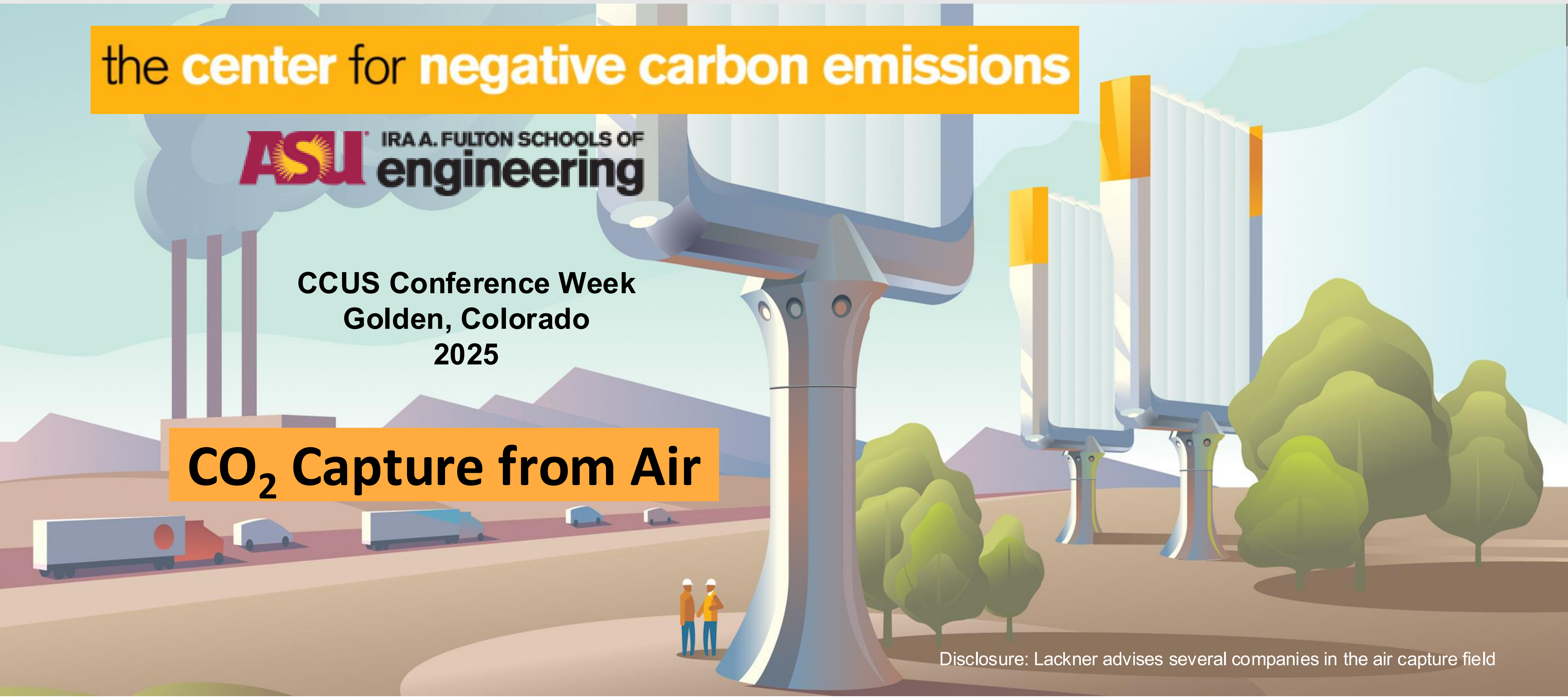


the center for negative carbon emissions

IRA A. FULTON SCHOOLS OF engineering

CCUS Conference Week
Golden, Colorado
2025

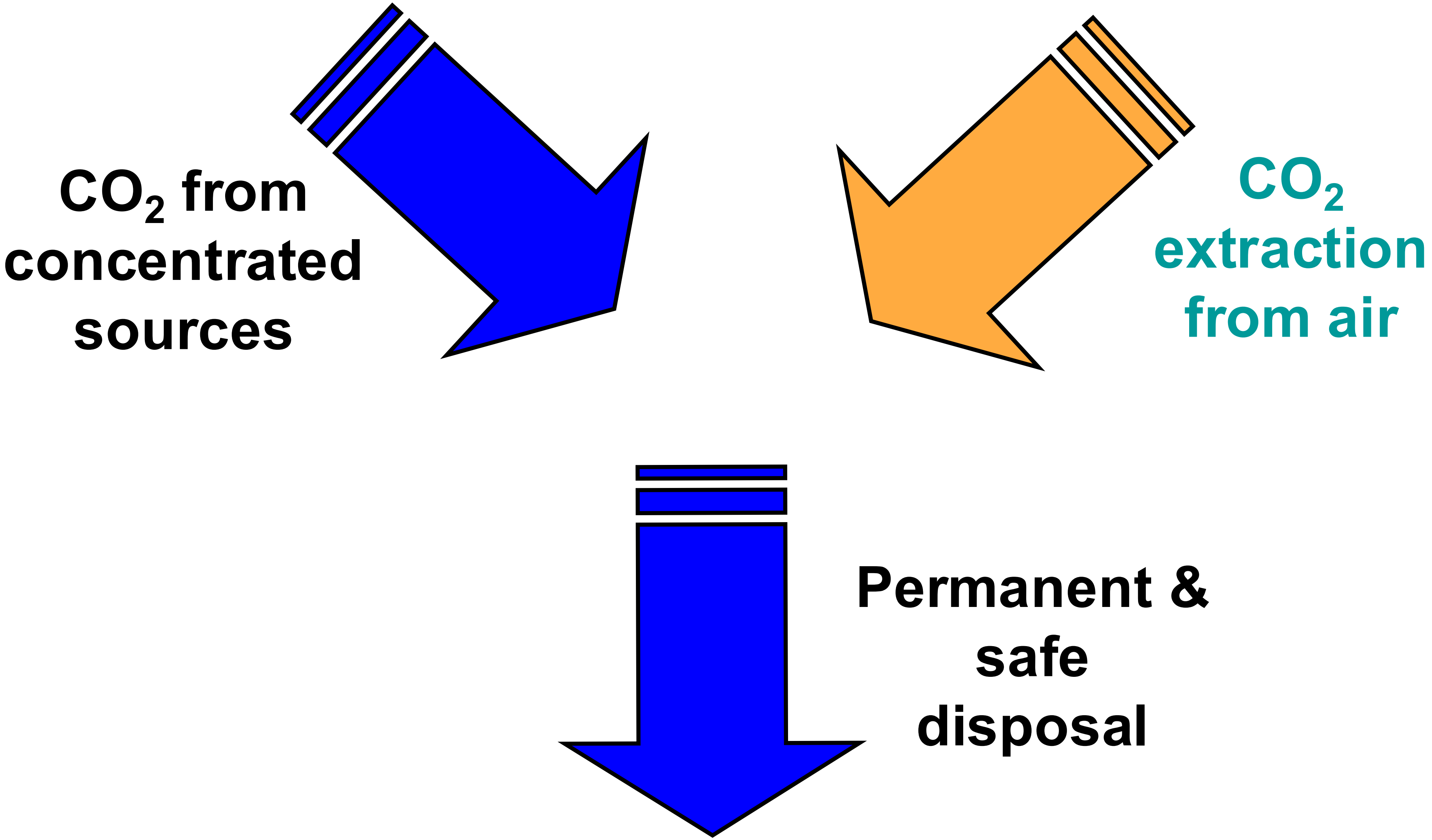
CO_2 Capture from Air

Disclosure: Lackner advises several companies in the air capture field

Julie Ann Wrigley Global Futures Laboratory
Arizona State University

Klaus Lackner
Founding Director, Professor at the School of Sustainable Engineering and the Built Environment
September 2025

