Scrubbing Carbon Dioxide From Ambient Air

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K S Lackner has co-founded GRT LLC, a company started to explore the feasibility of air capture. He is an advisor to its successor organization Kilimanjaro Energy, Inc. He has an ownership stake in the company

Introduction

CONTEXT FOR AIR CAPTURE

Plentiful Sustainable Energy

Energy is central to human well-being

World needs affordable, plentiful and clean energy for all

Clean energy can overcome many sustainability limits

Atmospheric CO_2 level must be stabilized

Fossil carbon is not running out

Energy

Food Water Minerals

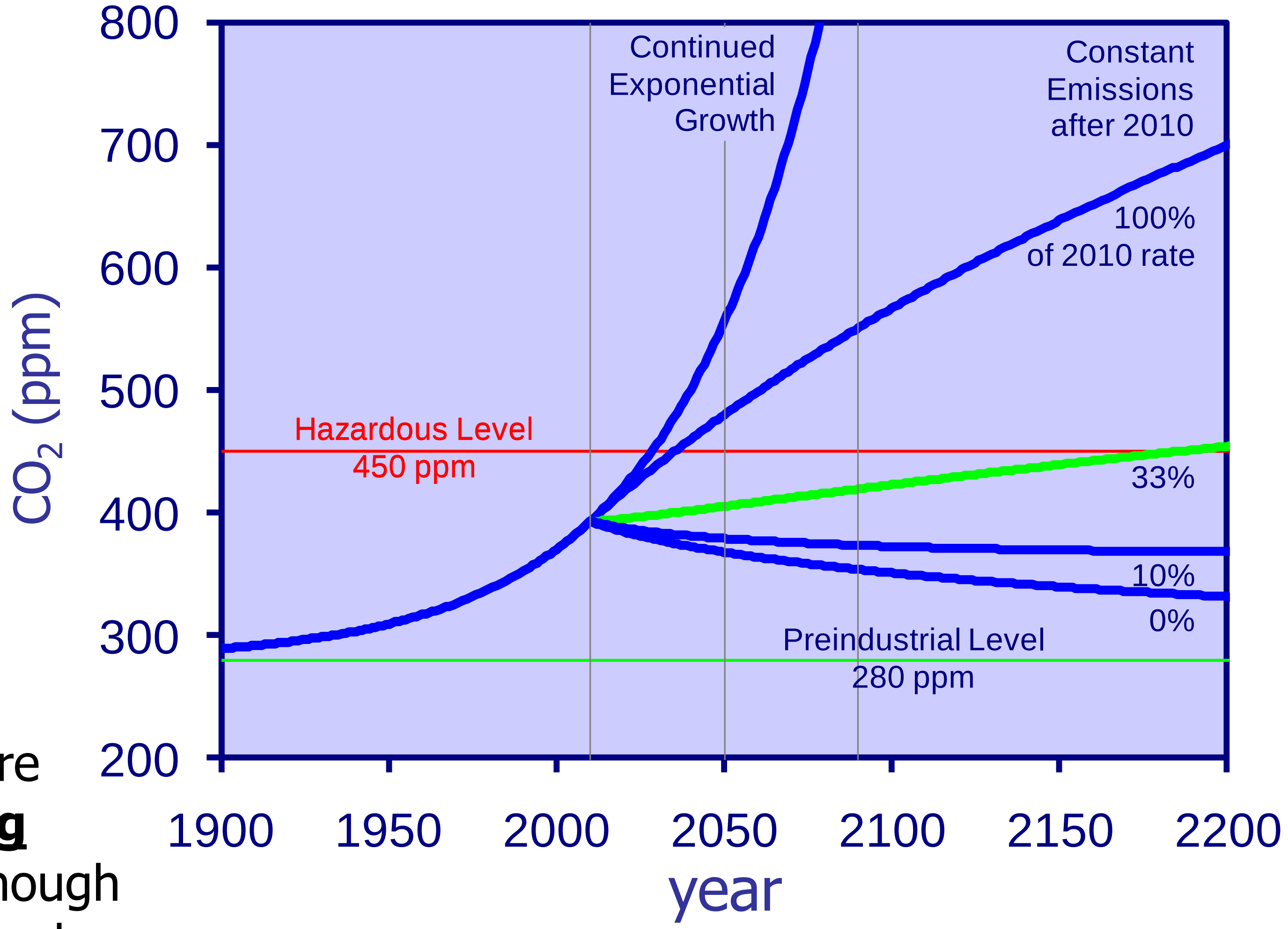
Environment

The Big Three Energy Options

wikipedia pictures

Environmental Limits – Not Resource Limits

Stabilize CO_2 concentration – not CO_2 emissions



ocean-air-biosphere reservoir is not **big** enough or **fast** enough to handle excess carbon

A different look at the carbon cycle

- **The concept of a single CO_2 lifetime in air is misleading**
- **CO_2 is extremely persistent … thermal effects linger even longer**
- **It is not about <u>stabilizing</u> emissions …but about <u>eliminating</u> all emissions**

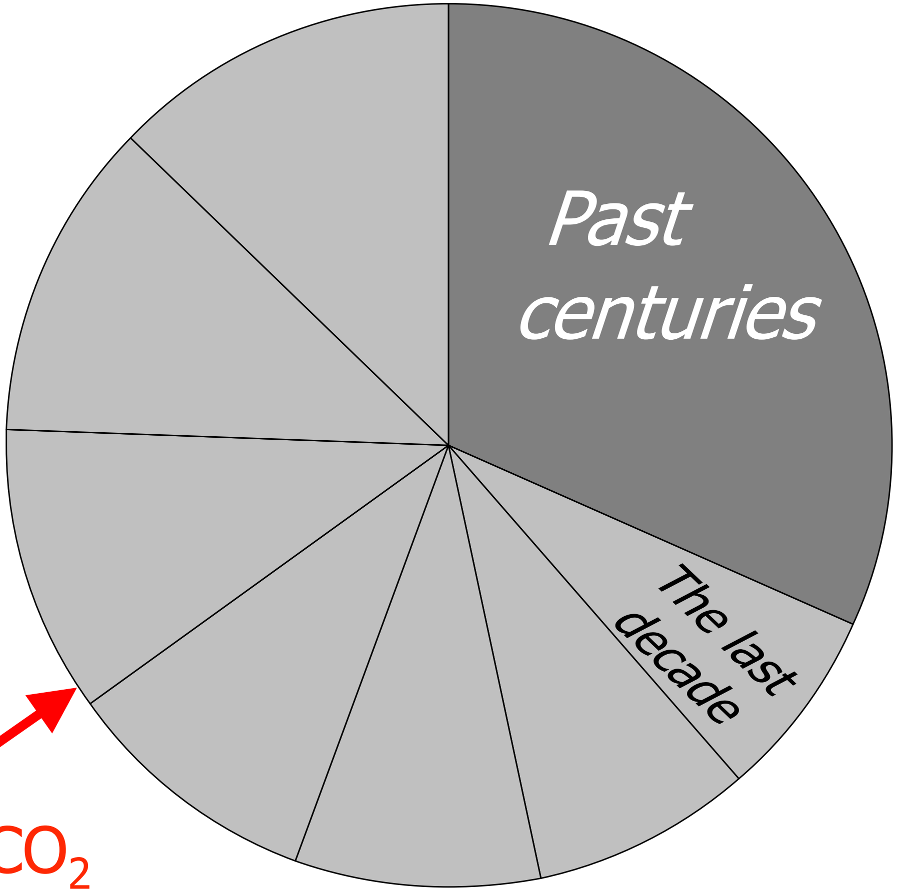
The "drain in the bathtub" clogs up as the tub is filling

Stock vs. Flow – Simple Calculus

Carbon dioxide capacity of the atmosphere is fixed
1 ppm ~ 4 Gt C, 15 Gt CO_2 (50% remains in the atmosphere)

900 Gt C

total



1 trillion tons of CO_2

500 ppm

The personal carbon allowance

~ 30 tons C for every person will lead to 450 ppm

Total permanent allotment

Picture from emercedes online blog: http://www.emercedesbenz.com/Aug08/08_001327_Mercedes_Benz_Econic_Semi_Trailer_Tanker_Trucks_Enter_Service_At_London_Farnborough_Airport.html

Without carbon capture and storage fossil fuels will have to be phased out

⌘

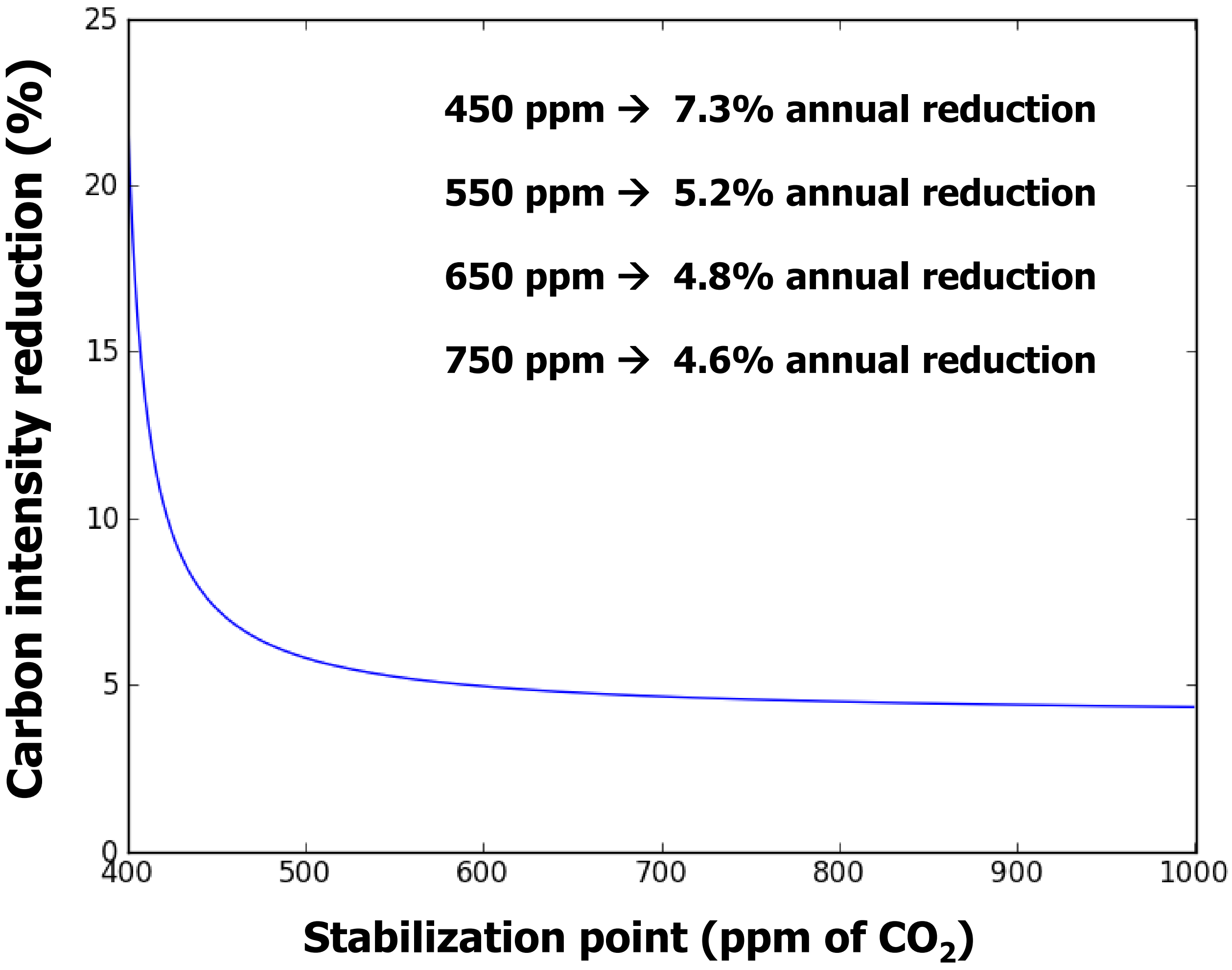
For every ton of fossil carbon extracted from the ground another ton will have to be returned

⌘

All carbon dioxide emitted to the air will need to be recaptured

Economy must decarbonize fast

Annual reduction in the world's carbon intensity (CO_2/GDP)



