Carbon Management Options:

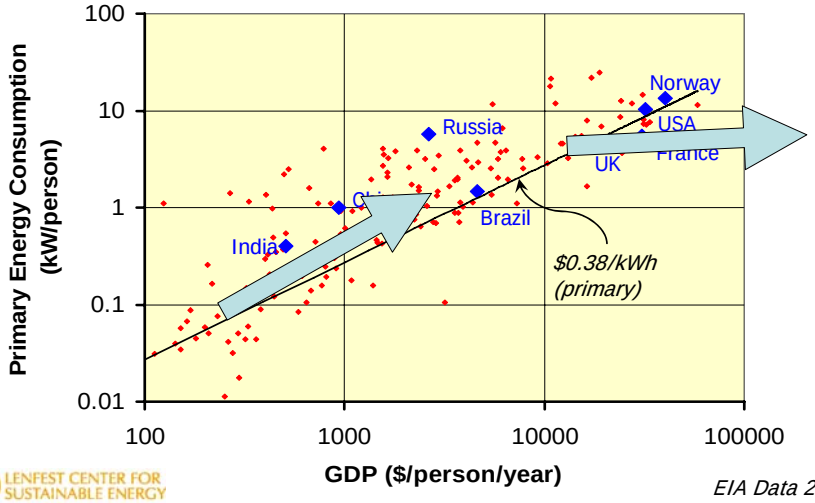
Maintaining access to abundant fossil fuels

Klaus S. Lackner

Columbia University

May 2007

Energy, Wealth, Economic Growth



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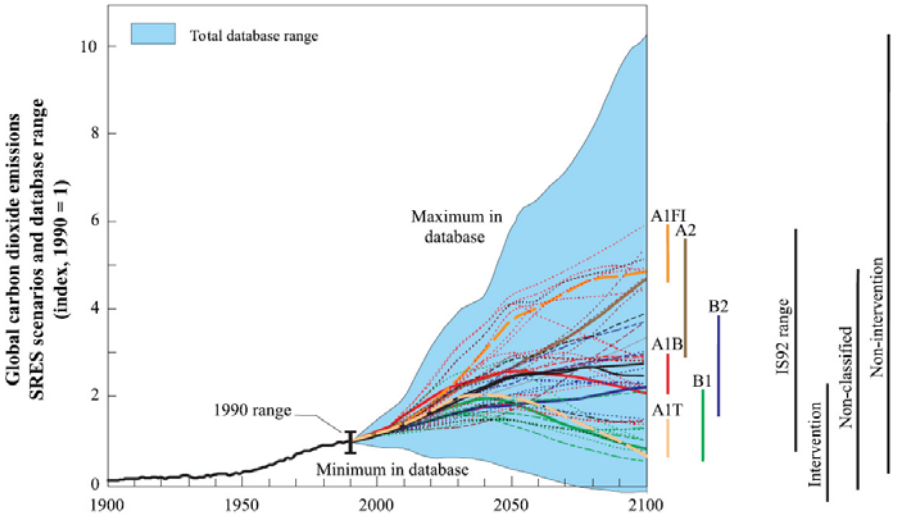
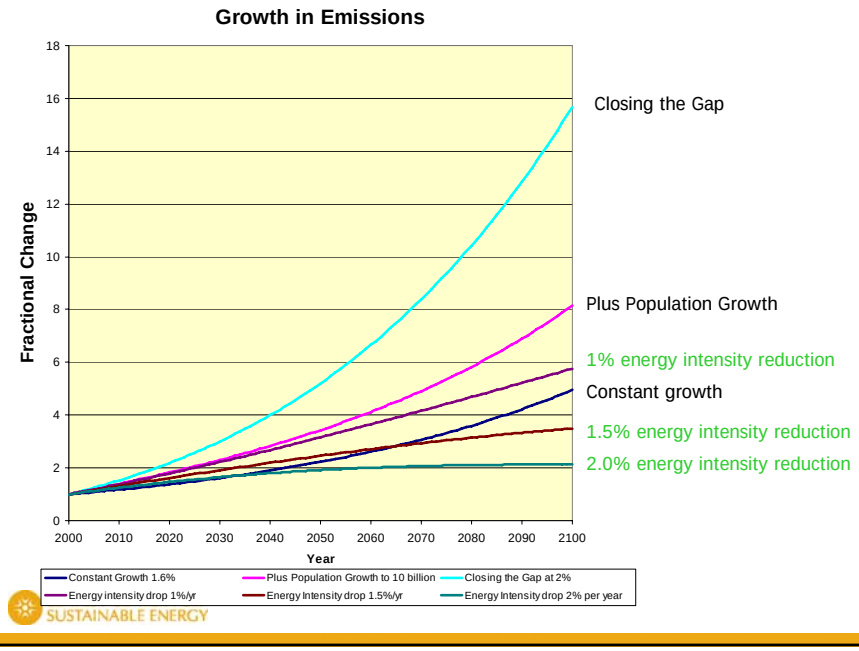
EIA Data 2002

