Managing Emissions from Fossil Resources

A Challenge to Technology and Policy

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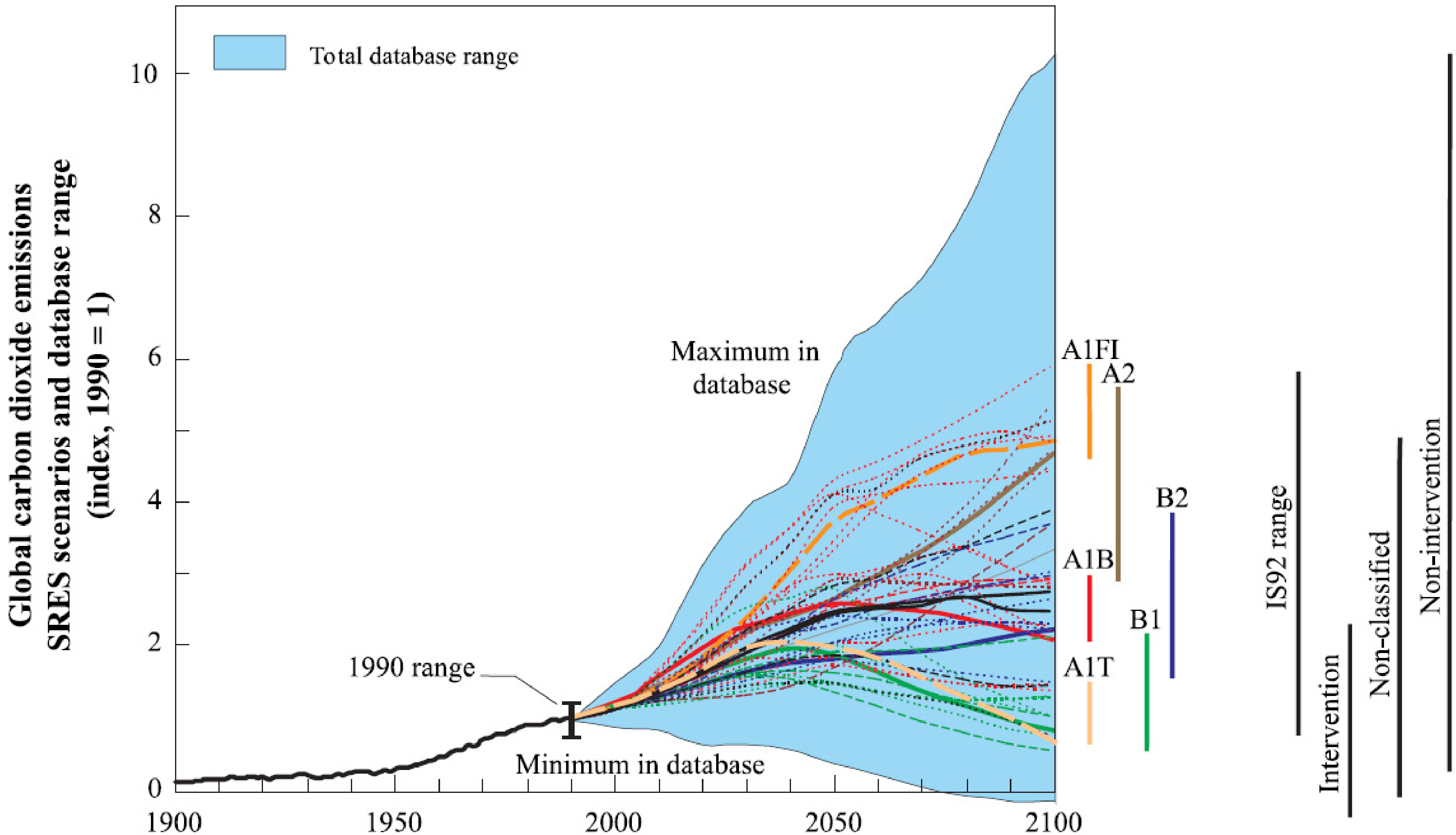
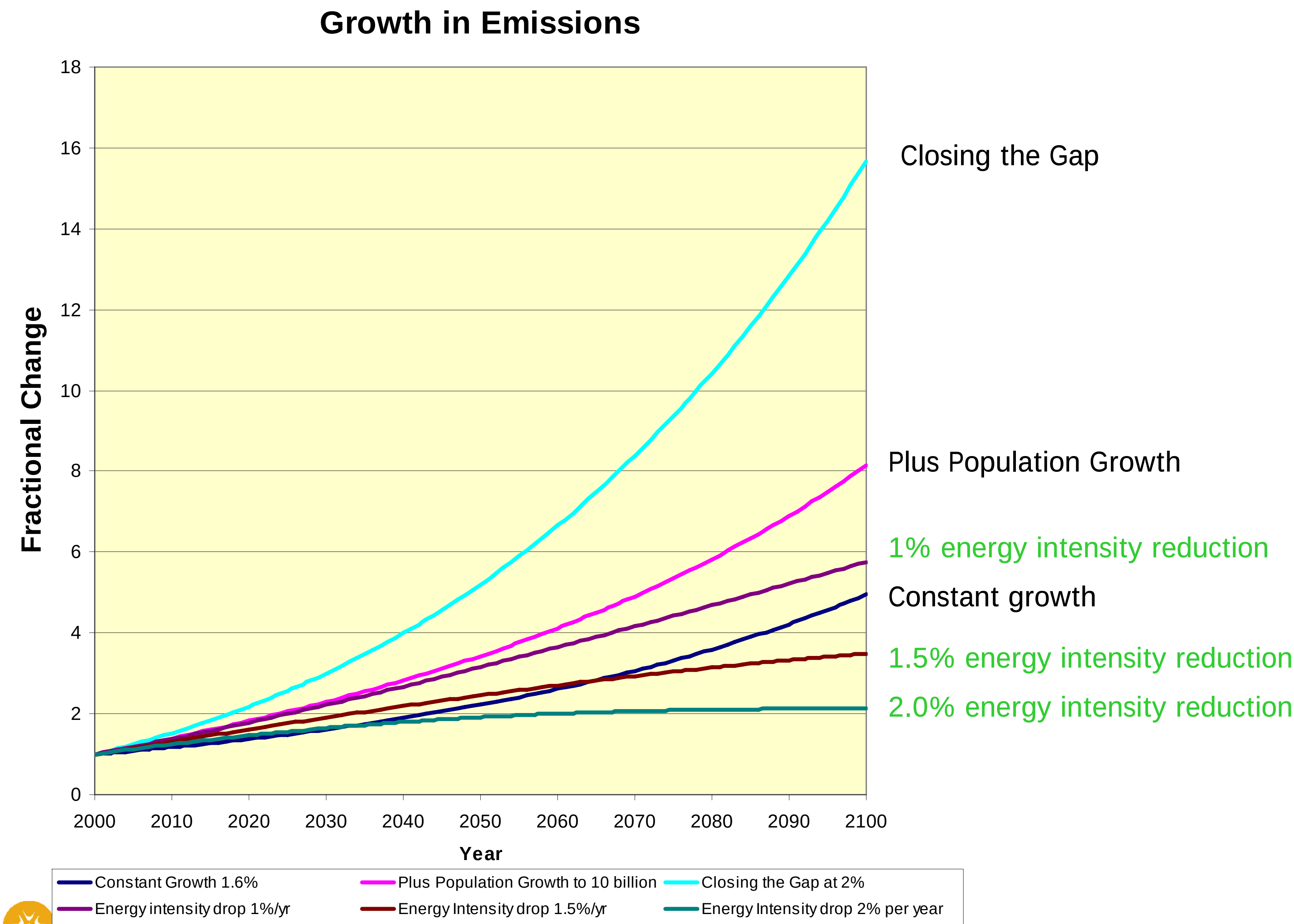
Columbia University

December 2007

IPCC Model Simulations of CO_2 Emissions




Growth in Emissions
Fractional Change
0
2
4
6
8
10
12
14
16
18
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
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

Resource Will Not Run Out

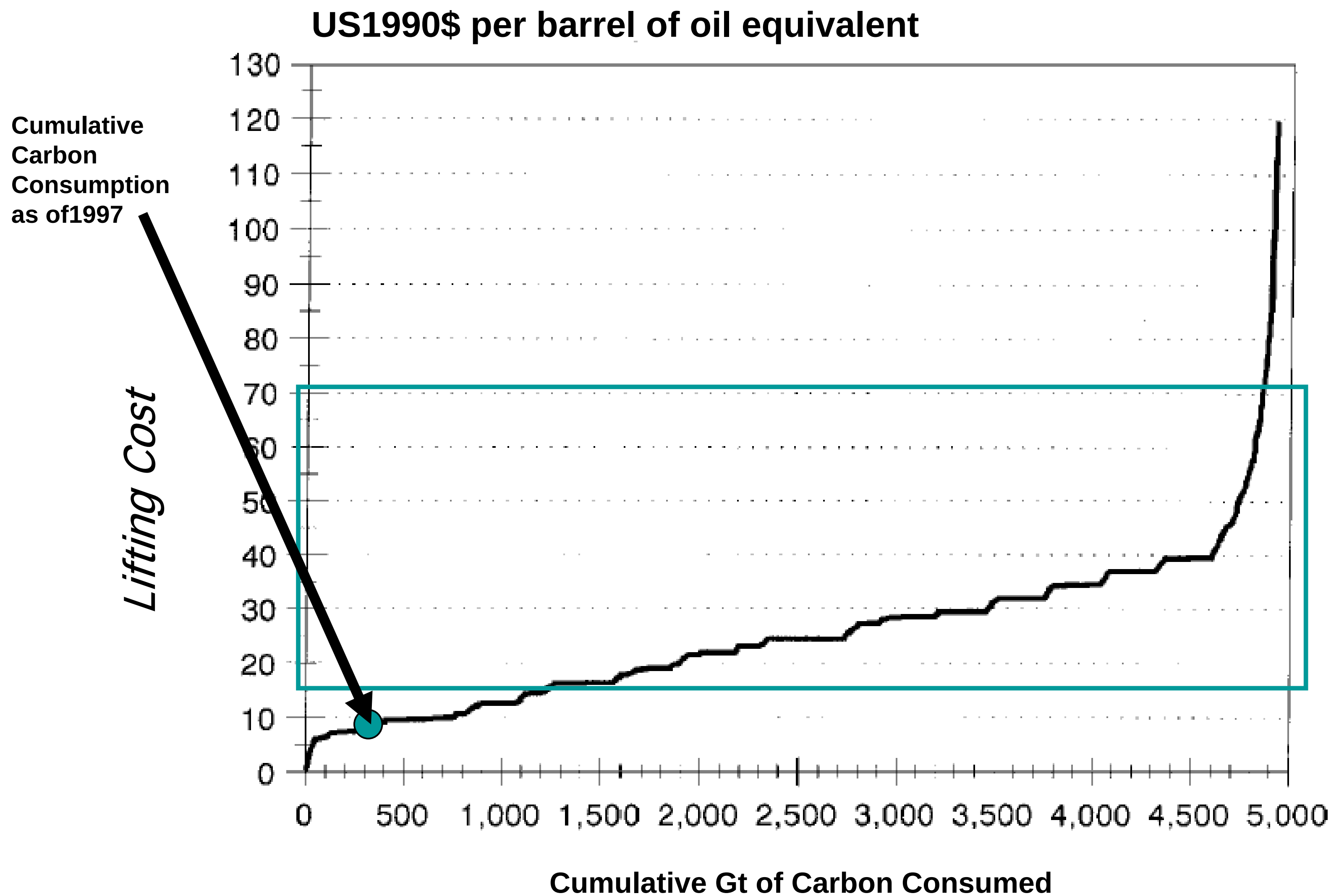
Table 9 Aggregation of global fossil energy sources—all occurrences, in Gtoe[a]

	Consumption 1860–1994	Consumption 1994	Reserves	Resources[b]	Resource base[c]	Additional occurrences
Oil						
Conventional	103	3.21	150	145	295	
Unconventional	6	0.16	183	336	519	1,824
Natural gas						
Conventional[d]	48	1.87	141	279	420	
Unconventional	—	—	192	258	450	387
Clathrates	—	—	—	—	—	18,759
Coal	134	2.16	1,003	2,397	3,400	2,846
Total fossil occurrences	291	7.40	1,669	3,415	5,084	23,815

[a]Sources: Historial consumption (46). Reserves, resources, and occurrences, see Tables 2–8.
— = negligible volumes.
[b]Reserves to be discovered or resources developed to resources.
[c]Resource base is the sum of reserves and resources.
[d]Includes natural gas liquids.