Net Zero Carbon Economy



Three Rules for Technological Fixes

D. Sarewitz and Richard Nelson (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)."

CDR = Carbon Dioxide Removal
= Extraction from the mobile carbon pool

- Biosphere extraction
  - Carbon removal via biomass will affect atmosphere in short order
  - Low-cost option but limited in scope
  - Siting limitations and scale limitations
- Ocean extraction
  - Thermodynamically equivalent to air capture
  - Immediate impact on the atmosphere
  - Carbon dilution in the ocean 1:26,000
- Air extraction (Direct Air Capture or DAC)
  - Fastest mixing times
  - Dilution 1:2,500
  - No siting limitations – no scale limitation
  - Cost must come down tenfold!!

DAC Systems

1 pointfive website

Carbon Engineering Website

Climeworks Website

Direct Air Capture

- Chemical process technology for extracting CO2 from ambient air
  - Distinct from photosynthetic (biological) systems
  - It collects carbon dioxide for use, disposal or both
  - CO_2 is available everywhere

- DAC separates sources from sinks
  - Allows for capture from diffuse sources
    - Cars, trucks, ships, airplanes
    - Boilers etc.
    - Past emissions

Direct Air Capture: Closing the Carbon Cycle on the Teratonne-Scale

- Air capture can produce feedstock for fuels and chemicals (DACCU)
  - Current rate of oil consumption generates 1.5 Teraton CO_2 in the 21st century
  - DAC can promote solar energy to become the dominant primary energy source
- Air capture can collect waste from past and future emissions (DACCS)
  - Collecting 100 ppm from the atmosphere requires 1.5 Teraton of CO_2 capture
  - Sequestration cannot be avoided anymore
- What else can reach this scale? (Trillion-dollar annual revenue industry)
  - Without competing with food production
  - Without large environmental footprints

DAC is exceptionally well positioned

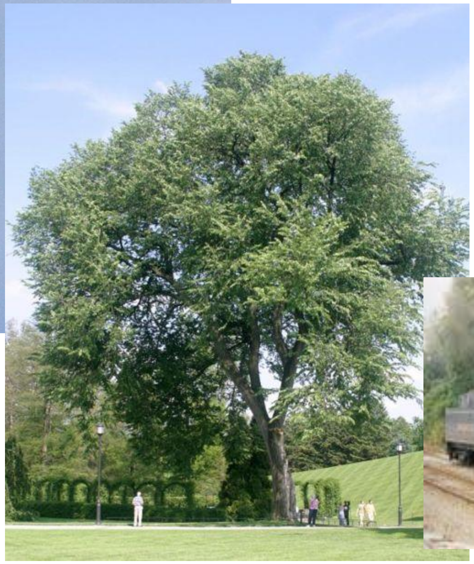
Technical Feasibility of DAC

- Plenty analogs that demonstrate technical feasibility
  - Carbon dioxide removal on submarines and space craft
  - Stripping CO_2 and H_2O from air for cryogenic air capture
  - Flue gas scrubbing for scale, but much higher concentrations
- DAC requires very different optimization
  - Extract CO_2 from air rather than clean it out
  - 100 to 300 times higher dilution than in flue gas capture

What is taking so long?

- Too different from established technologies
    - Heavier-than-air flight and direct air capture are (nearly) impossible with off-the-shelf technology

Wikipedia images



- Lack of market pull

Feasibility & Affordability?

CO_2 in air is dilute, and air is full of water

- Sherwood's relates costs scale linearly to dilution
- The air carries 10 to 100 times as much H_2O as CO_2
- First-of-a-kind apparatus is expensive (~$1000/tonne)

Not a conventional separation technology

Wikipedia picture

First: CO_2 in the air is not too dilute!

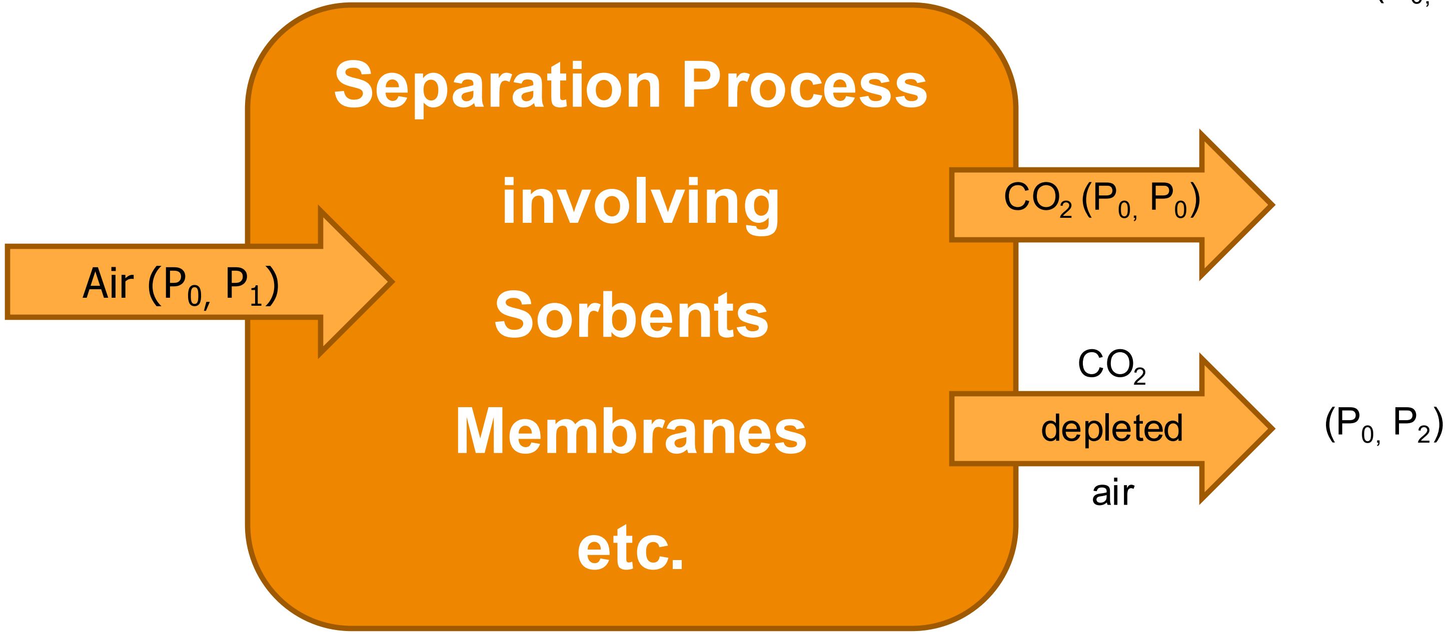
- One cubic kilometer of air
  - Passes through a windmill in the course of an afternoon
  - Carries $300 of kinetic energy
    - assuming a wind speed of 6m/s and a value of 5¢/kWh
  - Carries $21,000 of CO_2
    - assuming a tipping fee or commodity value of $30/ton

