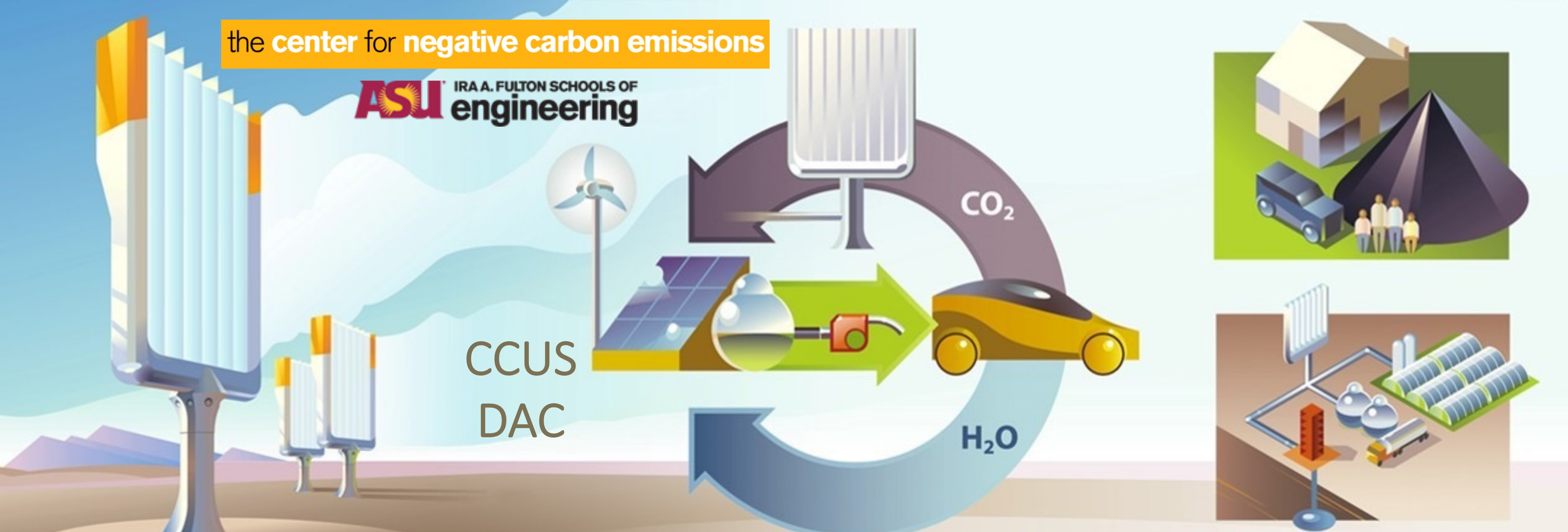


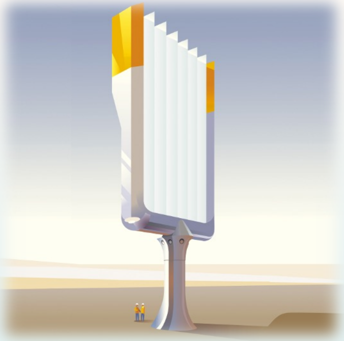
https://www.youtube.com/watch?v=4dHjCjrYcfs

Klaus S Lackner

Founding Director of the
Center for Negative Carbon Emissions
Arizona State University

Direct Air Capture

November 2022

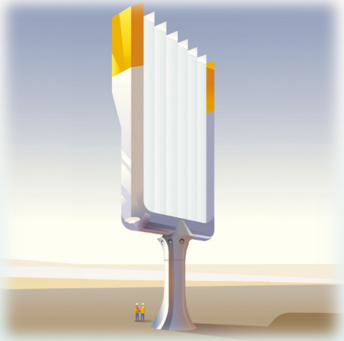


Preamble
A waste management paradigm

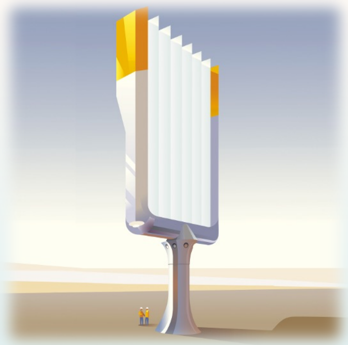
For every ton of carbon coming out of the ground another ton must be returned

- Focus is on carbon
- Essentially solves climate change and ocean acidification <u>if disposal is permanent</u>
- Best done by demanding a certificate of sequestration to permit carbon extraction
- Once implemented, all supply chains are carbon neutral (no need for LCA in the accounting)
- Creates a waste management paradigm
- Operations must be safe, environmentally sustainable and socially acceptable (low cost)
- Any "mobile" carbon collected from point sources or the environment can be used for sequestration
- Disposal comes with guarantees of future re-sequestration unless it is deemed permanent

Does not fix other environmental problems like methane emissions, N_2O emissions, deforestation, or social inequities



We live in a carbon overshoot world that still needs access to energy



CO_2 disposal is unavoidable even if expensive and unpopular

Many different storage options add up to a very large capacity in excess of what will be needed