H.H. Rogner, 1997

Carbon as a Low-Cost Source of Energy



H.H. Rogner, 1997

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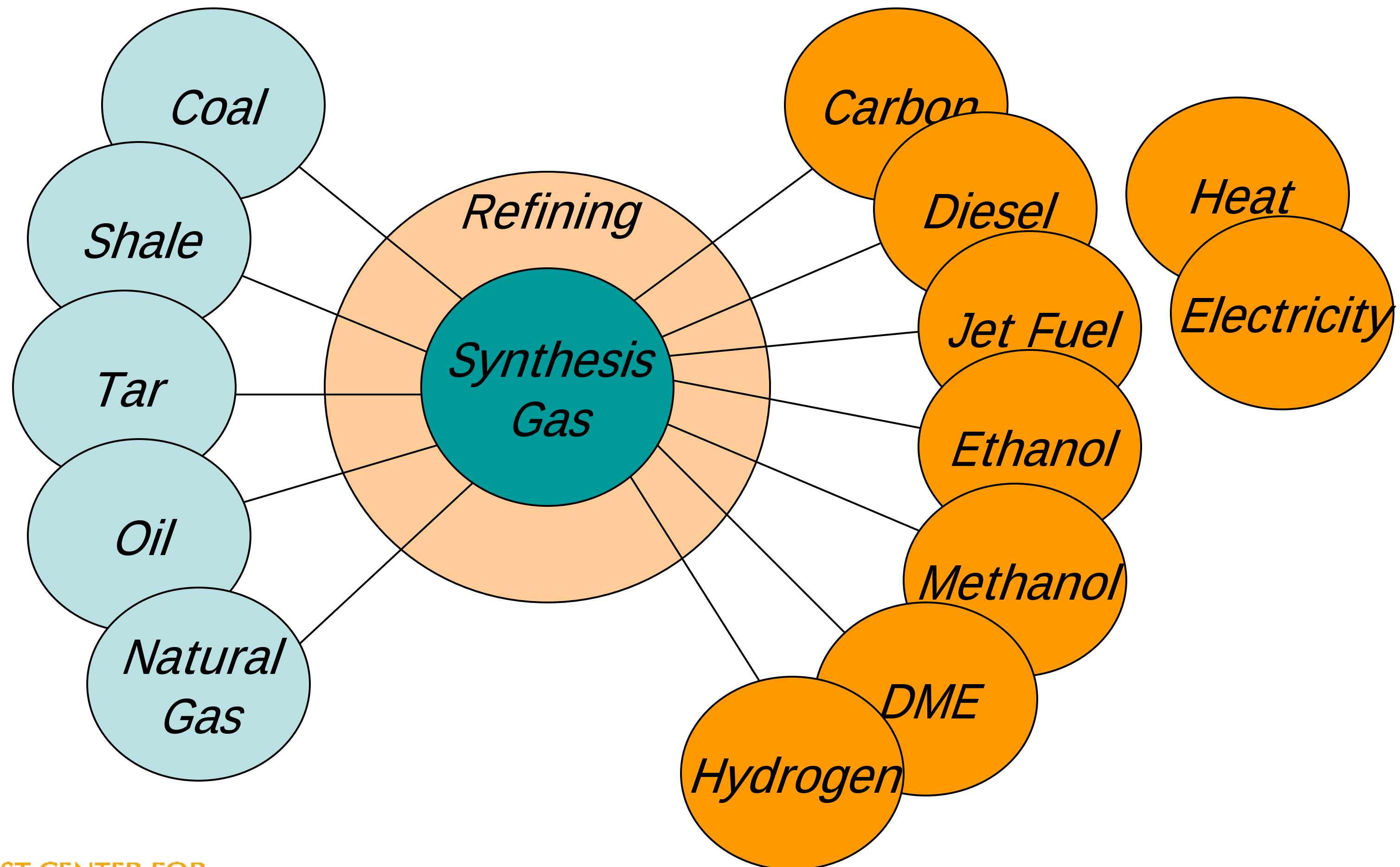
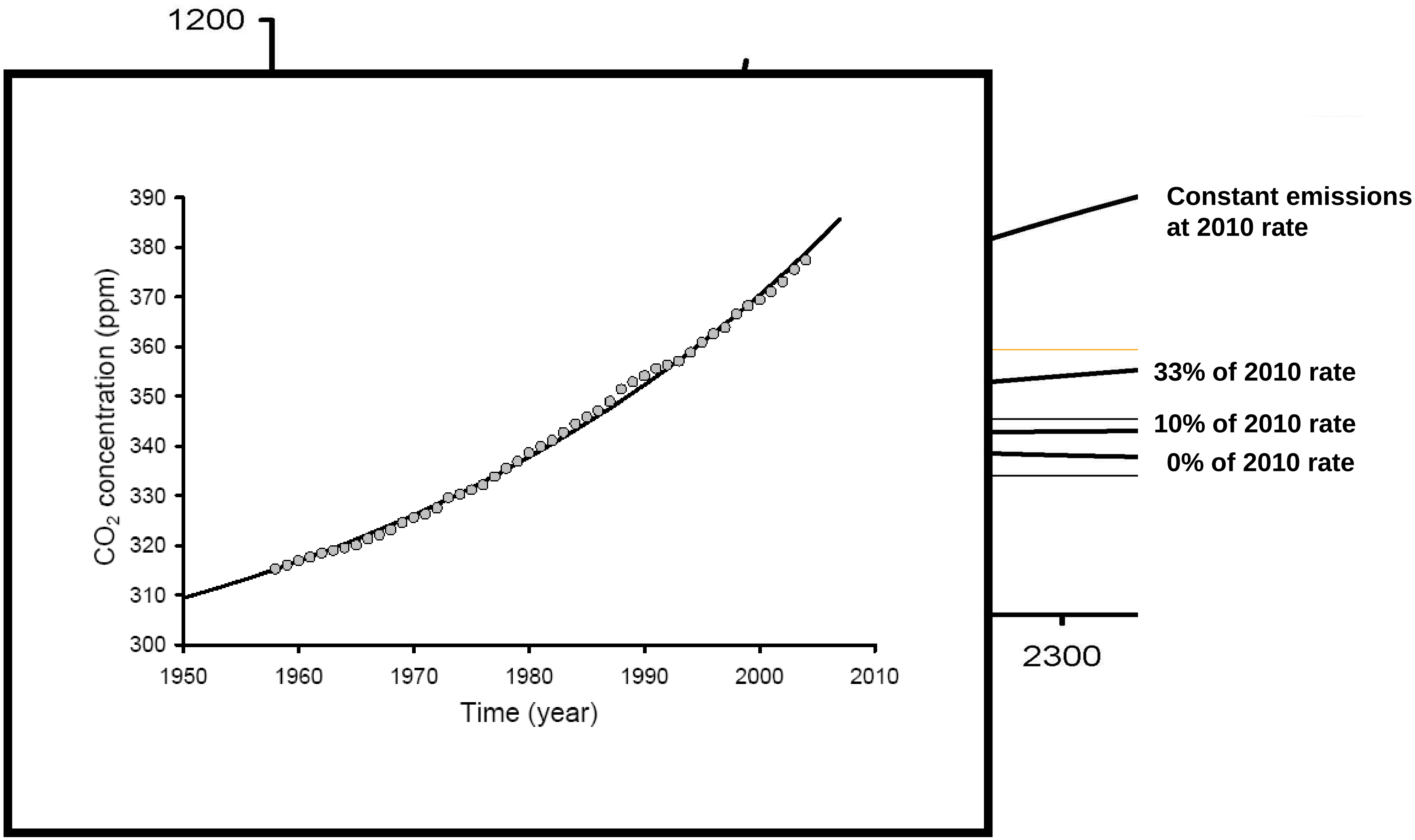
Fossil fuels are fungible



The Challenge:
Holding the Stock of CO_2 constant



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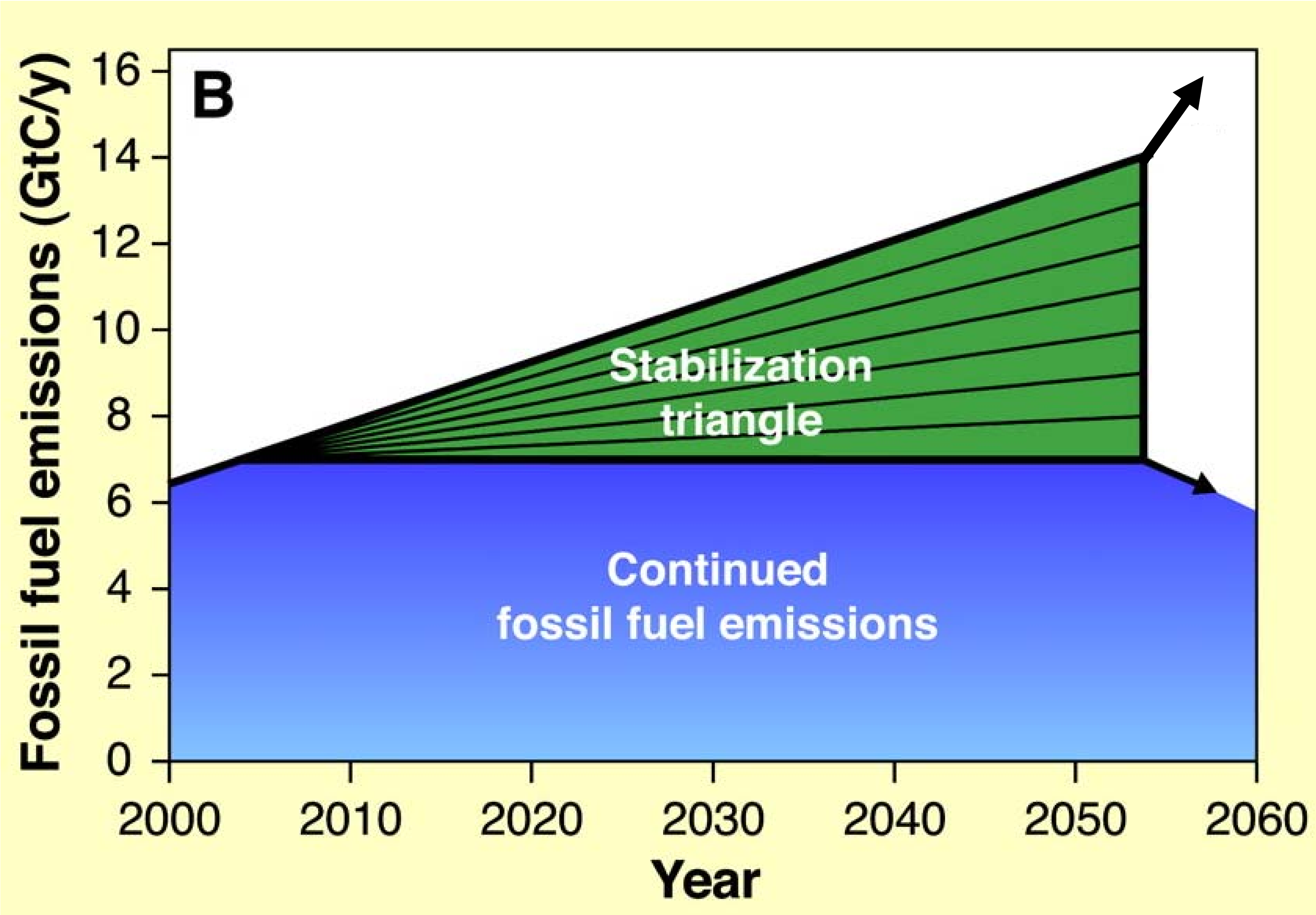

Pacala and Socolow, *Science* **305,** 968 – 972, (2004)

Orders of Magnitude

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A Triad of Large Scale Options

- Solar
  - Cost reduction and mass-manufacture
- Nuclear
  - Cost, waste, safety and security
- Fossil Energy
  - Zero emission, carbon storage and interconvertibility

Markets will drive efficiency, conservation and alternative energy

Small Energy Resources

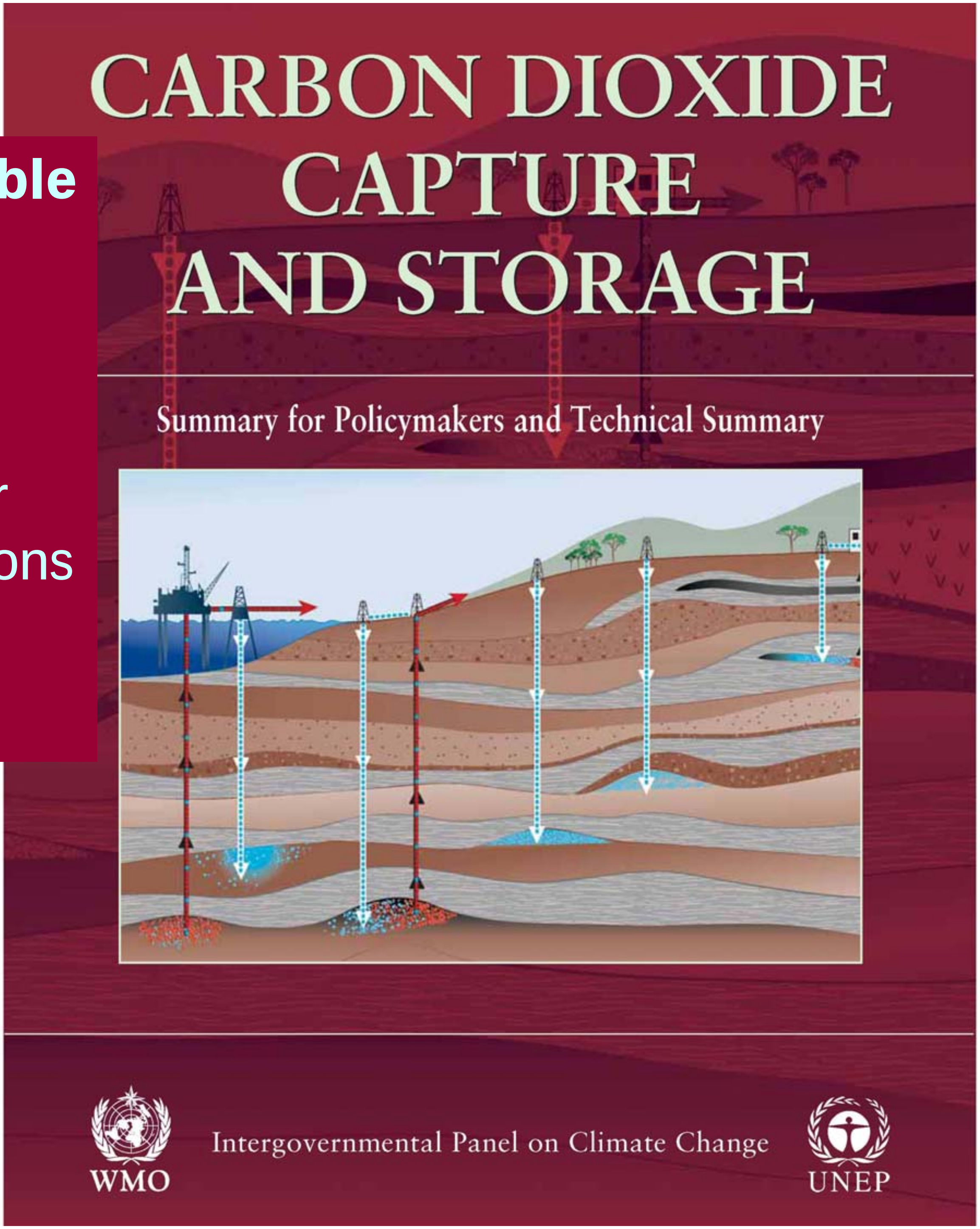
- Hydro-electricity
  - Cheap but limited
- Biomass
  - Sun and land limited, severe competition with food
- Wind
  - Stopping the air over Colorado every day?
- Geothermal
  - Geographically limited
- Tides, Waves & Ocean Currents
  - Less than human energy generation

CCS is technically feasible

It is affordable

It can start today

It is likely to be a major contributor to CO_2 reductions worldwide



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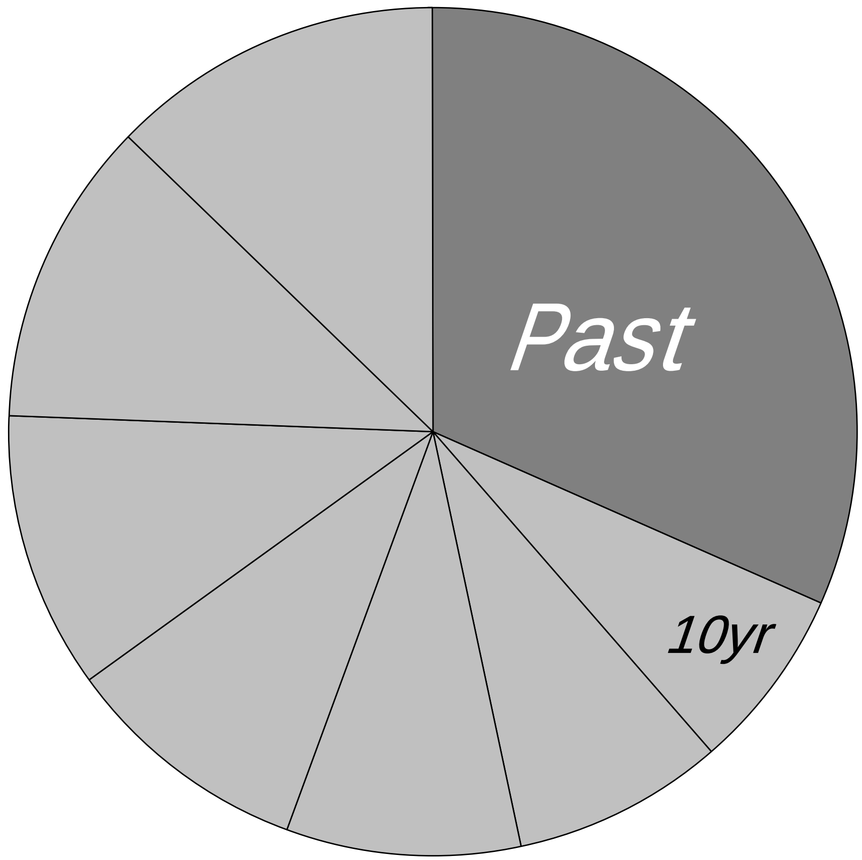
Dividing The Fossil Carbon Pie

