Net Zero Carbon Economy

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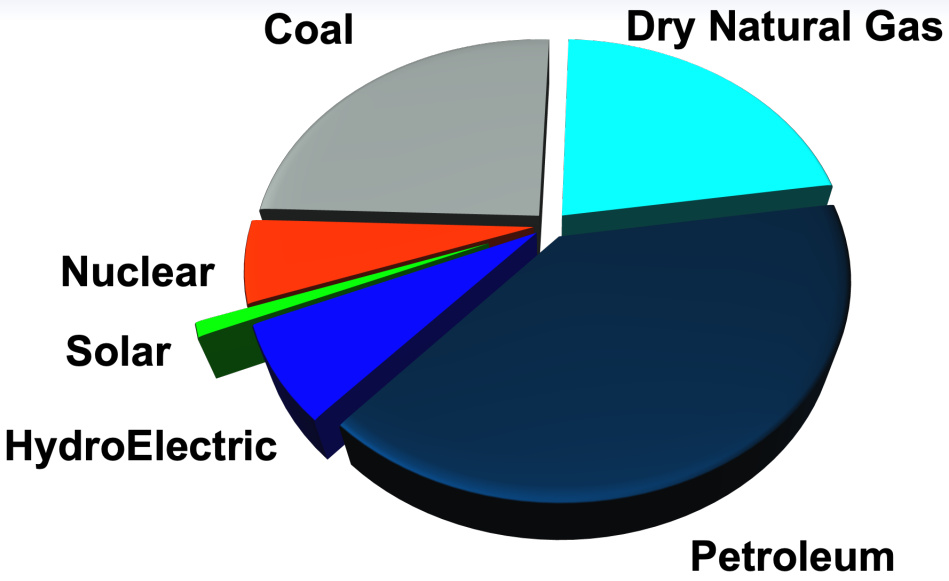
Energy needs to be
Cheap, Copious and Clean

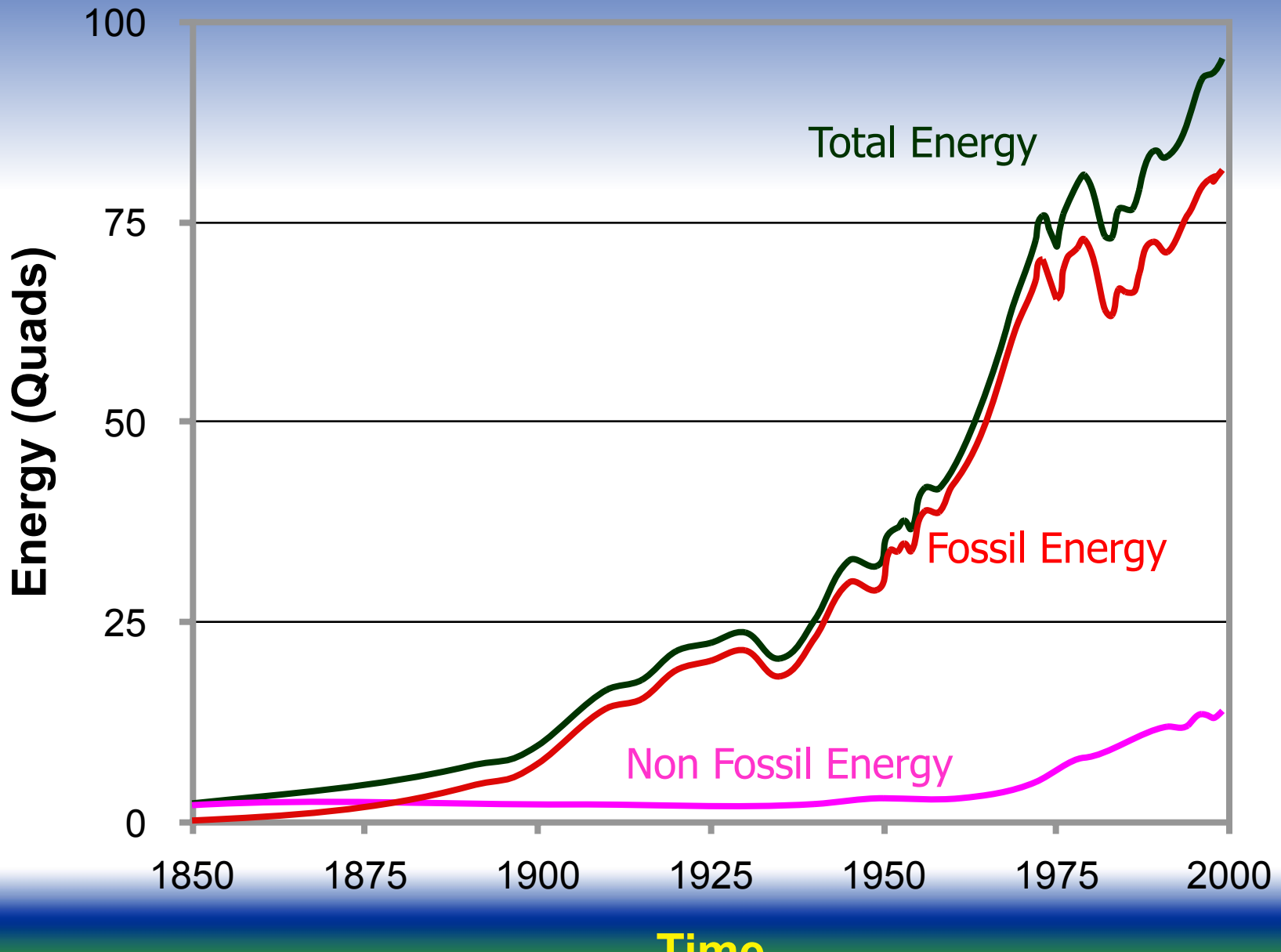
- Technology can only deliver two out of three
- Need nuclear, renewable and fossil energy option
- Fossil energy technology needs to manage the entire carbon cycle
- Transition to a Net Zero Carbon Economy

Fossil Fuels Contribute 86% of World Energy

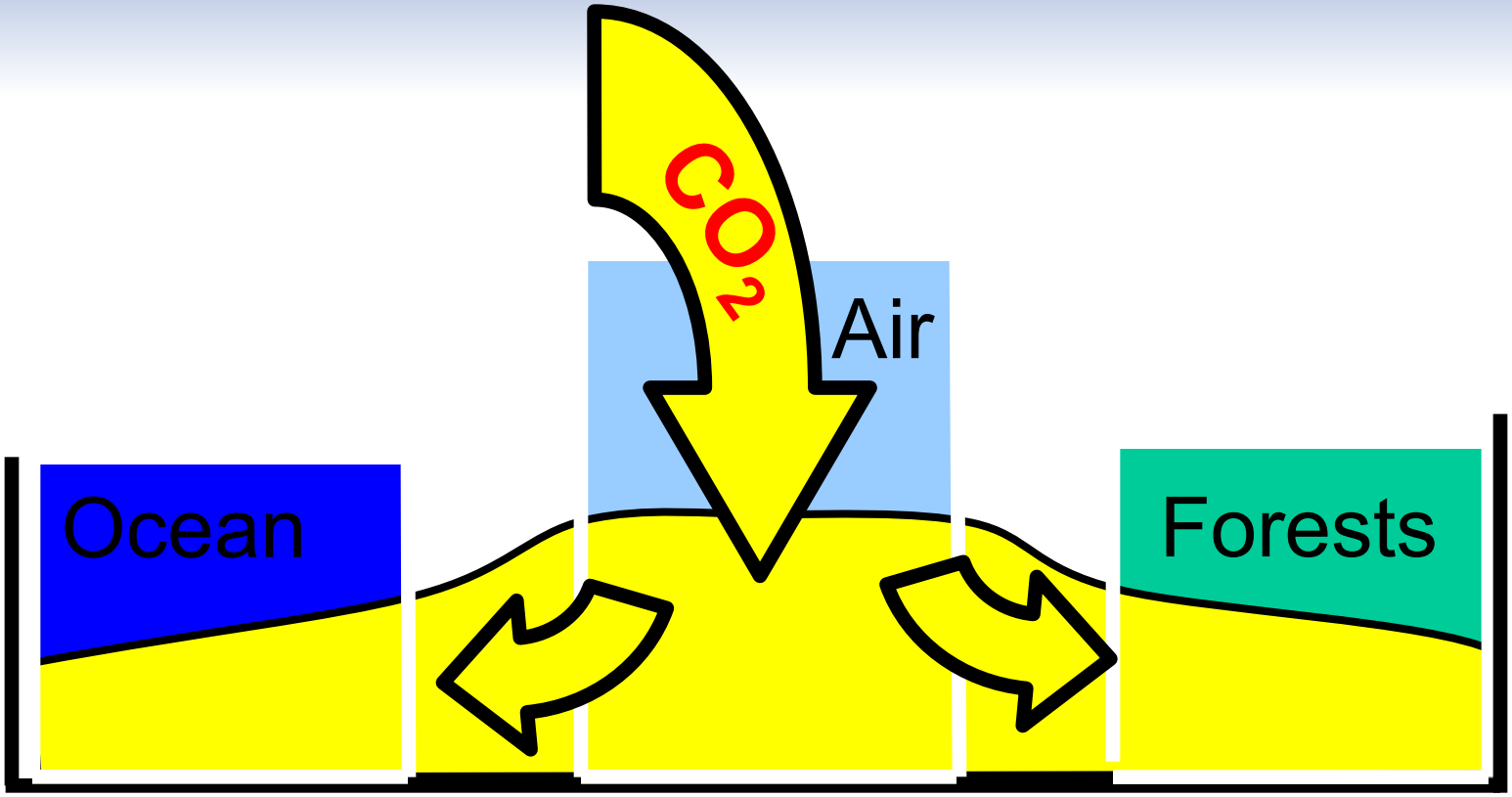


Ten billion people trying to consume energy as US citizens do today would raise world energy demand tenfold

US Annual Energy Consumption



CO_2 accumulates in the air



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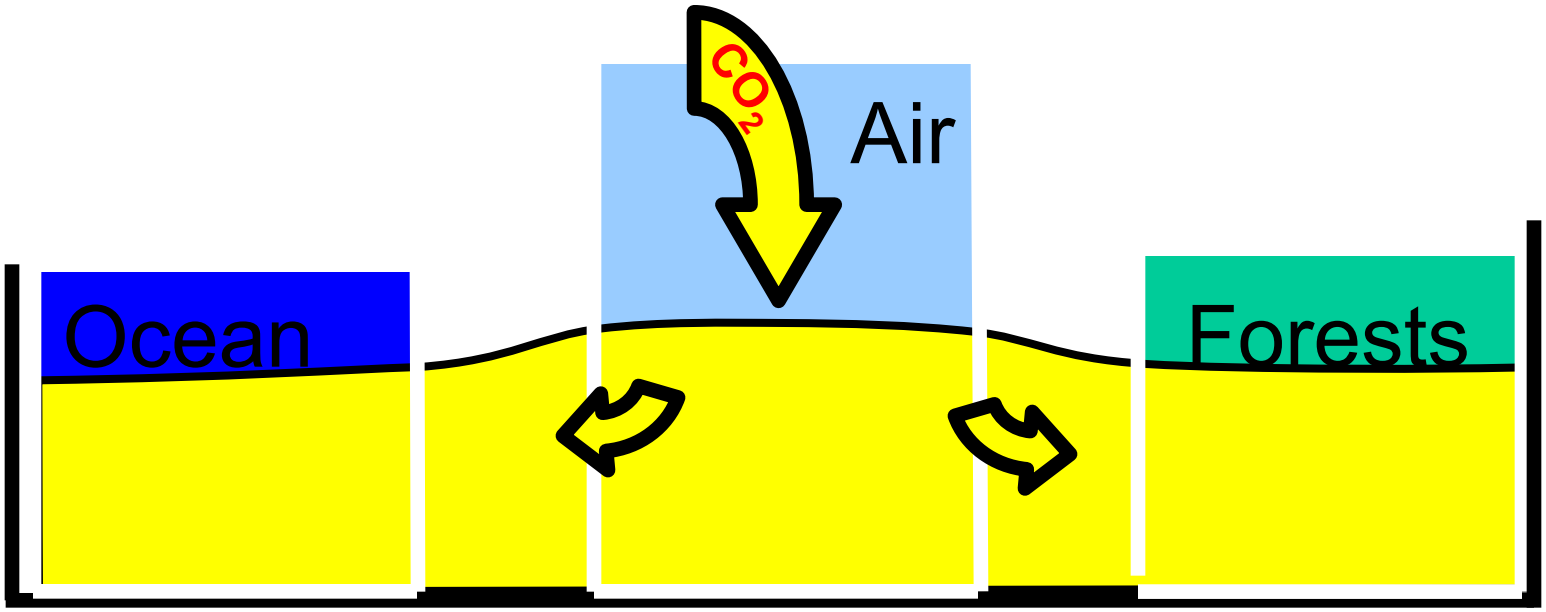

