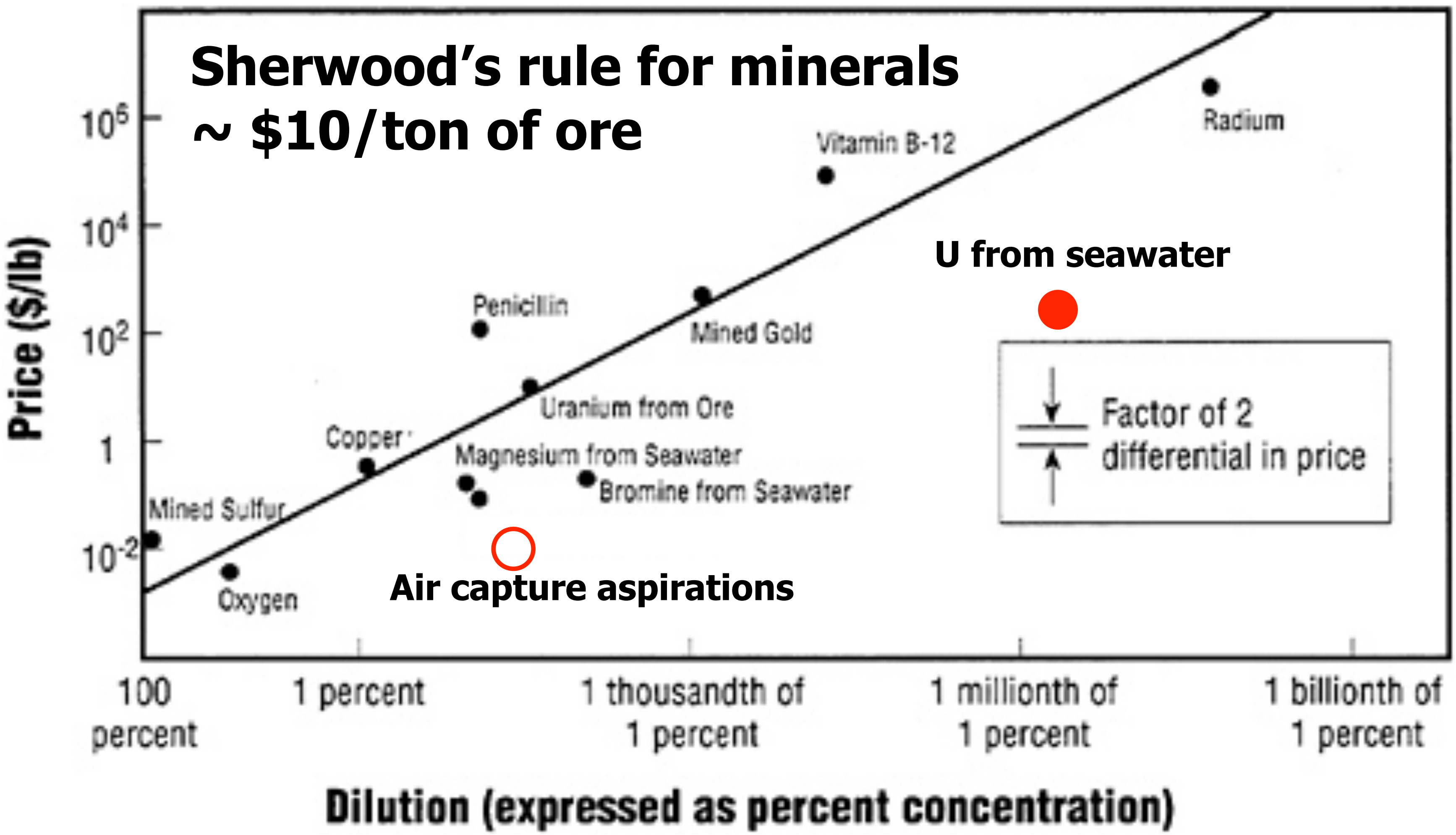
$$\Delta G = RT \log P/P_0$$



Sorbent regeneration dominates cost

Sherwood's Rule

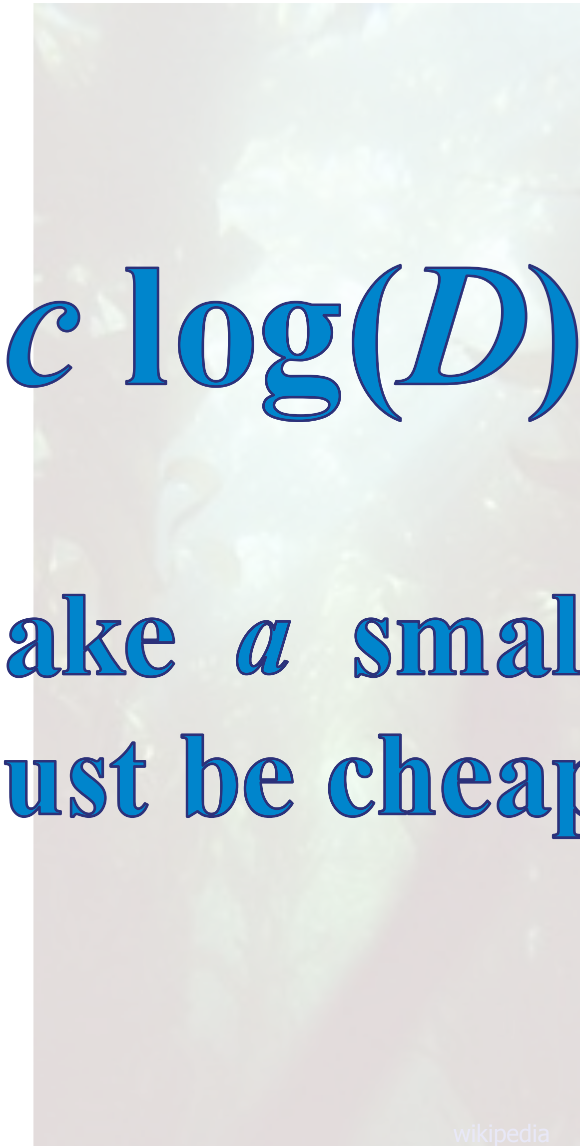
A challenge for dilute values



SOURCE: National Research Council (1987)

Artificial kelp to absorb uranium from seawater

- **Passive, long term exposure to water**
  - Braids of sorbent covered buoyant plastic
  - Anchored to the floor
  - Replaced initially active systems
- **Low energy sorbent**
  - Laminar flow over sorbent
  - Uptake is limited by boundary layer transport
- **Regeneration**
  - After harvesting the strings
- **Gross violation of Sherwood's Law**
  - Cost estimates range from $200 to $1200/kg
  - Sherwood $3 million/kg



$$Cost = a\,D + b + c\log(D)$$

must make *a* small

Air contacting must be cheap

Low cost comes with experience

$600 Per ton CO_2 — APS (low tech, first-of-a-kind)