900 Gt C

total



550 ppm

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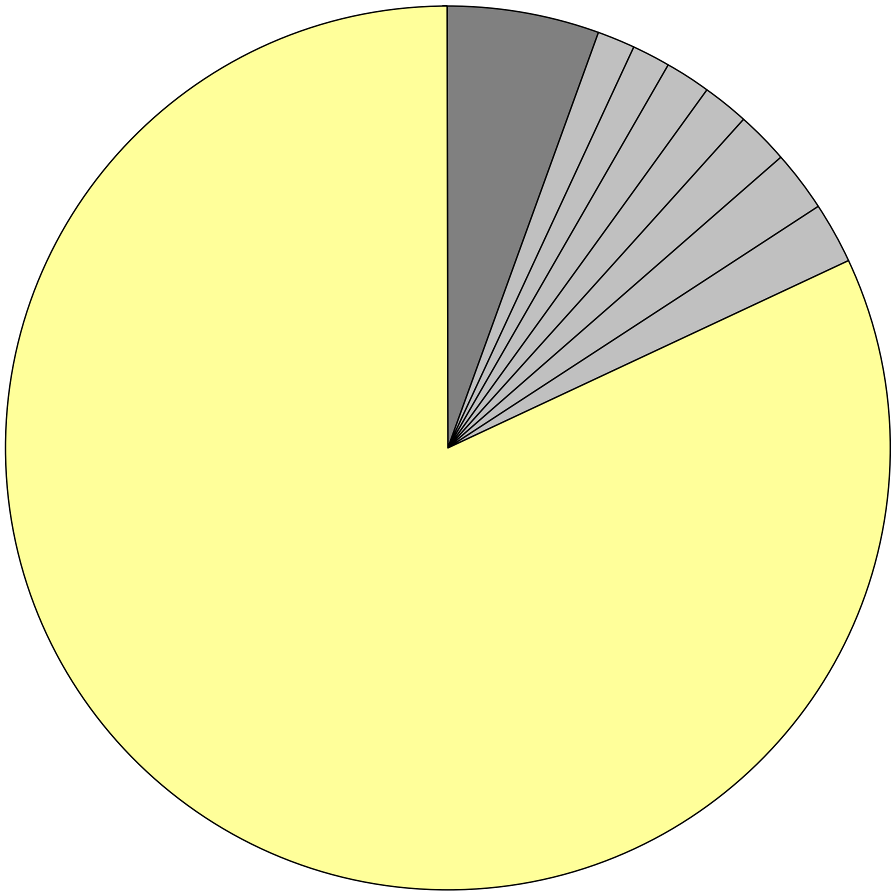
Removing the Carbon Constraint

5000 Gt C

total



Net Zero Carbon Economy

CO_2 from concentrated sources

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

CO_2 from distributed emissions

Capture from air

Permanent & safe disposal

Geological Storage
Mineral carbonate disposal

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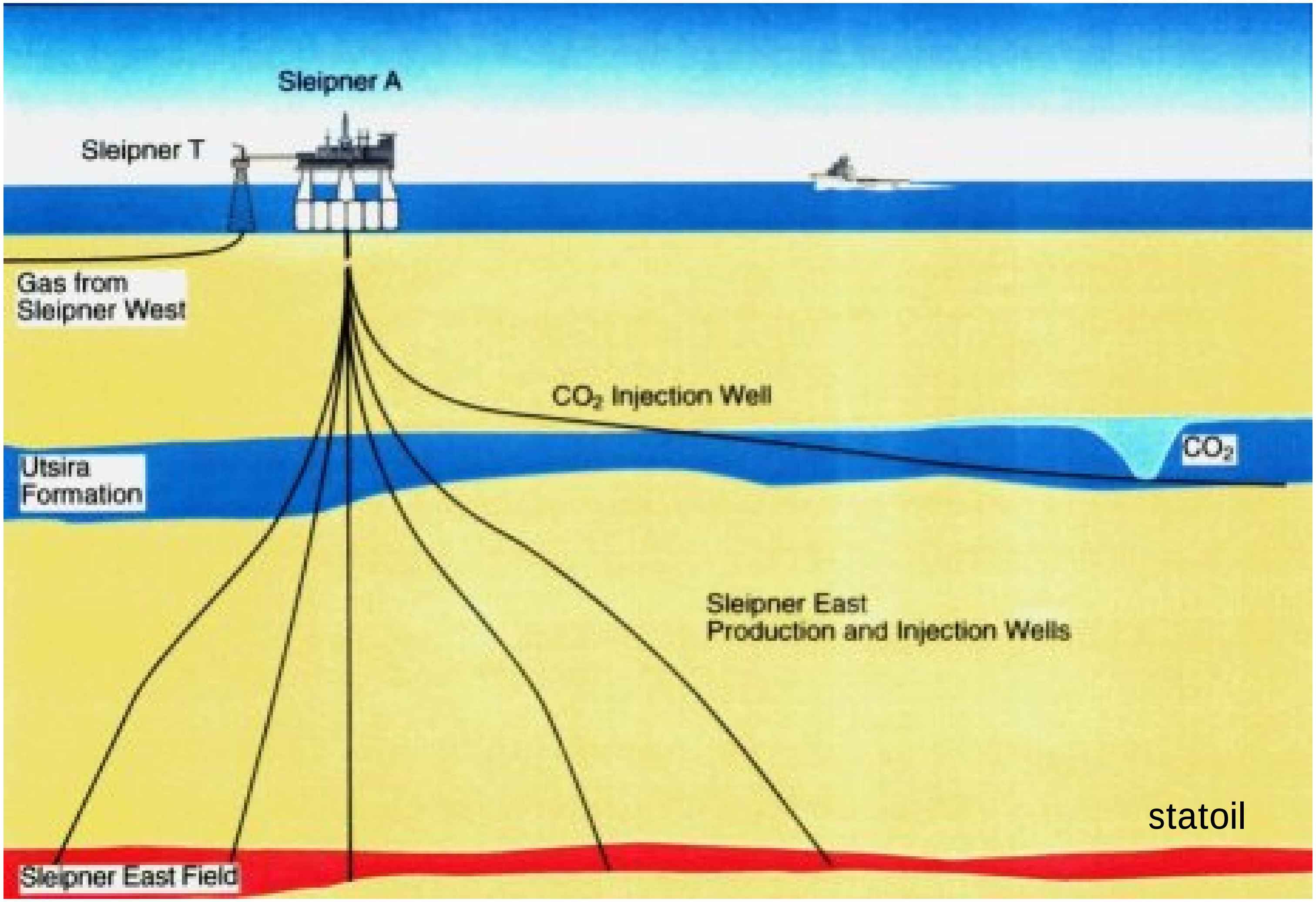
Underground Injection



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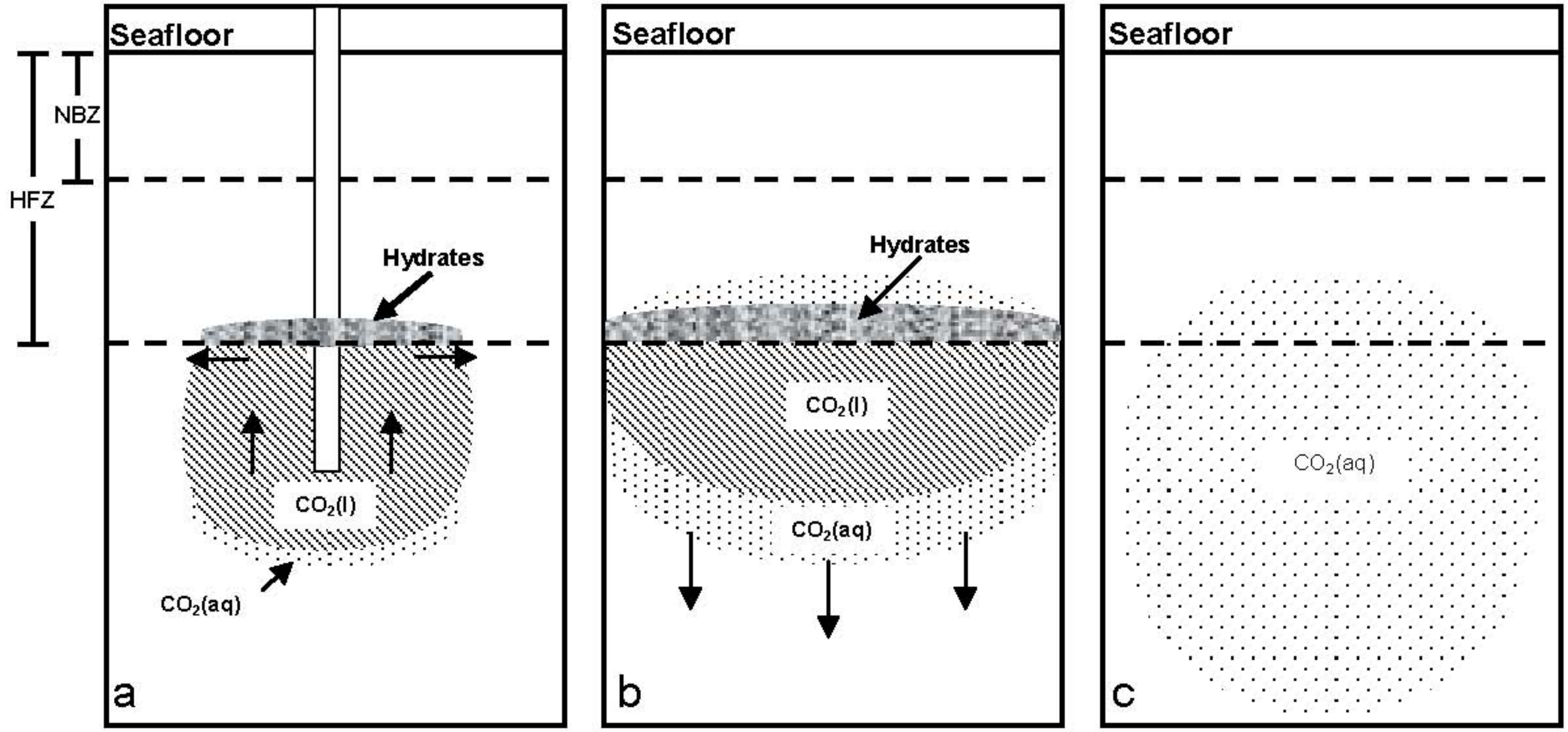
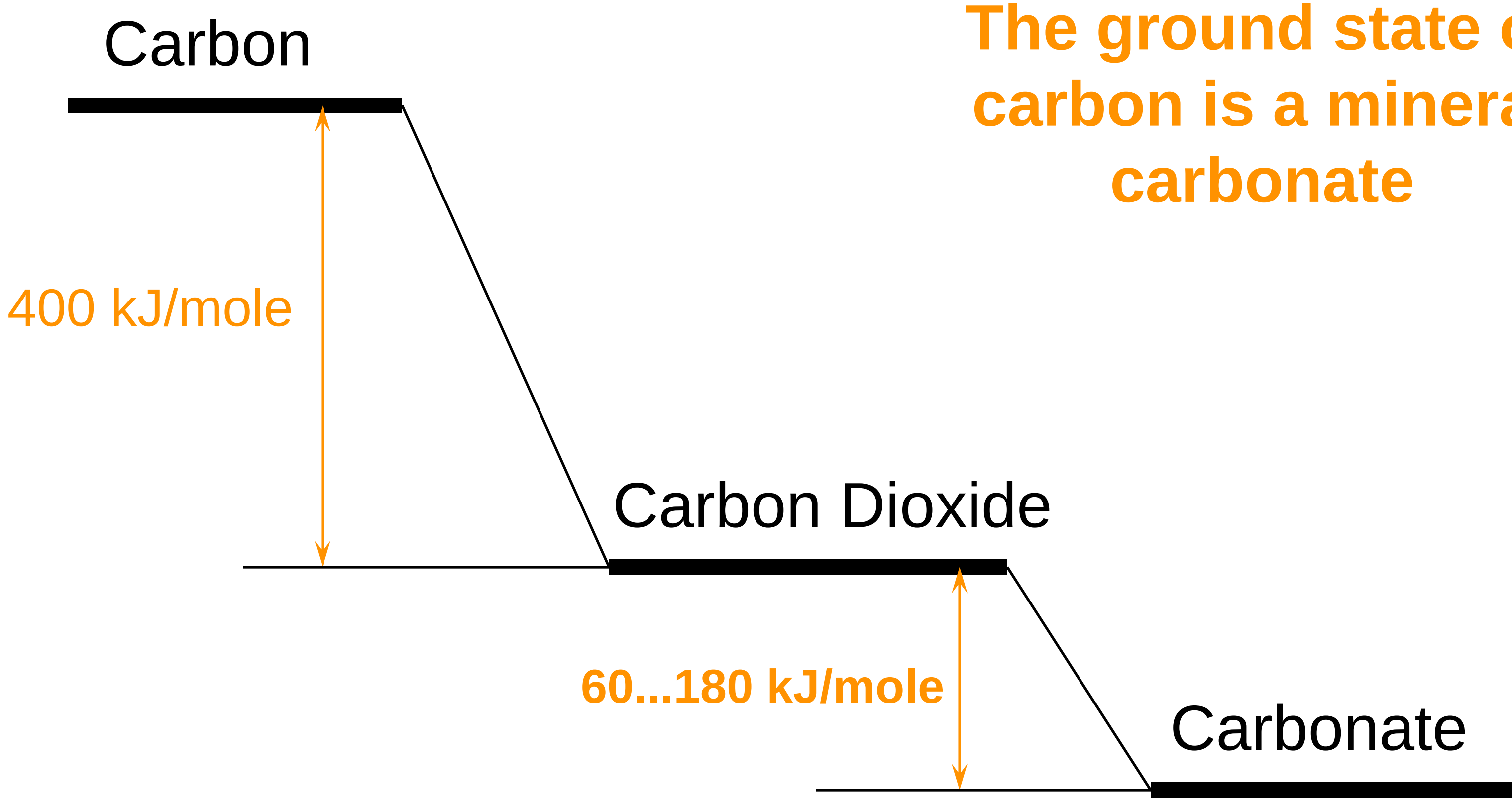
Gravitational Trapping
Subocean Floor Disposal

