Closing the Carbon Cycle

Technology for Stopping Climate Change

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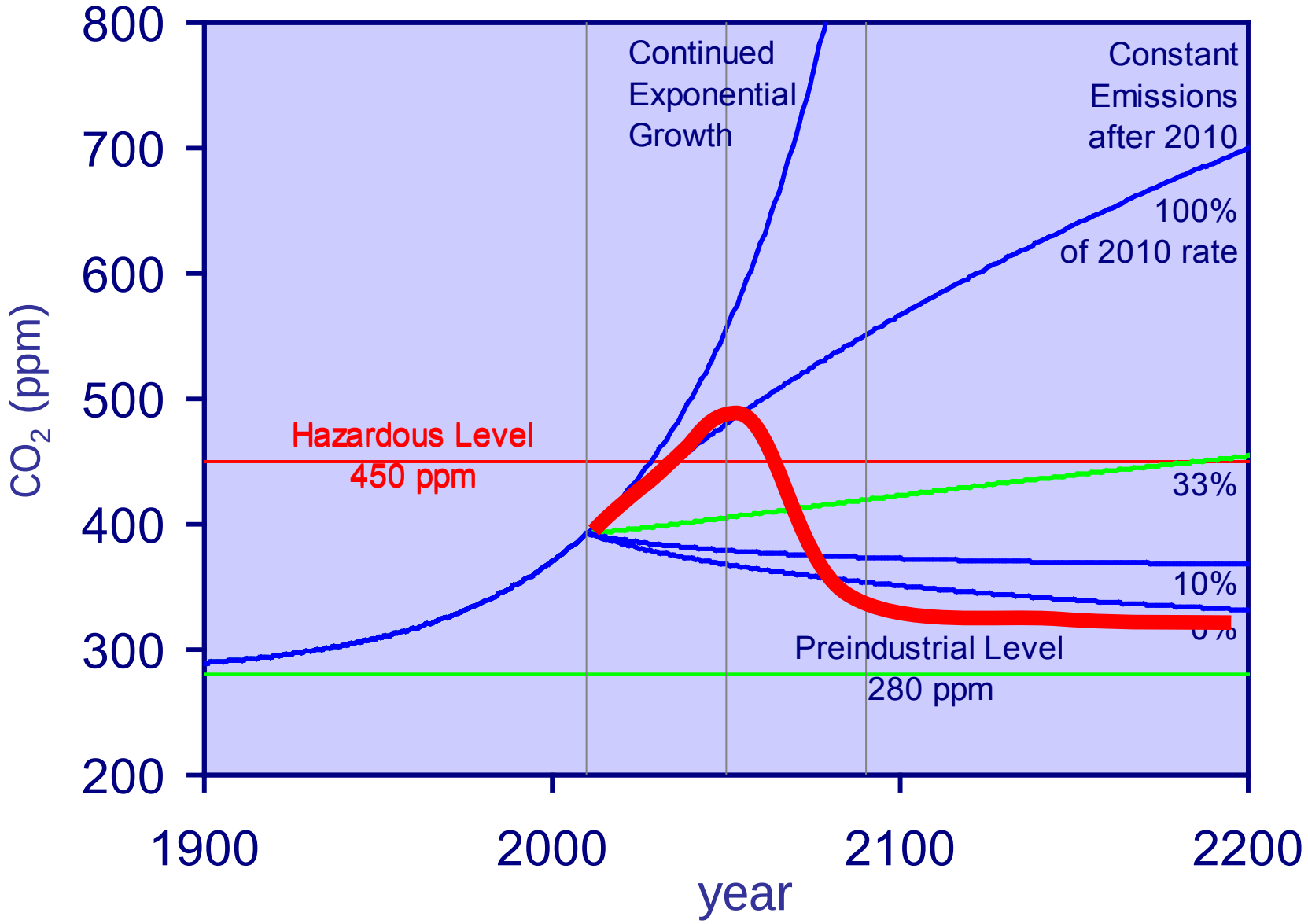
Carbon Management

- **Not about stabilizing emissions**
  …but about eliminating all emissions
- **The concept of a single CO_2 lifetime in air is misleading**
- **CO_2 is extremely persistent**
  … thermal effects linger even longer

The “drain in the bathtub” clogs up as the tub is filling

CO_2 Trajectories



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

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

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

The personal carbon allowance

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

IPCC: Need for Negative Emissions

- **Negative emissions require carbon storage**
  - Safe, permanent, and extremely 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
  - Ocean will largely return what it absorbed

Question of when – not if

Zero emission is a tall order

- **Orders of magnitude matter**
  - More CO_2 than all oil, gas and coal combined
  - The added oxygen weighs 2.7 times as much as the carbon
- **Stuck in a paradigm of incrementalism**
  - Reduce emissions from power plants
  - Utilize carbon
  - Wait for renewables to come on line
  - Leave the transportation sector alone

Lacking a sense of urgency

Technology solutions for climate

- **Need to push the technological envelope in carbon management**
  - Closing the carbon cycle is a necessity
  - Shrinking the carbon cycle is an option
  - 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**

