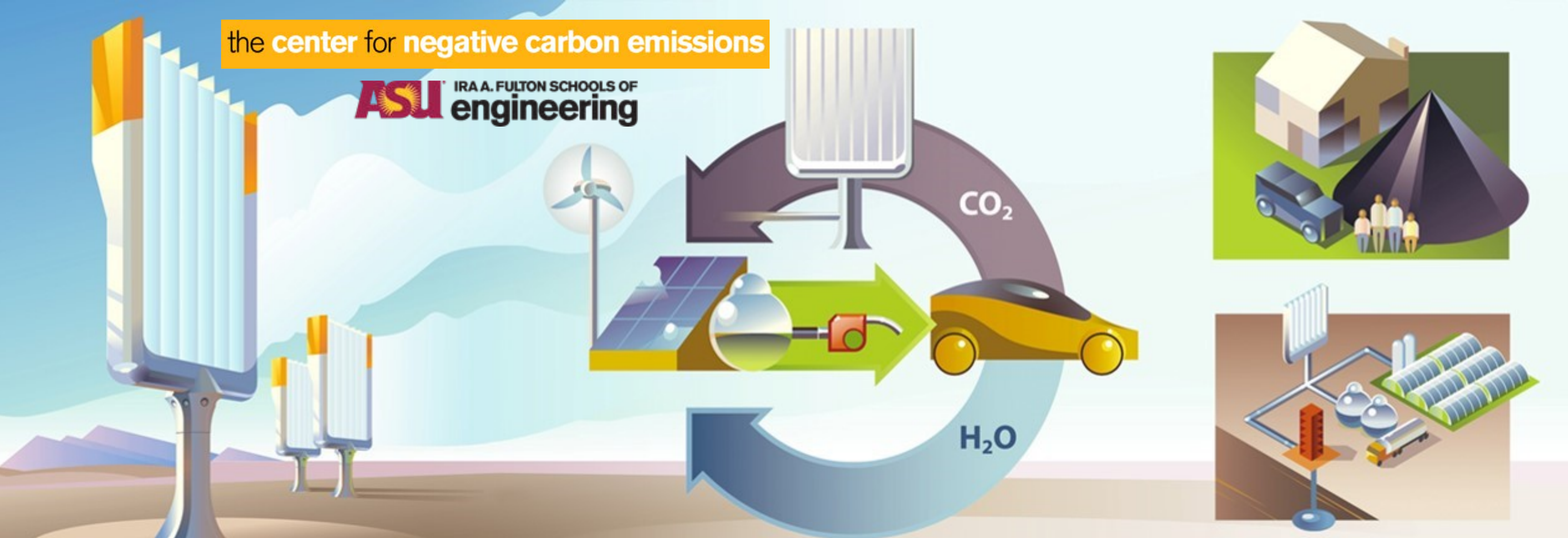
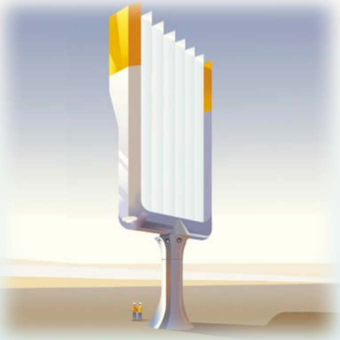


https://www.youtube.com/watch?v=4dHjCjrYcfs

Carbon Waste Management

Klaus S Lackner

September, 2017



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

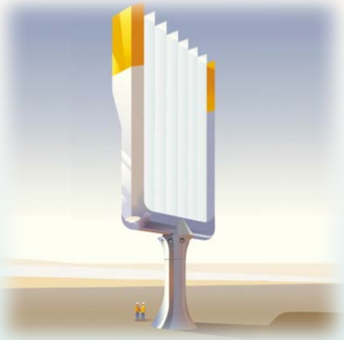
Moving to a waste management paradigm represents a big shift in dealing with CO_2