450 ppm → 7.3% annual reduction

550 ppm → 5.2% annual reduction

650 ppm → 4.8% annual reduction

750 ppm → 4.6% annual reduction

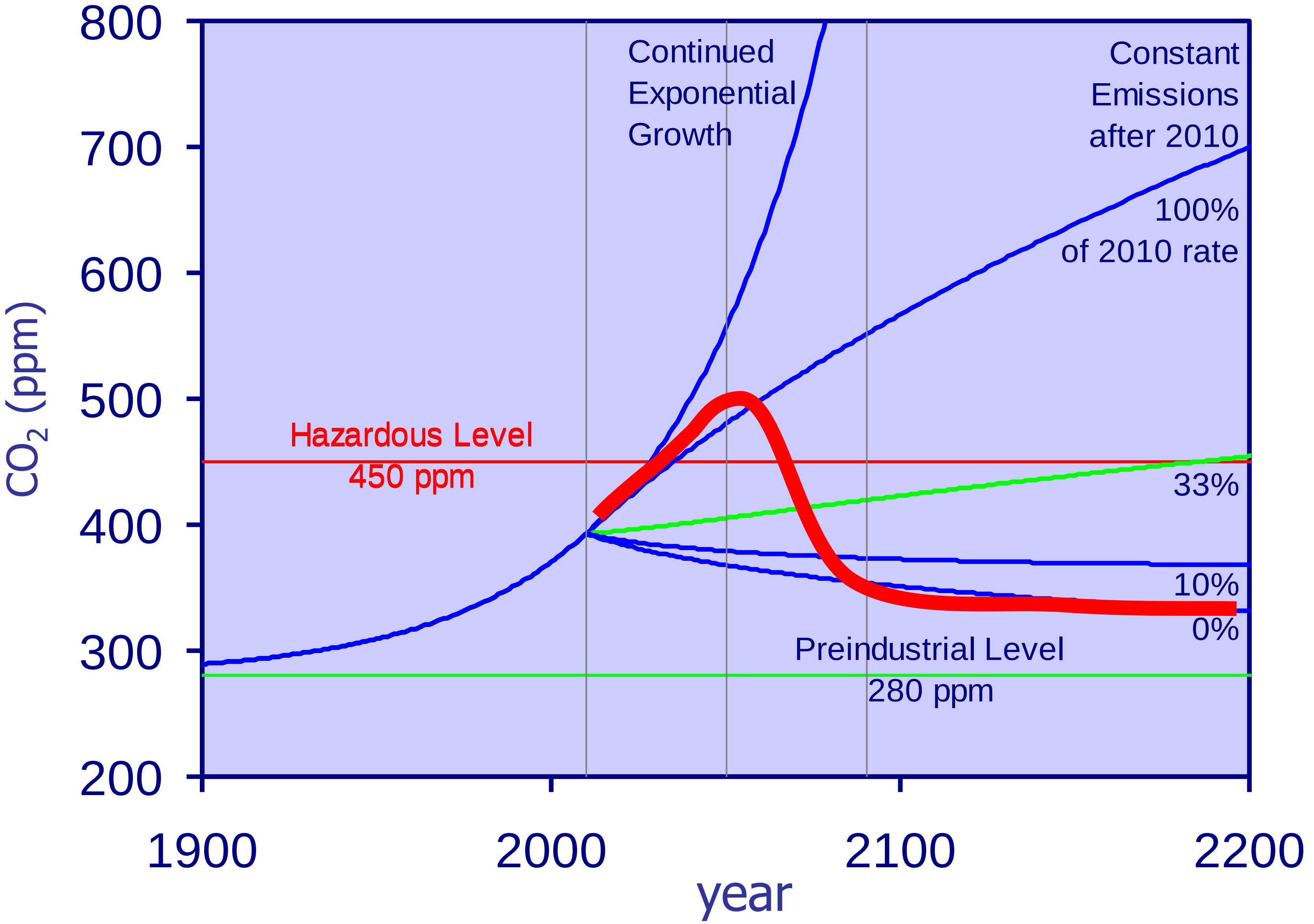
Must overcome 3% economic growth plus 1% population growth

IPCC: Need for Negative Emissions

- **Negative emissions require carbon storage**
  - Safe permanent, and large capacity
  - Needs more than natural processes
  - Needs more than biomass growth
- **Negative emissions require capture from air**
  - Needs more than biomass capture
  - Cannot be solved with power plant capture
- **Need for storage capacity is potentially large**
  - 100 ppm reduction requires 1500 Gt of CO_2 storage

Ask when – not if – CCS is needed

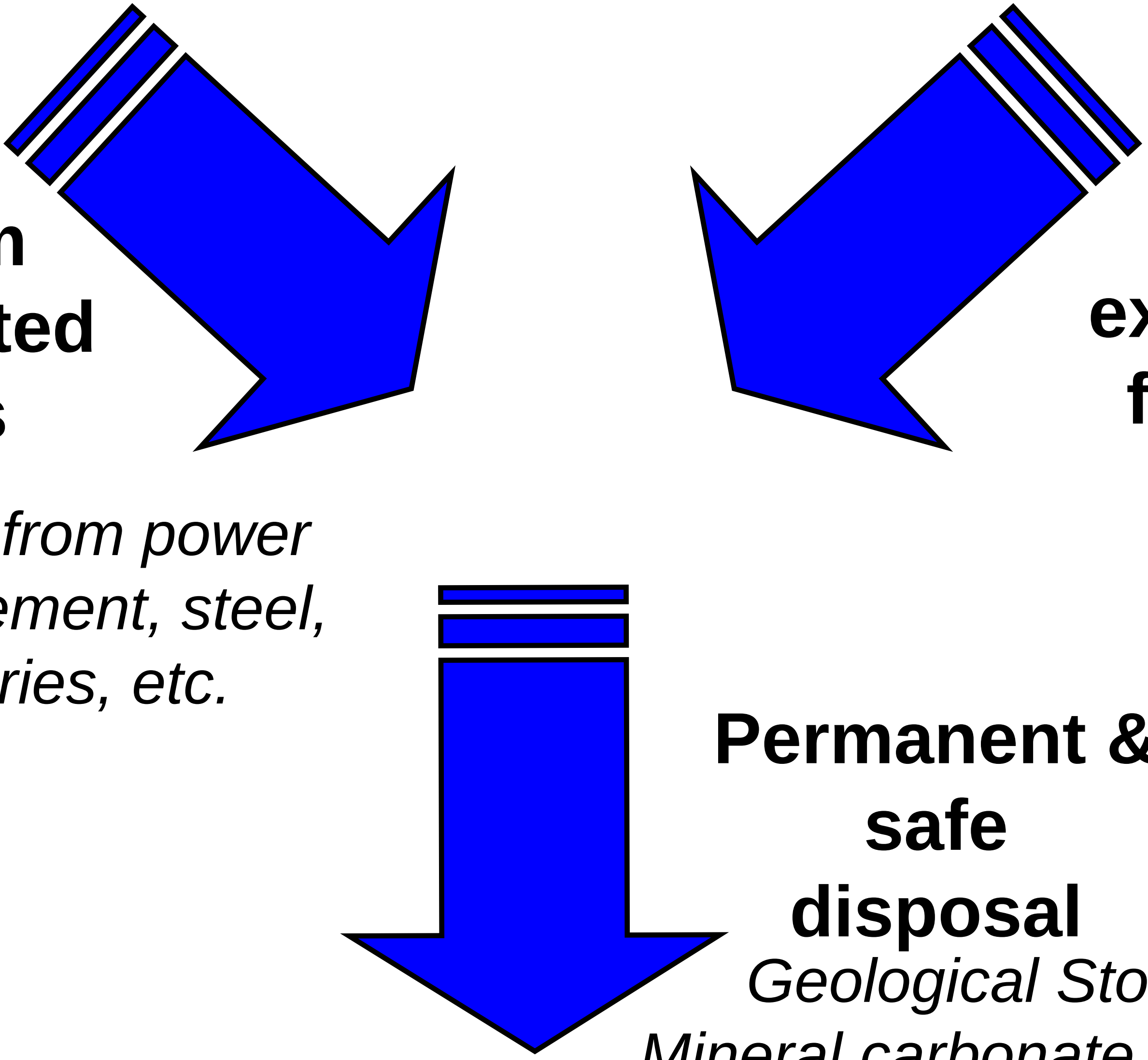
Coming back down?



Technology solutions for climate

- **Need to advance carbon management**
  - Closing the carbon cycle is a necessity
  - Shrinking the carbon cycle is an option
  - Nevertheless, we are committed to 1500 Gt of CO_2 disposal
- **Need to go beyond conventional solutions**
  - More than retrofits
  - More than one storage option
  - More than energy alternatives
  - More than energy efficiency
- **Need to operate at a formidable scale**
  - 100 ppm reduction is more than 20th century emission
  - 1500 Gt is 1/3 of the mass in Lake Michigan
  - Building a new industry in thirty years

Net Zero Carbon Economy



CO_2 from concentrated sources

Capture from power plants, cement, steel, refineries, etc.

CO_2 extraction from air

Permanent & safe disposal

Geological Storage
Mineral carbonate disposal
Ocean disposal

Power plant capture is not enough

- **A 70% reduction of a 30% contributor cannot achieve a 90 to 100% reduction**
  - Point sources only cover half of all emissions
  - Negative emissions require a new approach

Biomass capture is not enough

- **Agriculture satisfies human metabolism**
  - About 100 Watt per person
- **Can it provide primary energy demand?**
  - US: 10,000 Watt per person
- **Three way collision between**
  - Food supply
  - Energy demand
  - Environmental impact

Operating at the human energy scale is a severe challenge

Basic concepts

AIR CAPTURE CONCEPT

Air extraction can compensate for CO_2 emissions anywhere

separates sources from sinks

allows for negative emissions

Art courtesy Stonehaven CCS, Montreal

Air capture provides options

- **Maintaining access to fossil fuels**
  - Air capture as part of CCS
  - Focus on dispersed and mobile sources
  - Complementing power plant capture
- **Air capture with non-fossil energy**
  - Allowing liquid fuels in the transportation sector
  - Synthetic fuel production from CO_2 and H_2O
  - Requires cheap non-fossil energy
- **Air capture for drawing down CO_2**
  - First emissions must be stopped or canceled out
  - No excuse for procrastination

Art courtesy Stonehaven CCS, Montreal

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).

Concerns of the Critics

FEASIBILITY

Feasibility?

CO_2 in air is dilute and air is full of water

The air carries 10 to 100 times as much H_2O as CO_2

Wikipedia image

Air capture ≠ flue gas separation

- **APS Study (Socolow et al.)**
  - Too difficult, too costly, not practical
  - \$600 per ton of CO_2
- **House et al.**
  - Dilution is too extreme
  - Separation technology cannot be extrapolated
  - Second law efficiency unavoidably deteriorates
- **Conclusion: Don’t try to extrapolate**
  - Conventional technologies will have difficulties
  - Too much of an extrapolation
  - Extrapolation raises costs and uncertainties

Need non-conventional approach from the start

Wikipedia image

Out of the box thinking

No direct path …

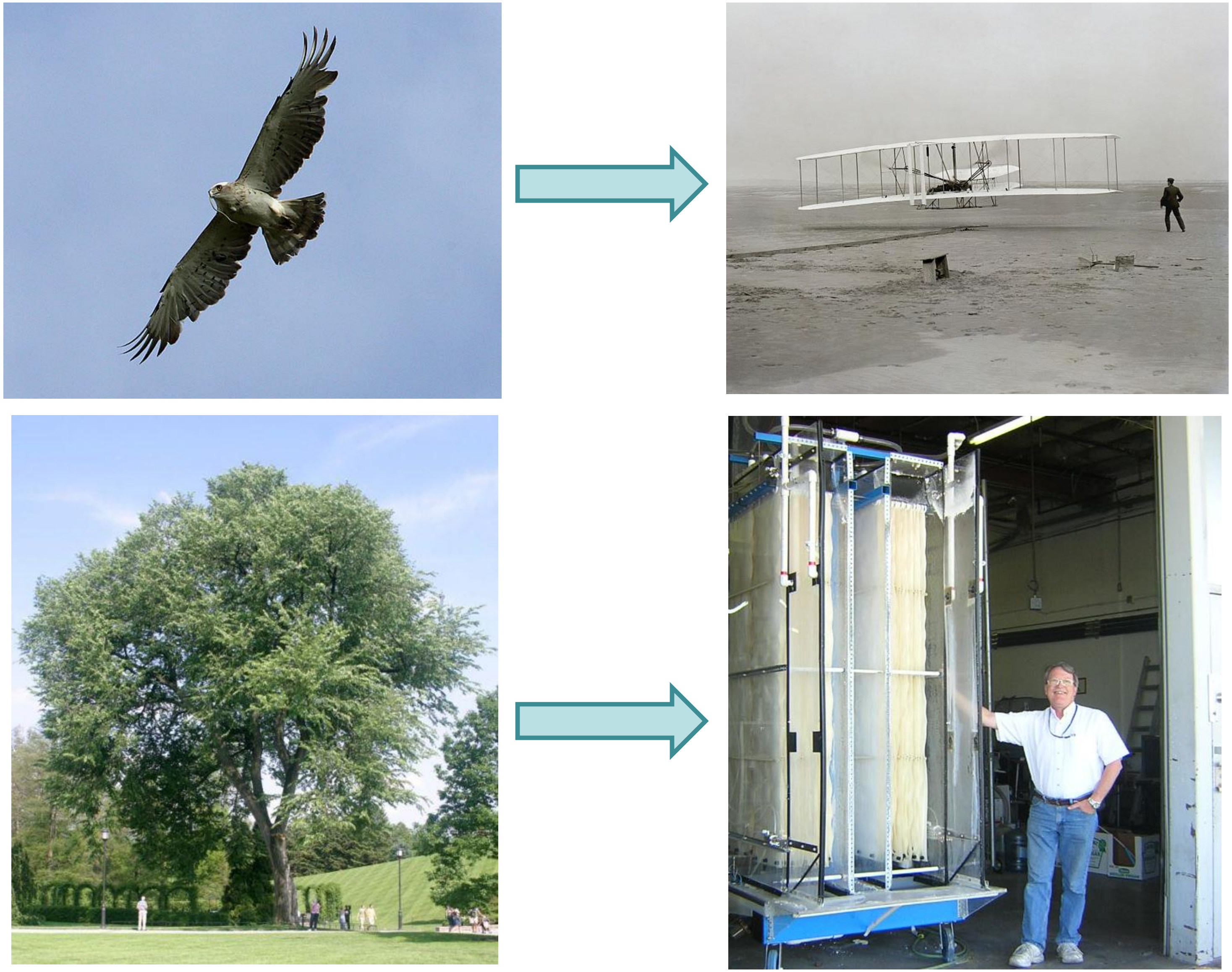
… from here …

… to there

Start from first principles
and
air capture is feasible

Wikipedia images

Inspiration comes from nature



Wikipedia images, GRT image

Technical challenges of air capture

- **Move huge volumes of air cheaply**
  - This is the term Sherwood warned about
- **Make good contact at low pressure drops**
  - Like a tree, like a lung, passive designs are favored
- **Avoid water capture**
  - There is far more water than CO_2 in the air
- **Avoid emissions of entrained liquid, vapors etc.**
  - Need to make air cleaner
- **Avoid expensive energy**
  - Low grade heat, water evaporation, wind energy
- **Find ways of bootstrapping from small niche markets**
  - Start small and grow
- **Take advantage of learning**

