Carbon Capture and Storage
An Overview of Options

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June 2010

Plentiful Sustainable Energy

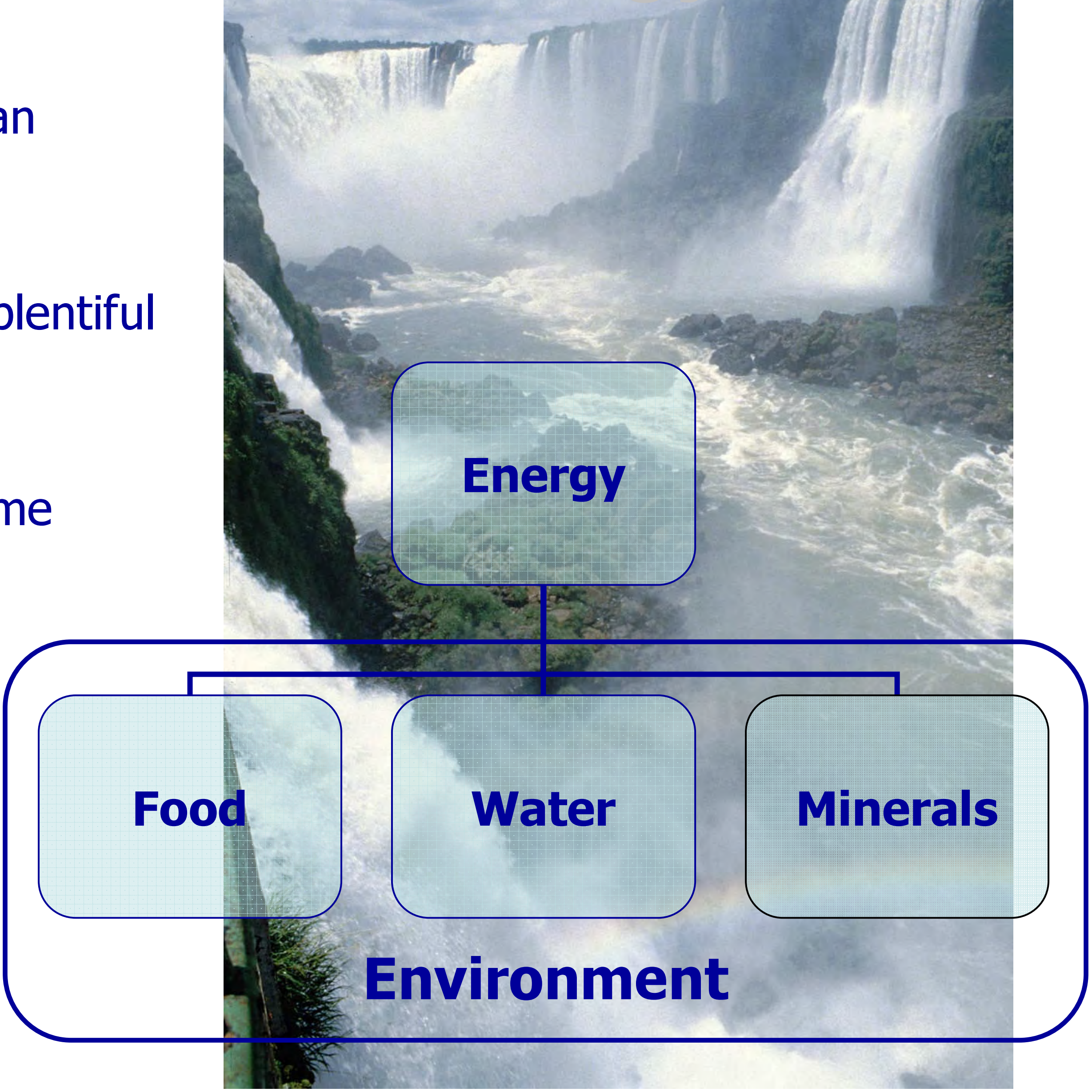
Energy is central to human well-being

World needs affordable, plentiful and clean energy for all

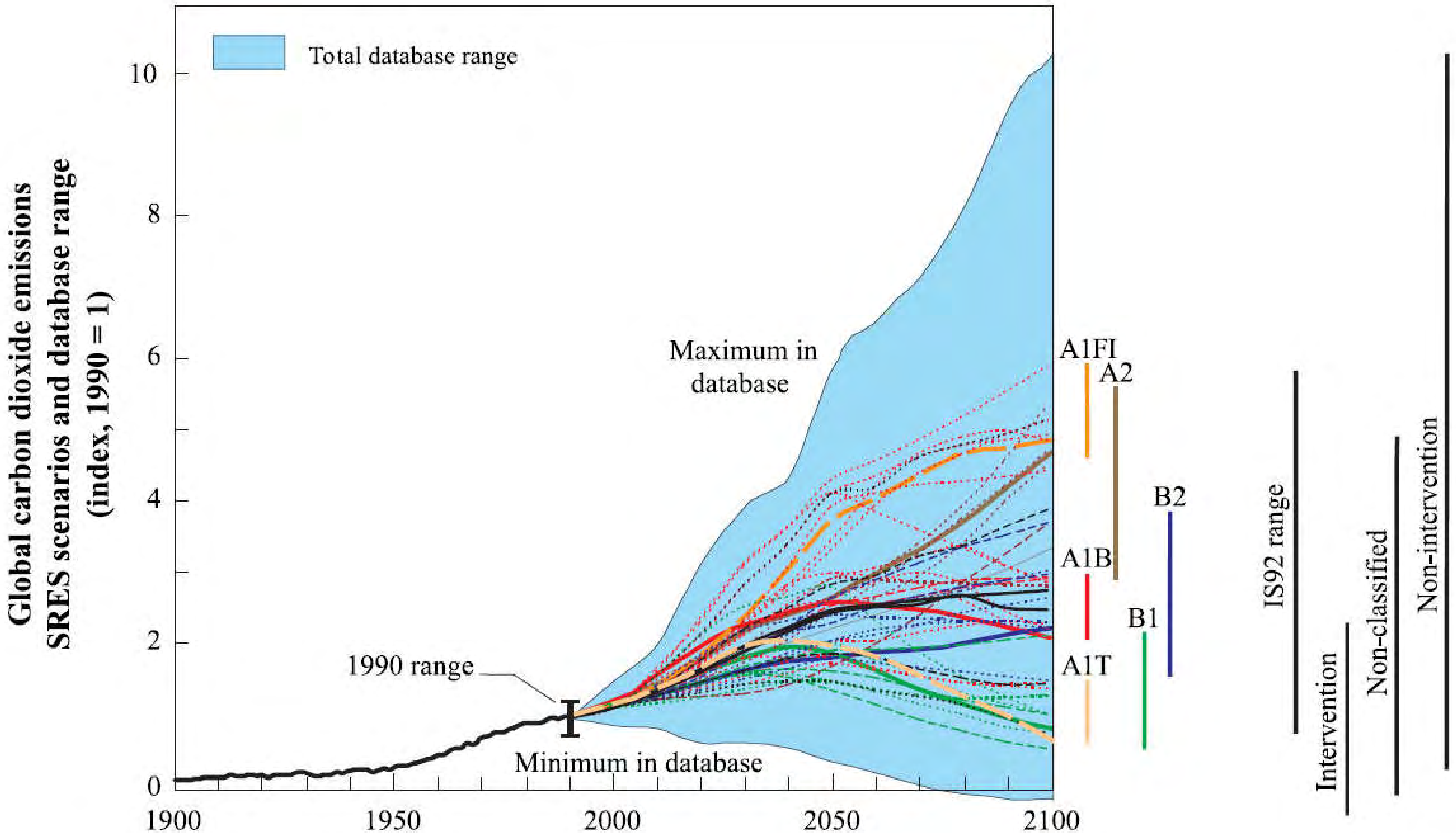
Clean energy can overcome other sustainability limits

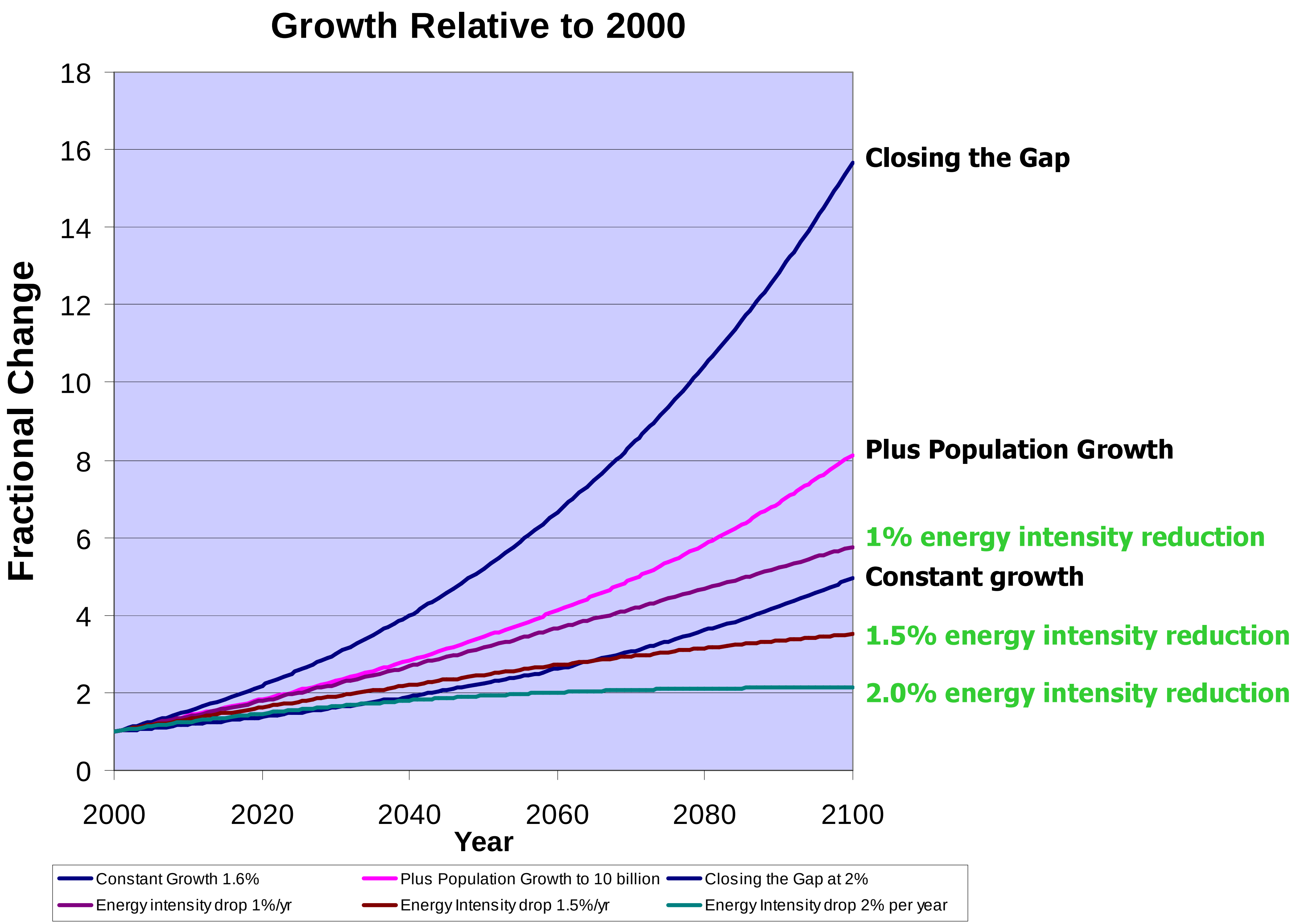
Atmospheric CO_2 level must be stabilized

Fossil carbon is not running out



IPCC Model Simulations of CO_2 Emissions

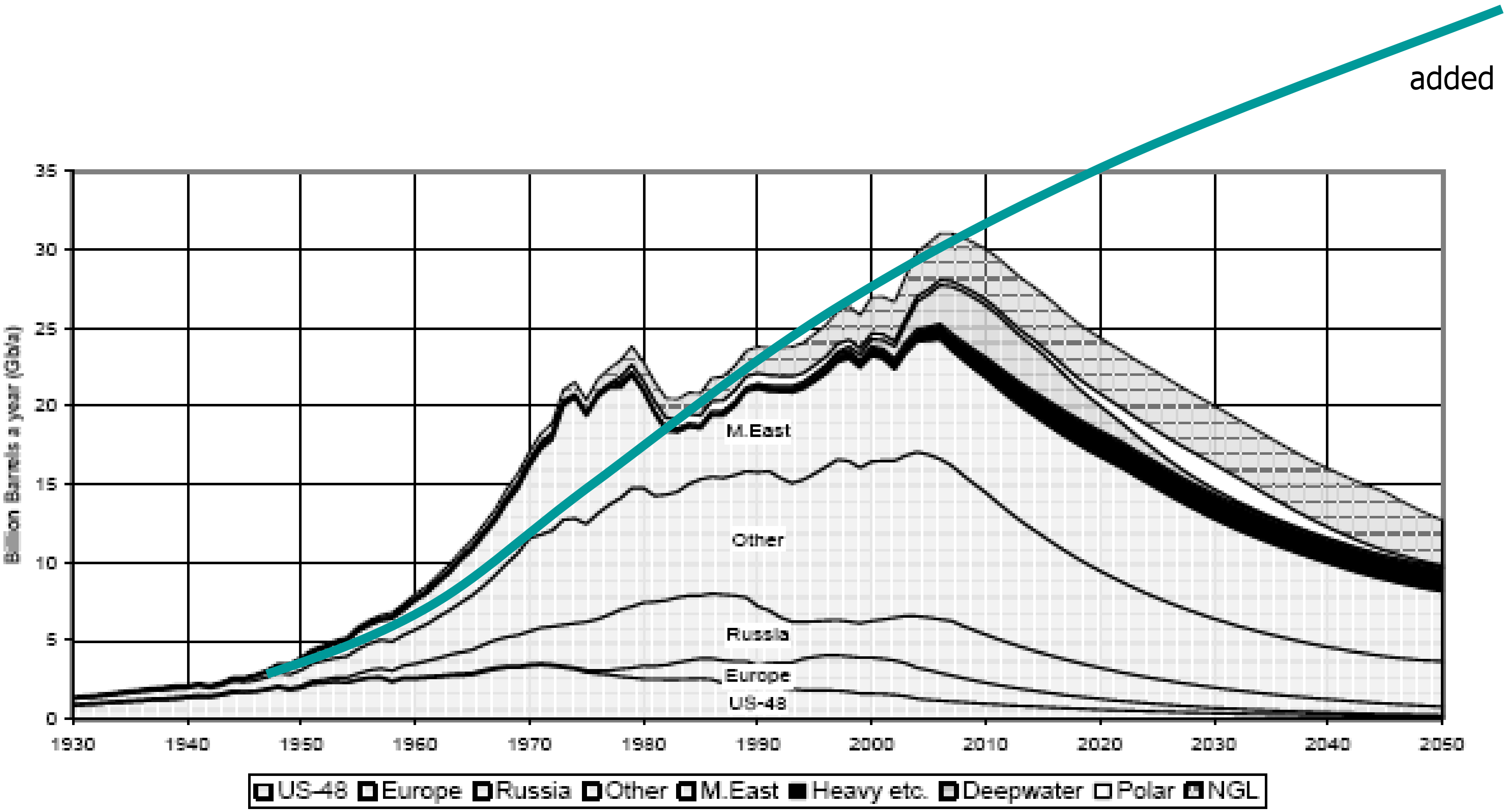



Growth Relative to 2000
Fractional Change
0
2
4
6
8
10
12
14
16
18
2000
2020
2040
2060
2080
2100
Year
Closing the Gap
Plus Population Growth
1% energy intensity reduction
Constant growth
1.5% energy intensity reduction
2.0% energy intensity reduction
Constant Growth 1.6%
Plus Population Growth to 10 billion
Closing the Gap at 2%
Energy intensity drop 1%/yr
Energy Intensity drop 1.5%/yr
Energy Intensity drop 2% per year

Future Energy Demand

- 15 – 100 TW
- 15 TW: Current use is a low end prediction
  - Extreme increases in efficiency
  - Move away from production of physical goods
- 50 TW: Business as usual
  - Large drop in energy intensity (efficiency, and change in activity)
  - No new energy drivers
- 100 TW: Past performance

Hubbert's Peak?



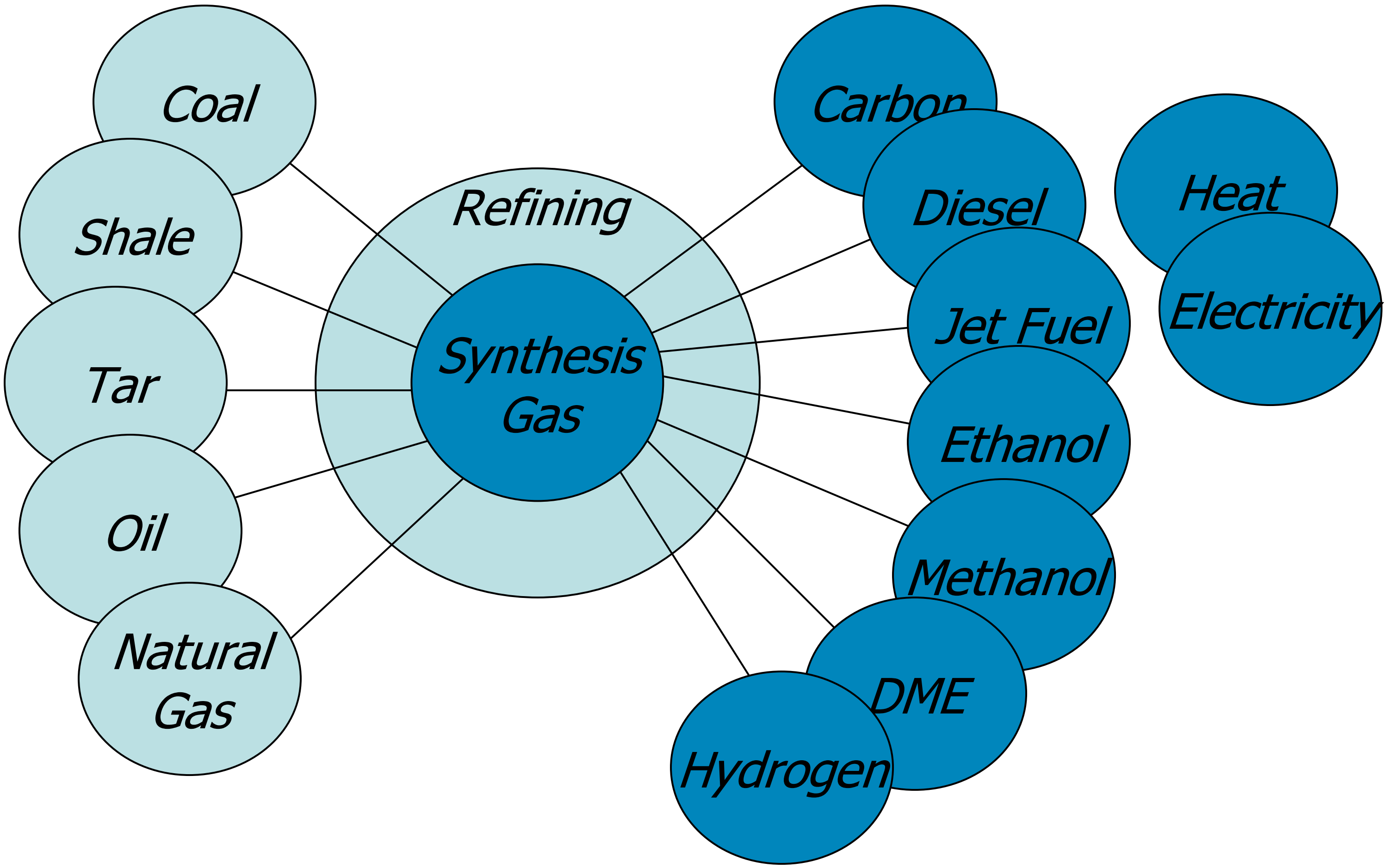
Source: Association for the Study of Peak Oil & Gas Newsletter

