Carbon Dioxide Separation from Coal and from Air

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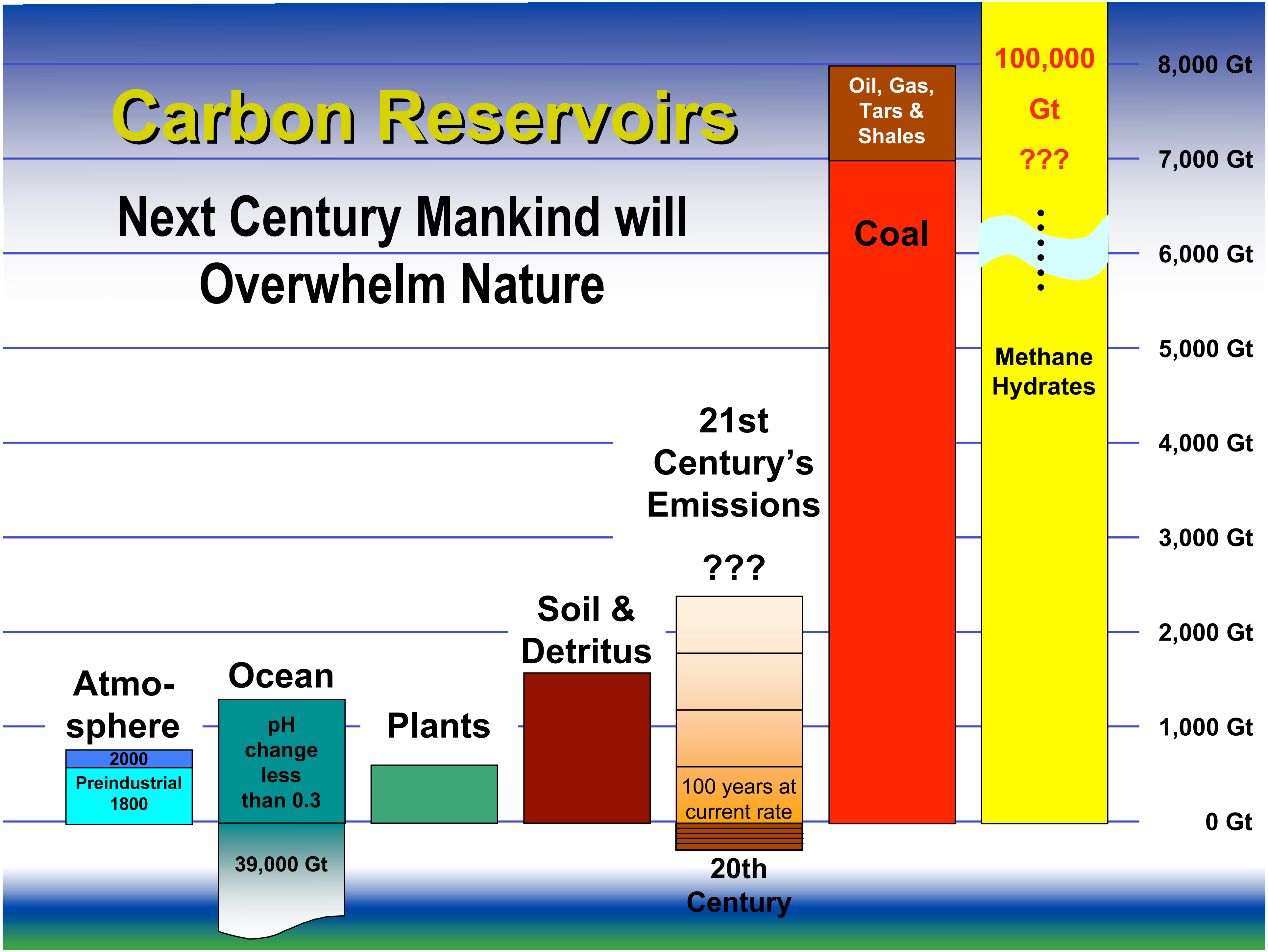
Two Extreme Approaches

- Separate energy from carbon as early as possible
  - Central power plants and hydrogen plants
  - Retrofitting is expensive
  - CO_2 disposal near energy consumers

- Collect equivalent amount of CO_2 from air
  - Distributed and mobile sources of CO_2
  - Avoids costly changes to infrastructure
  - CO_2 disposal in optimal sites


Carbon Reservoirs
Next Century Mankind will
Overwhelm Nature
Oil, Gas,
Tars &
Shales
Coal
100,000
Gt
???
Methane
Hydrates
8,000 Gt
7,000 Gt
6,000 Gt
5,000 Gt
4,000 Gt
3,000 Gt
2,000 Gt
1,000 Gt
0 Gt
21st
Century's
Emissions
???
Soil &
Detritus
Atmo-
sphere
2000
Preindustrial
1800
Ocean
pH
change
less
than 0.3
39,000 Gt
Plants
100 years at
current rate
20th
Century

Doubling CO_2?

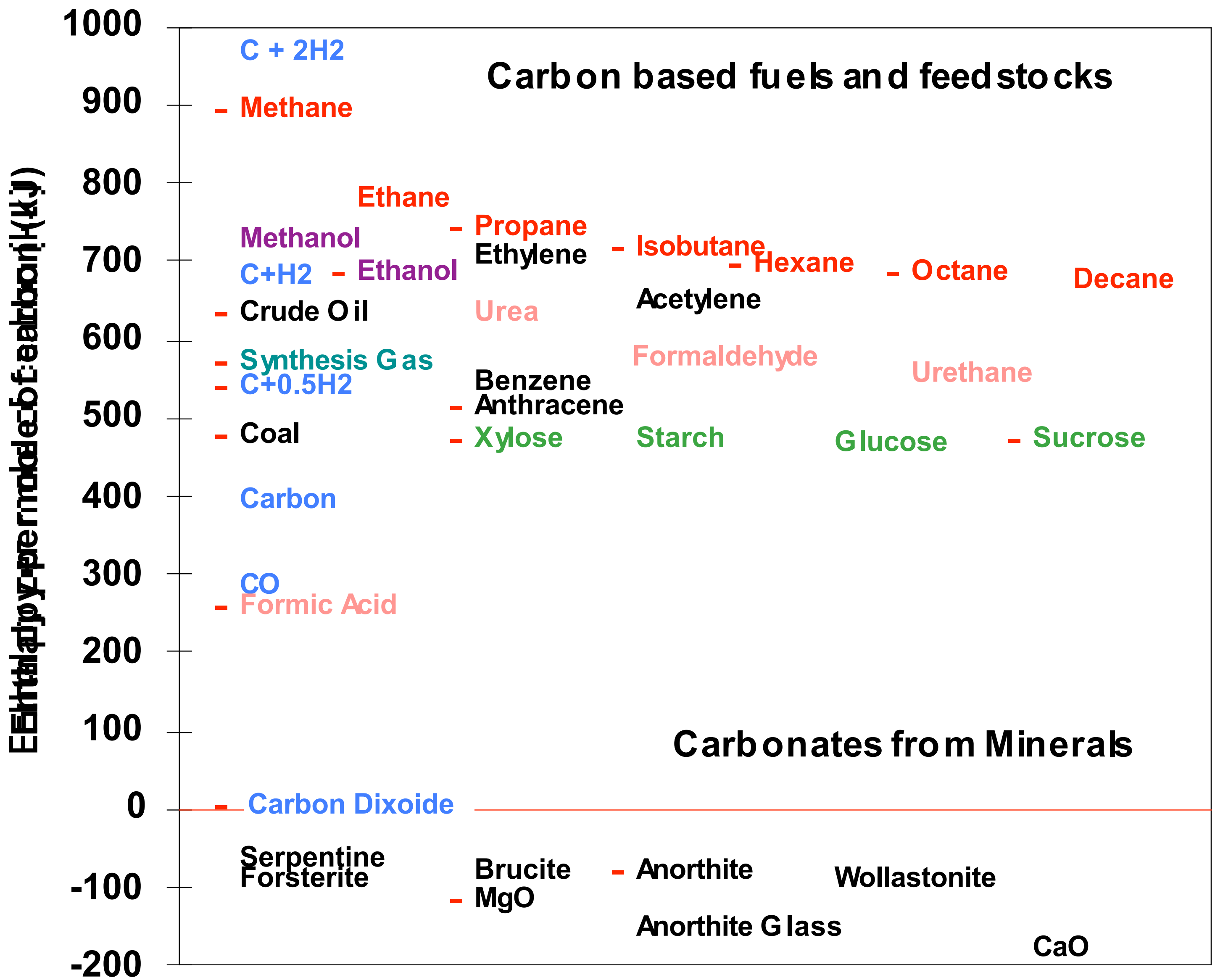
- The *per capita* emission allowance of 10 billion people sharing into current emissions would be 10% of the current US *per capita* output.
- Stabilizing CO_2 at twice the pre-industrial level would require a factor of three reduction from today.
- Taken together this would imply a factor of 30 reduction.
- However, there is a 50 year buffer before doubling will occur.