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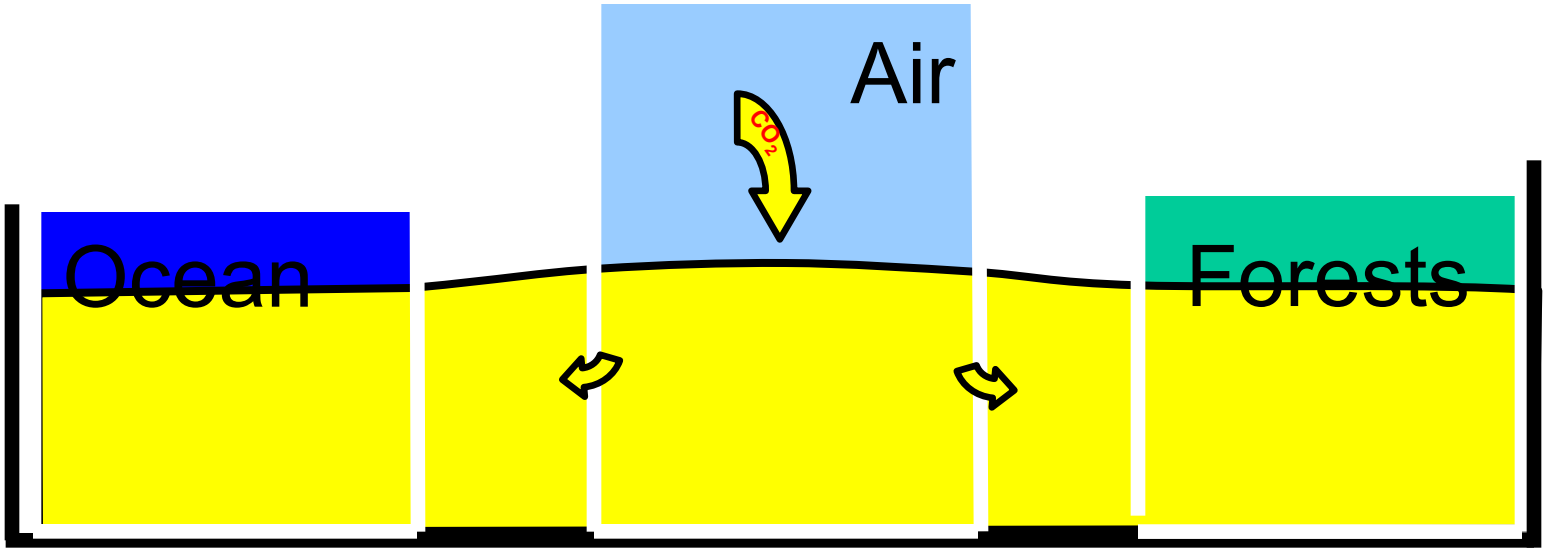
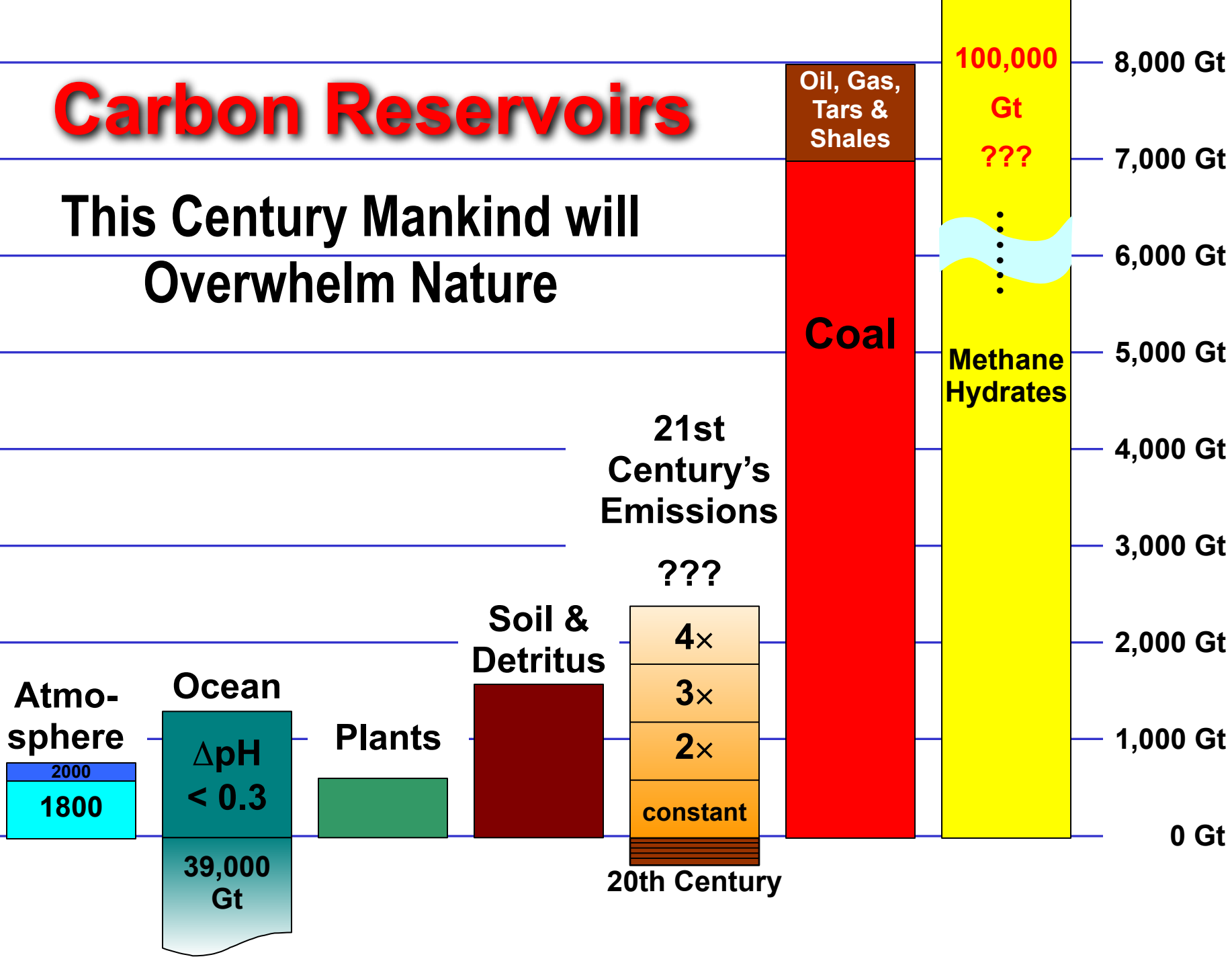


Carbon Reservoirs

This Century Mankind will Overwhelm Nature



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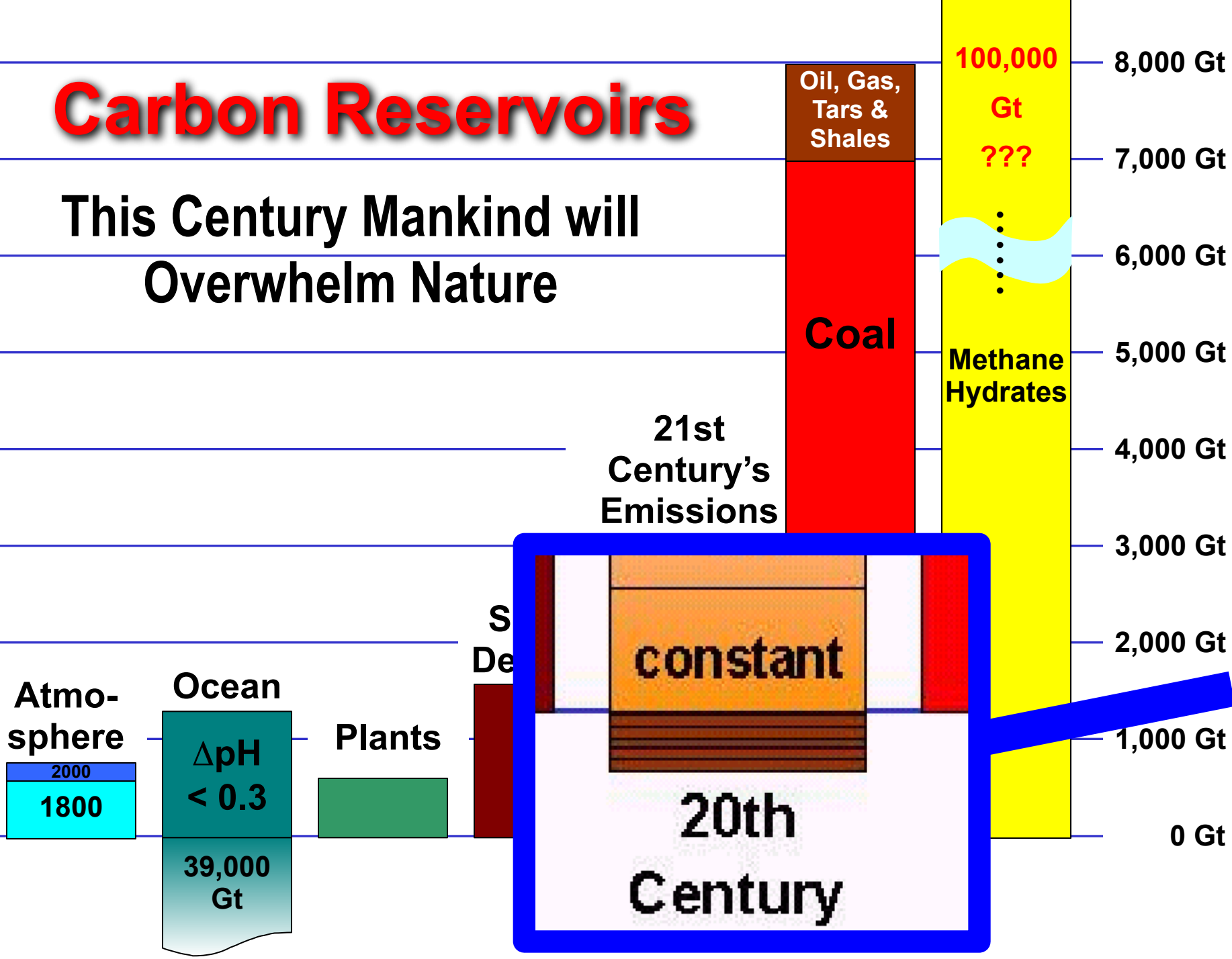