$500

$400

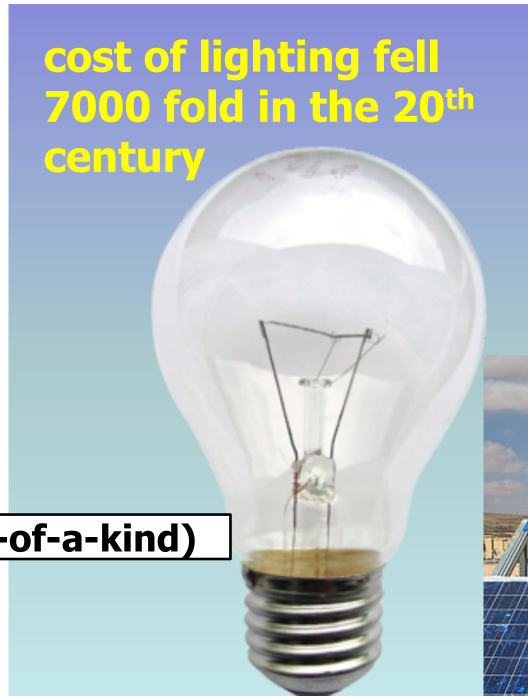
$300

GRT (first-of-a-kind)

$200

$100 — Practical interest

$0 — Raw material and energy limit (frictionless cost)



The Power of the Learning Curve

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

Wikipedia pictures

Spot the low cost power plant

Per unit of power, the cost of a car engine is about 100 times lower than that of power plants

wikipedia

Contactor: Wind energy – Air capture

Wikipedia picture

artist's rendering

Image courtesy Stonehaven production

Wind energy
~20 J/m³

CO_2 combustion equivalent in air

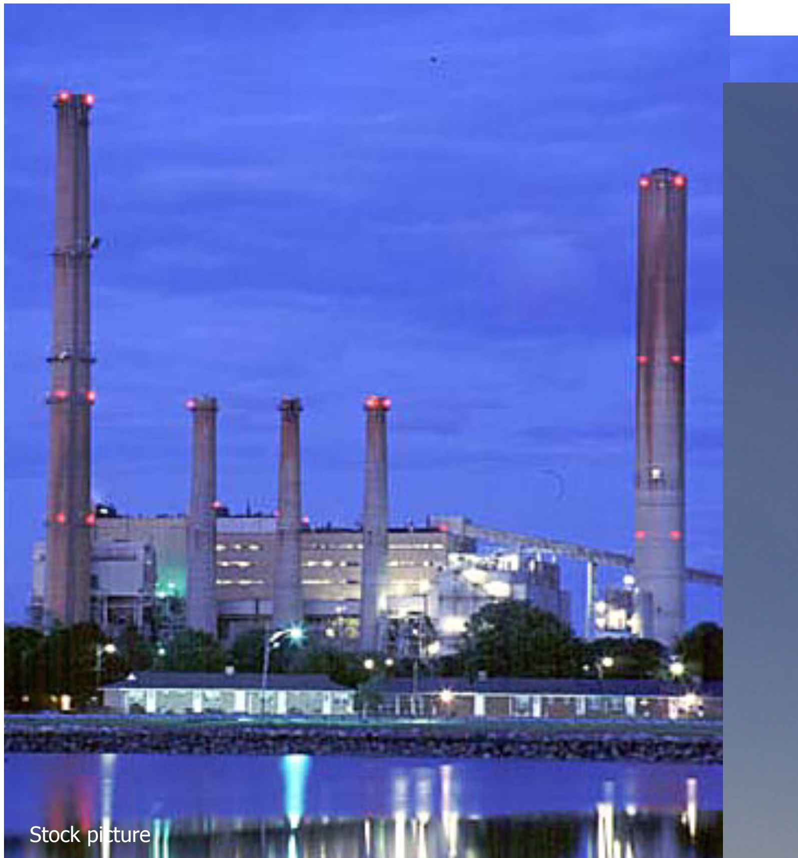
10,000 J/m³

Passive contacting of air is inexpensive

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

Extracting 20 J/m³ seems feasible

Regenerator: Flue Gas Scrubbing – Air Capture


Stock picture

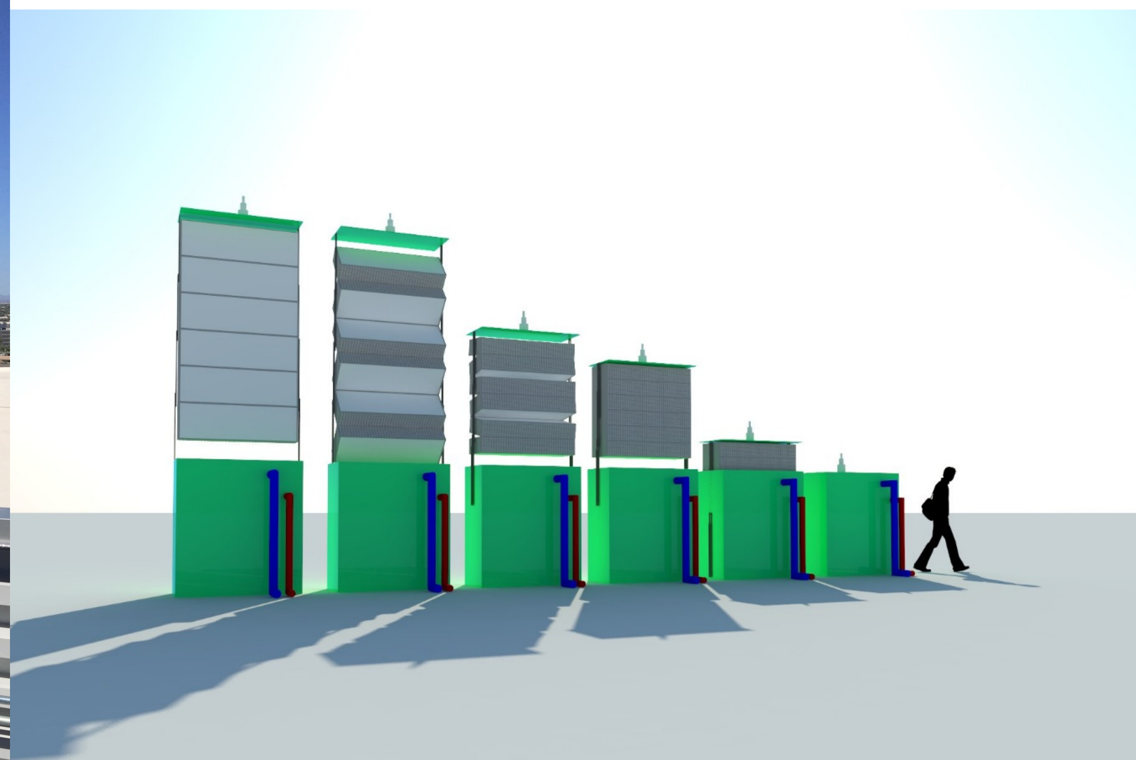
Sorbent regeneration slightly more difficult for air capture than for flue gas scrubbers