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

Second: Thermodynamics is not limiting

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

Total gas pressure P_0
CO_2 partial pressure P_x
Denoted as (P_0, P_x)



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

22 kJ/mol CO_2 vs. heat of combustion 400 – 900 kJ/mol CO_2
(Specific irreversible processes will always require more energy)

Air capture is sorbent based*

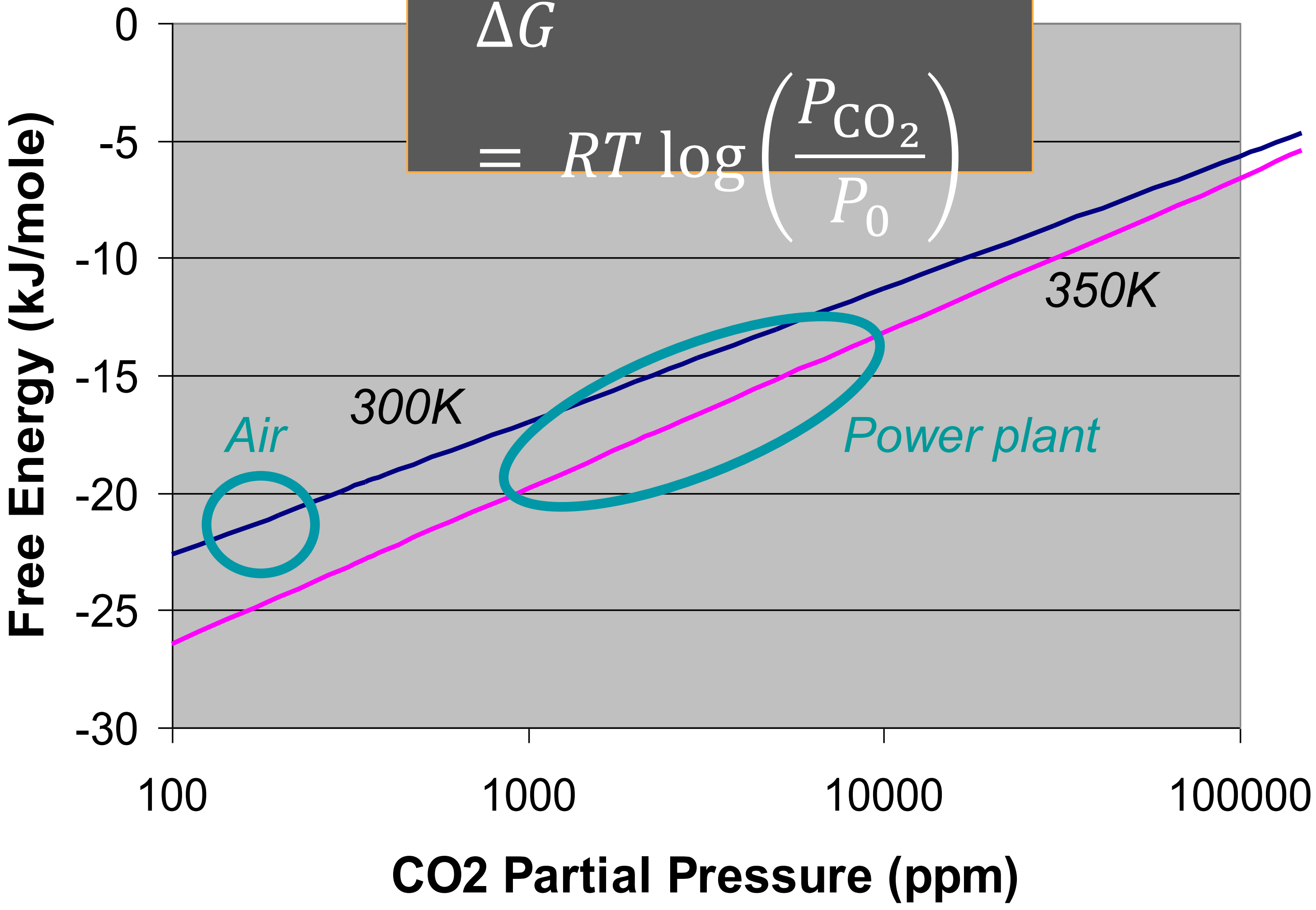
- Sorbents bind CO_2 without need for spending energy on the air
  - Concentration ratio is 1 : 2500
    - Sorbents postpone work to the regeneration step, only do work on CO_2
- All air capture sorbents are chemical sorbents
  - At 400 ppm only chemical bonds are strong enough, $|\Delta G| > 22$ kJ/mol
- Today's 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
- Solid sorbents deliver better kinetics

*The exception are active membranes. We are working on a moisture gradient to pump CO_2 against a concentration gradient