Wind energy – Air capture

Wikipedia picture

artist’s rendering

Wind energy
~20 J/m^3

CO_2 combustion equivalent in air

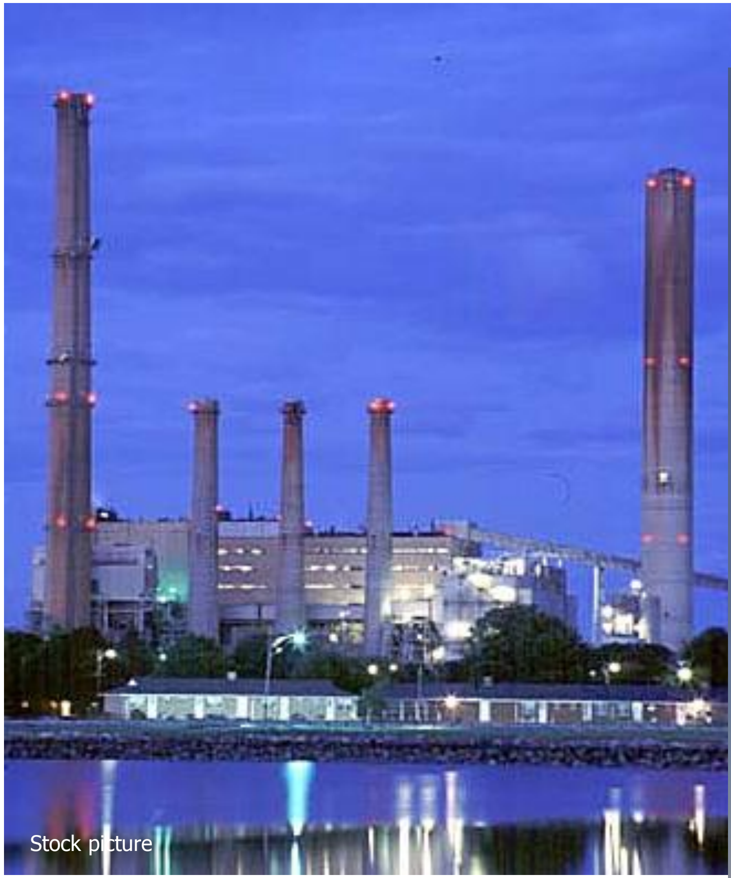
10,000 J/m^3

<u>Passive</u> contacting of the air is inexpensive

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

Extracting 20 J/m^3 seems feasible

Flue Gas Scrubbing – Air Capture



Stock picture

artist's rendering

Only binding energy to the resin is affected by the initial CO_2 concentration

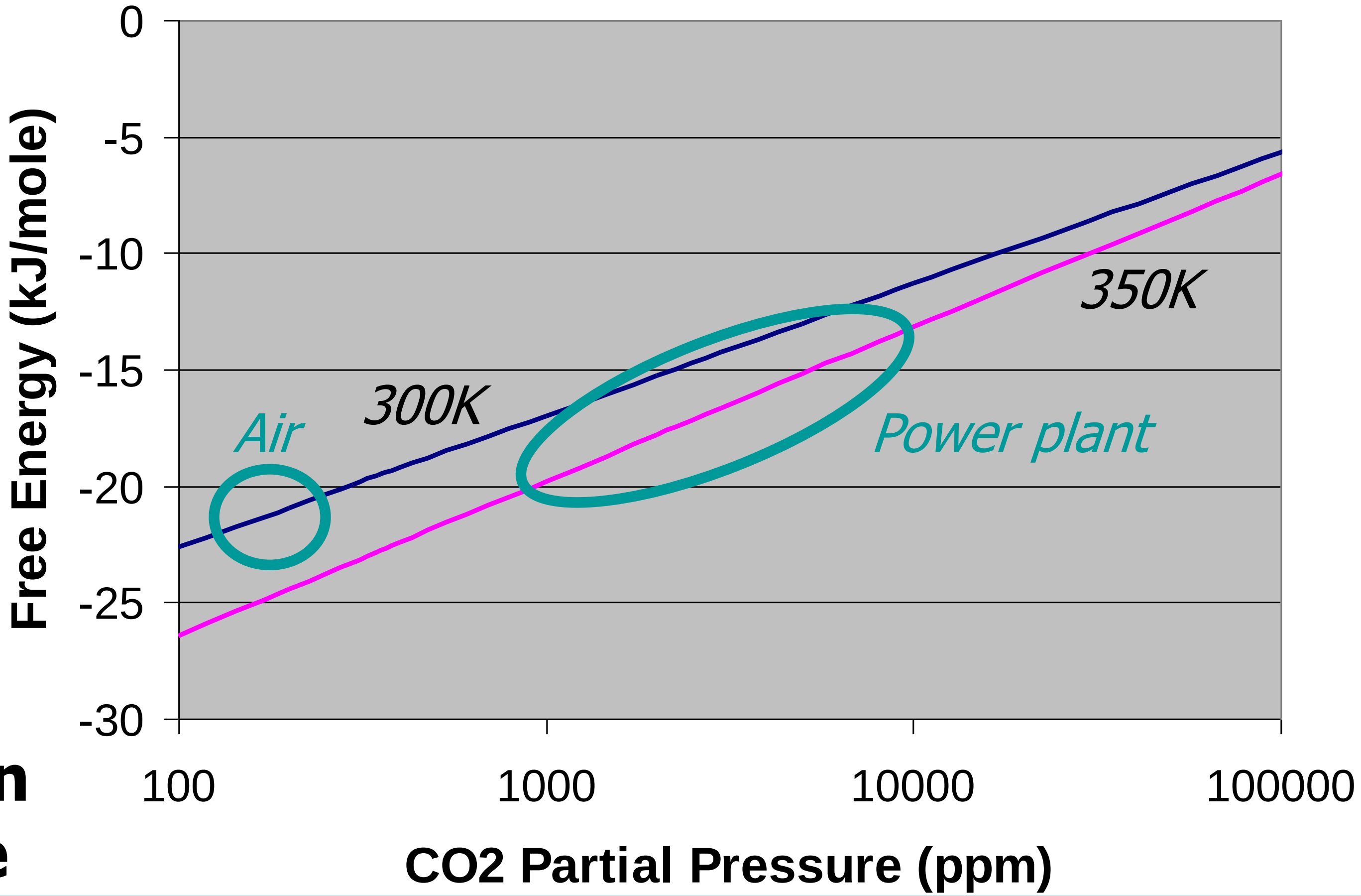
Dominant costs are similar for air capture and flue gas scrubbing

Sorbent regeneration slightly more difficult for air capture than for flue gas scrubbers, effort scales with log of the dilution

Sorbent Strength

depends logarithmically on CO_2 concentration at collector exit

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

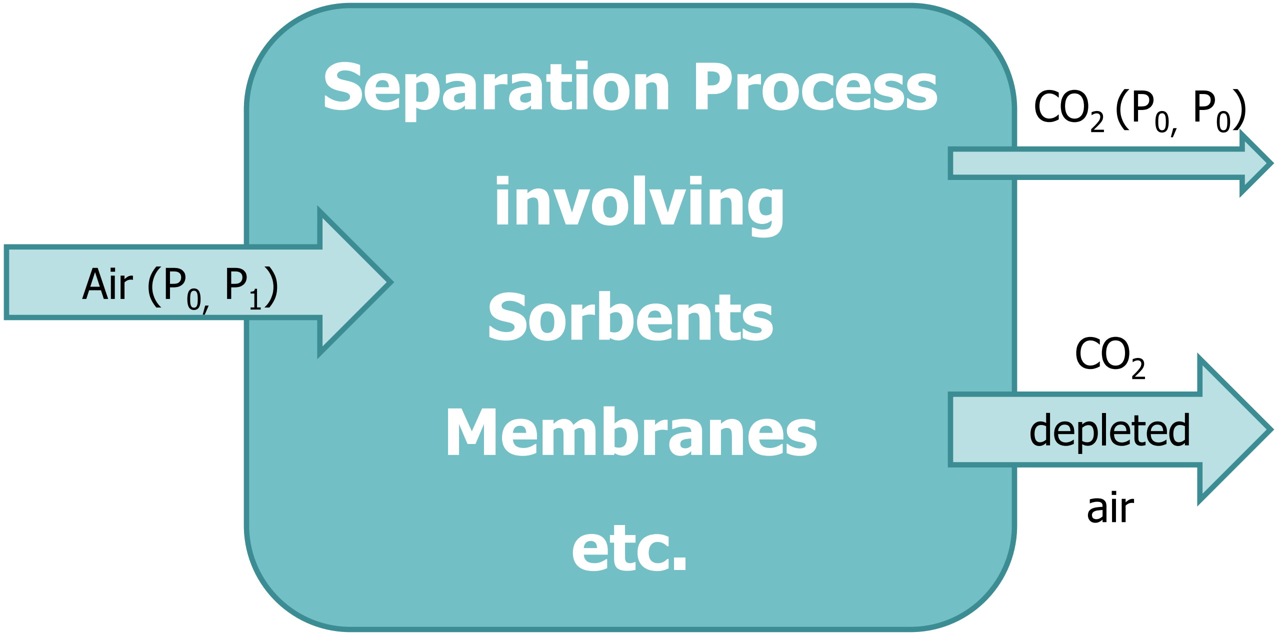


Sorbent regeneration is expensive

Thermodynamics works

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)



Separation Process

involving

Sorbents

Membranes

etc.

Air (P_0, P_1)

CO_2 (P_0, P_0)

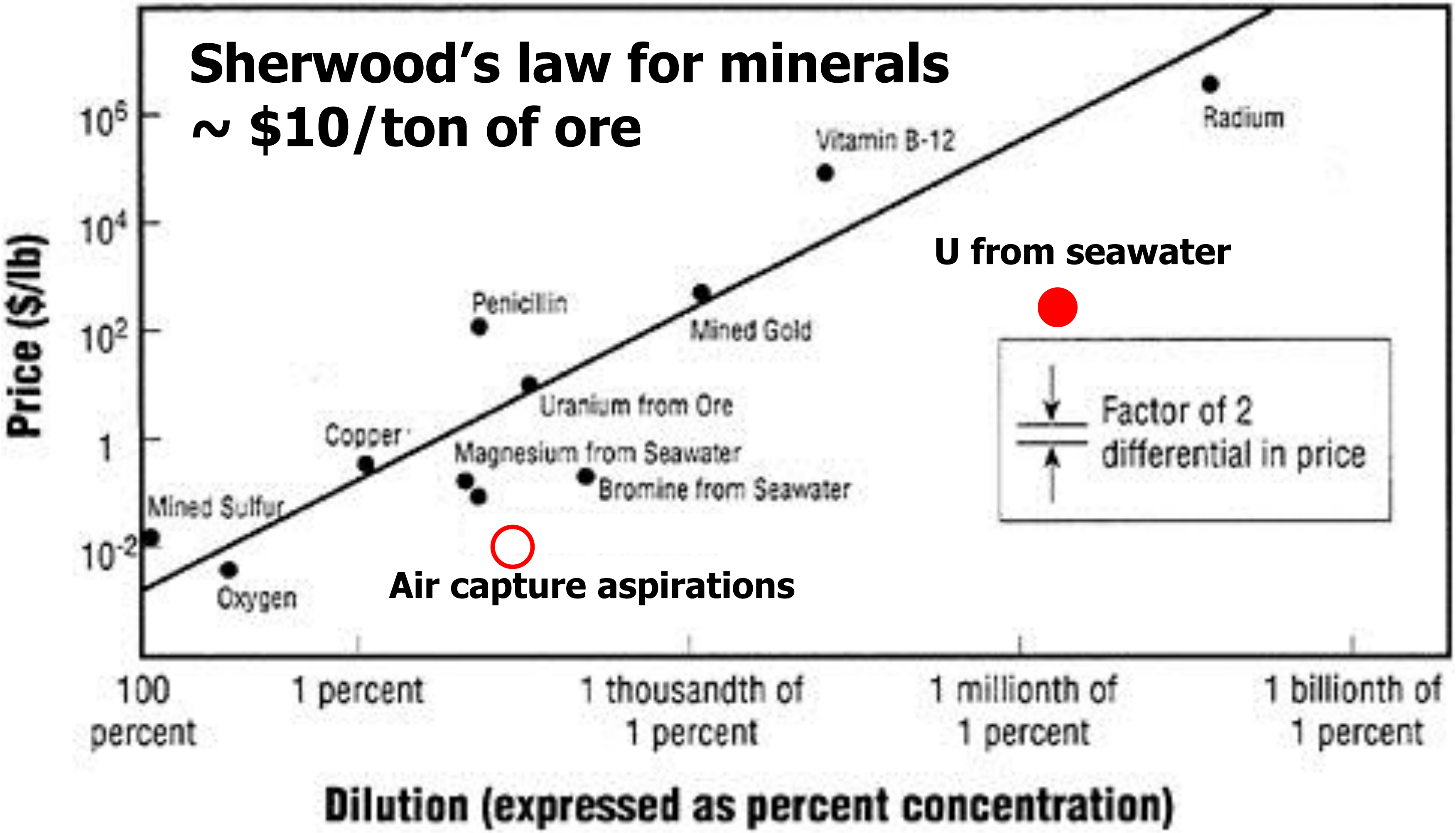
CO_2 depleted air (P_0, P_2)