- **Recapturing 100 ppm from the atmosphere**
  - Requires storage capacity for 1500 Gt of CO_2
  - This assumes 4 Gt C per ppm
    - *Half of the emitted CO_2 escaped to the ocean or the biosphere*
    - *This will be returned when CO_2 concentrations in the air start dropping*
- **1500 Gt CO_2 of storage capacity:**
  - In saline aquifers as liquid CO_2
  - In basalts as carbonates
  - Ex situ mineral sequestration in carbonate rocks
- **Needs regulatory frameworks**
  - Disposal needs to be mandatory
  - Disposal needs to be certified

Issues in Environmental Science and Technology, 38
Geoengineering of the Climate System
Edited by R.E. Hester and R.M. Harrison

Published by the Royal Society of Chemistry, www.rsc.org

The Use of Artificial Trees

KLAUS S. LACKNER

ABSTRACT

Direct capture of carbon dioxide from ambient air with devices that resemble trees could contribute to a net zero carbon economy and even support a level of negative emissions sufficient to drive the concentration of carbon dioxide in the atmosphere in a matter of decades back down to acceptable levels. Direct air capture adds a new capture method to the carbon capture and storage technology suite. It can work with all storage options and cancel out emissions from any source. Point sources, in the main, would be better off capturing their own emissions instead of releasing them to the atmosphere. Capture from air would likely focus on emissions from the transportation sector. Here, air capture can also support a closed carbon cycle that starts with carbon dioxide from the air and non-fossil energy and produces liquid fuels which, after use, return their carbon back to the atmosphere. Air

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Carbon Dioxide Disposal in Carbonate Minerals†

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Brookings Papers on Economic Activity
2005, no. 2 (2005): 215-284.

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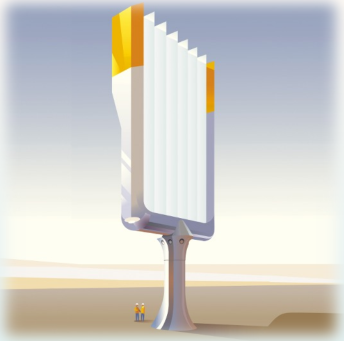
A Robust Strategy for Sustainable Energy

Once again the debate has intensified over whether energy as a commodity is running out. Just six or seven years ago the world seemed awash in oil, yet today many pundits predict the end of oil and indeed the end of

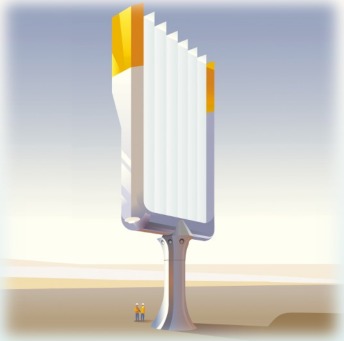


What counts as Direct Air Capture?

- **Extraction of carbon dioxide from ambient air**
  - Typically excludes natural processes (even deliberate ones)
    - *extraction through photosynthesis (e.g., BECCS)*
    - *extraction via natural geochemical processes*
  - Focus on technical processes
    - *Usually excludes extraction from reservoirs in direct contact with air*
      - extraction of carbon from ocean water or biomass reservoirs
    - *Definitely excludes extraction from "sequestered carbon"*
      - coal, or mineral carbonates

These are matters of definition

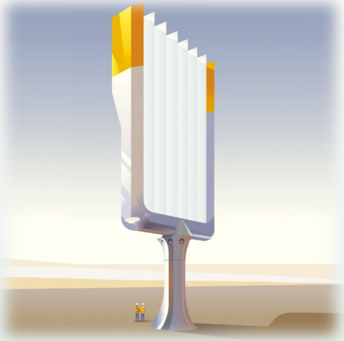
All removal of mobile and mobilized carbon counts



Certification requires Extraction from the mobile carbon pool

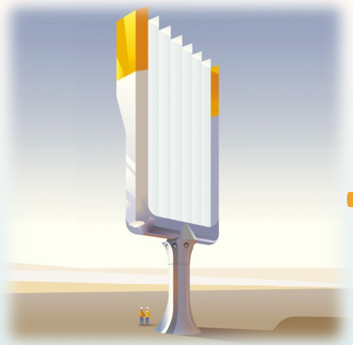
Closely Coupled Reservoirs

- **Biosphere**
  - Carbon removal via biomass will affect atmosphere in short order
  - Low-cost option but limited in scope
  - Siting limitations and scale limitations
- **Ocean**
  - Thermodynamically equivalent to air capture
  - Immediate impact on the atmosphere
  - Carbon dilution in the ocean 1:26,000
- **Atmosphere**
  - Fastest mixing times
  - Dilution 1:2,500
  - No siting limitations no scale limitation



CO_2 removal from air has a long history

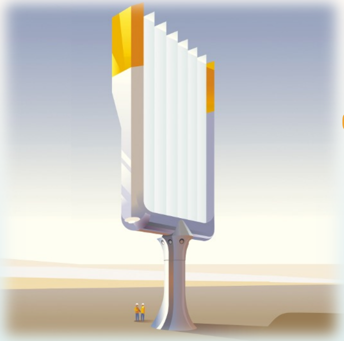
- **Removal of CO_2 from air (without deliberate collection)**
  - In submarines and spacecraft
    - *Ten times higher concentrations!*
  - For air liquefaction
    - *Linde, Praxair, Air Products, BOC (etc.) have done far more air capture than Climeworks*
    - *Very different optimization – near total removal, costs are attributed to air*
- **Suggested for fuel production fifty years ago**
  - Meyer Steinberg for nuclear-powered aircraft carriers
  - Stucki et al. in the nineties for alternative fuels (running out of oil)
  - Hard to justify in the presence of petroleum