Both Methods Require Carbon Dioxide Disposal Options

Constraints on Disposal

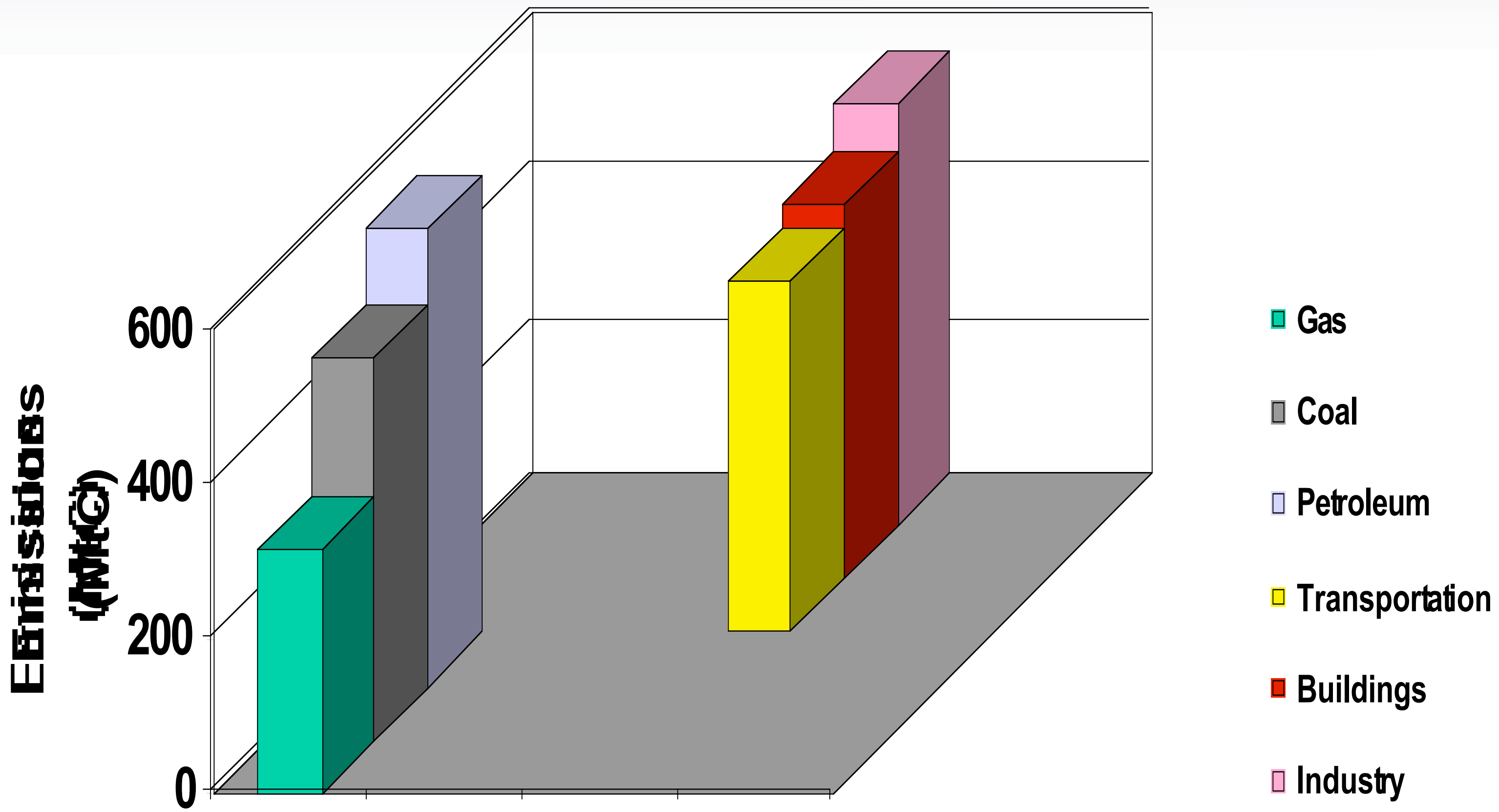
- Safety
- Minimum Environmental Impact
- No Legacy for Future Generations
- Permanent and Complete Solution
- Economic Viability

Extracting Energy from Carbon makes CO_2 or Carbonate

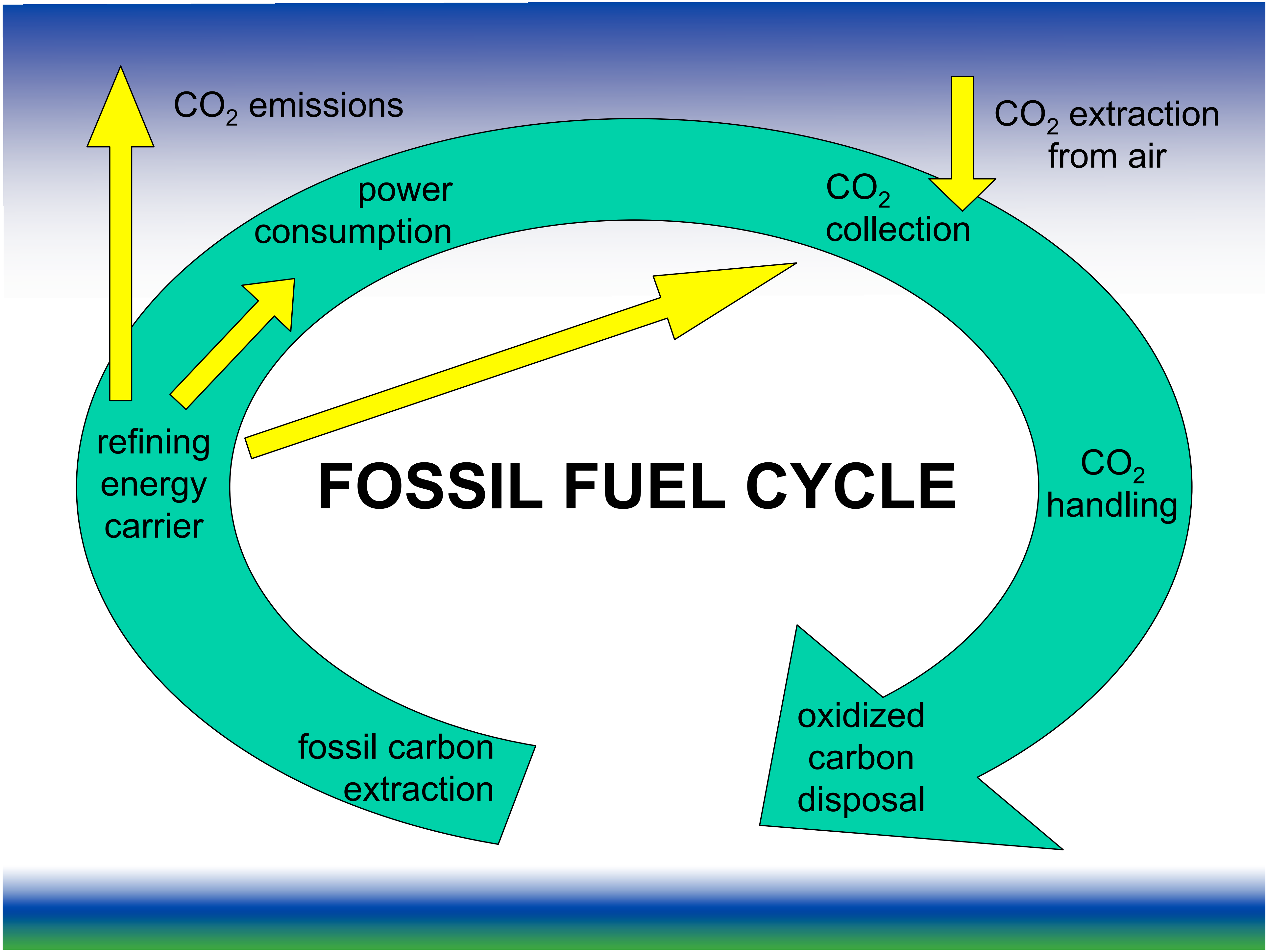


Consumption & Source Breakdown

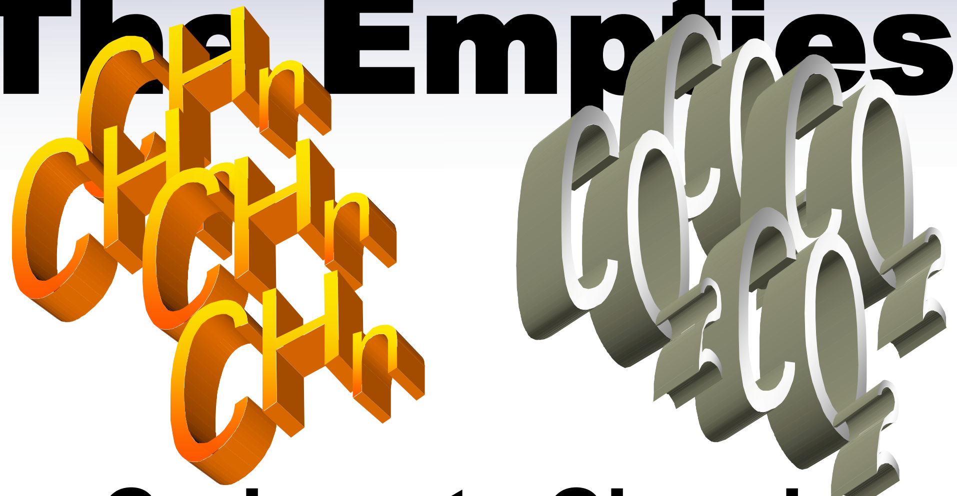
1995 US Carbon Emissions
million metric tons of carbon equivalent (MtC)



A large fraction of all CO_2 is generated by small or mobile sources for which collection at the source is too difficult


CO_2 emissions
CO_2 extraction from air
power consumption
CO_2 collection
refining energy carrier
FOSSIL FUEL CYCLE
CO_2 handling
fossil carbon extraction
oxidized carbon disposal

Take Back The Empties



Zero Emission Coal

Net Zero Emission from Transportation Fuels

Carbonate Chemistry

- **Redesign Power Plant so that it provides a concentrated stream of CO_2**

  CaO based CO_2 acceptor process leads to an ultra-efficient power plant design

- **Collect the CO_2 directly from the air**

  CO_2 in air is a much more lucrative target than the kinetic energy harvested as wind energy

- **Dispose of CO_2 in a safe and permanent form**

  Mineral carbonates are permanent, stable and require no energy to form

Power plants that capture their own CO_2 need to be optimized around this concept

Generate a concentrated, pressurized stream of CO_2

- Avoid combustion of carbon with air
- Revisit processes that looked uneconomic because they require pure oxygen or must remove CO_2 to complete the reaction

Optimize the overall process

The separation step should also contribute to the energy production:

- Solid Oxide Fuel Cells separate oxygen from air while producing electricity.
- Membrane separation can remove CO_2 from the reaction products while driving the hydrogen production forward.
- Absorbers, can remove CO_2 while providing heat to perform steam reforming.