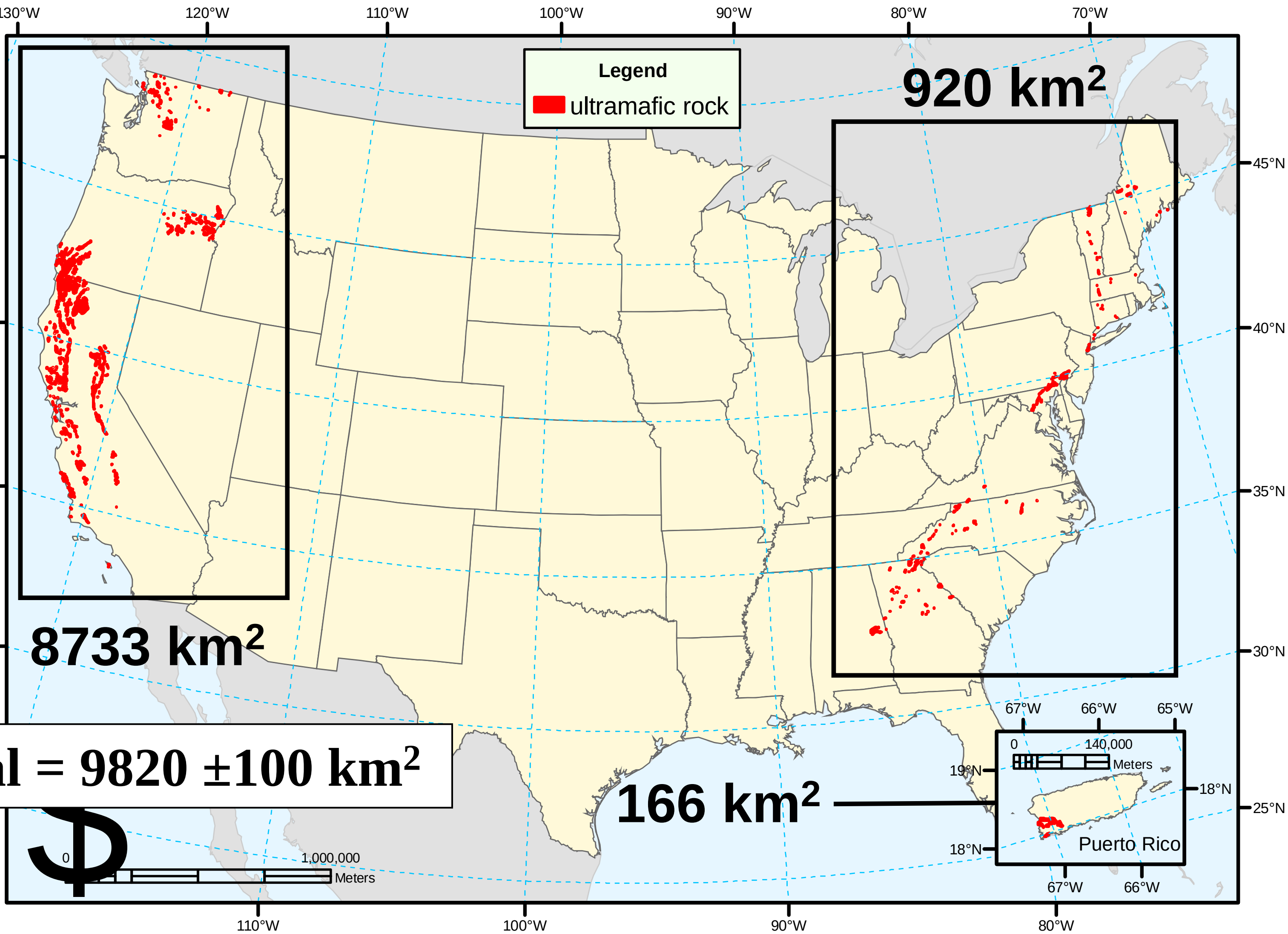


Energy States of Carbon



The ground state of carbon is a mineral carbonate

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



Total = 9820 ±100 km²

Mineral Sequestration

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

Rockville Quarry


Belvidere Mountain, Vermont
Serpentine Tailings

Oman Peridotite

Photo: Juerg Matter

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Net Zero Carbon Economy

CO_2 from concentrated sources

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

CO_2 from distributed emissions

Capture from air

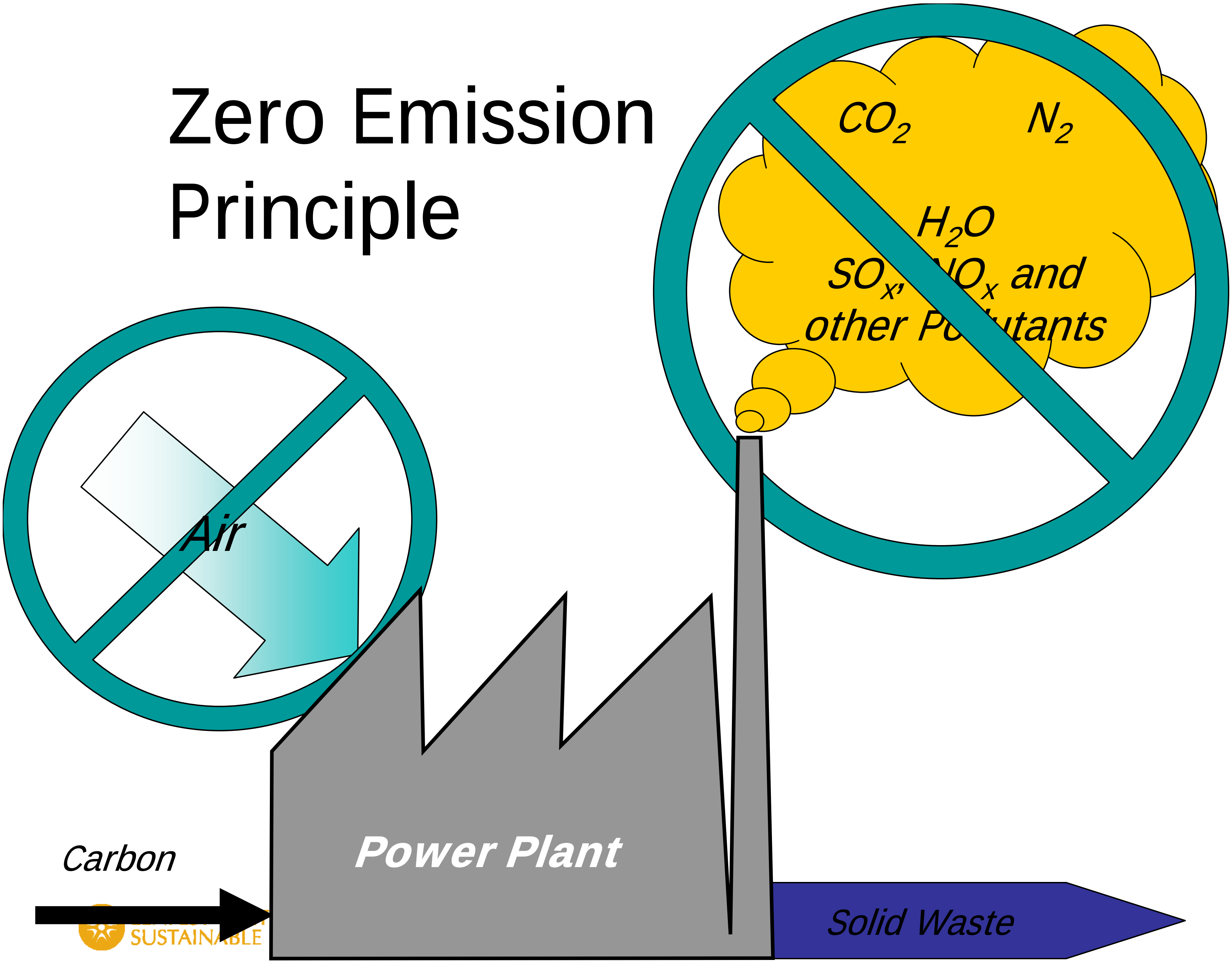
Permanent & safe disposal

Geological Storage
Mineral carbonate disposal

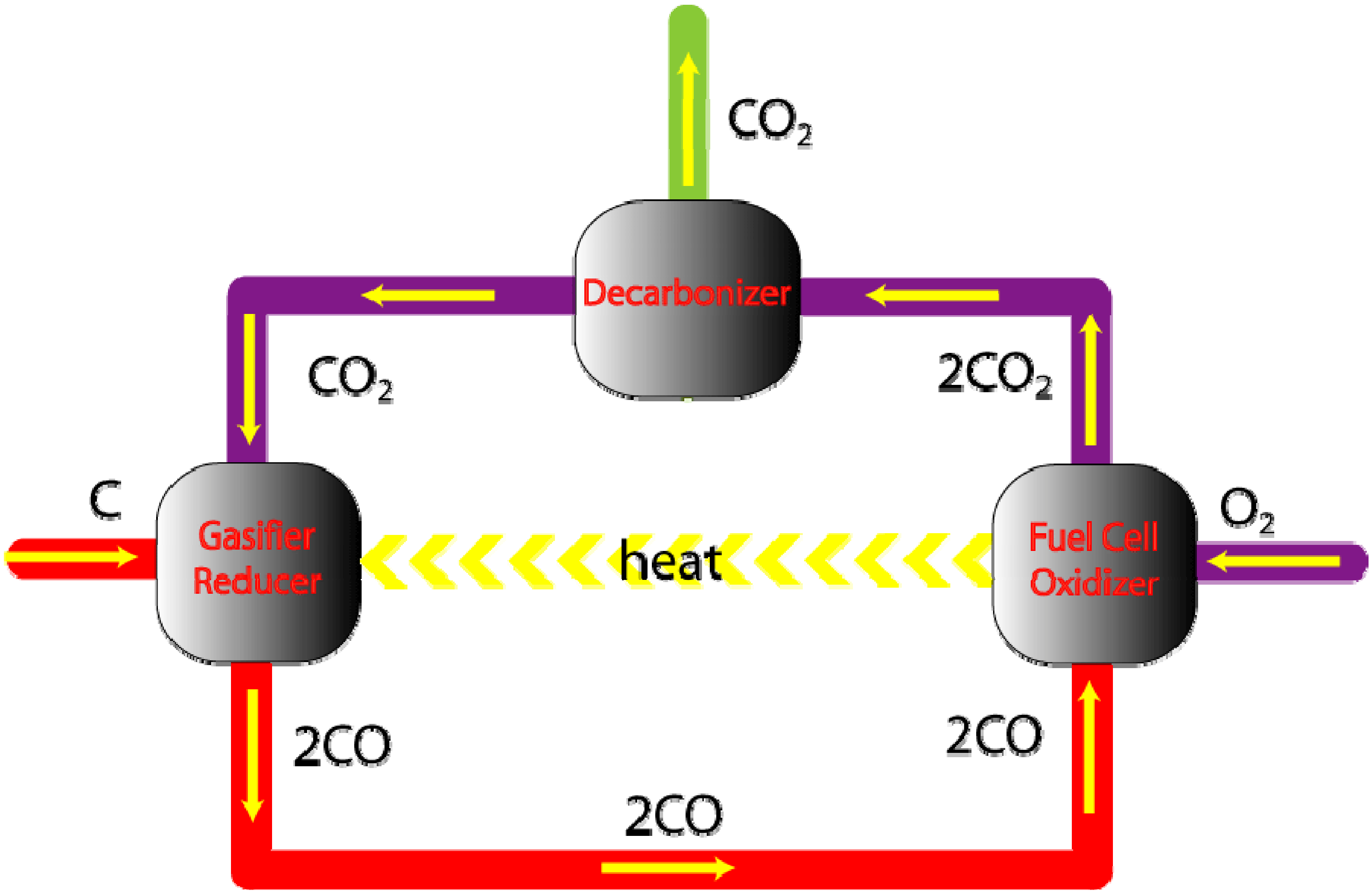
Many Different Options

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

Zero Emission Principle



Boudouard Reaction



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Carbon makes a better fuel cell