Dilution is manageable
There is plenty of CO_2 in the air

- **One cubic kilometer of air**
  - Passes through a windmill in an afternoon
  - Carries $300 of kinetic energy
    - *assuming a wind speed of 6m/s and an energy value of 5¢/kWh*
  - Carries $21,000 of CO_2
    - *assuming a CO_2 tipping fee or commodity value of $30/ton*

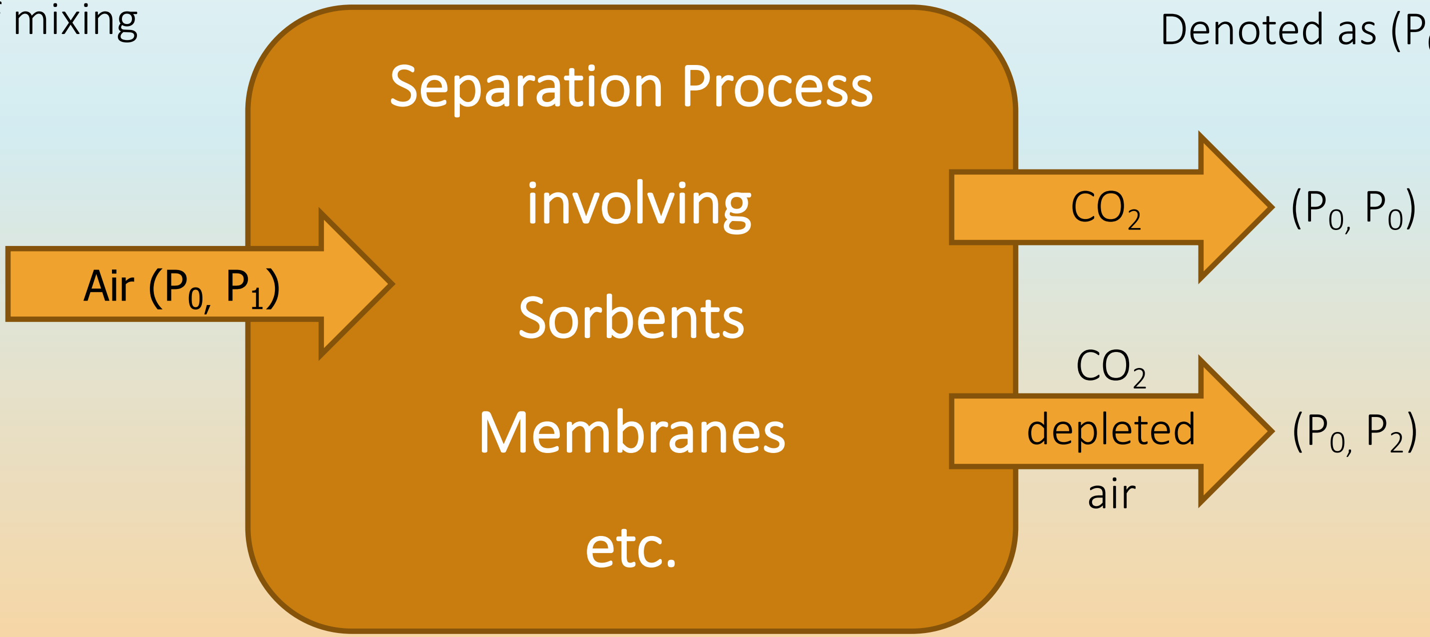
As a source of CO_2, the air is 70 times more valuable than as a source for wind energy.
Wind energy is routinely harvested



Thermodynamics is not limiting

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)

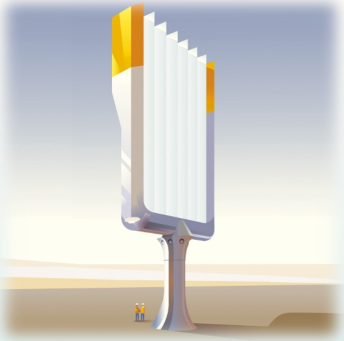


$$\Delta G = RT\left(\left(\frac{P_0 - P_2}{P_1 - P_2}\right)\frac{P_1}{P_0}\ln\frac{P_1}{P_0} - \left(\frac{P_0 - P_1}{P_1 - P_2}\right)\frac{P_2}{P_0}\ln\frac{P_2}{P_0} + \left(\frac{P_0 - P_1}{P_0}\right)\left(\frac{P_0 - P_2}{P_0}\right)\frac{P_0}{P_1 - P_2}\ln\frac{P_0 - P_1}{P_0 - P_2}\right)$$

All practical processes fall far short

22 kJ/mol of CO_2 vs. 700 kJ of energy extracted

(Specific irreversible processes have higher free energy demands)