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

Specific irreversible processes have higher free energy demands

Capture of CO_2 from ambient air

not your run-of-the-mill separation problem



Sherwood's law for minerals

~ \$10/ton of ore

U from seawater

Air capture aspirations

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

wikipedia

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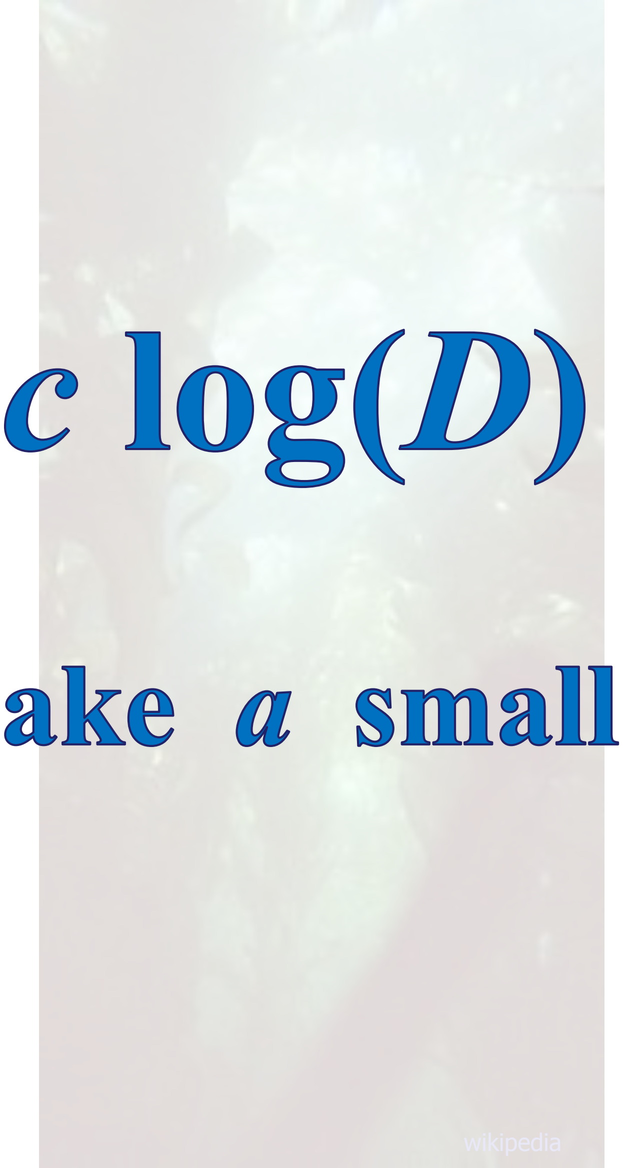
$$Cost = a\,D + b + c\,\log(D)$$

must make a small



wikipedia

An Example Technology

OUR APPROACH TO AIR CAPTURE

After initial work at both
Los Alamos and Columbia

GRT[*] demonstrated air capture
in Tucson in 2007[**]

Klaus Lackner
Allen Wright
Gary Comer

Proof of principle

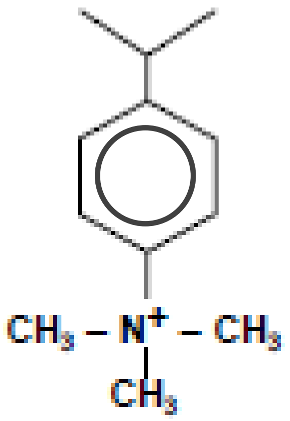
☑

[*] Now Kilimanjaro Energy, Inc.
[**] KSL is an advisor the company

Anionic Exchange Resins

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

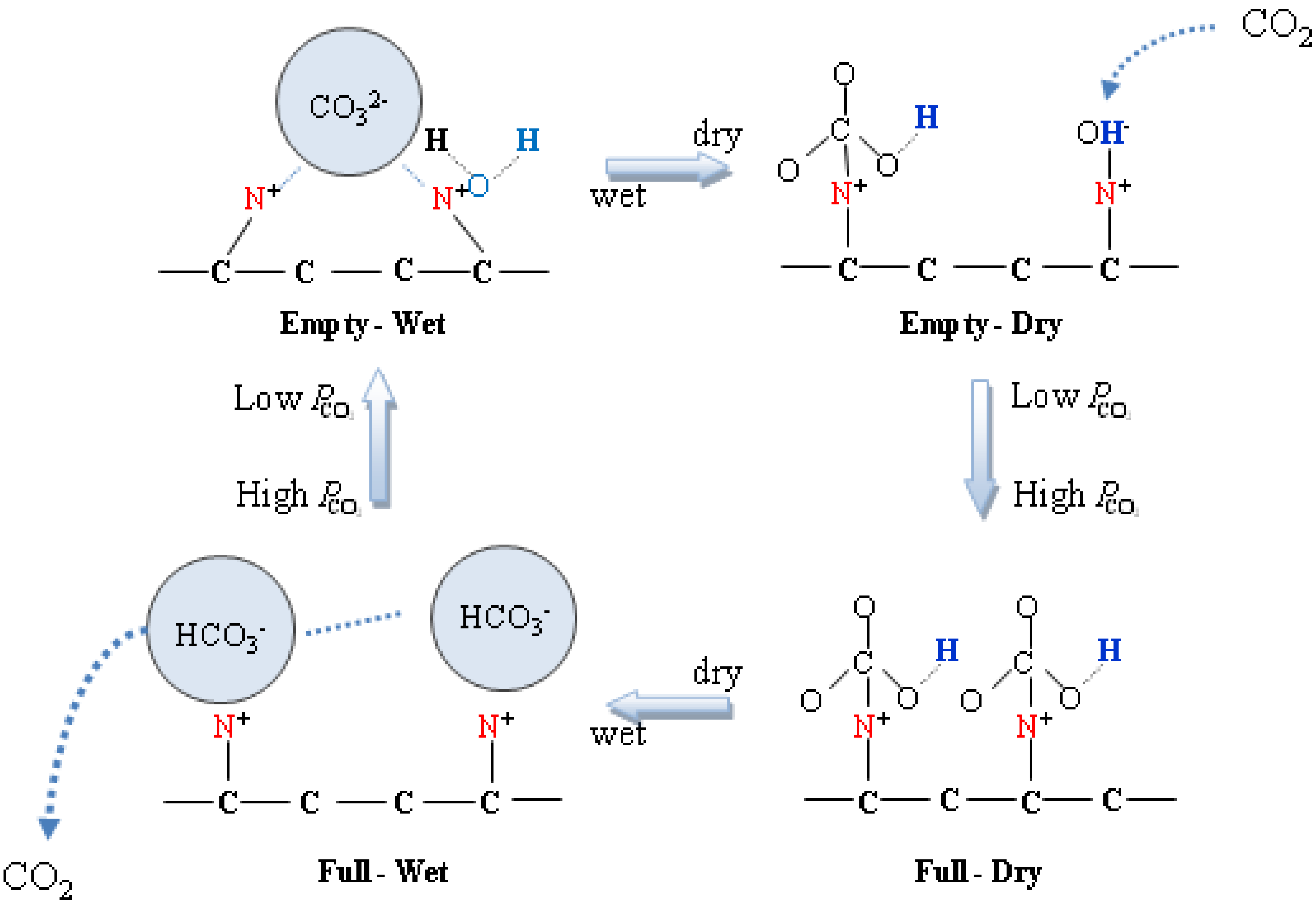
Type I Strong Base Resins



- 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
  - $2HCO_3^- \rightarrow CO_3^{--} + CO_2 + H_2O$

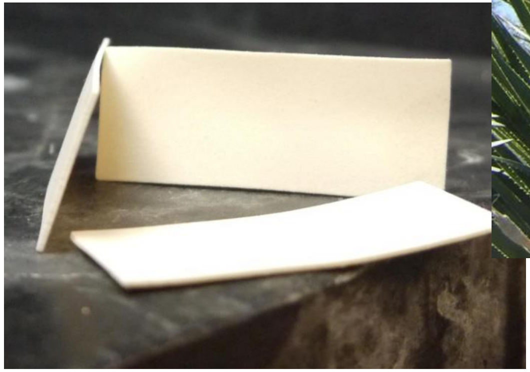
Moisture driven CO_2 swing

The moisture swing – water driven



Sorbent material

thin sheets



Snowpure electrochemical membrane (1mm thick)

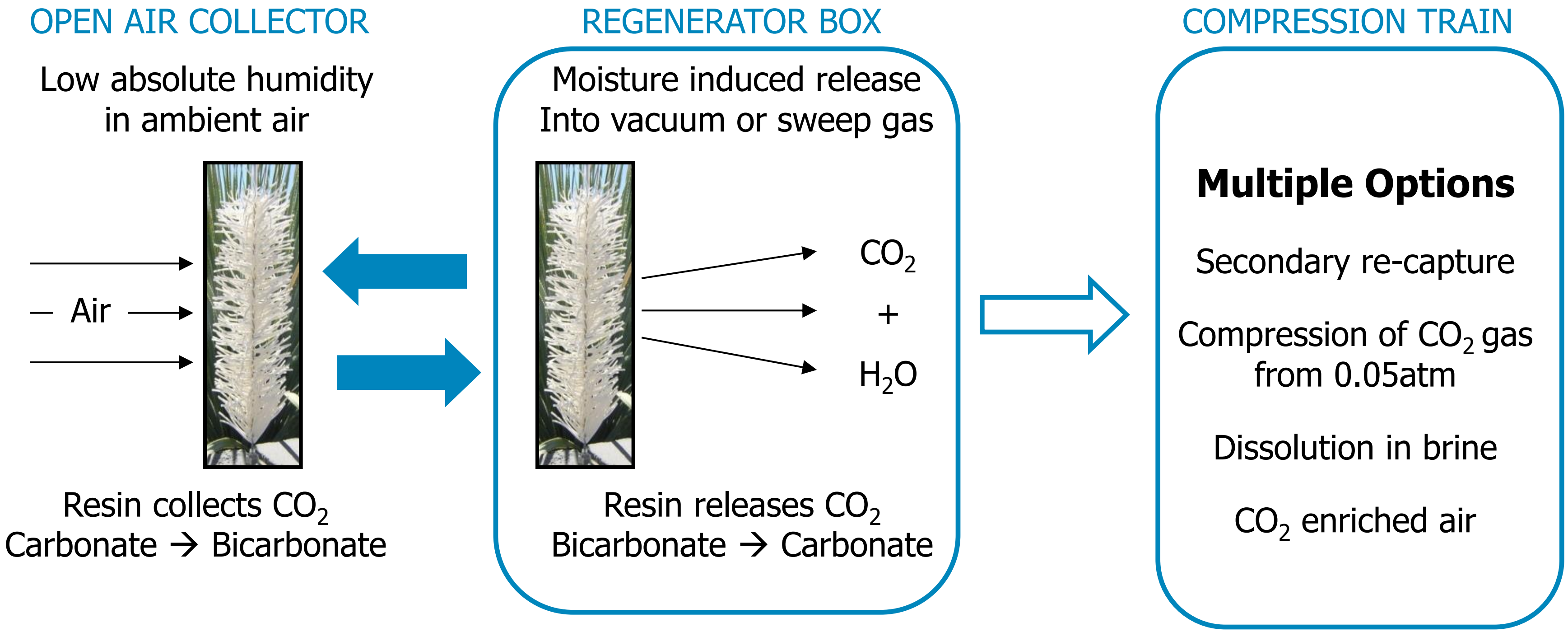
Polypropylene matrix with embedded fine resin particles (25μm)