$C + O_2 \rightarrow CO_2$

no change in mole volume

entropy stays constant

$\Delta G = \Delta H$

$2H_2 + O_2 \rightarrow 2H_2O$

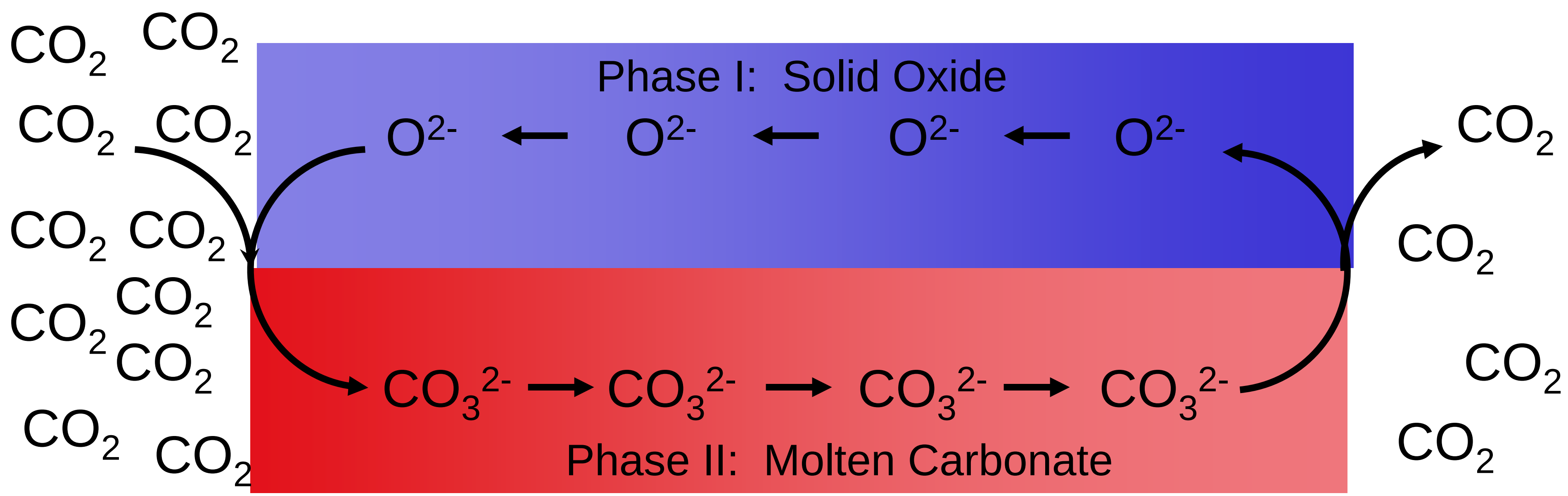
large reduction in mole volume

entropy decreases in reactants

made up by heat transfer to surroundings

$\Delta G < \Delta H$

Proposed Membrane



Multi-Phase Equilibrium

$$CO_2 + O^{2-} = CO_3^{2-}$$

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Net Zero Carbon Economy

CO_2 from concentrated sources

CO_2 extraction from air

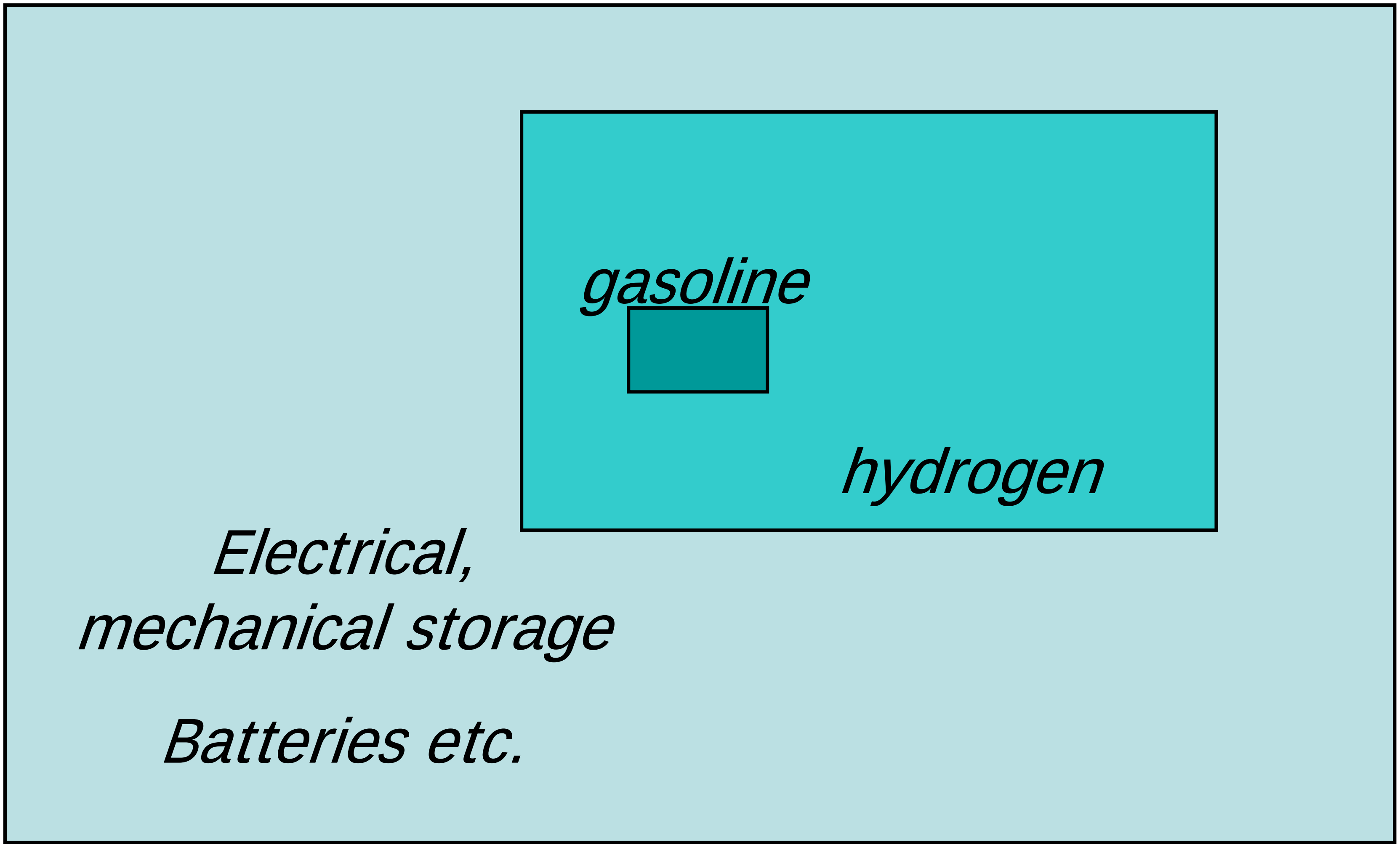
Permanent & safe disposal

Air Capture: A Different Paradigm

- Leave existing infrastructure intact
- Retain quality transportation fuels
- Eliminate shipping of CO_2
- Open remote sites for CO_2 disposal
- Enable fuel recycling with low cost electricity

Separate Sources from Sinks

Relative size of a tank



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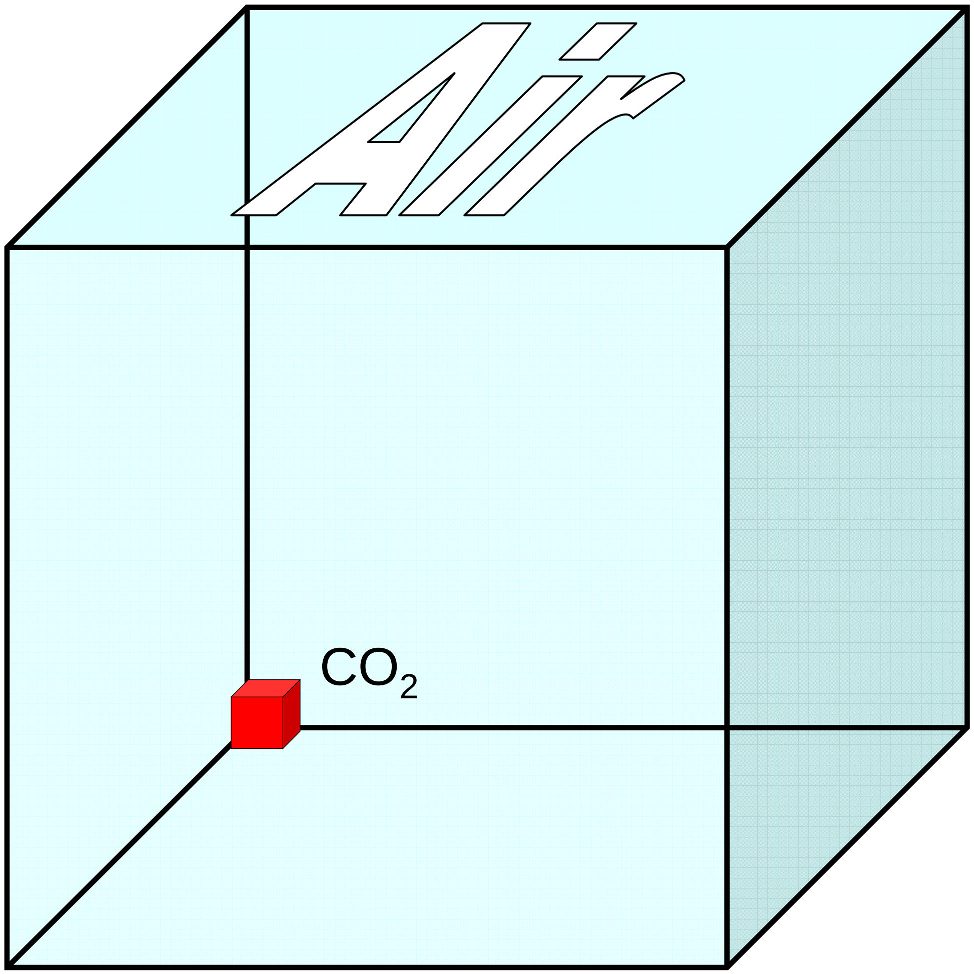
Challenge: CO_2 in air is dilute

- Energetics limits options
  - Work done on air must be small
    - compared to heat content of carbon
    - 10,000 J/m^3 of air
- No heating, no compression, no cooling
- Low velocity 10m/s (60 J/m^3)

Solution: Sorbents remove CO_2 from air flow

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

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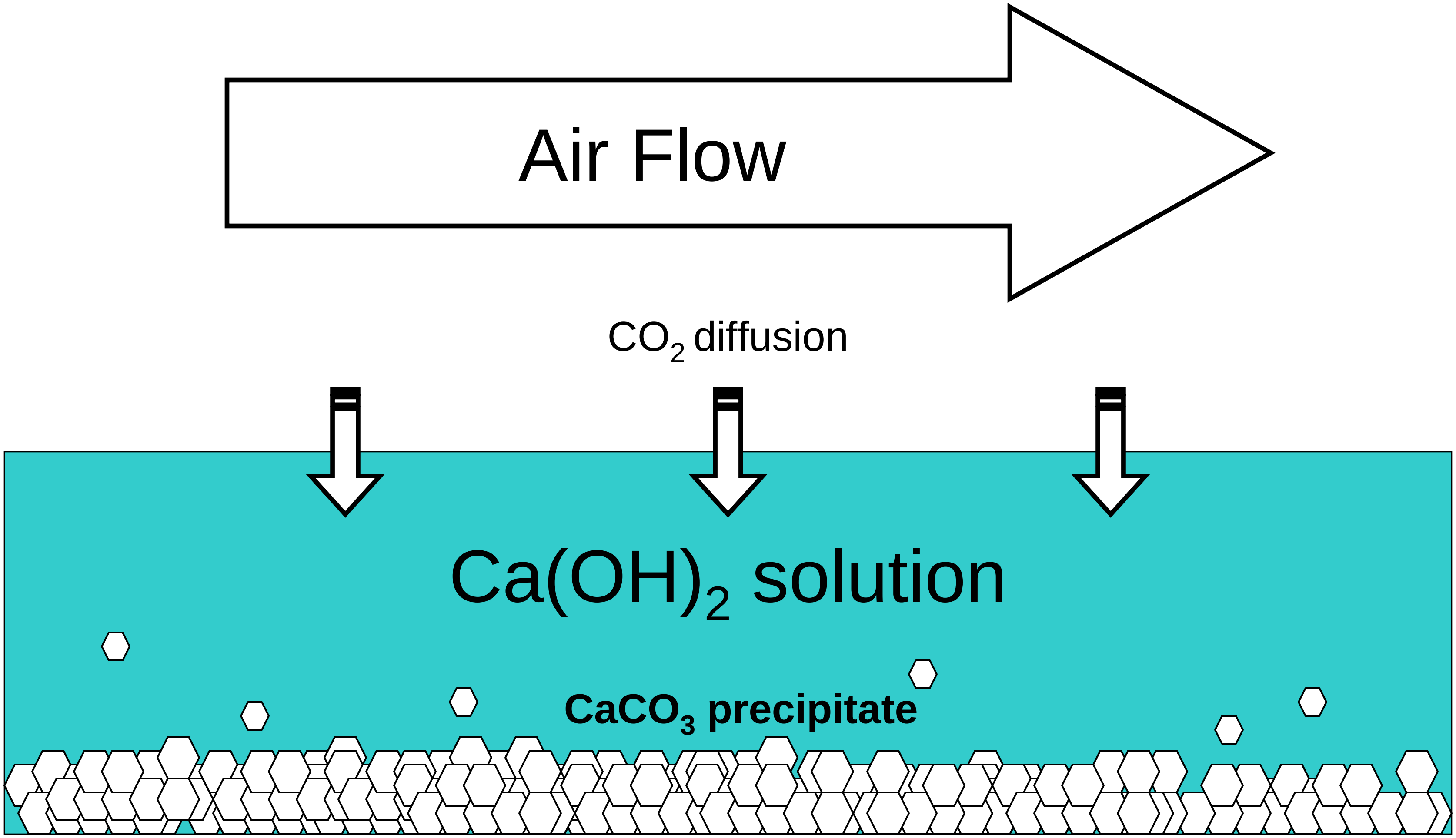
Volumes are drawn to scale

$Ca(OH)_2$ as an absorbent



CO_2 mass transfer is limited by diffusion in air boundary layer

<u>How much wind?</u>

(6m/sec)

Wind area that carries 10 kW

$0.2\ m^2$

for CO_2

Wind area that carries 22 tons of CO_2 per year

50 cents/ton of CO_2 for contacting

$80\ m^2$

for Wind Energy

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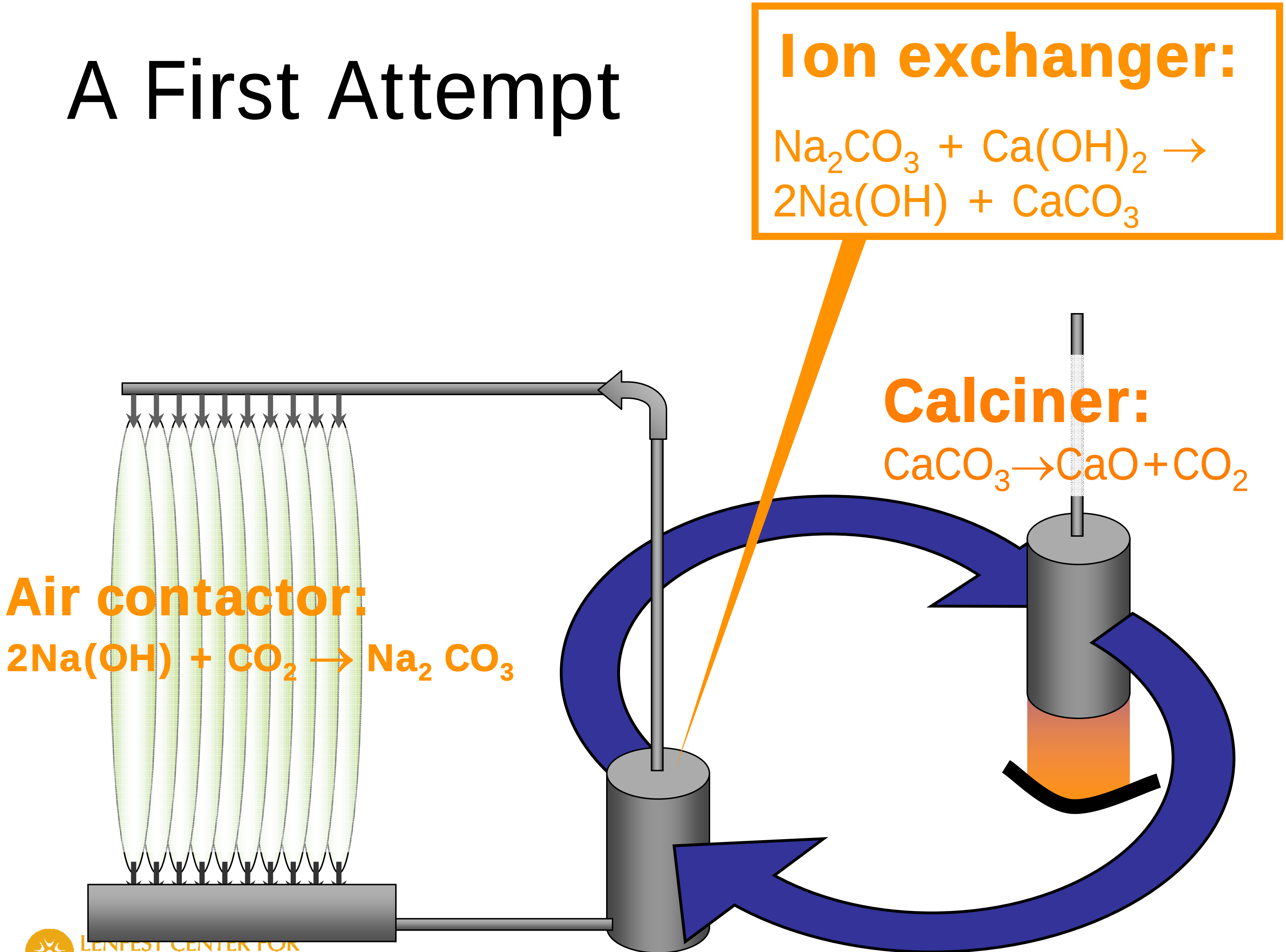
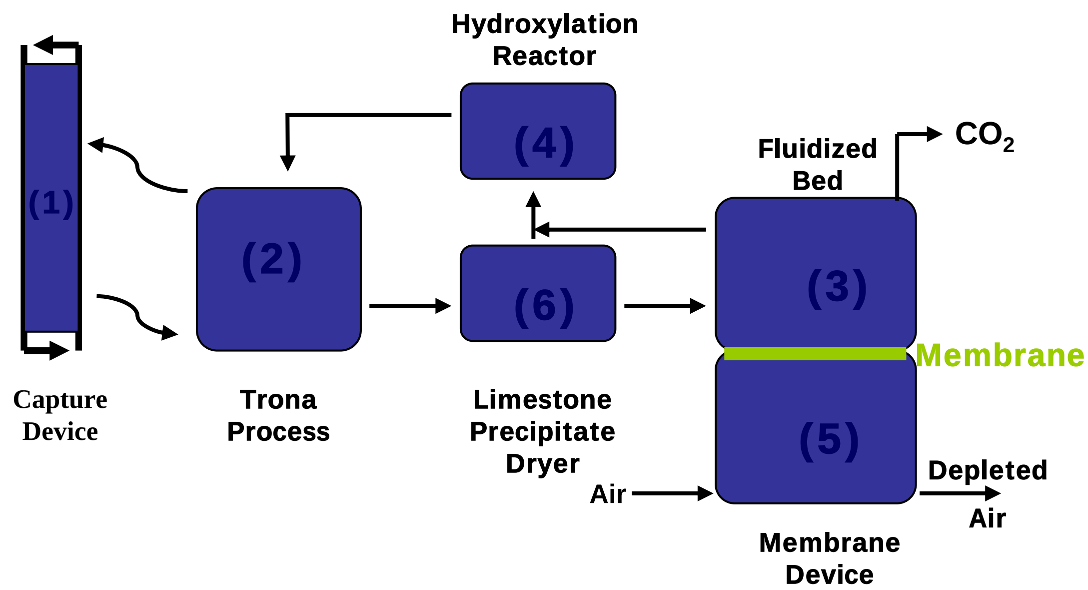
A First Attempt