Adressing climate change is about risk management

Navigating between climate catastrophe and economic collapse

- **Reducing atmospheric CO_2 minimizes climate risk**
  - Air capture allows for a return to safe CO_2 concentrations
  - It does not entirely eliminate the climate damage risk
- **Point source storage minimizes economic risk**
  - Access to fossil carbon reduces risk of energy shortages
- **Multiple options for storage minimizes all risks**
  - Geological storage may fall short
    - Physical limitations
    - Public perception and acceptance
    - Liability issues

Power plant capture is not enough

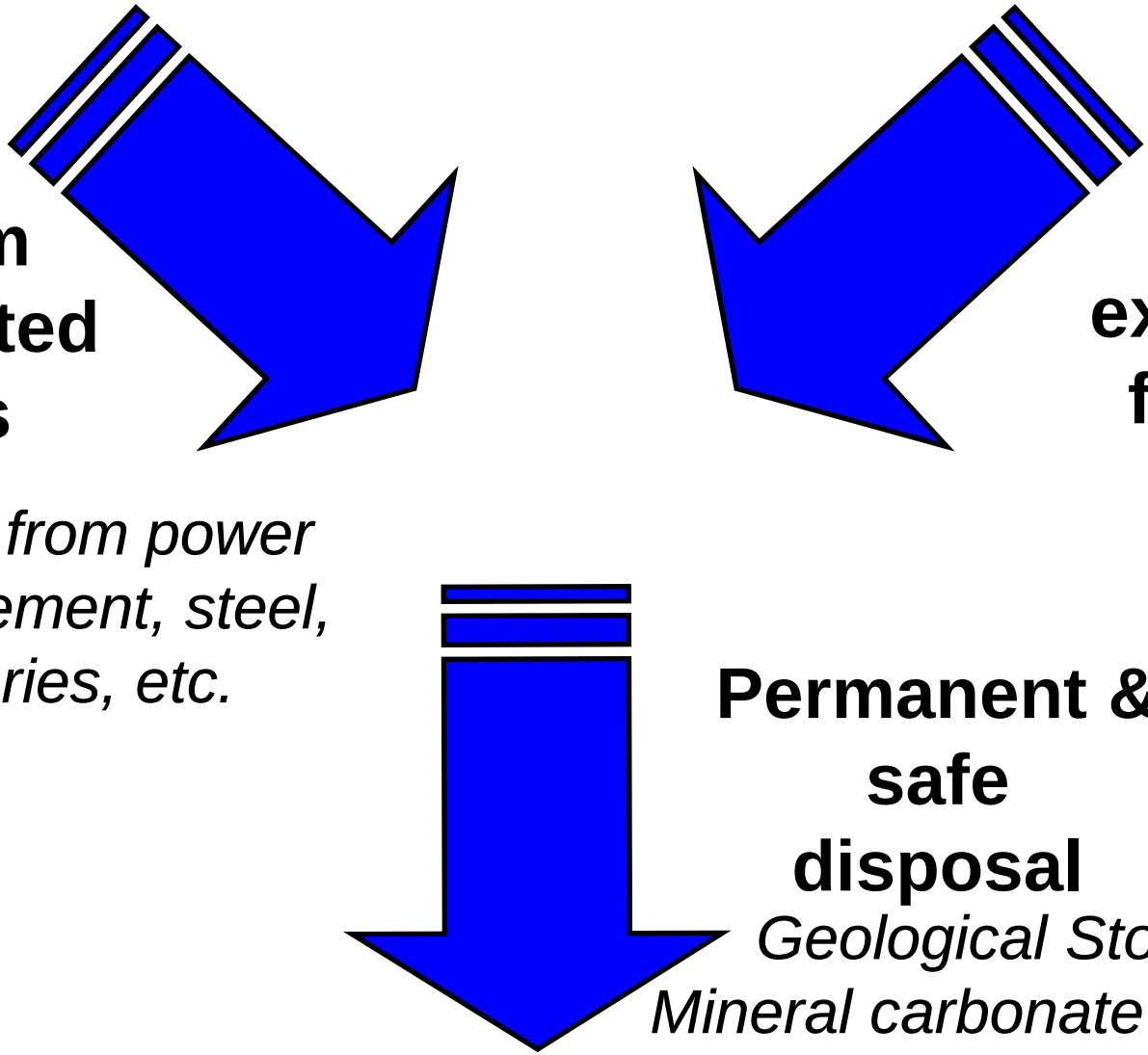
- **A 70 % reduction of a 30 % contributor cannot achieve a 90 to 100 % reduction**
  - Point sources only cover half of all emissions

- **Geological storage is important … but not enough**
  - Problems with local availability
  - Uncertainty of long term storage
  - Public acceptance issues
  - Need for alternatives to cover unquantified risks

Biomass 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

Net Zero Carbon Economy



Carbon Storage / Disposal is the biggest part of the problem

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Scale dwarfs all other industrial scales with the exception of water