Required Sorbent Strength

depends logarithmically on CO_2 concentration at collector exit

$$\Delta G = RT \log\left(\frac{P_{CO_2}}{P_0}\right)$$

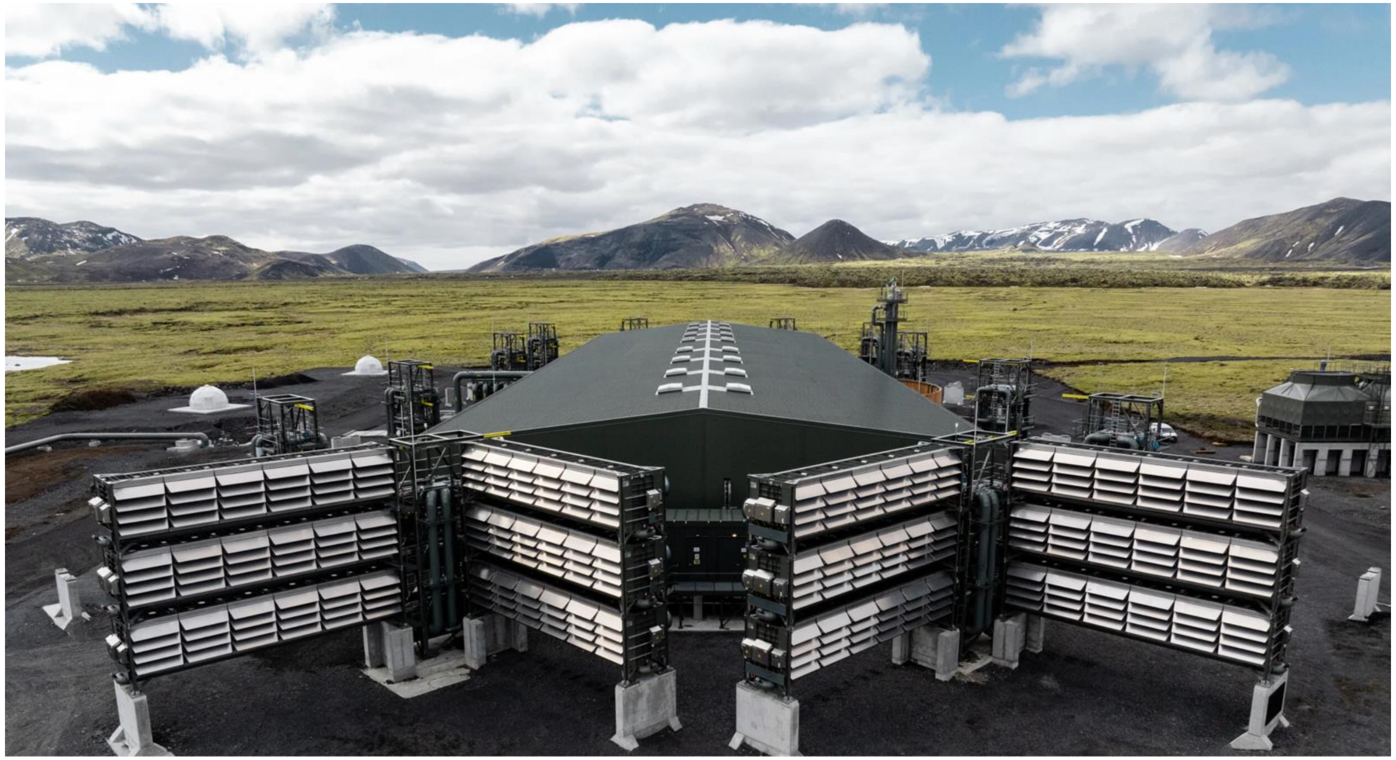


Disagrees with Sherwood's Rule

Third: Direct Air Capture is too expensive

- Tax incentives (45Q, LCFS in the US and California) provide about $200/tonne
- No DAC company is currently selling actual credits on this basis

$250 to $1,000/tonne



Climeworks Website

Sherwood's Rule is avoidable

Cost of separation scales linearly with dilution *D*

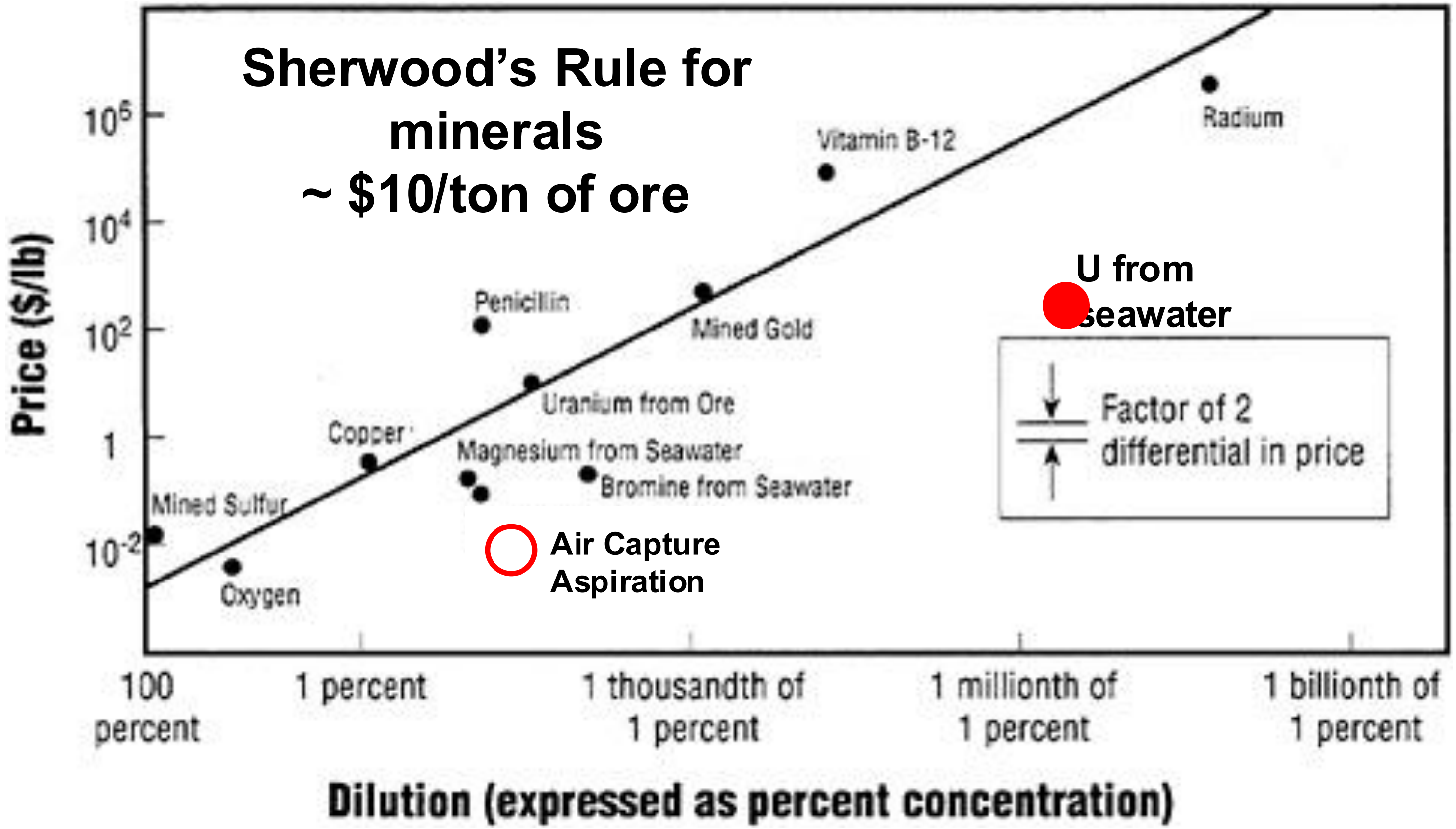
Sherwood's Rule

- The cost of the first step in the separation dominates

- $Cost = aD + b + c\log D$

Bulk processing

Thermodynamic separation



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

Artificial kelp to absorb uranium from seawater

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

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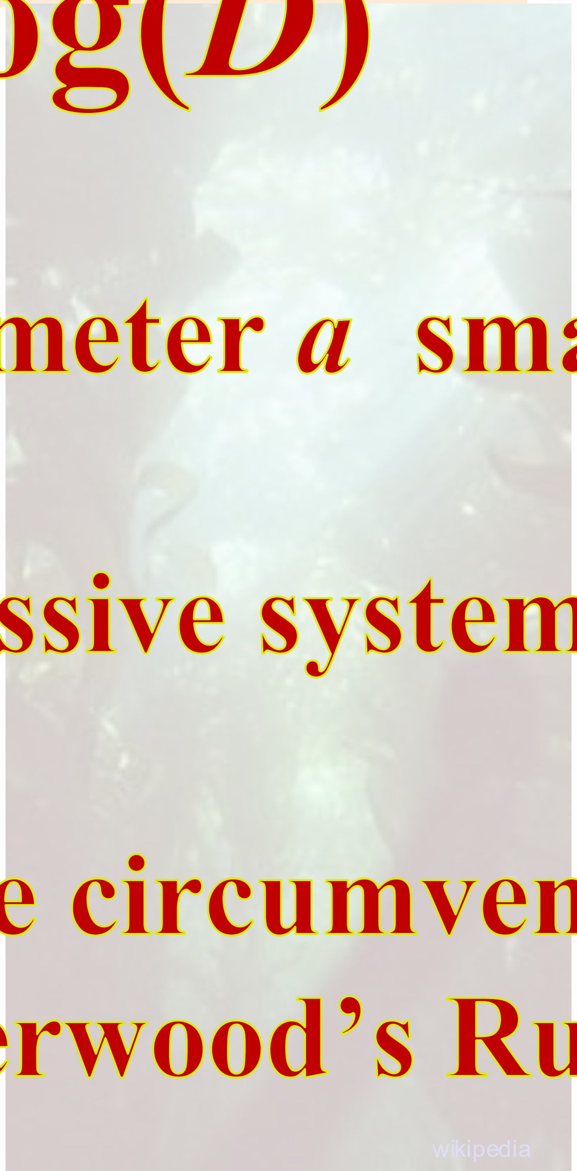