Fossil Fuels Are Plentiful

- Coal resources alone could be 3000 to 5000 Gt of carbon
  - 400 Gt consumed since1800
  - annual production of 8 Gt/yr of fossil carbon
- Beware of “resource” vs. “proven reserve”

Curve fitting of past production does not make the known resources go away

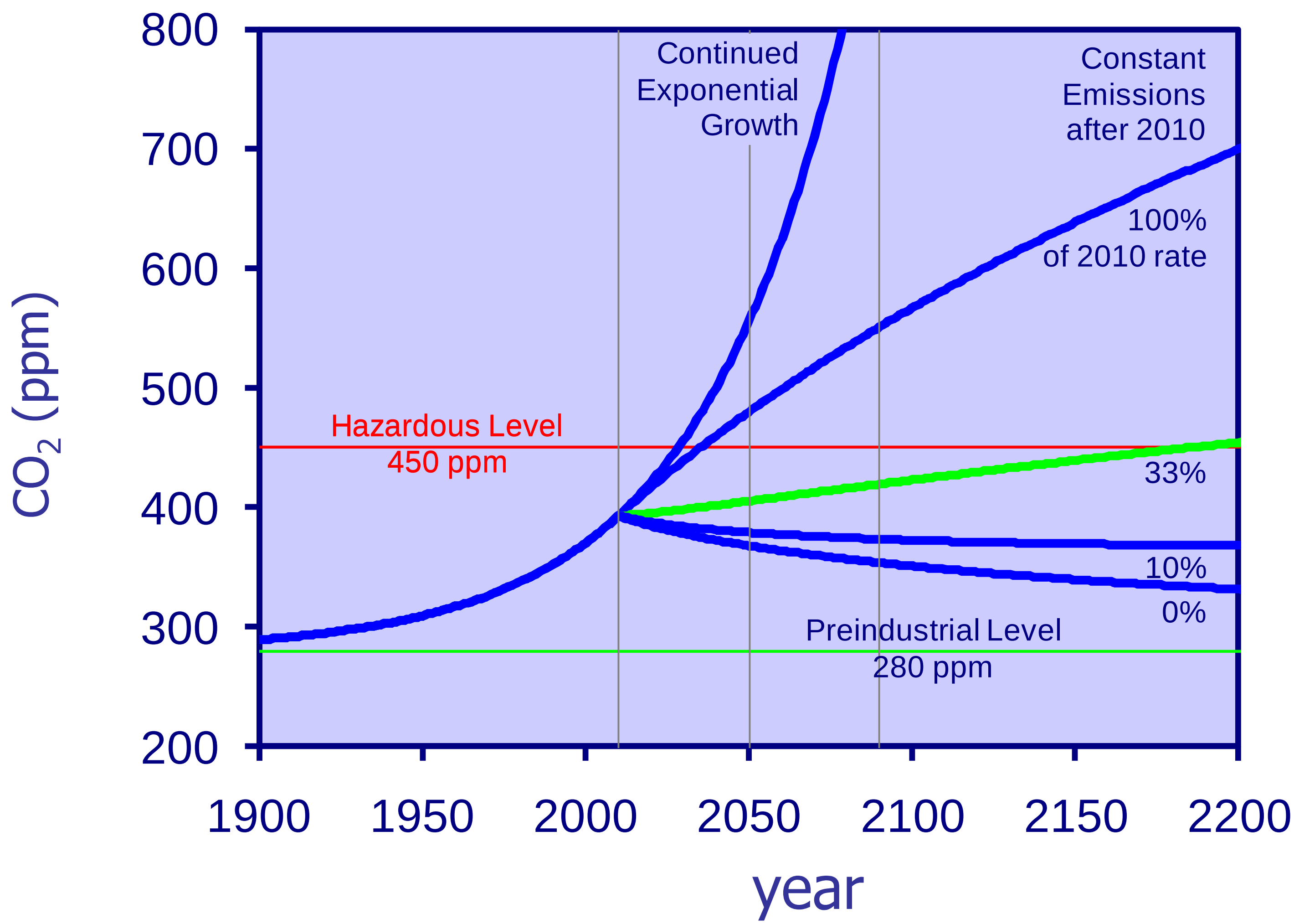
Fossil fuels are fungible …



… and they are not running out

Environmental Limits – Not Resource Limits

Stabilize CO_2 concentration – not CO_2 emissions



The Big Three Energy Options

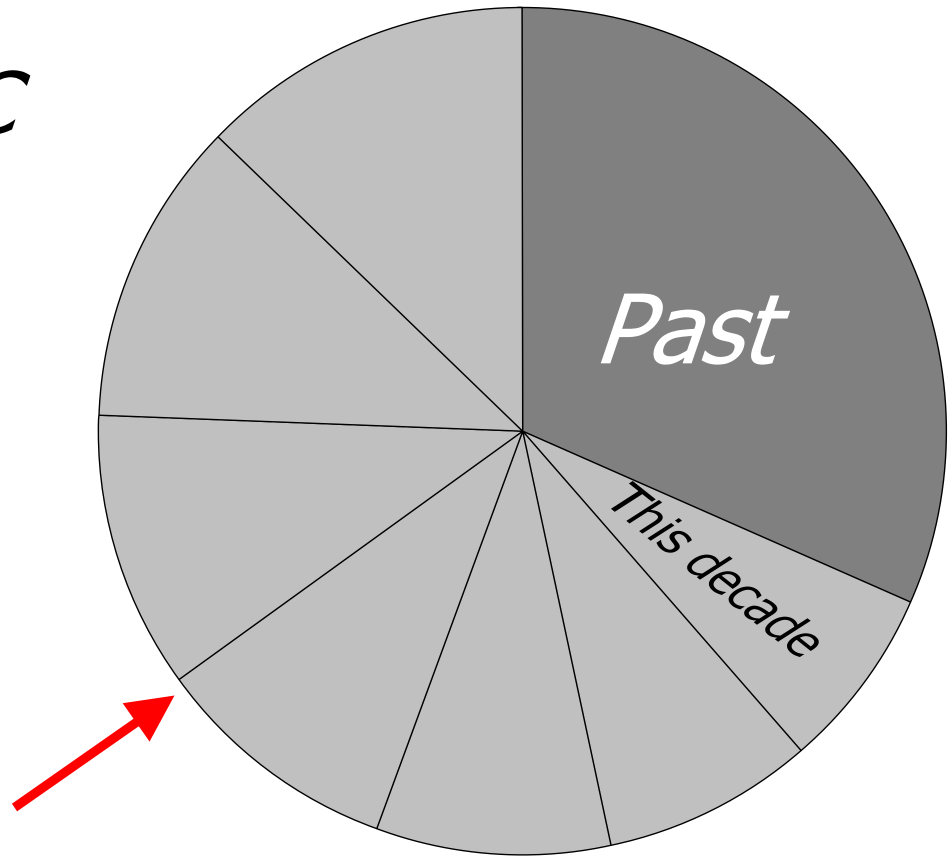
Cost effective options, but not at full scale

Without Carbon Capture and Storage fossil fuels will have to be phased out

Dividing The Fossil Carbon Pie

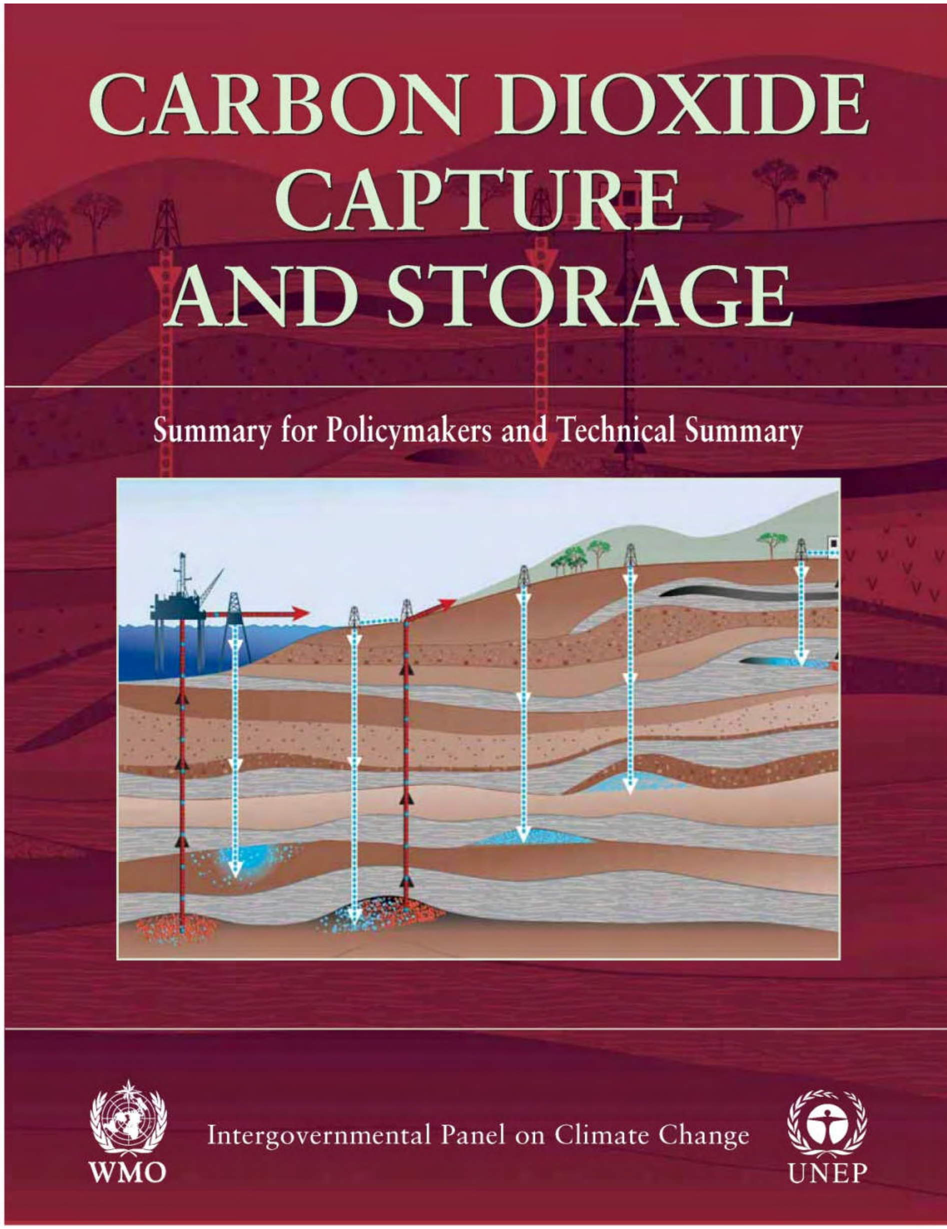
900 Gt C

total

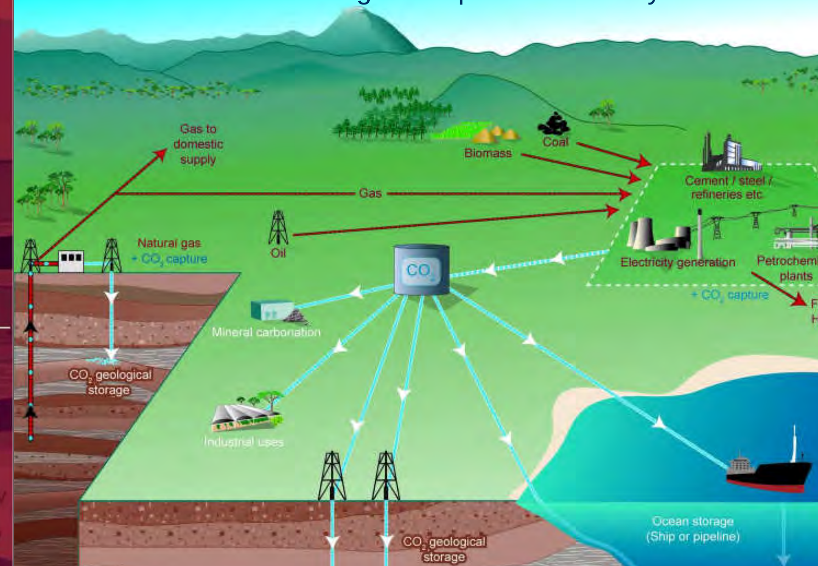


1 trillion tons

550 ppm

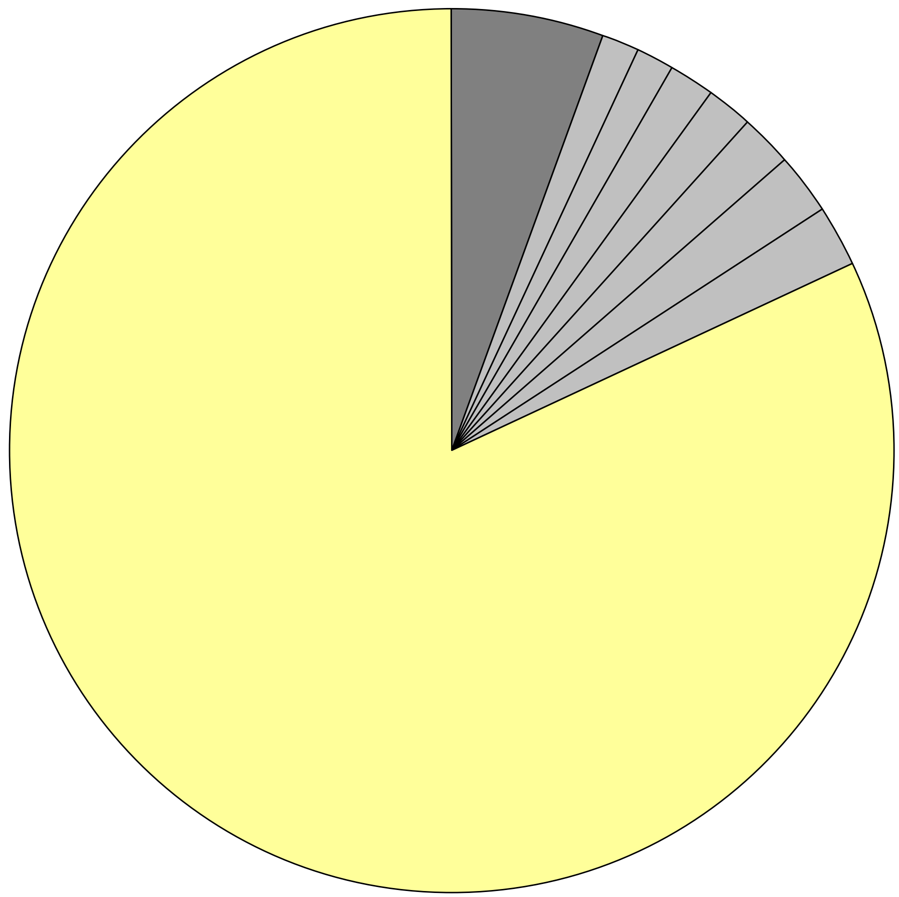


Schematic diagram of possible CCS systems



Removing the Carbon Constraint

5000 Gt C total



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

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Many Different Options

- Flue gas scrubbing – retrofit
  - MEA, ammonia, chilled ammonia, …
- Oxyfuel Combustion – retrofit and new
  - Naturally zero emission
- Integrated Gasification Combined Cycle – new plant
  - Difficult as zero emission
- AZEP Cycles – innovative design
  - Mixed Oxide Membranes
- Fuel Cell Cycles – innovative design
  - Solid Oxide Membranes

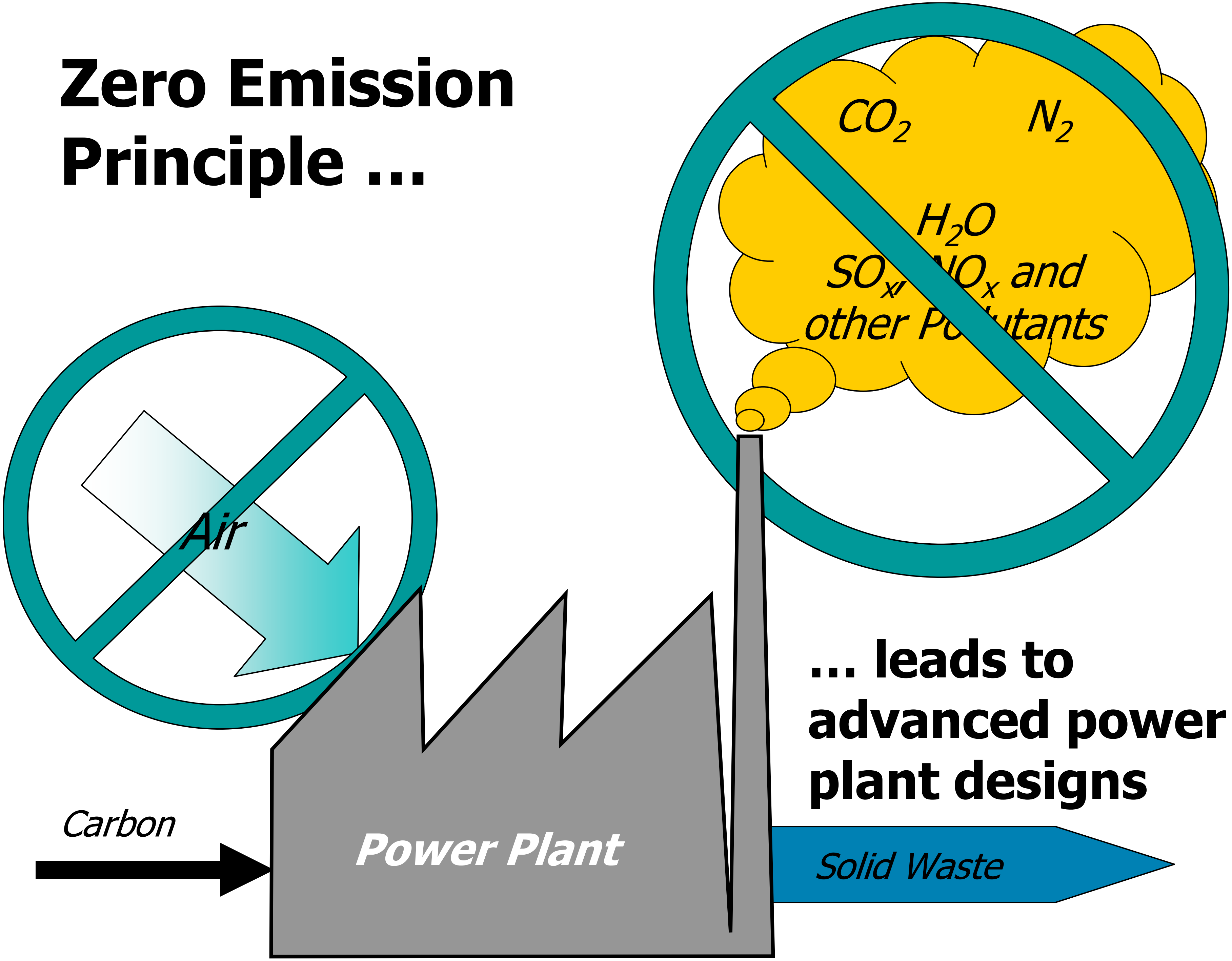
Problem needs solutions on many different timescales