Anaerobic Hydrogen Production

(The CO_2 Gas Acceptor Process)

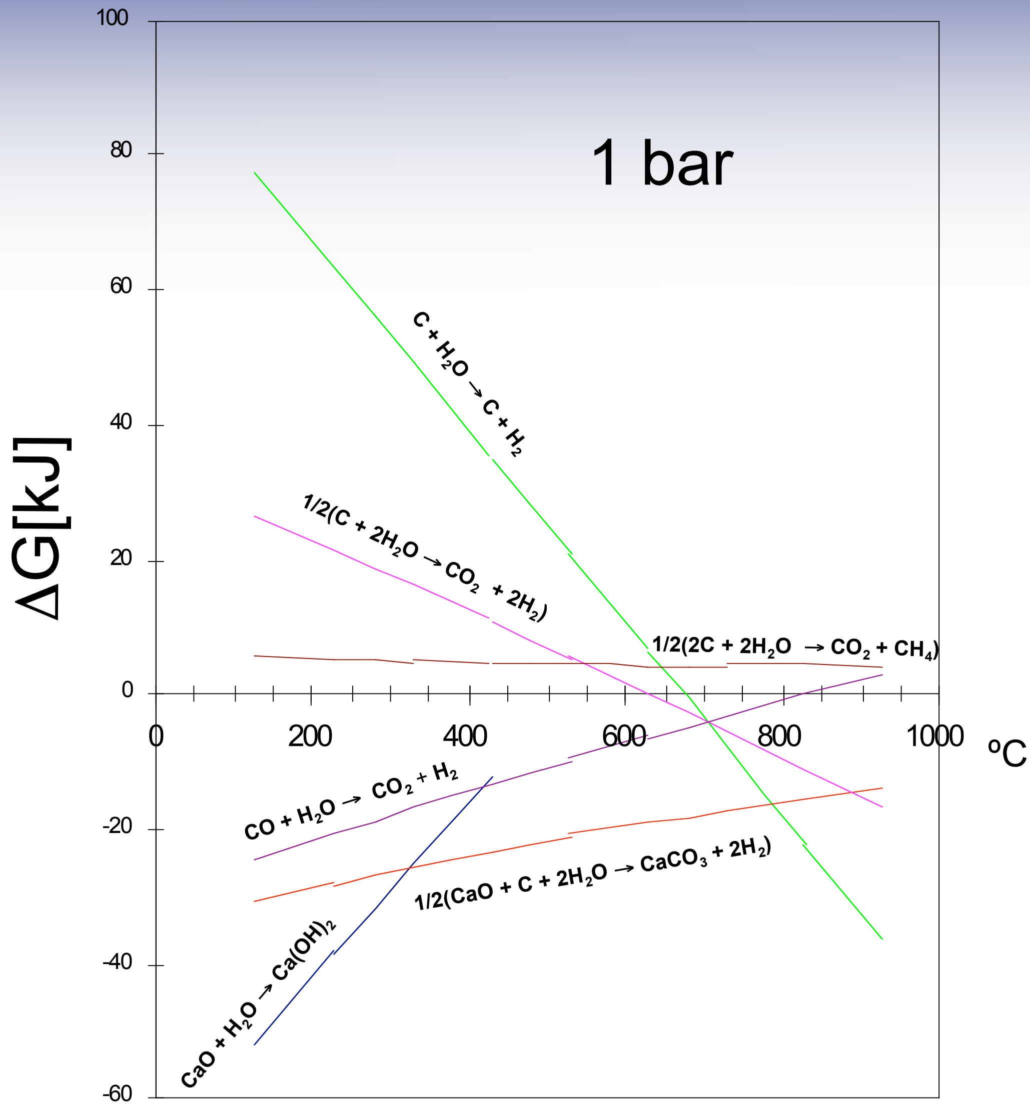
- **Based on old idea (early 1900's)**
  - 1970's Pilot Plant in Rapid City, South Dakota (CONSOL)
  - Plan to modernize older idea using new technology
- **Change emphasis and apply new concepts**
  - Incorporate CO_2 Capture
  - Increase the power generation efficiency
  - Incorporate Fuel Cells
  - Bury the CO_2 permanently

The Basic Reactions

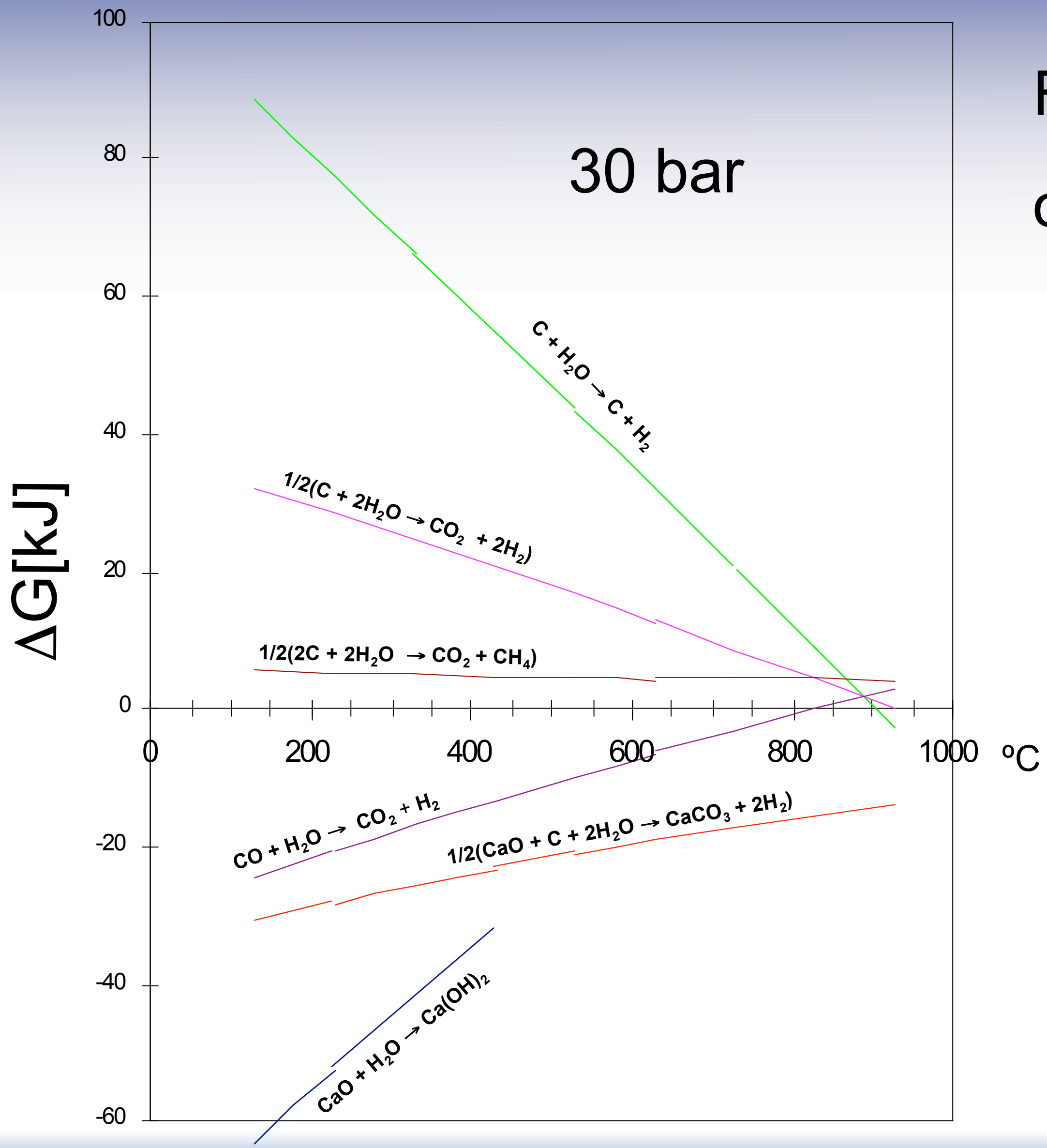
$CaO + CO_2$	$\Leftrightarrow$	$CaCO_3$	+ 178.8 kJ
$C + 2H_2O$	$\Leftrightarrow$	$CO_2 + 2H_2$	– 178.2 kJ
$C + 2H_2$	$\Leftrightarrow$	CH_4	+ 74.8 kJ
$CH_4 + 2H_2O$	$\Leftrightarrow$	$CO_2 + 4H_2$	– 253.0 kJ
$C + O_2$	$\Leftrightarrow$	CO_2	+ 393.5kJ
$2H_2 + O_2$	$\Leftrightarrow$	$2H_2O$	+ 571.7kJ