IPCC Model Simulations of CO_2 Emissions





Resource Estimates

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

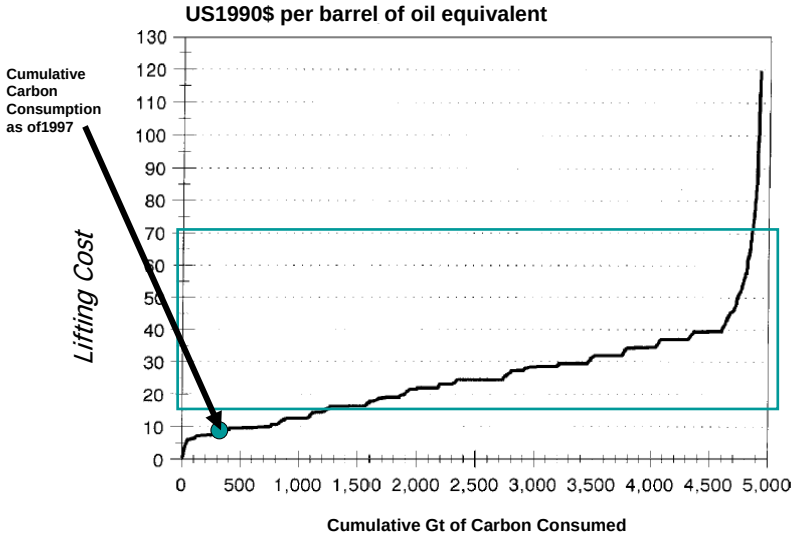
	Consumption					
	1860–1994	1994	Reserves	Resources[b]	Resource base[c]	Additional occurrences
Oil						
Conventional	103	3.21	150	145	295	
Unconventional	6	0.16	183	336	519	1,824
Natural gas						
Conventional[d]	48	1.87	141	279	420	
Unconventional	—	—	192	258	450	387
Clathrates	—	—	—	—	—	18,759
Coal	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

SUSTAINABLE ENERGY

Carbon as a Low-Cost Source of Energy



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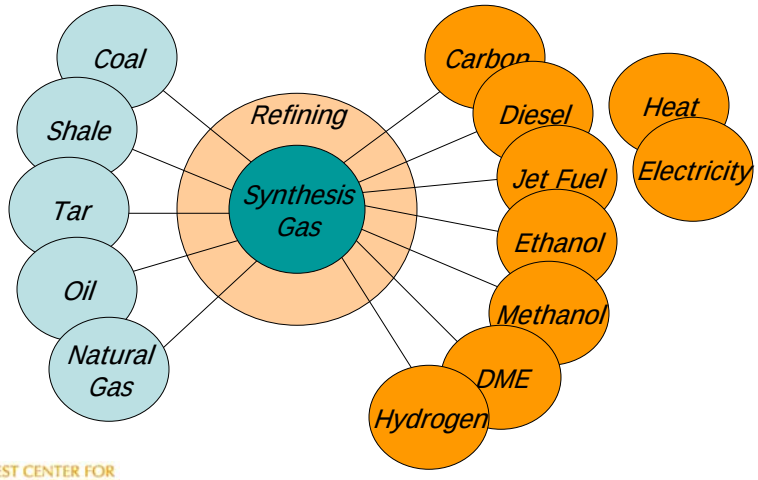
H.H. Rogner, 1997