Collecting CO_2 at High Efficiency

- Integration rather than flue gas scrubbing
- CO_2 capture enables zero emission
- Fossil fuels are energy ores
- Power plants refine the ore
- Cost of sequestration will drive efficiency

60% to 80% conversion efficiency

Zero Emission Principle …



… leads to advanced power plant designs

Carbon makes a better fuel cell

$C + O_2 \rightarrow CO_2$

no change in mole volume

entropy stays constant

$\Delta G = \Delta H$

$2H_2 + O_2 \rightarrow 2H_2O$

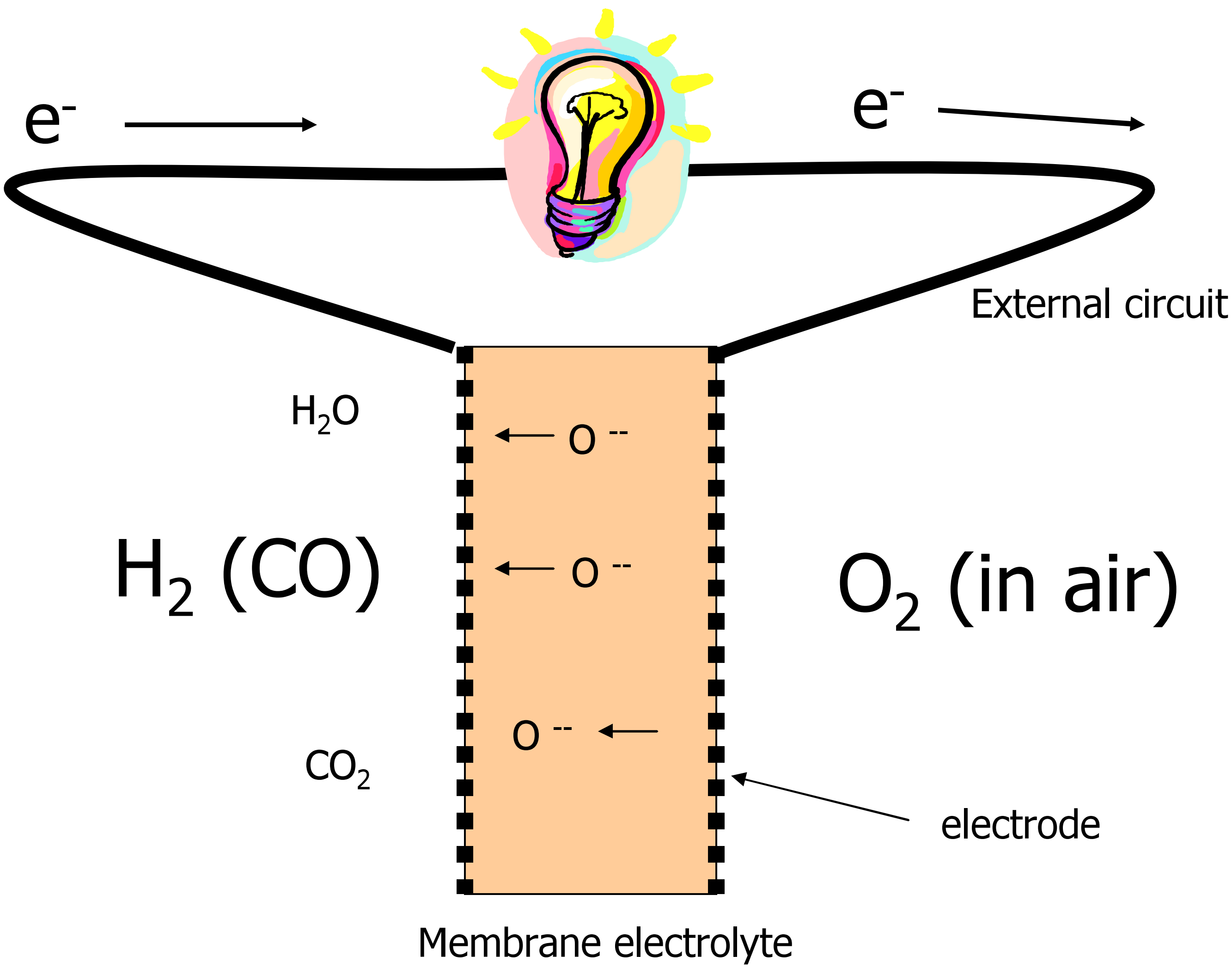
large reduction in mole volume

entropy decreases in reactants

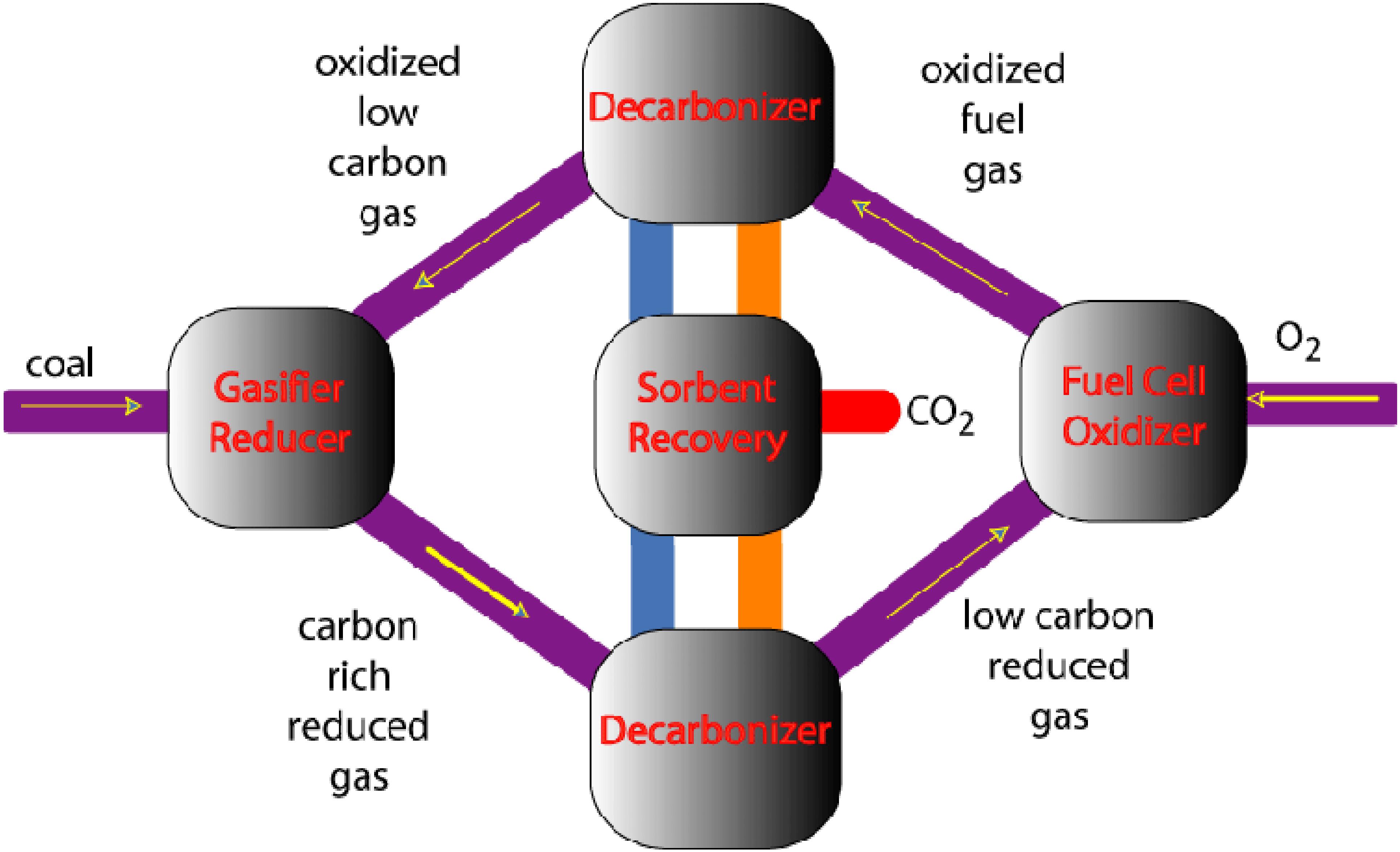
made up by heat transfer to surroundings

$\Delta G < \Delta H$

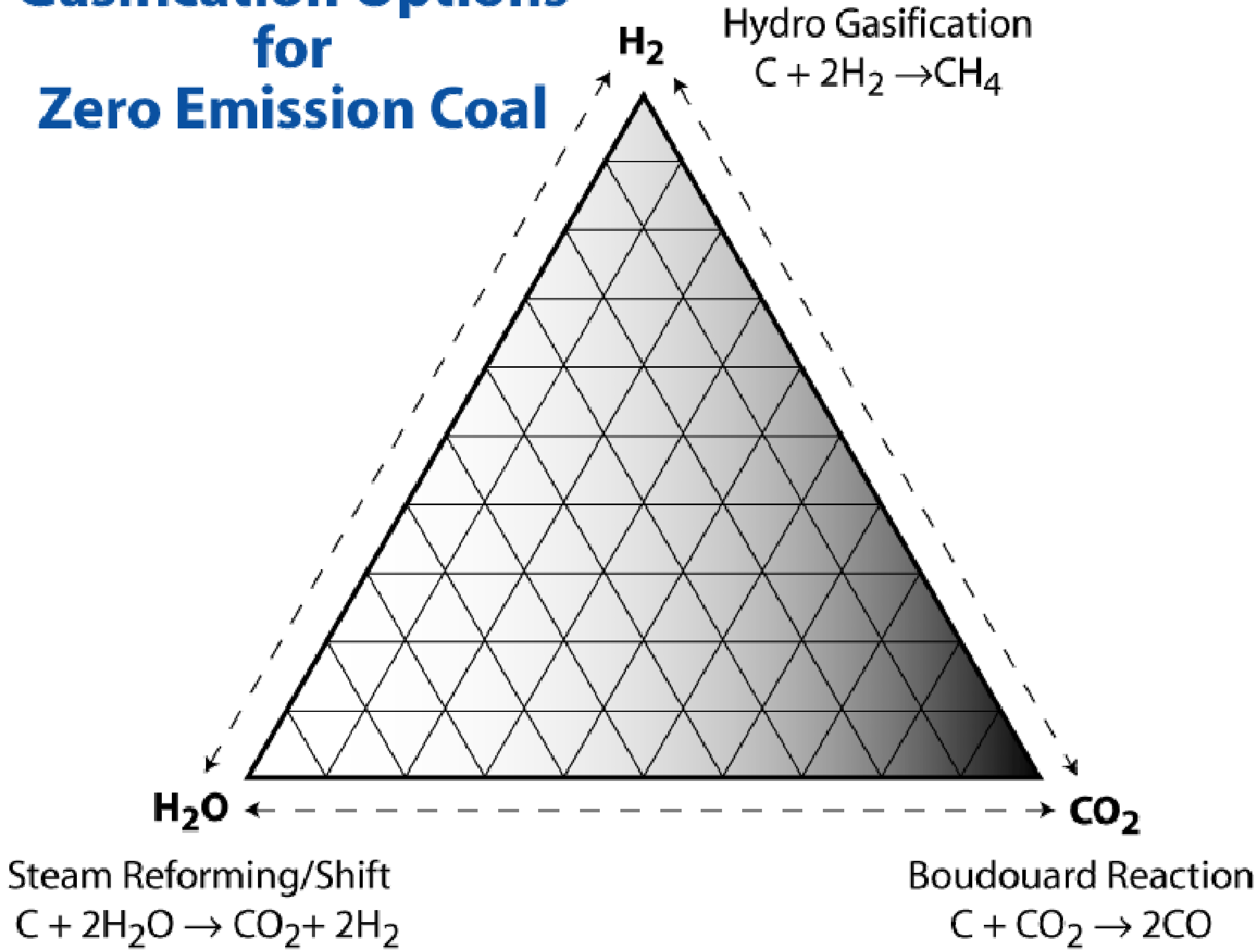
A Solid Oxide Fuel Cell



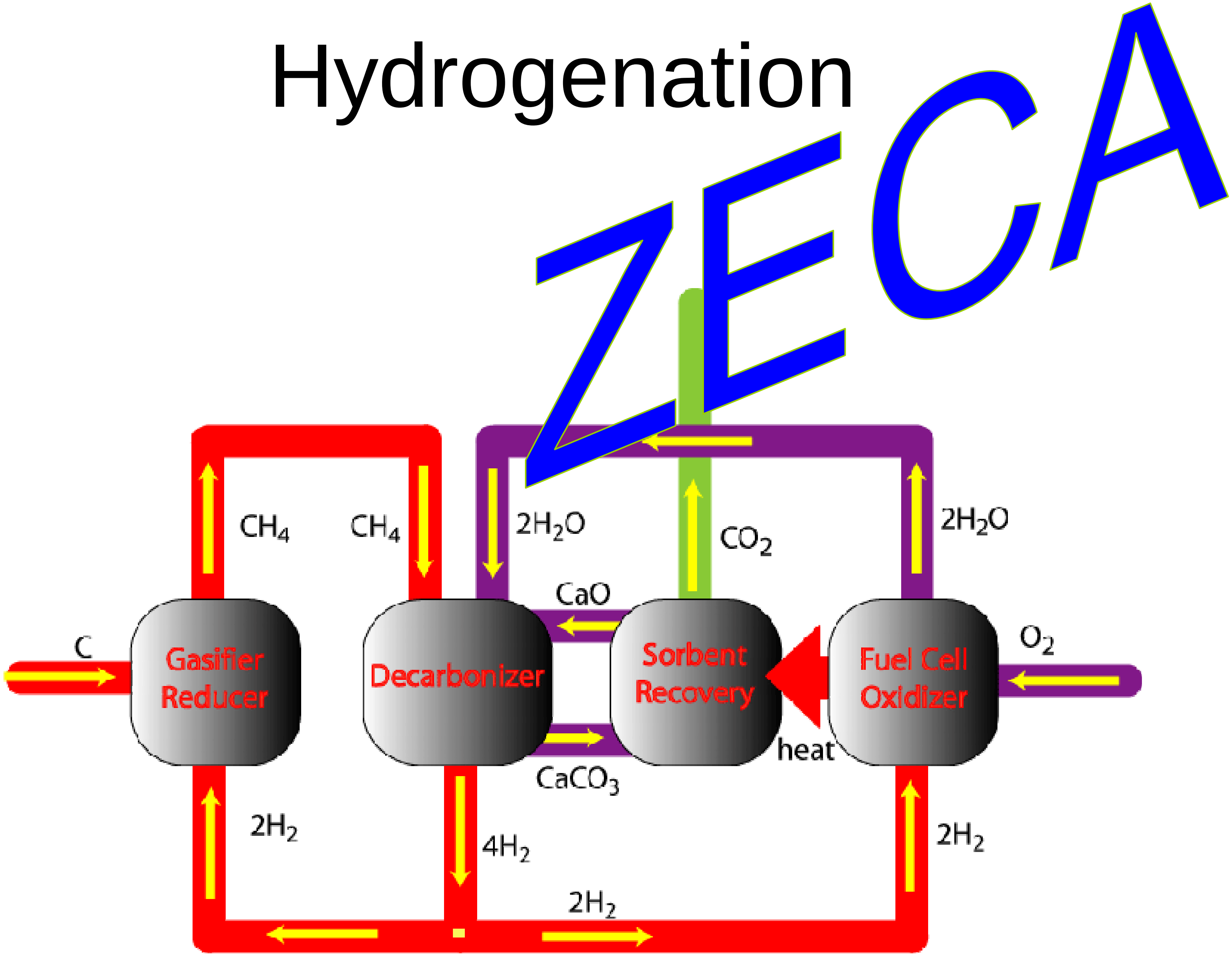
Advanced Zero Emission Power Plants



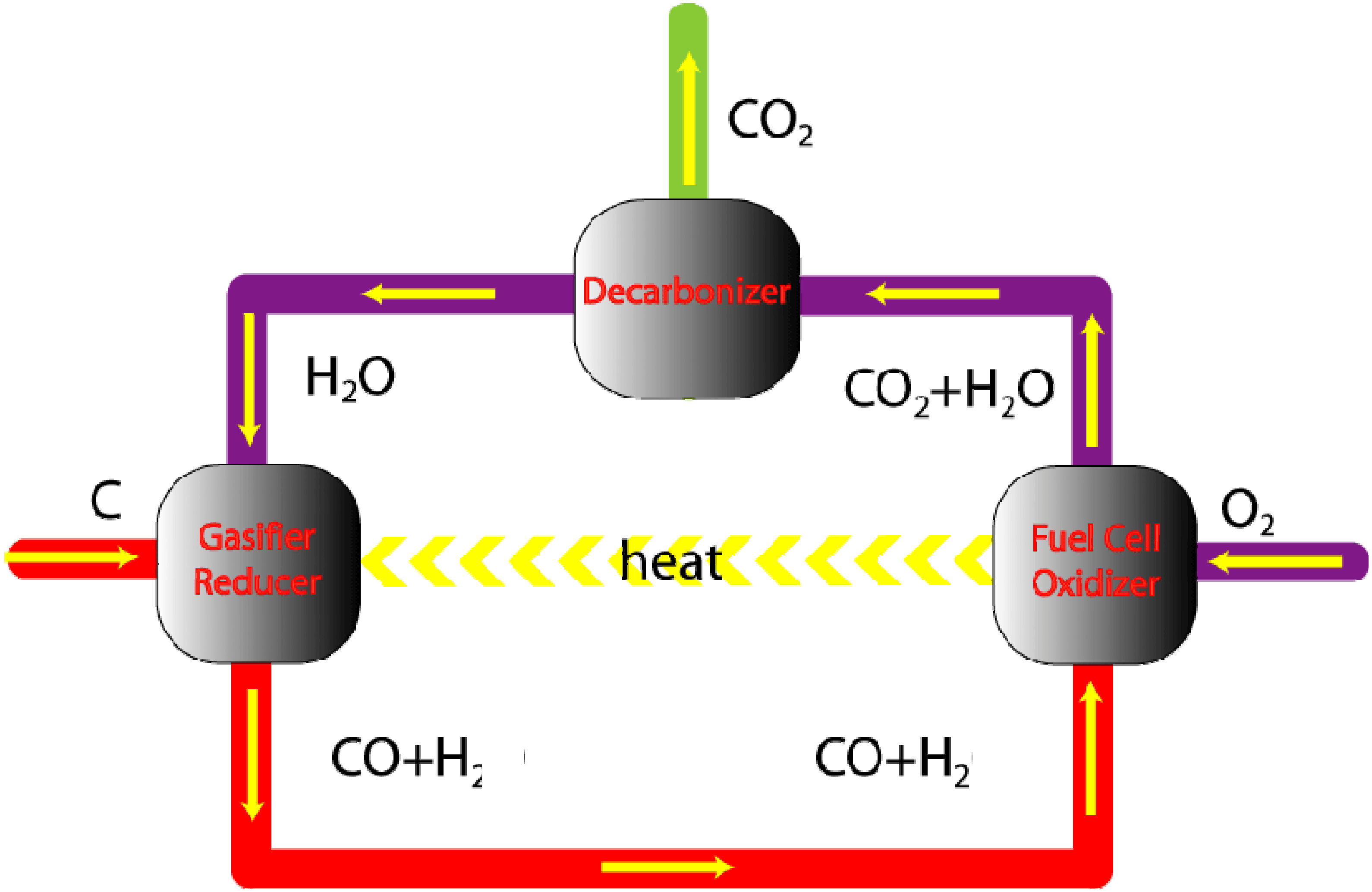
Gasification Options for Zero Emission Coal