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

Free Energies of Reactions



Free Energies of Reactions



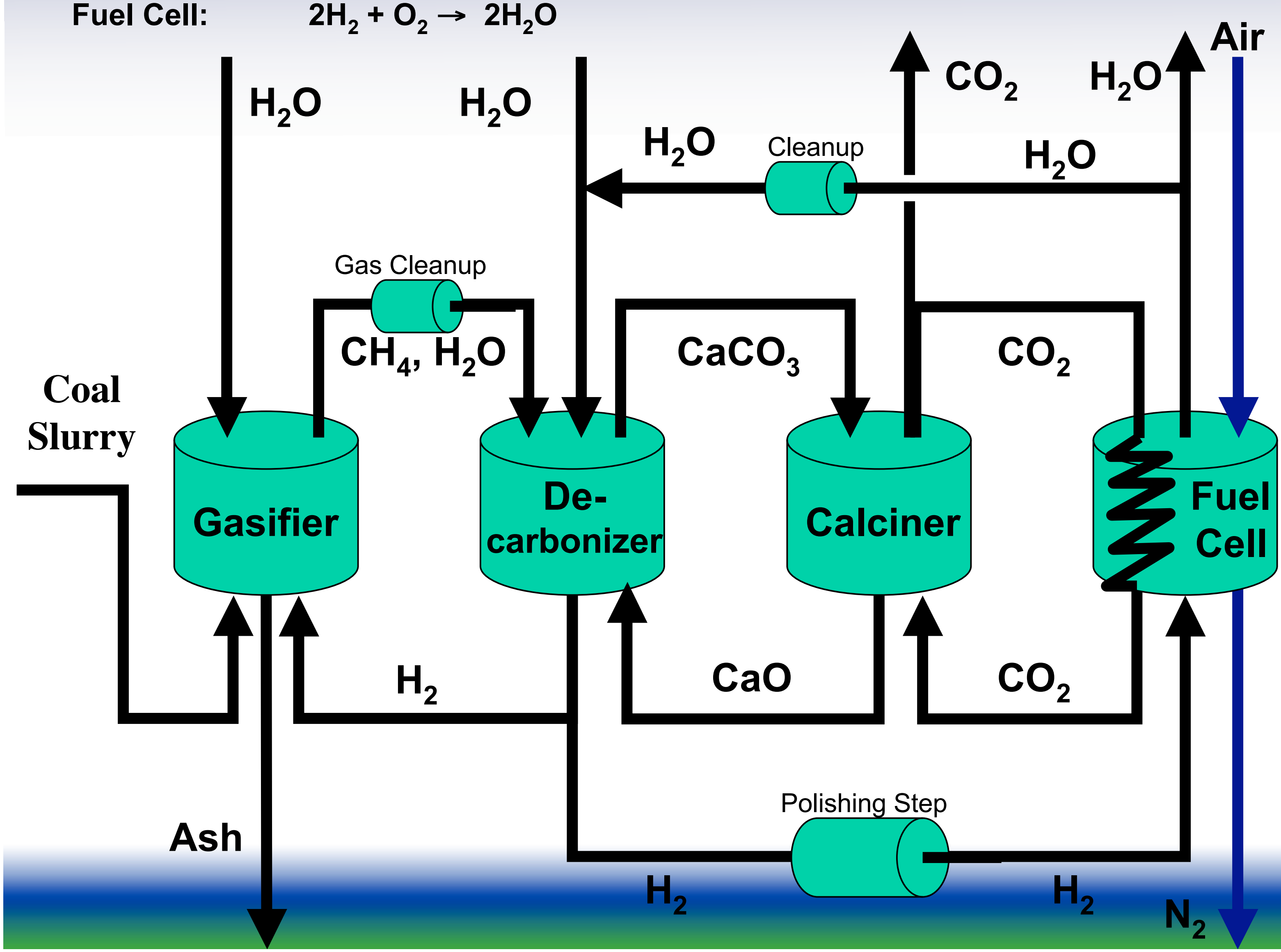
ZERO EMISSION COAL POWER PLANT

Gasifier: $C + 2H_2 \rightarrow CH_4$, $H_2O(l) \rightarrow H_2O(g)$

Decarbonizer: $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$, $CO_2 + CaO \rightarrow CaCO_3$

Calciner: $CaCO_3 \rightarrow CaO + CO_2$

Fuel Cell: $2H_2 + O_2 \rightarrow 2H_2O$



Hydrogen carries heat of combustion of coal plus heat of carbonation of CaO to the fuel cell

This amounts to 150% of the heat content of the coal. Solid oxid fuel cell pays back the "energy loan" with thermo-dynamically unavoidable waste heat.

Efficiency of fuel cell in terms of heat content of coal is boosted by factor 1.5. Theoretical efficiency is 93%.

We expect lowest cost hydrogen available today.

