the center for negative carbon emissions
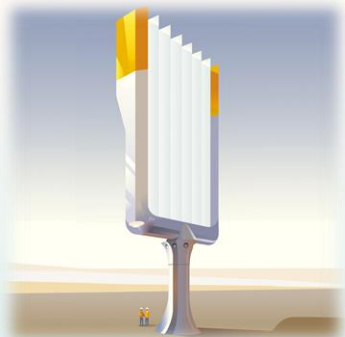
ASU IRA A. FULTON SCHOOLS OF engineering

CO$_2$

H$_2$O

https://www.youtube.com/watch?v=4dHjCjrYcfs
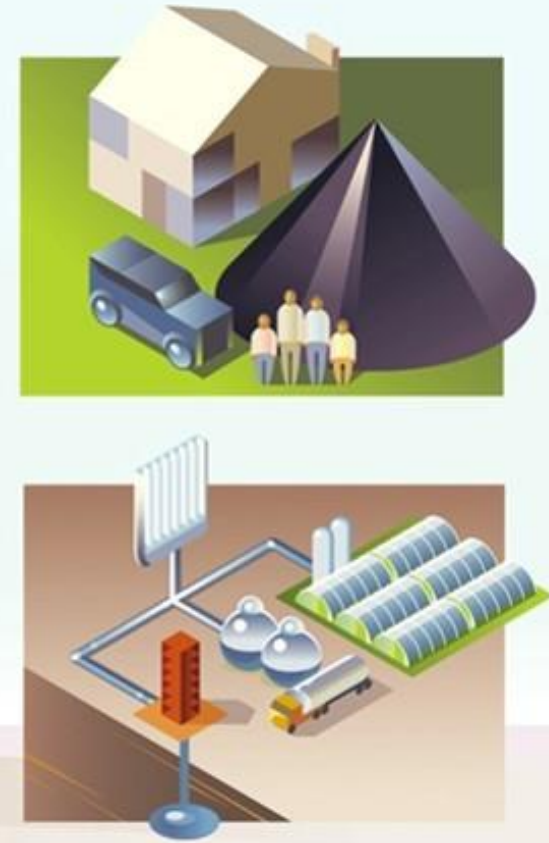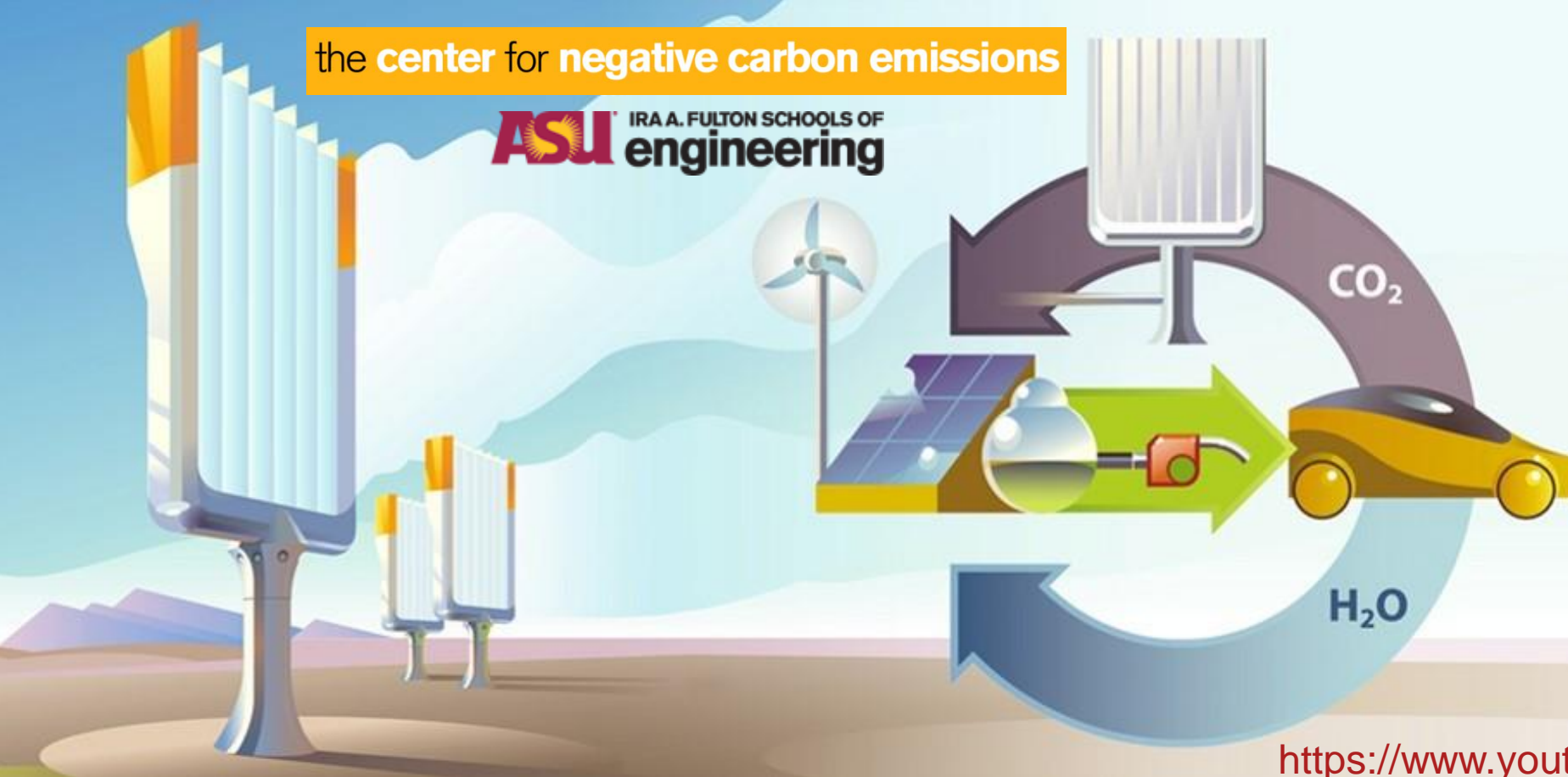
Direct Air Capture as a Tool for Carbon Management

Klaus S Lackner

May 3, 2017

1

Carbon dioxide piles up like garbage

- Carbon dioxide emissions stay in the atmosphere for centuries

- Warming from carbon dioxide lasts for a millennium

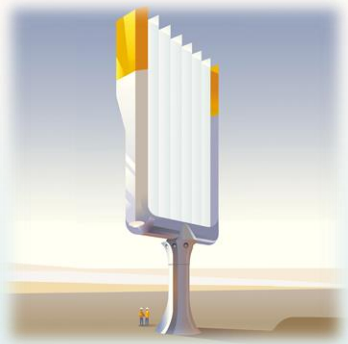- Excess carbon acidifies the ocean for millennia

Moving to a waste management paradigm represents a big shift in dealing with CO_2