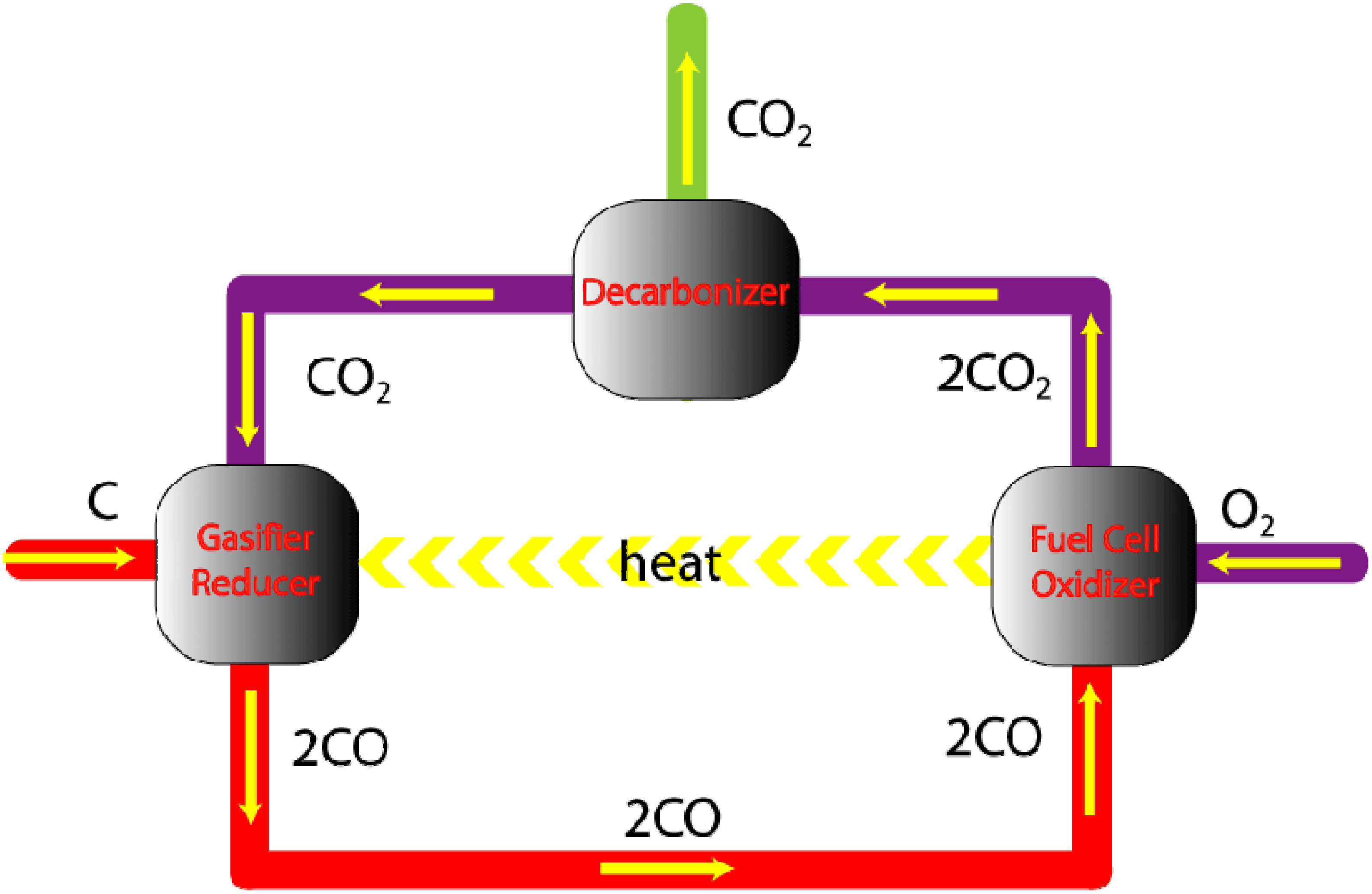
Hydrogenation



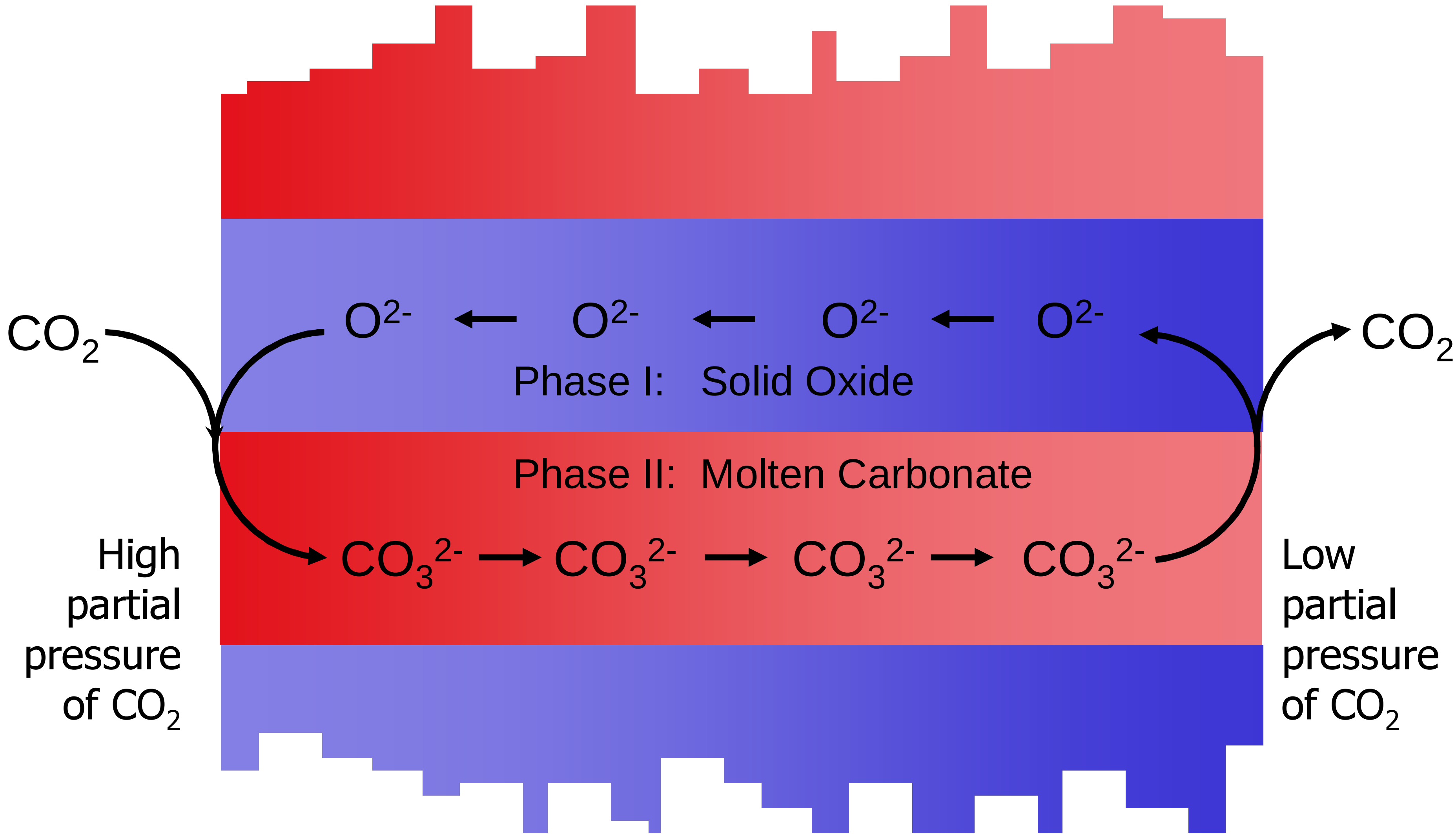
Steam Reforming



Boudouard Reaction

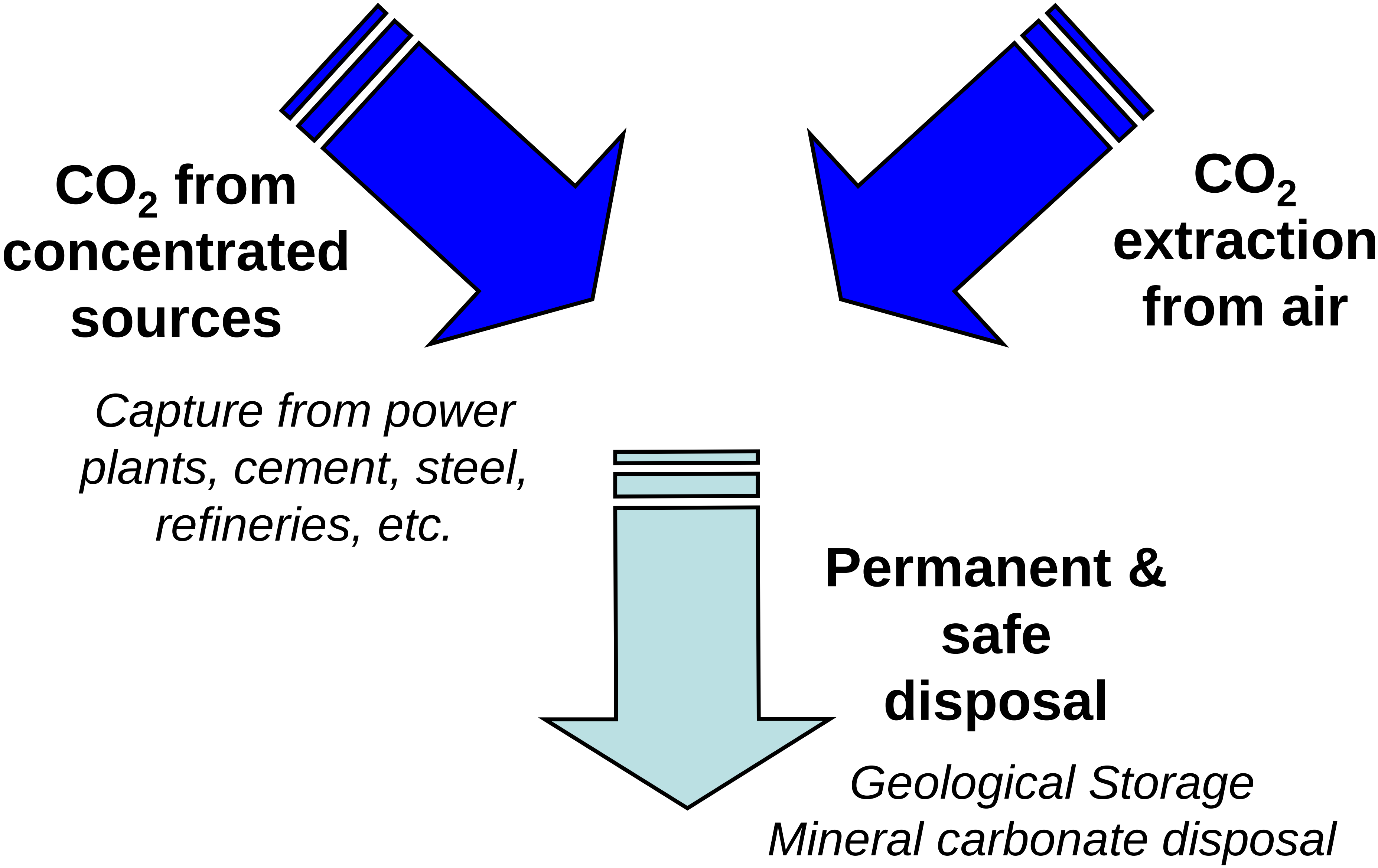


CO_2 Membrane



Jennifer Wade

Net Zero Carbon Economy



Limited Options - Large Scale

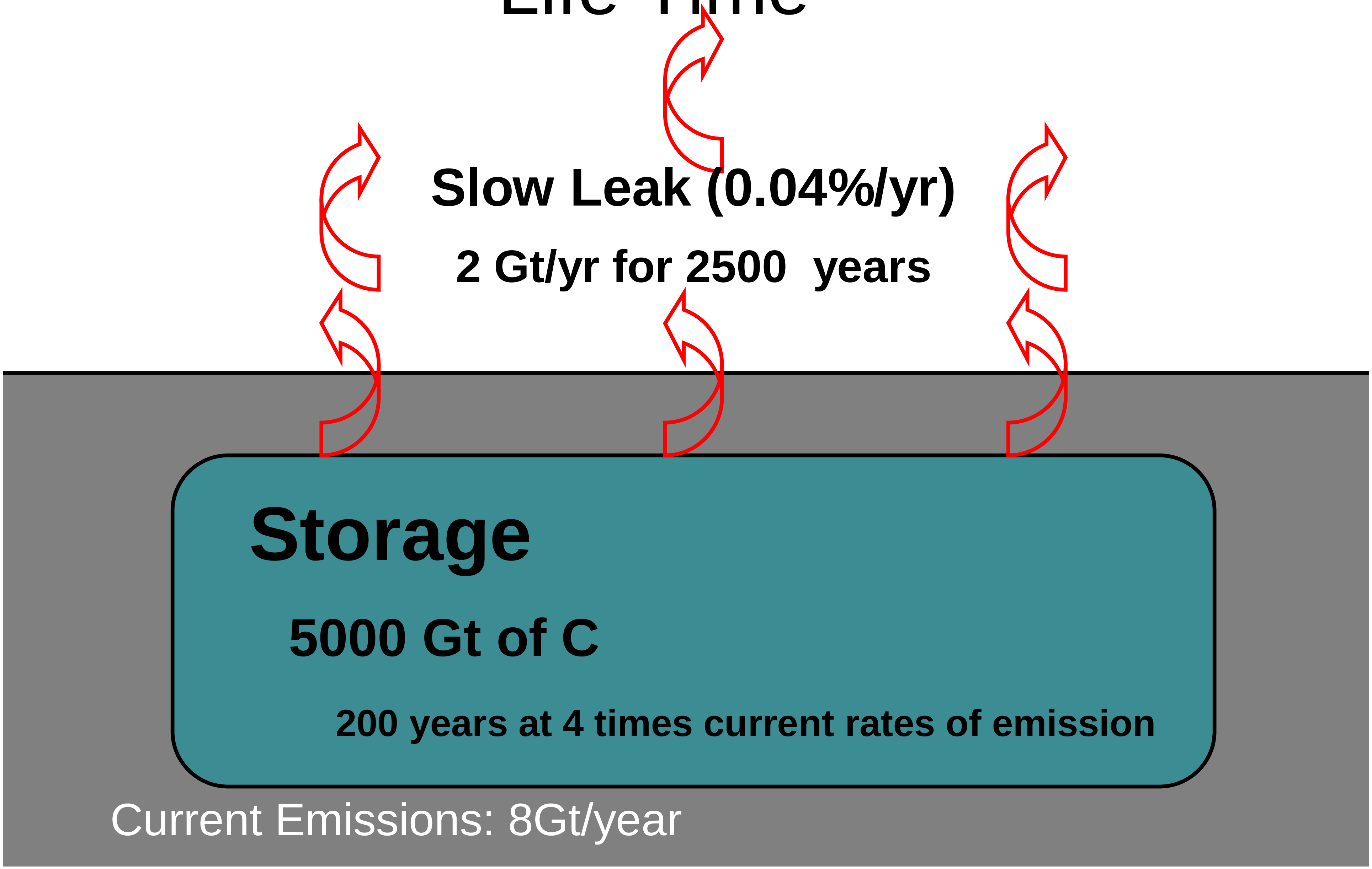
- **Geological Storage**
- **Mineral Sequestration**
- **Ocean Disposal**
- **Bio-Sequestration**

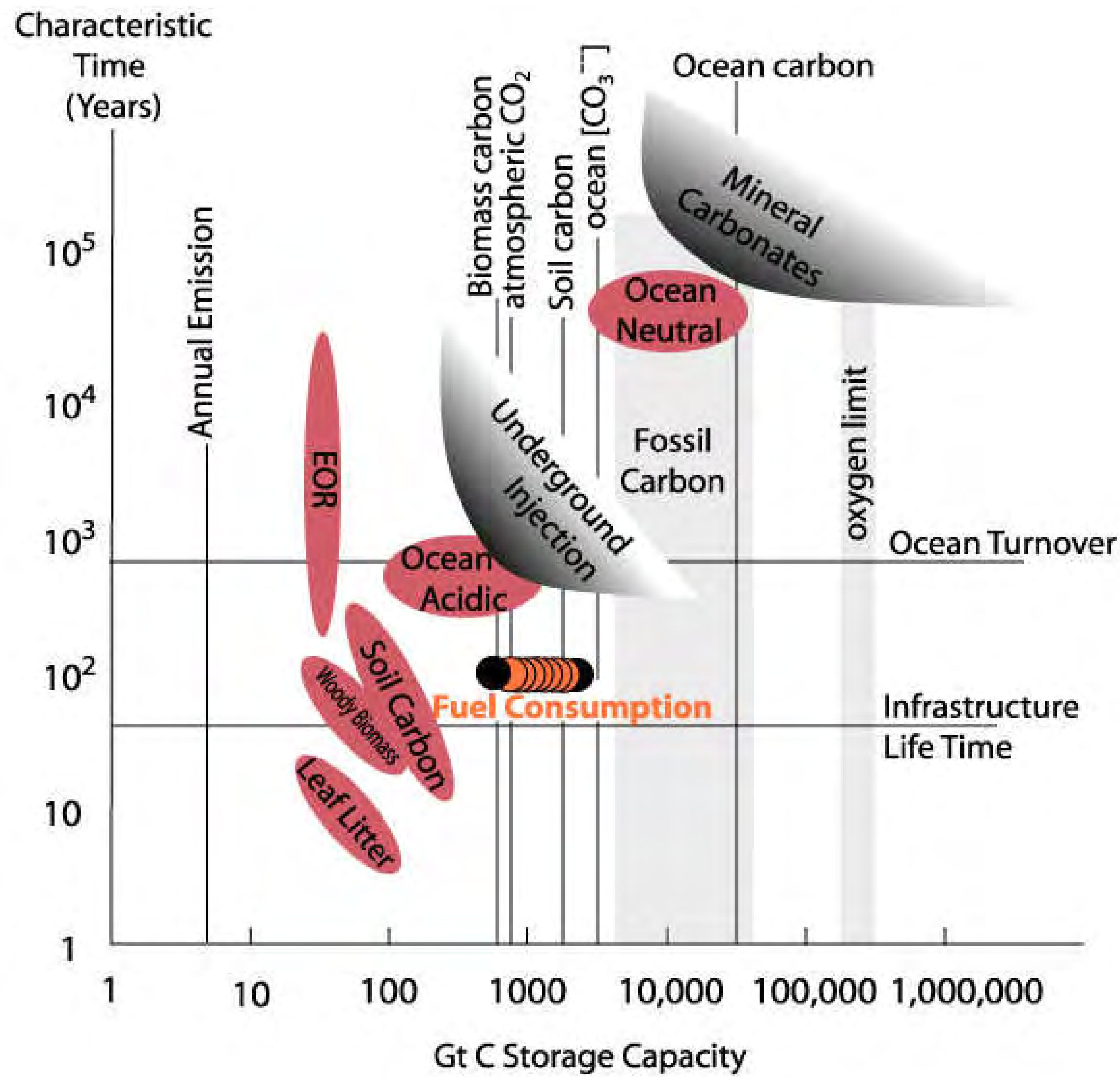
Disposal is the most difficult part of CCS