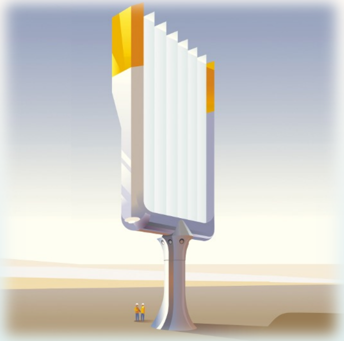


Direct Air Capture is Operational

Climeworks is doing it right now

- **Skeptics have been proven wrong**
  - Sherwood’s Rule does not apply
  - Energy consumption is still high but lower than predicted
  - Costs are still high but lower than predicted

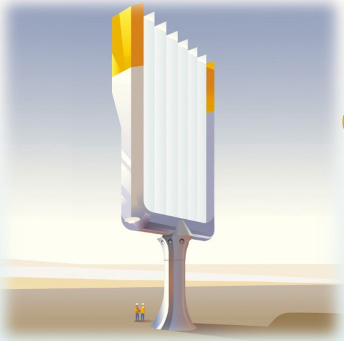
Still a long way to go: from a practical perspective DAC is ten times too expensive



How does direct air capture work?

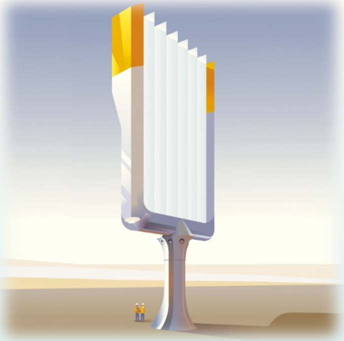
- **Nearly every DAC process …**
  - uses sorbents to extract CO_2 from air passing over surfaces
    - *Air is pushed or sucked through filters, or moves with the wind over surfaces*
    - *Sorbent thermodynamics and kinetics is far from settled*
    - *Solid or liquid sorbents*
  - regenerates sorbents using by changing conditions
    - *thermal swings, pressure swings, moisture swings, voltage swings or current applications*
    - *Flue gas sorbents are not yet mature, air capture sorbents are in their infancy*
    - *Nevertheless, they work, it is now an issue of optimization*
  - cleans and pressurizes the raw CO_2 stream for downstream applications
    - *Significant cost contributor, but not much different from flue gas scrubbing*
    - *Clean CO_2*

Conceptually similar to flue gas scrubbing, but very different optimization due to two orders of magnitude larger dilution



The challenge of high dilution

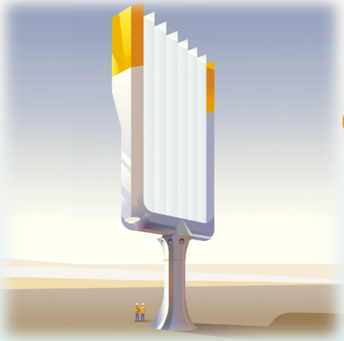
- **Thermodynamic constraints are not binding**
  - 22 kJ/mol to draw from 200 ppm to 1 atm, 33 kJ/mol for liquid CO2 (0.7 GJ/tonne, 200 kWh/tonne)
  - Air capture (like extraction of U from seawater) overcame Sherwood's Rule
    - *Sherwood's empirical rule of thumb assumes that costs scale linearly with dilution*
    - *Sherwood's law stands in contrast to thermodynamic energy demand, which scales logarkthmic*
- **Nevertheless, high dilution limits options**
  - Cannot afford to perform much work on the air
    - *Heating, cooling, drying, and pressurizing the air are very expensive*
    - *Any work done on the air is multiplied 2500 folds when charged to CO_2*
    - *Blowers are costly*
      - accelerating air to 17 m/s or pressurizing it by 180 Pa requires an amount of energy equal to the thermodynamic cost of extracting half of its CO_2 content and deliver it at 1atm pressure
    - *Drying is costly*
      - Energy demand for water removal per unit of water is comparable to that of removing CO_2. Water content is 100 times larger than CO_2 content.
    - *Sorbent binding energy is easily 3 to 10 times larger than thermodynamic requirements*
    - *Heat dissipation in thermal swings are large*
- **Sorbent costs are challenging**
  - Severe lifte time and cost constraints
    - *At 100,000 cycles 1 kg of sorbent collected about 1 tonne of CO2*



Our Approach to DAC

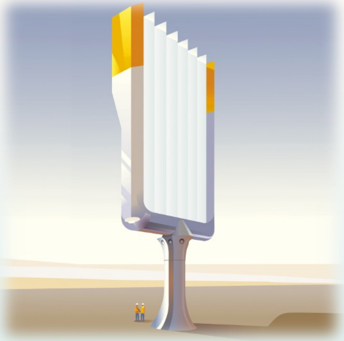
- **Aimed at carbon management**
  - Proposed carbon dioxide removal 1995
  - Balancing emissions that cannot be dealt with more cheaply
    - *Airplanes, trucks, planes, cars(?), …*
    - *First publication for specific approach 1999*
    - *Test in the laboratory 2003*
    - *First attempt at commercialization 2004—2008*

Allen Wright with a functional prototype in 2007
Combination of moisture swing and electroswing