Process Reactions



(1) $2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$ ΔH^o = - 171.8 kJ/mol

(2) $Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$ ΔH^o = 57.1 kJ/mol

(3) $CaCO_3 \rightarrow CaO + CO_2$ ΔH^o = 179.2 kJ/mol

(4) $CaO + H_2O \rightarrow Ca(OH)_2$ ΔH^o = - 64.5 kJ/mol

(5) $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ ΔH^o = -890.5 kJ/mol

(6) $H_2O_{(l)} \rightarrow H_2O_{(g)}$ ΔH^o = 41. kJ/mol

Source: Frank Zeman

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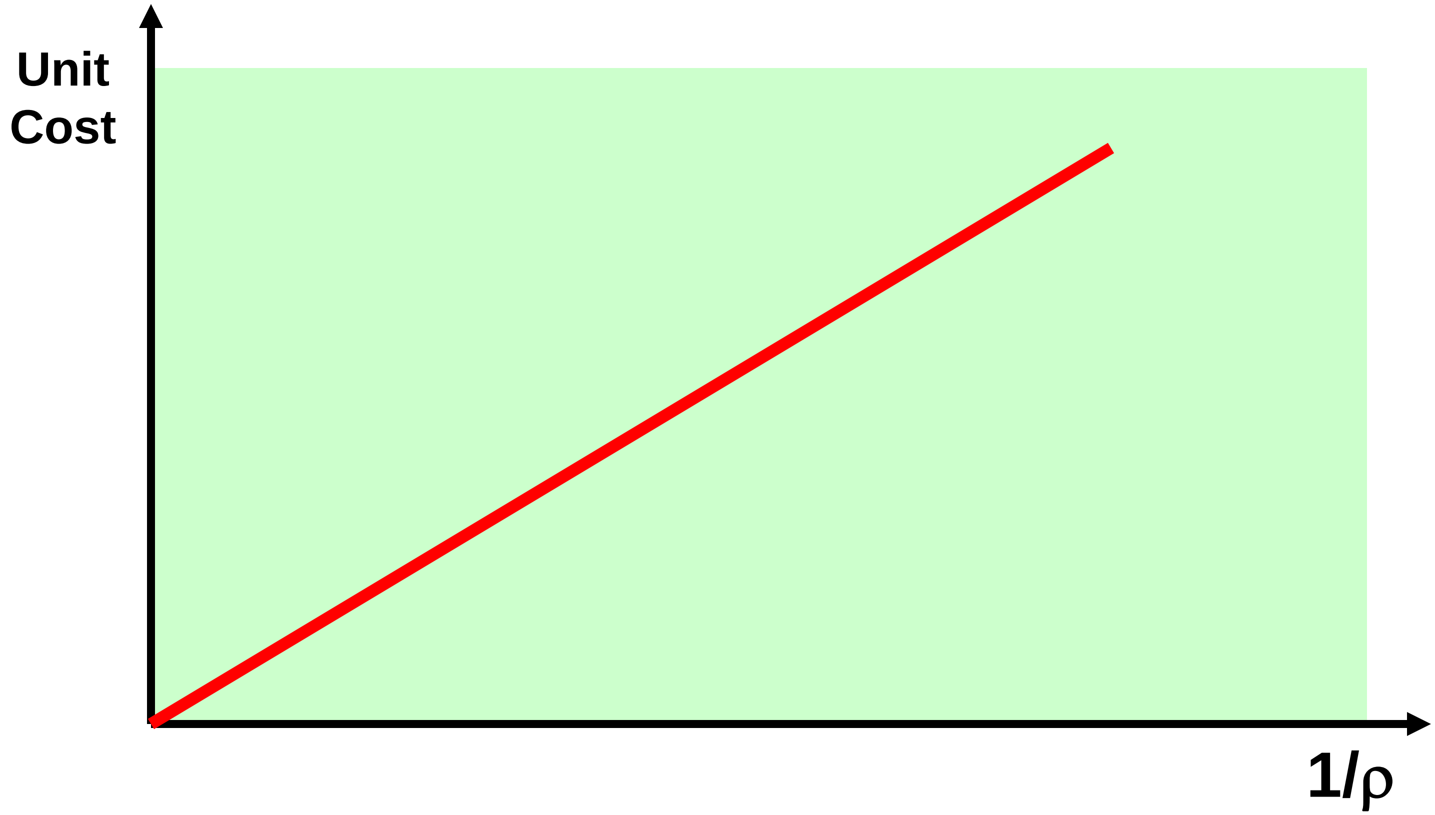
Cost of Contacting the Air



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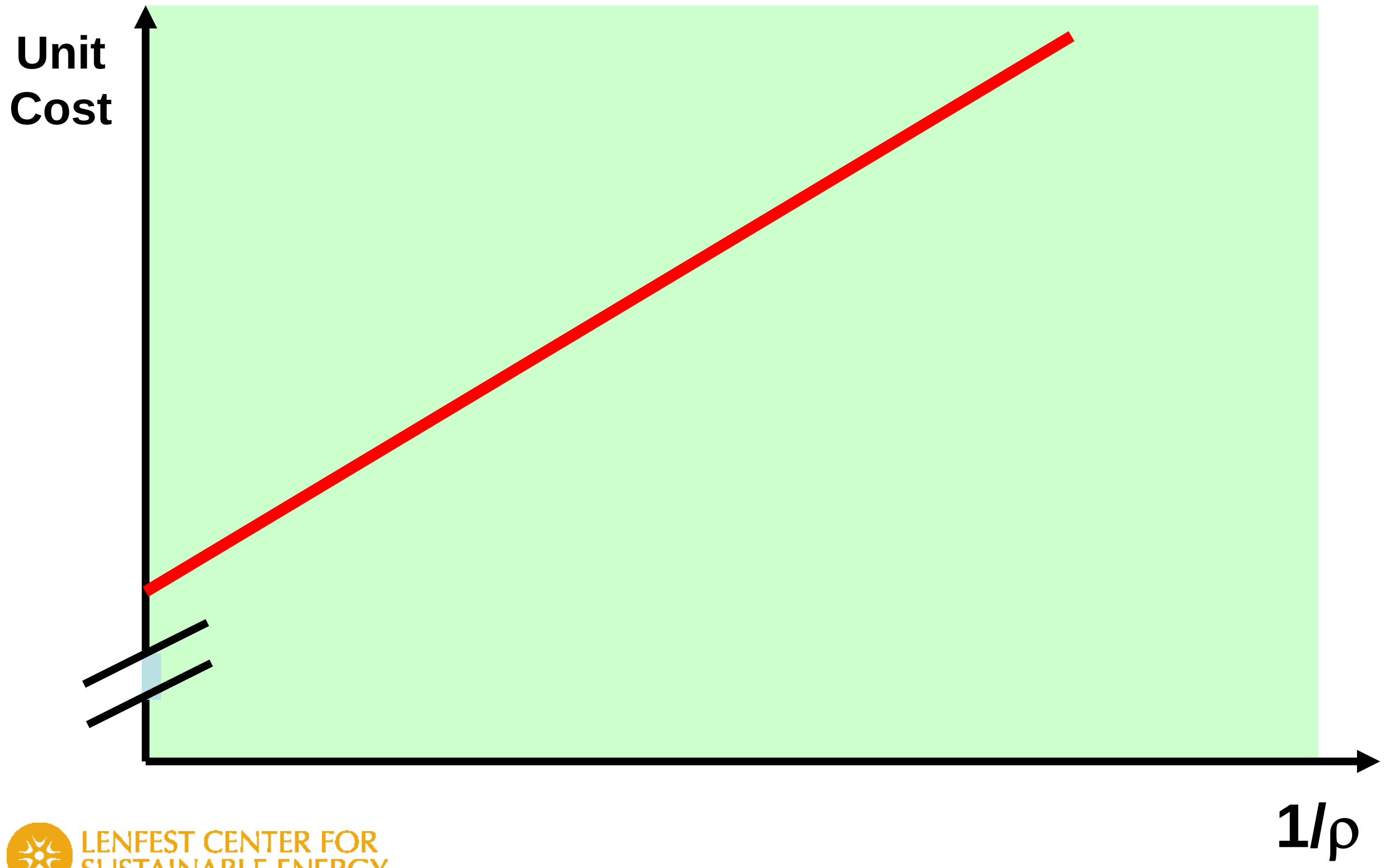
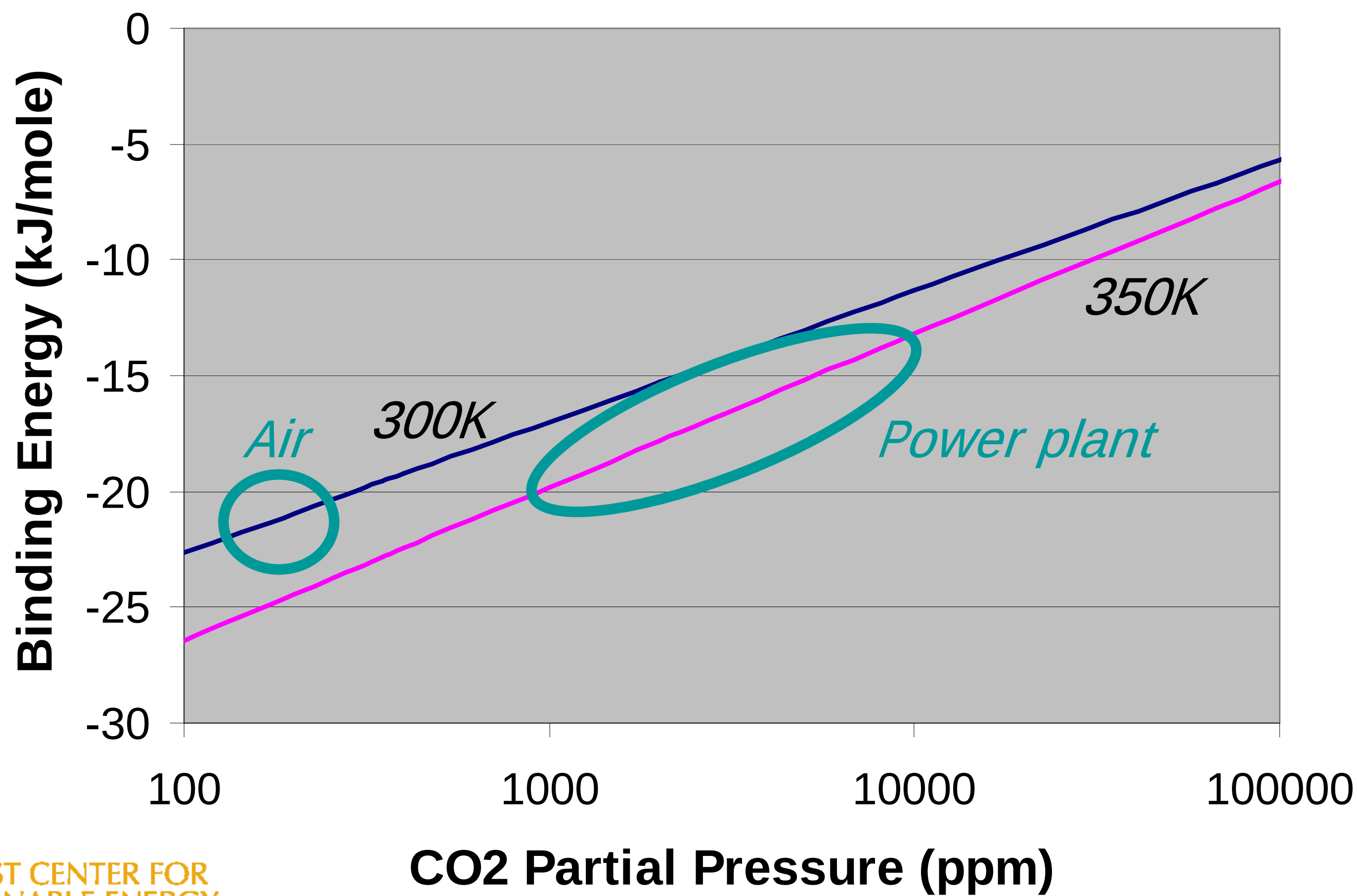
Cost of CO_2 from Air