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



The global carbon budget is heading into overdraft

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

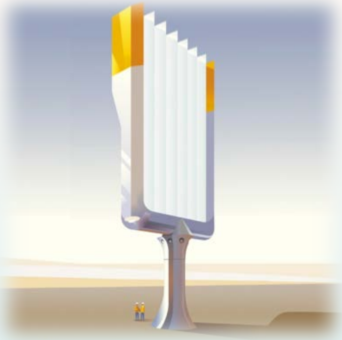
- *Promised emissions reductions will reach 4°C, business as usual more than 6°C*
- *Cannot stop anymore in time*

IPCC: need negative emissions

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

Major business risk for investors
Opportunity for leaders

http://www.emercedesbenz.com/Aug08/08_001327_Mercedes_Benz_Econic_Semi_Trailer_Tanker_Trucks_Enter_Service_At_London_Farnborough_Airport.html



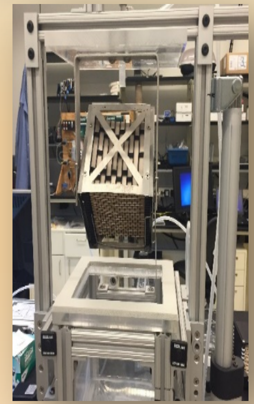
Technologies for Carbon Management

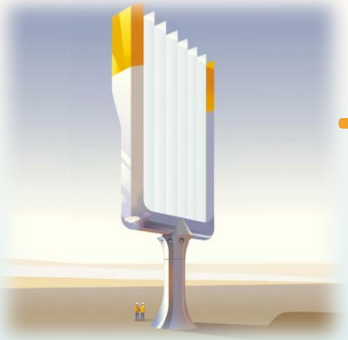
- **Carbon Storage**
  Disposal of excess carbon underground
  Established technology but not at scale

- **Point Source Capture**
  Proven but not widely deployed

- **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

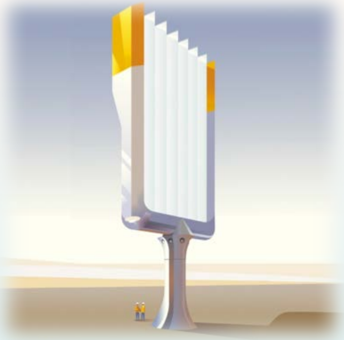
- Costs imposed by physics are affordable
  energy requirement is less than 5% of energy in carbon
- Other technologies have solved more difficult extraction problems
  Passive collectors can pull uranium out of seawater at reasonable cost (100,000 times more dilute than CO_2 in air)

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 100 to 500 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 is Real

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

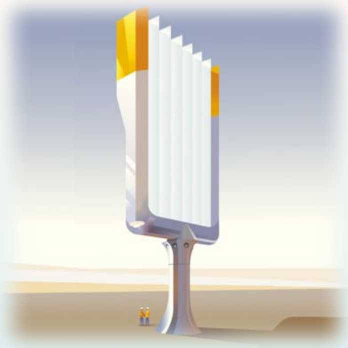
Carbon Engineering

CLIMEWORKS

global thermostat

….

Research is proceeding at a number of universities
ASU, Georgia Tech, Columbia University,
ETH Zurich, Sheffield University, Zhejiang University, …