Energy Balance

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

$$O_2 + 2H_2 \rightarrow 2H_2O + 571.7\ kJ$$

178.8 kJ

$$CaCO_3 + \textit{heat} \rightarrow CaO + CO_2$$

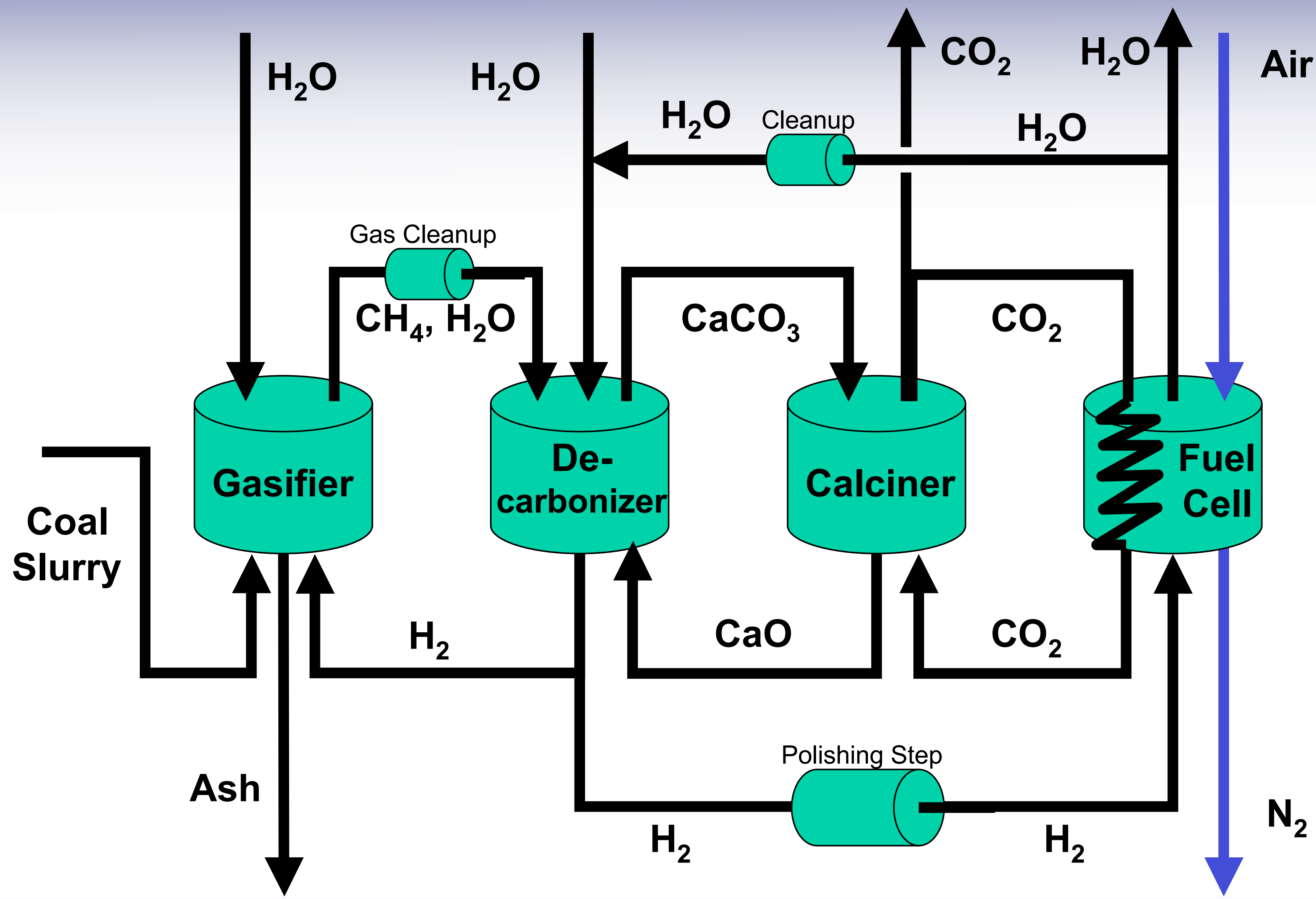
392.9 kJ

Output

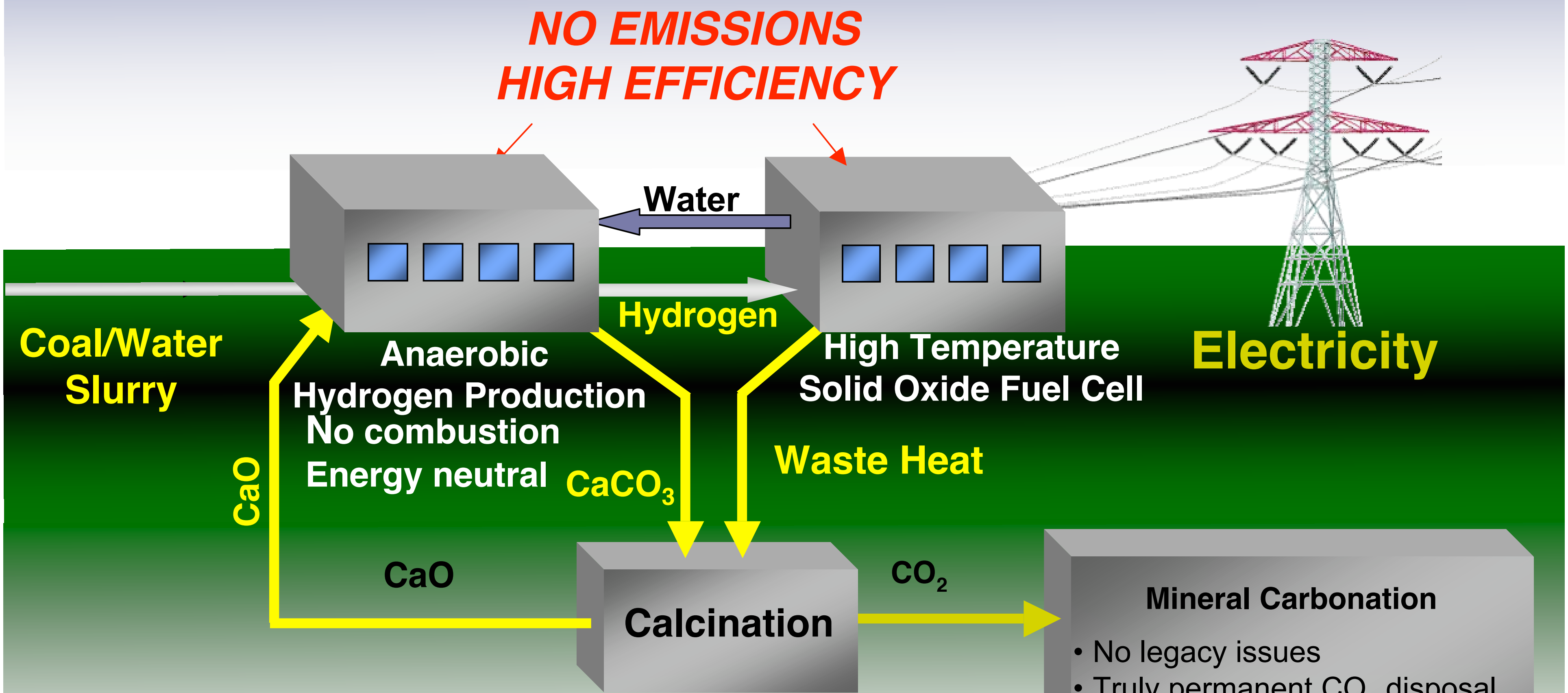
Compare to

$$C + O_2 \rightarrow CO_2 + 393.5\ kJ$$

Zero Emission Coal



Zero Emission Anaerobic Hydrogen/Electricity Production



Coal to electricity with extremely high efficiency

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

Zero Emission Coal Alliance (ZECA)
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**
- **Doubled Efficiency**
- **Economic Implementation**

Strengths of the process

- No costly oxygen separation
- No high temperature membrane gas separation
- Ultra-high efficiency
- No air processing, minimal NO_x
- Concentrated stream of CO_2 ready for disposal
- All potential emissions handled at once

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

ALBANY'S BREAKTHROUGH

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

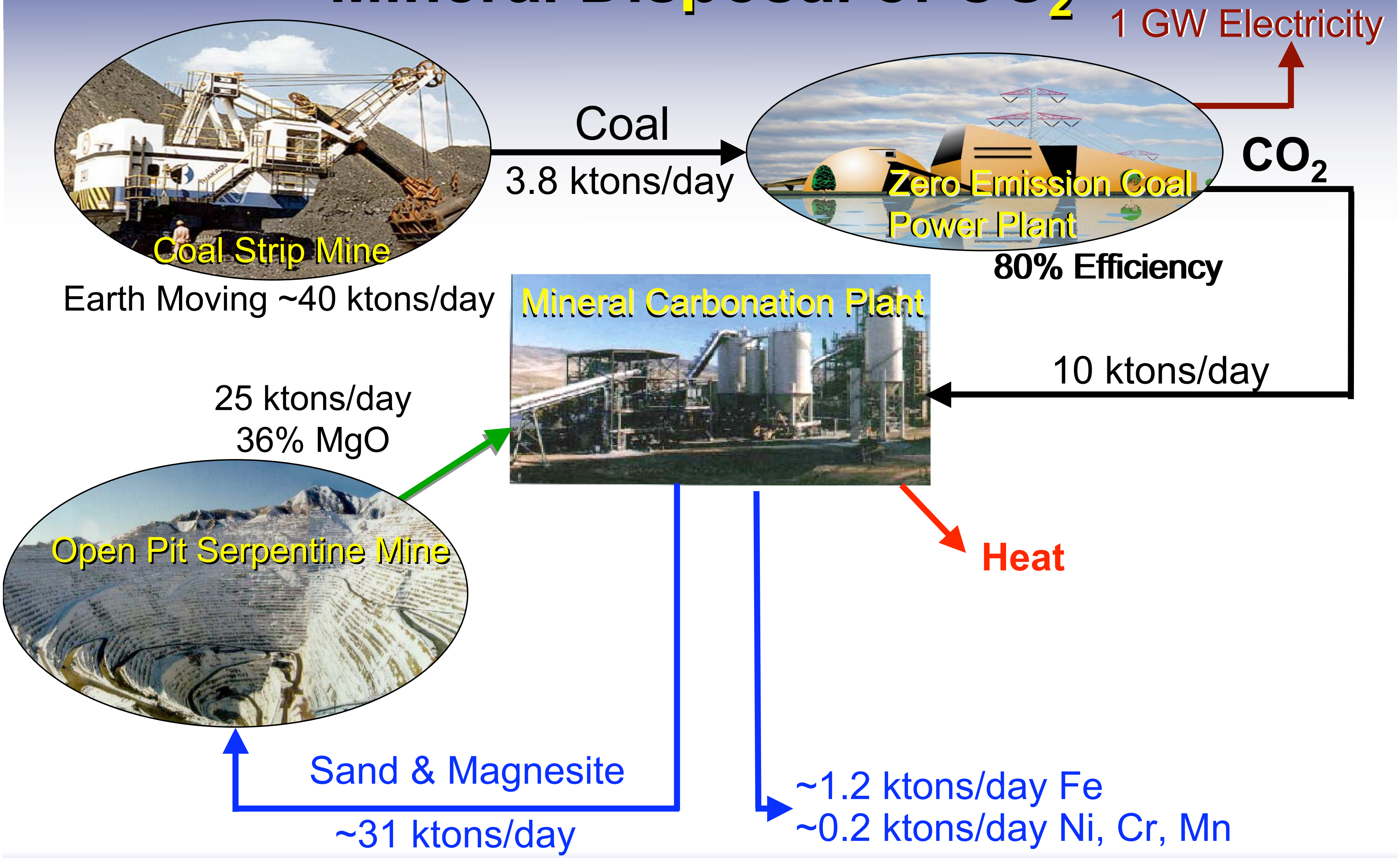
Albany Research Center, Albany OR

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

200,000 years reduced to 3 hours

Suggests simple cost-effective implementation

Mineral Disposal of CO_2



Mining, Crushing & Grinding Cost: $7/t of CO_2 Chemical Processing Cost $10/t of CO_2 No credits for byproducts