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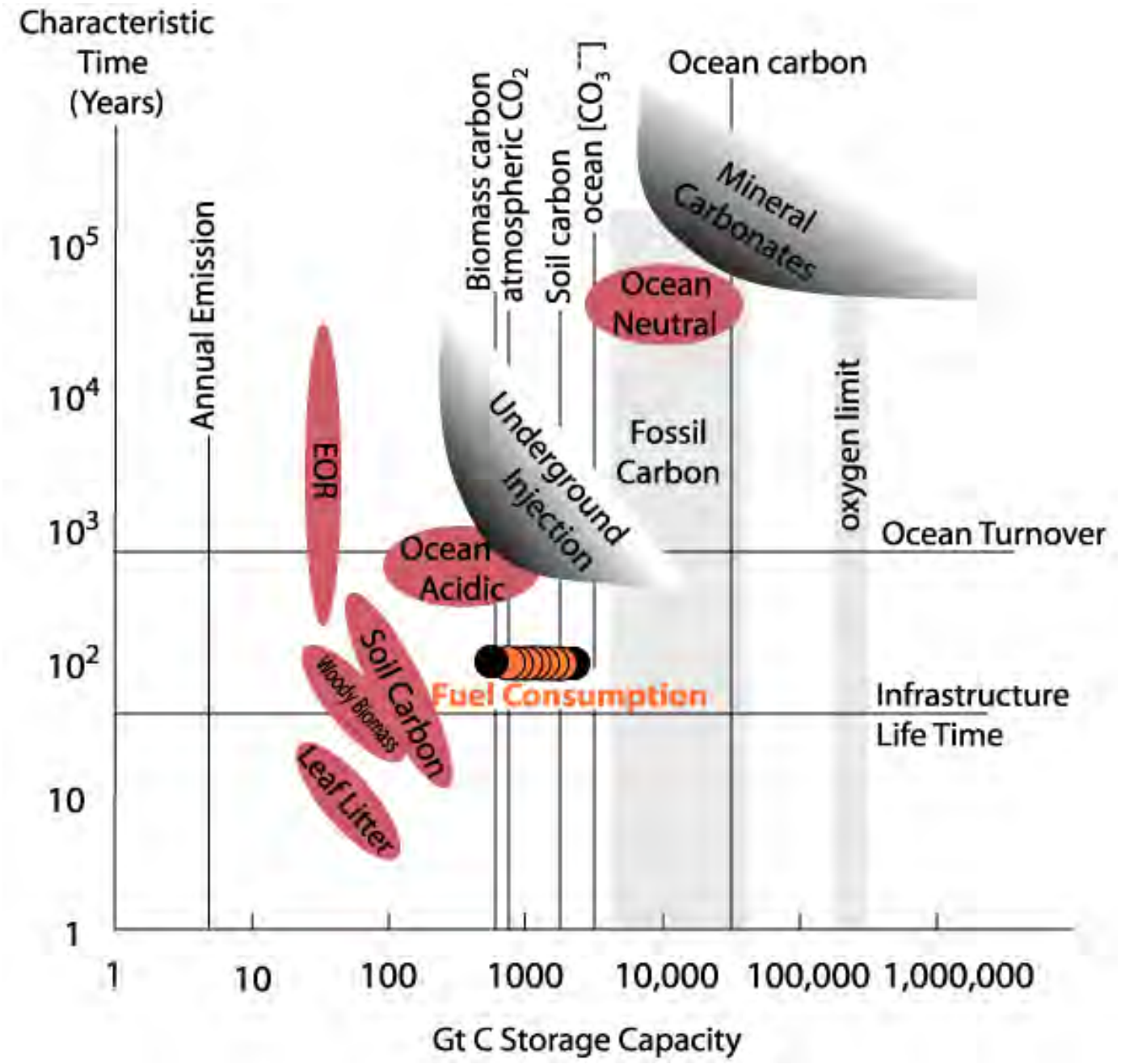
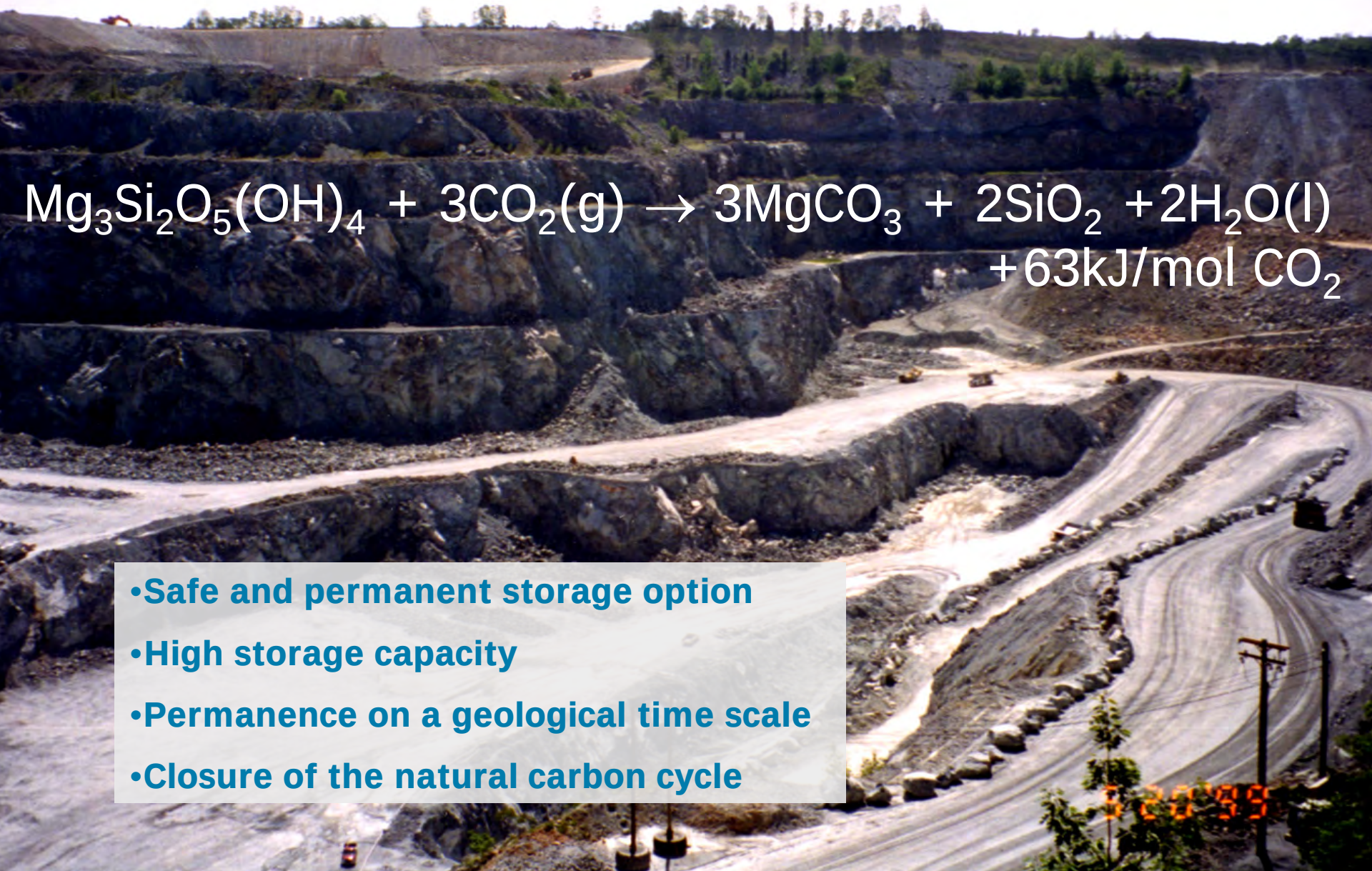