Fossil fuels are fungible



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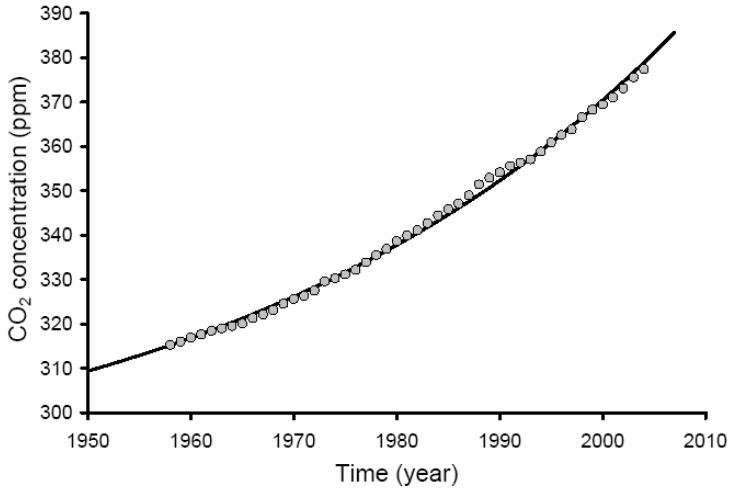
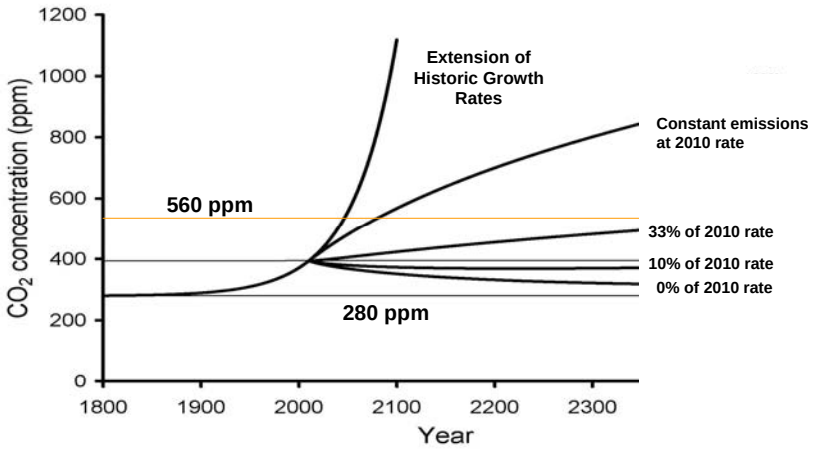
Comparison With Keeling's Data