Lake Michigan

21^{st} century carbon dioxide emissions could exceed the mass of water in Lake Michigan

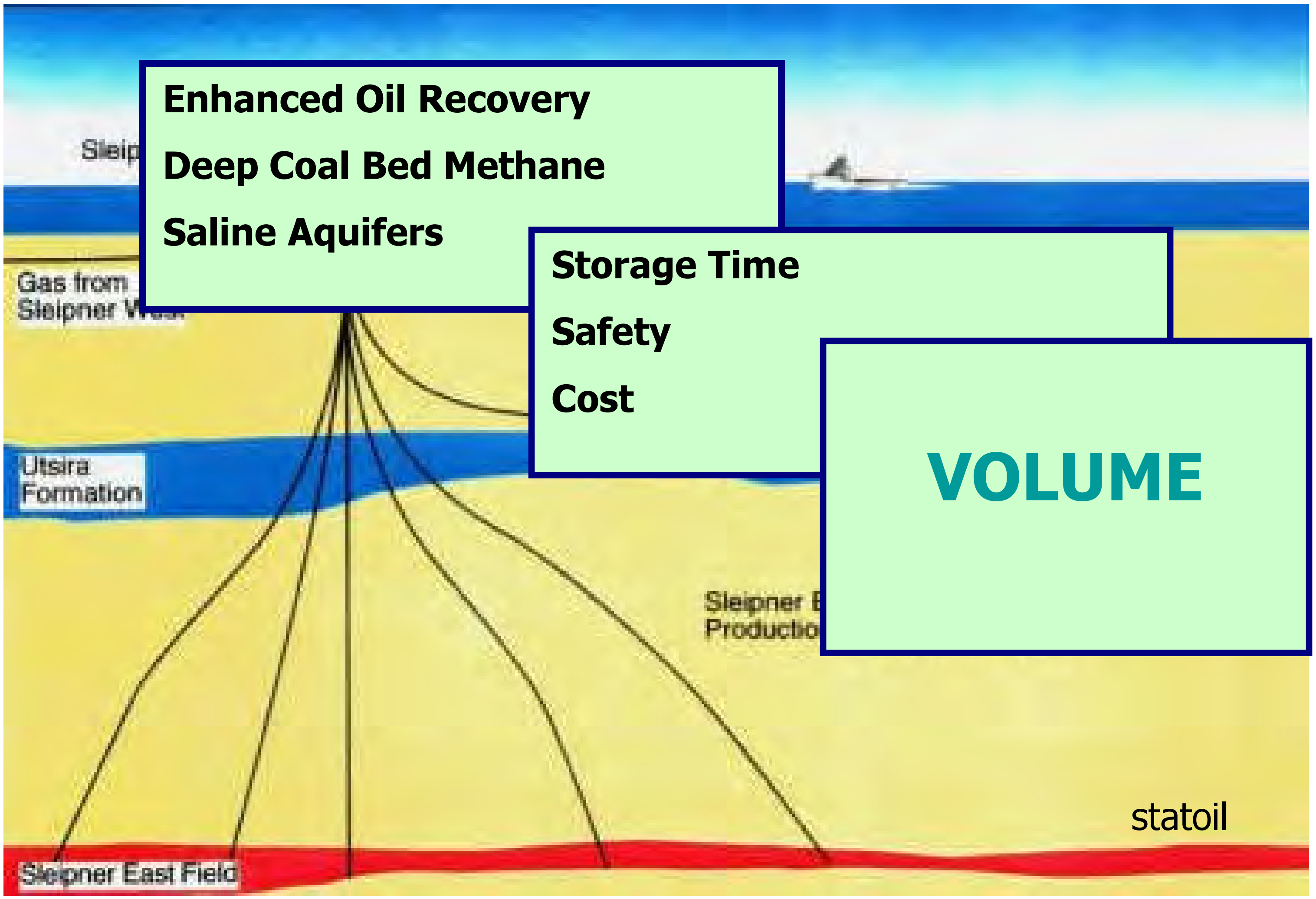
Storage
Life Time





Characteristic
Time
(Years)
10^5
10^4
10^3
10^2
10
1
1
10
100
1000
10,000
100,000
1,000,000
Gt C Storage Capacity
Annual Emission
EOR
Biomass carbon
atmospheric CO2
Soil carbon
ocean [CO3--]
Ocean carbon
Mineral Carbonates
Ocean Neutral
Underground Injection
Fossil Carbon
oxygen limit
Ocean Turnover
Ocean Acidic
Soil Carbon
Woody Biomass
Leaf Litter
Fuel Consumption
Infrastructure
Life Time

Underground Injection



- **Enhanced Oil Recovery**
- **Deep Coal Bed Methane**
- **Saline Aquifers**

- **Storage Time**
- **Safety**
- **Cost**

VOLUME

Standard Technology

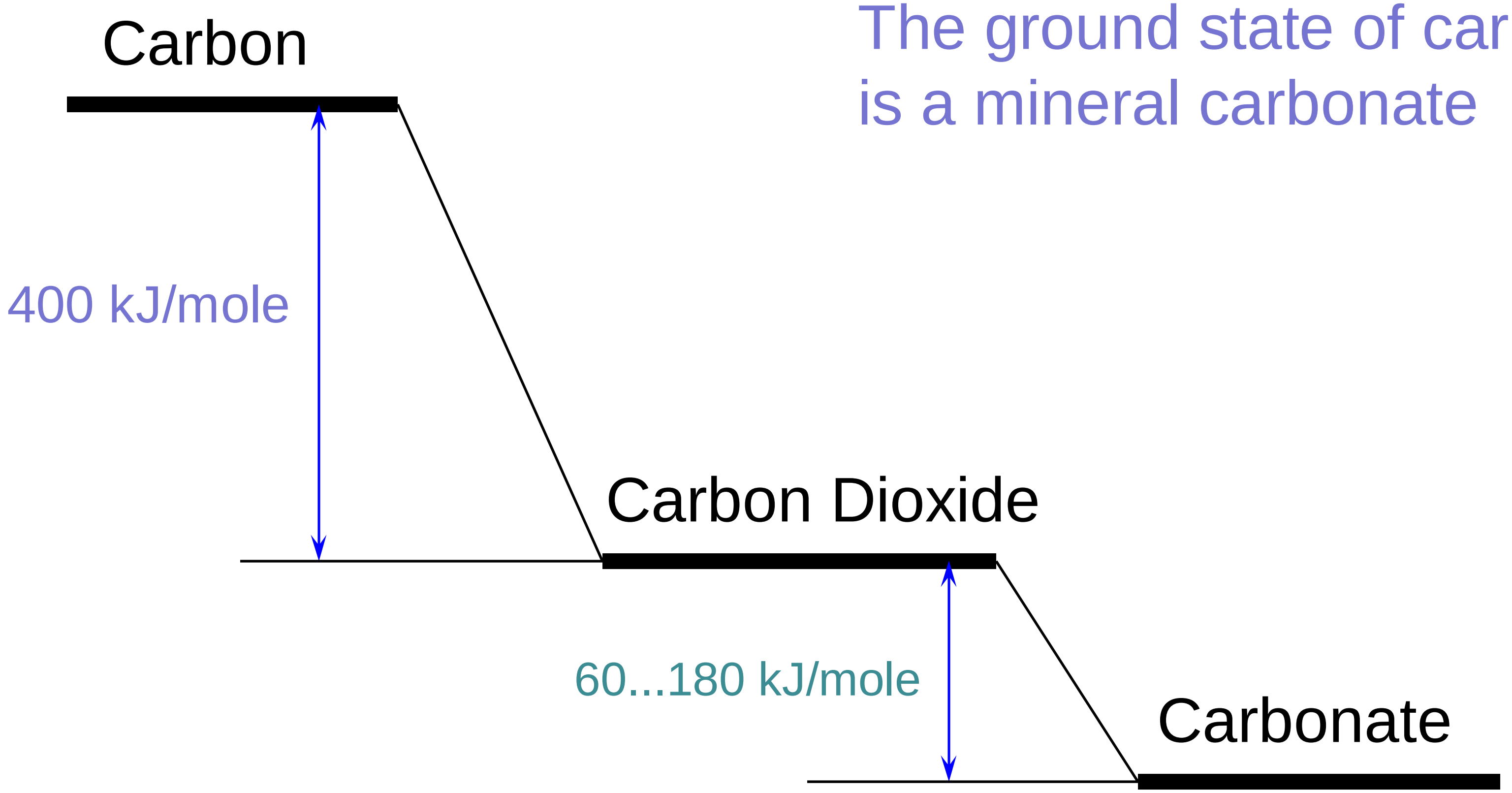
- Conventional drilling
- Based on conventional reservoir engineering
- Practical experience in enhanced oil recovery
- Well explored, successful sites:
  – Sleipner, Weyburn, In Salah, West Texas …

Issues with geological storage

- Loss rate
- Safety and monitoring
- Accounting and monitoring
- Managing huge injection volumes

Energy States of Carbon

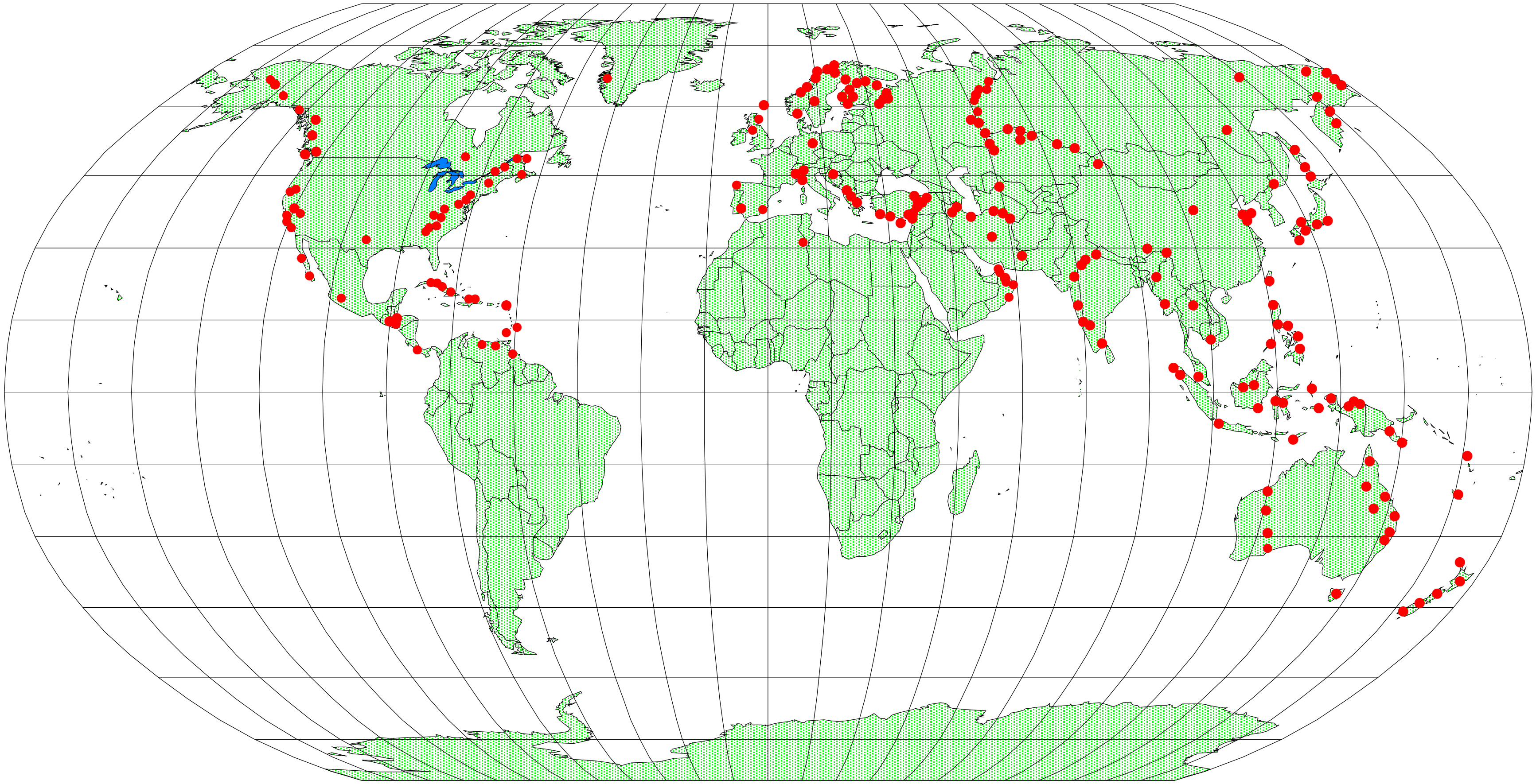
The ground state of carbon is a mineral carbonate



Serpentine and Olivine are decomposed by acids

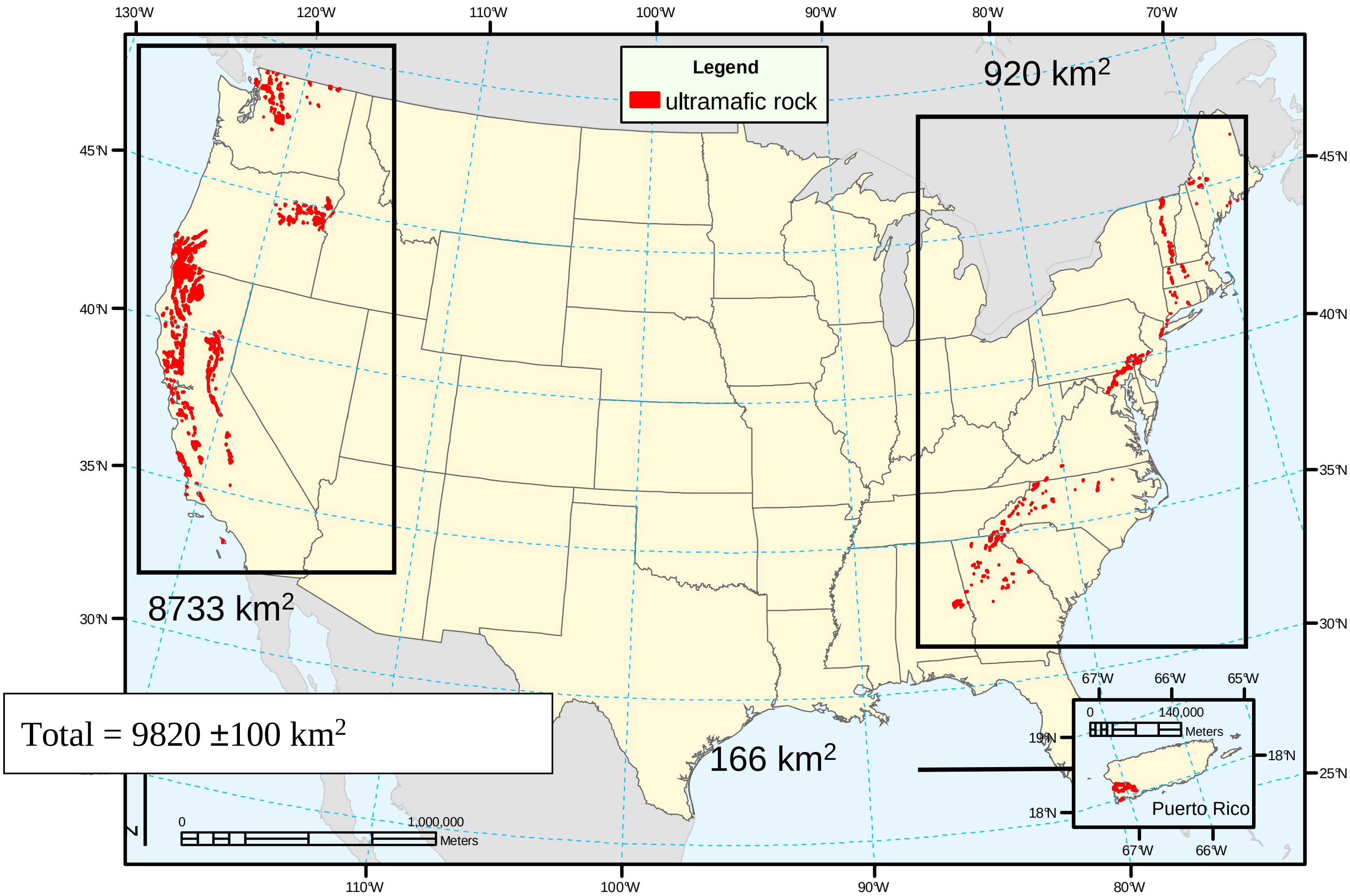
- Carbonic Acid - Requires Pretreatment
- Chromic Acid
- Sulfuric Acid, Bisulfates
- Oxalic Acid
- Citric Acid
- …

Peridotite and Serpentinite Ore Bodies

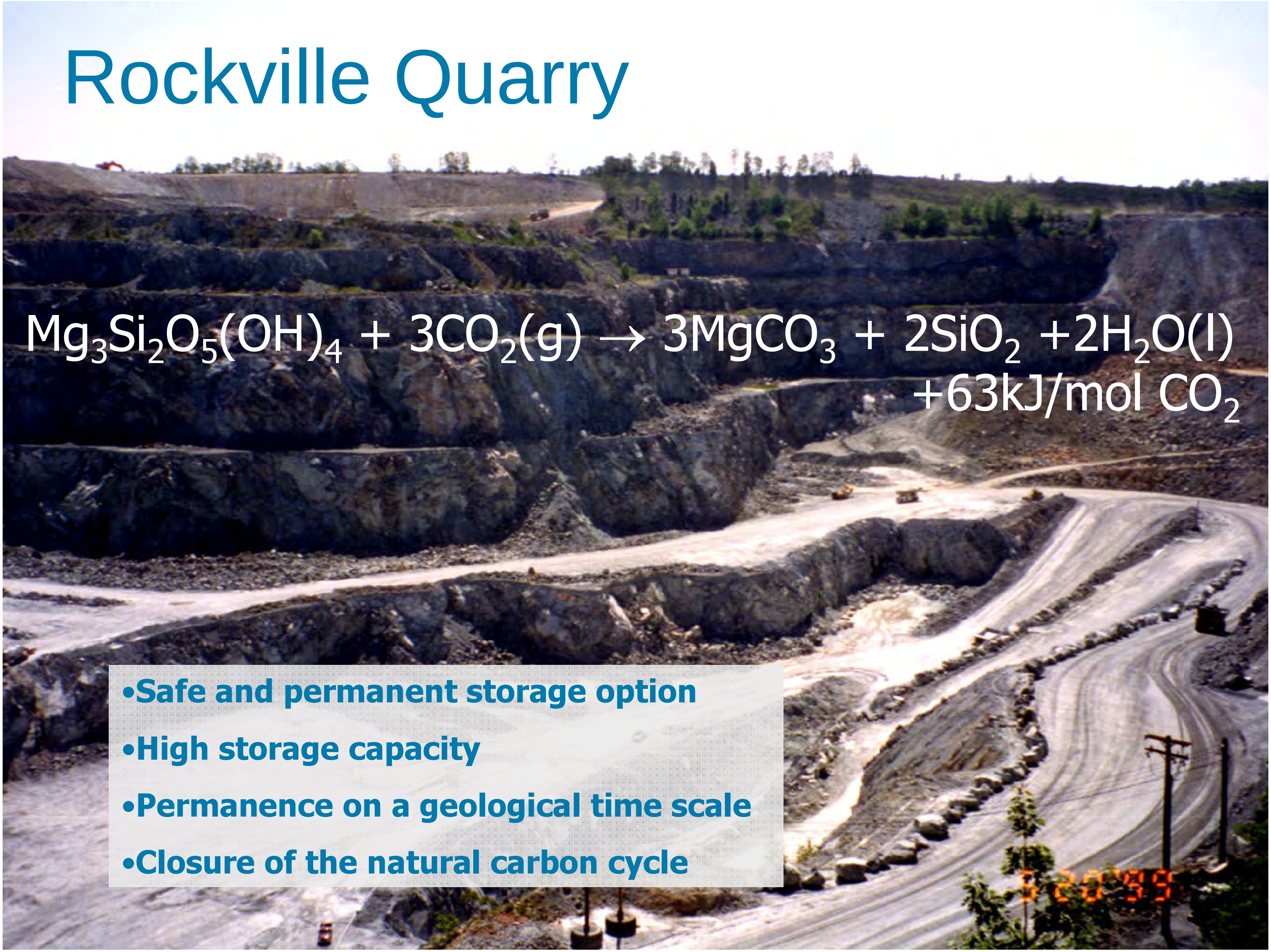


Magnesium resources that far exceed world fossil fuel supplies

Bedrock geology GIS datasets – All U.S. (Surface area)