artist's rendering
Image courtesy Stonehaven production

Dominant costs are similar for air capture and flue gas scrubbing

Center for Negative Carbon Emissions

Outside prototype

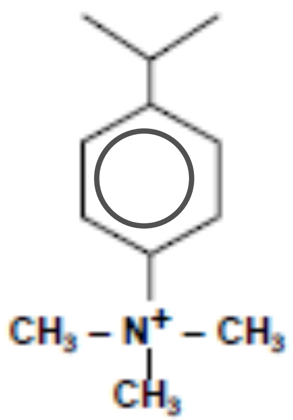


Working towards a public demonstration

Sorbent Choice: Anionic Exchange Resins

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

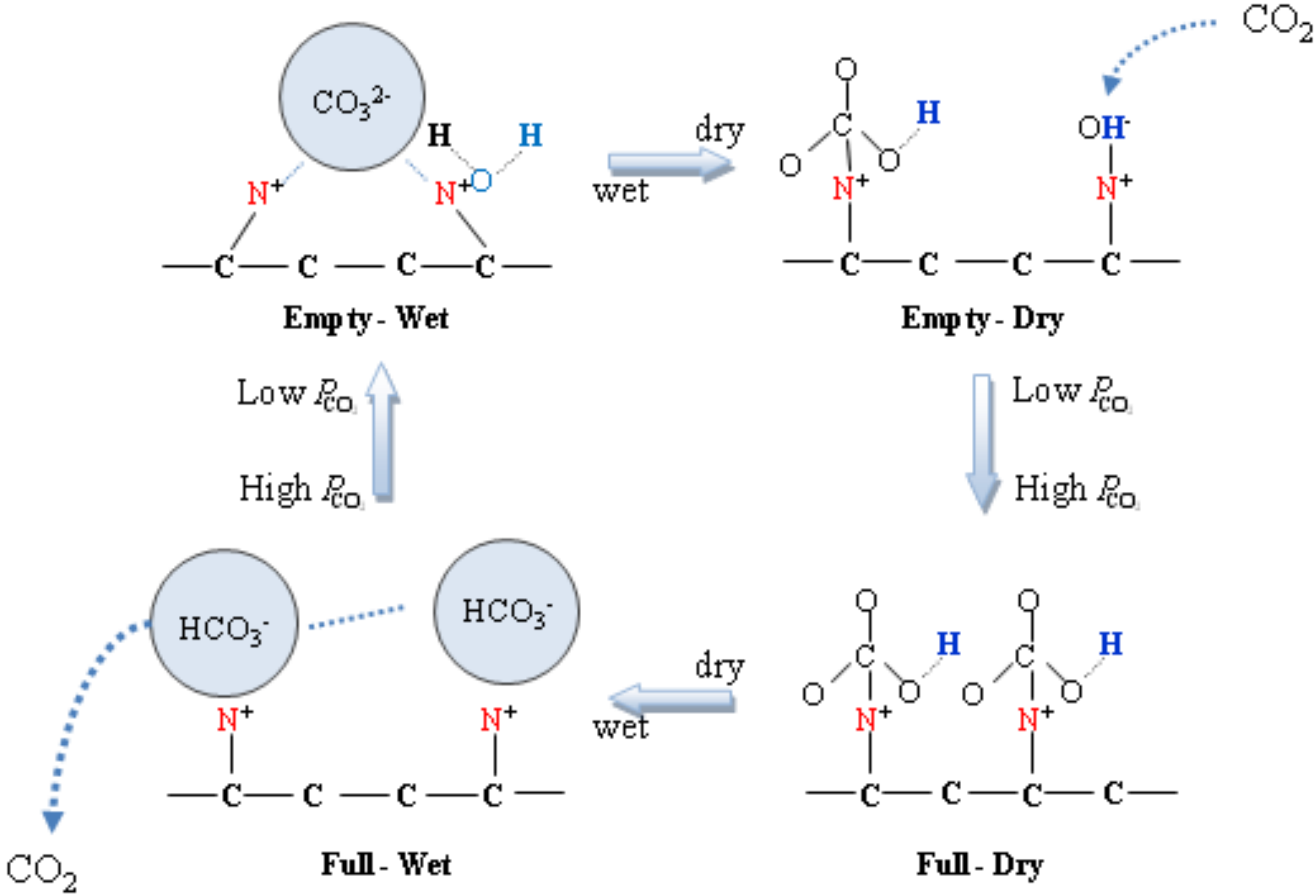
Type I Strong Base Resins



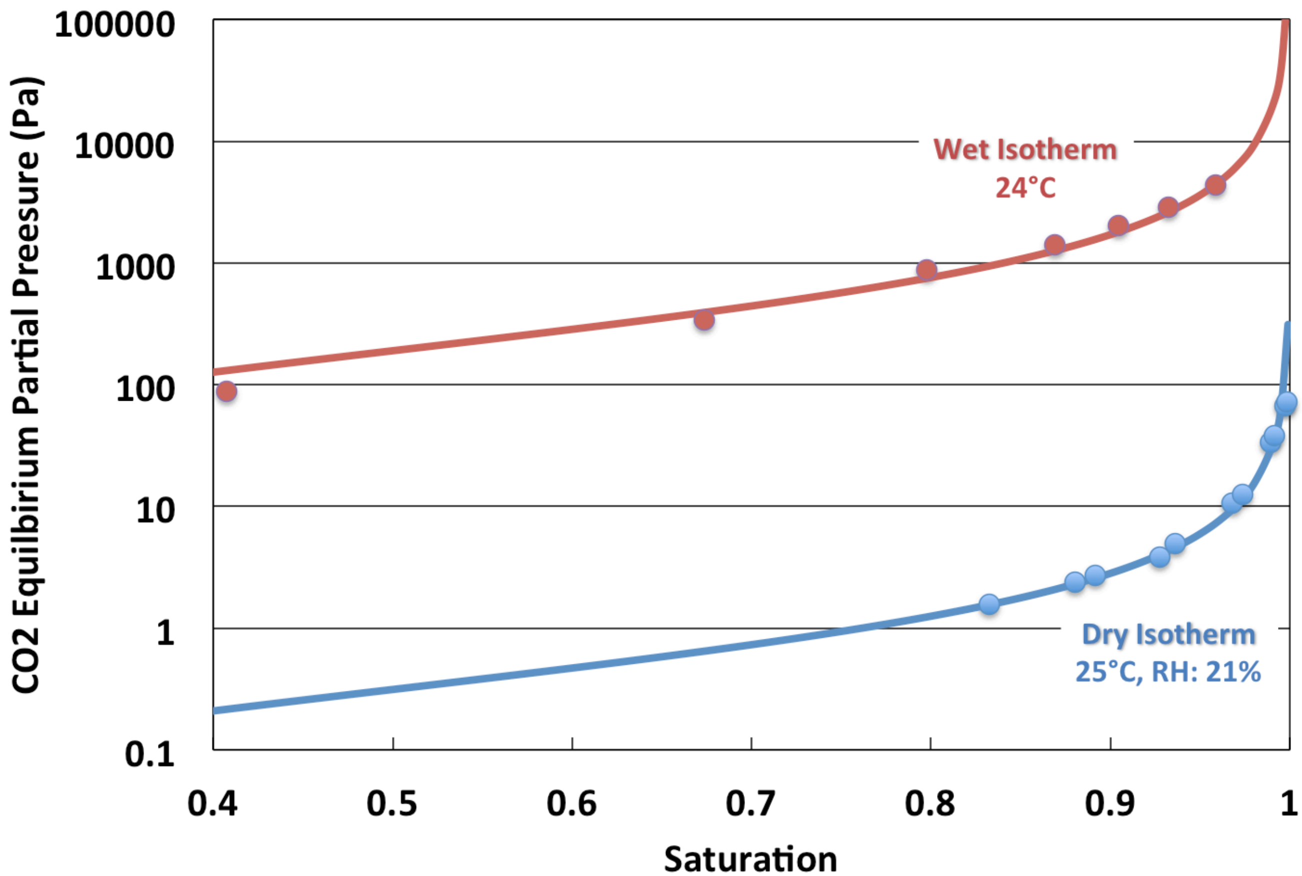
- Positive ions fixed to polymer matrix
  - Negative ions are free to move