The Challenge:
Holding the Stock of CO_2 constant



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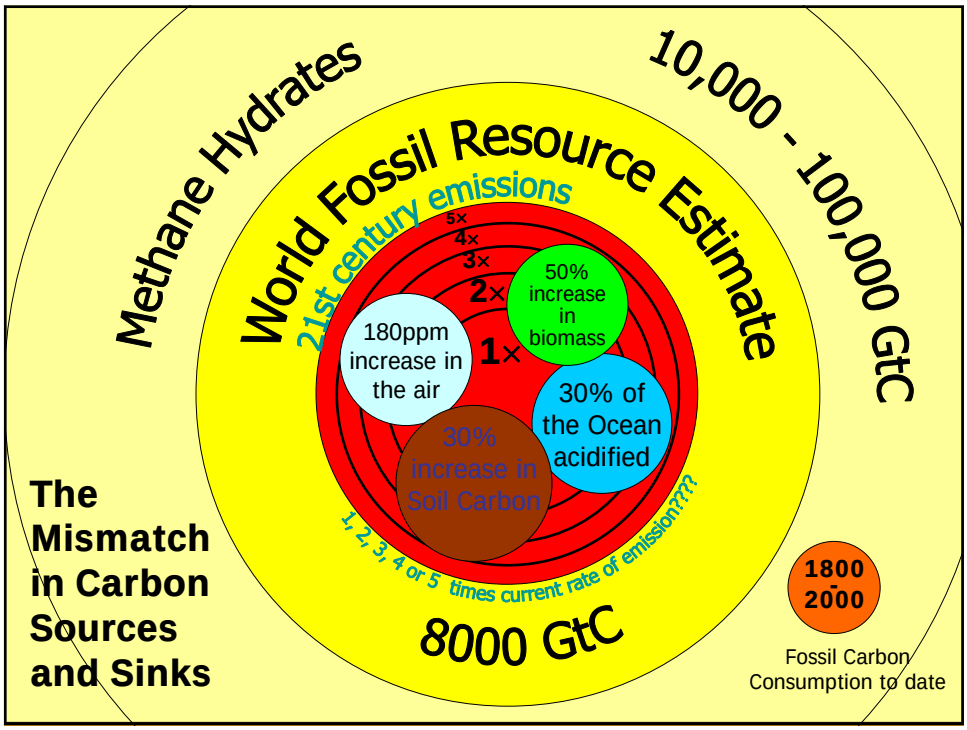
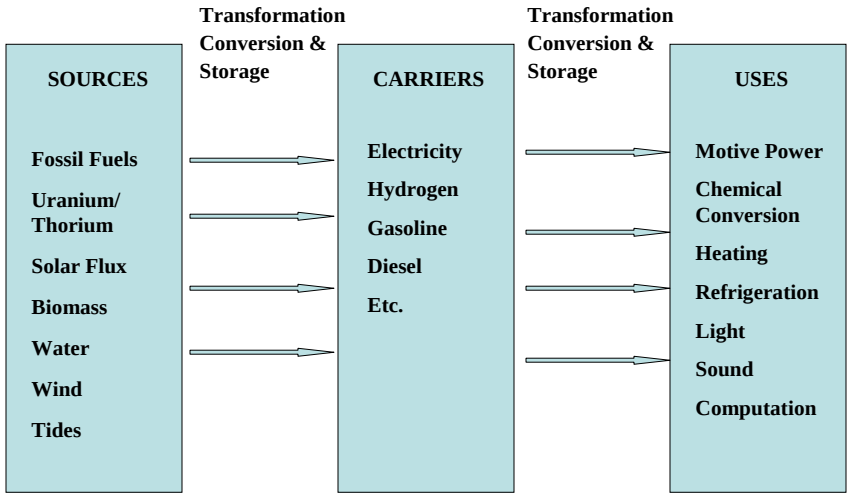


The Mismatch in Carbon Sources and Sinks

Carriers Connecting Sources to Uses



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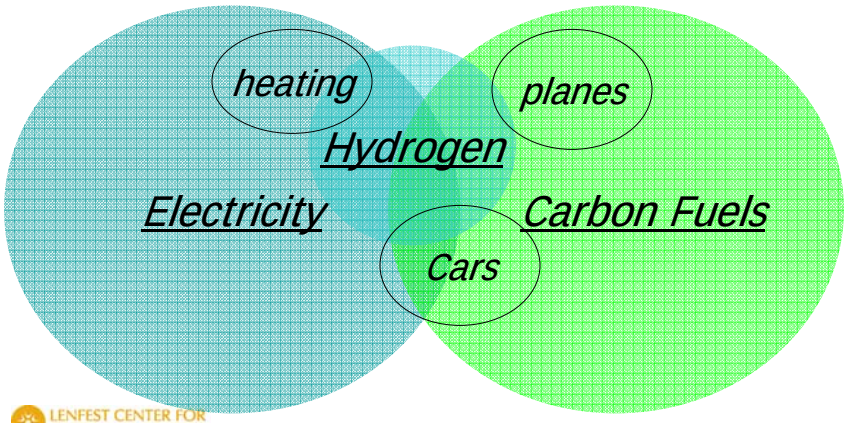
Roles and Interchange of Energy Carriers

Fuel Flexibility



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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