Quaternary ammonium cations Carbonate/bicarbonate form

1.7 mol/kg charge equivalent

Novel Regenerator Chemistry

Moisture Swing Absorption



OPEN AIR COLLECTOR

Low absolute humidity
in ambient air

Air

Resin collects CO_2
Carbonate → Bicarbonate

REGENERATOR BOX

Moisture induced release
Into vacuum or sweep gas

CO_2 + H_2O

Resin releases CO_2
Bicarbonate → Carbonate

COMPRESSION TRAIN

Multiple Options

Secondary re-capture

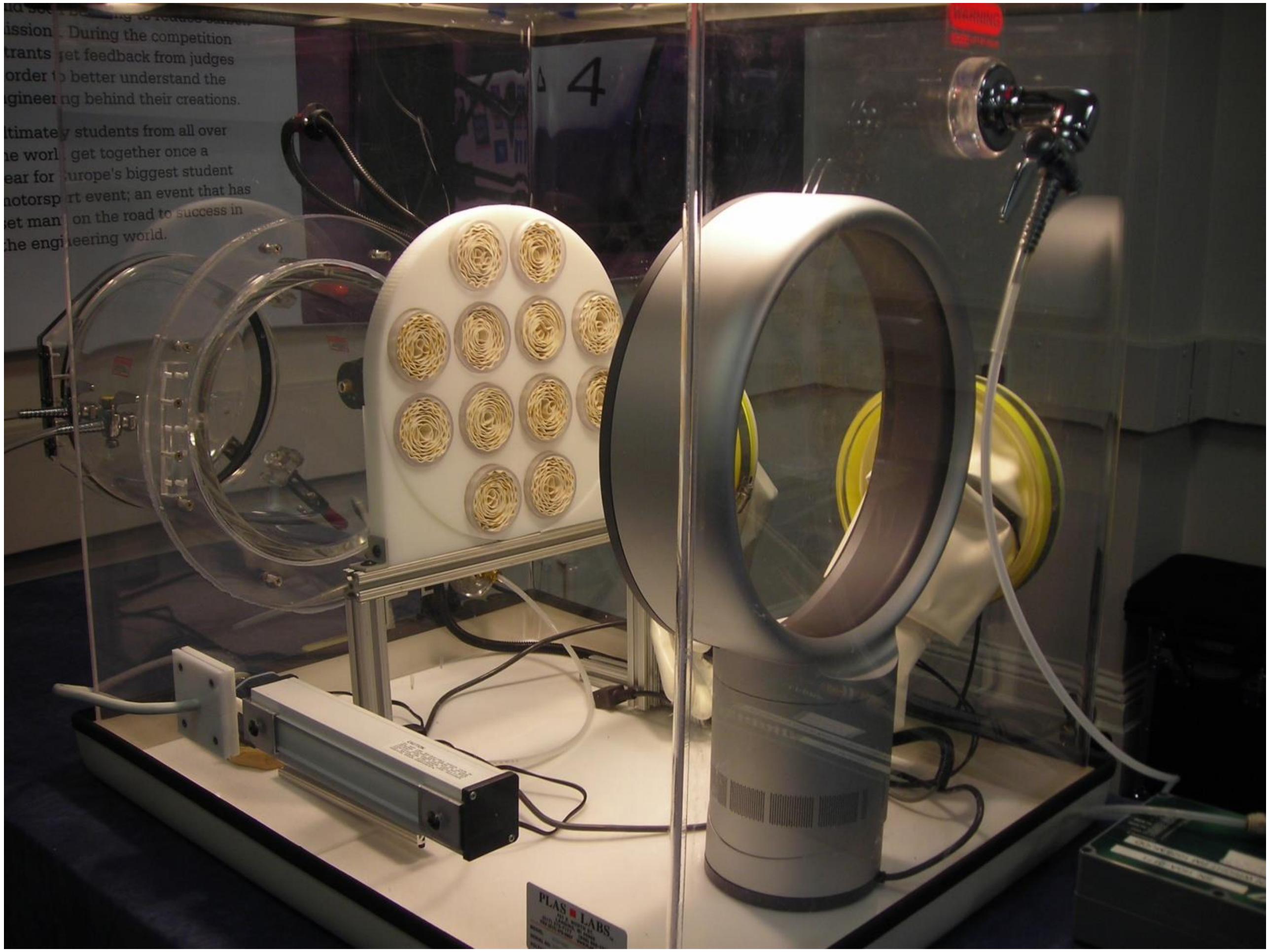
Compression of CO_2 gas
from 0.05atm

Dissolution in brine

CO_2 enriched air

- Moisture swing consumes water, mechanical energy and/or heat
- Water "only" for producing CO_2 enriched air (5%)
- 50 kJ/mol of CO_2 of electric power (for the evacuation based system)
- 10 liter of water per kg of CO_2 (much 100 times less than biomass)

Demonstration unit



Make the air do your work

- **Air carries kinetic energy**
  - Plenty to move the air
- **Air carries thermal energy**
  - sufficient to evaporate water
- **Air carries chemical potential**
  - out of equilibrium with water
  - sufficient to compress CO_2 two hundredfold

Take advantage of the resource you have

Wikipedia image

Addressing the scope of the problem

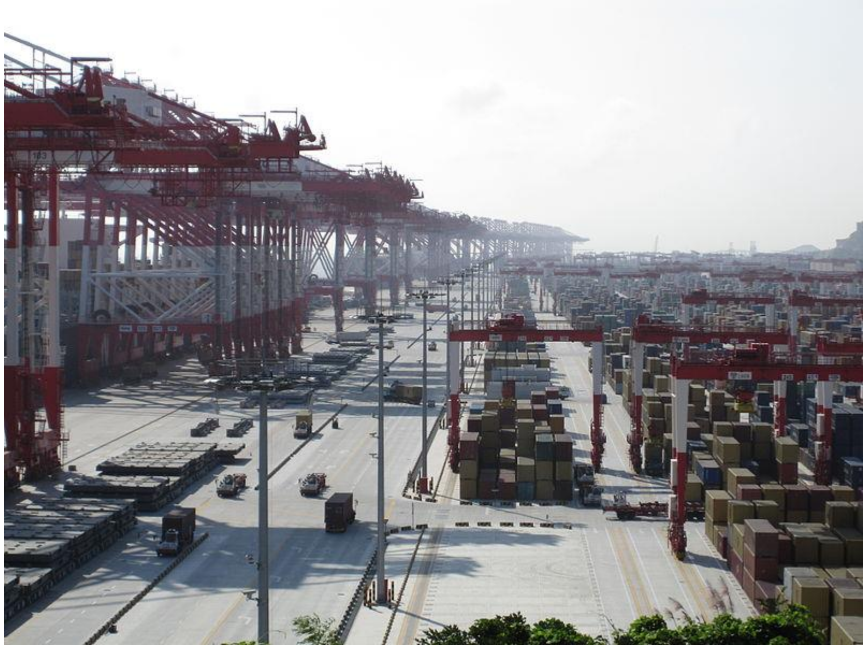
GOING TO SCALE

Stabilizing climate with small machines
Many one-ton-per-day units

100 million units would
eliminate world emissions

With 10 year life time,
production must be
10 million units per
year

Required production capacity small on world scale

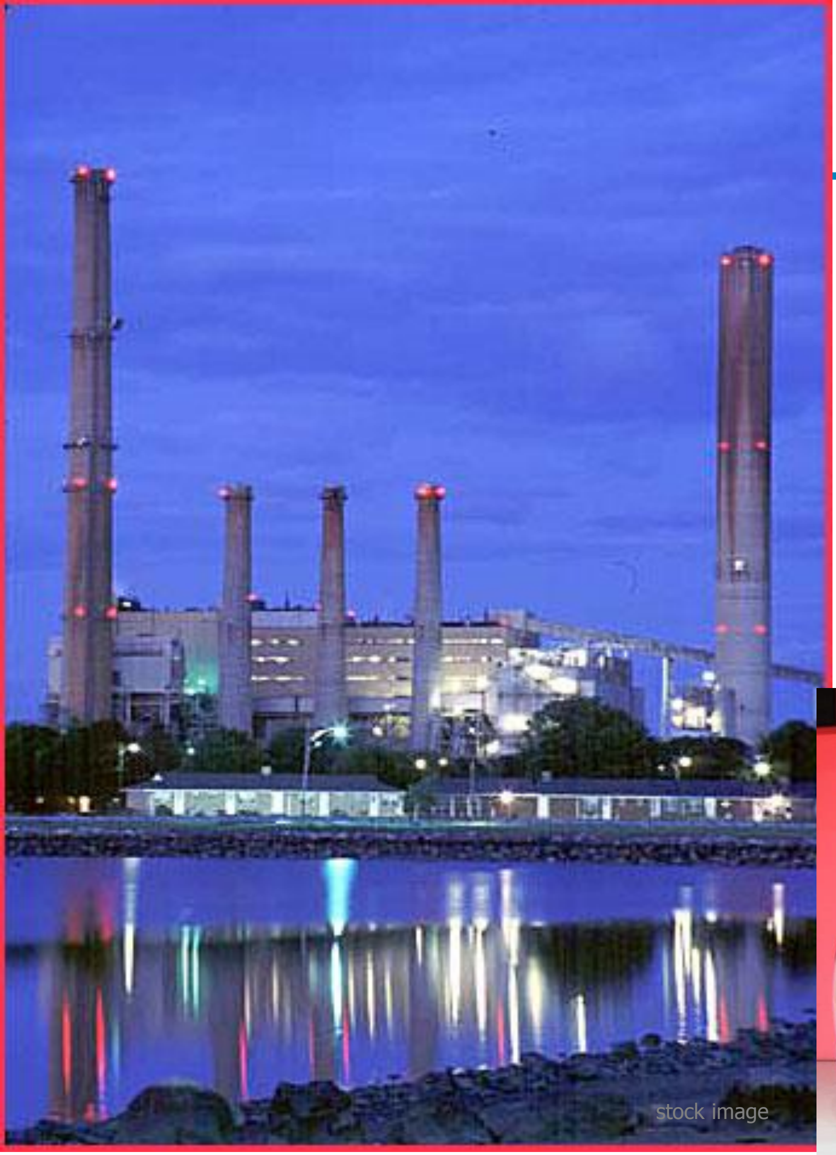


Shanghai harbor processes 30 million containers a year

World car and light truck production: 80 million per year

Shanghai container port, wikipedia picture

Spot the low cost power plant



stock image

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

wikipedia

Automation allows for small units

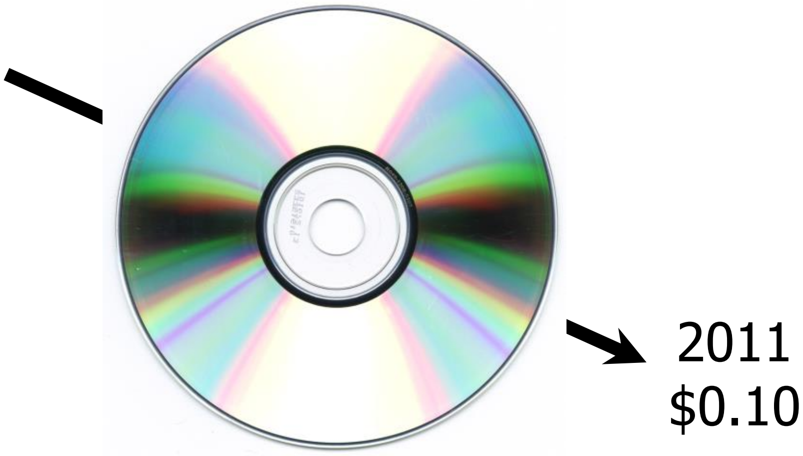
http://wot.motortrend.com/google-autonomous-car-testing-fleet-adds-lexus-rx-450h-logs-300000-miles-245621.html

Cost Issues

ECONOMIC VIABILITY

Economics

- Costs of future technologies are unpredictable
- First of a kind costs are always large
- Frictionless costs of air capture are very small
- Learning and mass production have yielded huge cost reductions
- Initial cost estimates appear encouraging



1980
$20

2011
$0.10

Economic feasibility is reached at $100/ton of CO_2

Low cost comes with experience

$600 Per ton CO_2 — **APS (low tech)**

$500

$400

$300

GRT (first of a kind)

$200

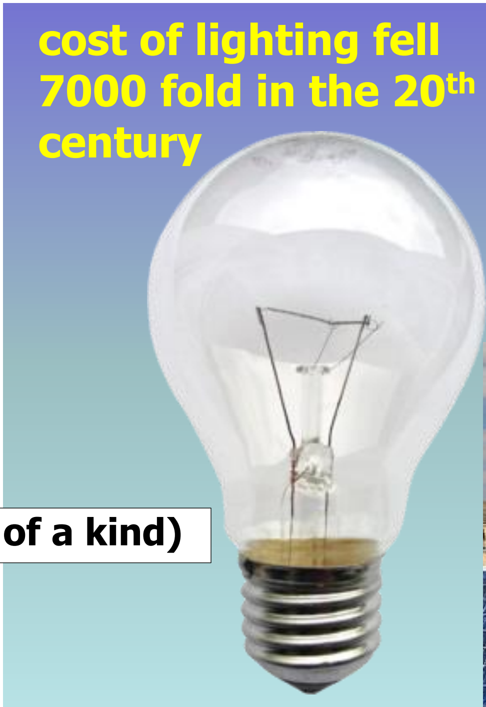
Current estimates

$100

CO_2 enriched air

Raw material and energy limit (frictionless cost)