must make parameter *a* small

passive systems!

Wind driven air capture circumvents Sherwood's Rule


CARBON
COLLECT
MechanicalTree™
www.carboncollect.com

Irreducible Cost

- Raw inputs and outputs
  - provide lower bounds on costs that exclude inefficiencies, friction, and dissipation
- Lower bound
  - The difference between initial costs and the frictionless limit can be large and may never go to zero.
- Irreducible cost per tonne
  - Thermodynamic requirement (separation and compression) 215 kJ → $2.15 … $10.75
    - Sherwood's rule does not change it
  - Equipment cost $10-20/kg
    - Sorbent captures 3 mol/kg, cycle time 1000 sec, sorbent 1/3 of total mass
    - 10%/yr discount rate
    - $0.70 to $1.50/tonne
- Land use cost is insignificant

$10 - $20/tonne
This is what learning could aim for

Air Capture can avoid Sherwood's Rule

DAC need not crush or grind air

Dominant cost is sorbent regeneration

somewhat more energetic than flue gas sorbent recovery

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

Extracting kinetic energy from air at 20 J/m^3 is feasible

Image courtesy Stonehaven production

Wind energy ~20 J/m^3

CO_2 combustion equivalent in air

10,000 J/m^3

Contacting of air can be inexpensive

Regeneration cost are slightly larger than for flue gas scrubbing

Cost of DAC is important

- Policy and consumers ultimately care about price
  - Difference between price and cost can be huge
- It is future costs not today's costs that matter
  - Huge cost reductions are common
- Unfortunately, cost is a slippery concept
  - Costs today are very different from costs tomorrow
  - Supply chain costs are other producers' prices
  - Supply chain costs respond to demand

How to maximize the odds

Cost under mass production – The learning curve

- Doubling cumulative output lowers the reducible part of the cost by a factor $\varepsilon \sim 0.8$
- $L = 1 - \varepsilon$ is known as the learning rate

$$k(n) = c(n) + r$$

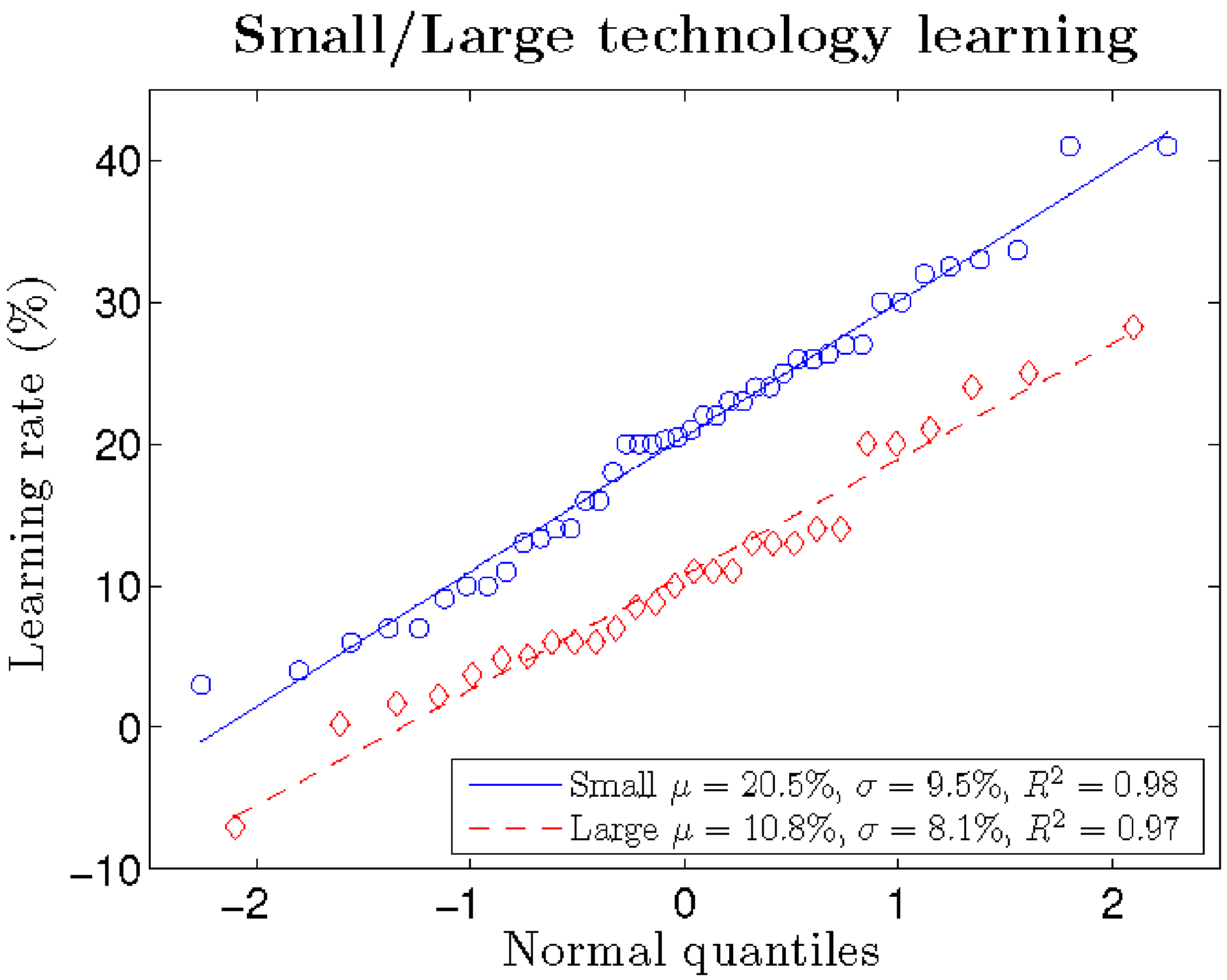
$$c(n) = c_1\, \varepsilon^{\log_2 n} = c_1\, n^{\log_2 \varepsilon}$$

$$\log_2 \varepsilon = \alpha - 1$$

$k(n)$ is the cost of the n^{th} unit ($k(1) = \$500/\text{t}$)
r is the irreducible cost ($r = \$30/\text{t}$)
$c(n)$ follows a power law $c(n) = c_1\, n^{\alpha-1}$
α is the power coefficient that relates total cost to cumulative size of production