Sorbent Choices



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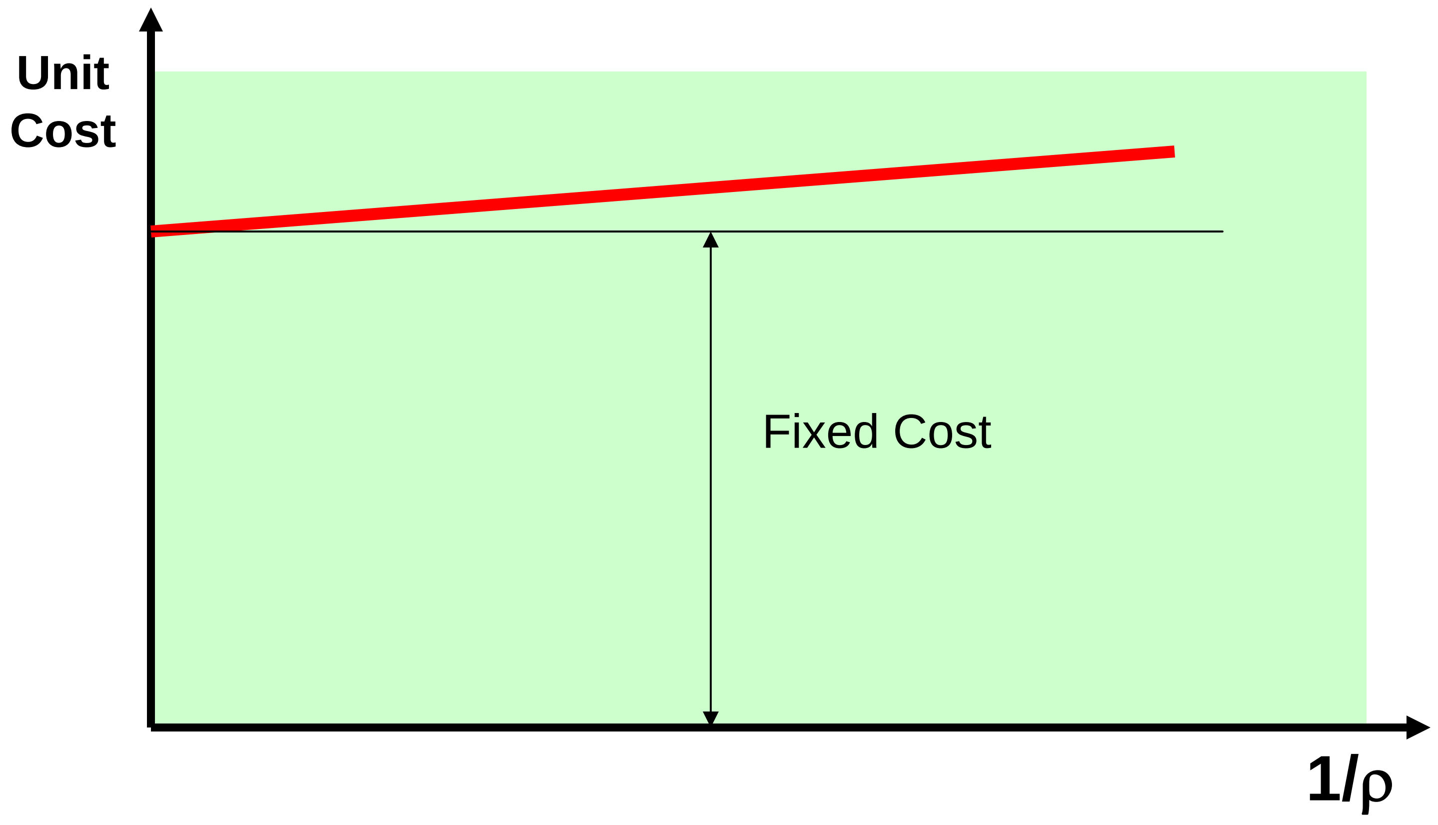
Cost of CO_2 from Air (rescaled)



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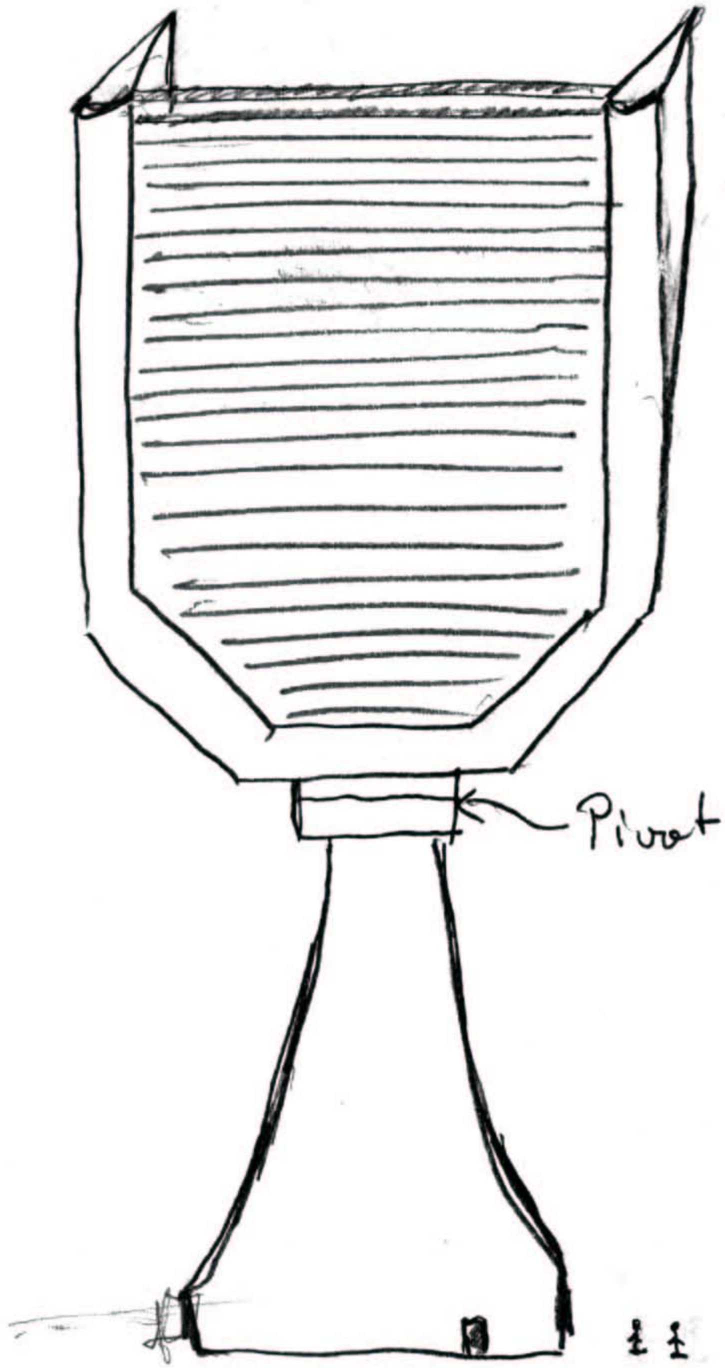

60m by 50m

3kg of CO_2 per second

90,000 tons per year

4,000 people or

15,000 cars

Would feed EOR for 800 barrels a day.

250,000 units for worldwide CO_2 emissions


GRT’s Vision

The first of a kind

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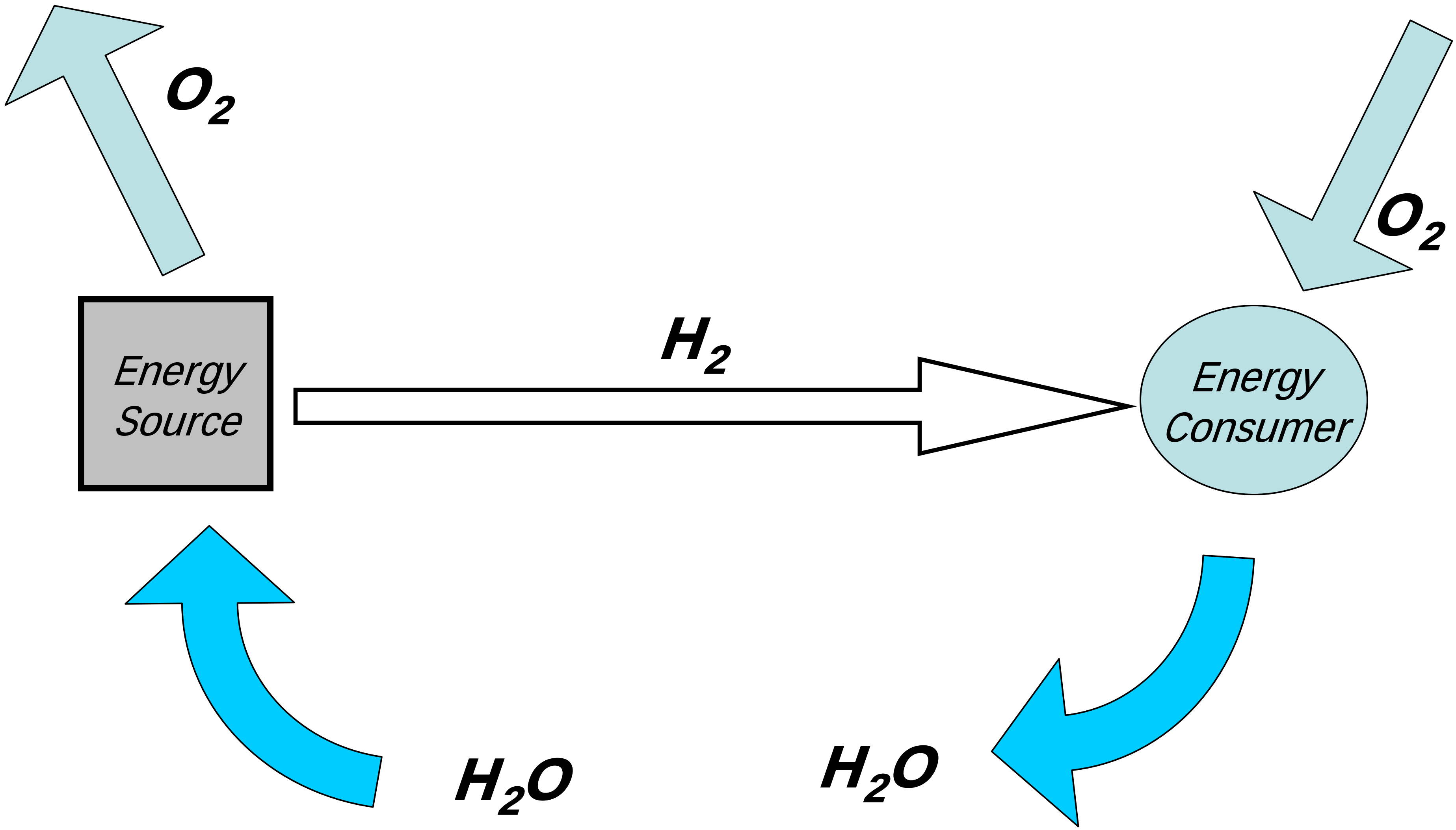
Materially Closed Energy Cycles



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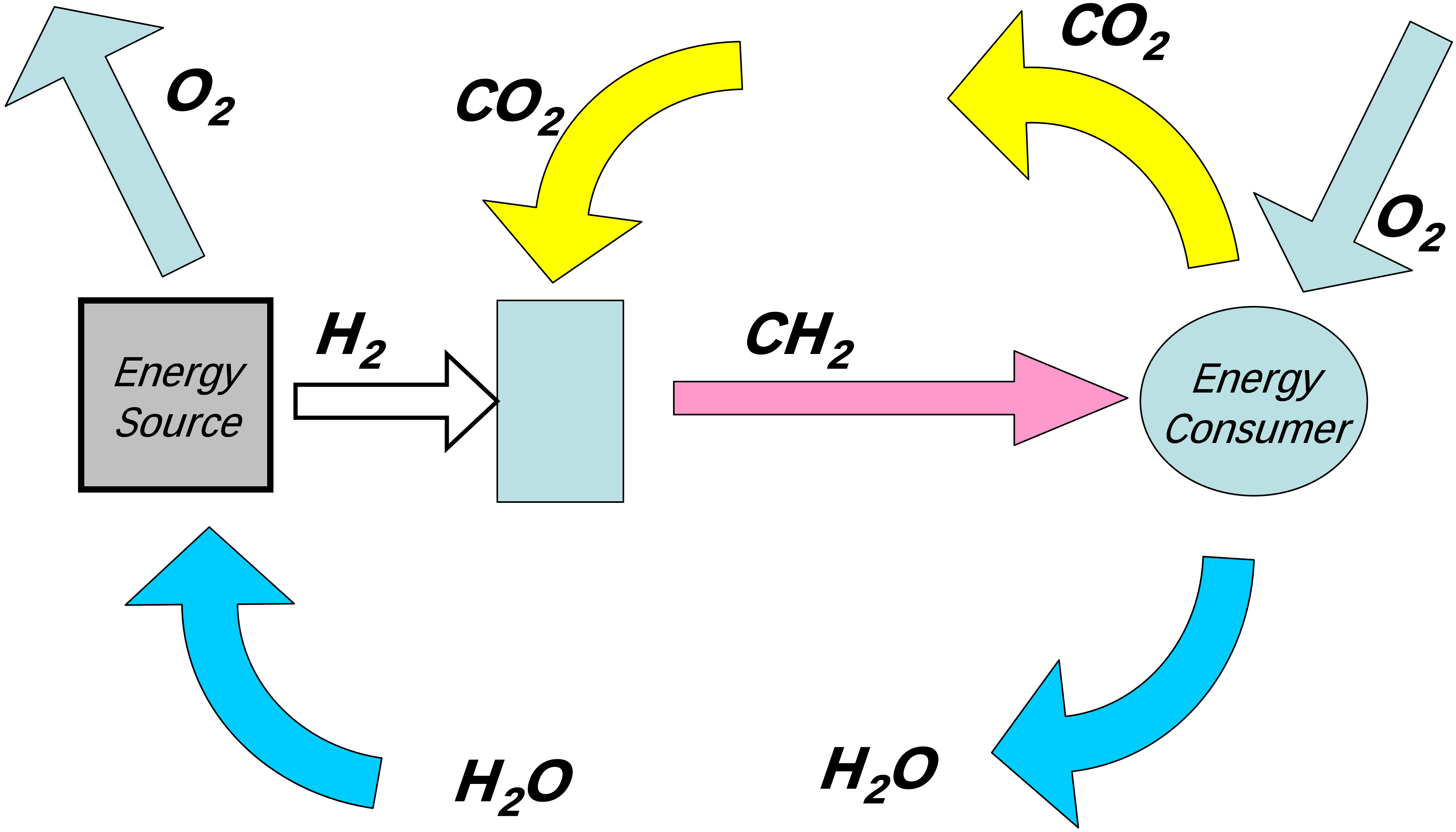