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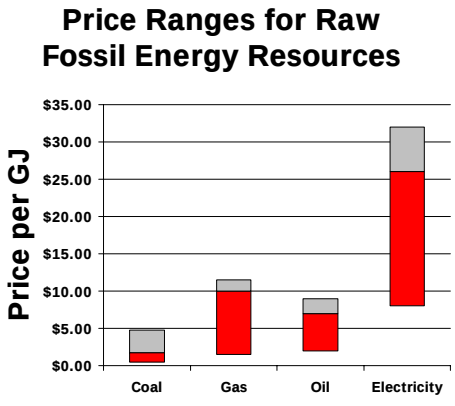
The hydrogen economy cannot run on electricity

There are no hydrogen wells

Tar, coal, shale and biomass could support a hydrogen economy.

Wind, photovoltaics and nuclear energy cannot.



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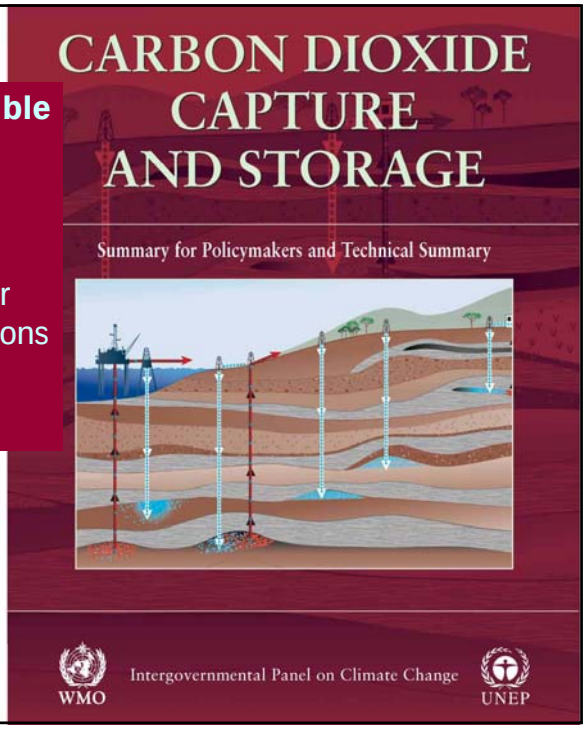
CCS is technically feasible

It is affordable

It can start today

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



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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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Decarbonizing Energy Carriers

- All Electric Economy
  - Stationary uses
- Hydrogen Economy
  - Heating and transportation
- Extraction of CO_2 from Air
  - Biomass
  - Chemical Extraction

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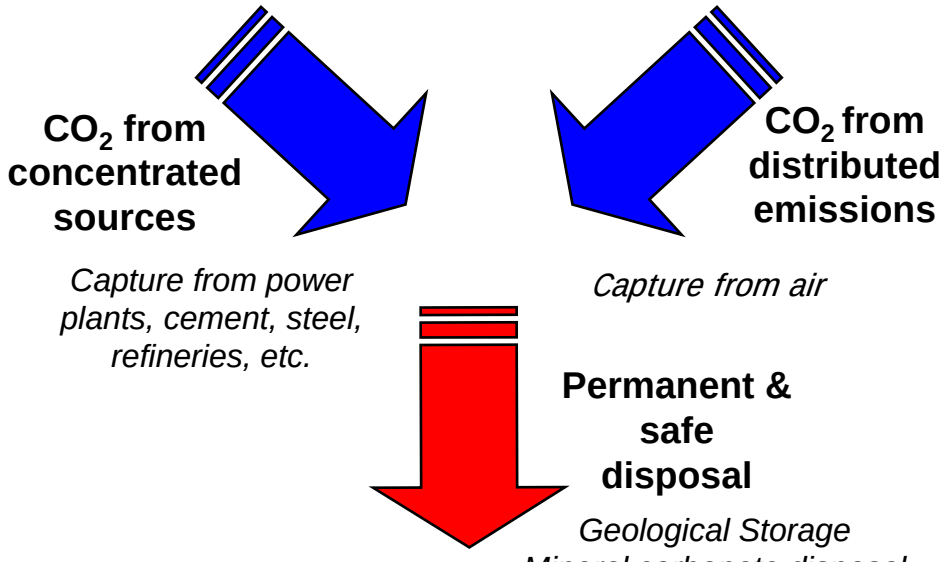
Net Zero Carbon Economy