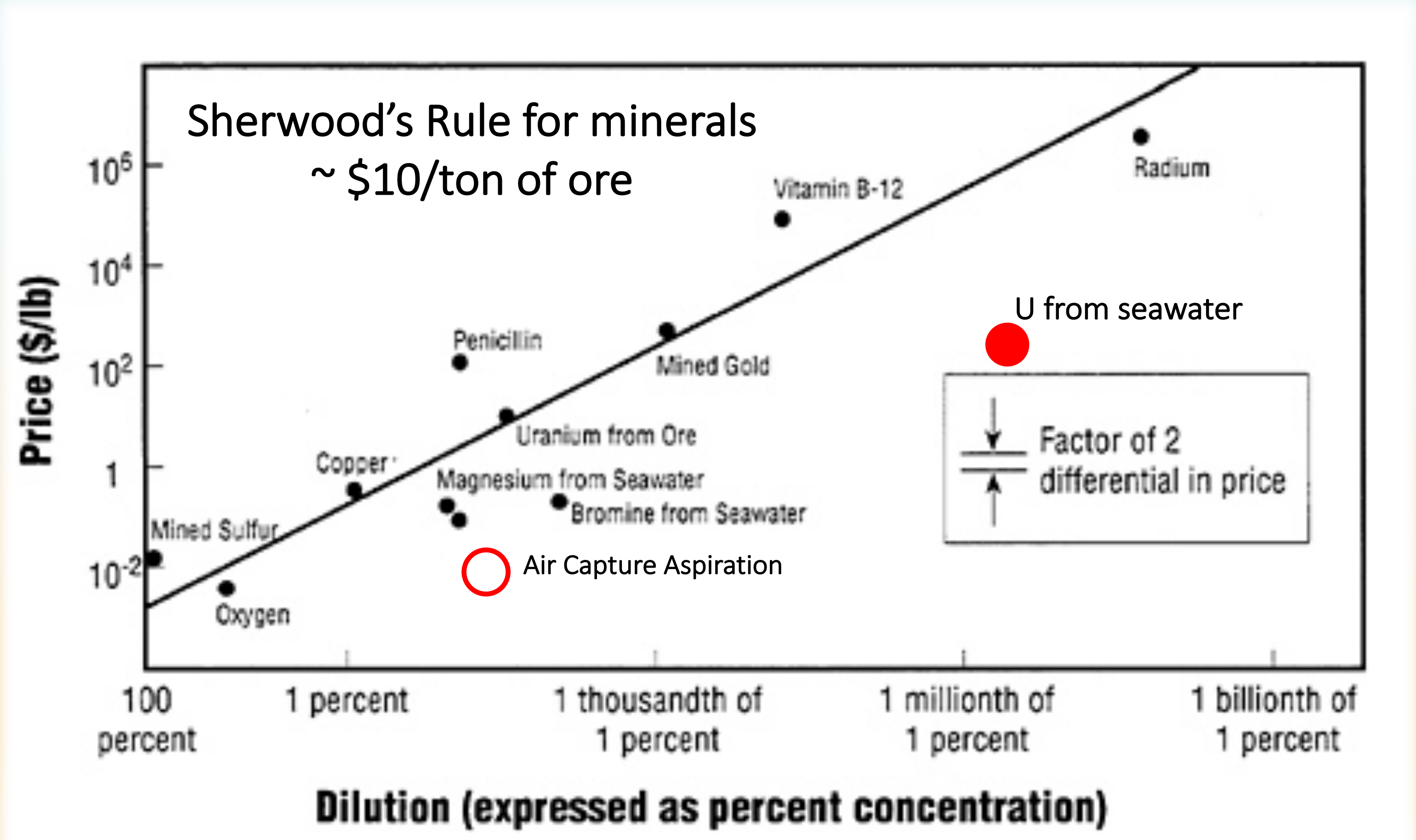
Avoiding Sherwood's Rule

Cost of separation scales linearly with dilution *D*

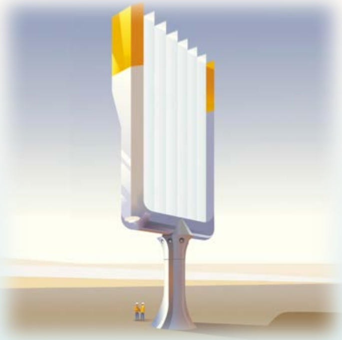
Sherwood's Rule

The cost of the first step in the separation dominates

$$\mathit{Cost} = \underbrace{aD}_{\text{Bulk processing}} + \underbrace{b + c\log D}_{\text{Thermodynamic separation}}$$