CO_2 Extraction from Air

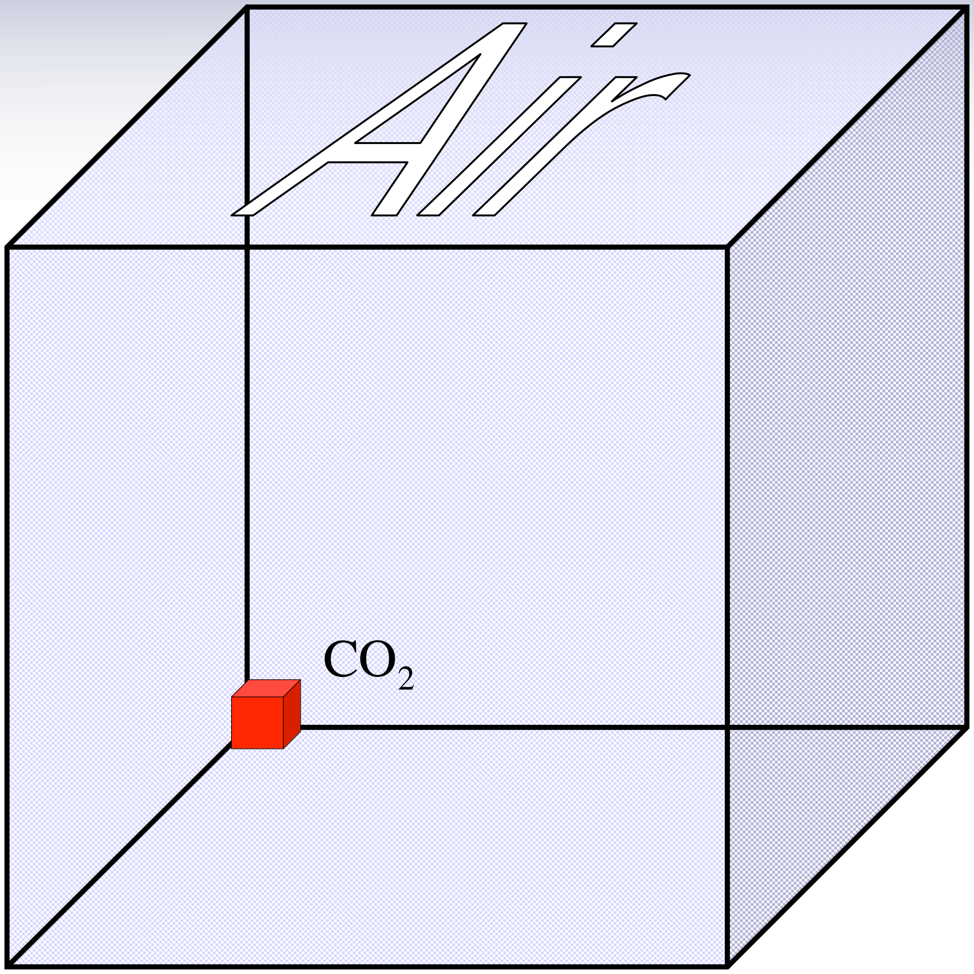
- Decouple CO_2 production and sequestration
  - Optimize disposal and power generation separately
  - Atmosphere acts as carbon conveyor belt
  - Atmosphere is a huge buffer/storage reservoir that can smooth out variations in emission

Biomass takes CO_2 from Air

- Biomass is rate limited not by CO_2, but sunlight
  - Rate is limited at 1-3% of conversion efficiency

- Biomass is not CO_2 but energy recycling
  - Life time biomass is too short for storage
  - Energy is returned to the carbon molecule for reuse

1 m^3 of Air



40 moles of gas, 1.16 kg

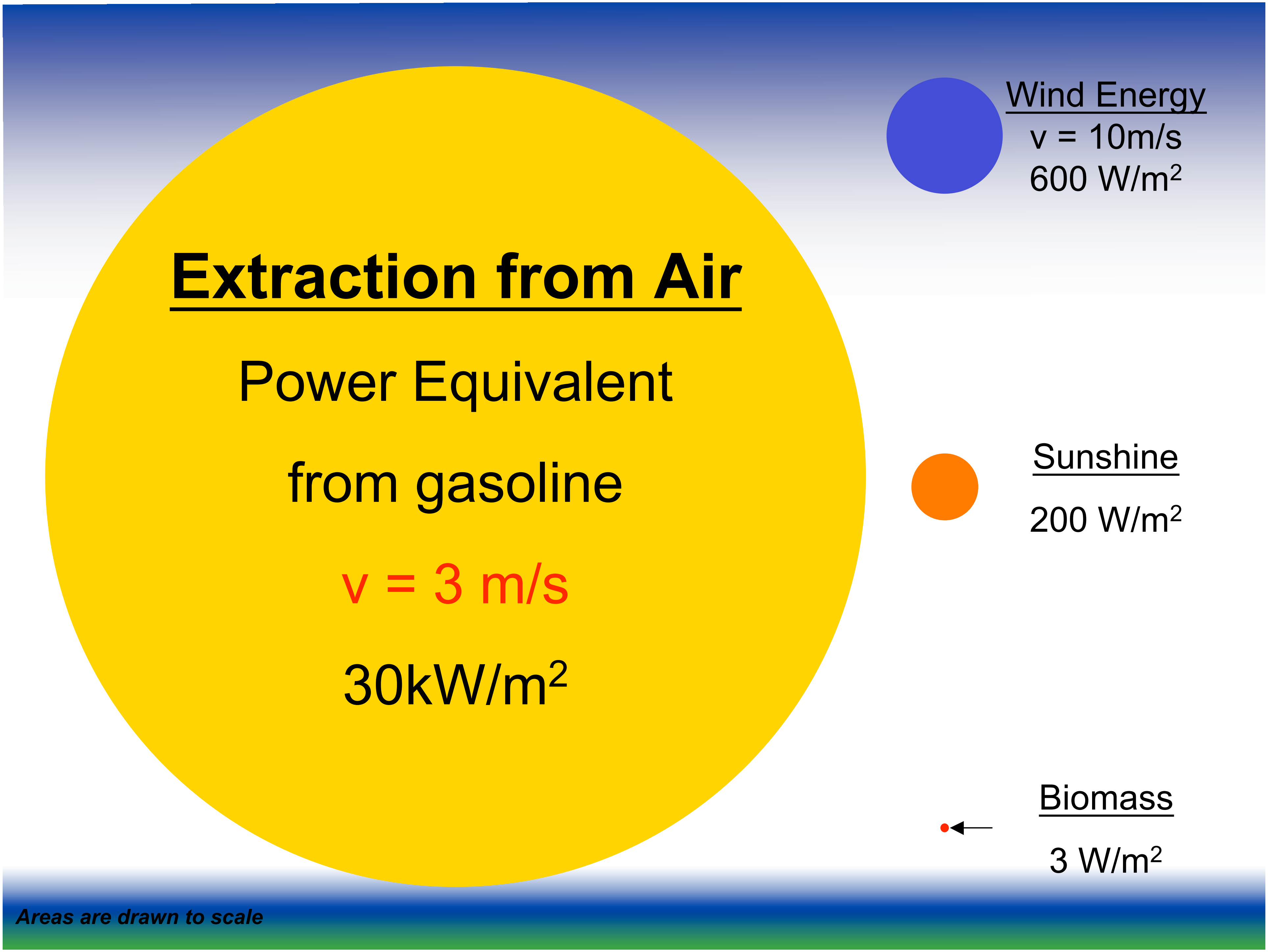
wind speed 10 m/s

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

0.015 moles of CO_2

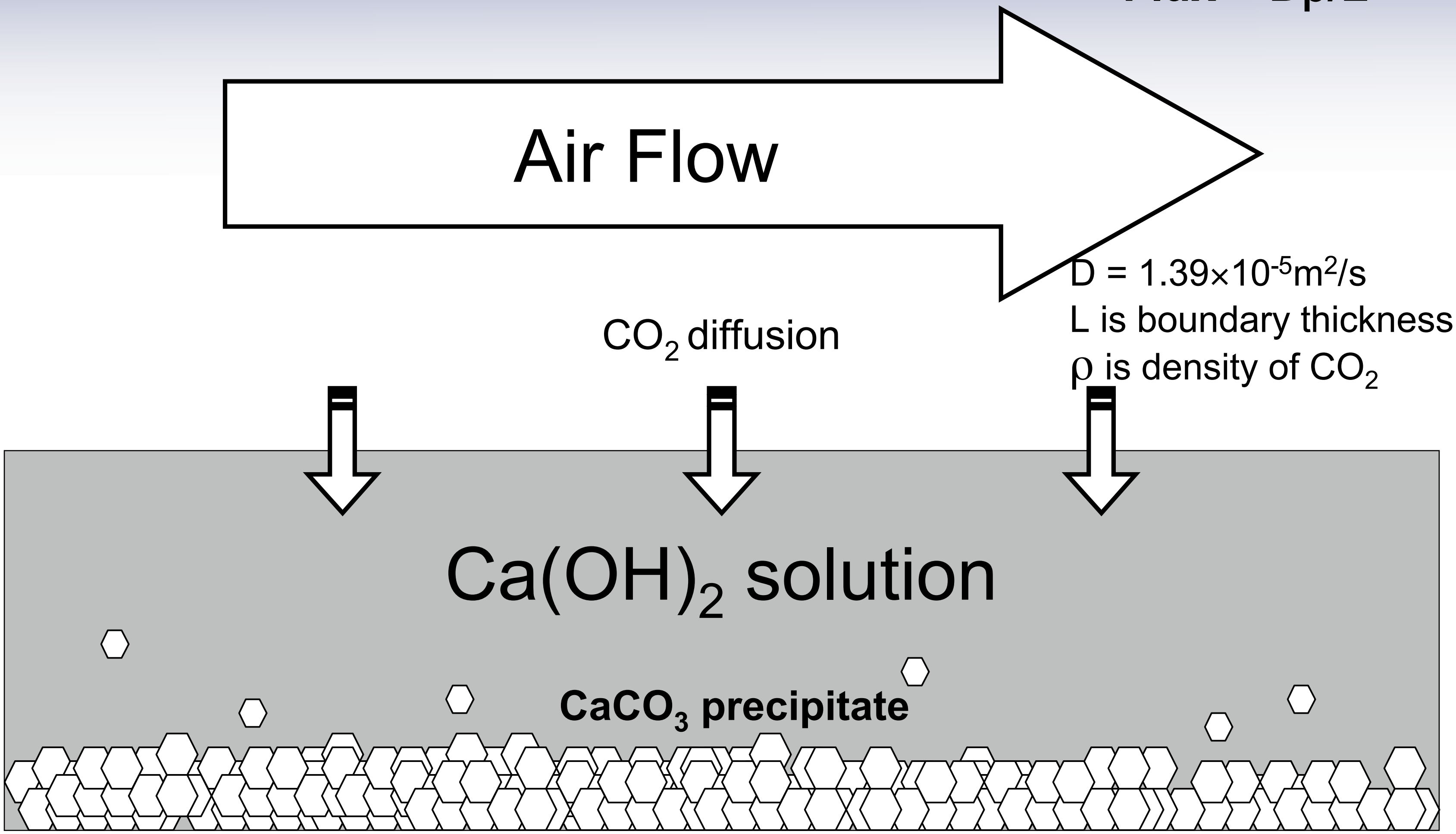
produced by 10,000 J of gasoline

Volumes are drawn to scale


Extraction from Air
Power Equivalent
from gasoline
v = 3 m/s
30kW/m²
Wind Energy
v = 10m/s
600 W/m²
Sunshine
200 W/m²
Biomass
3 W/m²
Areas are drawn to scale