Reduce, Reuse, Recycle + DISPOSAL
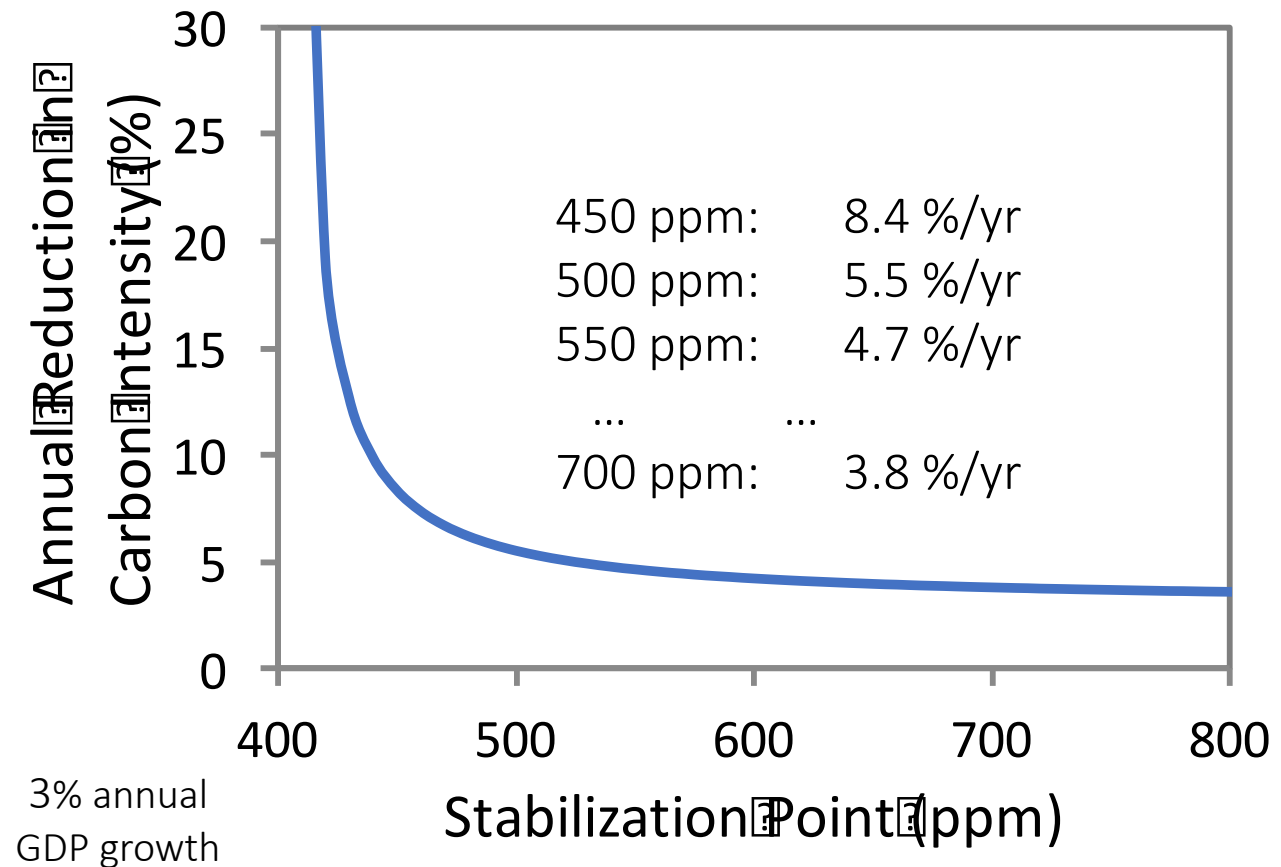
Cost of disposal motivates Reuse

Need to convince people and corporations to clean up their CO_2 garbage
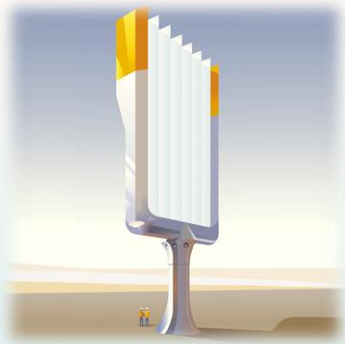Create a movement like recycling

Simple Carbon Math

- 1 ppm = 7.5 Gt CO_2 in the air

- CO_2 spreads to ocean and biosphere
  - *On the century scale half moves out*

- 1ppm = 15 Gt CO_2 emissions

- Current level of CO_2 in the air:

  405 ppm – or 450 ppm$_e$

- 2°C warming: 450 ppm(e?)

- Rate of increase 2.5 ppm/year
  - *Driven by ~35-40 Gt CO_2 per year*

Required annual carbon intensity reduction (C/GDP) depends on the targeted stabilization point

450 ppm:	8.4 %/yr
500 ppm:	5.5 %/yr
550 ppm:	4.7 %/yr
…	…
700 ppm:	3.8 %/yr

3% annual GDP growth

Annual Reduction in Carbon Intensity (%)

Stabilization Point (ppm)

3

The global carbon budget is heading into overdraft

Carbon Credit Card

Paris Agreement: hold warming below 1.5°C or at most 2°C

- *Promised emissions reductions will reach 4°C, business as usual more than 6°C*
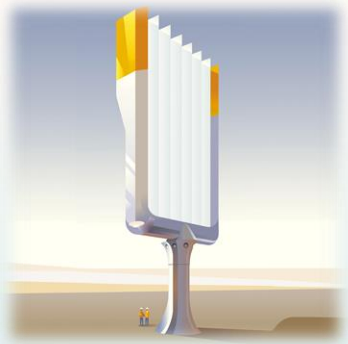- *Cannot stop anymore in time*

IPCC: need negative emissions

- *Pulling CO_2 back from the air*
- *Storing CO_2 safely and permanently*

The per capita fuel allotment for 2°C
Must last for generations
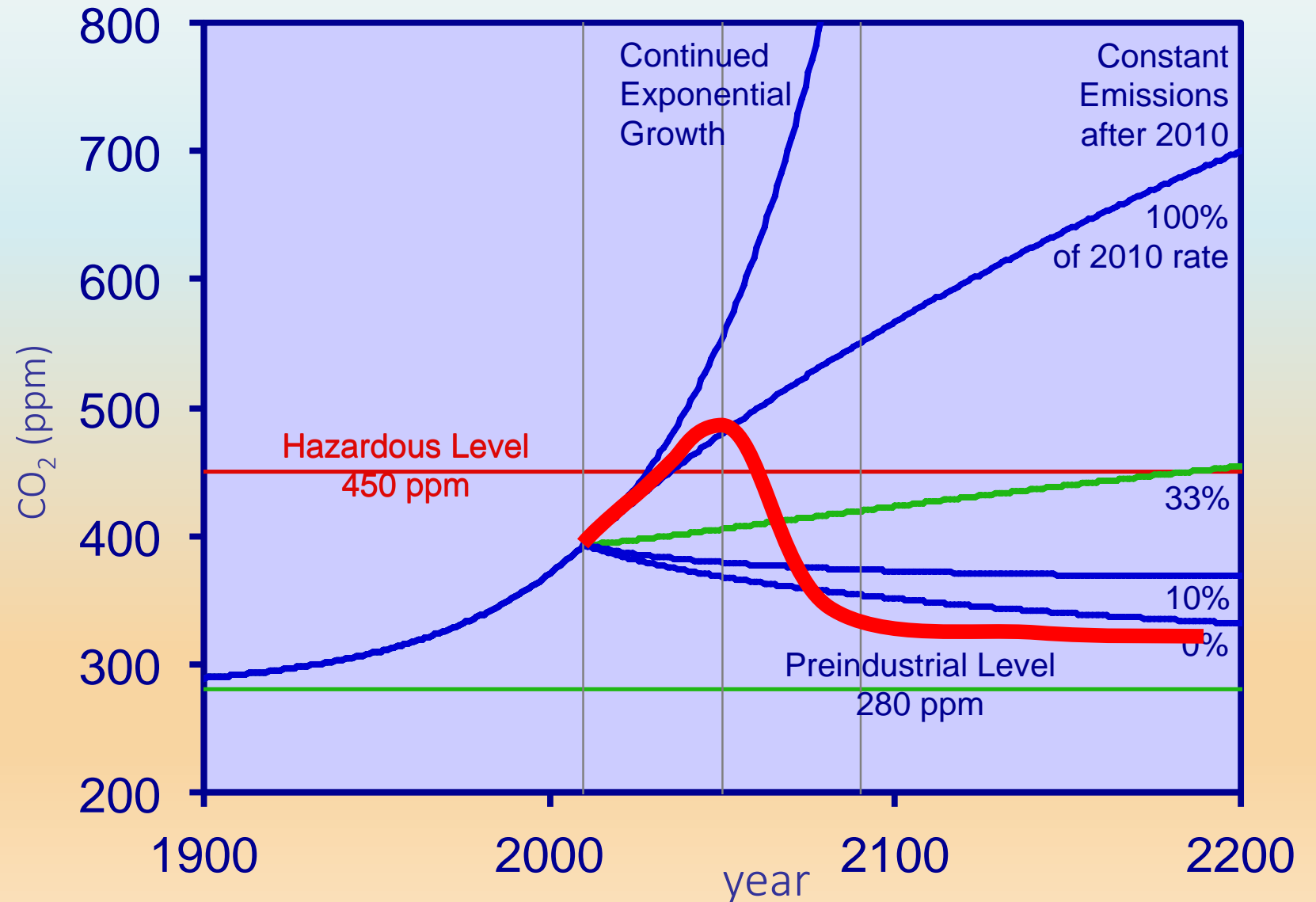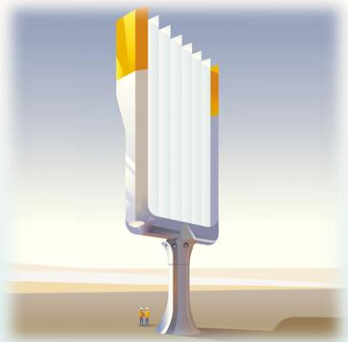
Major business risk for investors
Opportunity for leaders

IPCC calls for negative emissions

Need to recover CO_2 from the environment

Need storage capacity 100 ppm – 1500 Gt CO_2

More than all the emissions of the 20th century

Build a Carbon Management Industry in 30 Years?