$0



cost of lighting fell 7000 fold in the 20th century

price dropped fortyfold

price dropped hundredfold

The Power of the Learning Curve

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

Wikipedia pictures

Mining the air for CO_2

CO_2 is everywhere available

- CO_2 is an industrial commodity
  - price varies with location
    - $100/ton ($50/t … $300/t)
  - transport distance sets cost
  - typical local demand is small

▪Art courtesy Stonehaven CCS, Montreal

CO_2 Markets

- **Merchant CO_2**
  - Markets are small and distributed
- **Chemical commodities**
  - E.g. urea, often attached to point sources
- **Biomass production**
  - Greenhouse, algae reactors
    - Limit water consumption, produce food/fuels
    - Operate with CO_2 enriched air
- **Enhanced oil/gas recovery**
  - Air capture aims at small fields, exploratory work in the absence of pipelines
- **Synthetic renewable fuels**
  - Input is excess, intermittent renewable power, often distributed
  - Energy rather than CO_2 drives cost
- **Sequestration**
  - Remote locations engender less resistance

Air capture has a competitive advantage in satisfying small, distributed or remote demands

Can bootstrap from small scales

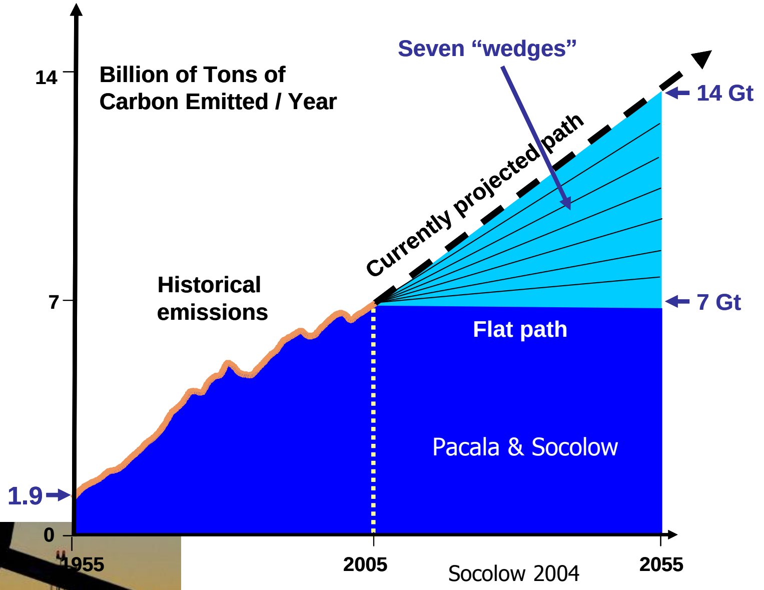
- **Small existing CO_2 markets make it possible to start**
  - Without government support for huge pilot plants
  - With a profitable learning phase
  - Learning on a small scale
  - Basic R&D will be useful

Addressable CO_2 Markets are large

As learning lowers costs the market for CO_2 will grow even before there is a climate-based carbon price

CO_2 Market Consumers	Market Basis	Addressable Share %	Price Point \$/ton CO_2	Annual Prodn. Mt CO_2	Market Size M\$/yr
Horticulture/Greenhouses					
Glasshouse (world)	40,000ha	10%	100-200	1.2	200
Plastic (world)	1.5 Mha	1%	100-200	4.5	600
Merchant CO_2					
US	8Mt/yr	10%	100-300	0.8	200
World	30Mt/yr	10%	100-300	3.0	1,000
Enhanced Oil Recovery					
Current Use	44 Mt/yr	1%	20-50	0.4	20
World Oil	90Mbbl/day	3%	50-200	136	10,000
CO_2 Reductions					
14 Wedges	1Gt CO_2/yr^2	7%*	30-50		
14 Wedges in 2015	10Gt CO_2/yr	7%*	30-50	700	35,000