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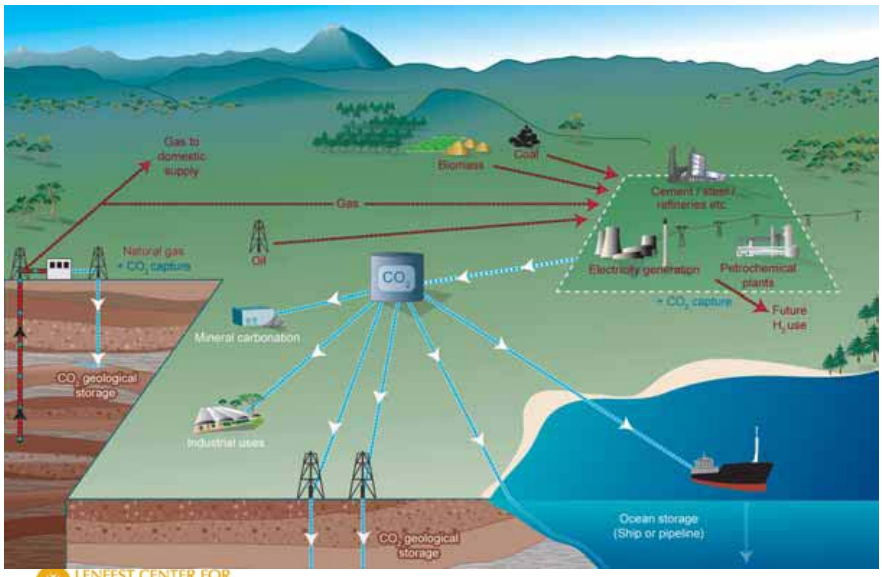
Carbon Management



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Sequestration at the Verge of Commercial Development

- Economic realities not quite there yet
- Projects require special circumstances
  - Statoil
  - Pilot Plants

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CCS moves to industry

- Oil Companies: BP, Statoil, Shell
  - Big projects – but small on global scale
  - Oil companies own one technology
- Utilities and Equipment Makers
  - Need options and technologies
  - Vattenfall, Babcock & Wilcox, Air Liquide, Alstom

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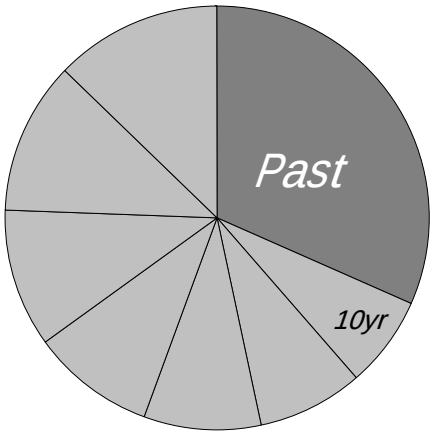
Dividing The Fossil Carbon Pie

900 Gt C

total



550 ppm

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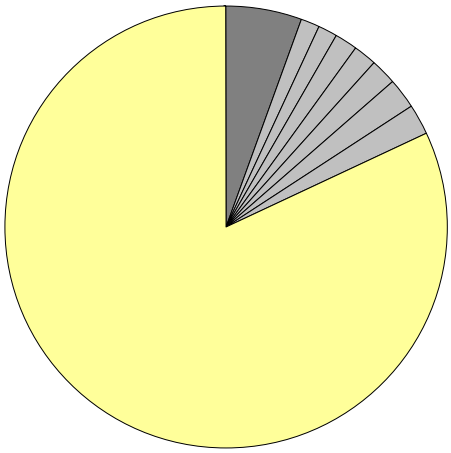
Removing the Carbon Constraint

5000 Gt C

total



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Storage Life Time

Slow Leak (0.04%/yr)