The Early Approaches

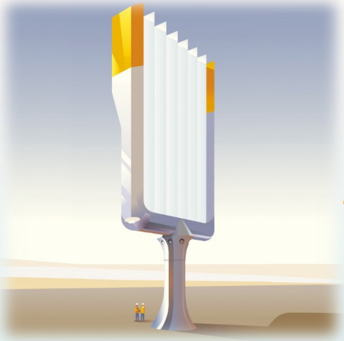
- **Liquid vs. Solid Sorbent**
  - Hydroxide solutions prove feasibility
  - Solid sorbents are faster and have lower binding energies
- **Passive vs. Active**
  - Air handling costs are significant
  - Passive systems can avoid them (Trees or windmills)
- **Thermal Swing vs. Moisture Swing**
  - Energy consumption in sorbent regeneration is large
  - Water is a cheaper source of exergy



Novel Approaches

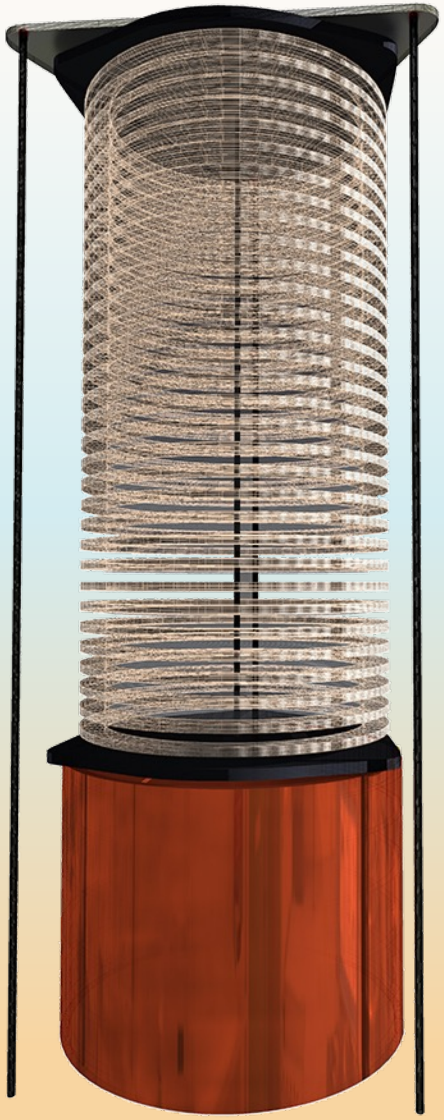
- Electrochemical Recovery
- In situ electrochemical recovery (voltage swing)
- Active membrane systems
- Passive membrane systems

Suddenly there is a plethora of options and a huge number of companies

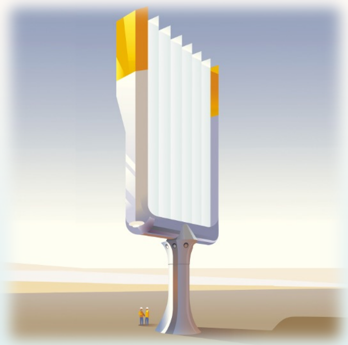


ASU's Direct Air Capture

- **Passive System**
  - Moisture Swing Sorbent
  - Thermal Swing Sorbent
  - Innovative Membrane Designs
- **Mass Manufacturing Design**
- **Two Stage Concentrator**



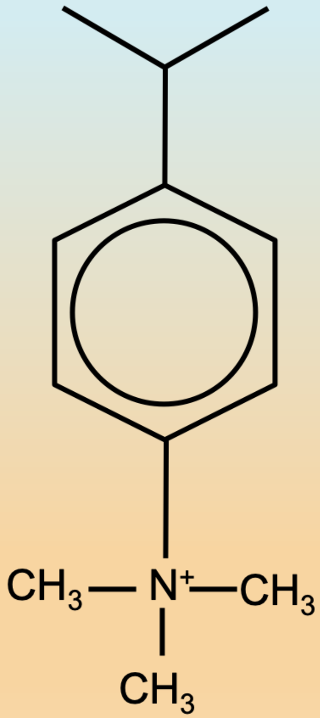
Making Air Capture Affordable



Moisture Swing Sorbent for Low Energy Air Capture

Anionic Exchange Resin: Solid carbonate "solution"
Quaternary ammonium ions form strong-base resin