Decarbonization
Energy efficiency
Renewables
Biomass

Adaptation
Managing impacts of climate change

Capture & Use
Transforming CO_2 into valuable products

Capture & Storage
Restoring C-balance through long-term sequestration

Pulling CO_2 back from the air

Progress, but
Not Fast Enough
Not Large Enough

Increasingly
Necessary

Market Driven
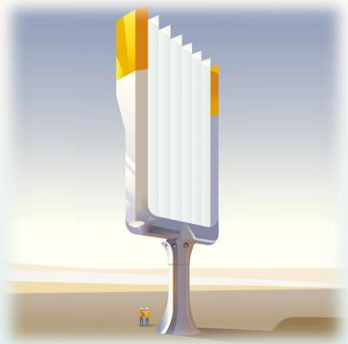Approach

Waste
Disposal
Paradigm

Before 2050:   For every ton of carbon dioxide released to the atmosphere another ton of carbon dioxide will have to be extracted

After 2050:   Lower CO_2 content of the atmosphere with CO_2 scrubbers

We are falling behind!

Graphics adapted from CO_2 initiative

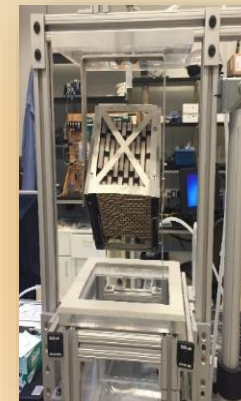# Technologies for Carbon Management

- ## Carbon Storage
  - Disposal of excess carbon underground
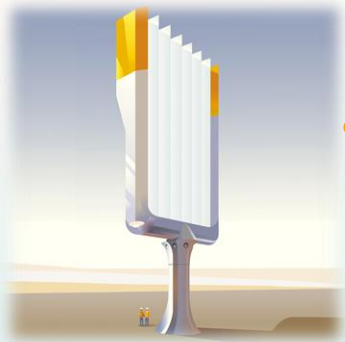 - Established technology but not at scale

- ## Fuel Synthesis
  - Converting renewable energy into liquid fuels
  - Based on proven technology, needs scaling

- ## Direct Air Capture of Carbon Dioxide
  - Novel technology we have introduced
  - Needs demonstration and scaling

Technology Gap: Direct Air Capture

Need: Closure of carbon cycle via Direct Air Capture (DAC)
- Only Direct air capture can scale to close the carbon cycle through the air

Feasibility: Technology works in submarines, but is still too expensive
- Costs imposed by physics are affordable
  - *energy requirement is less than 5% of energy in carbon*
- Other technologies have solved more difficult extraction problems
  - *Passive collectors can pull uranium out of seawater at reasonable cost (100,000 times more dilute than CO_2 in air)*

Cost: Design choices and learning by doing can drive cost down
- Passive device standing in the wind like a windmill minimizes energy and capital costs
- Our moisture swing sorbents trade expensive energy for cheap water
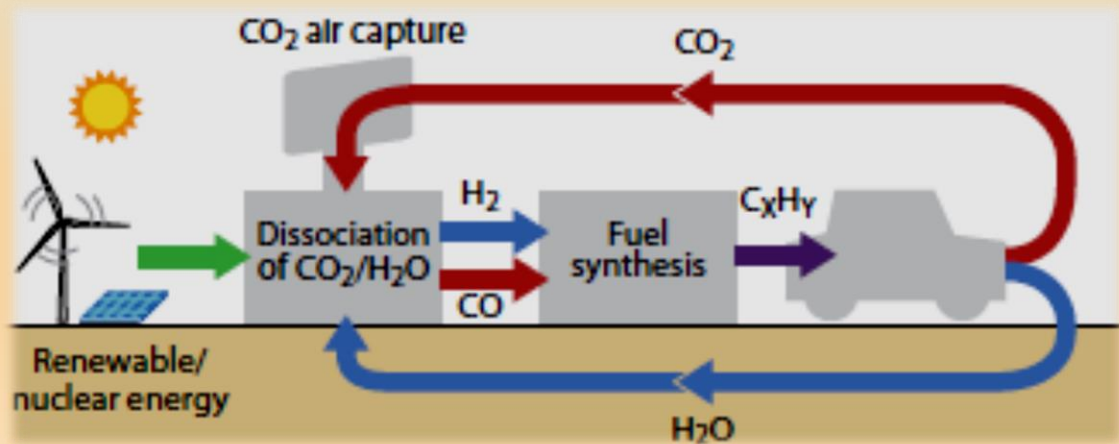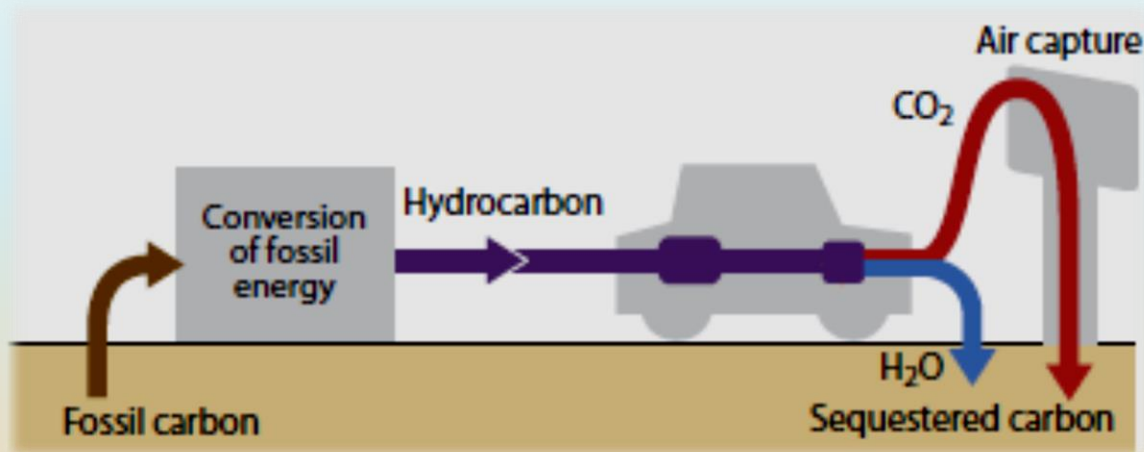- Mass manufacturing can drive cost down by huge factors

An air collector could capture 1000 times as much CO_2 as is avoided by an equally sized windmill.

Mass production can drastically reduce cost
(photovoltaic panels, computers, cars)
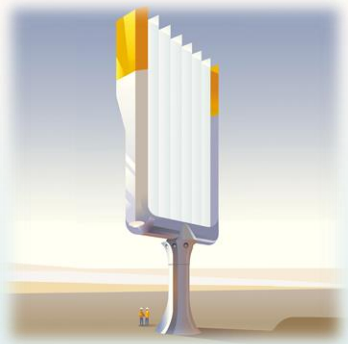
Air Capture of CO_2 is an enabling technology

Air capture eliminates all exceptions
No emission source remain exempt
Separates sources from sinks

Air capture can draw down CO_2
Paying back carbon overdraft
Requires vast CO_2 storage capacity