Rockville Quarry



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

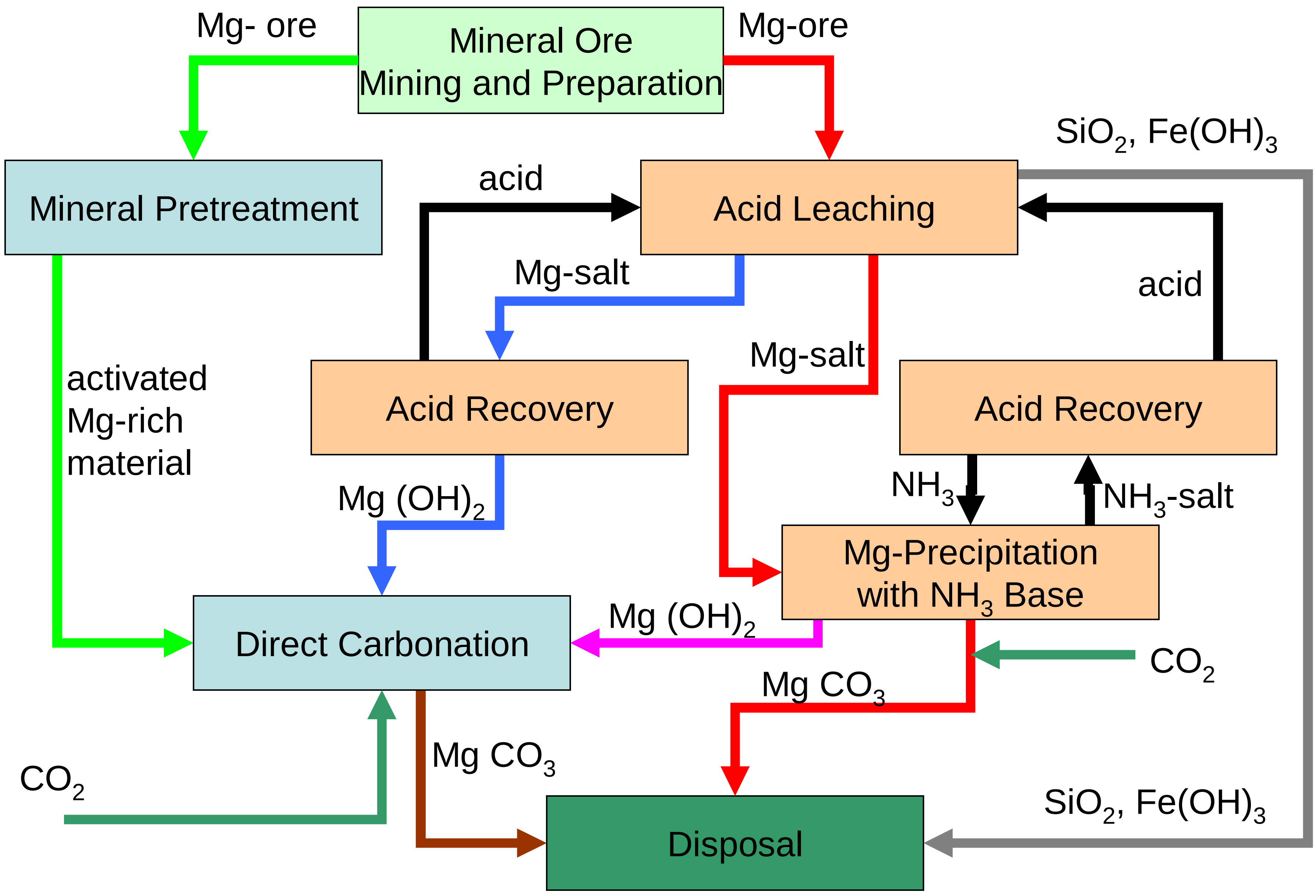
- **Safe and permanent storage option**
- **High storage capacity**
- **Permanence on a geological time scale**
- **Closure of the natural carbon cycle**


Belvidere Mountain, Vermont
Serpentine Tailings

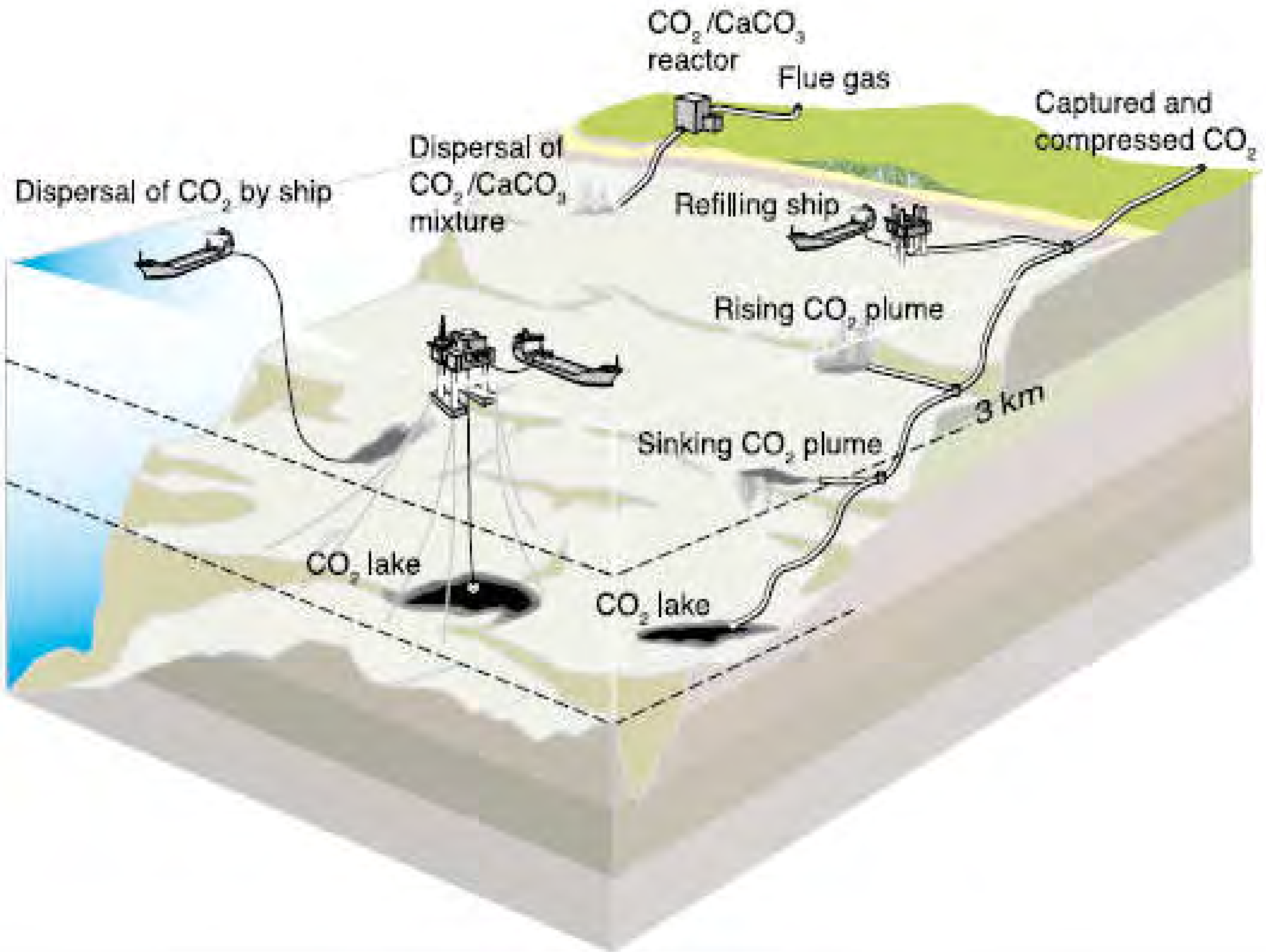
Oman Peridotite

Issues with Mineral Sequestration

- Cost
- Mining Scale
- Mining Impacts and mined materials
  - Trace elements
  - Mined materials can be hazardous
- Complex chemistry


Mineral Ore
Mining and Preparation
Mg- ore
Mg-ore
Mineral Pretreatment
Acid Leaching
SiO_2, $Fe(OH)_3$
acid
Mg-salt
acid
activated
Mg-rich
material
Acid Recovery
Mg-salt
Acid Recovery
NH_3
NH_3-salt
Mg $(OH)_2$
Mg-Precipitation
with NH_3 Base
Mg $(OH)_2$
Direct Carbonation
CO_2
Mg CO_3
Mg CO_3
CO_2
SiO_2, $Fe(OH)_3$
Disposal

Ocean Disposal



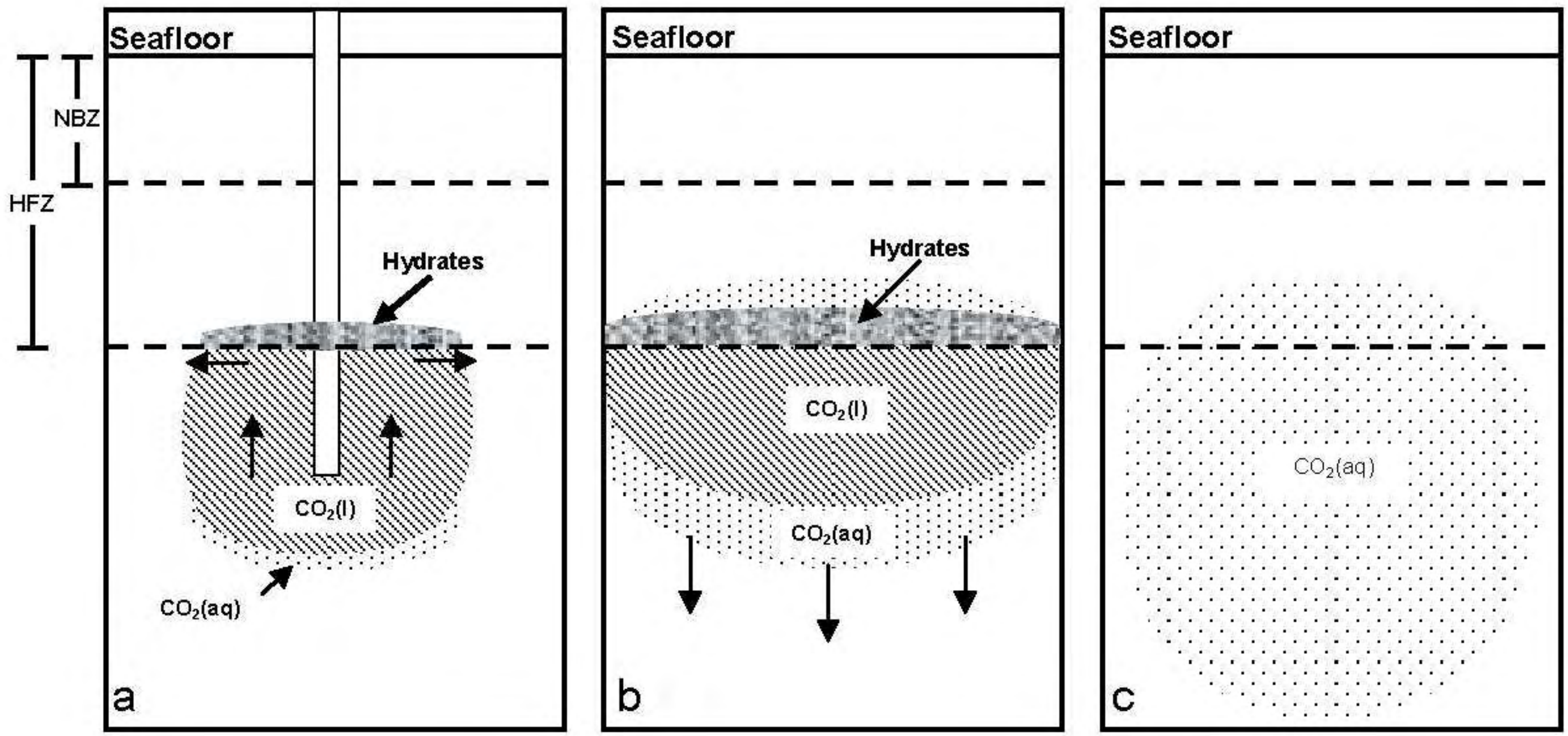
Ocean Floor Engineered Sites

- Clathrates
- Covers, bags etc.
- Trenches
- Inclusion in Ocean Sediments
  - Nuclear waste legacy

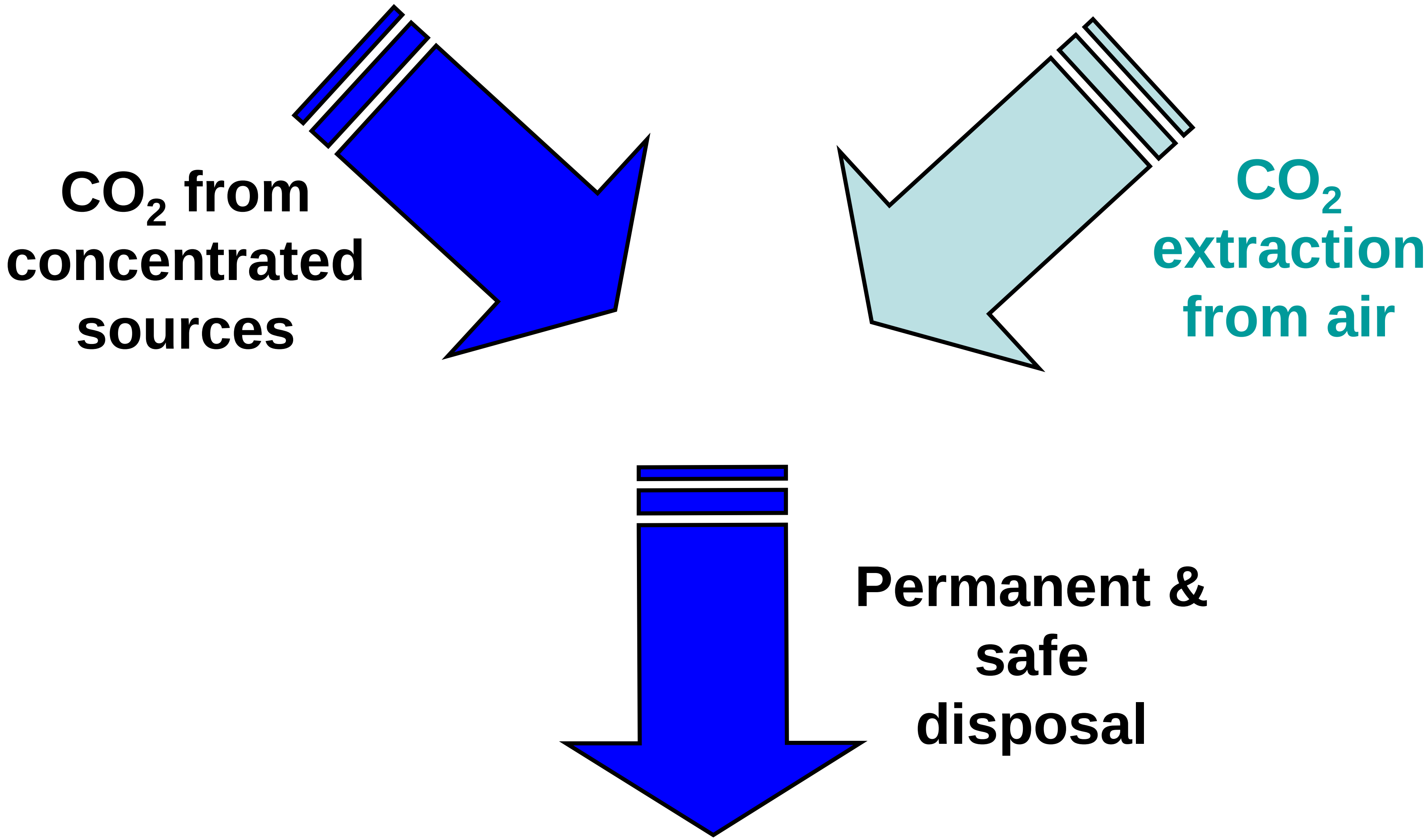
In situ Mineral Sequestration

- Changing 30 minutes into 30 years
  - Move from serpentine to basalt
  - Aqueous formations
  - Mineral Trapping