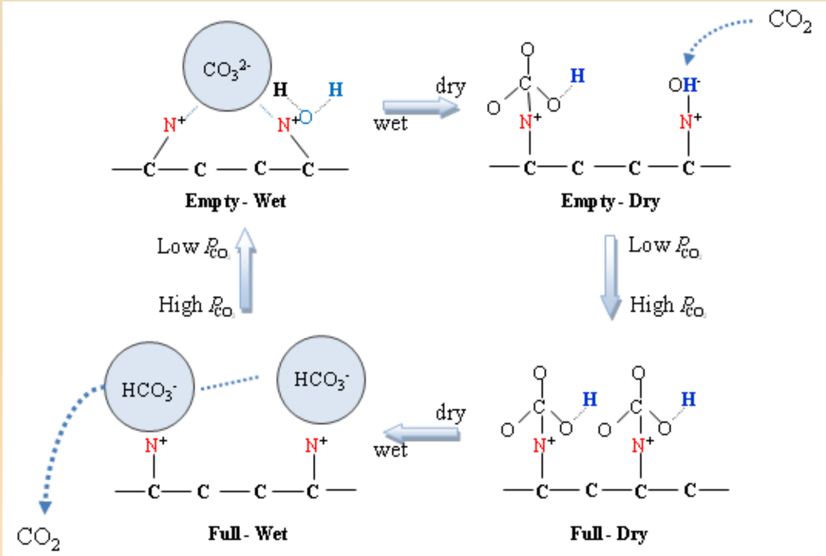
Type I Strong Base Resin

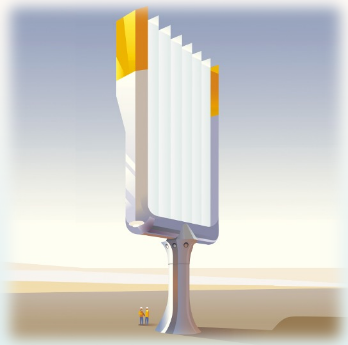


2 to 2.5 mol/kg of charge
1 to 1.25 mol/kg of CO_2 capacity
Durable, life time 10 to 20 years

- 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 and unloads to carbonate
  - $2HCO_3^- \rightarrow CO_3^{--} + CO_2 + H_2O$
- Intermediate product stream is air with 5% CO_2
- Ion hydration drives CO_2 affinity
- $CO_3^{--} + H_2O \rightarrow HCO_3^- + OH^-$
  equilibrium is driven by water content

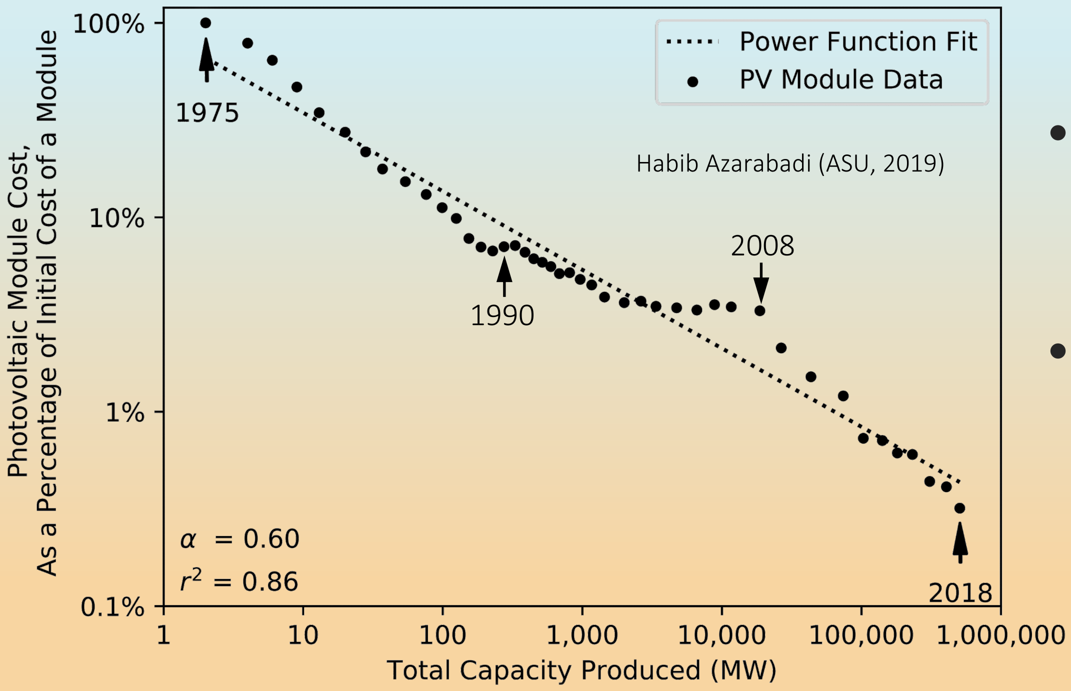
Limited to dry climates with access to water (salt content?)





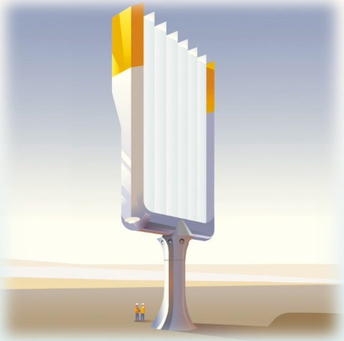
Mass Production Paradigm

Cost reduction in mass manufacture have reduced costs by orders of magnitude



- **Photovoltaic power has shown the way**
  - Other technologies show similar rates of improvement
    - *Computers, cars, appliances (small mass-produced items fare better)*
- **Direct Air Capture is just entering the race**
  - Starting point is much better than for renewable power
    - *Requires 10-fold reduction rather than 100-fold reduction*