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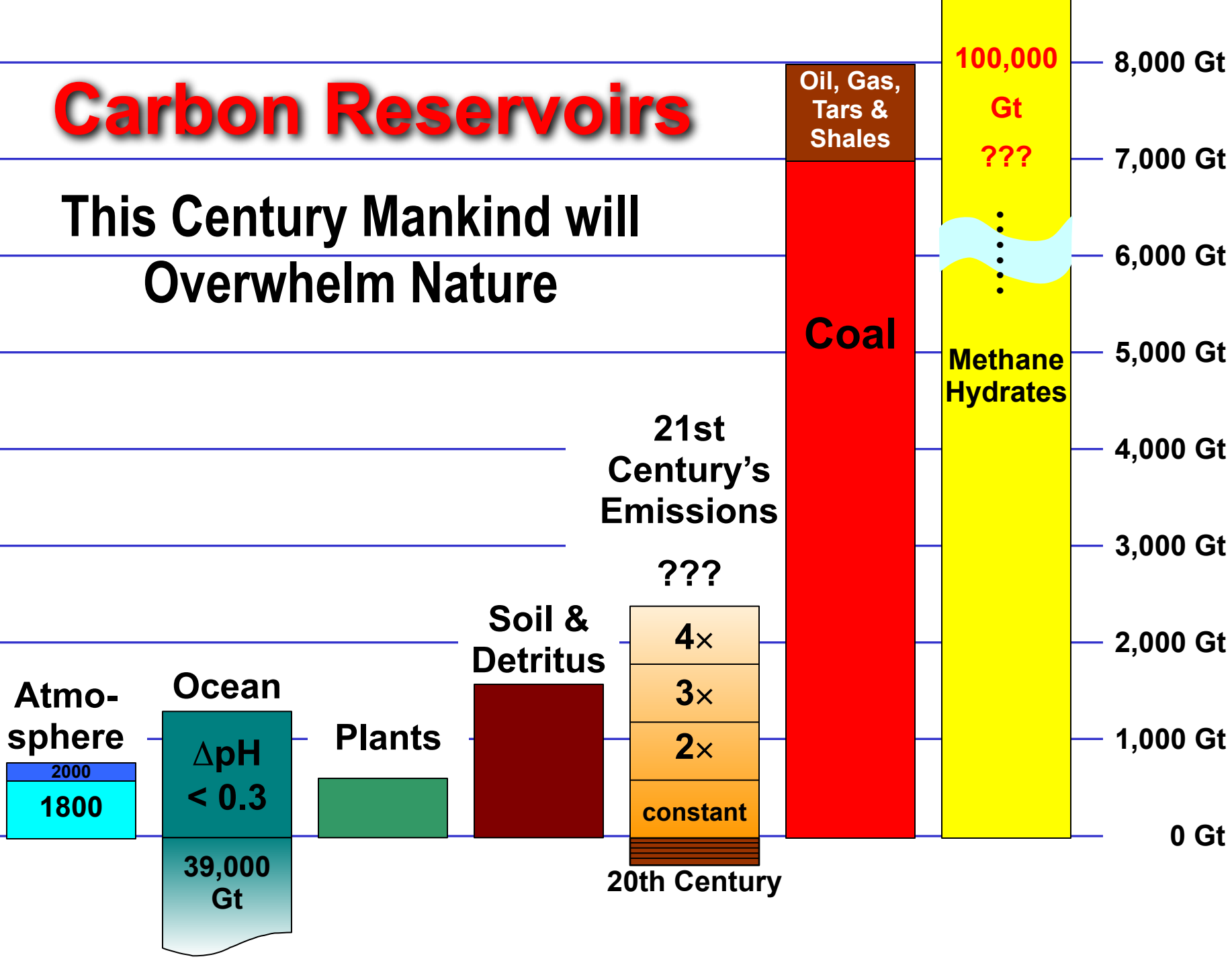
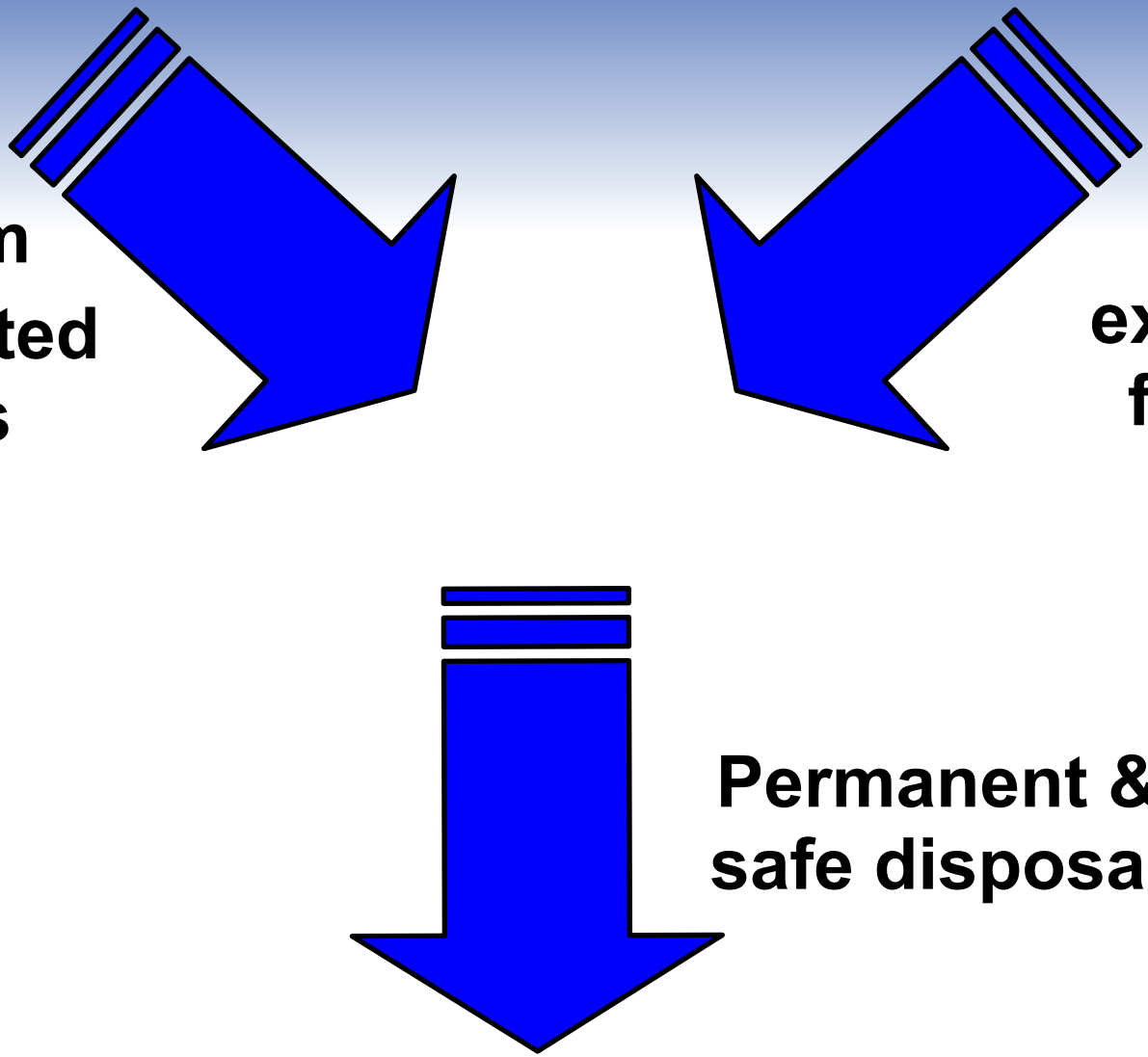


Net Zero Carbon Economy



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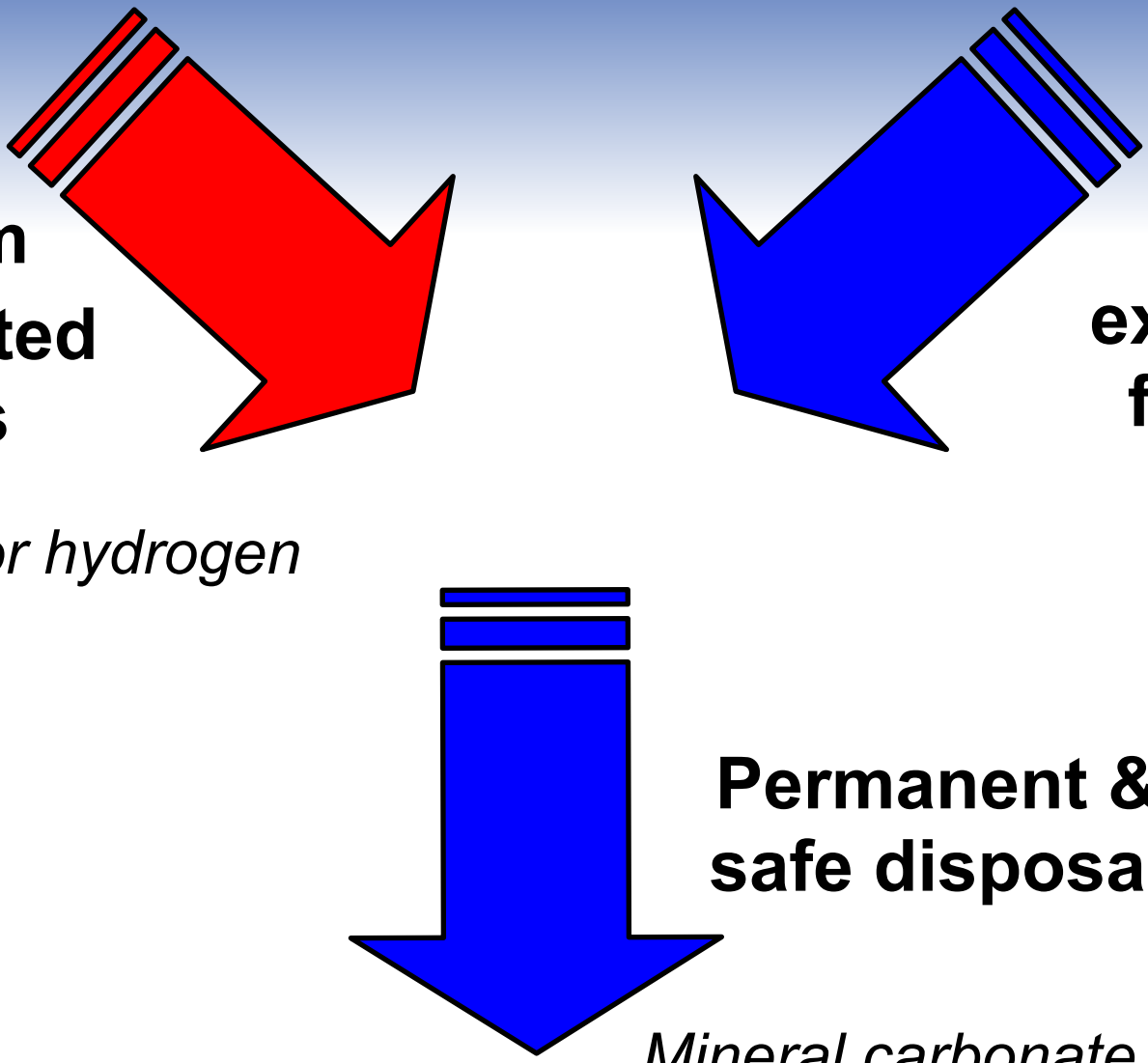

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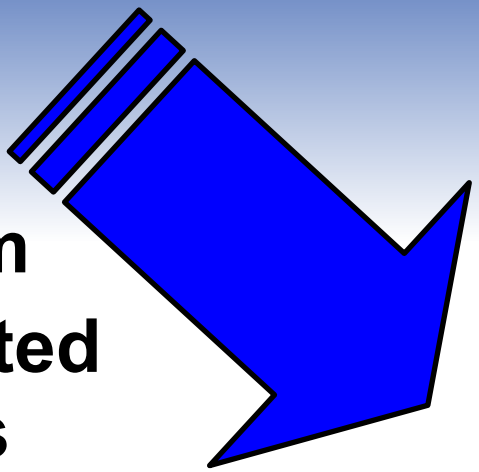
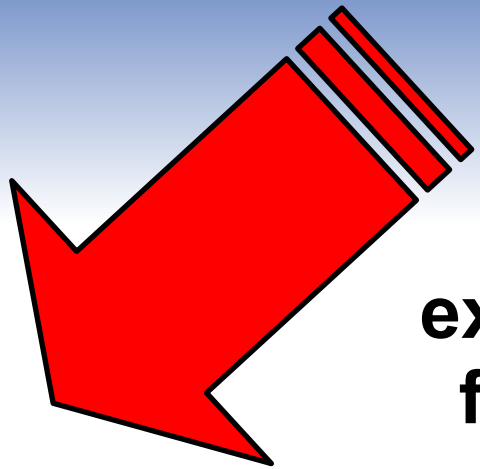


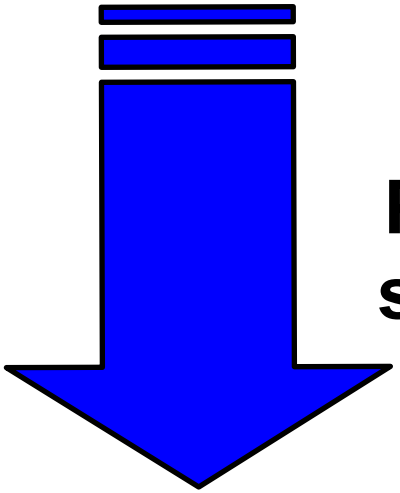
CO_2 from concentrated sources



CO_2 extraction from air

Biomass & Chemical Processes

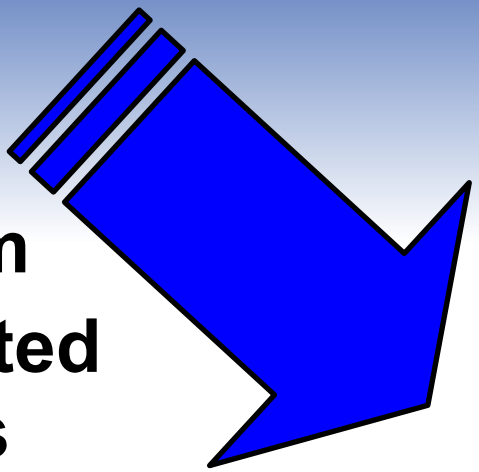
Mobile Sources Unchanged Infrastructure

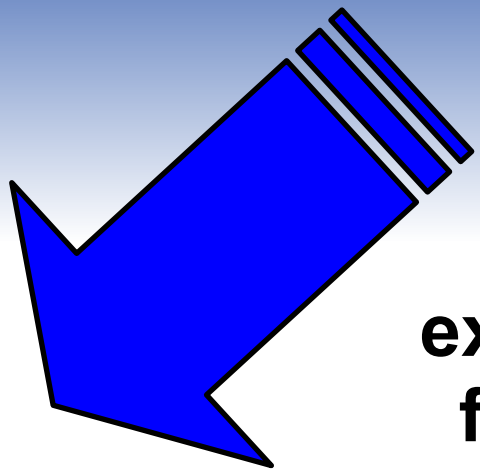


Permanent & safe disposal

Net Zero Carbon Economy

CO_2 from concentrated sources

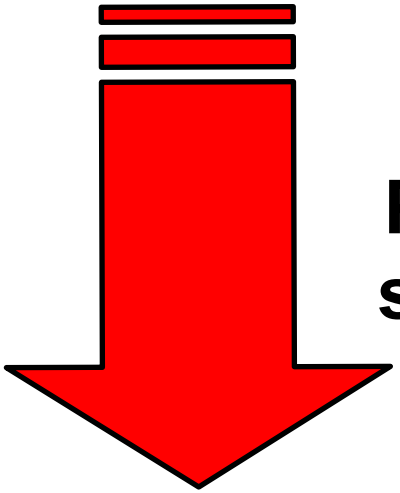




CO_2 extraction from air

Mineral Carbonate Disposal:

Accelerated rock weathering



Permanent & safe disposal

Net Zero Carbon Economy

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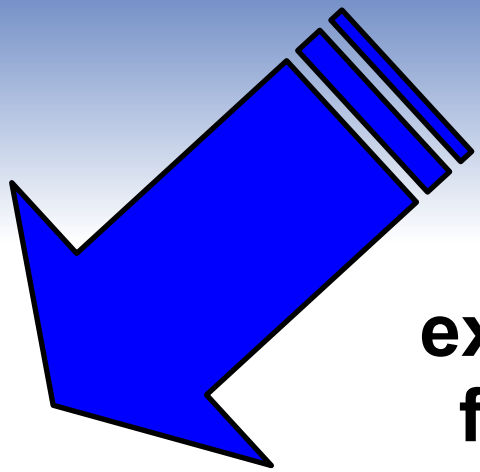
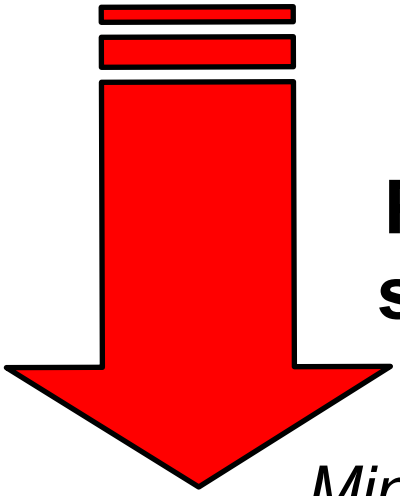


CO_2 extraction from air

electricity or hydrogen

ZECA Plant



Permanent & safe disposal

Mineral carbonate disposal

Zero Emission Technology
Assuring the Future of Coal and other fossil fuels

- Fossil energy is plentiful and essential
- Coal reserves are virtually unlimited
- Zero emission goal is crucial for the future of coal
- Zero emission technology is feasible

ZECA, the Zero Emission Coal Alliance, plans to demonstrate the technology

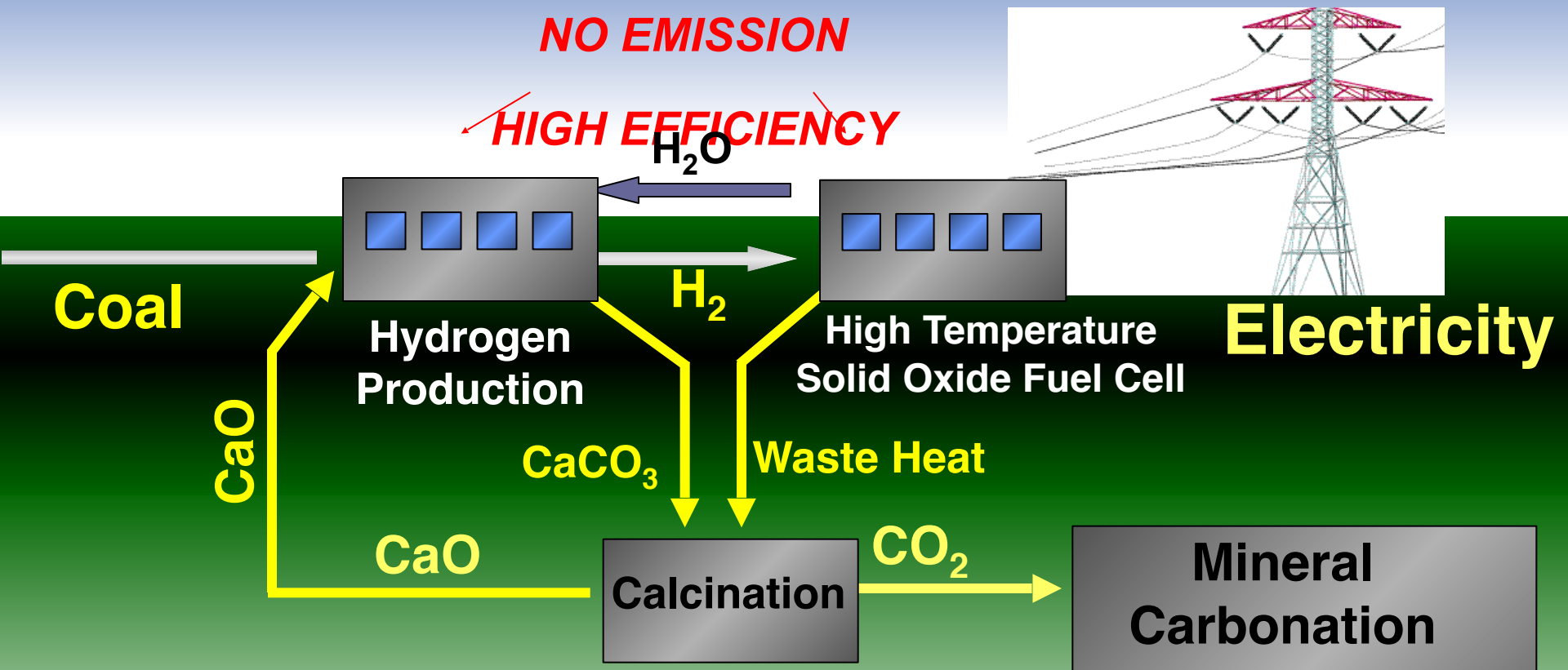
Zero Emission Coal Alliance

- ZECA has eighteen members
  - mainly coal producers and coal users in the United States, Canada, Australia and Europe
- ZECA commissioned Nexant
  - to perform a feasibility study and to deliver a technical and business plan
- ZECA plans to pilot the technology in five years
  - Move on to commercialization

ZECA's Long Term Goal: Zero Emission for Sustainable Energy

- **Zero Emission**
  - No CO_2, SO_X, NO_X, no particulates, no mercury
- **Permanent Disposal of CO_2**
  - Not a temporary patch that comes back to haunt us
- **Match Future Energy Demand**
  - Hundreds of years of fossil energy even at increased demand
- **Minimal Environmental Impact**
  - Avoid legacy issues
- **Doubled Efficiency**
  - Reduce cost of carbon dioxide disposal
- **Economic Implementation**
  - No energy penalty, single step eliminates all pollutants

Zero Emission Coal Plant Generating Electricity or Hydrogen

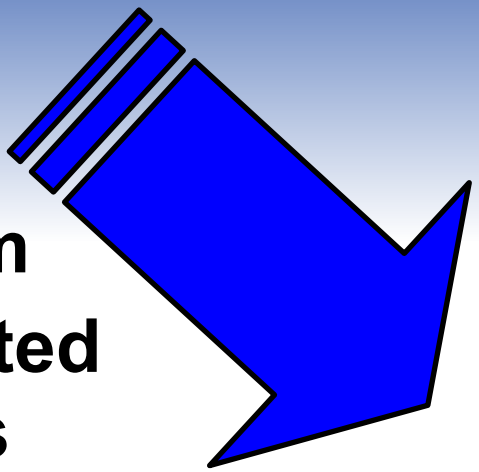


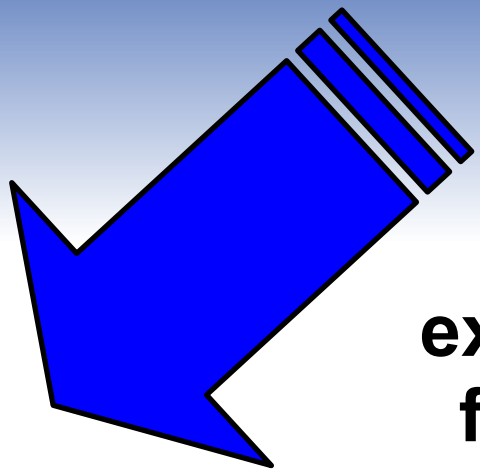
Coal to electricity with extremely high efficiency

- Process heat from fuel cell fully recycled
- 50% less CO_2 even without disposal
- Capture all emission products

Net Zero Carbon Economy

CO_2 from concentrated sources

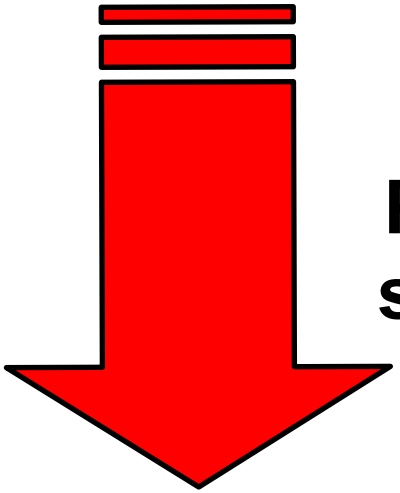




CO_2 extraction from air

Mineral Carbonate Disposal:

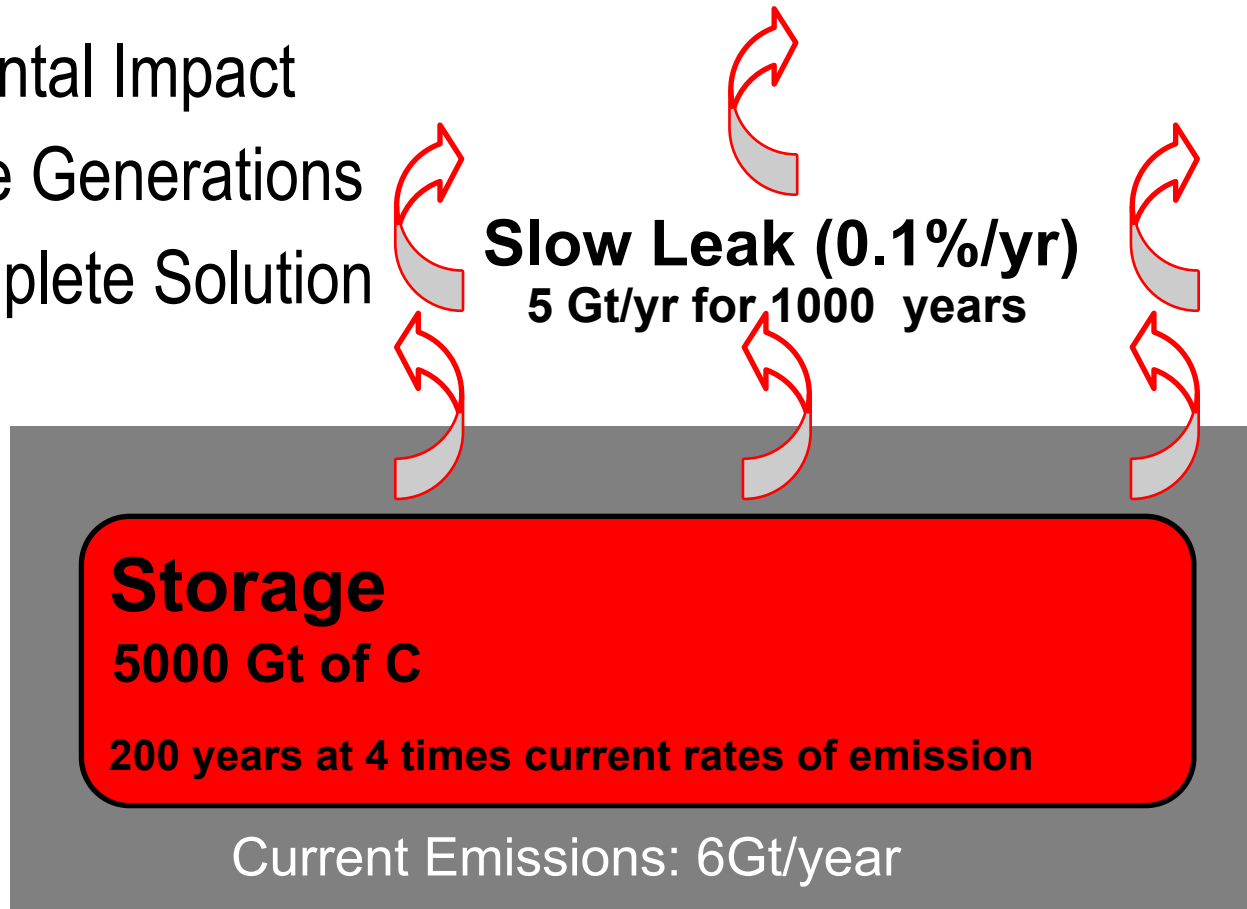
Accelerated rock weathering



Permanent & safe disposal

Constraints on Disposal Methods

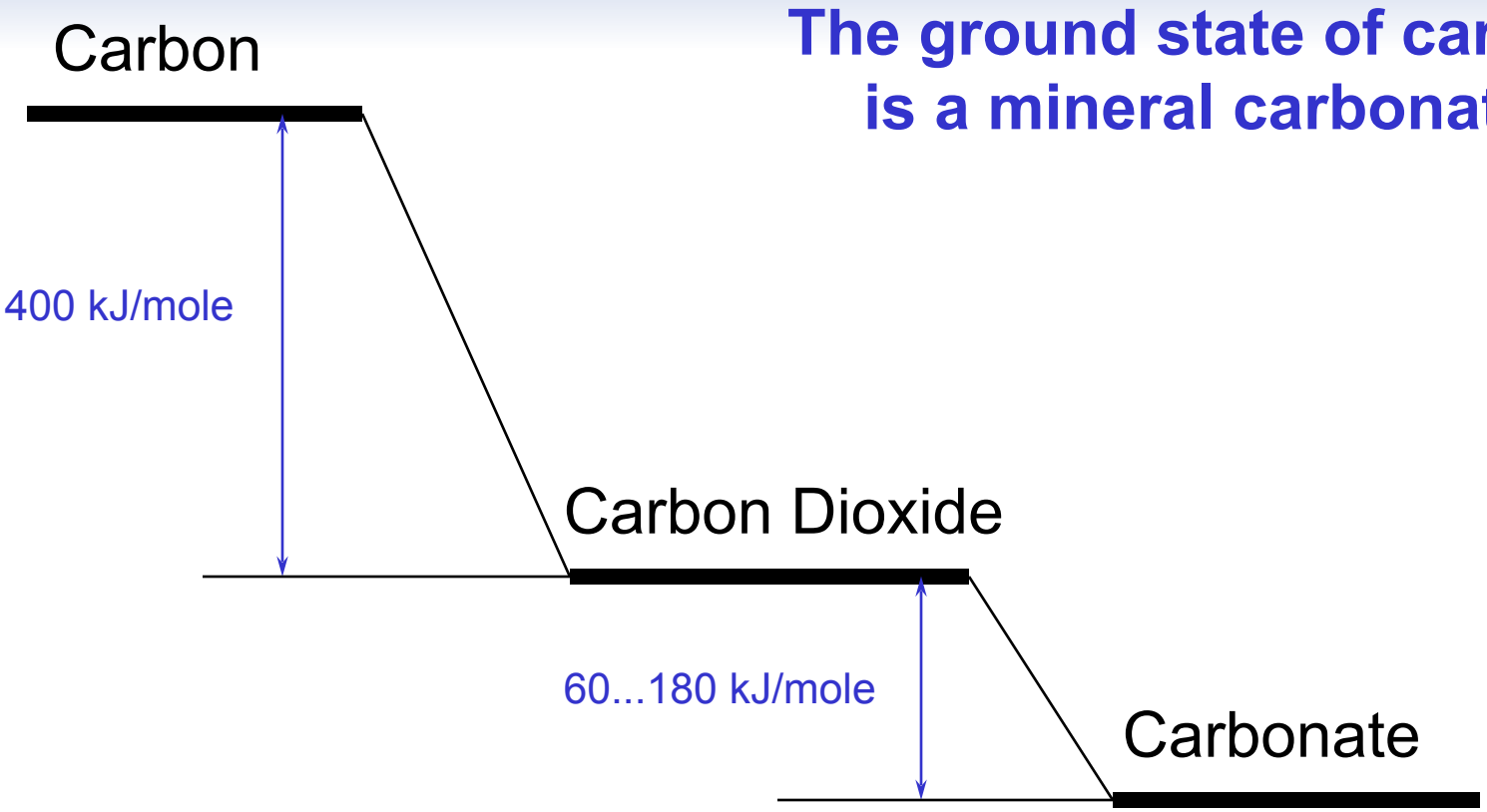
- Safe Disposal
- Minimum Environmental Impact
- No Legacy for Future Generations
- Permanent and Complete Solution
- Economic Viability



Permanent CO_2 Sequestration Through Accelerated Rock Weathering

- Simple acid-base reaction binds CO_2
- Magnesium silicates provide the base
- Process speeds up natural geologic reactions
- Process is exothermic
- CO_2 is sequestered permanently in inert form

Energy States of Carbon



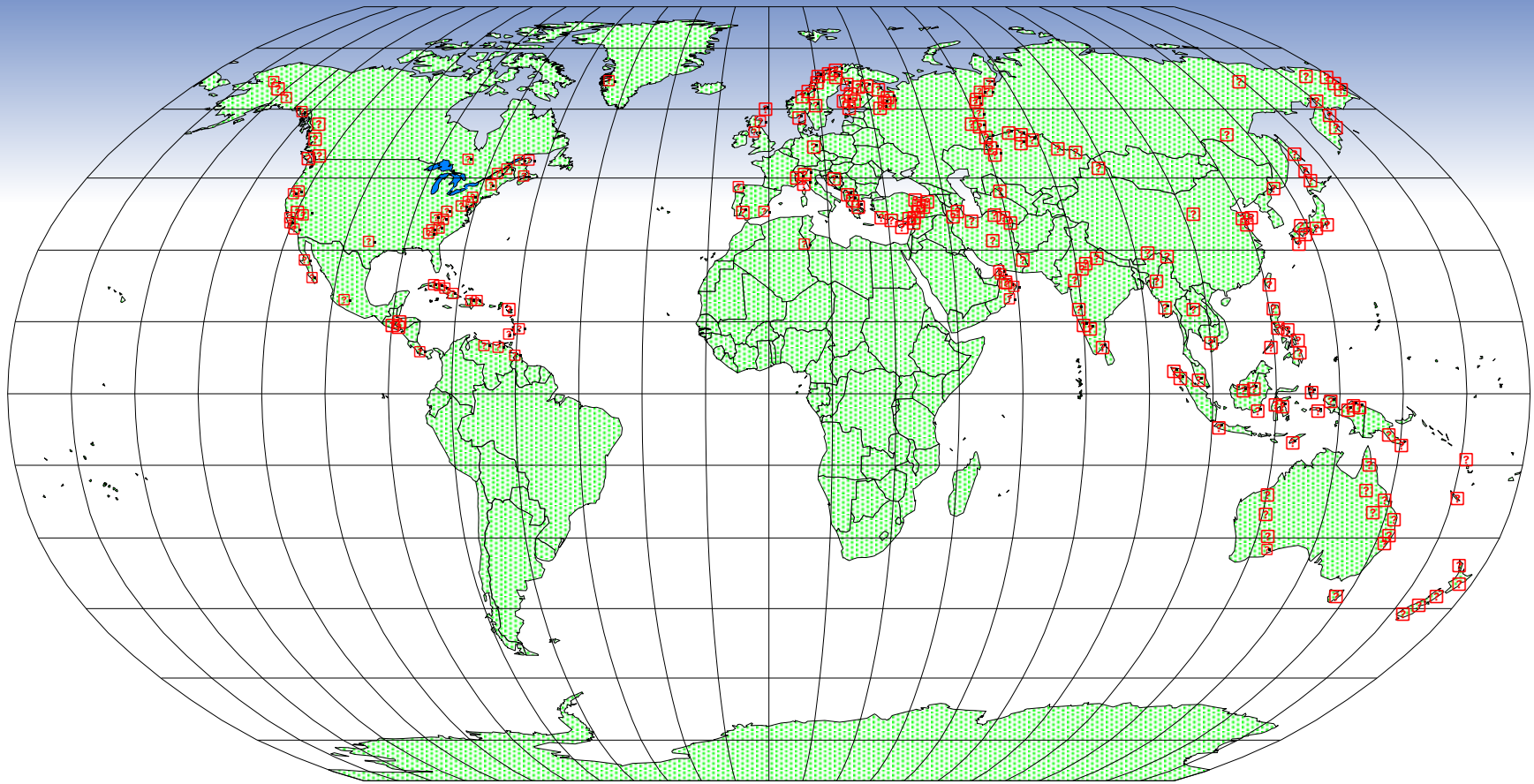
The ground state of carbon is a mineral carbonate

Net Carbonation Reaction for Serpentine

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

heat/mol CO_2 = -63.6 kJ

Peridotite and Serpentinite Ore Bodies



Magnesium resources that far exceed world fossil fuel supplies

Mineral Disposal of CO_2

Coal
3.8 ktons/day

1 GW Electricity

CO_2

80% Efficiency

Earth Moving ~40 ktons/day

25 ktons/day
36% MgO

10 ktons/day

Heat

Sand & Magnesite
~31 ktons/day

~1.2 ktons/day Fe
~0.2 ktons/day Ni, Cr, Mn

Mining, crushing & grinding: \$7/t CO_2 — Processing: \$10/t CO_2 — No credit for byproducts

ALBANY'S BREAKTHROUGH

W.K. O'Conner, D.C. Dahlin, D. N. Nilsen, R. P. Walters & P.C. Turner

Albany Research Center, Albany OR

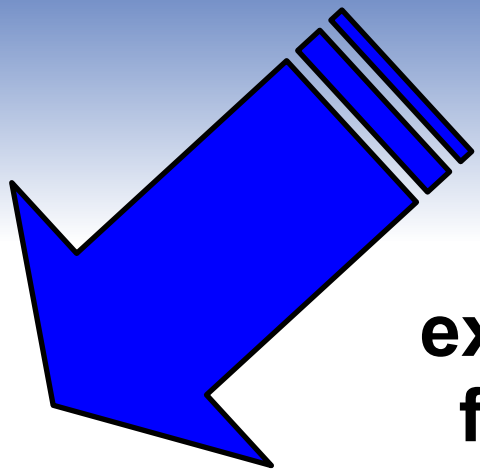
$$Mg_3Si_2O_5(OH)_4 + 3CO_2(g) \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O(l)$$

200,000 years reduced to 1/2 hour

Suggests simple cost-effective implementation

Net Zero Carbon Economy

CO_2 from concentrated sources



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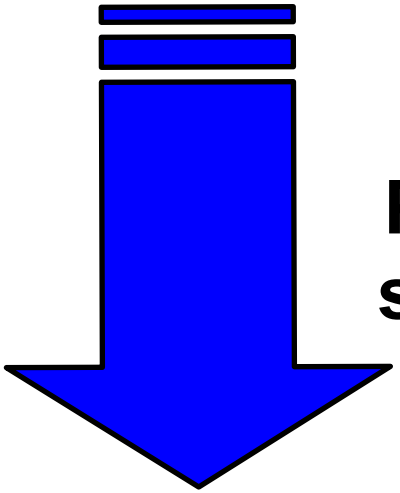
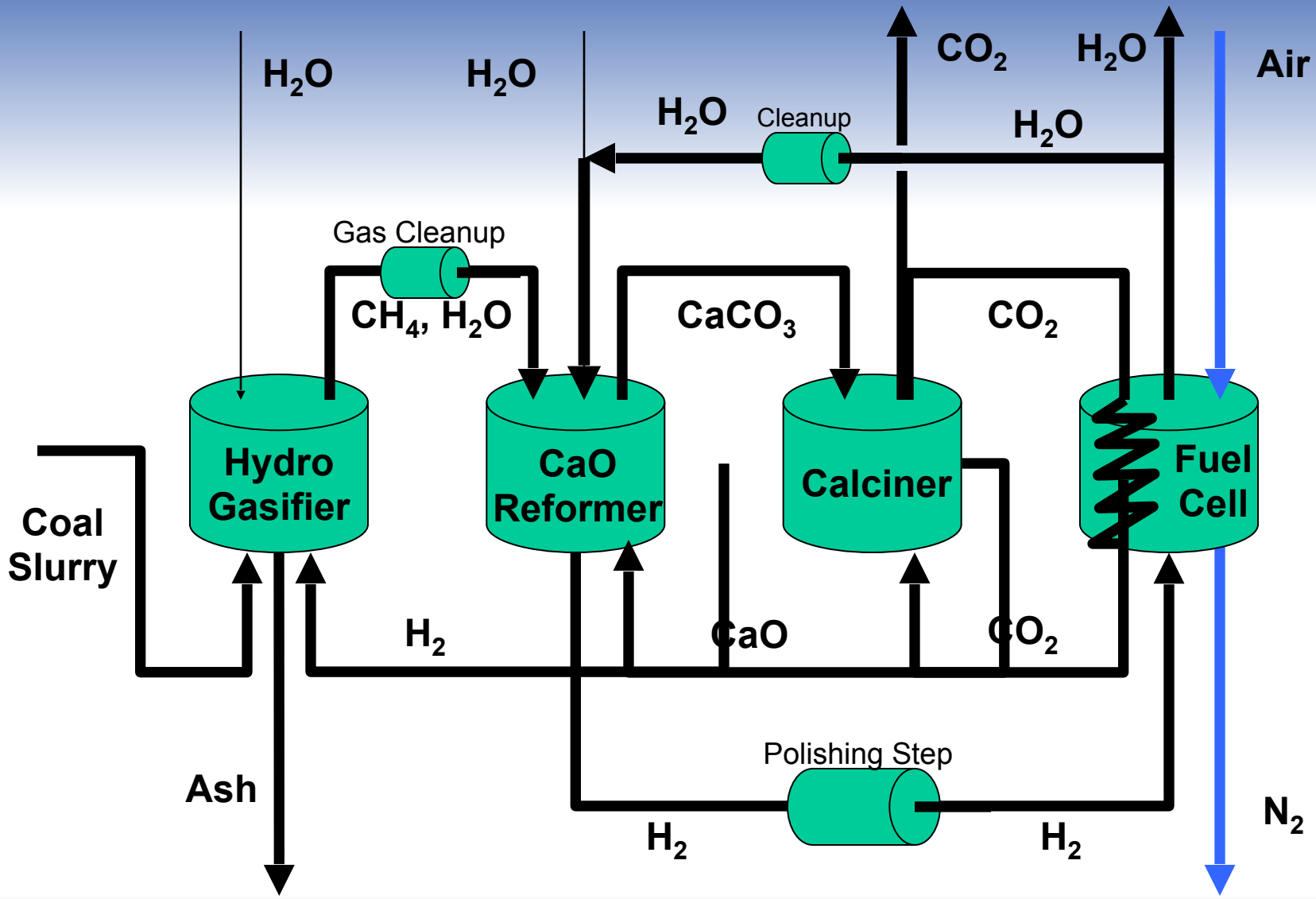