Air capture enables non-fossil liquid fuels
Synthetic fuels from CO_2 and H_2O
Energy storage & liquid fuels
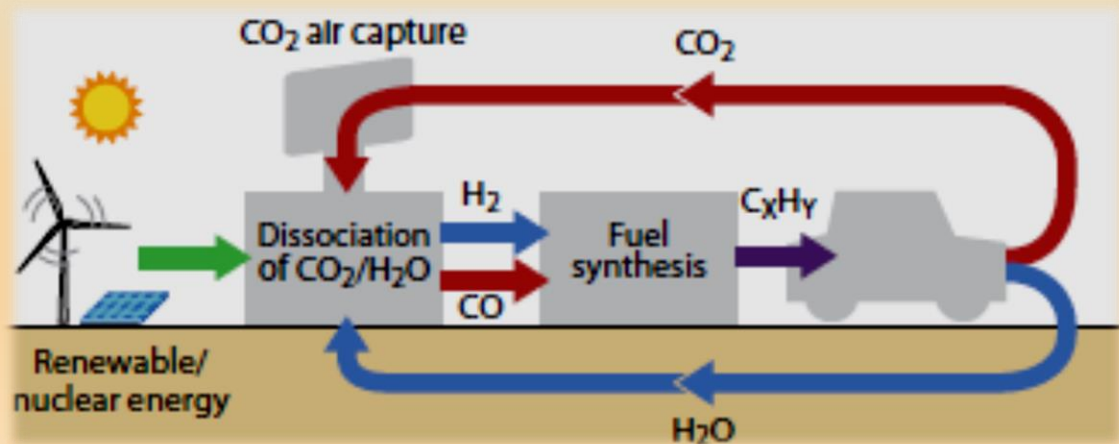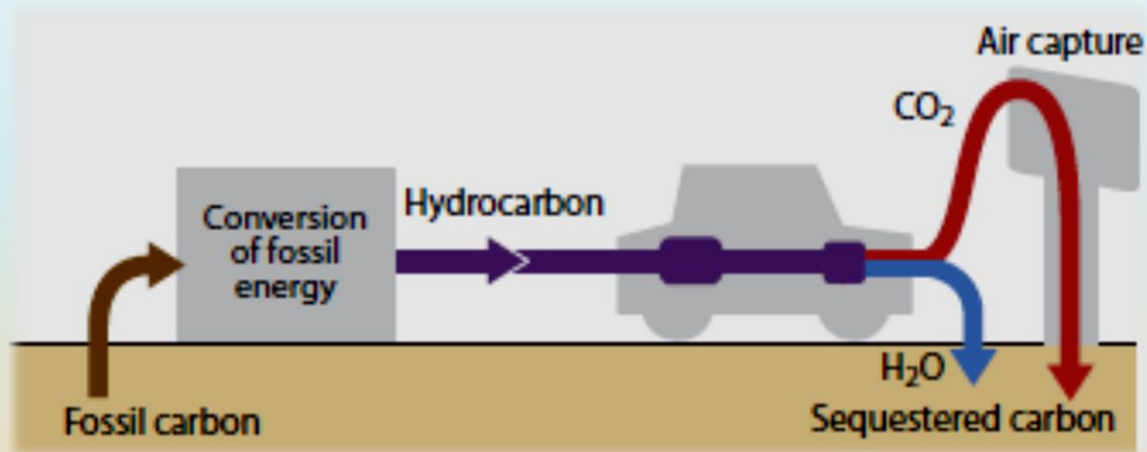Requires cheap non-fossil energy

Air capture enables fossil liquid fuels
Carbon use balanced by sequestration
Requires cheap CO_2 storage

Markets will determine the balance between different options
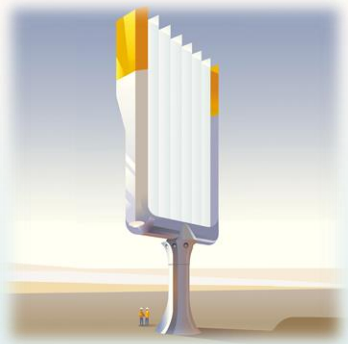
Direct Air Capture balances the carbon budget through storage or fuel synthesis

Air capture devices are mechanical trees

- Thousand times faster than natural trees
- Collect current and past emissions
- Deliver CO_2 for disposal or fuel synthesis
- Can operate at global scale
- Air transports CO_2 for free
- No need for pipelines

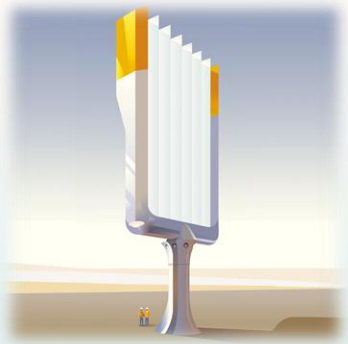Markets will determine the balance between different options
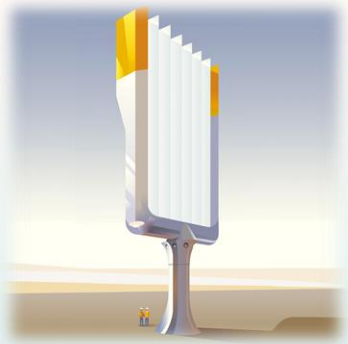
Feasibility & Affordability?
CO_2 in air is dilute and air is full of water

- 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)

Not a conventional separation technology

Wikipedia picture
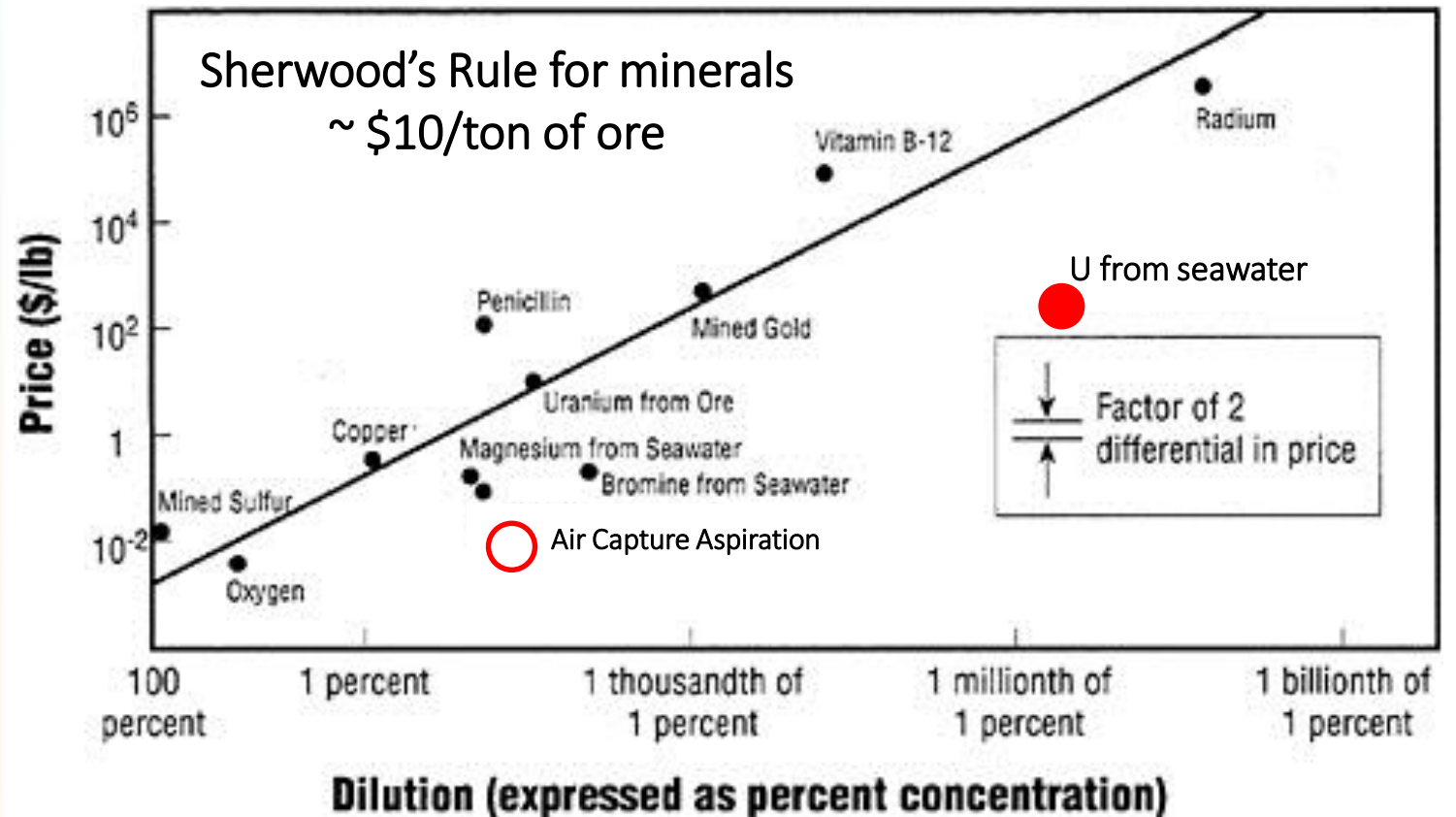
Cost of separation scales linearly with dilution D

Sherwood's Rule

The cost of the first step in the separation dominates

$$Cost = \underline{aD} + \underline{b + c \log D}$$

Bulk processing

Thermodynamic separation

Sherwood's Rule for minerals ~ $10/ton of ore
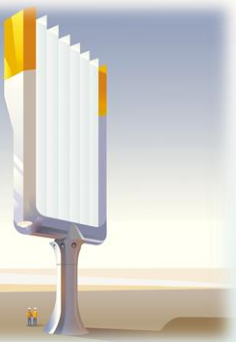
U from seawater

Air Capture Aspiration

Factor of 2 differential in price

SOURCE: National Research Council (1987)