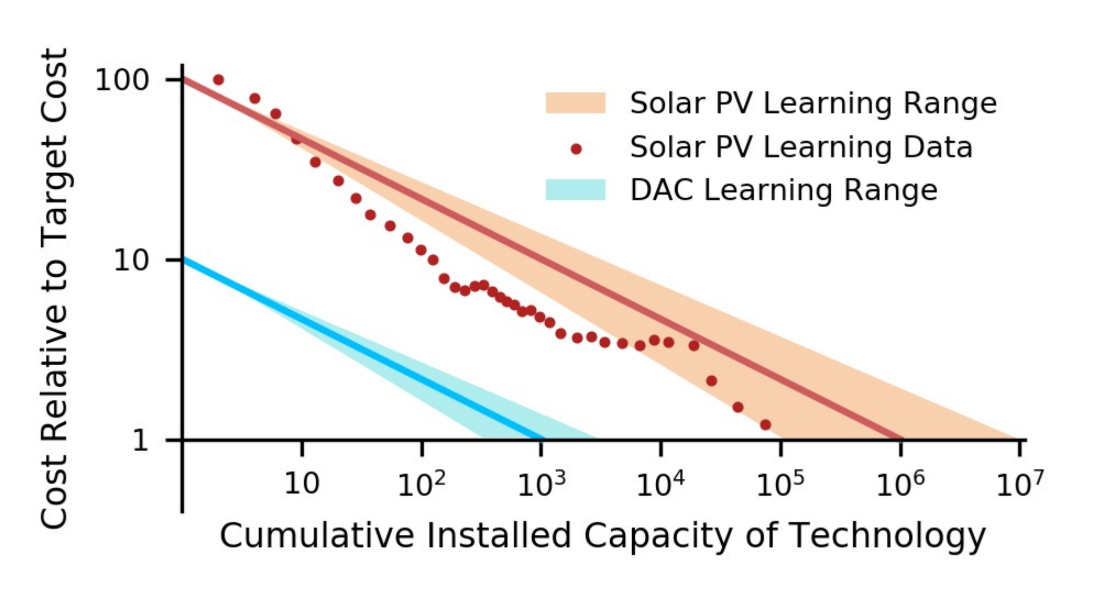
Unit costs follow power laws in terms of cumulative production
The power law coefficient $(\alpha - 1)$ is typically on the order of -1/3

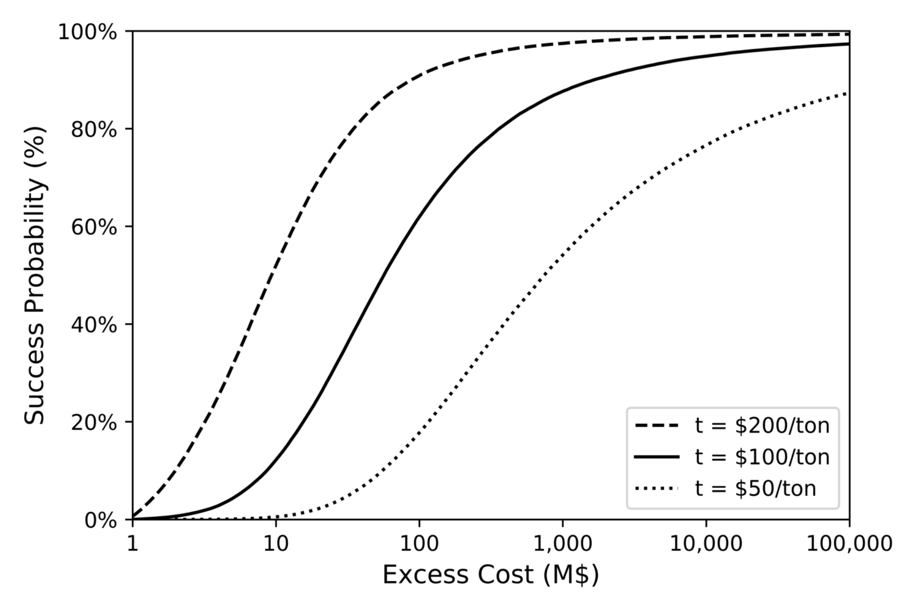


Reducing the cost of DAC Following a power law

Monte Carlo estimate of excess cost

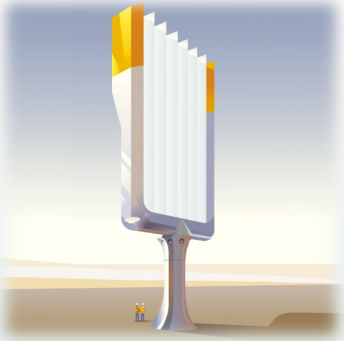
(the subsidy required to sell from the start at the target price)





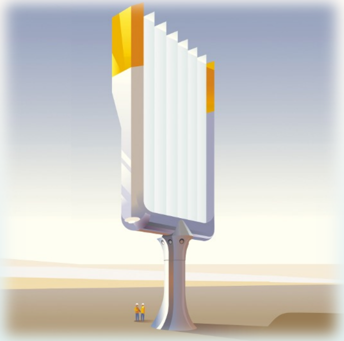
$k(n) = c(n) + r$ and $c(n) = c_1\, \varepsilon^{\log_2 n} = c_1\, n^{\log_2 \varepsilon}$ and $\log_2 \varepsilon = \alpha - 1$

$k(n)$ is the cost of the n^{th} unit ($k(1) = \$500$/t) , r is the irreducible cost ($r = \$30$/t), $c(n)$ follows a power law, α is the power coefficient that relates total cost to cumulative size of production, α = 2/3 implies rapid cost reductions, but it is damped by r, resulting in an effective logarithmic slope that over the range of interest changes from 2/3 to 4/5.