Permanent & safe disposal

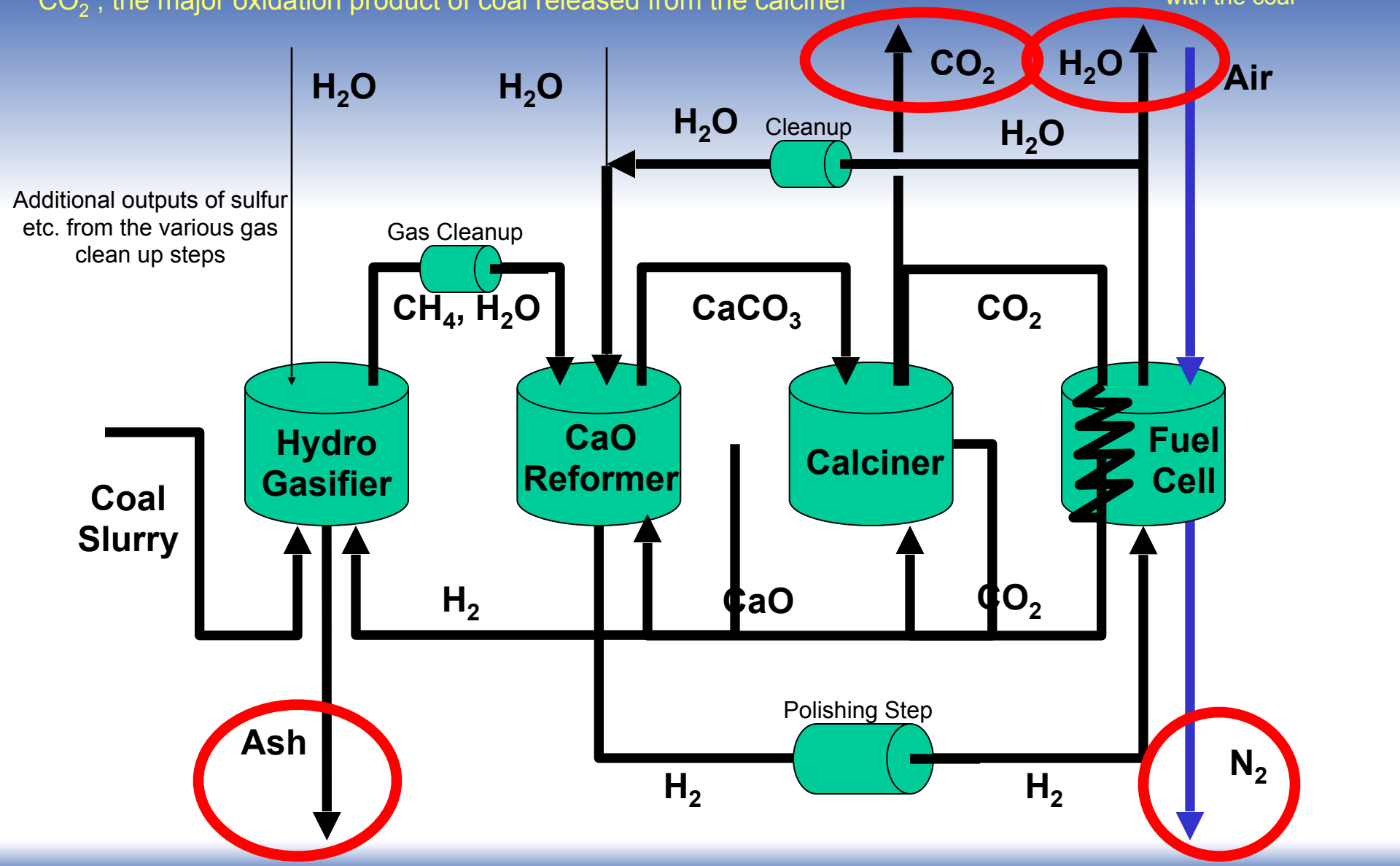
Zero Emission Coal



Outputs of the Process

CO_2 , the major oxidation product of coal released from the calciner

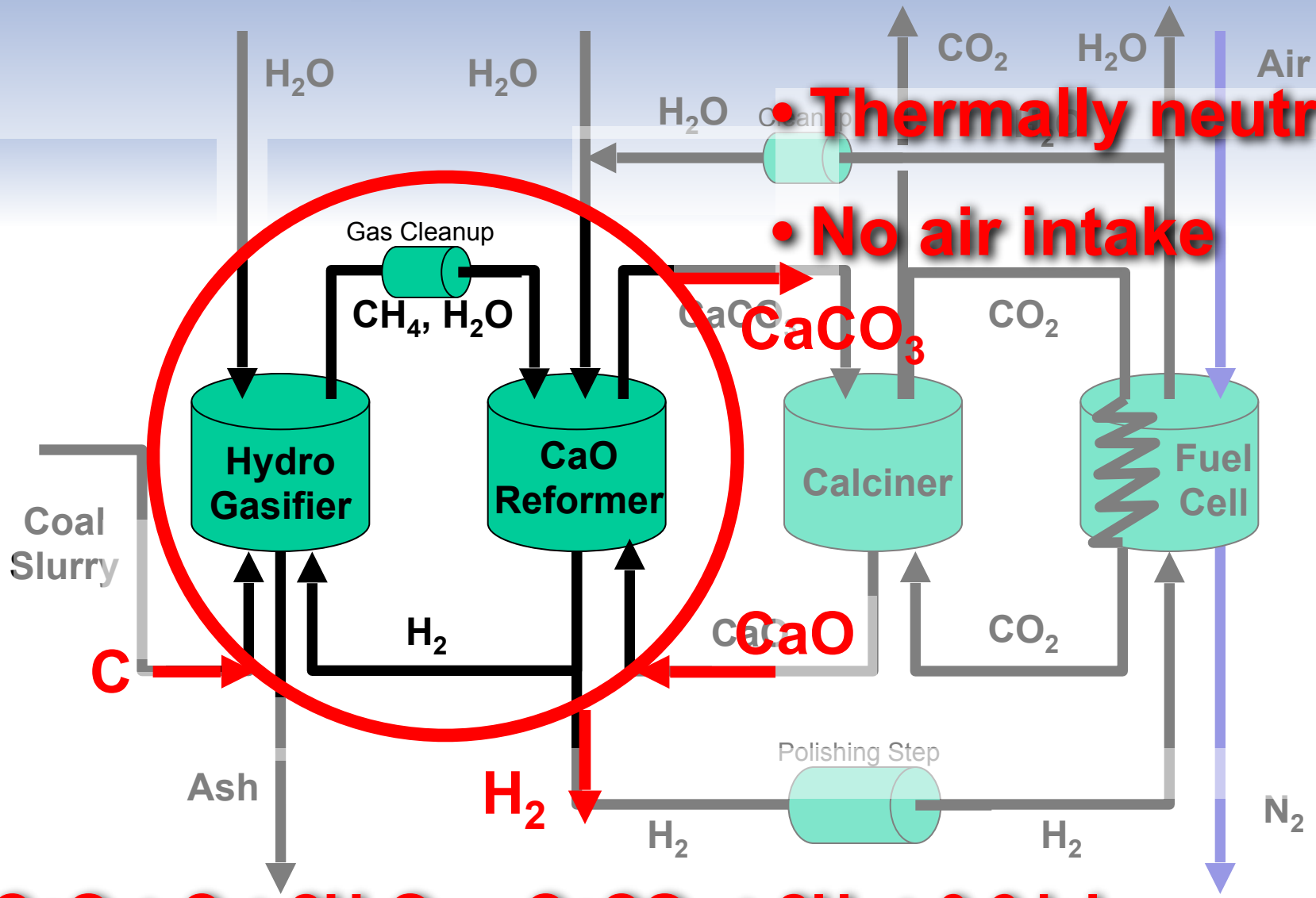
Excess H_2O from oxidized hydrogen in the coal and water that entered the gasifier with the coal



Ash from the gasifier, introduced with the coal

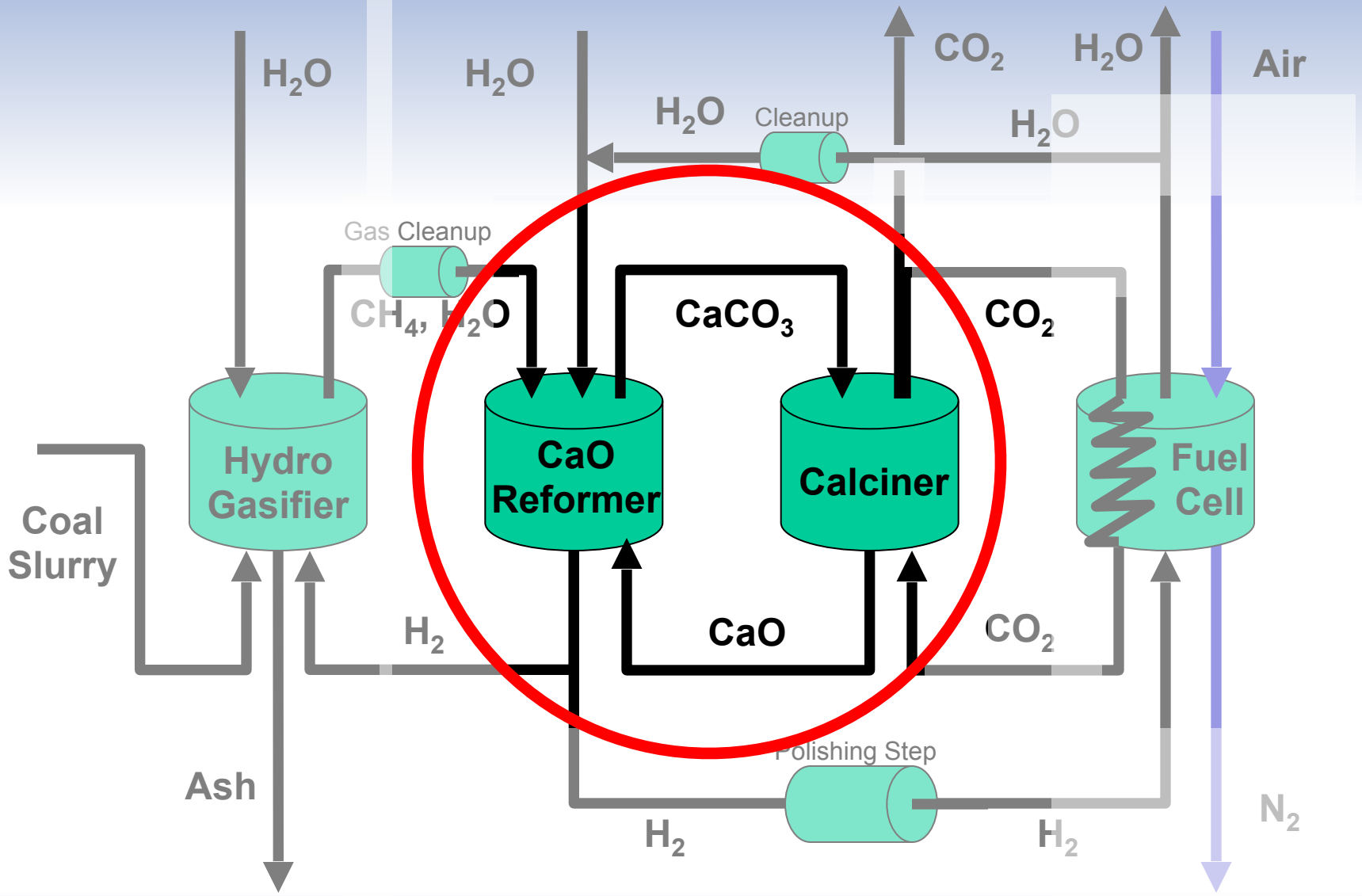
Oxygen depleted air (N_2) that passed only through the airside of the fuel cell