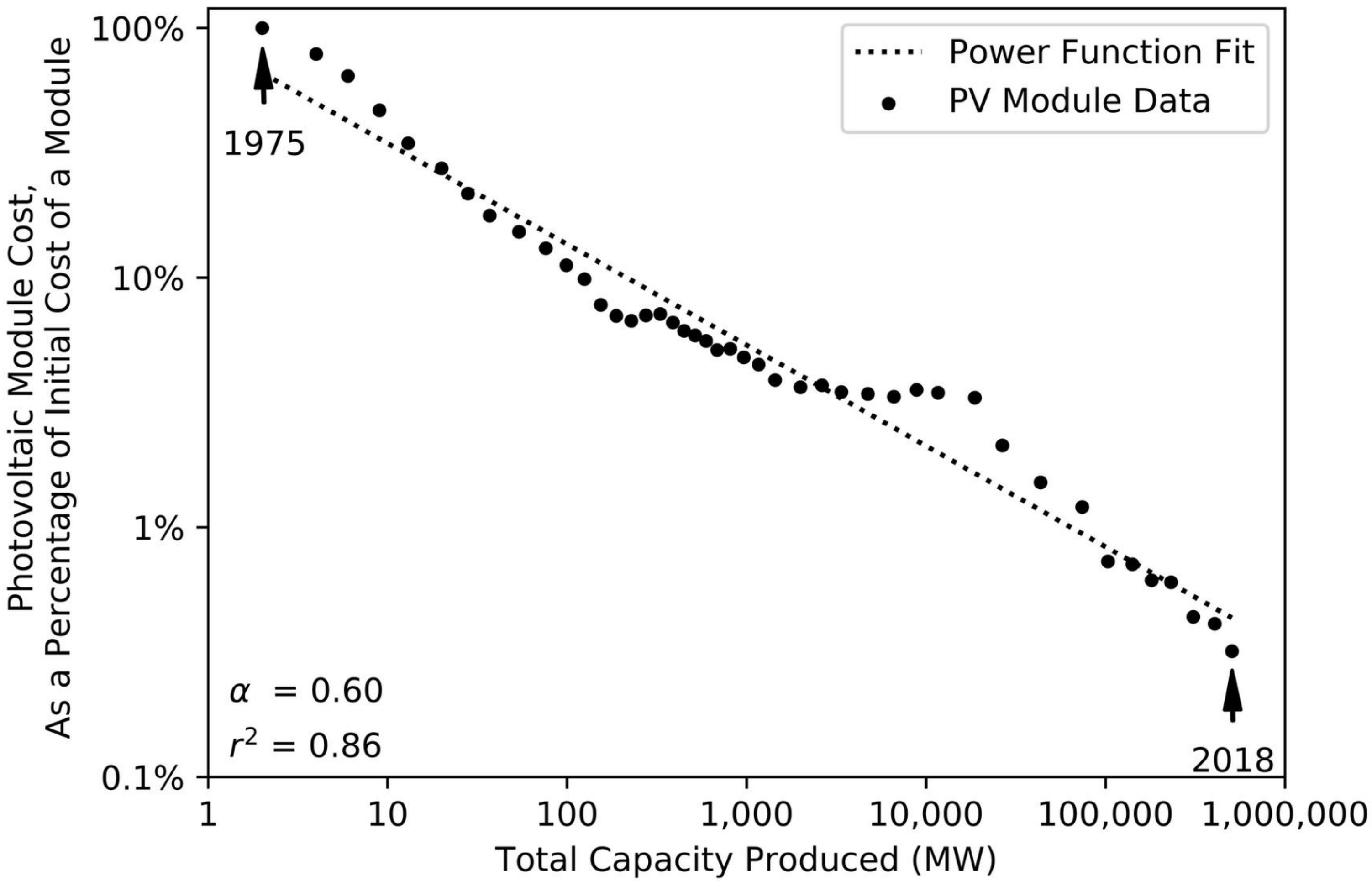
Learning works better for small units

- Range of learning coefficients $(1 - \varepsilon)$ changes with size



Eric Dahlgren, Ph. D. Thesis 2013

Solar Energy Costs are Dropping Fast



Habib Azarabadi, ASU

Growing a million-fold, the cost of solar energy dropped 100-fold

Industries forced into modularity often do well

- Automobile industry
- Smart phone industry
- Solar photovoltaic industry
- Wind industry (?)

Cost reductions are faster in numbering up
Risks are reduced
Response to market changes is flexible
Multiple approaches can be tested

Demand Curves

- Market avoids stalling if

$$k(n) < P(n) \quad \text{for all } \; n$$

With $n_d\ (P)$, the demand curve and $n_c(P)$ the inverse cost curve,
The equivalent statement is

$$n_d\ (P) \geq n_c(P) \;\; \text{for all } P$$

$$n_d(P) \geq \left(\frac{P - R}{c_1}\right)^{-\frac{1}{\alpha}}$$

Attributes of a good DAC technology

- Low starting cost
  - Low capital and maintenance
  - Low energy inputs
- High learning rate
  - Rates vary across industries and technologies
- Low irreducible cost
  - For normal scaling costs should be acceptable at a 1000-fold increase
  - Climate action requires million-fold increase which means operation near the limit
  - Winners are impossible to predict