  - Negative ions are hydroxides, OH^-
- Dry resin loads up to bicarbonate
  - $OH^- + CO_2 \rightarrow HCO_3^-$ (hydroxide → bicarbonate)
- Wet resin releases CO_2 to carbonate
  - $2HCO_3^- \rightarrow CO_3^{--} + CO_2 + H_2O$

Moisture driven CO_2 swing

Moisture Swing

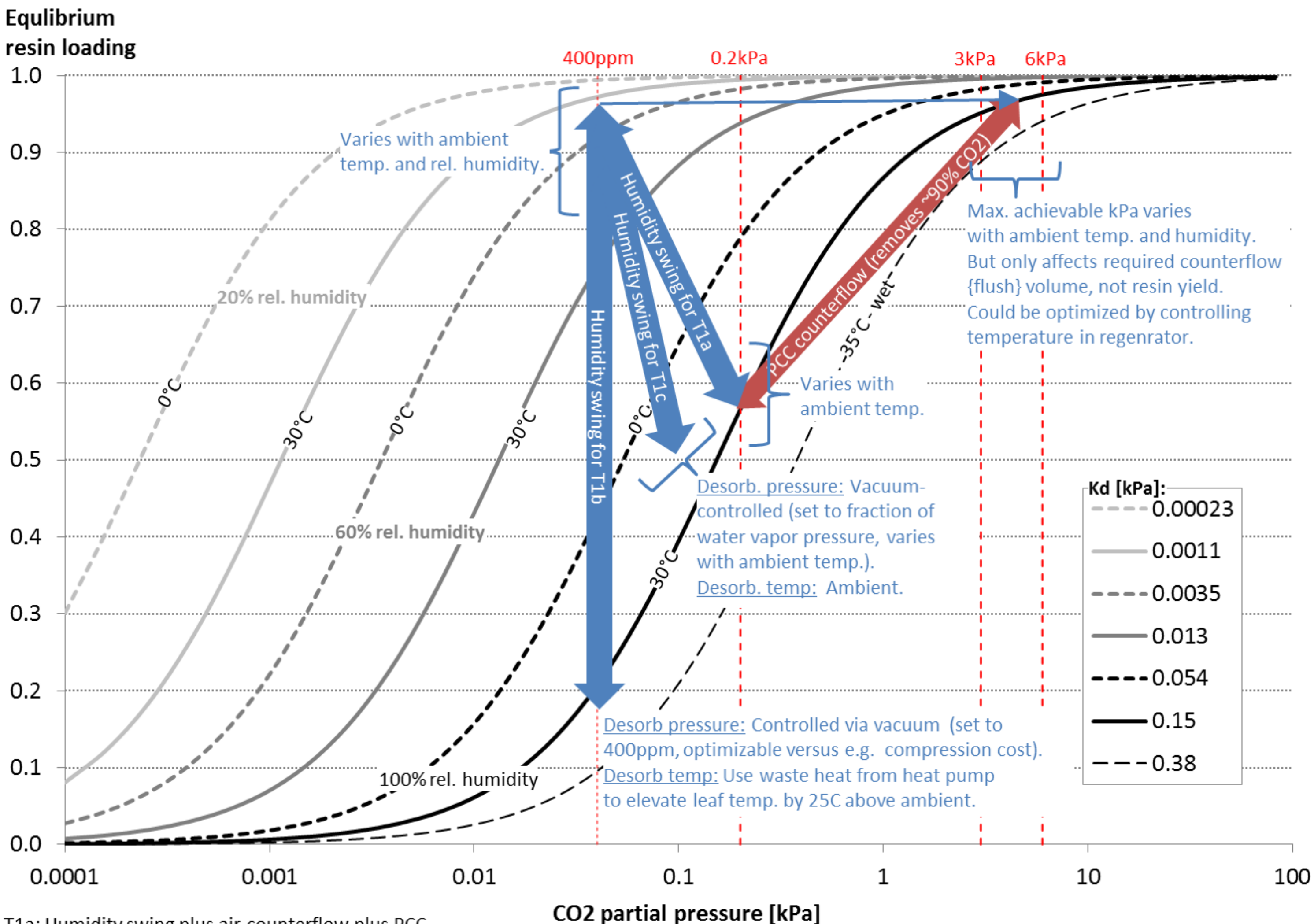


The Moisture Swing



Tao Wang et al

Humidity swing: Yield and desorption pressure strongly dependent on ambient temp., rel. humidity, and optional heat management and evacuation of regenerator