Getting to scale

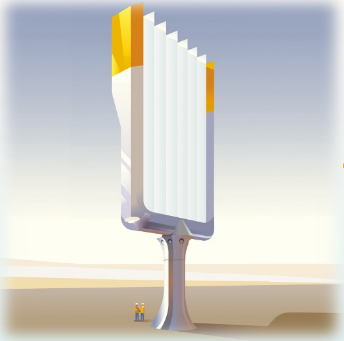
- **From kilotons to Gigatons per year**
  - Cost reductions could be an order of magnitude
  - No climate impact yet
- **Commercial markets in the Megatons**
  - Three orders of magnitude larger than today's scale
  - Prices between $60/ton an $300/ton
    - *Large geographic and temporal variation*
  - Foothold for a new technology
    - *Waiting for climate change policy*
    - *Which is already on its way*



DAC produces CO_2

Now what?

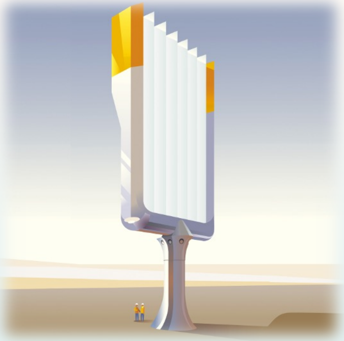
- **For small uses of commercial CO_2**
  - *Insignificant impact on carbon balance*
  - *Could be economic without carbon constraints*
    - but development costs are too high
  - *Demonstrates technology and starts learning curve*
- **For large scale use of CO_2**
  - *Fuel production (plus chemical feed-stock)*
  - *Displaces fossil fuels*
- **For sequestration**
  - *Carbon removal and far-end of pipe CCS*
  - *Makes fossil fuels carbon neutral*
  - *Negative emissions at the 40 Gt/yr scale (100 ppm in 40 years)*



A Closed Carbon Cycle Supported by Renewable Energy

- **Outputs**
  - **Electricity for direct use and batteries**
    - *Current focus of attention, limited to short term storage*
  - **Synthetic fuels for transport and long-term energy storage**
    - *Technically feasible and circumvents intermittency challenge*
    - *Markets need to find optimal penetration of fuels*
    - *Raw and intermittent PV is cheaper than chemical energy in natural gas*
  - **Waste CO_2 for long-term disposal**
    - *Disposal of CO_2 for climate restoration*

The cost of solar electricity is approaching the cost of chemical energy in natural gas



Numbering up: 100 million container-sized units could balance current world emissions

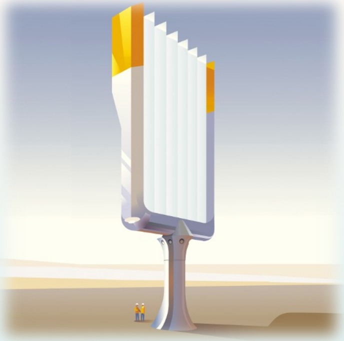
eliminate a 100 ppm overshoot in 40 years
or provide feedstock for liquid fuels at current rate

10-year life time implies a production capacity of 10 million per year

Container sized units could capture 1 ton CO_2/day

World car and light truck production:
90 million per year

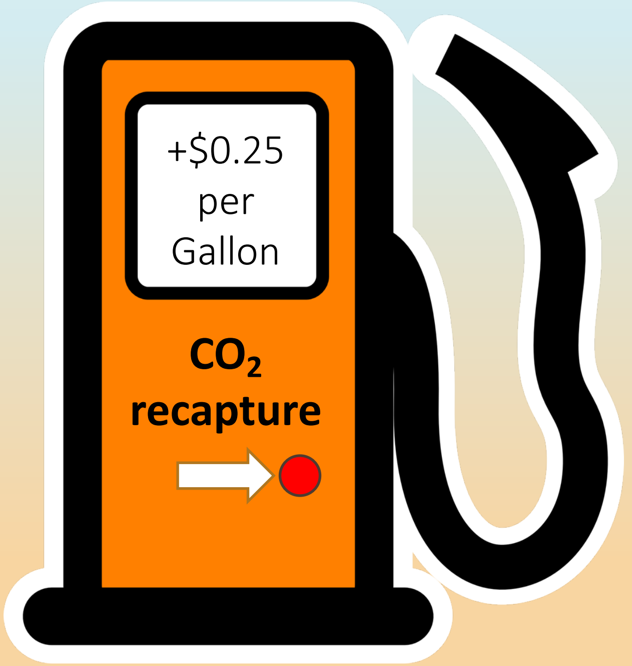
wikipedia pictures



How to get started: Engage Volunteers

Government Support, Strategic Interest, Environmental Advocacy

- **Oil companies could offer carbon neutral gasoline**
  - Assume initial removal cost: $100/ton of CO_2
    - *Reachable with current development efforts*
  - $50 covered by US Tax Credit (45Q)
    - *Passed into law in the spring of 2018*
  - $25 taken on by the oil company
    - *Based on interest to establish the technology*
  - $25 offered by volunteer = 6 cents/liter
    - *Like green electricity premium*



Demonstrate the policy, build support, and learn down costs

Avoid phony offsets!