2 Gt/yr for 2500 years

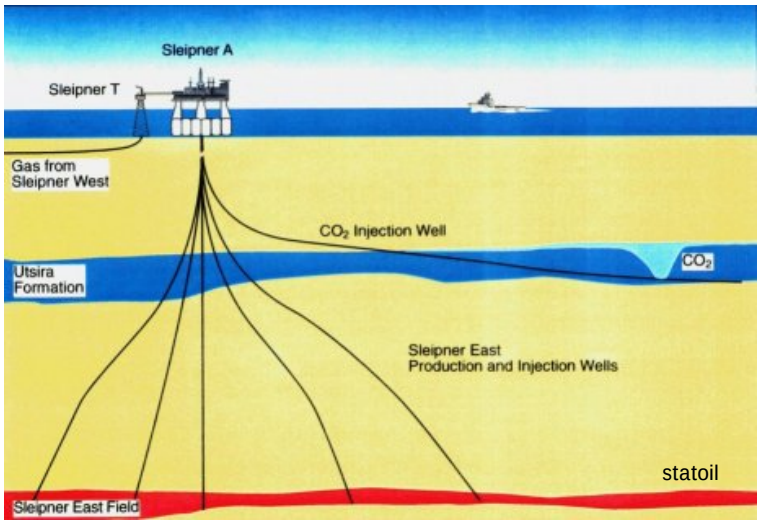
Storage

5000 Gt of C

200 years at 4 times current rates of emission

Current Emissions: 6Gt/year

Underground Injection



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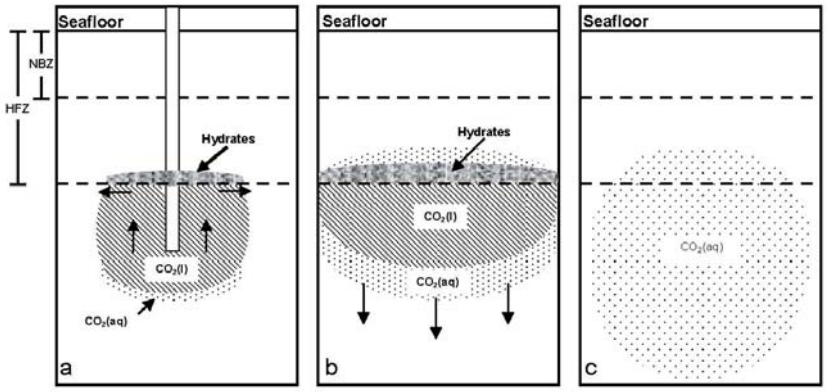
Gravitational Trapping Subocean Floor Disposal



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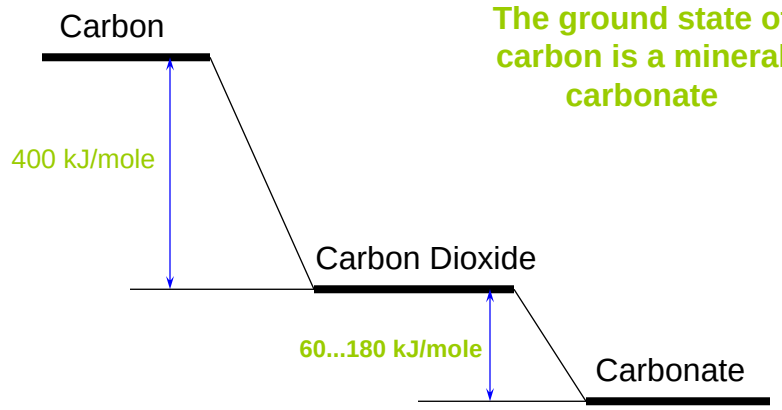
Energy States of Carbon