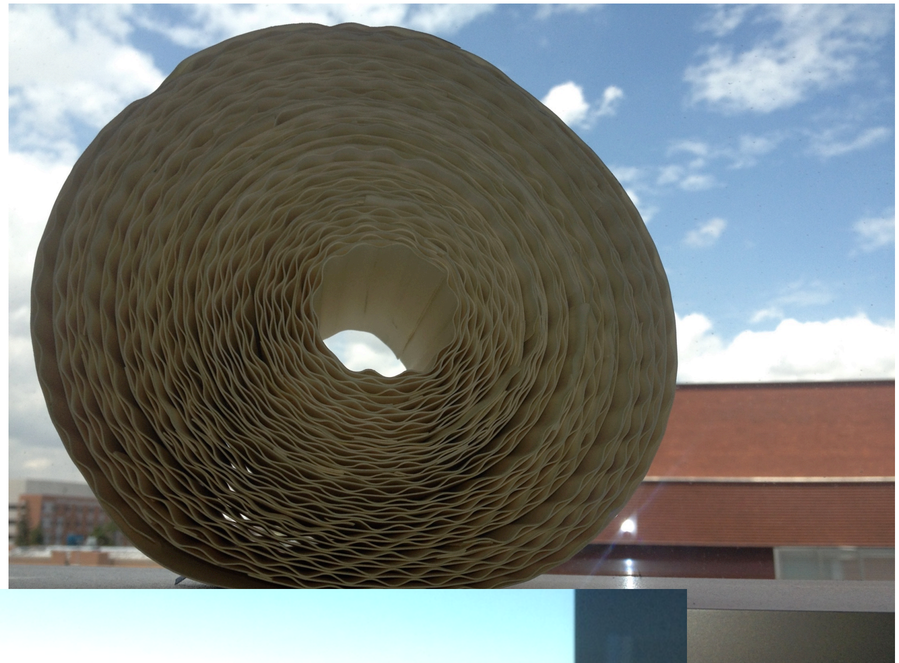
T1a: Humidity swing plus air-counterflow plus PCC
T1b: Humidity swing plus vaccum
T1c: Humidity swing plus NaCO3-flush counterflow plus vaccum

* Uses Wang et al. EST 2011 and PCCP 2013

Contactor & Regenerator

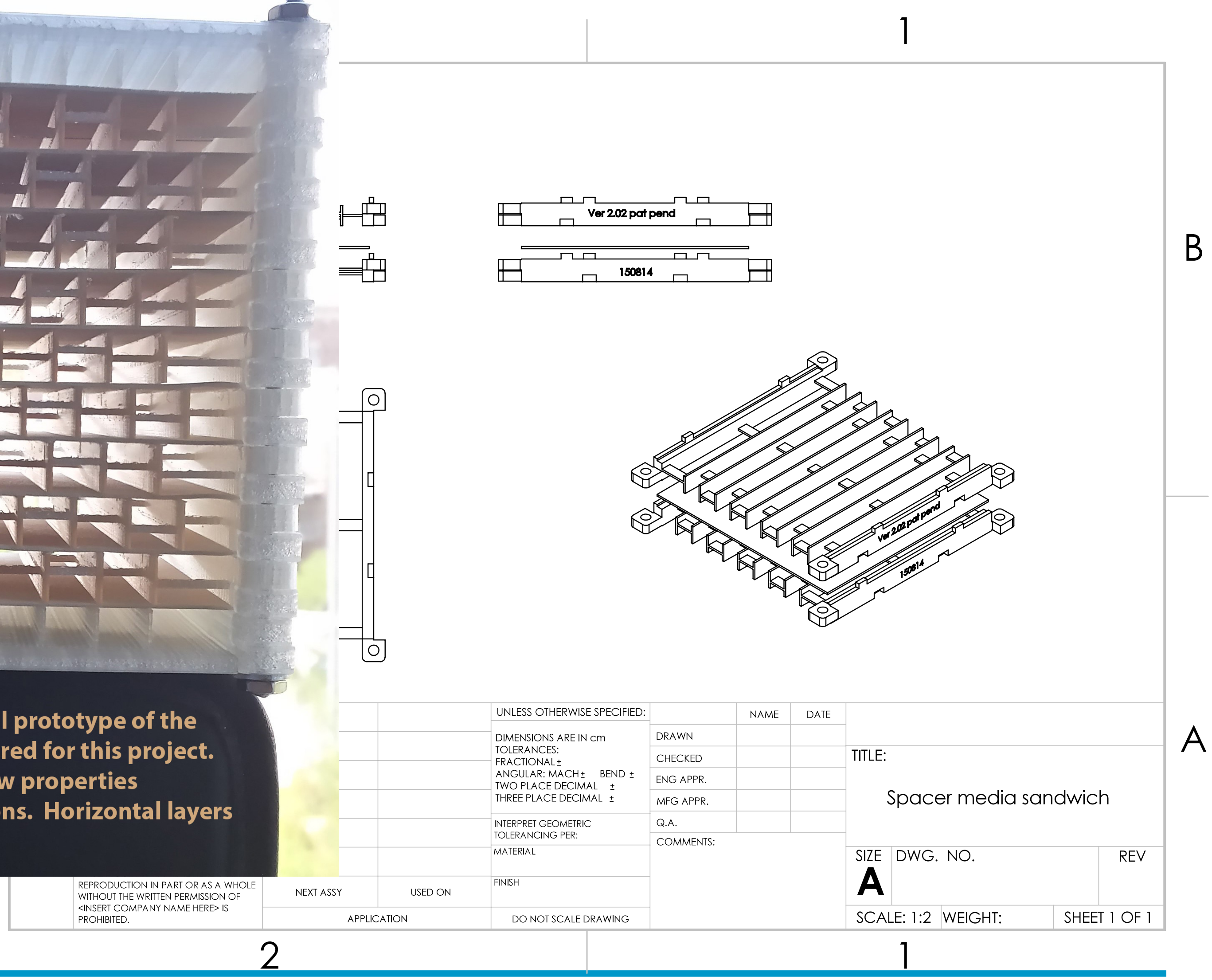
- "monolith" with simple flow path
  - Momentum loss (pressure drop) and CO_2 loss follow similar transport laws
  - Optimal design balances transport resistance in air to transport resistance in wall
  - Given the wall resistance this defines the optimal dimensions
- Wind driven flow as contactor
- Moved for regeneration with water