Wind energy – Air capture

Monoliths as low-pressure drop air filters

ASU small test unit

Wikipedia picture

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

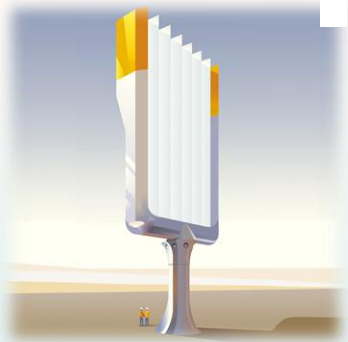Extracting kinetic energy from a source of 20 J/m³ is feasible

Wind energy ~20 J/m³

CO_2 combustion equivalent in air

10,000 J/m³

Passive contacting of air is inexpensive

artist's rendering

Image courtesy Stonehaven production

Required Sorbent Strength
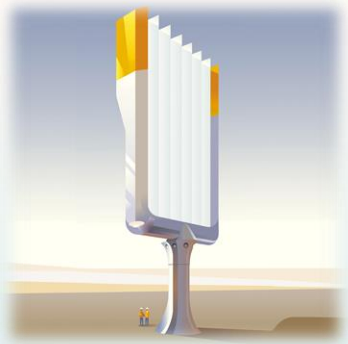
depends logarithmically on CO_2 concentration at collector exit
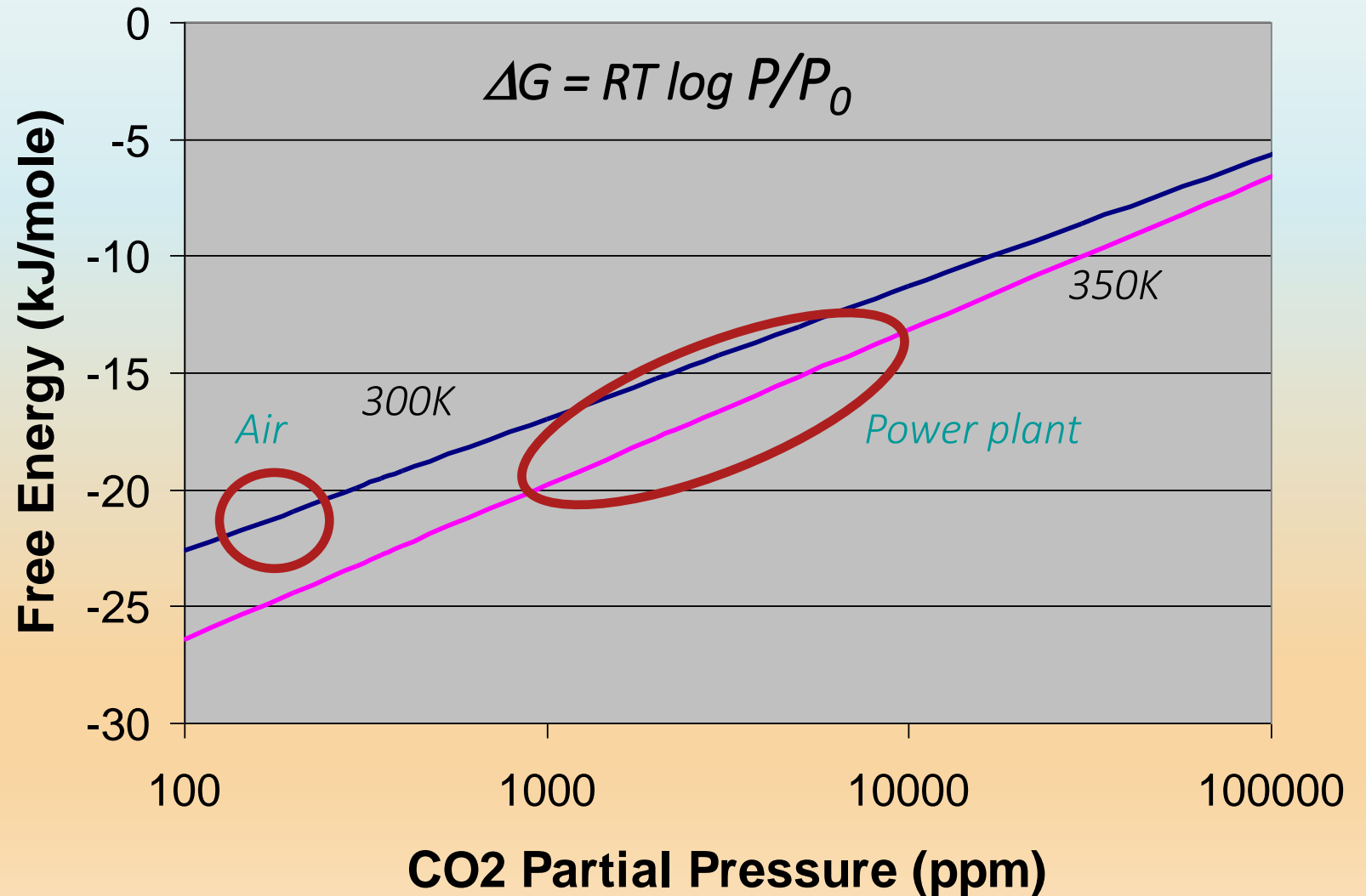
Sorbent
regeneration
dominates cost

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

350K

300K

Air

Power plant

Free Energy (kJ/mole)

0
-5
-10
-15
-20
-25
-30

CO2 Partial Pressure (ppm)

100   1000   10000   100000

Regenerator: Flue Gas Scrubbing – Air Capture

Stock picture

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
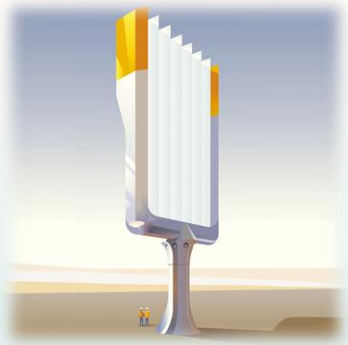
Air Capture is Real

- Several start-ups have working prototypes
- Different approaches, different markets
- Gaining experience, demonstrating costs
- Establishing a new technology

Carbon Engineering

CLIMEWORKS

global thermostat

Research is proceeding at a number of universities
ASU, Georgia Tech, Columbia University,
ETH Zurich, Sheffield University, Zhejiang University, …
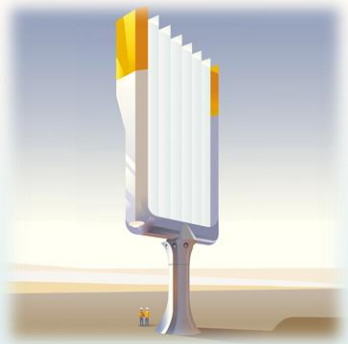
# ASU's air capture design

- Passive wind-driven design avoids Sherwood's objection
- Moisture controlled sorbent reduces energy consumption
- Mass production of small units drives costs down

Prototype tested on the roof
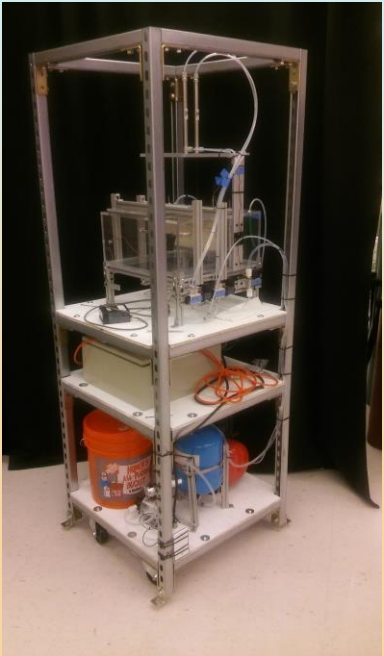
Lessons are applied in a DOE project to feed CO_2 to algae