Gravitational Trapping
Subocean Floor Disposal



Net Zero Carbon Economy



After Initial Work at Los Alamos and Columbia

GRT is to demonstrate air capture in Tucson

Allen Wright
Gary Comer

Deliver proof of principle

☑

KSL joined the company

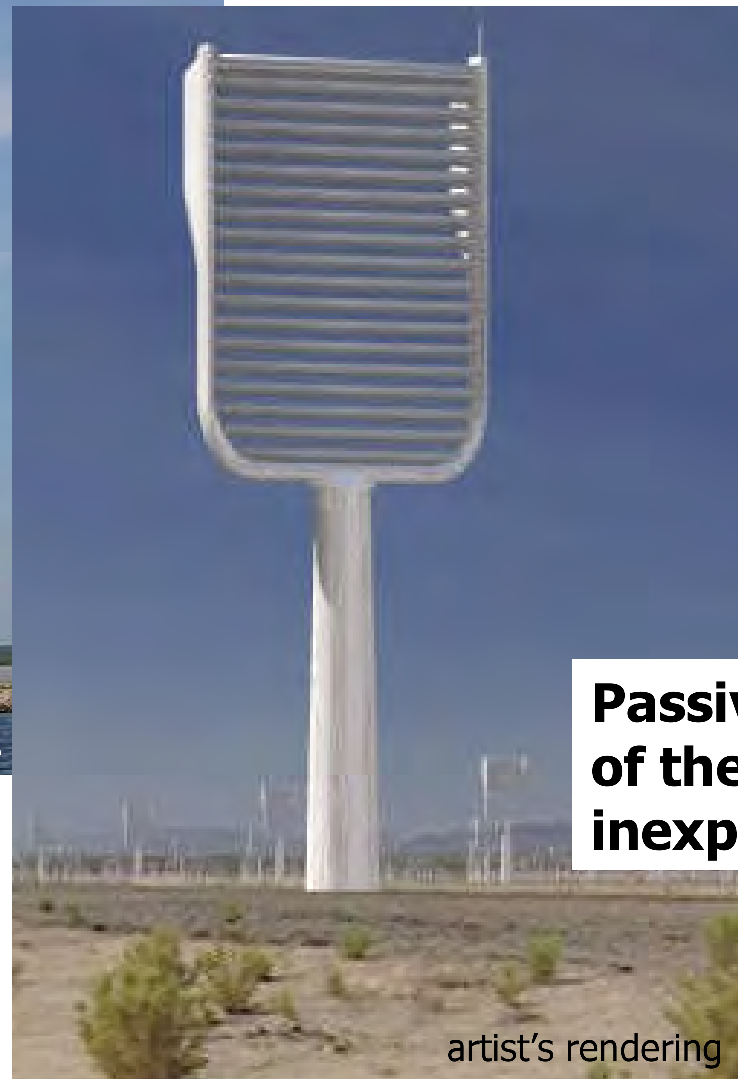
Separate Sources from Sinks

- ***Air Extraction can compensate for CO_2 emissions anywhere***

- Art courtesy Stonehaven CCS, Montreal

Wind energy – Air capture


Wikipedia picture


artist's rendering

Wind energy
~20 J/m^3

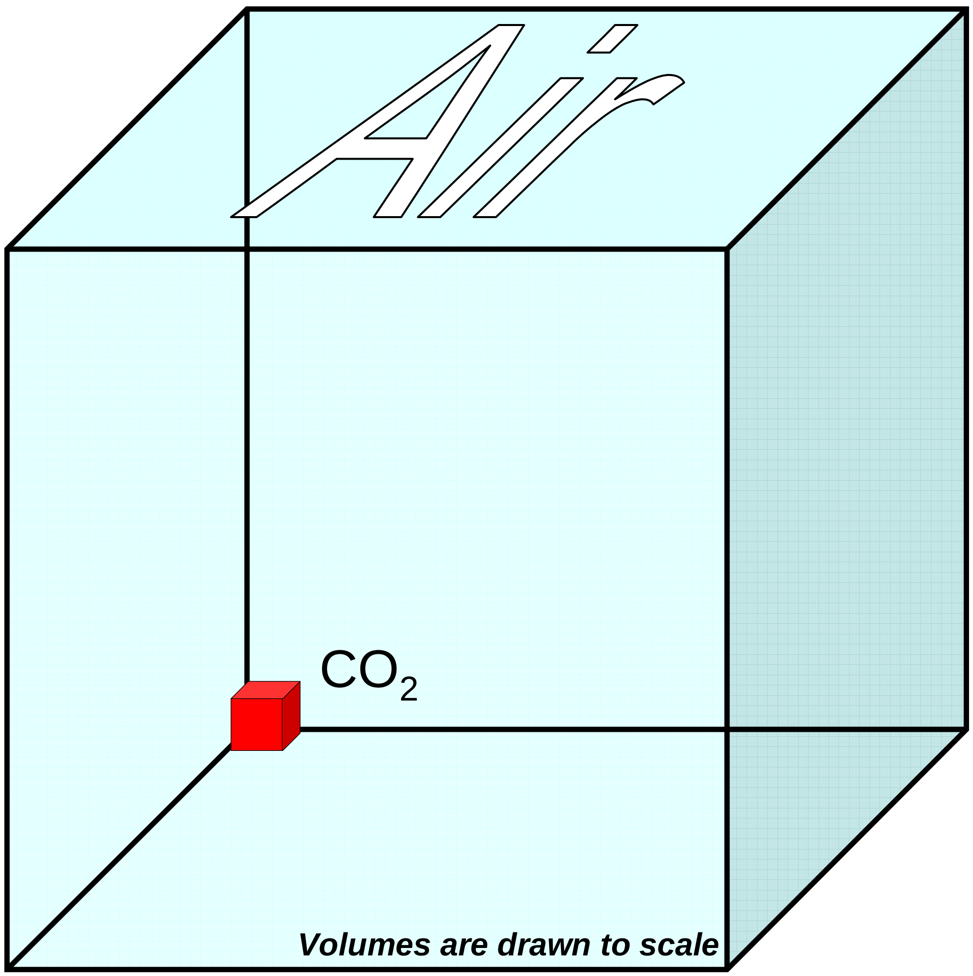
CO_2 combustion equivalent in air

10,000 J/m^3

Passive contacting of the air is inexpensive

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

CO_2 Capture from Air



1 m^{3}of Air

40 moles of gas, 1.16 kg

wind speed 6 m/s

$$\frac{mv^2}{2} = 20\,\mathrm{J}$$

0.015 moles of CO_2

produced by 10,000 J of gasoline

Flue Gas Scrubbing – Air Capture

artist's rendering

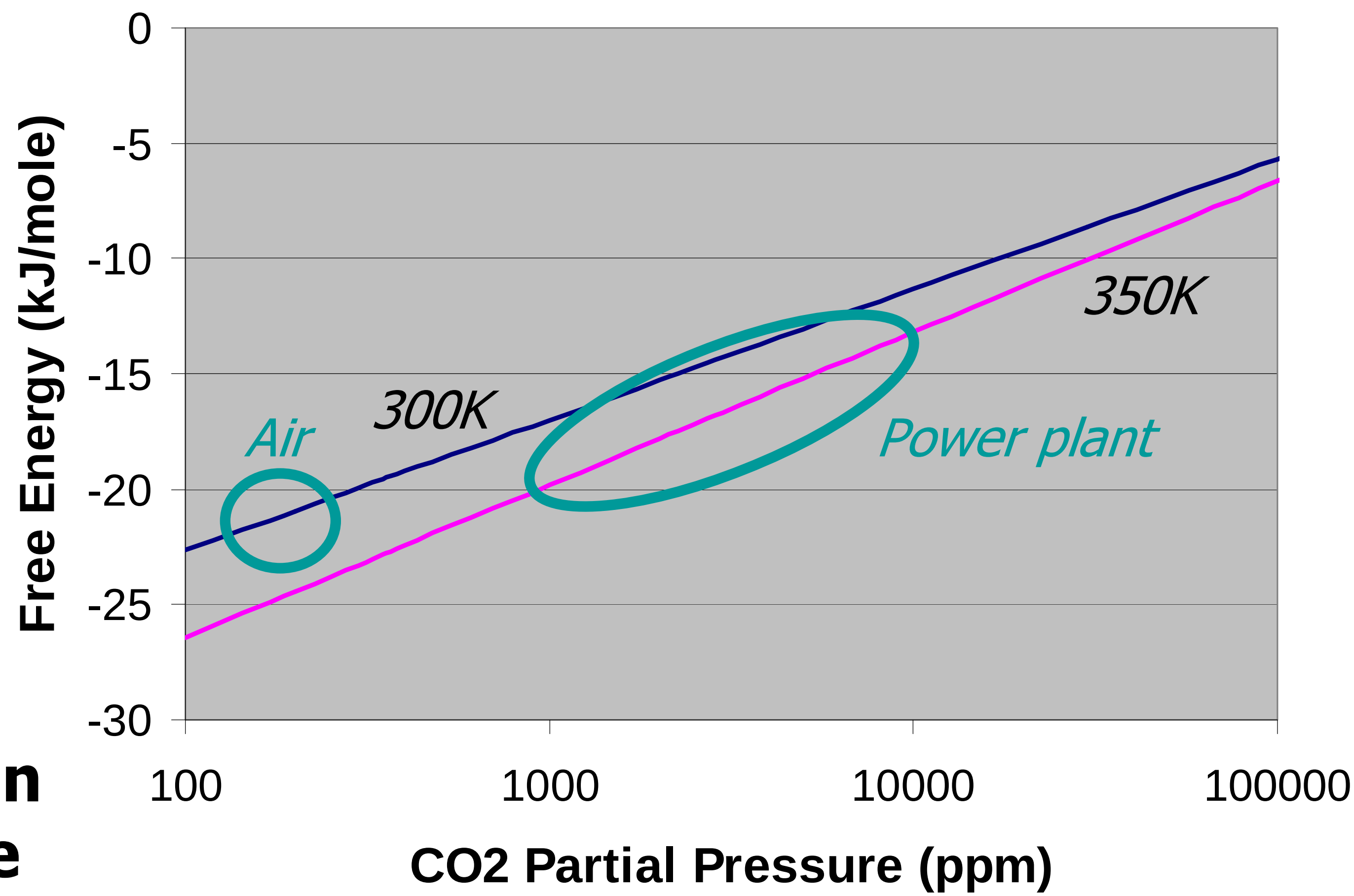
Dominant costs are similar for air capture and flue gas scrubbing

Sorbent regeneration slightly more difficult for air capture than for flue gas scrubbers

Sorbent Strength

depends logarithmically on CO_2 concentration at collector exit

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



Sorbent regeneration is expensive

Anionic Exchange Resins

Solid carbonate "solution"
Quaternary amines form strong-base resin

- 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

Novel Regenerator Chemistry

Moisture Swing Absorption

OPEN AIR COLLECTOR

Low absolute humidity
in ambient air

Air

Resin collects CO_2
Carbonate → Bicarbonate

REGENERATOR BOX

High absolute humidity
without air

CO_2 + H_2O

Resin releases CO_2
Bicarbonate → Carbonate

COMPRESSION TRAIN

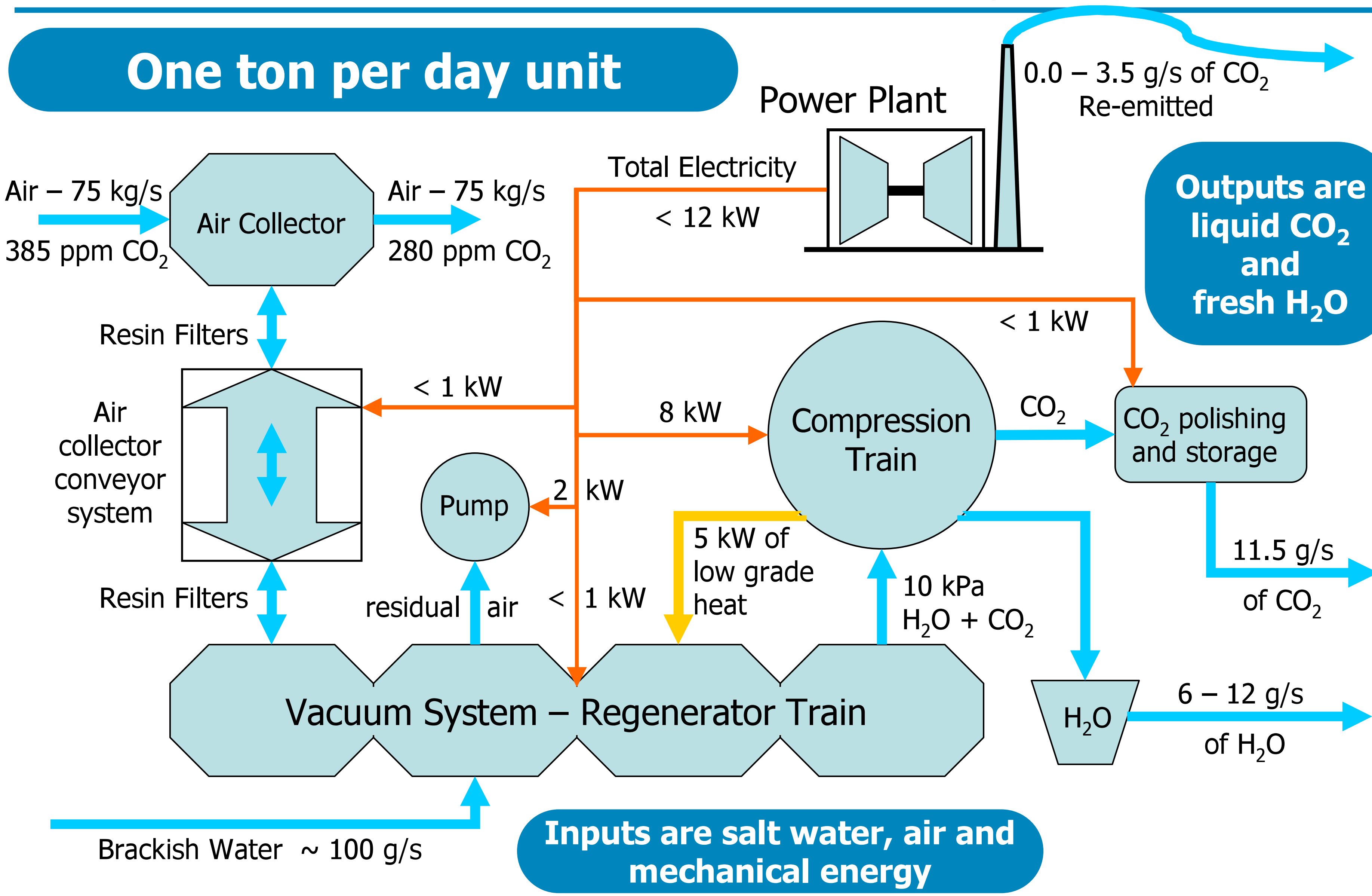
Water vapor condenses out with compression (< 2.5 kJ/mol of CO_2)

CO_2 is compressed to liquid conditions (22 kJ/mol of CO_2)

Heat release is harnessed for raising temperature of regenerator (45°C)

- Moisture swing consumes water and electric power
    - 50 kJ/mol of CO_2
    - 10 liter of saline water per kg of CO_2

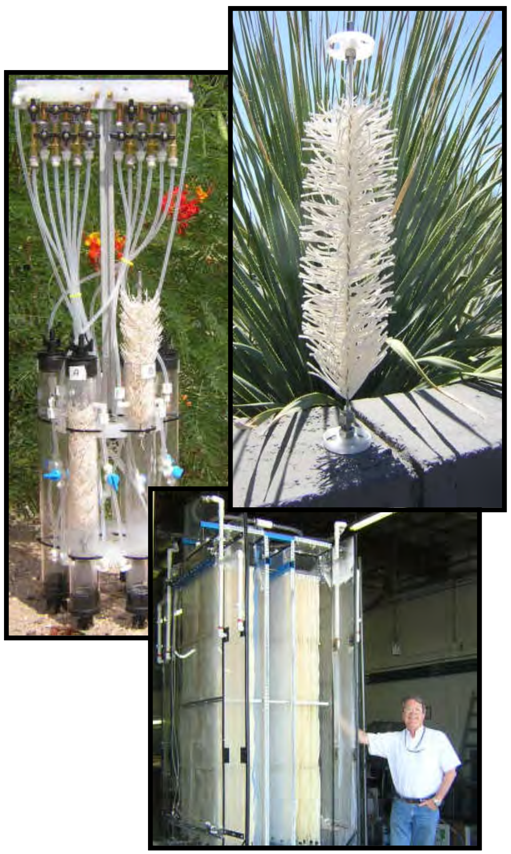
Air Capture Material and Energy Flow

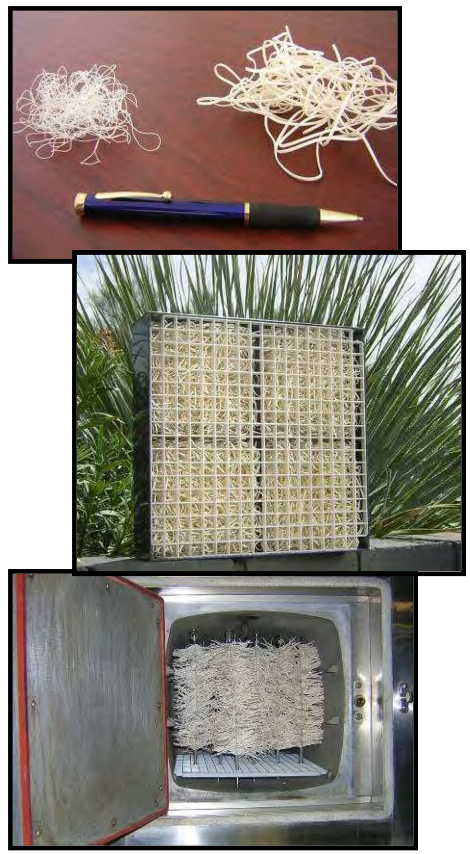


Collecting CO_2 with Synthetic Trees

From Technology Validation to Products

Prototypes of Capture Modules → **Advancing the Resin Technology** → **Mass-Manufactured Air Capture Units**





Setting the scale for 1 ton/day

- 2 × 30 panels
  - 2.5m × 1m × 0.3m
- 2 × 2500 kg of resin
  - 10,000m^2 of surface
- 6 × Chambers
  - 4m^3 each
- One Container
  - 86m^3
  - can hold all panels

Assembly line based automation

Air Capture Economics

Move to mass manufacturing
Initial cost are high – but less than local market prices

Cost Items	Cost Impacts
Raw materials	Low
Energy	Low
Manufacturing	High
Maintenance	High
CO_2 Storage	Initially None