Filter Units

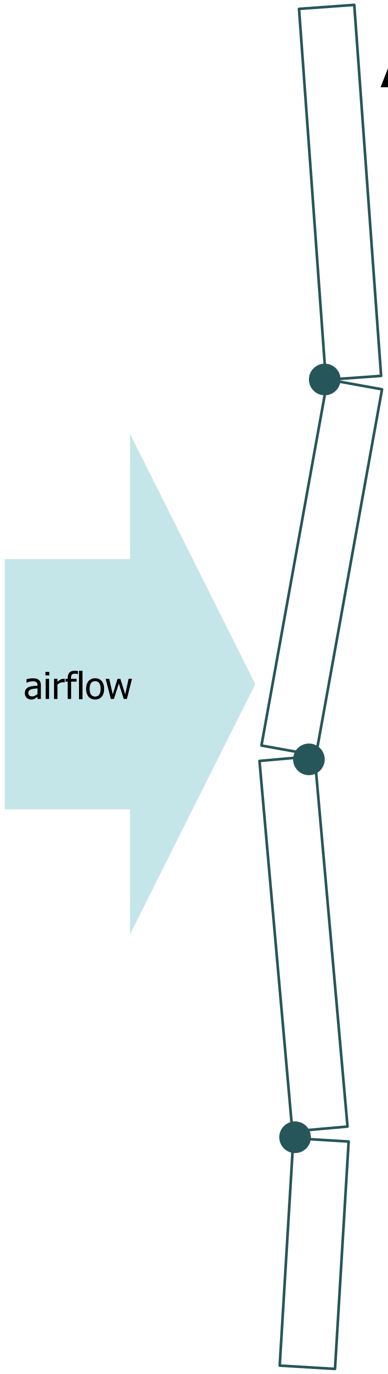


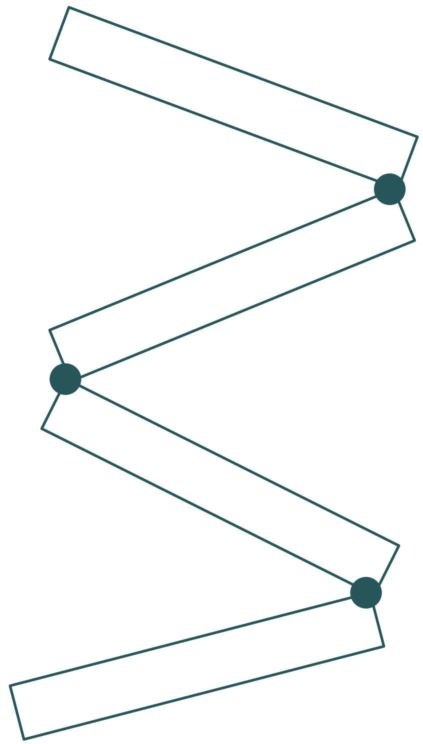
Approximation of a monolith

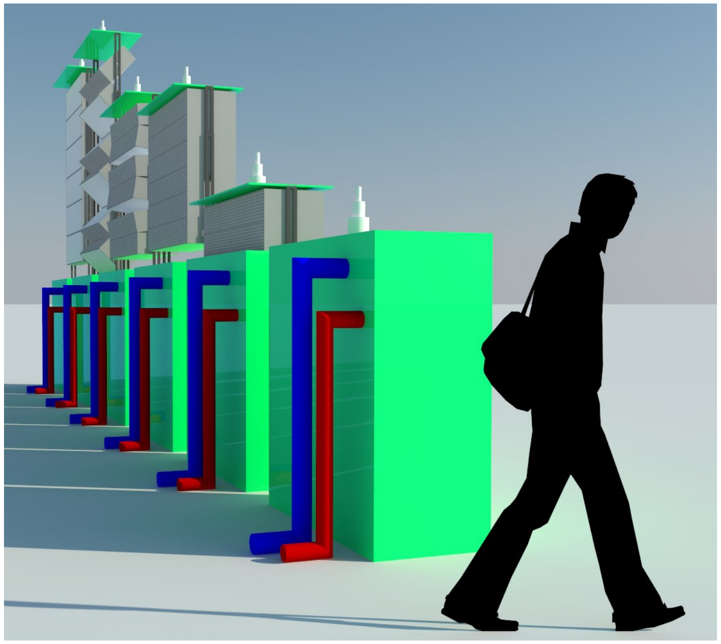
Figure 4: A small operational prototype of the filter module design considered for this project. The filter has superior air flow properties compared to previous versions. Horizontal layers are active sorbent material.