CO_2 Acceptor Process



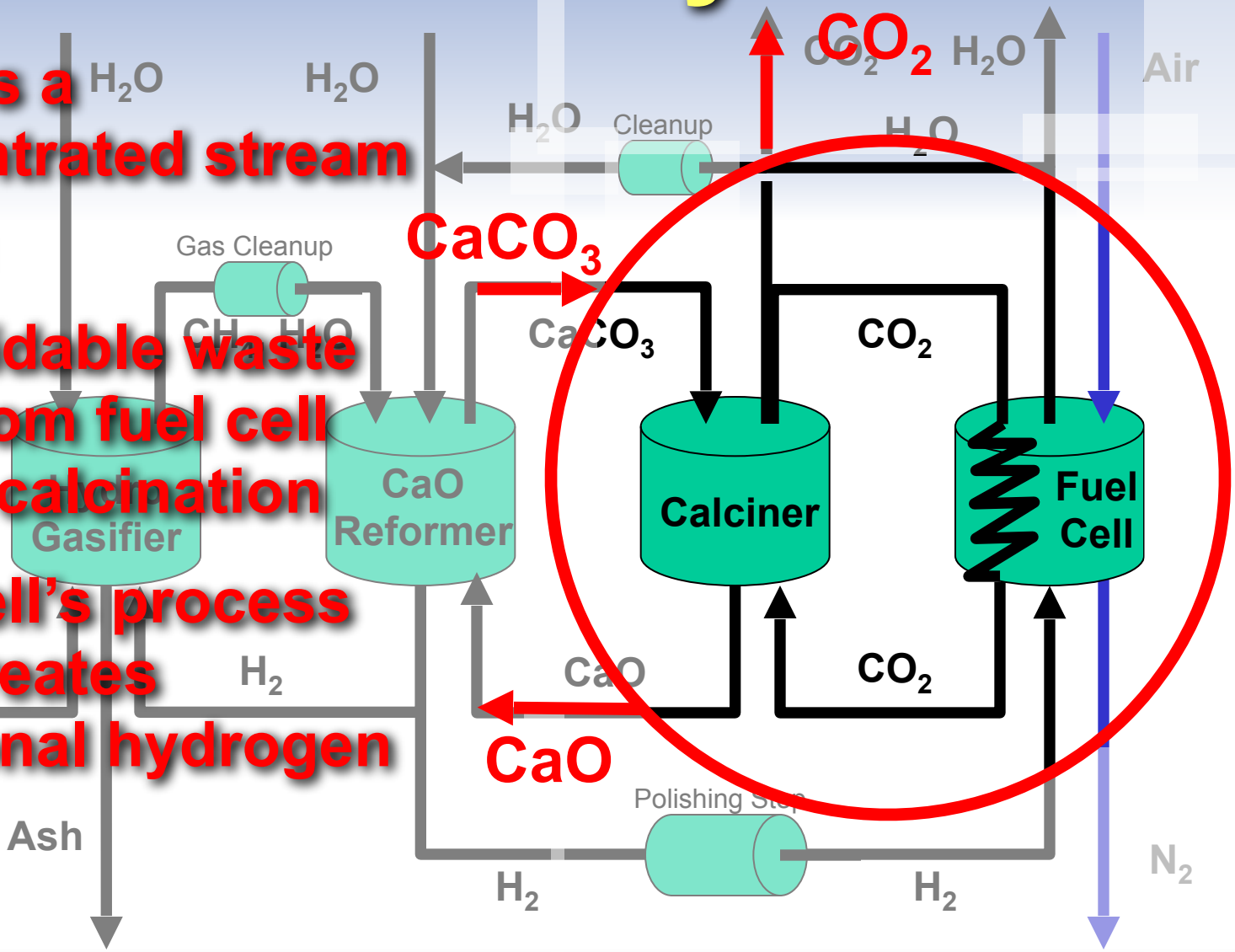
$$CaO + C + 2H_2O \rightarrow CaCO_3 + 2H_2 + 0.6\ kJ$$

CaO Recycle Loop



Heat Recycle

- Creates a concentrated stream of CO_2
- Unavoidable waste heat from fuel cell drives calcination
- Fuel cell's process heat creates additional hydrogen

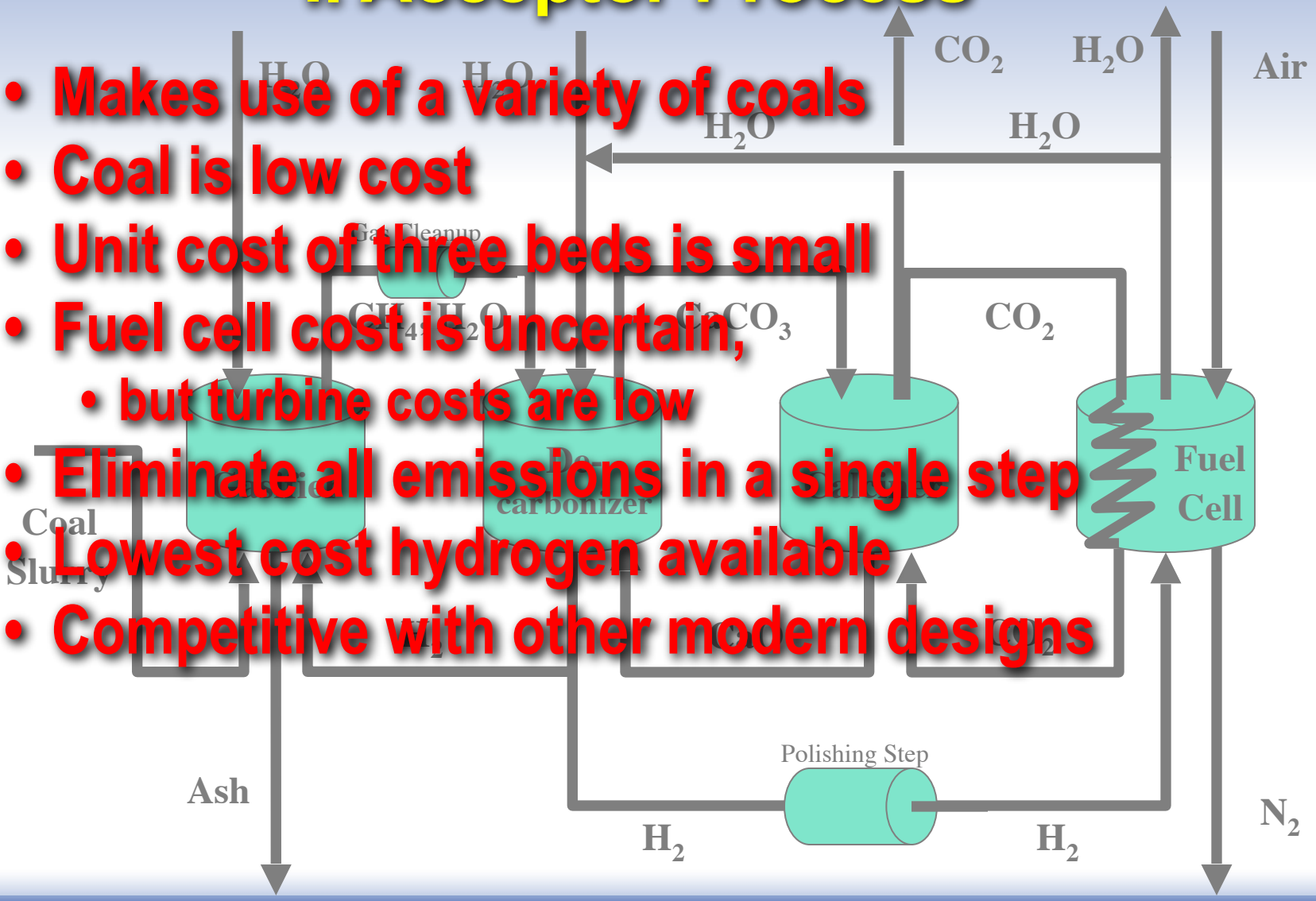


CaO Energy Loan

- H_2 carries 150% of the energy stored in carbon
- Downstream conversion efficiency boosted by 150%
- Need to pay back the energy loan from CaO
- May use waste heat for calcination

Economic Considerations
I. Acceptor Process

- Makes use of a variety of coals
- Coal is low cost
- Unit cost of three beds is small
- Fuel cell cost is uncertain,
  - but turbine costs are low
- Eliminate all emissions in a single step
- Lowest cost hydrogen available
- Competitive with other modern designs



Economics
II. Mineral Carbonate Disposal

Coal
3.8 ktons/day

Power Plant
80% Efficiency

Earth Moving ~40 ktons/day

Carbonation Plant

10 ktons/day

25 ktons/day
36% MgO

Open Pit

Sand & Magnesite

~1.2 ktons/day Fe
~0.2 ktons/day Ni, Cr, Mn

Disposal Costs for a Zero Emission Coal Plant

- **Mining cost is well understood, 0.3¢/kWh$_e$**
- **Transportation costs are well understood**
  - **shipping coal is 0.1¢/kWh$_e$**
- **Chemical processing cost needs to be proven**
  - **simple processes are cost effective, $0.4¢/kWh$_e$**

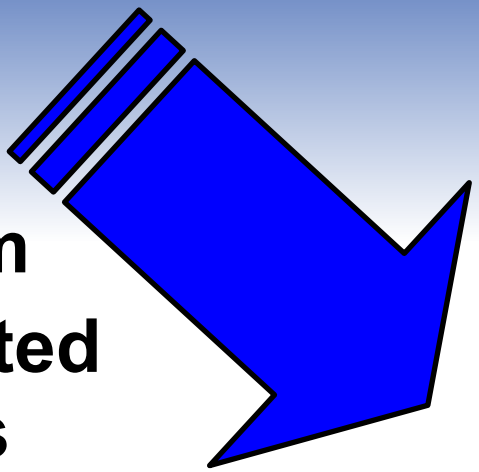
0.8¢/kW is equivalent to $20/t of CO_2

This cost would be covered by PM 2.5

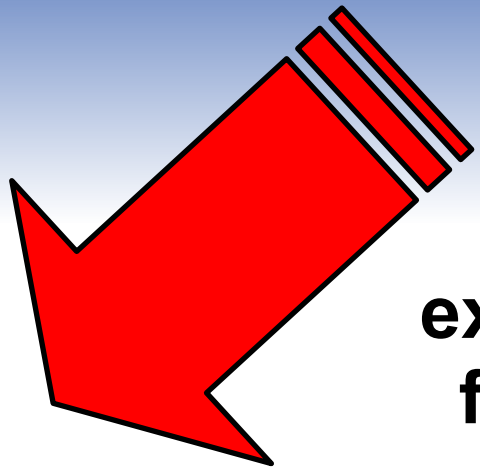
ZECA's Path

- **Avoid the use of air in the oxidation of carbon**
  - carbon dioxide acceptor process
- **High efficiency reduces cost of CO_2 disposal**
  - electrochemical process using SOFC
- **Permanent and safe disposal avoids long term costs of monitoring**
  - stable mineral carbonate