SOURCE: National Research Council (1987)



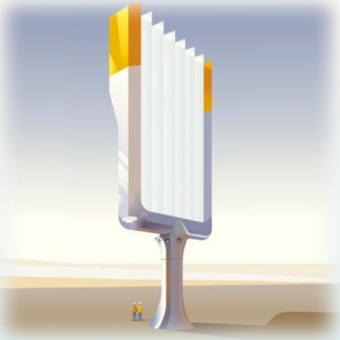
ASU’s air capture design

- 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

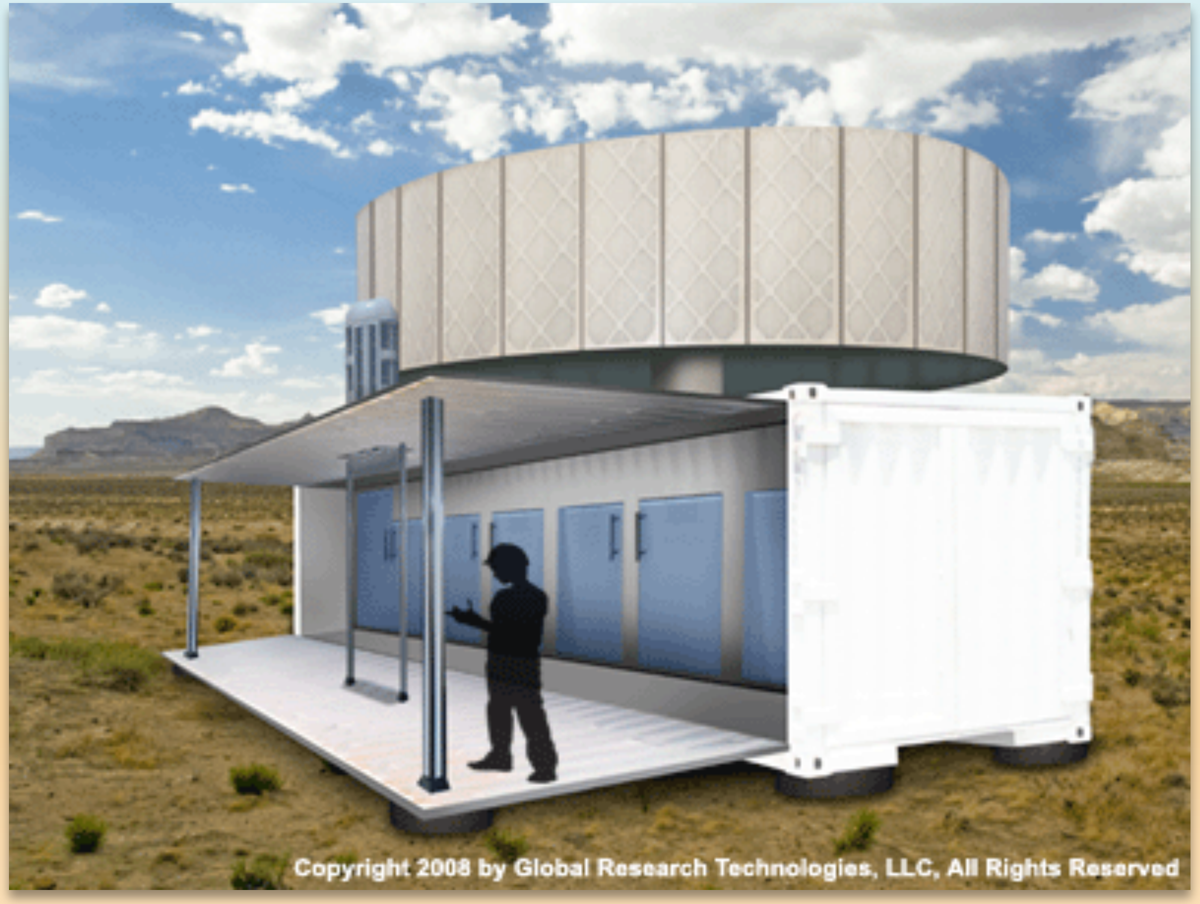
Lessons are applied in a DOE project to feed CO_2 to algae





How to move to scale?