Characteristic Time (Years)
10^5
10^4
10^3
10^2
10
1
Annual Emission
Biomass carbon
atmospheric CO_2
Soil carbon
ocean $[CO_3^{--}]$
Ocean carbon
Mineral Carbonates
Ocean Neutral
Underground Injection
Fossil Carbon
oxygen limit
Ocean Turnover
EOR
Ocean Acidic
Soil Carbon
Woody Biomass
Leaf Litter
Fuel Consumption
Infrastructure Life Time
1
10
100
1000
10,000
100,000
1,000,000
Gt C Storage Capacity

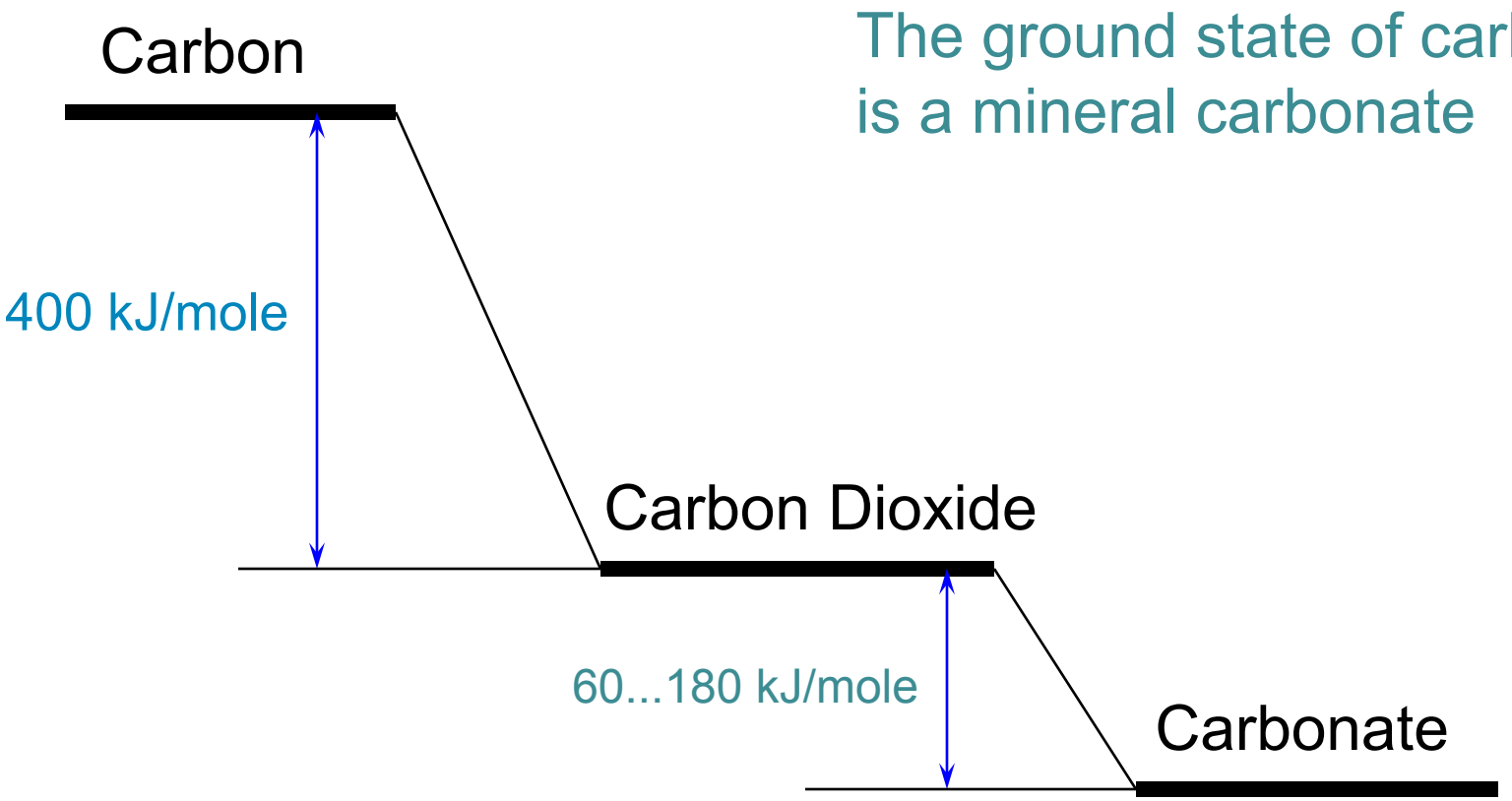
Mineral Sequestration



$$Mg_3Si_2O_5(OH)_4 + 3CO_2(g) \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O(l) + 63kJ/mol\ CO_2$$

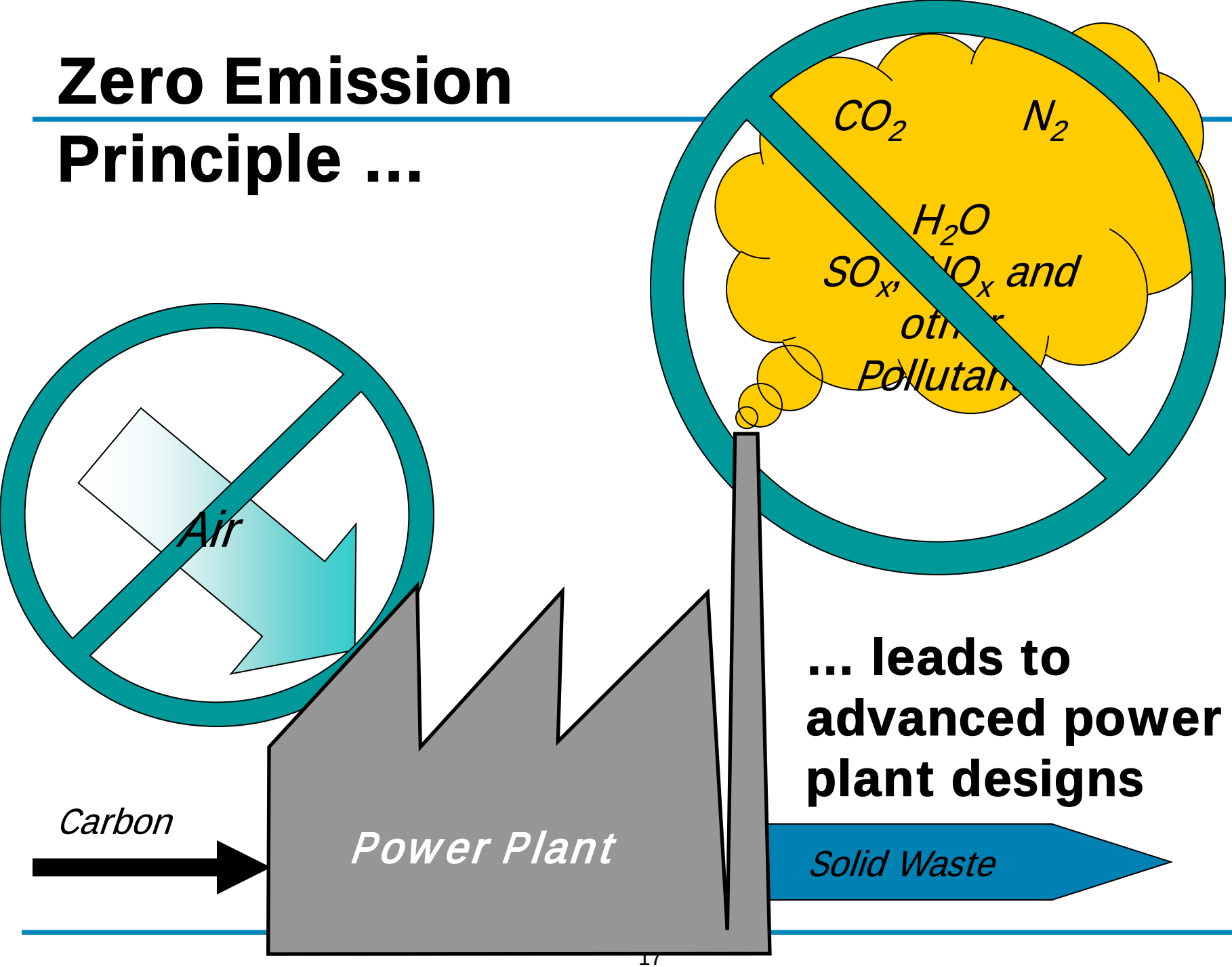
- **Safe and permanent storage option**
- **High storage capacity**
- **Permanence on a geological time scale**
- **Closure of the natural carbon cycle**