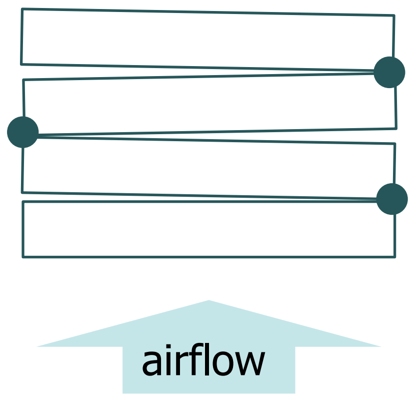


Accordion shape of the collector unit

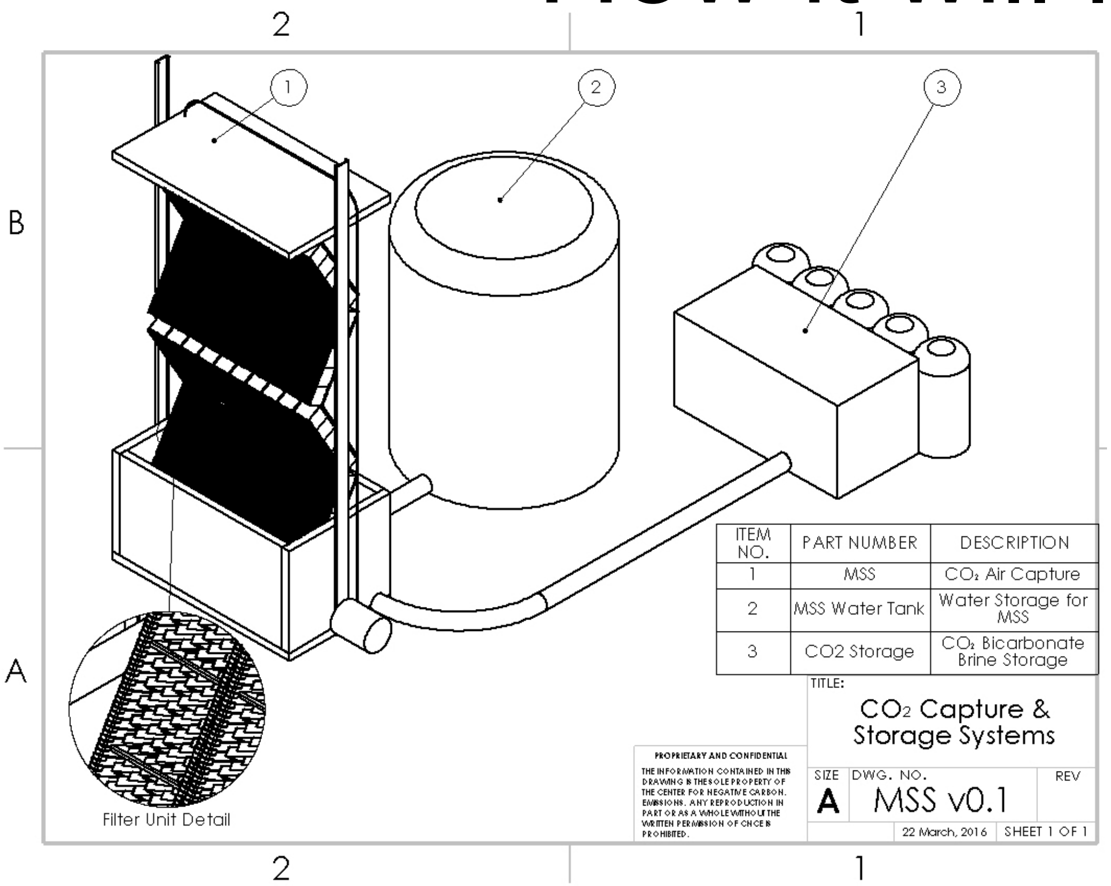


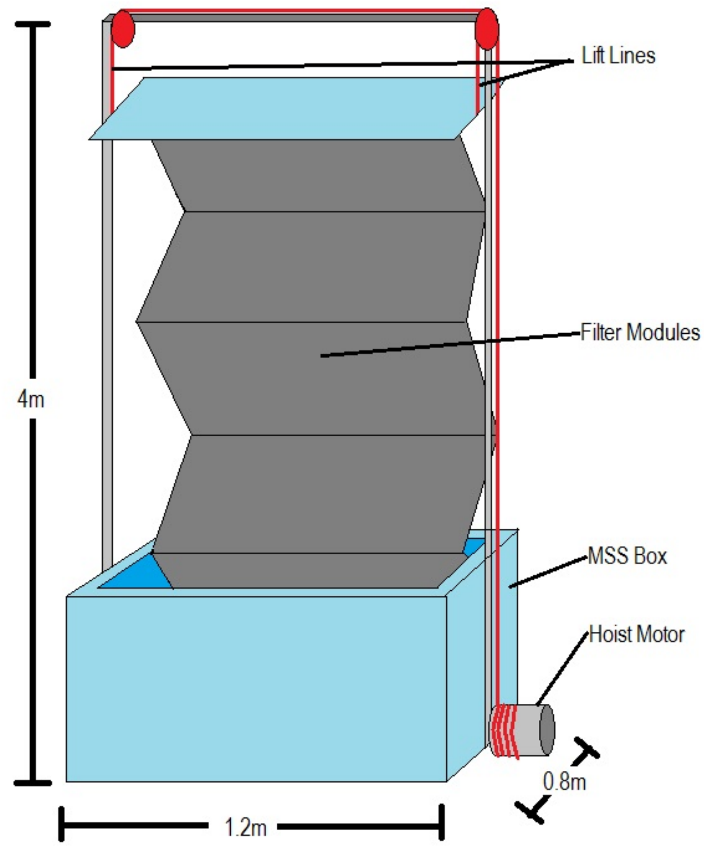






How it will look



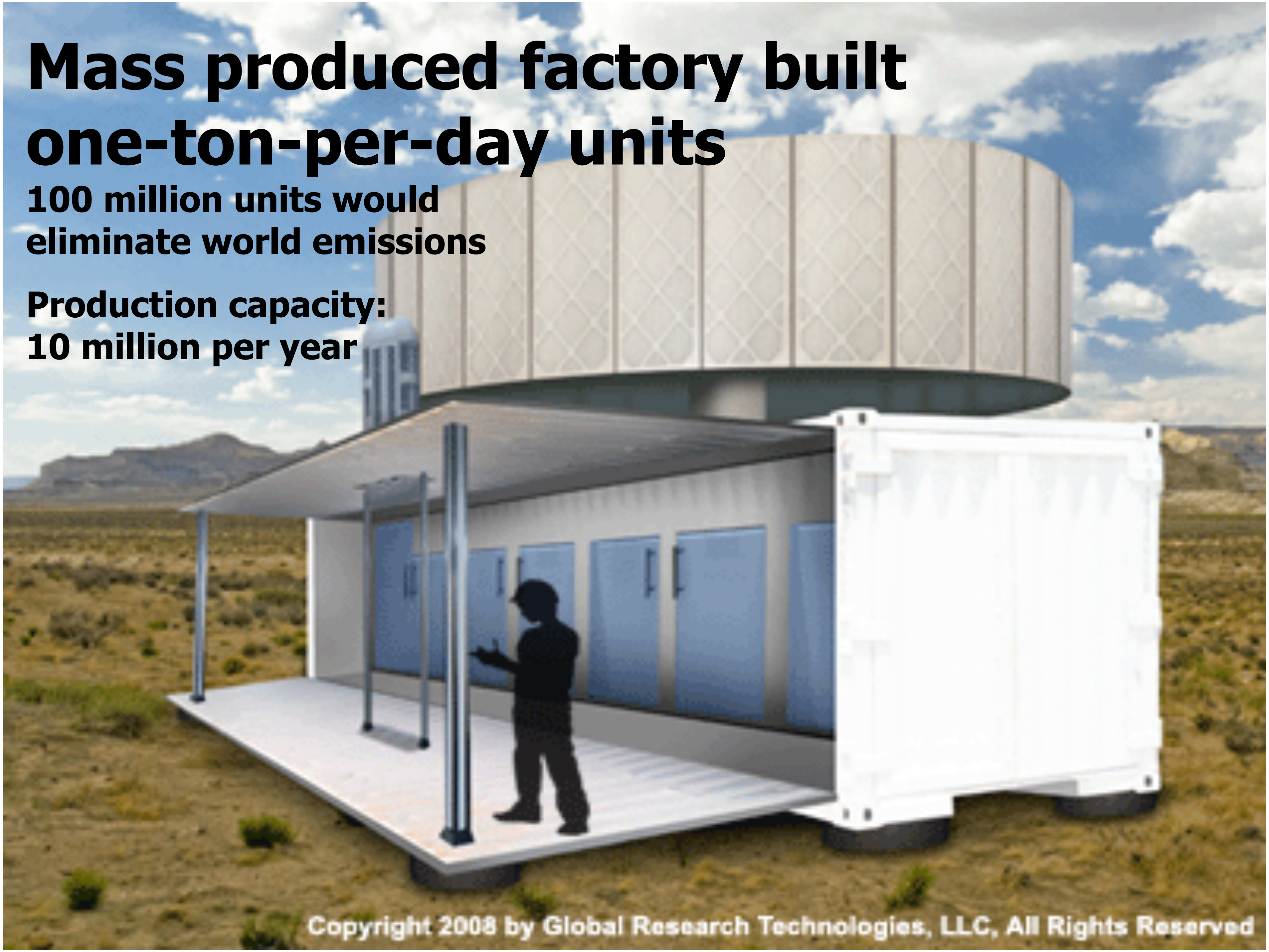


Jason Kmon, March 2016

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

100 million units would eliminate world emissions

Production capacity: 10 million per year



Required production capacity small on world scale

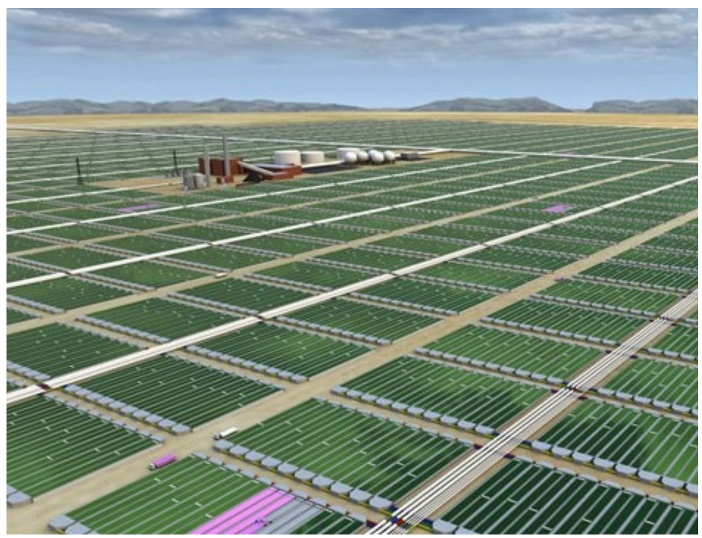