$Ca(OH)_2$ as an absorbent

Flux = Dρ/L



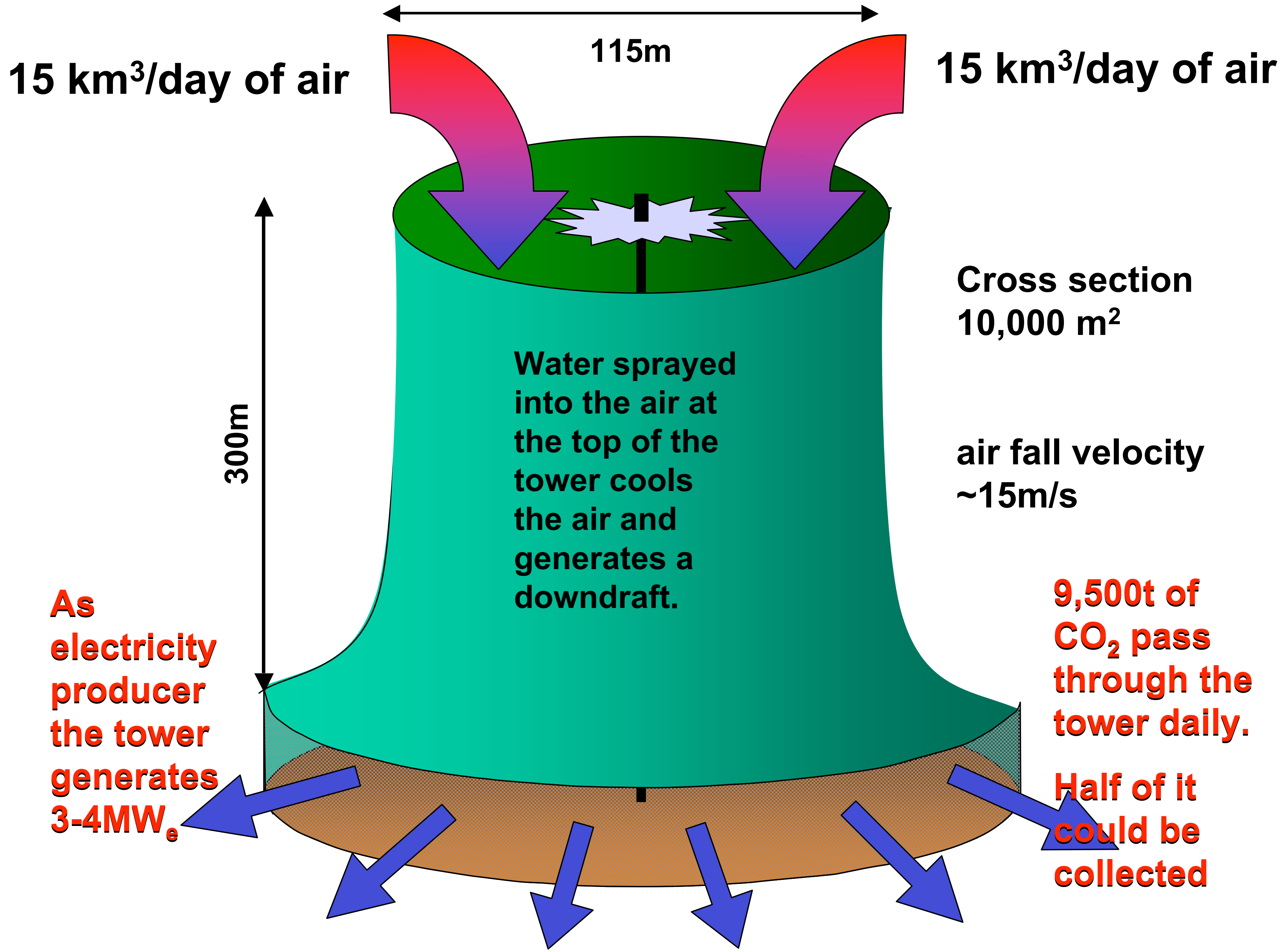
CO_2 mass transfer is limited by diffusion in air boundary layer

Diffusion Limit

- CO_2 diffusion through air limits uptake
- Flux = $D\rho/L$
  - $D = 1.39\times10^{-5} m^2/s$, diffusion coefficient
  - L is boundary thickness
  - ρ is density of CO_2

- For a tube of 2.5 mm in diameter,

  CO_2 will be removed after 6 cm.



115m
15 km³/day of air
15 km³/day of air
300m
Cross section
10,000 m²
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

Wind Energy vs. CO_2 Collection

Wind Energy

- Convection tower, Wind Mill etc.
- Extract kinetic energy
- Wind Turbines
- 30% extraction efficiency
- Throughput
  $130 W/m^2$ @ 6m/s wind
- Cost
  \$0.05/kWh

CO_2 Collection

- Convection tower, absorbing “leaves”, etc.
- Extract CO_2
- Sorbent Filters
- 30+% extraction efficiency
- Throughput
  $3.8 g/(s \cdot m^2)$ @ 6m/s wind
- Cost *by analogy*
  \$0.50/ton of CO_2

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

Cost Comparison

\$10/ton of CO_2

≈ 0.9¢/kWh for a coal fired power plant (33%eff.)

≈ 0.4 ¢/kWh for a gas turbine plant (45%eff.)

≈ pipelining cost for one ton of CO_2 for 1,000 km

≈ 8 ¢/gallon of gas

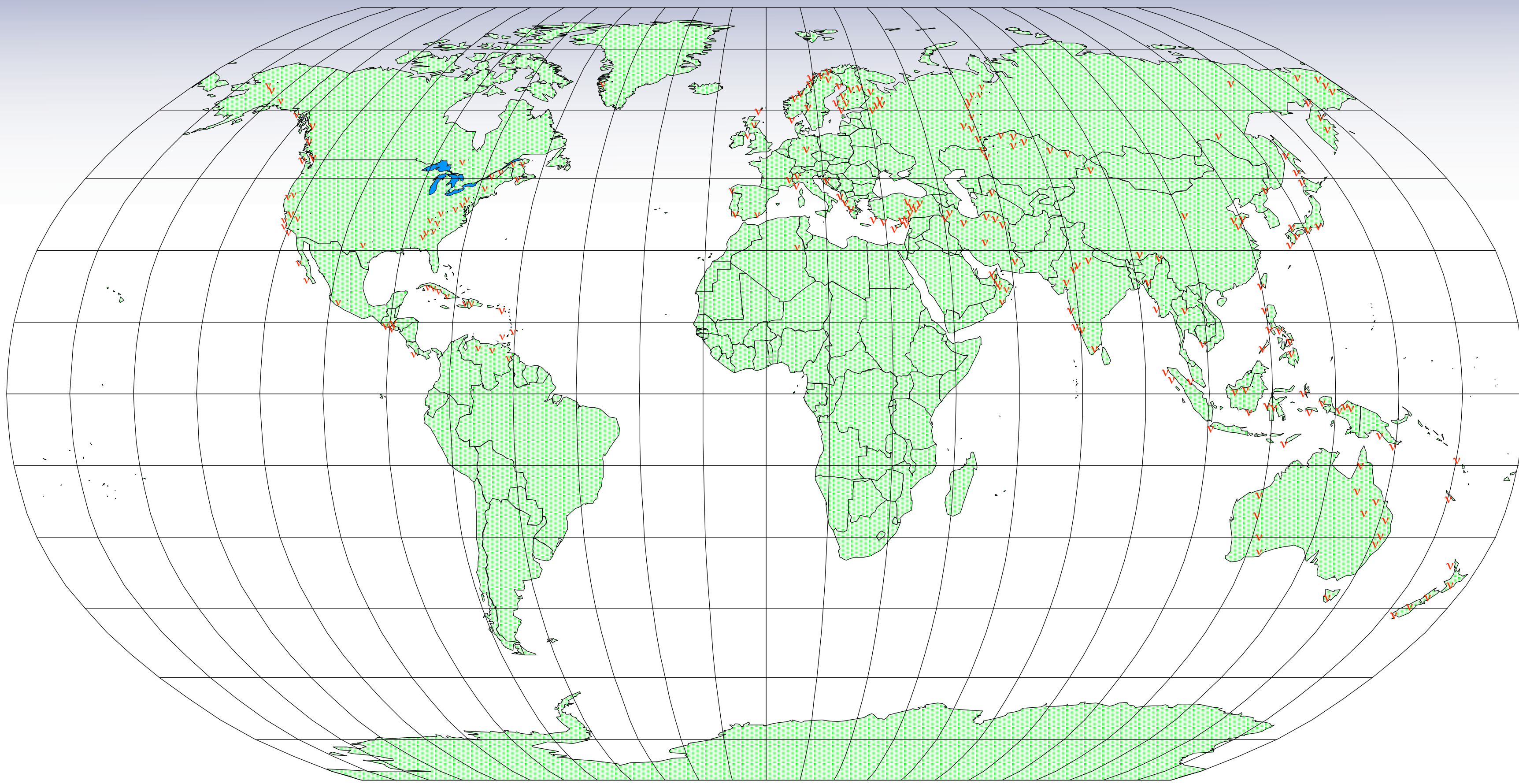
System can be designed to:

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

Peridotite and Serpentinite Ore Bodies



Magnesium resources that far exceed world fossil fuel supplies

Trading Carbon Dioxide

- All countries can participate in the permanent removal of excess carbon through air extraction and subsequent carbon dioxide disposal

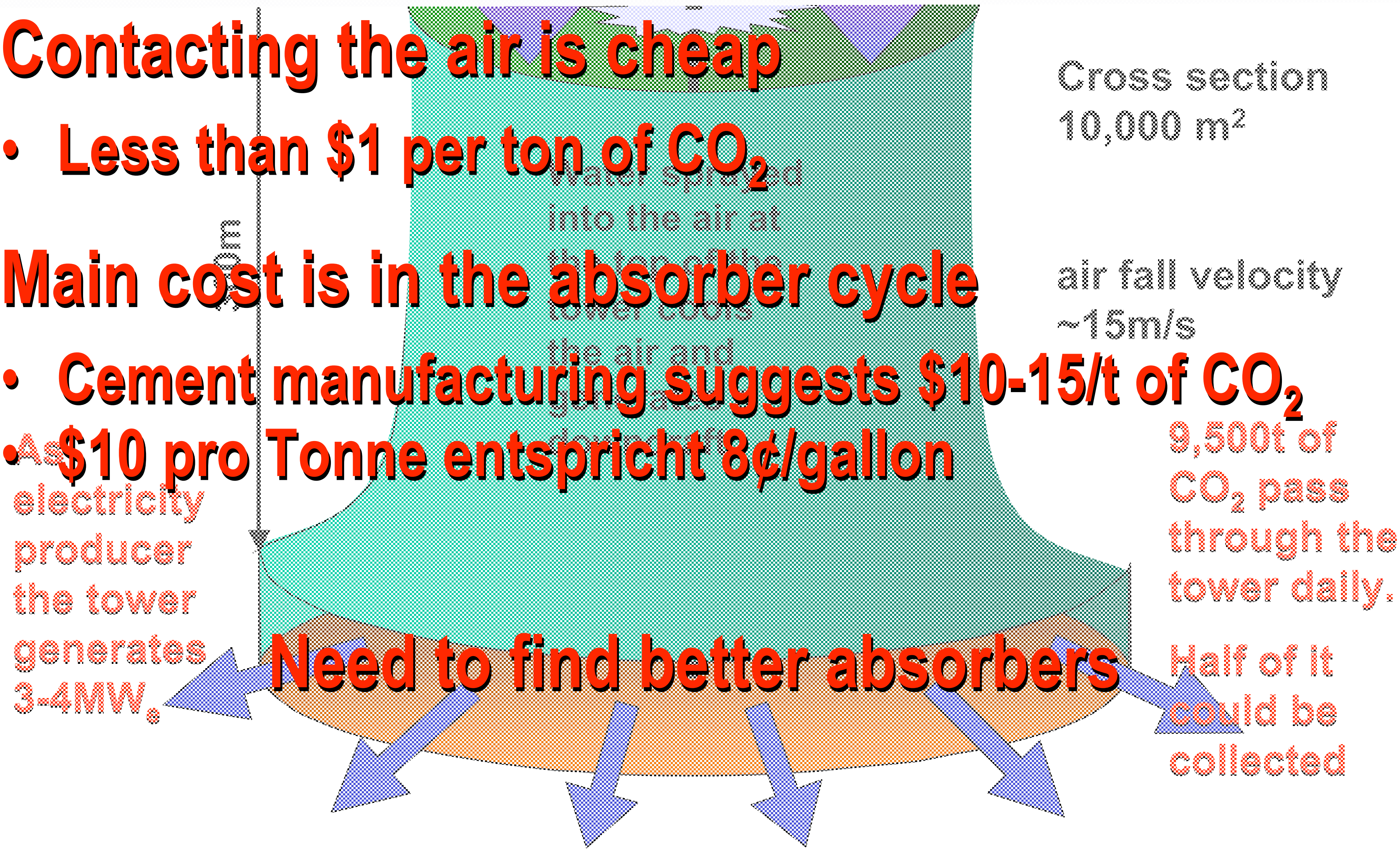
Costs
I. CO_2 Extraction from Air

Contacting the air is cheap

- Less than $1 per ton of CO_2

Main cost is in the absorber cycle

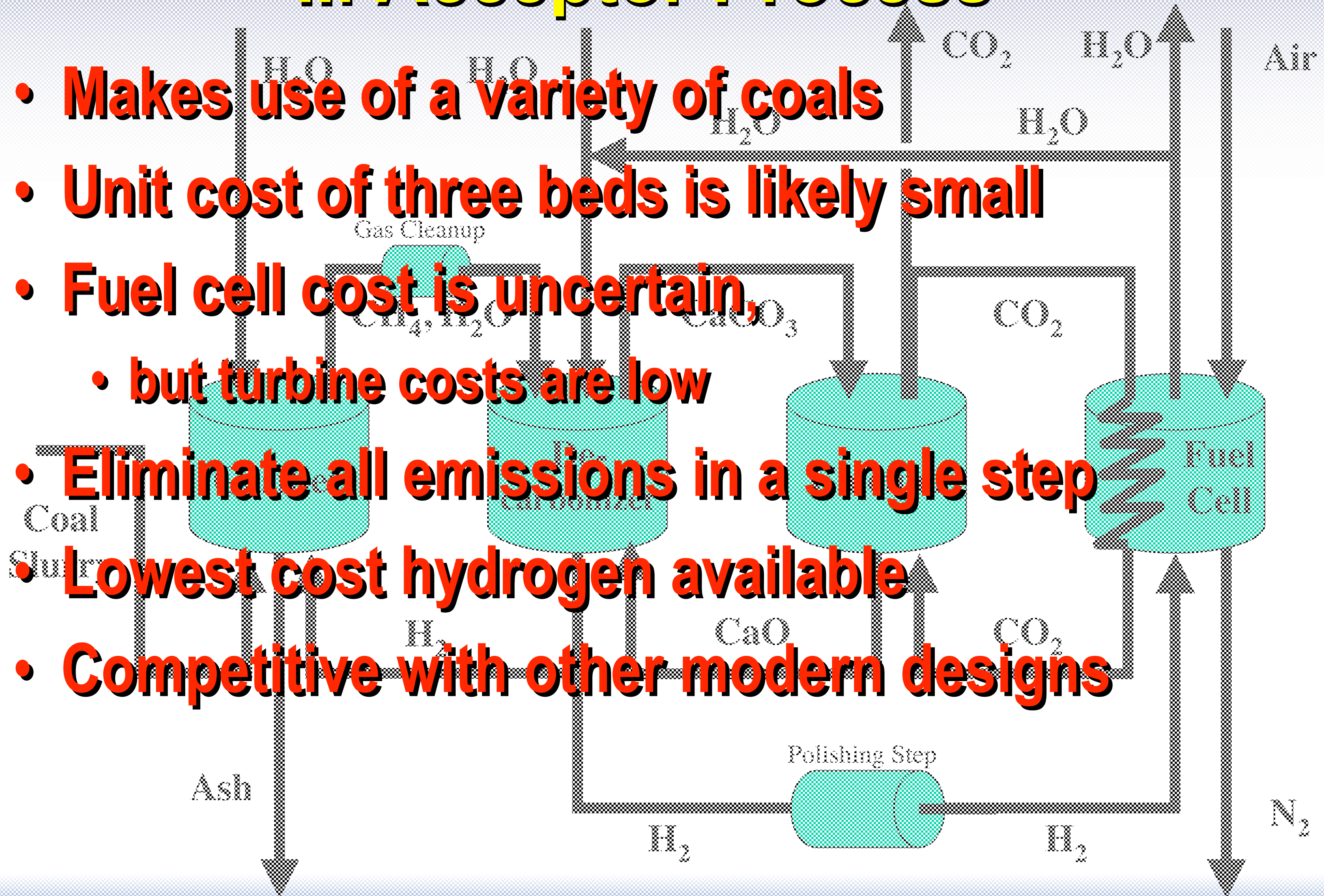
- Cement manufacturing suggests $10-15/t of CO_2
- $10 pro Tonne entspricht 8¢/gallon



Need to find better absorbers

Economic Considerations
II. Acceptor Process

- Makes use of a variety of coals
- Unit cost of three beds is likely 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
III. Mineral Carbonate Disposal

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