Energy States of Carbon



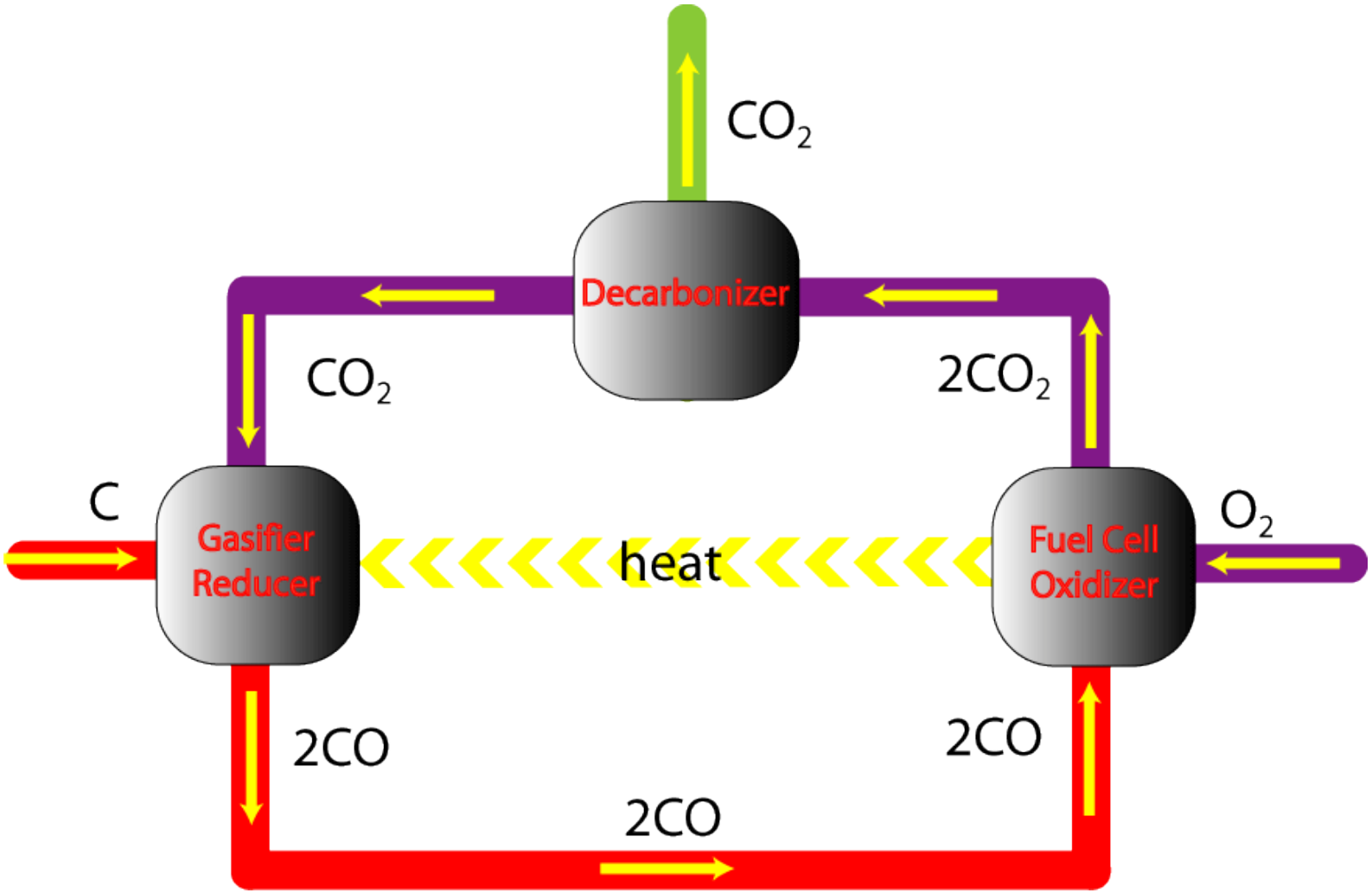
The ground state of carbon is a mineral carbonate