* 7% represents one wedge



Socolow 2004

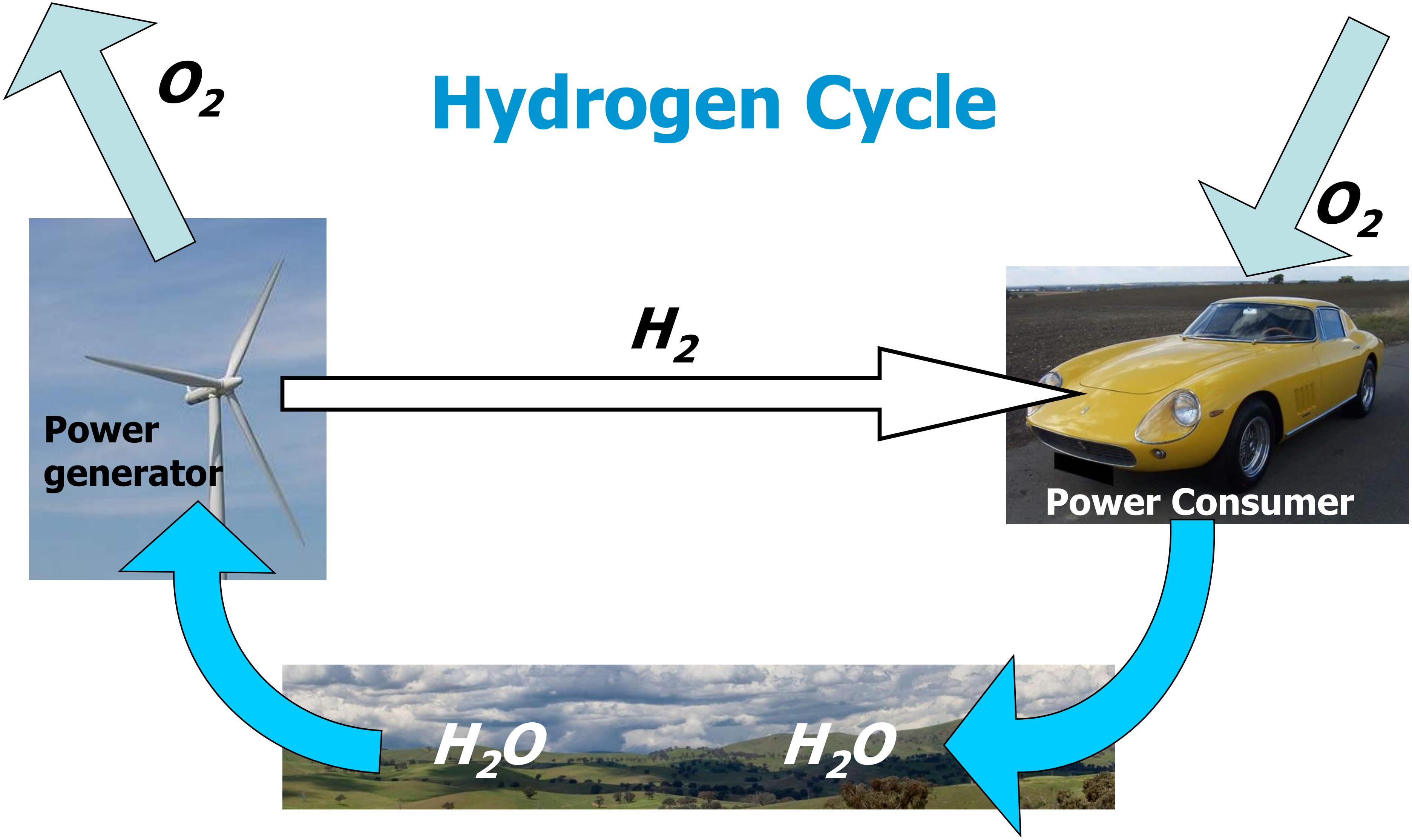
Algae are an emerging market

Greenhouses are an immediate market

Closing the fuel cycle

SYNTHETIC FUELS

Fuel market: Hydrogen



Hydrogen Cycle

O_2

Power generator

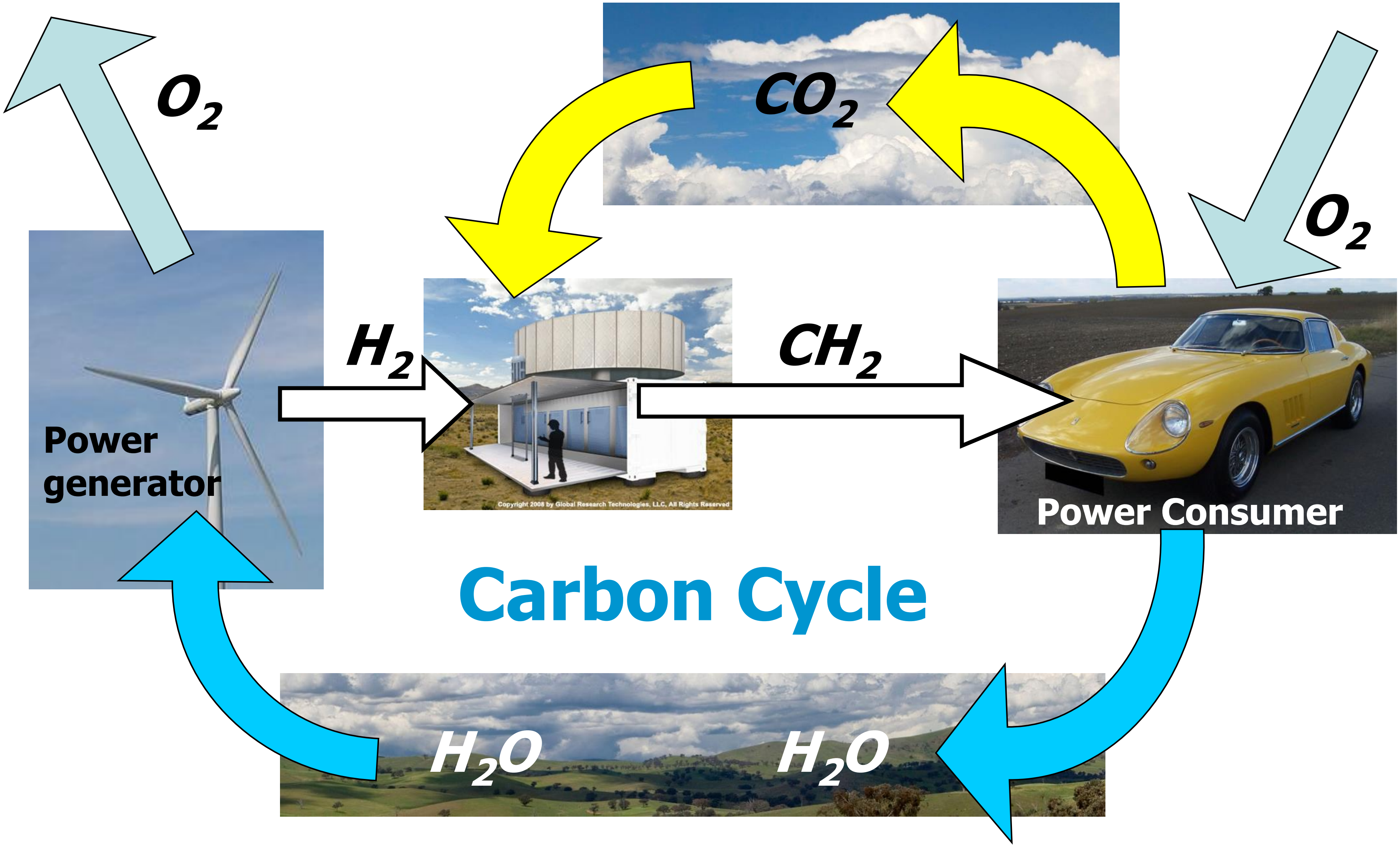
H_2

Power Consumer

O_2

H_2O H_2O

Fuel market: non-fossil fuels carbon



O_2

CO_2

O_2

H_2

CH_2

Power generator

Power Consumer

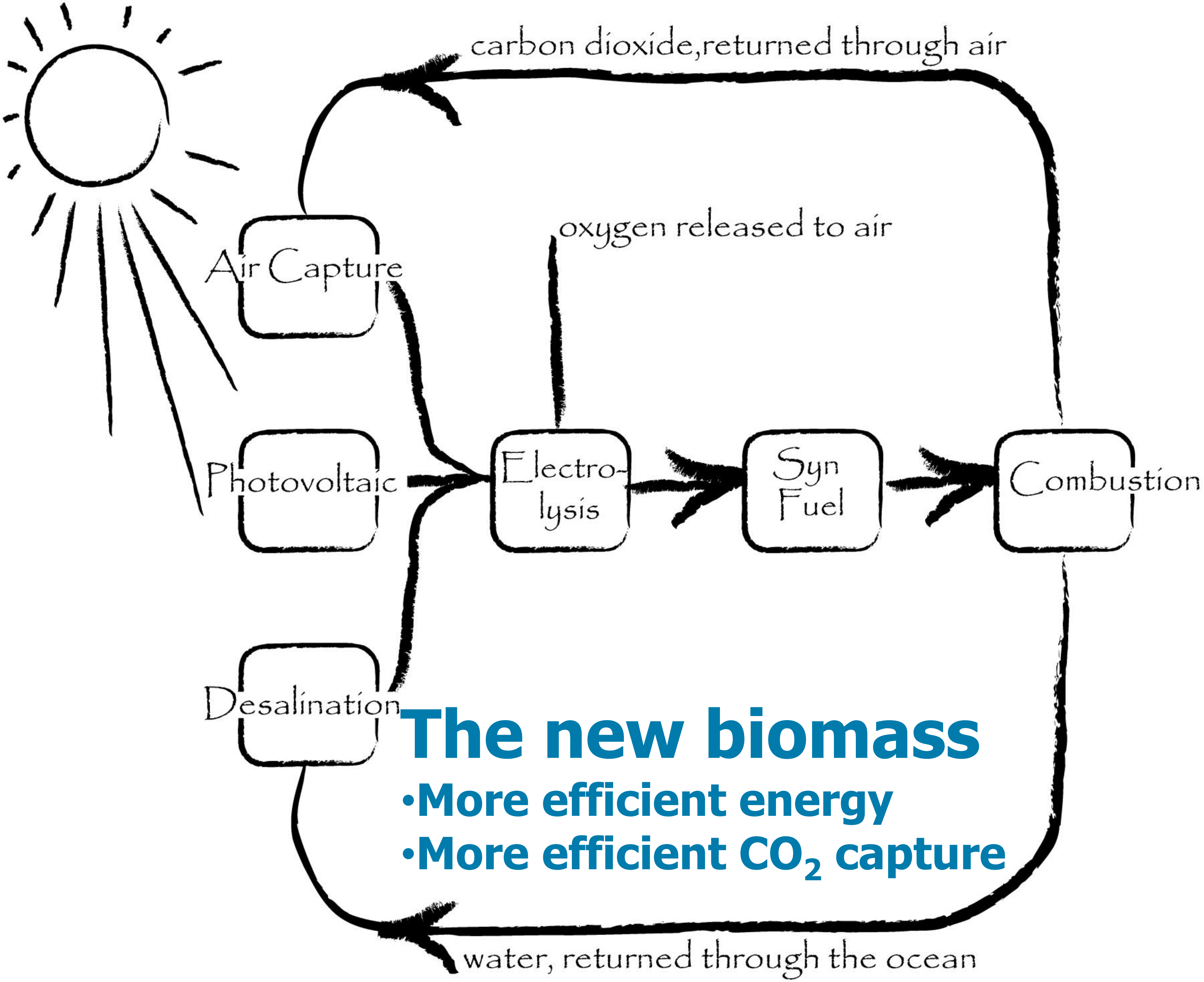
Carbon Cycle

H_2O

H_2O

The new biomass

- More efficient energy
- More efficient CO_2 capture



A long term vision:
two complementary energy carriers

- **Electricity**
  - Responsive
  - No emissions at point of consumption
  - Stationary applications
  - No energy storage
  - Large plants can capture most of their CO_2

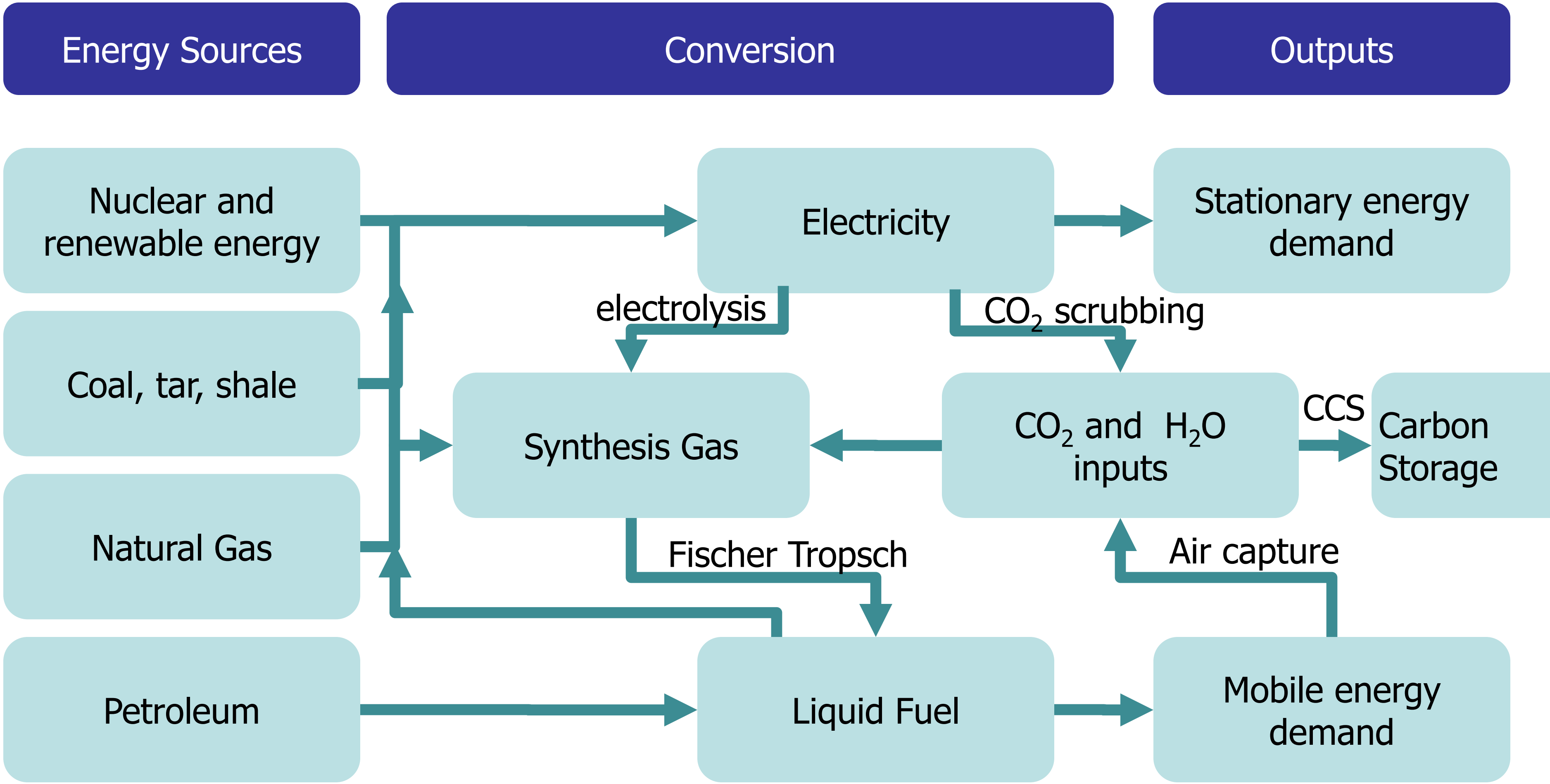
- **Liquid fuels**
  - Easily stored
    - on board for transportation
    - for electricity storage
  - Extremely high energy density
  - Produce CO_2 at point of use – Air capture

The power of liquid fuels

Liquid fuels vs. Batteries

- 2 orders of magnitude higher energy density in fuel
- CO_2 once emitted stays in the air unless captured
- High capital cost limits length of battery charge/discharge cycle