Net Zero Carbon Economy



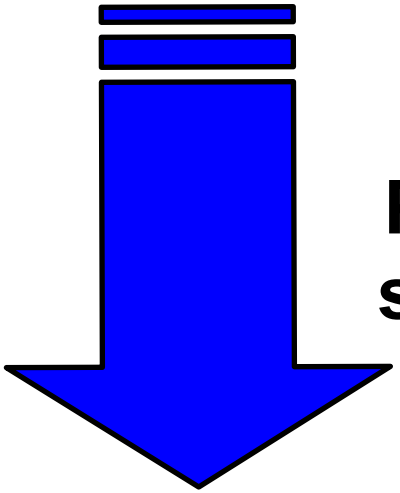
CO_2 from concentrated sources



CO_2 extraction from air

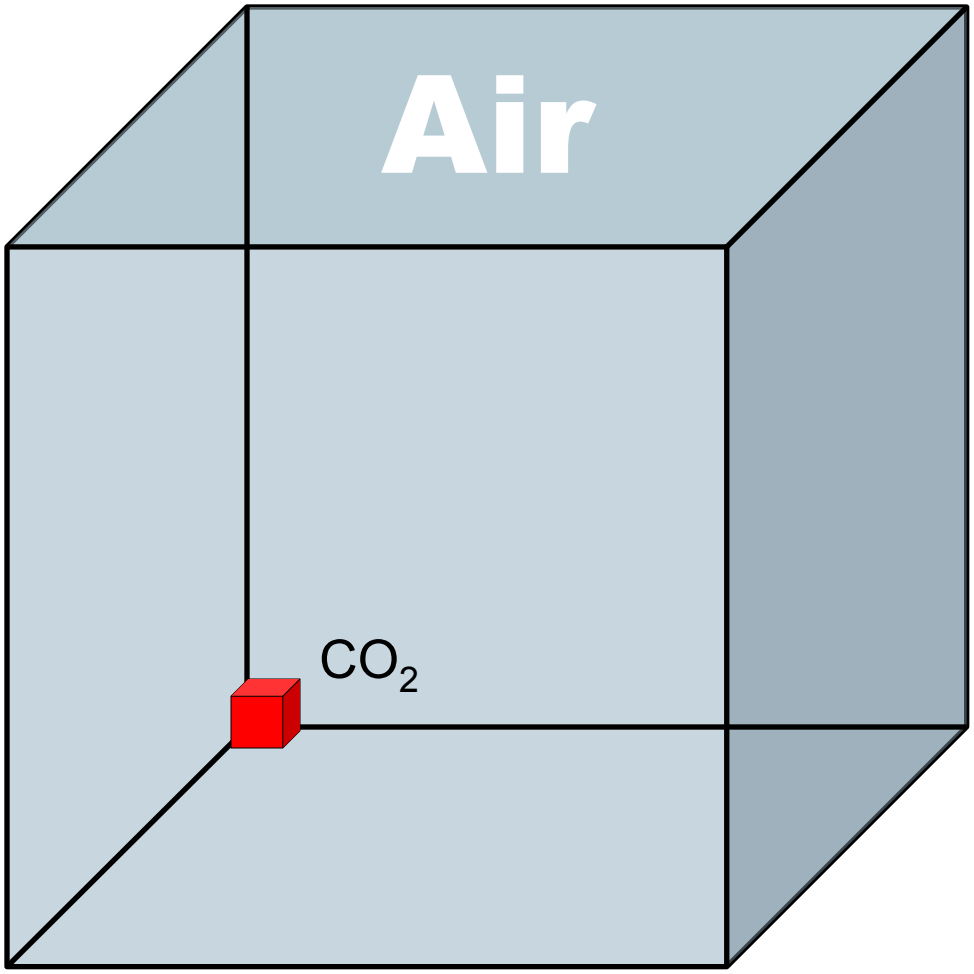
Biomass & Chemical Processes

Mobile Sources Unchanged Infrastructure



Permanent & safe disposal

1 m^3 of Air



40 moles of gas, 1.16 kg

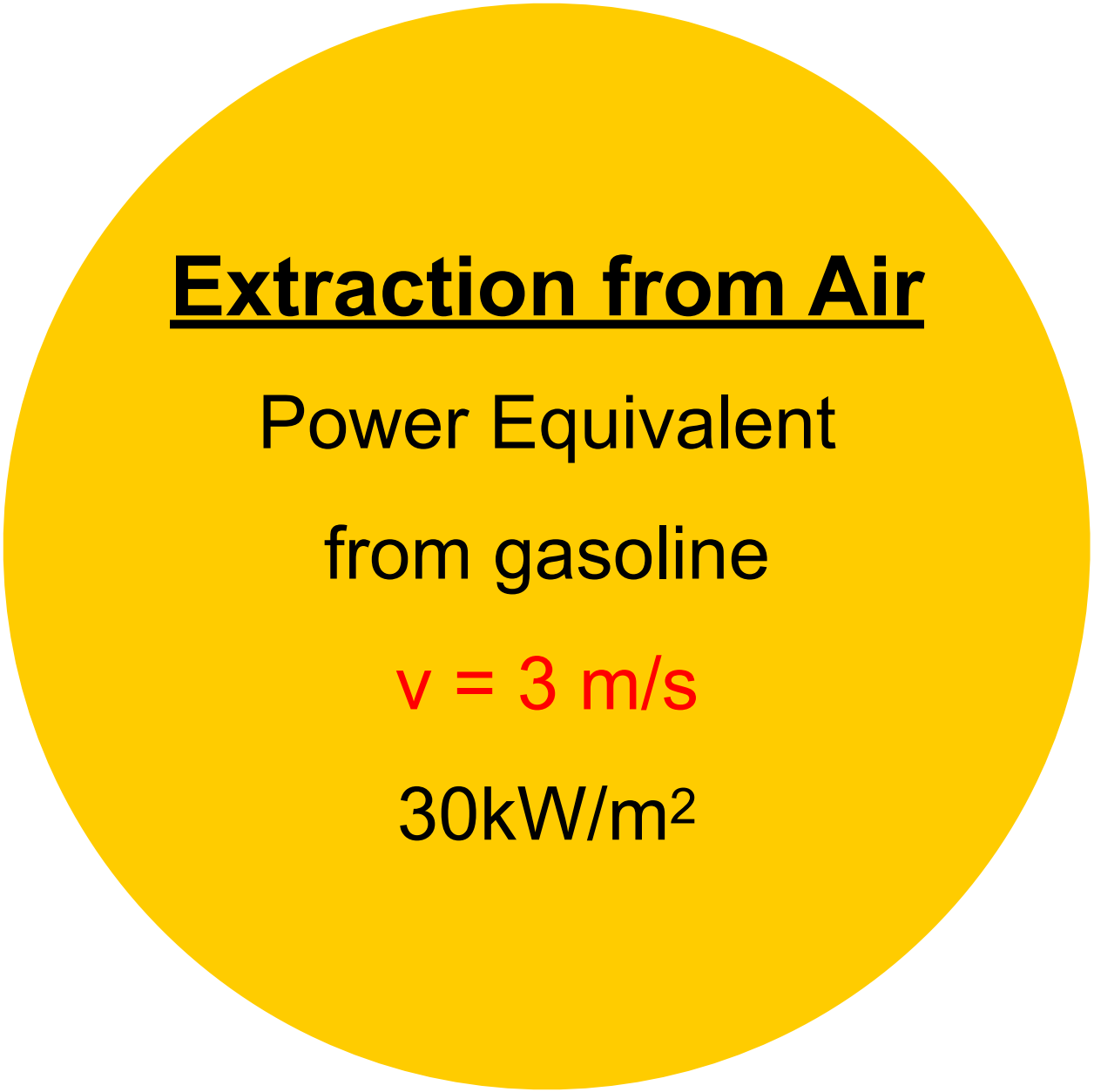
wind speed 10 m/s

$$\frac{mv^2}{2} = 60\ \text{J}$$

0.015 moles of CO_2

produced by 10,000 J of gasoline

Volumes are drawn to scale

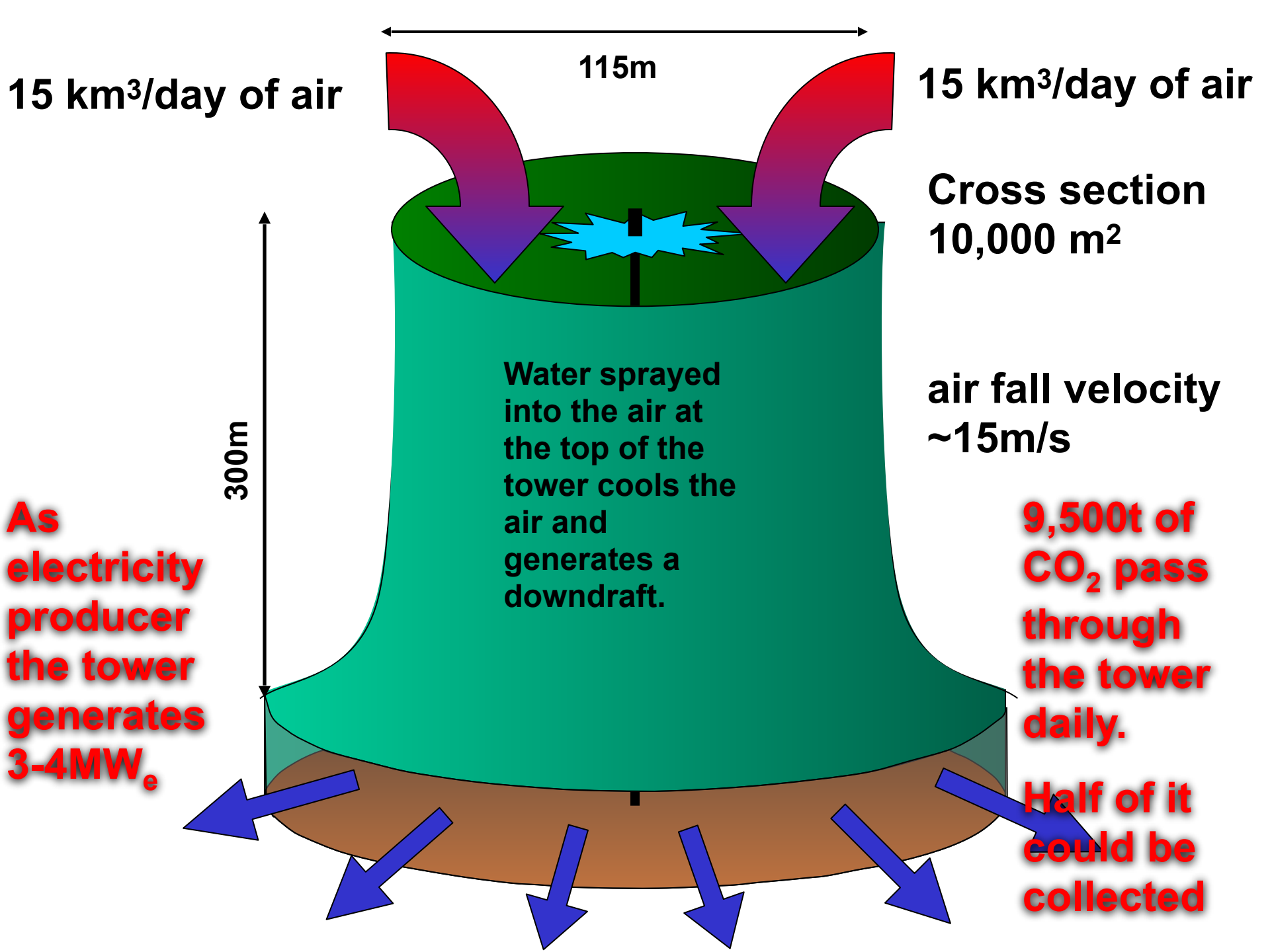


Wind Energy
v = 10m/s
600 W/m²

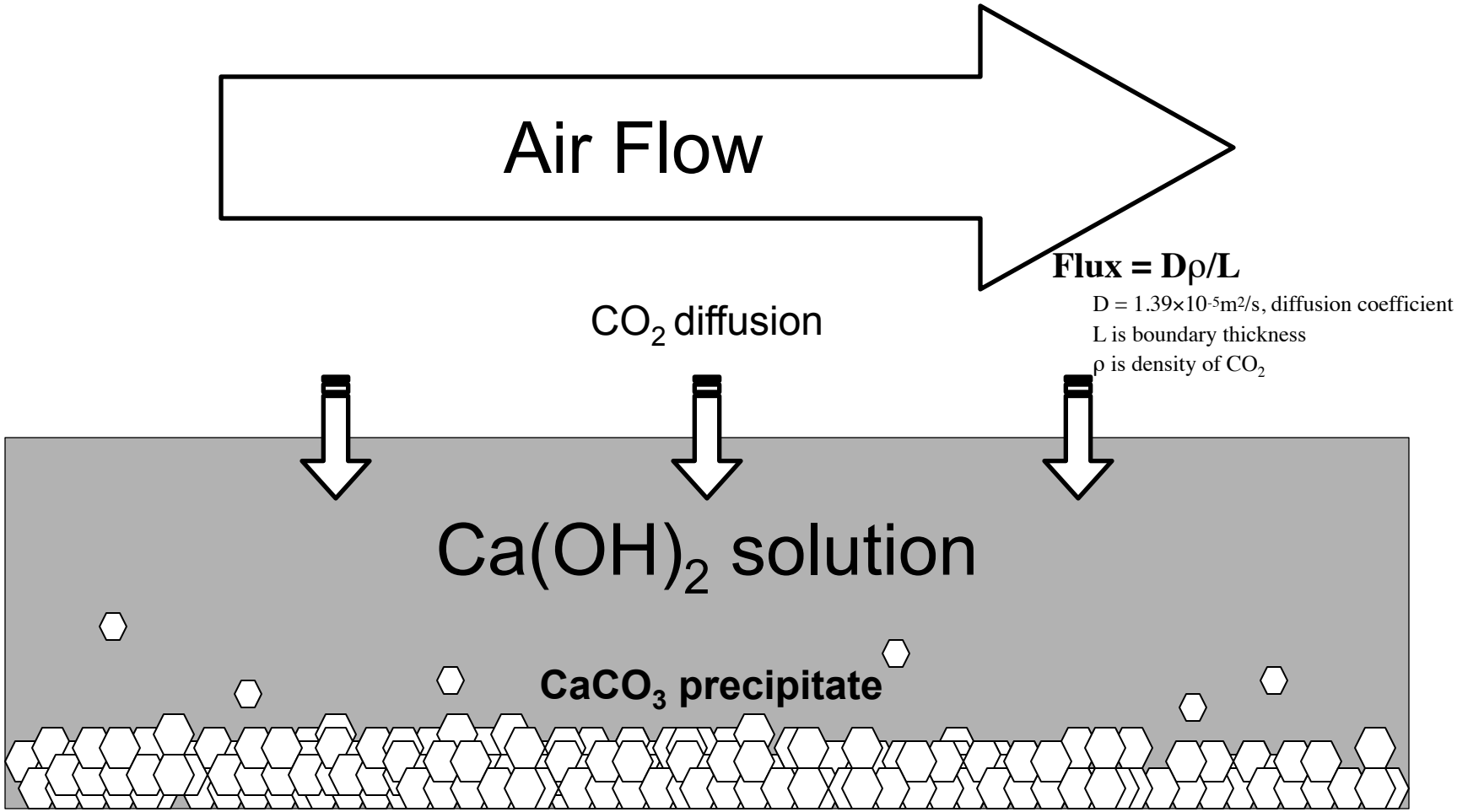
Sunshine
200 W/m²

Biomass
3 W/m²

Areas are drawn to scale


115m
15 km³/day of air
15 km³/day of air
Cross section
10,000 m²
300m
Water sprayed into the air at the top of the tower cools the air and generates a downdraft.
air fall velocity ~15m/s
As electricity producer the tower generates 3-4MWe
9,500t of CO2 pass through the tower daily.
Half of it could be collected

$Ca(OH)_2$ as an absorbent



CO_2 mass transfer is limited by diffusion in air boundary layer

Wind Energy - CO_2 Collection

Wind Energy

- Convection tower, Wind Mill etc.
- Extract kinetic energy
- Wind Turbines
- 30% extraction efficiency
- Throughput
  130W/m² @ 6m/s
- Cost
  $0.05/kWh

CO_2 Collection

- Convection tower, absorbing "leaves", etc.
- Extract CO_2
- Sorbent Filters
- 30+% extraction efficiency
- Throughput
  0.64g/(s·m²) @ 6m/s
- Cost by analogy
  $0.50/ton of CO_2

Large Additional Cost in Sorbent Recovery

Cost is in Sorbent Recovery

- **ENERGY COST**
  - Recovery of the absorbent (CaO)
    - 179kJ/mole or 0.14 tons of coal per ton of CO_2
    - Assume four times the cost for capital and operation

$11/ton of CO_2

Disruptive Technology

System can be designed to:

- **Slow the rate of CO_2 increase**
- **Plateau CO_2 level by CO_2 removal equal to production**
- **Return CO_2 levels to those of earlier times**

No change in infrastructure necessary

Carbon Credits

- Oil from the Persian Gulf
  - could be certified as carbon neutral
  - with CO_2 left behind in Oman's Coastal Range

  - Does not require international agreement

Take Back The Empties