Aggregate modules into sail-like structures

a) open

b) closing

Airflow
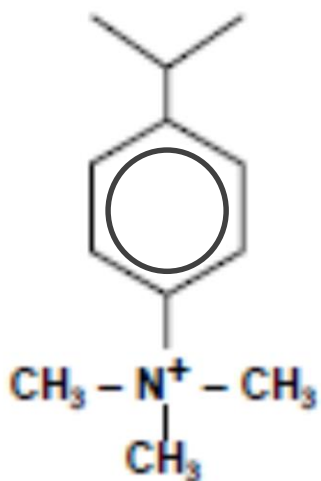Wind

c) closed

Internal
airflow
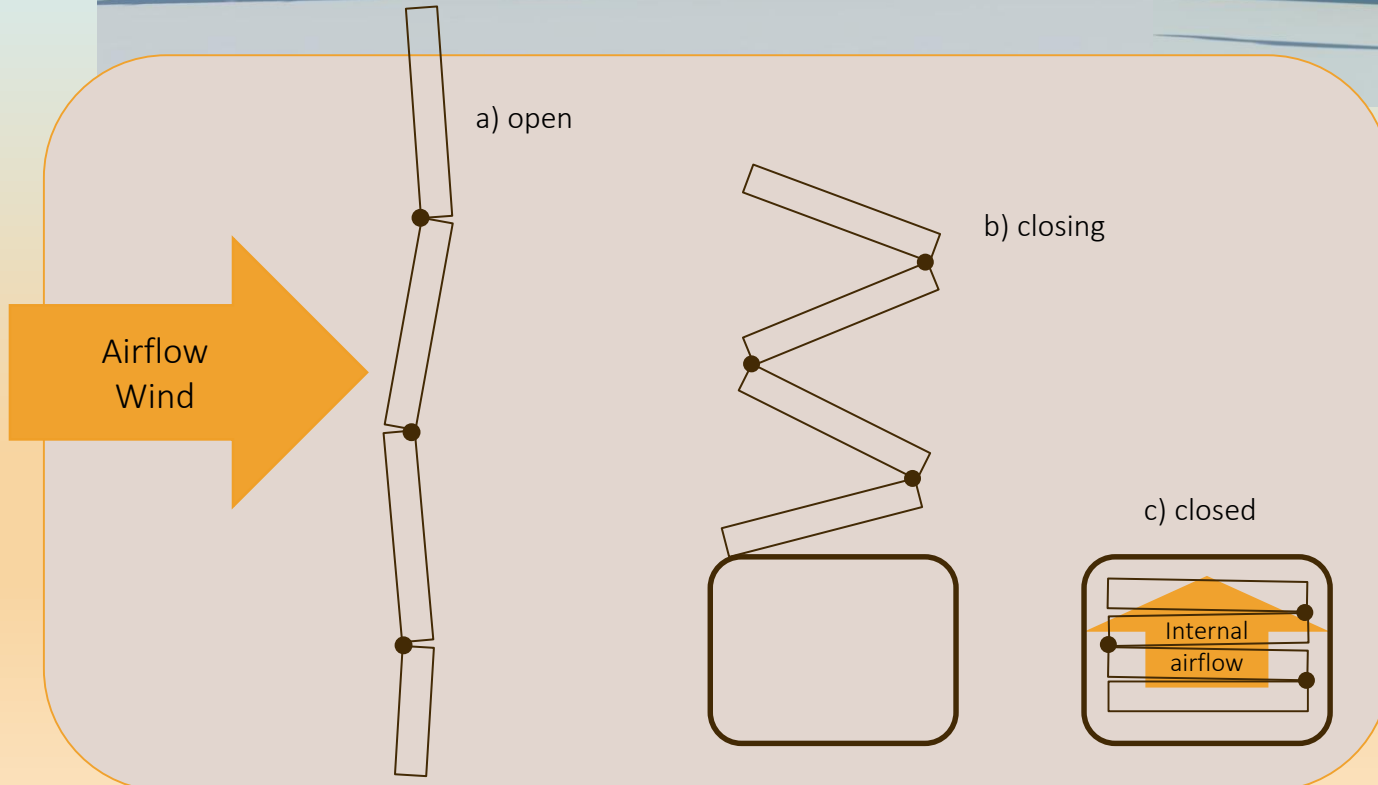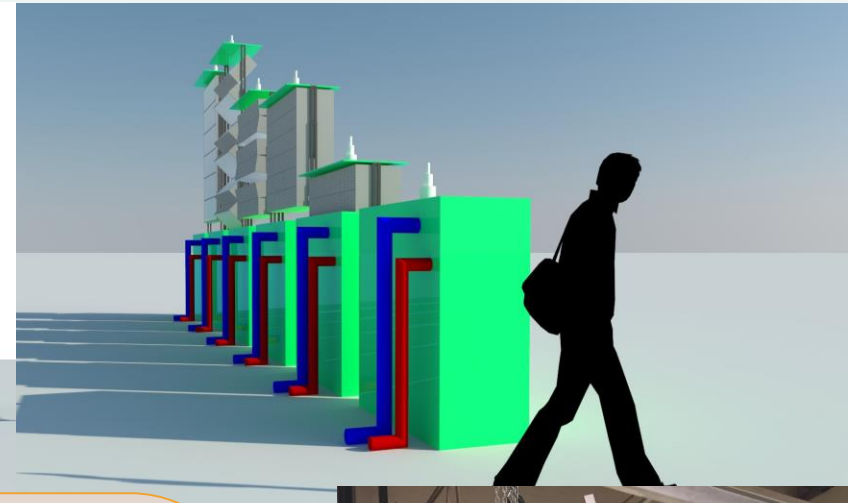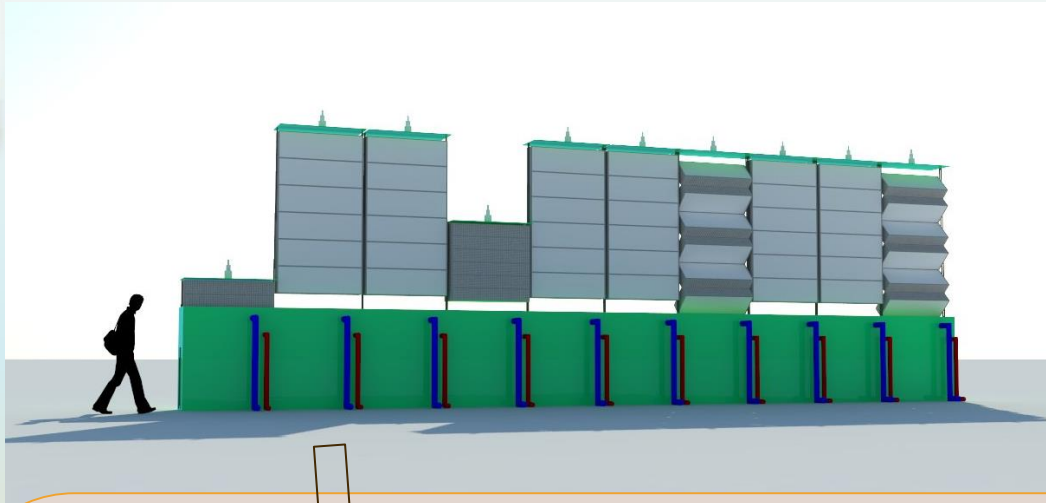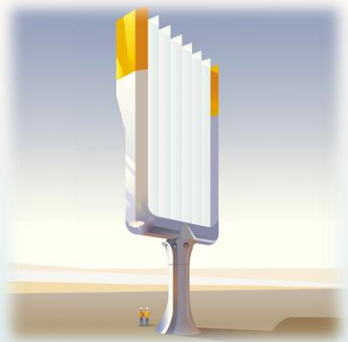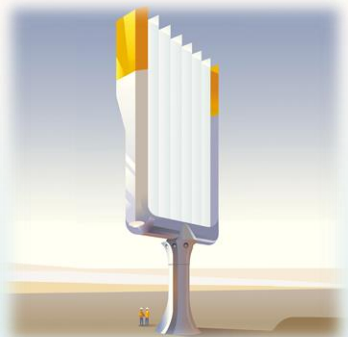
# Moisture Swing Sorbent for Low Energy Air Capture