Carbon neutral energy systems



Energy Sources

Conversion

Outputs

Nuclear and renewable energy

Coal, tar, shale

Natural Gas

Petroleum

Electricity

Synthesis Gas

Liquid Fuel

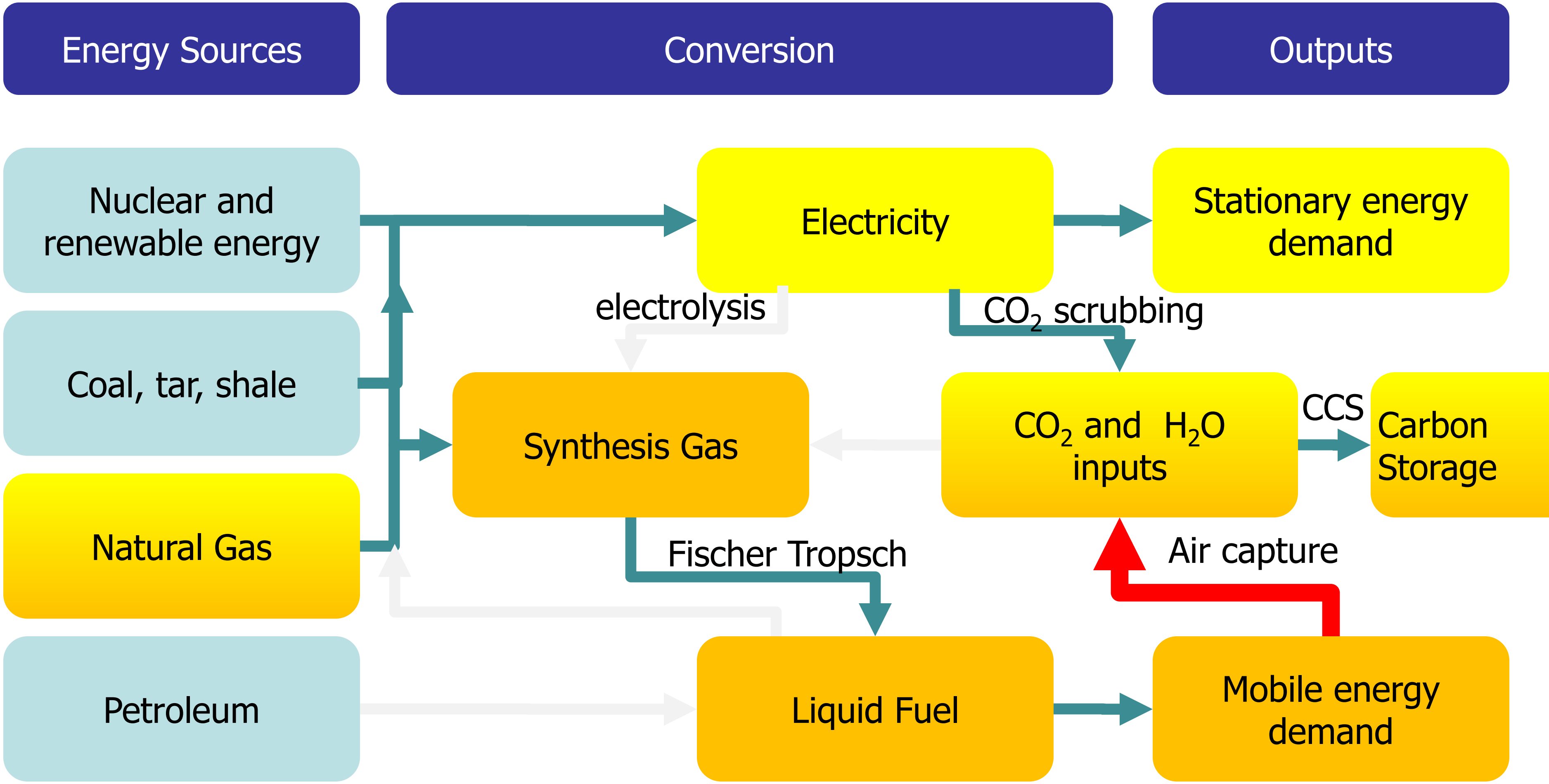
CO_2 and H_2O inputs

Stationary energy demand

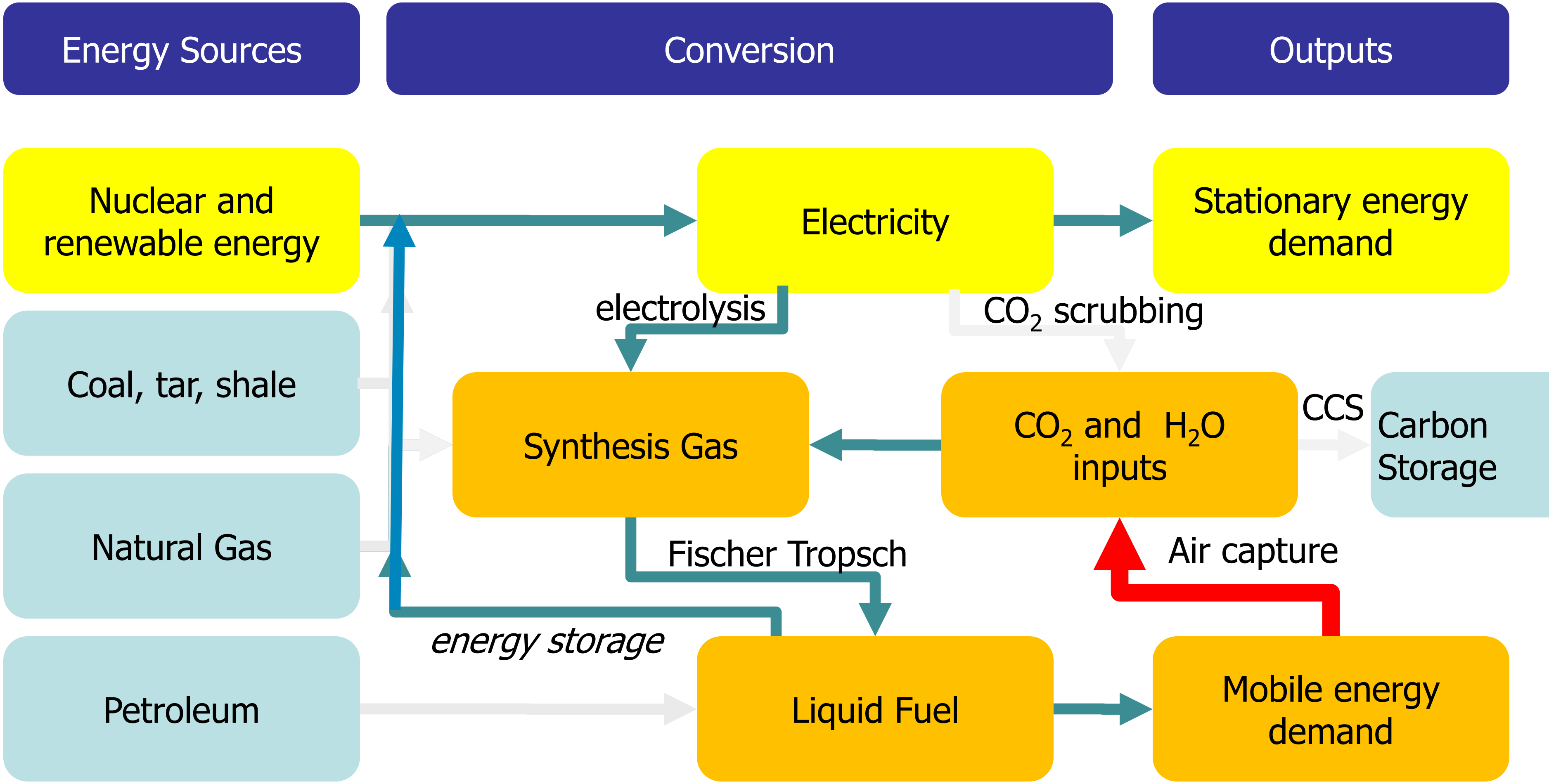
Carbon Storage

Mobile energy demand

Carbon neutral energy systems



Carbon neutral energy systems



Conclusion

POLICY IMPLICATIONS

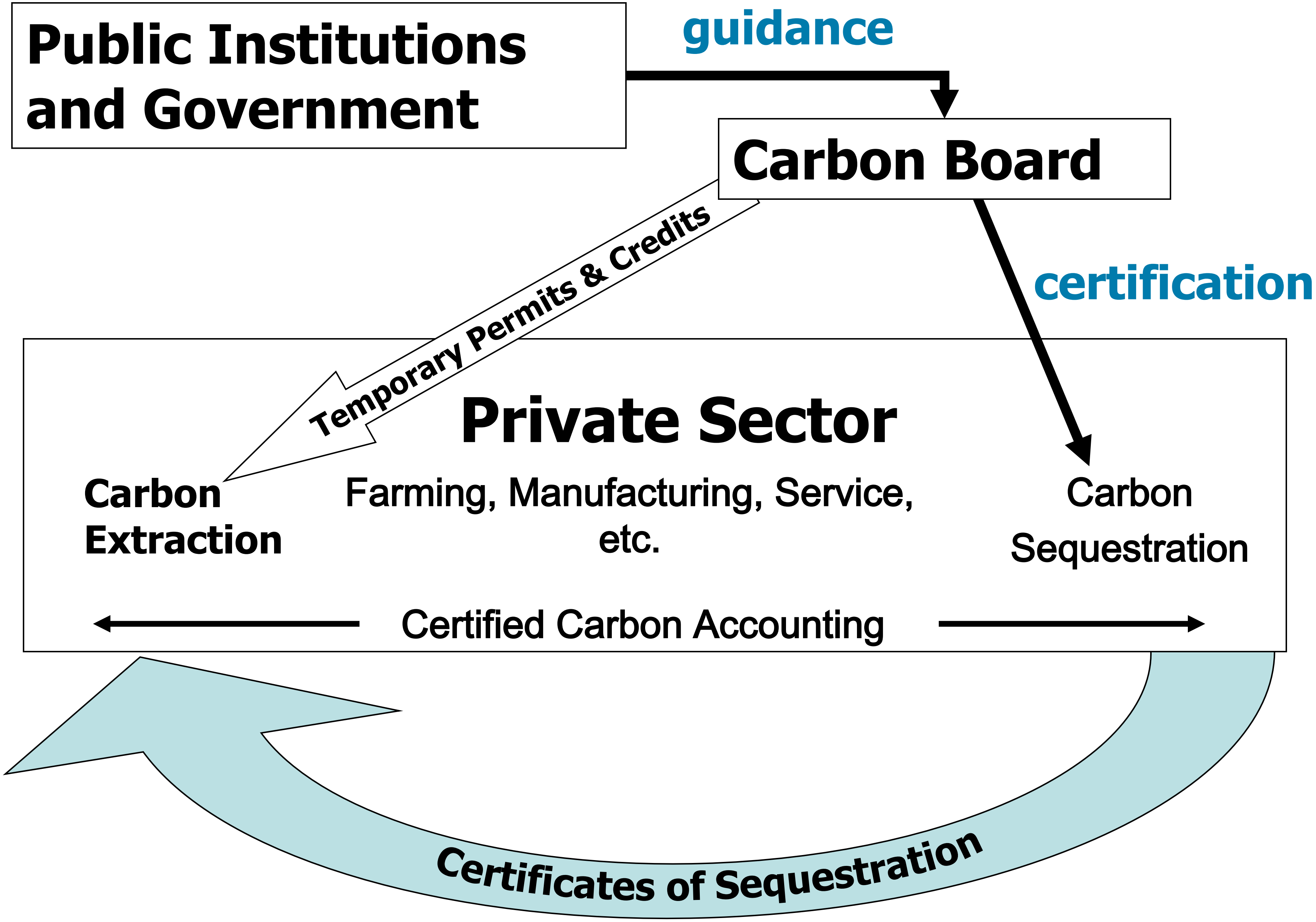
Emissions become reversible

- **Air capture puts a price on emissions**
    - Accidental and intentional releases can be remedied
    - Costs can be assigned to emitters
- **Not a good reason to delay action**
    - Moral hazard argument is coming too late
    - The world has delayed unduly and now needs air capture

Air capture is the capture of last resort

- can handle emissions from any and all sources
- sets upper limit on cost of carbon management
- assures feasibility of zero carbon scenarios
- provides a solution to the risk of leaky storage
- encourages point source capture

Wikipedia picture



Public Institutions and Government

guidance

Carbon Board

certification

Temporary Permits & Credits

Private Sector

Carbon Extraction

Farming, Manufacturing, Service, etc.

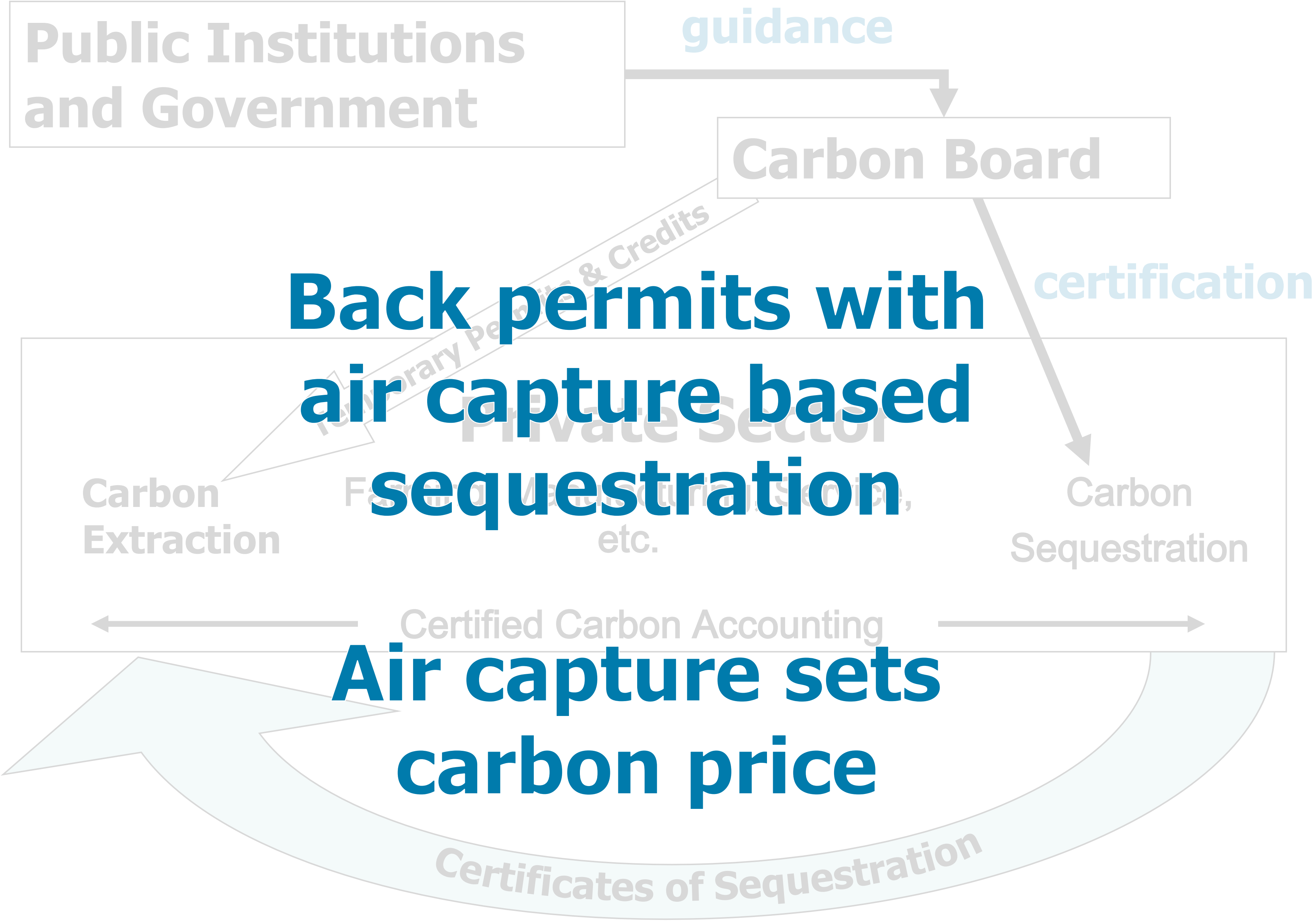
Carbon Sequestration

Certified Carbon Accounting

Certificates of Sequestration

Back permits with air capture based sequestration

Air capture sets carbon price



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Air capture and international carbon policies

- **Carbon border adjustment in trading**
  - Physical reductions can be attached to goods traded
- **International carbon capture and storage credits**
  - Generated by remote air capture and storage facilities
  - On behalf of poor countries, on behalf of uncooperative nations
- **Access to large, remote storage sites**
  - Avoid NIMBY/NUMBY of urban areas
- **Synthetic fuels from remote renewable energy sites**
  - Markets for countries with sunshine, wind, hydro or geothermal energy

Creating a world wide carbon price

Alternatives

- **Industry will find alternatives**
  - Renewable and nuclear energy
  - Point source capture and storage
  - Closed cycle liquid fuels (with air capture)
- **Air capture acts as a competitor**
  - Once established it will motivate other actions
  - A fraction of the market will stay with air capture
- **Air capture deals with all emissions**
  - Alternatives will occupy niches or sectors

Conclusions

AIR CAPTURE IS VALUABLE

Air capture is worth pursuing

- **A powerful tool for fighting climate change**
    - Outperforms biomass capture
    - Important policy tool in creating carbon reductions
- **No physical reasons why it could not work**
    - Not an extrapolation of conventional technologies
    - Thermodynamics and kinetics work out – carbon negative with coal
    - Technical feasibility has been demonstrated
    - Same processes are deployed routinely in other industries
- **Cost reductions appear feasible**
    - APS process is six times too expensive, but it is a first of a kind
    - Mass production and novel sorbent can drive cost reduction
    - Learning curves in other fields have reduced cost 10 to 100-fold
    - Several companies claim low costs already
    - Frictionless cost is very low

High risk – high return investment

- **Risk is mitigated by limiting unit scale of operation**
  - Avoid large capital expenditures of operating huge units
  - Avoid long development cycles typical of scaling up
  - Scale up in numbers by entering a sequence of ever large markets
- **Return is amplified by world-wide applicability**
  - Carbon reductions via air capture create an export industry
- **Return is amplified by motivating other options**
  - Air capture puts a ceiling on the price of carbon
  - Air capture cost are driven down by learning in real markets
  - Technically easier options (like power plant capture) can and will compete by achieving lower costs in their respective sectors
- **Small markets allow bootstrapping**
- **Policy support is critical**

Air Capture Center

integrating a new idea into Academia

Demonstration

Field deployed prototypes

Establish rapid prototyping capability

Continuous improvement and continuous operation

Learning by doing in multiple iterations

Basic Science

Sorbent chemistry, physics and thermodynamics

Separation Science

System engineering, scaling and automation, techno-economics

Sustainability science, human interfaces

Policy-Outreach

Study policy implications of air capture technology

Move policy makers to a zero-emission world

Connect to industry and venture capital

Seek support from foundations & sovereign wealth funds

Creating IP Pool

New ideas change the world

- Steam Engine
- Trains & Ships
- Telephones
- Automobile
- Television
- Airplanes
- Internet

Unpredicted and unmodeled, these inventions changed the course of future societal developments in unexpected ways