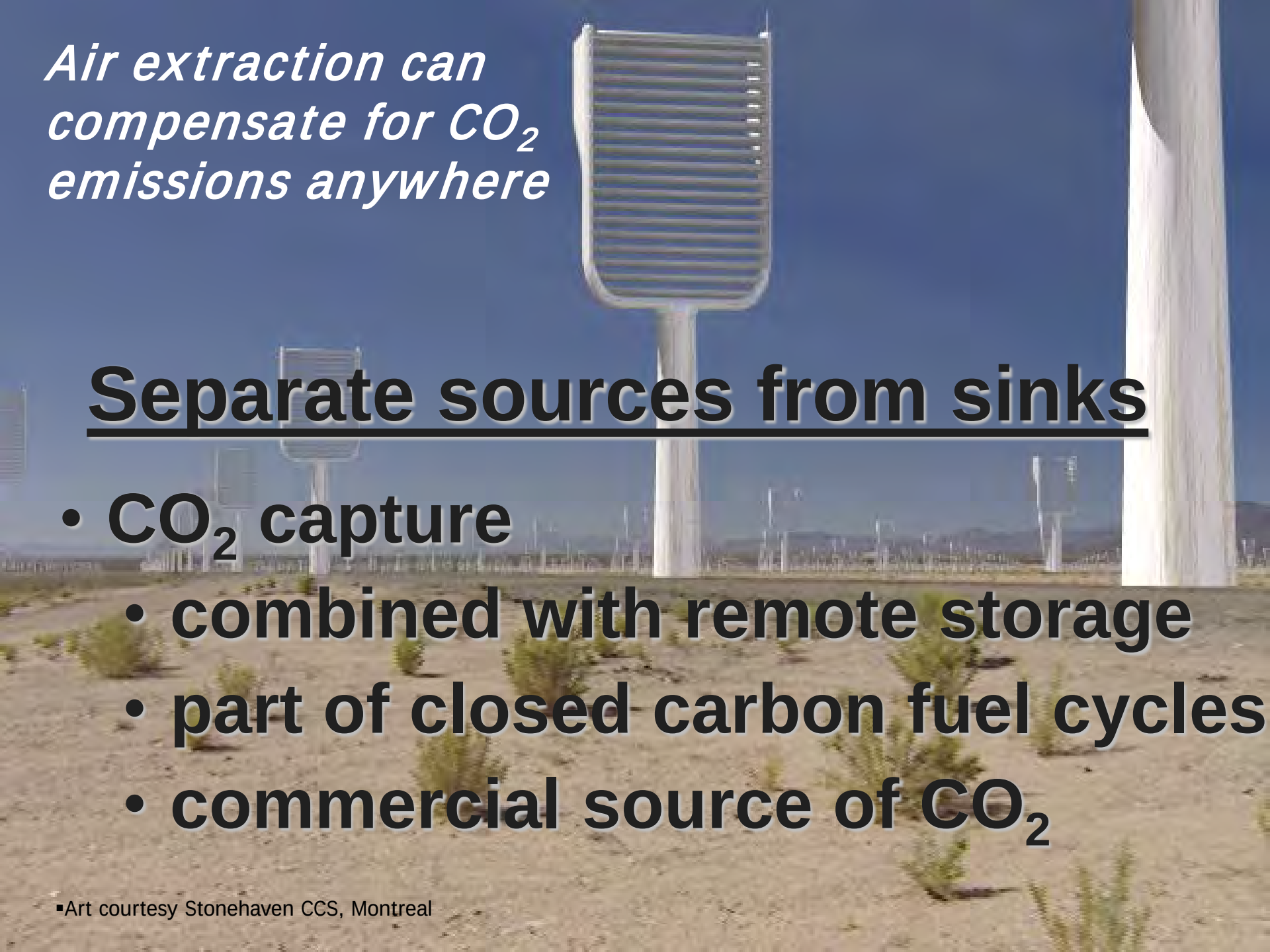
Zero Emission Principle ...