Launch: Single Mobile Units
No innovation, catalog prices for parts

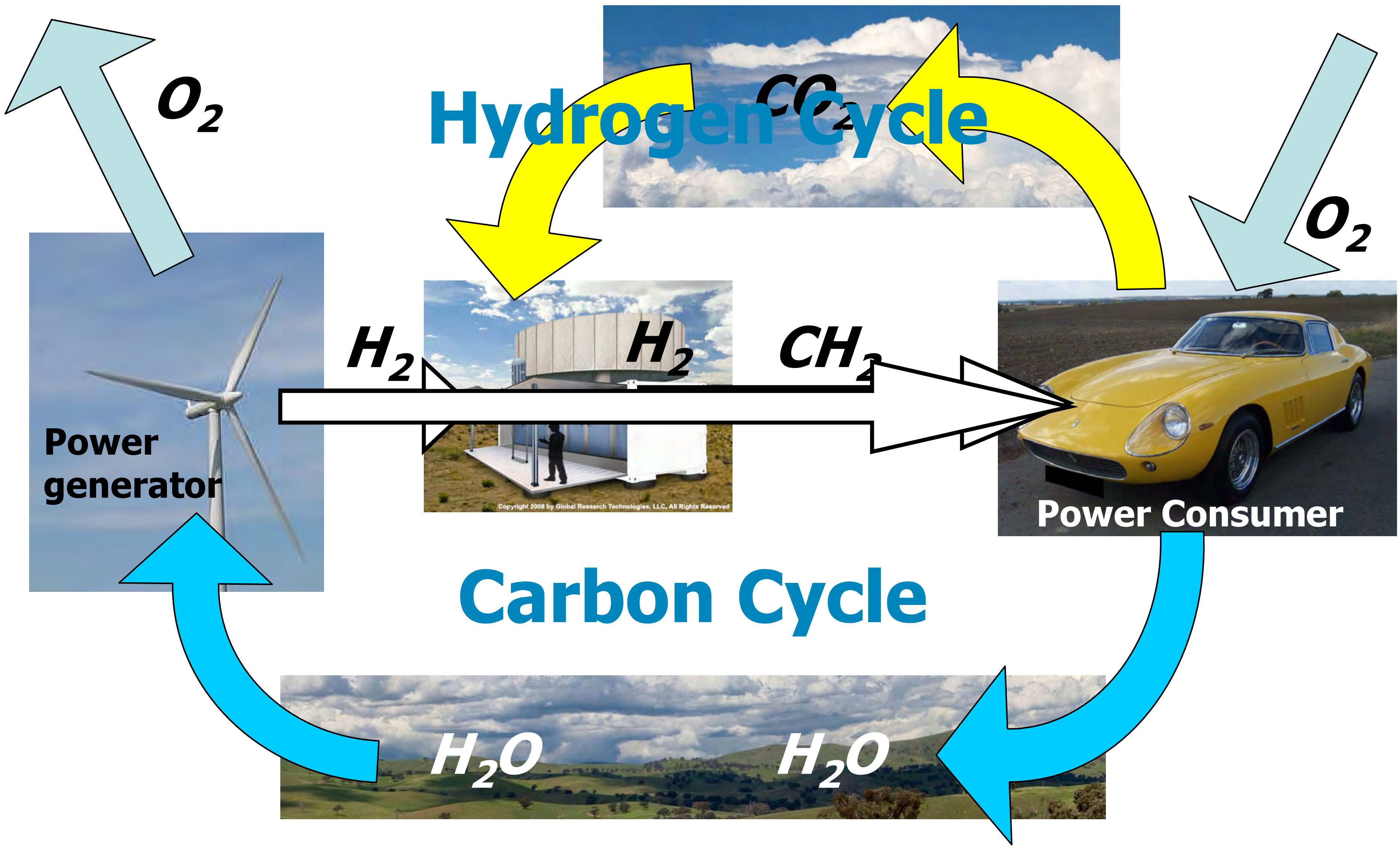
- Unit cost: ~$200k / unit
- Operating Costs*: ~$125 / ton of CO_2
- CO_2 Delivery Price: ~$250 / ton of CO_2
- CO_2 Output: ~ 1 ton / day / unit
- Units can be mass-manufactured
- Delivered in standard shipping containers

Maturity: Air Capture Parks
Learning and streamlining
Improvements in resins

- Unit cost: < $20k / unit
- Operating Costs*: < $20 / ton of CO_2
- CO_2 Delivery Price: ~ $30 / ton of CO_2
- CO_2 Output: ~ 1-3 tons / day / unit
- Range of collector styles, recovery systems

* Operating costs include all electrical, water, labor and material inputs

Closing the Cycle - Synthetic Fuels



Going to Scale (Mass Production)

- 10 million units @ 1/tonne per day
  - capture 3.6 Gt CO_2 per year (12% of emissions)
  - Require annual production of 10 million
    - Assume 10 year life time
    - Compared to 70 million cars and light trucks
- 100 million units would lower CO_2 in the air

Monitoring and Verification

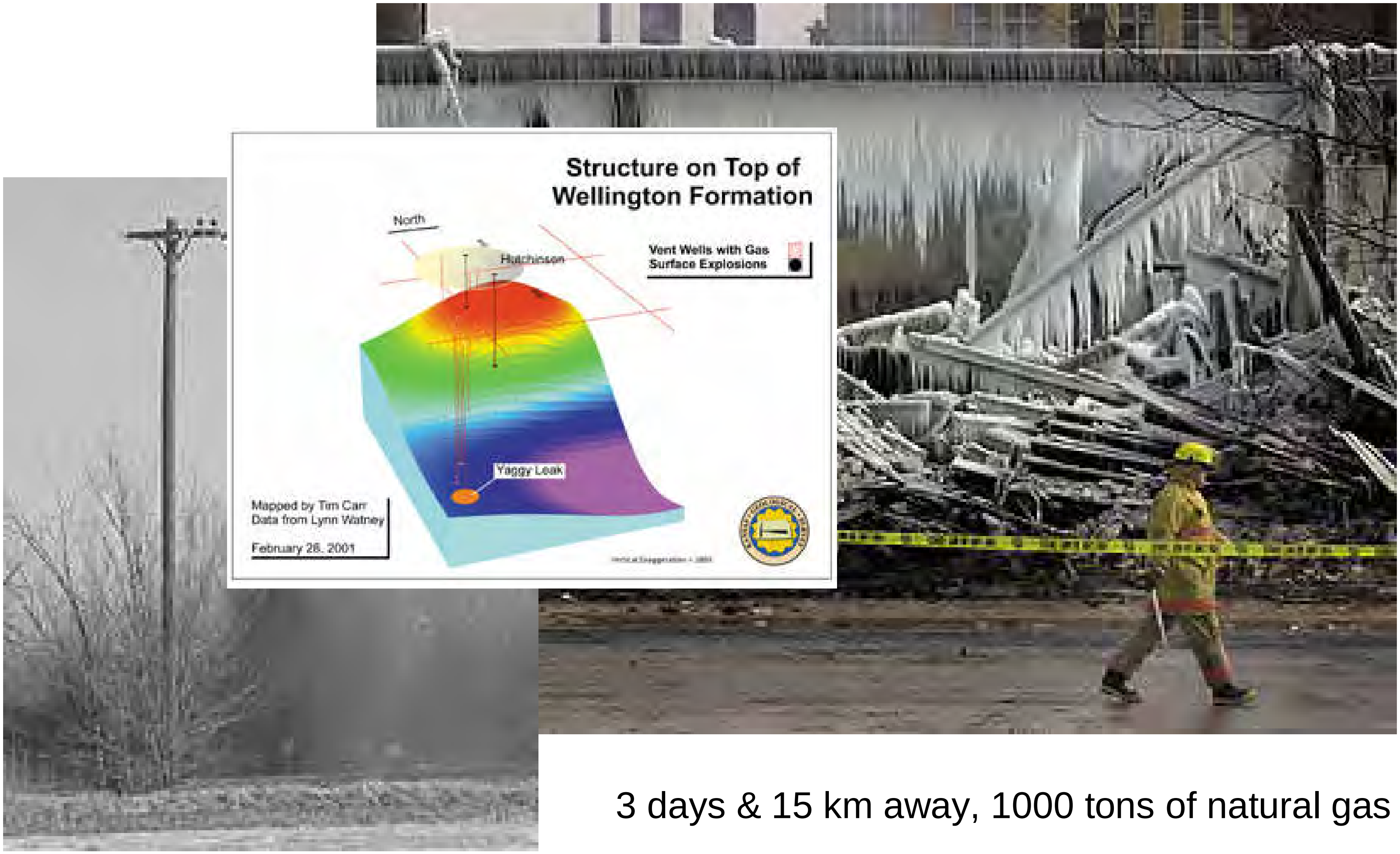
Safety and environmental issues

Efficacy and accounting issues

Safety

- **Good choice of reservoir**
  - Safe, well understood cap rock sealing the formation
- **Build in escape valve to relieve pressure**
  - Most concerns are removed, if CO_2 is released
  - However, resulting emission must be counted
  - Air capture can compensate

Hutchinson, Kansas January 17, 2001



3 days & 15 km away, 1000 tons of natural gas

M. Lee Allison, Geotimes, October 2001

Storage involves a public good

- Who owns the pore space?
- Who monitors the pore space?
- How do we know storage is safe?
- How do we know we accomplished anything?

By Contrast:

Capture and transport only require a carbon price or performance standards

Principles of Underground Storage

- Storage must be safe
  - Capability of an emergency release is important
  - Continuous safety monitoring is important
- Storage must be effective
  - Even harmless leakage negates CCS
- Storage must be verifiable
  - System must be transparent, not require trust
  - Need technologies for monitoring
  - Positive inventory techniques are necessary
- Storage must last
  - Life time of storage has to be thousands of years

Manage Underground Storage

- CO_2 injection creates three distinct problems
  - Volume addition
    - By far biggest problem
    - Can be solved by removing water (desalination)
  - Buoyancy
    - Can be solved by going very deep
    - Requires careful monitoring
  - Chemical Change
    - Must be managed, anticipated and understood
    - Small problem for most reservoirs
    - Usually irreversible, sometimes severe

Volume Increase

- Pressure management
  - Fluids are nearly incompressible
  - Volume injections are large
  - Pressure field provides tele-connection to distant reservoirs

    - water quality from aquifer intrusions
    - artesian wells
    - seismic stability

Buoyancy of CO_2

- Finding and opening fractures
- Long term return to the atmosphere

Solutions:

Continuous monitoring or sub-ocean floor injection

Irreversible Chemistry

- Minimize negative impacts of unintended reactions
- Rely on chemistry being slow or well planned

Volume increase and buoyancy problems can be fixed simply by removing CO_2.

However, chemistry changes are irreversible.

Dealing with Rare Events

- Prior Definition of Off-Ramps
  - Unexpected seismic events
  - Salt water intrusions
  - Artesian Wells
  - CO_2 appears outside the formation

If these events happen, the injection must be reversed

Demand Positive and Quantitative Accounting

- Measure how much CO_2 is injected
- Watch it distribute underground
- Develop generally accepted standards for measuring the amount of carbon stored
- Inventory measurements are critical

Current techniques are all qualitative

Use C-14 for tagging for positive accounting

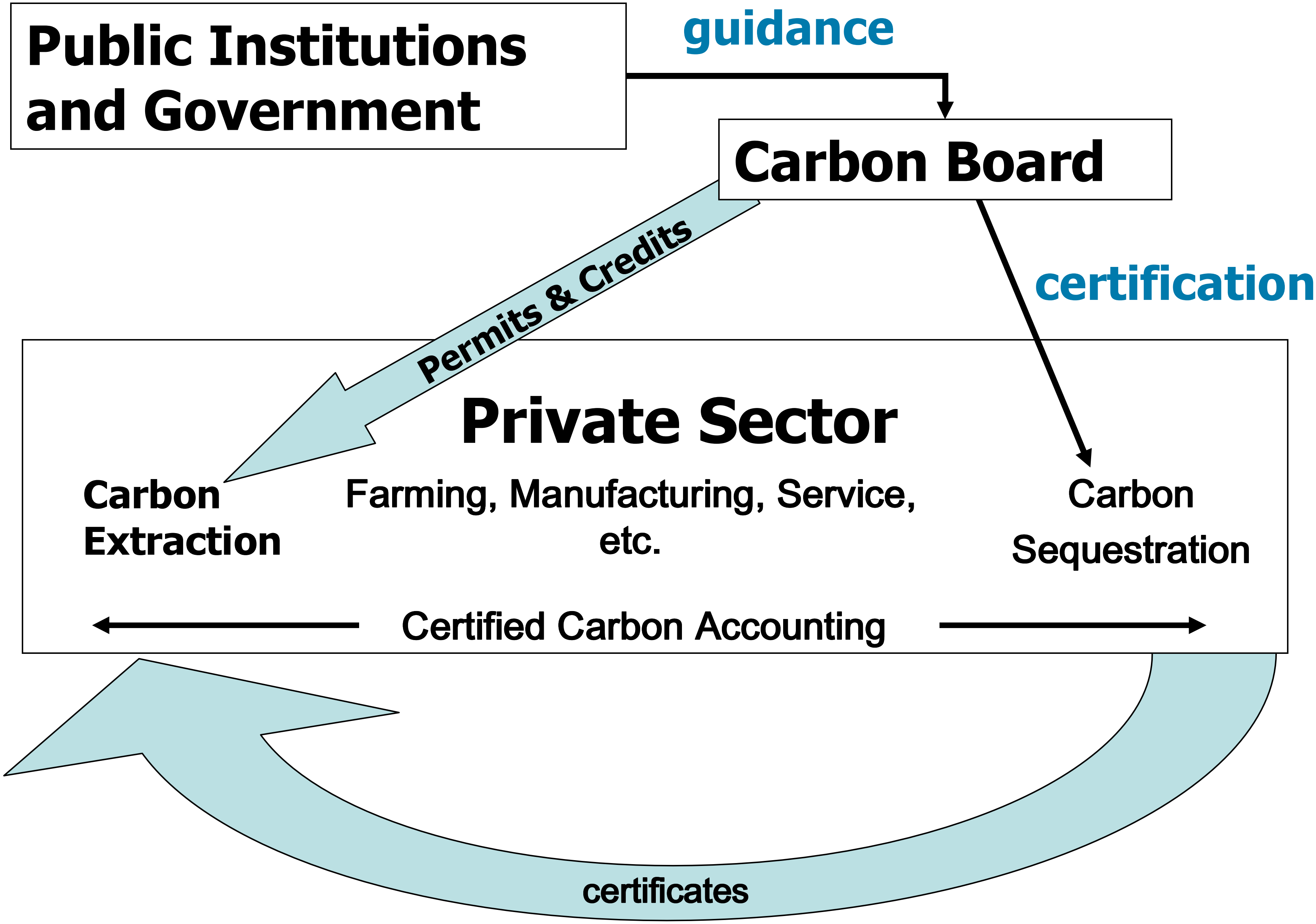
- Surface carbon is C-14 live
  - 1.3 parts per trillion
- Fossil fuel carbon is C-14 free
  - Add C-14, 1 microgram per ton
  - Air captured CO_2 is naturally tagged
  - C-14 content never exceeds natural levels
- Not suitable for leak detection
  - Inventory tool
  - Resolves disputes
  - Does not fractionate

C-14 Monitoring

- Why C-14
  - It will not fractionate from the carbon
  - It is unique in most underground formations
  - It is harmless (C-14 content is like that on the surface)

What Happens if CO_2 is released?

- Site becomes an emitter
  - Damage equals the price of CO_2
  - Air capture can set the price
- Liability is indefinite
  - Owners of the site are treated as potential emitters
- Buying certificates of sequestration



Public Institutions and Government
guidance
Carbon Board
Permits & Credits
certification
Private Sector
Carbon Extraction
Farming, Manufacturing, Service, etc.
Carbon Sequestration
Certified Carbon Accounting
certificates

Price carbon at the well

- Mobilizing and demobilizing carbon
  - Trade carbon mobilization against carbon fixation
  - Accounting is easiest upstream
- Rational design with minimal exceptions
  - Once mobilized carbon need not be tracked
  - Create certificates of sequestration
- Carbon leakage becomes emission
  - Remobilization is the same as mobilization
  - Only one flavor of "certificate of sequestration."

Steps toward a sustainable future

- Public buy-in
- R&D support
- Equitable regulations
  - International fairness
  - Social fairness
  - Intergenerational fairness

Options

- Regulating Sectors
  - Performance Standards
  - Portfolio requirements
  - Technology Choices
    - E.g. nuclear or renewable portfolios
- Carbon Price and Carbon Limits
  - Cap and Trade
  - Taxes
  - Pricing at the well

Immediate Options

- Increased Efficiency
  - driven by price
- Reduction in Consumption
  - driven by price
- Fuel Switching (Coal to methane)
  - Sporadically discouraged by price

Best achieved by performance standards

Carbon Capture and Storage

For every ton of carbon extracted from under the ground
another ton of carbon
must be returned

How to get started?

- Regulatory and institutional frameworks
  - Carbon Price
  - Regulatory oversight

- Public Engagement and Public Trust
  - Transparency
  - Accountability
  - Reversibility

- Emphasis on ready technologies and minimum infrastructure change
  - Geological storage
  - Air Capture

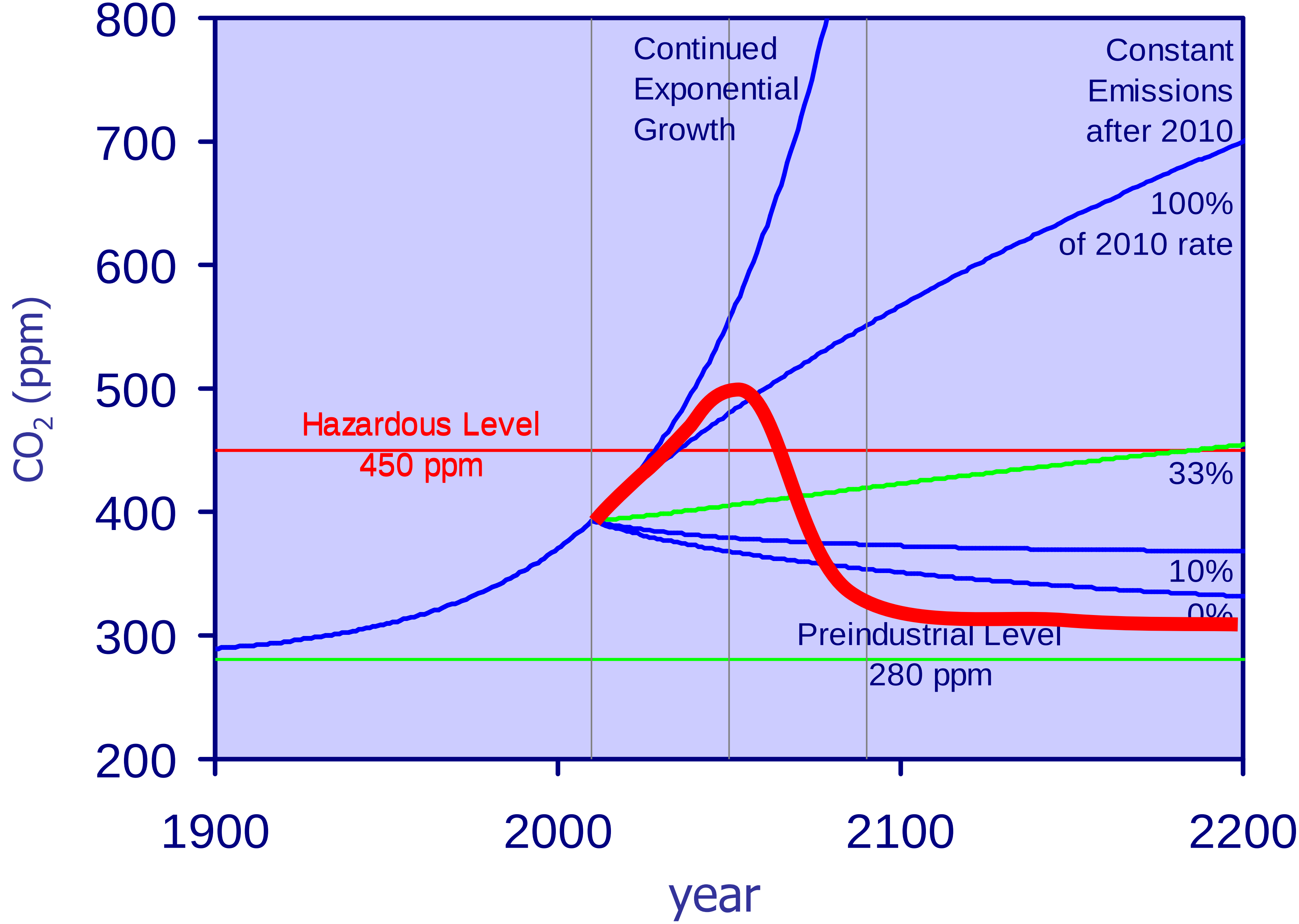
- Research and Development
  - This is not business as usual

Placing big bets on the big three

- Renewable (particularly solar)
- Nuclear (first fission then fusion)
- Fossil Carbon with CCS

Without CCS, the transition to zero carbon is very difficult

Coming back down




Höchstgeschwindigkeit 20 km/h