Shanghai harbor processes 30 million containers a year

World car and light truck production: 80 million per year

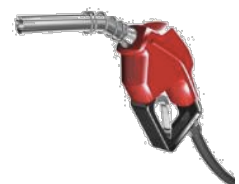
Shanghai container port, wikipedia picture

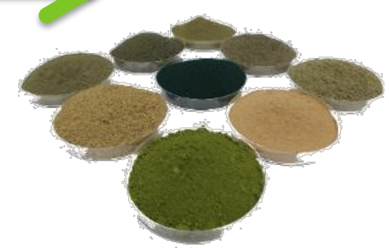
Atmospheric CO_2 Capture and Membrane Delivery

CO_2



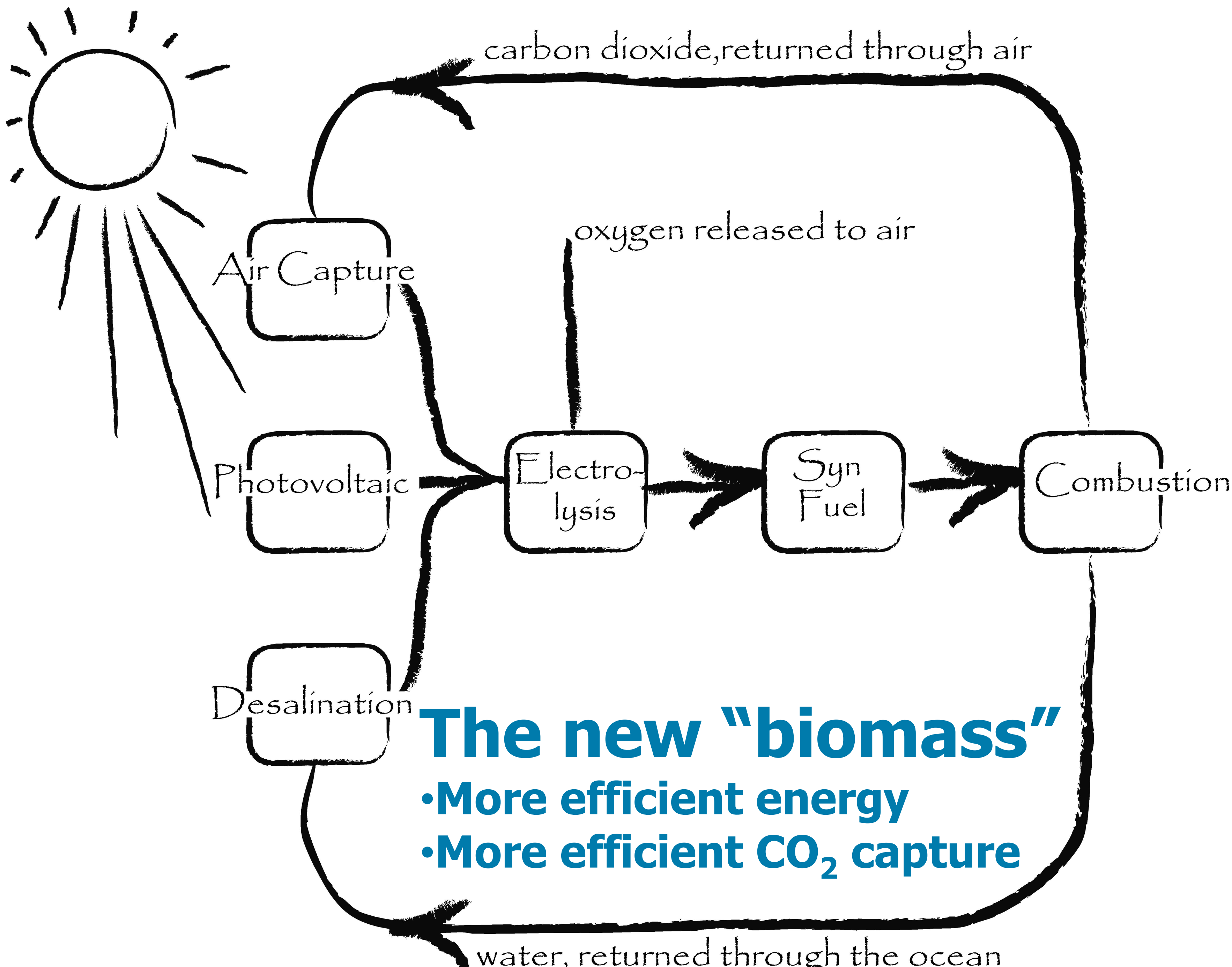
Large-scale algae cultivation (courtesy of Joule®)





Bioplastics

Rittmann and Lackner, DOE TABB



The new "biomass"

- More efficient energy
- More efficient CO_2 capture