Experiment with many different approaches

Many small startups probe the technology space

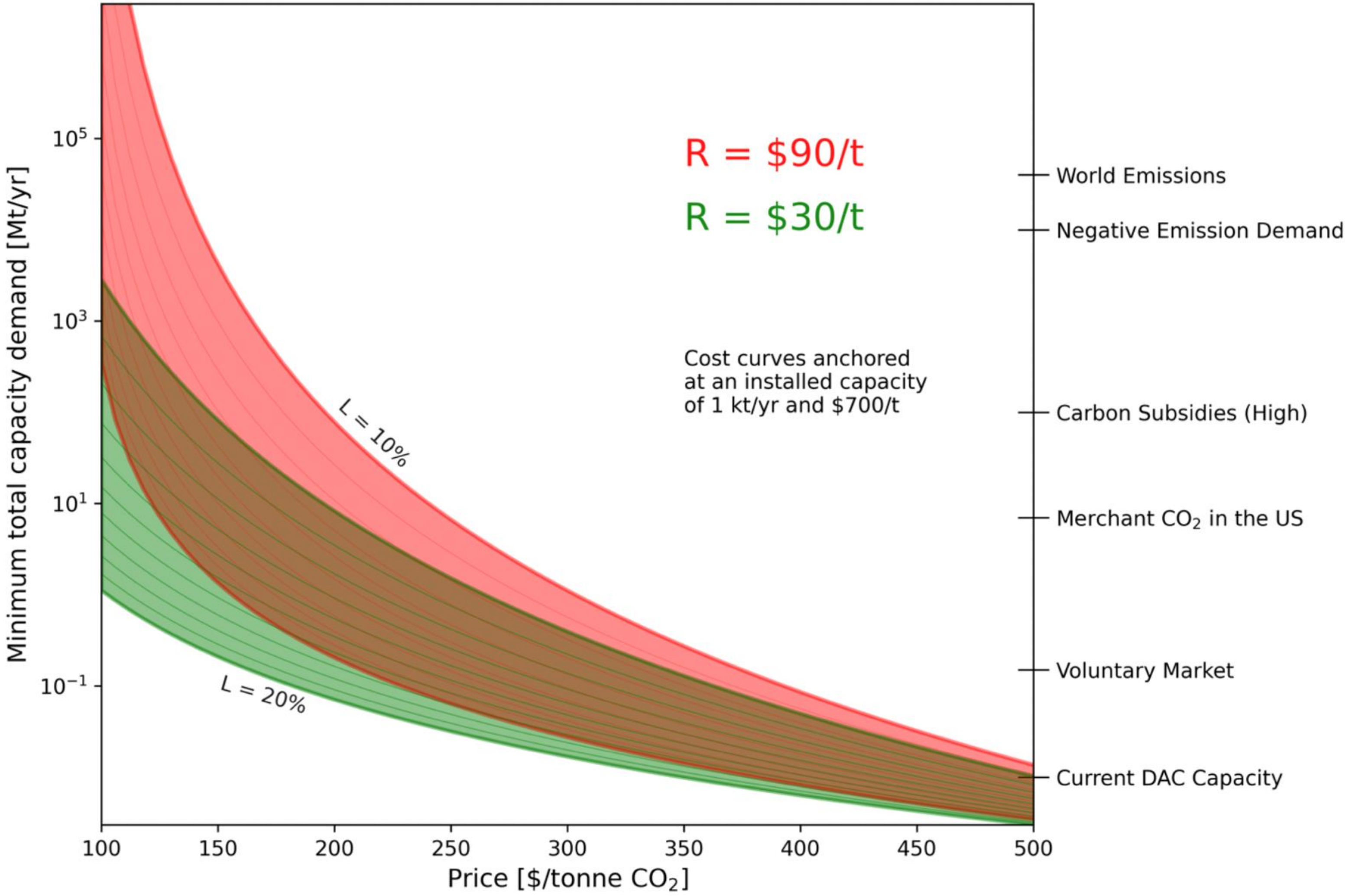
Enable scaling by a modular approach

What scale do we need?

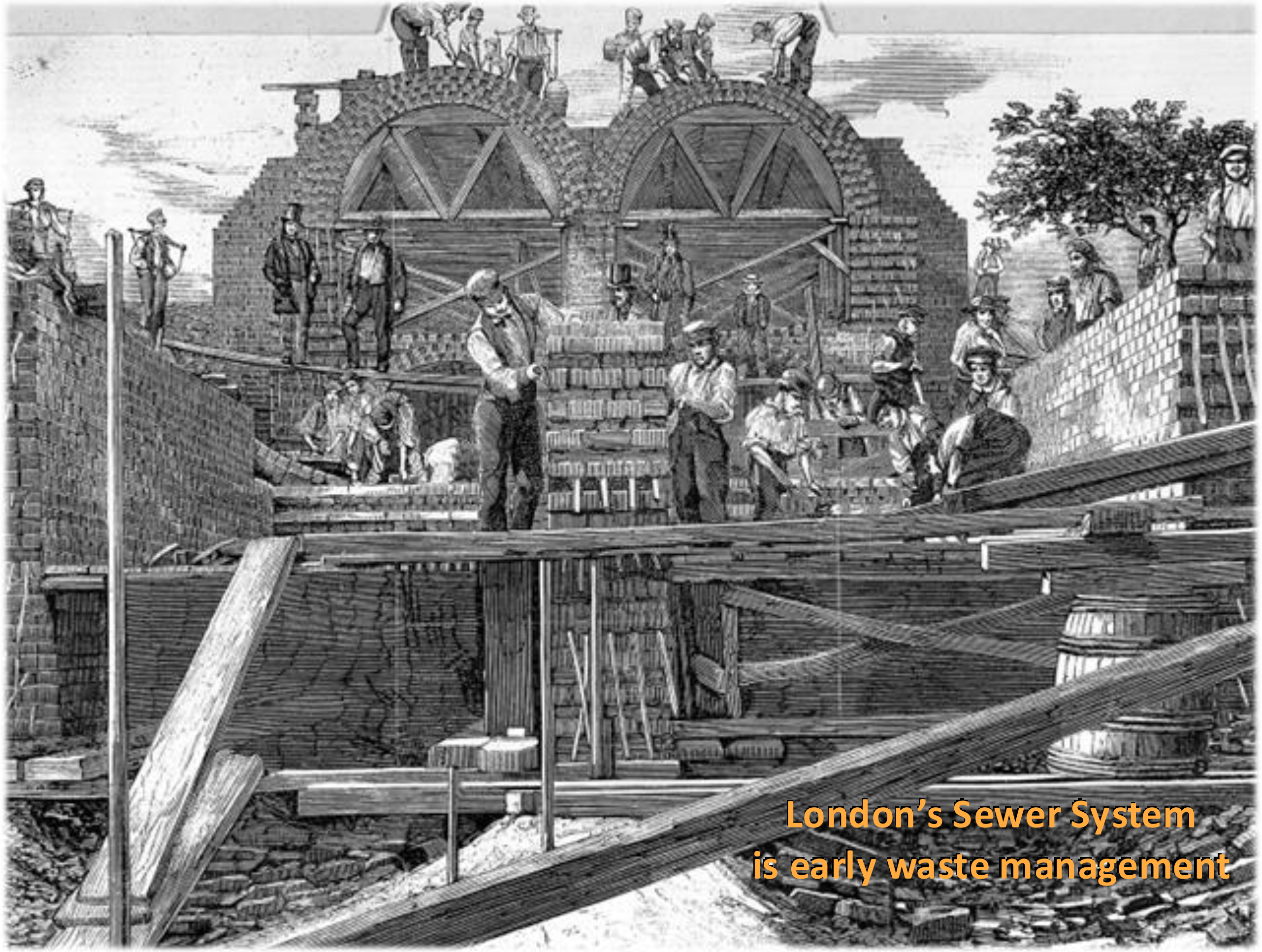
- 40 Gt/yr three different ways
  - Roughly current rate of emissions
  - Emissions at the end of the century of carbon intensity is reduced fivefold
  - Lowering CO_2 in the atmosphere by 100 ppm over 40 years
- How much time do we have?
  - 10 years?
  - 50 years?
  - 100 years?