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



100 million units would eliminate current world emissions

Rely on learning

Mass production approach

Find markets

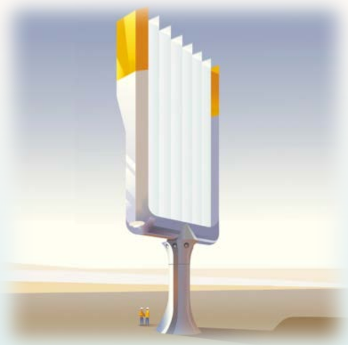
Small commercial niches

Create value proposition

Value is ultimately derived from cleanup

Waste management paradigm

Technology can reach global scales with proper market incentives



Production Capacity

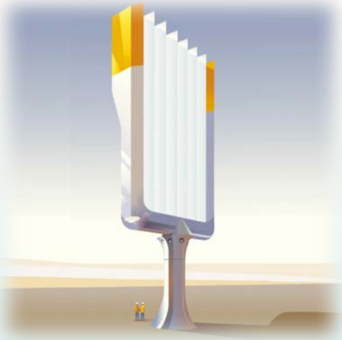
10 year life time implies a production capacity of 10 million per year

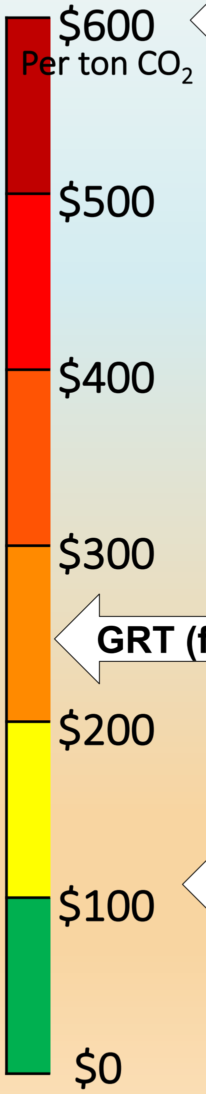
Shanghai harbor processes
30 million full containers a year

World car and light truck production:
80 million per year

wikipedia pictures

Low cost comes with experience



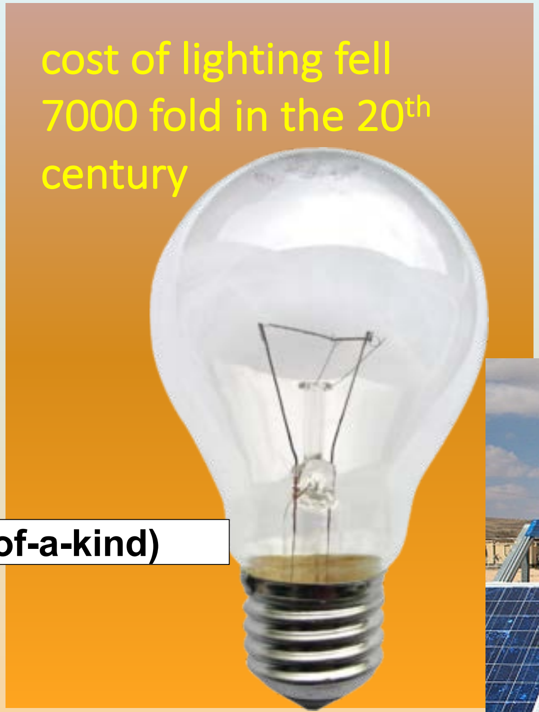


APS (low tech, first-of-a-kind)

GRT (first-of-a-kind)

Practical interest

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