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

Type I Strong Base Resins

- Positive ions fixed to polymer matrix
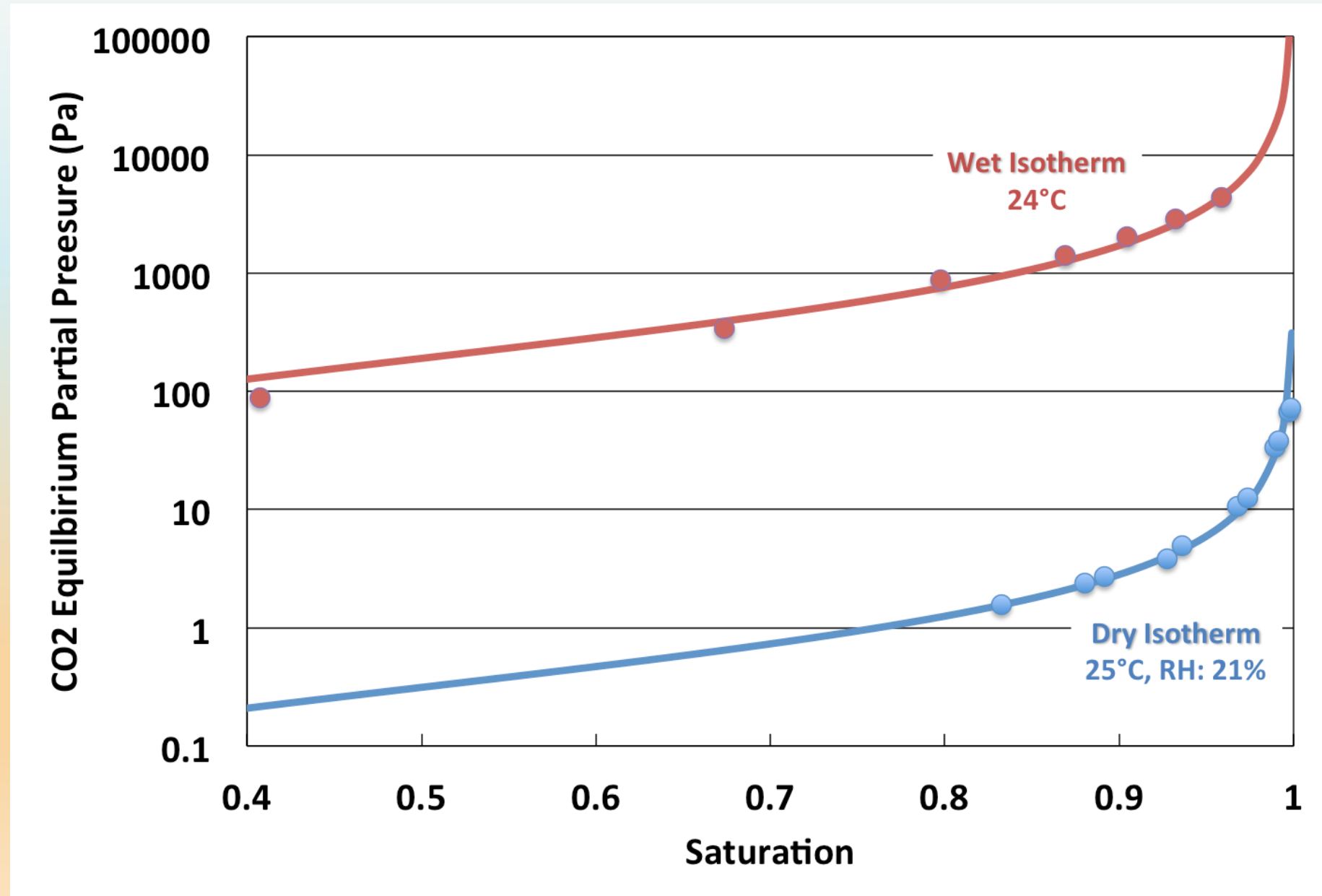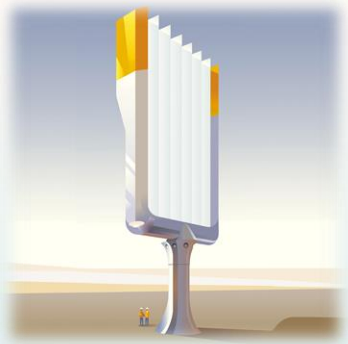 - Negative ions are free to move
  - Negative ions are hydroxides, OH^-

- Dry resin loads up to bicarbonate
  - $OH^- + CO_2 \rightarrow HCO_3^-$ (hydroxide $\rightarrow$ bicarbonate)

- Wet resin releases CO_2 and unloads to carbonate
  - $2HCO_3^- \rightarrow CO_3^{--} + CO_2 + H_2O$

Novel moisture driven CO_2 swing
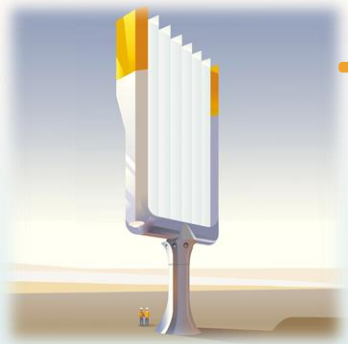
The Moisture Swing

Tao Wang, Lackner & Wright

How to move to scale?

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

Copyright 2008 by Global Research Technologies, LLC, All Rights Reserved

100 million units would eliminate current world emissions

Rely on learning
Mass production approach

Find markets
Small commercial niches
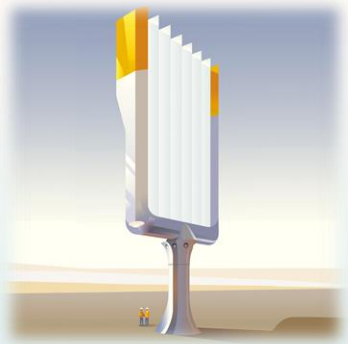
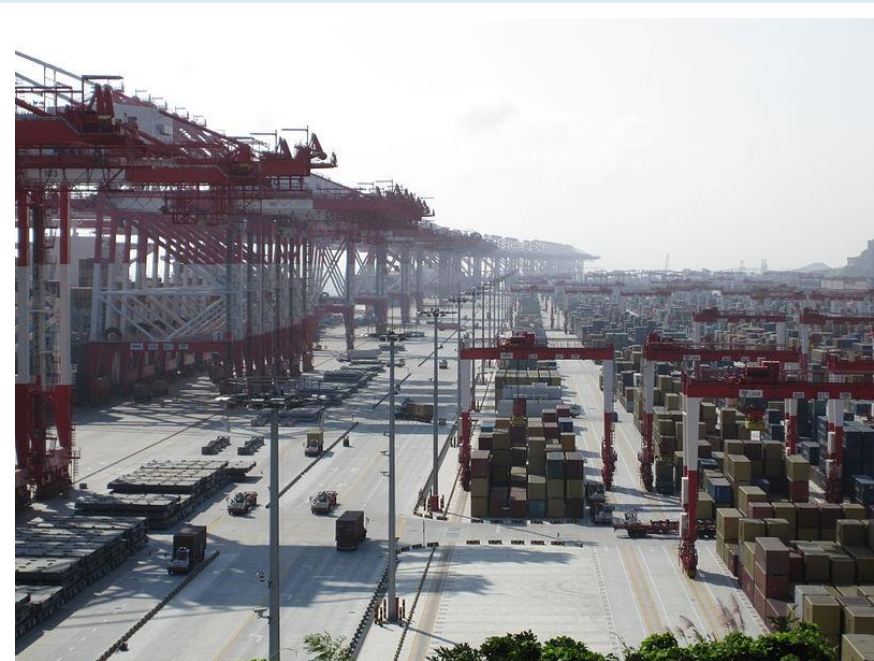## Create value proposition
Value is ultimately derived from cleanup
Waste management paradigm