At this scale even “natural” solutions turn technical

Learning rates matter



Waste problems have been solved before



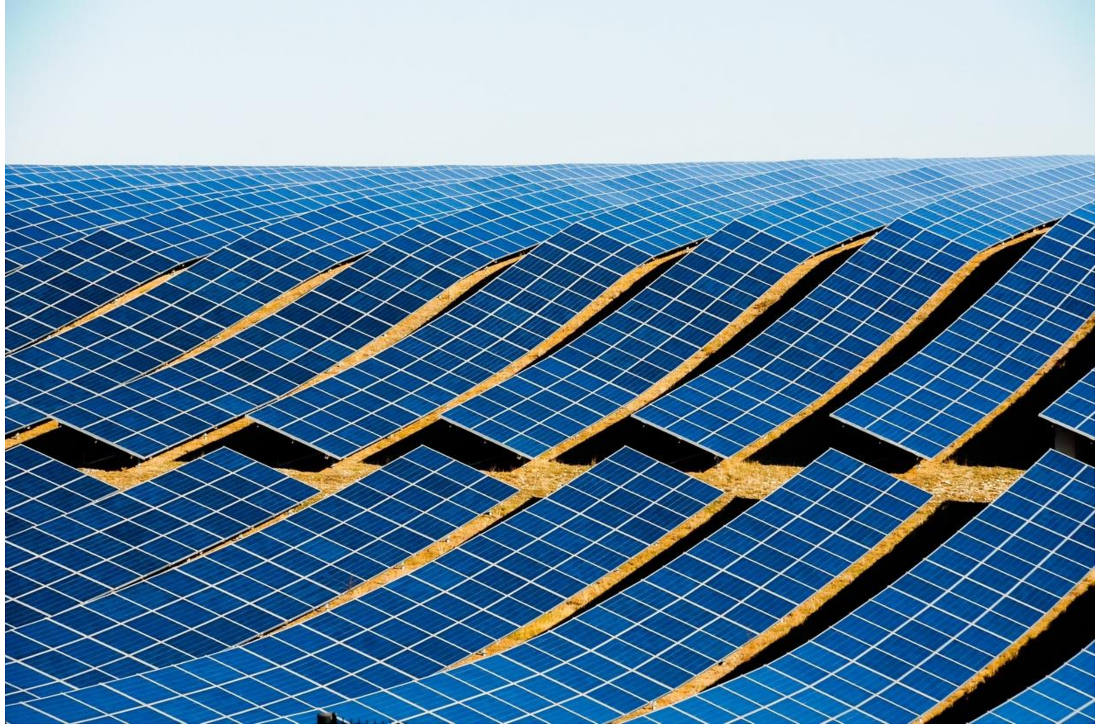
https://commons.wikimedia.org/wiki/File:The_main_drainage_of_the_Metropolis_Wellcome_M0011720.jpg

- Waste management is a lucrative service industry that need to be built
- CO_2 waste is global and can be addressed globally
- Carbon recycling will be driven by the cost of waste disposal

DAC provides Carbon Capture of last resort

- Its advantage is it can be done anywhere and for any emissions
  - Likely operates where CO_2 is needed or energy is available
- Unless there is no need for DAC, it will set the price of carbon
  - Harsh commodity business, but so are many other necessities
- Net negative carbon economies require CDR technologies
  - Can balance out past emissions and emissions difficult to capture at the source
  - DAC offers the possibility of returning carbon to the developing countries

Photovoltaic power will challenge fossil energy even without carbon constraints!

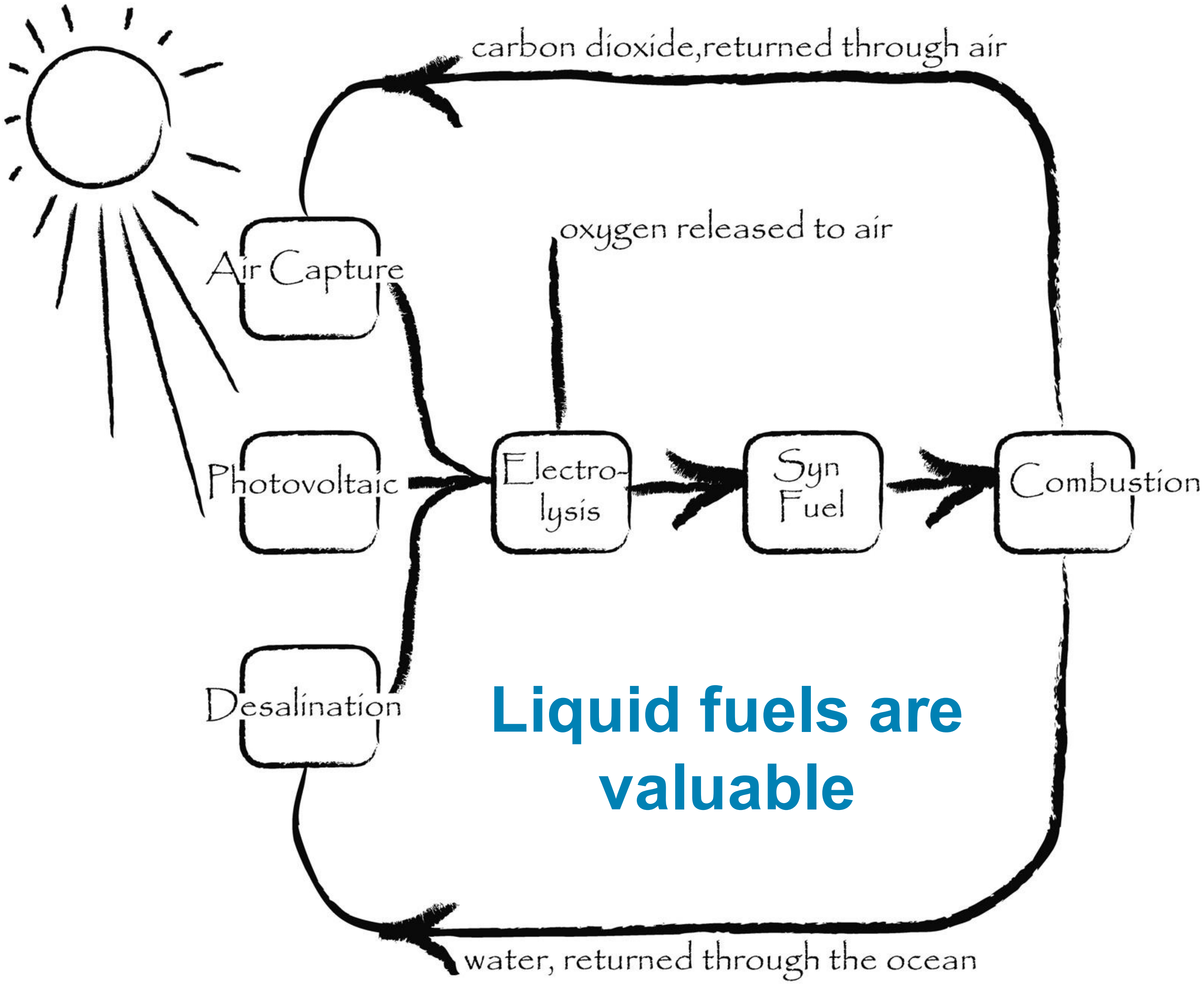


Pixabay stock

- It is the cheapest source of electricity
- Its energy can be stored in liquid fuels
- Cheap storage and easy transport

Disclosure: Klaus Lackner is a board member of Aircela Inc. founded by a one of his former students. It produces liquid fuels from CO_2 from air

Carbon emissions and fossil fuels can separate



Liquid fuels are valuable

Technology usually succeeds if asked to deliver

- The first aircela machine
  - Taking CO_2 from air, water and electricity to make gasoline
  - Designed for Photovoltaic Power

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