... leads to advanced power plant designs

Boudouard Reaction





Separate sources from sinks

- CO_2 capture
  - combined with remote storage
  - part of closed carbon fuel cycles
  - commercial source of CO_2

▪Art courtesy Stonehaven CCS, Montreal

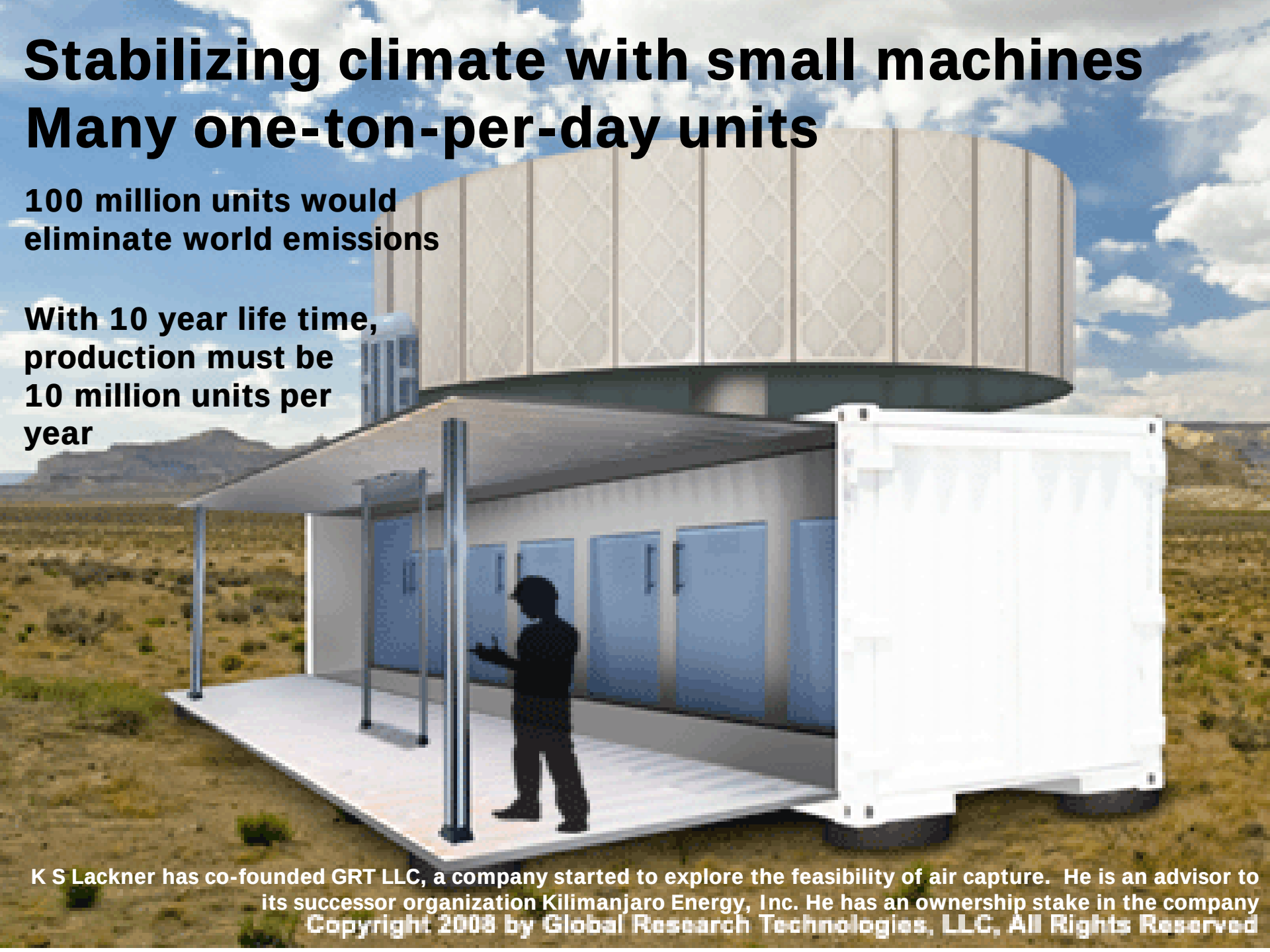
Air capture

- **Air capture for 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 procrastinationn – already too late
  - Ocean will return much of its CO_2
    - (count past fossil fuel emissions not ppm in the air)

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



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

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

For new technologies, low cost comes with experience

$600 Per ton CO_2 — APS (low tech)

$500

$400

$300

GRT (first of a kind)

$200

Current estimates

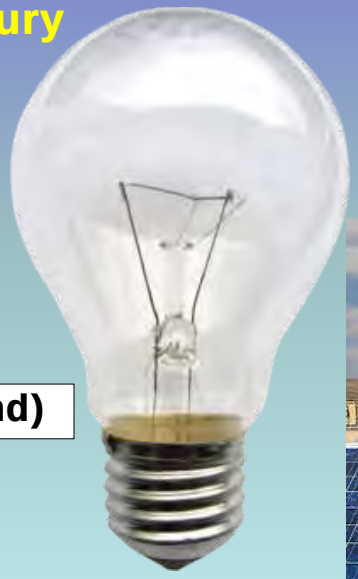
$100

CO_2 enriched air

Raw material and energy limit (frictionless cost)

$0

cost of lighting fell 7000 fold in the 20th century



The power of the learning curve

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

Wikipedia pictures

Technology for abating climate change

- Storage and capture from all sources
- Provide alternatives to geological storage
- Create negative emissions by air capture
- Access remote storage sites by air capture
- Removal from air is a necessity

Think big – there is no alternative