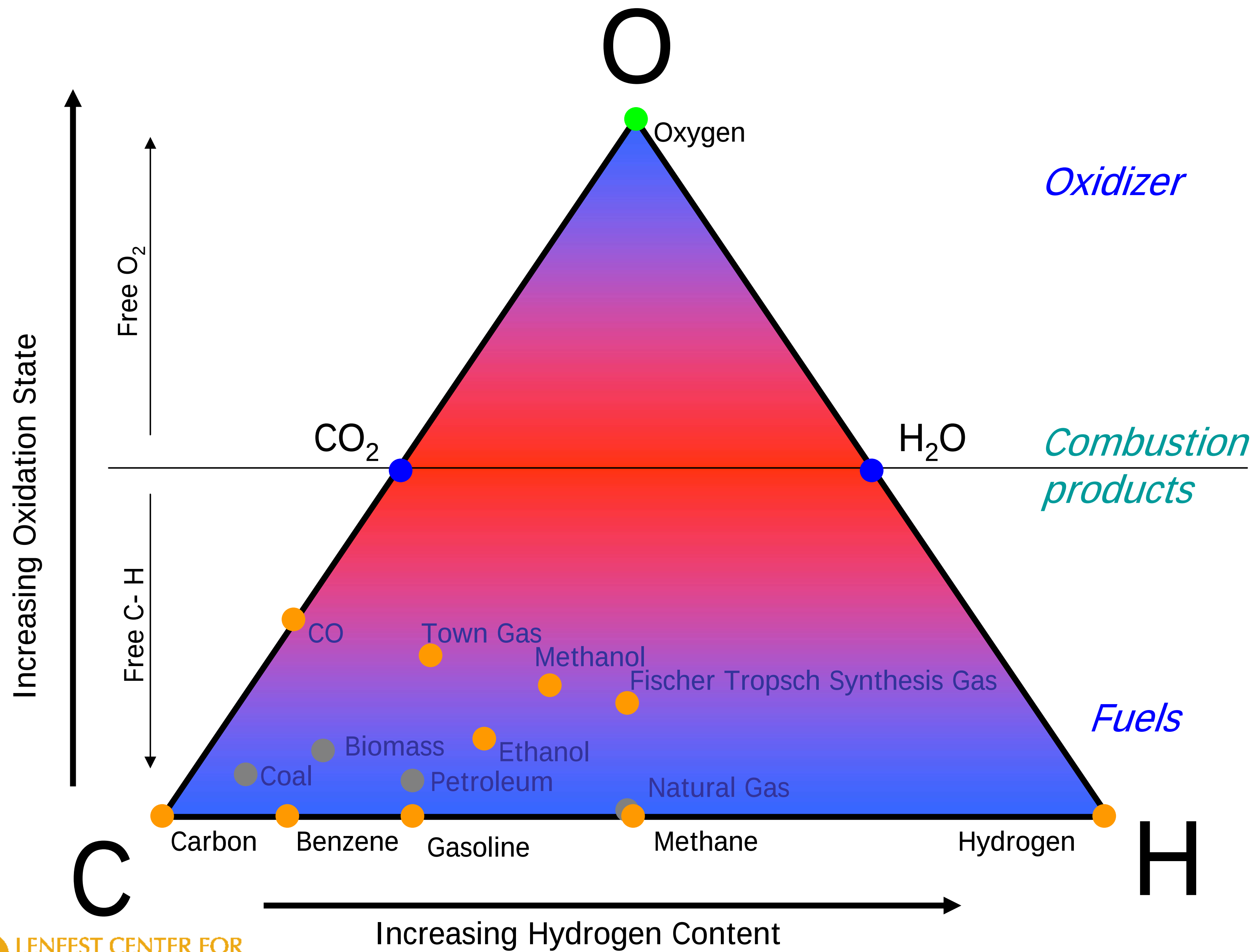

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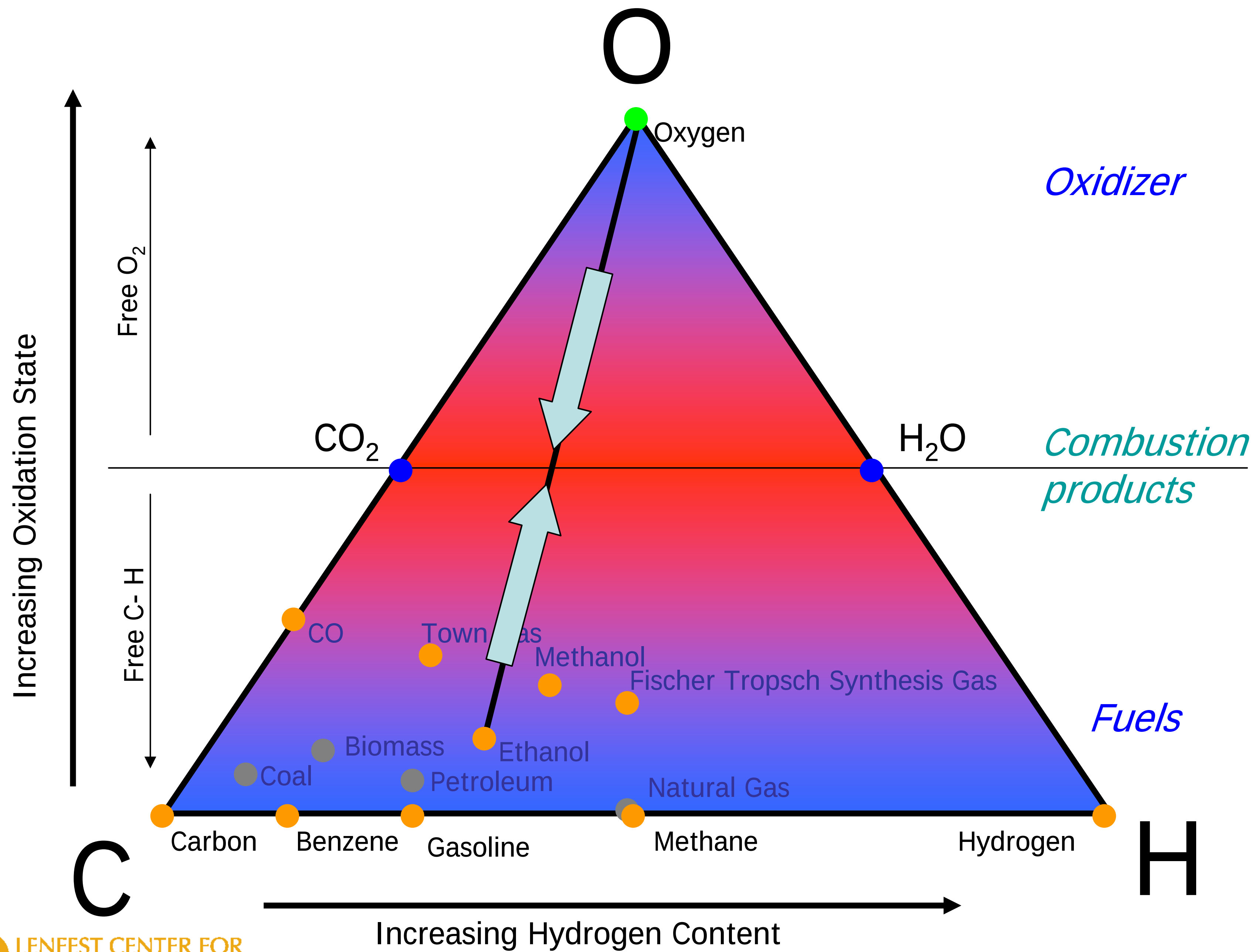
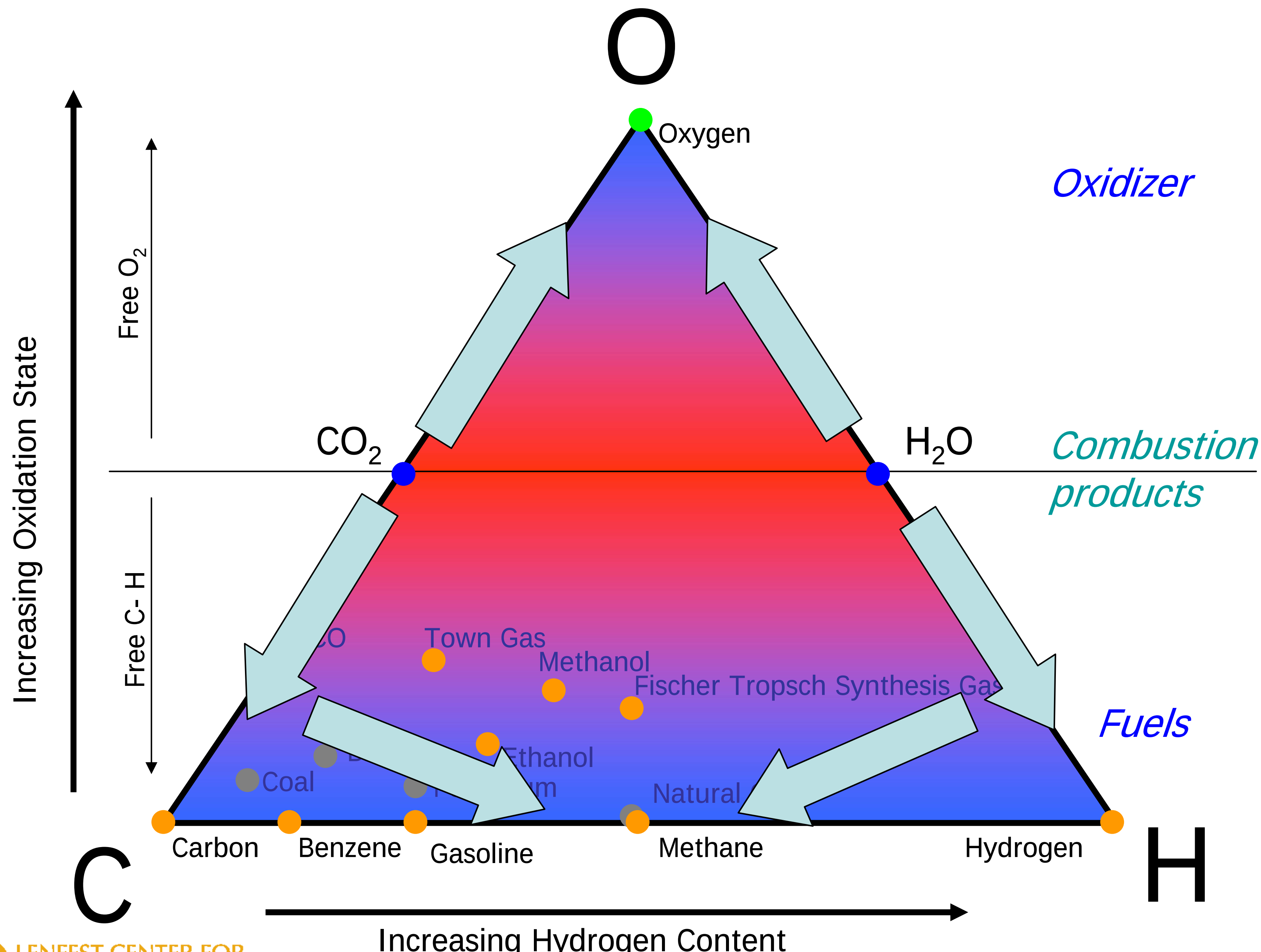

O
Oxygen
Oxidizer
Free O_2
Increasing Oxidation State
CO_2
H_2O
Combustion products
Free C- H
CO
Town
Methanol
Fischer Tropsch Synthesis Gas
Fuels
Biomass
Ethanol
Coal
Petroleum
Natural Gas
Carbon
Benzene
Gasoline
Methane
Hydrogen
C
H
Increasing Hydrogen Content



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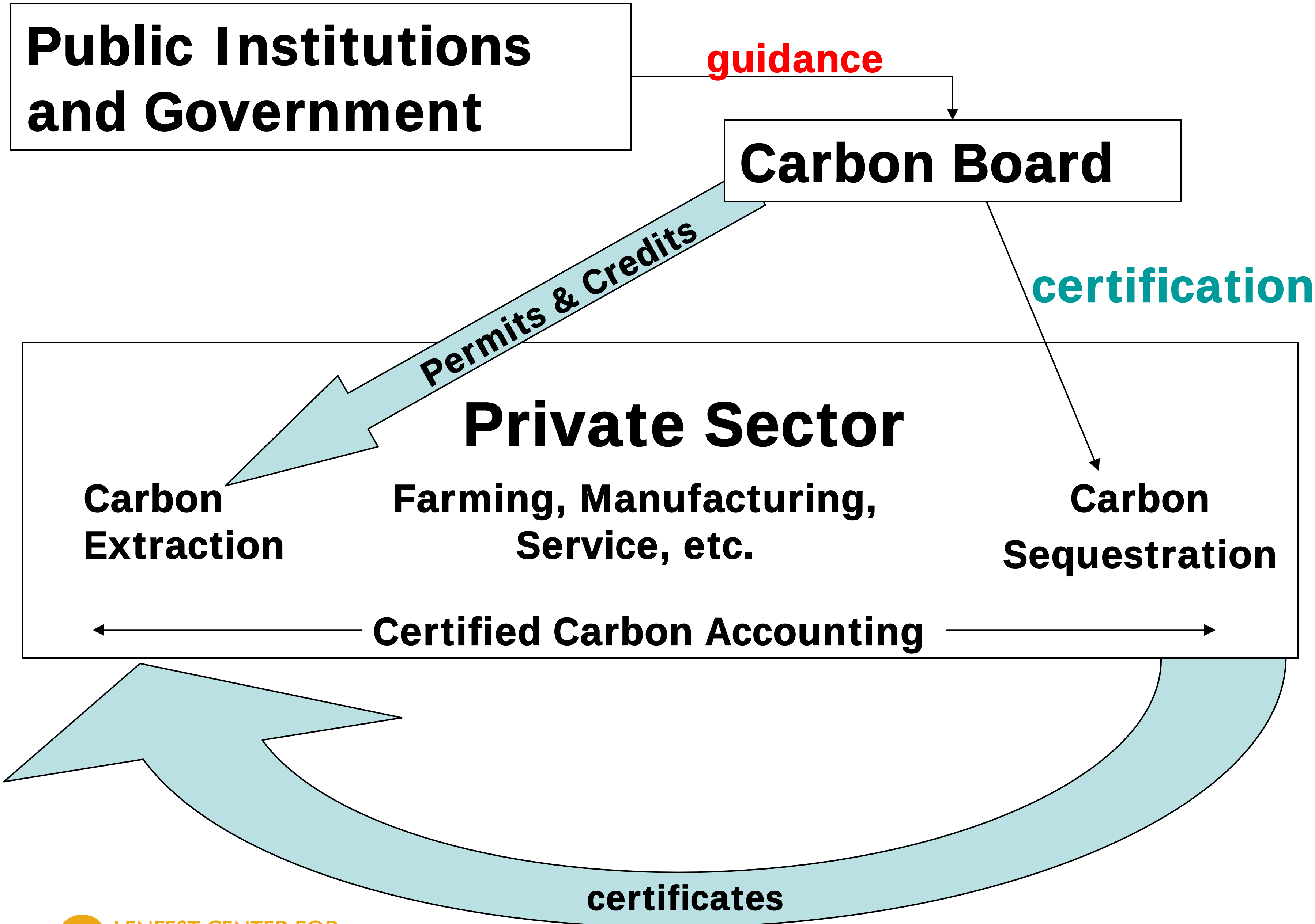
Carbon Capture and Storage for Carbon Neutral World

- CCS simplifies Carbon Accounting
  - Ultimate Cap is Zero
  - Finite amount of carbon left


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

1,5 PS
Höchstgeschwindigkeit 20 km/h