Technology can reach global scales with proper market incentives

Production Capacity

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

Shanghai harbor processes
30 million full containers a year

World car and light truck production:
80 million per year

Low cost comes with experience
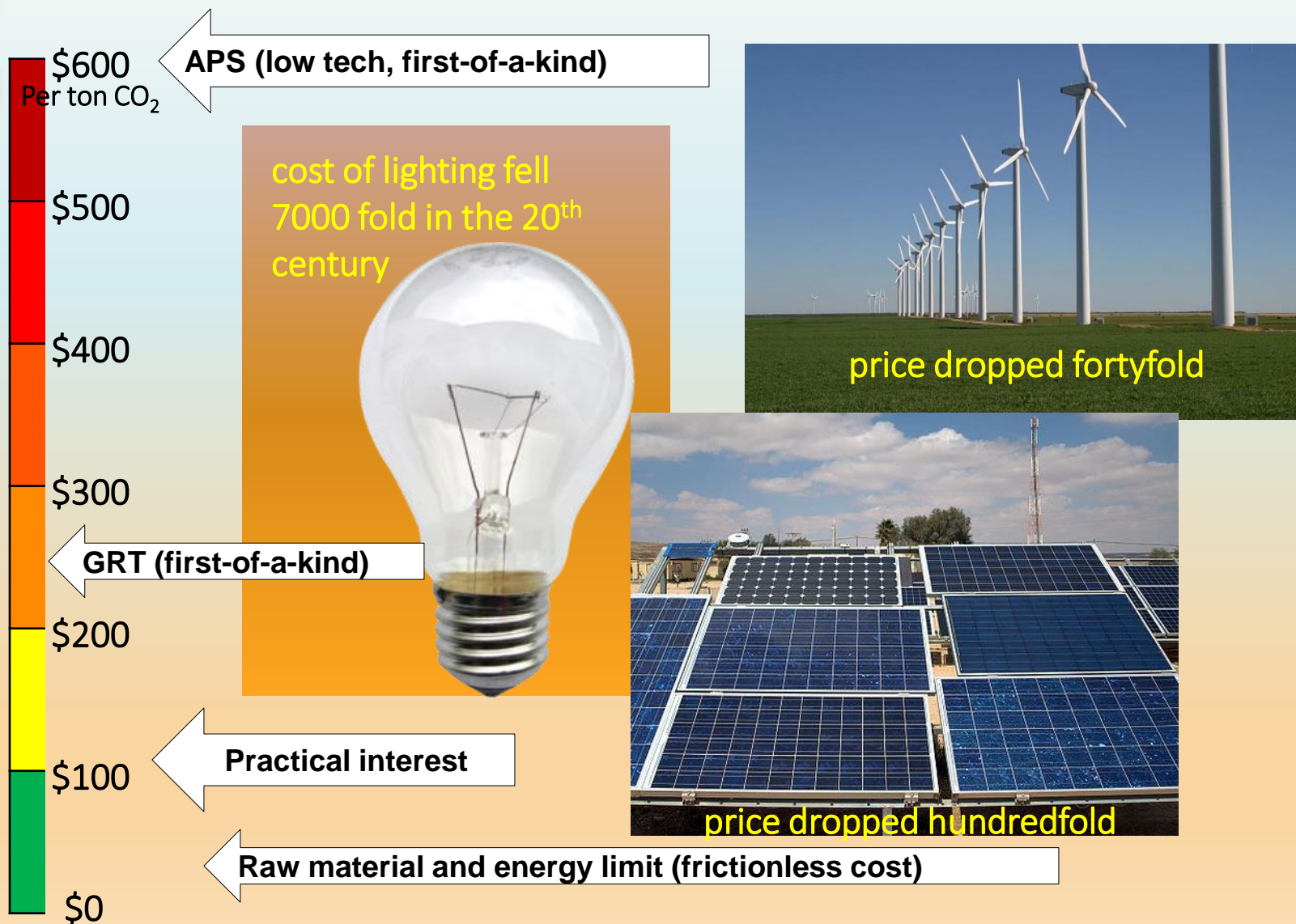
The Power of the Learning Curve

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

$600
Per ton CO_2

$500

$400

$300

GRT (first-of-a-kind)

$200

$100

Practical interest

$0

Raw material and energy limit (frictionless cost)

cost of lighting fell 7000 fold in the 20th century

price dropped fortyfold

price dropped hundredfold

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

Wikipedia pictures
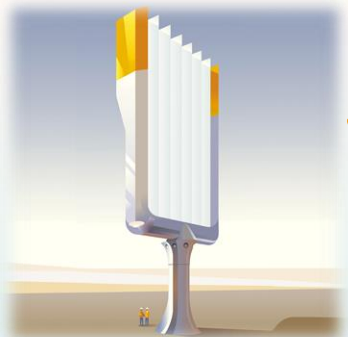
Value Propositions

Voluntary repayment of carbon debt for individuals and sustainably minded-corporations

This is how recycling became a business, how renewable energy is paid for

Volunteers create a carbon price, regulatory policies will follow

Societal license to operate for carbon producers

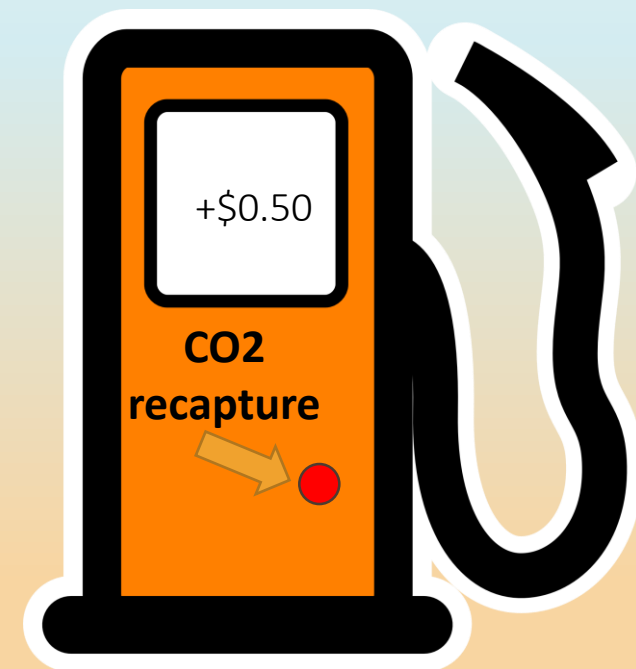*Without air capture, liquid fuels will have to be phased out*

Protecting assets in the ground

Natural gas is not running out and a valuable resource

New business opportunity around waste management

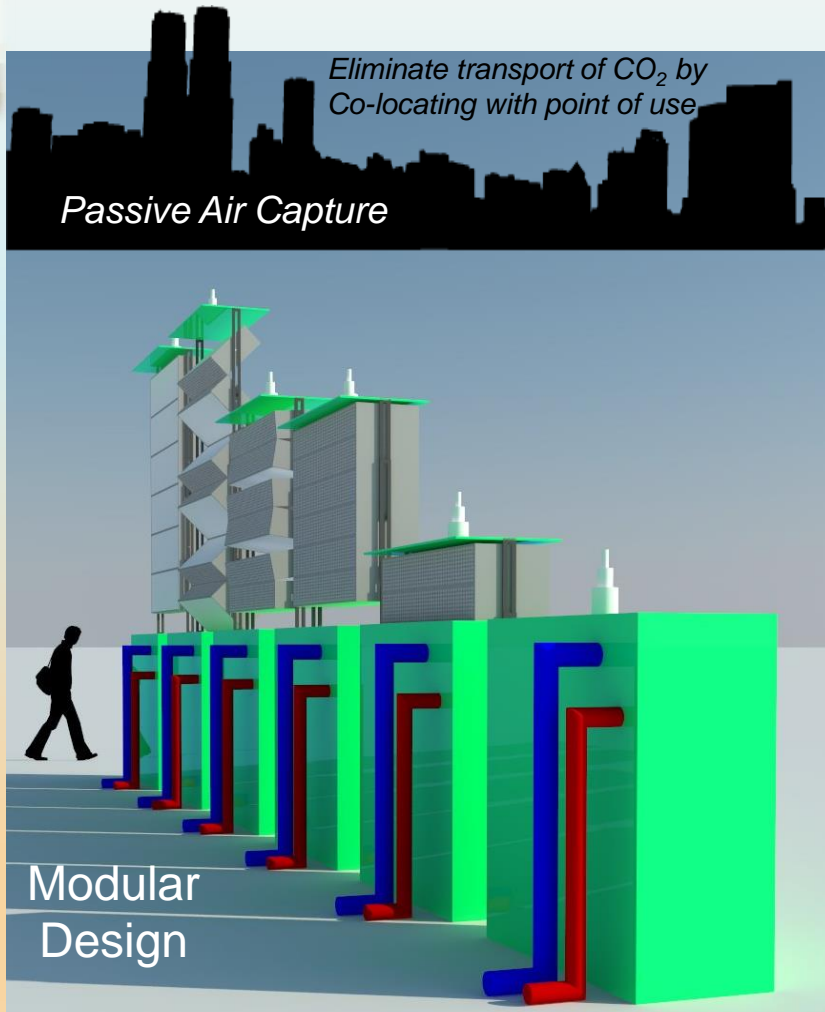*Waste management for garbage and sewage has been built into lucrative enterprises*

Reducing future liabilities

+$0.50

CO2 recapture

Imagine a button at the pump to take back the 20 pounds of CO_2 emitted from a gallon of gasoline

How to move forward?

Eliminate transport of CO_2 by Co-locating with point of use

Passive Air Capture

Modular Design

- First-of-a-kind pilot to deliver concentrated CO_2 (98%)
- Cost target below $100/ton
- One-ton-per-day demo-unit derisks technology

Buy Back the Carbon Campaign

- Government funding is in doubt
  Top down approaches have not worked
- Immediate economic incentives for carbon reuse are small
  Fossil carbon is always cheaper
- Philanthropic outlook and volunteers can deliver results
  Outreach, Education, Demonstration, Implementation

Leadership can kick-start the field of carbon management

- Establish in the minds of individuals and institutions the need to clean up excess carbon
- Create negative emissions
- Test and demonstrate small, nimble, affordable and scalable technologies, market mechanisms and policies
- Offer universities as testbeds