The ground state of carbon is a mineral carbonate

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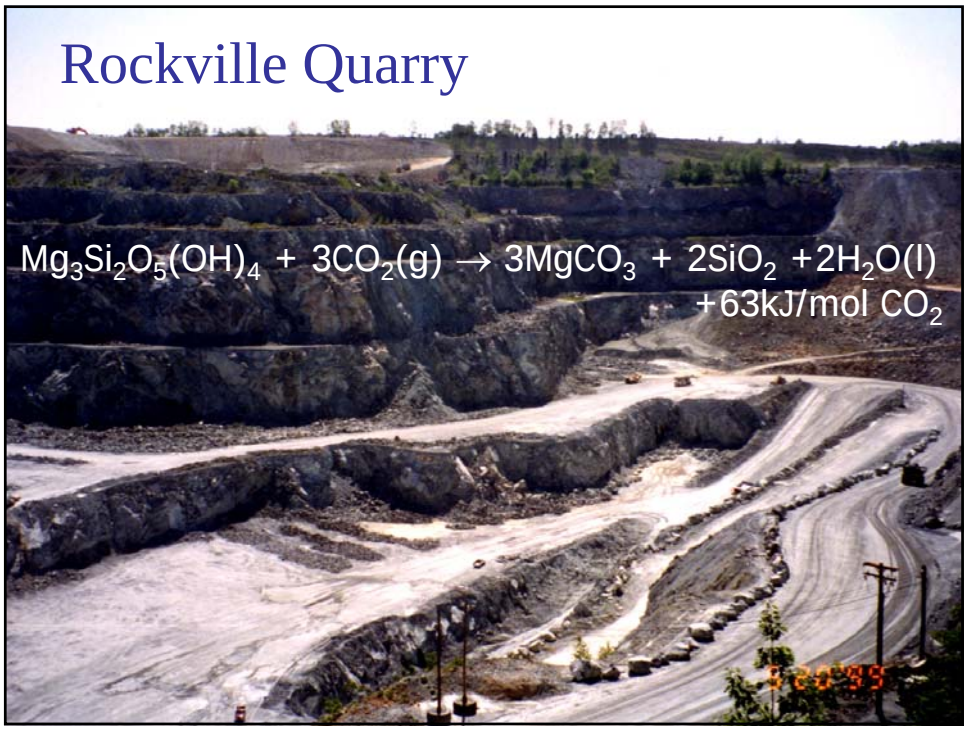
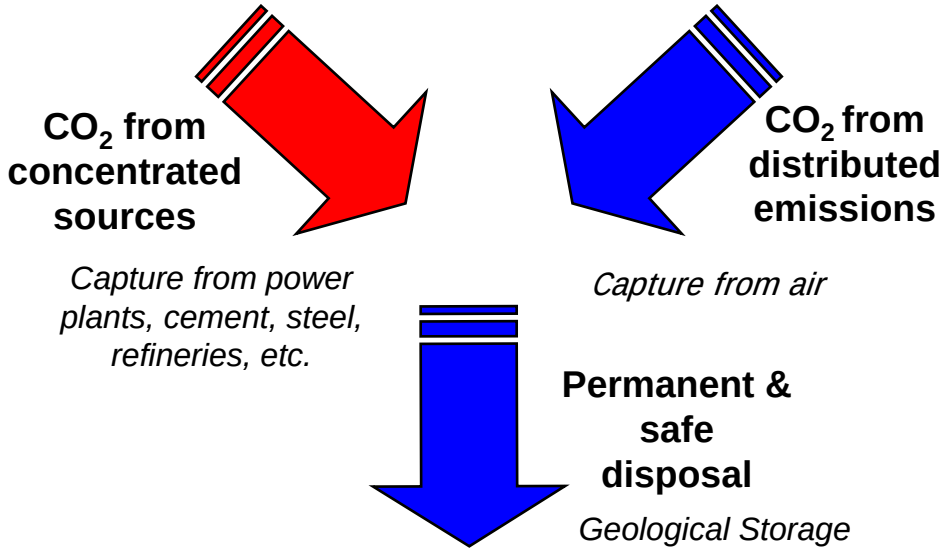
Rockville Quarry



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

Net Zero Carbon Economy



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Adapting Power Plants

- Amine Scrubbing
  - Plus variations on the theme
- Oxygen Blown Combustion
  - Entry to zero emission plants
- IGCC with Capture

Completely changes the mass flow in the power plant

- Emphasis on better efficiency

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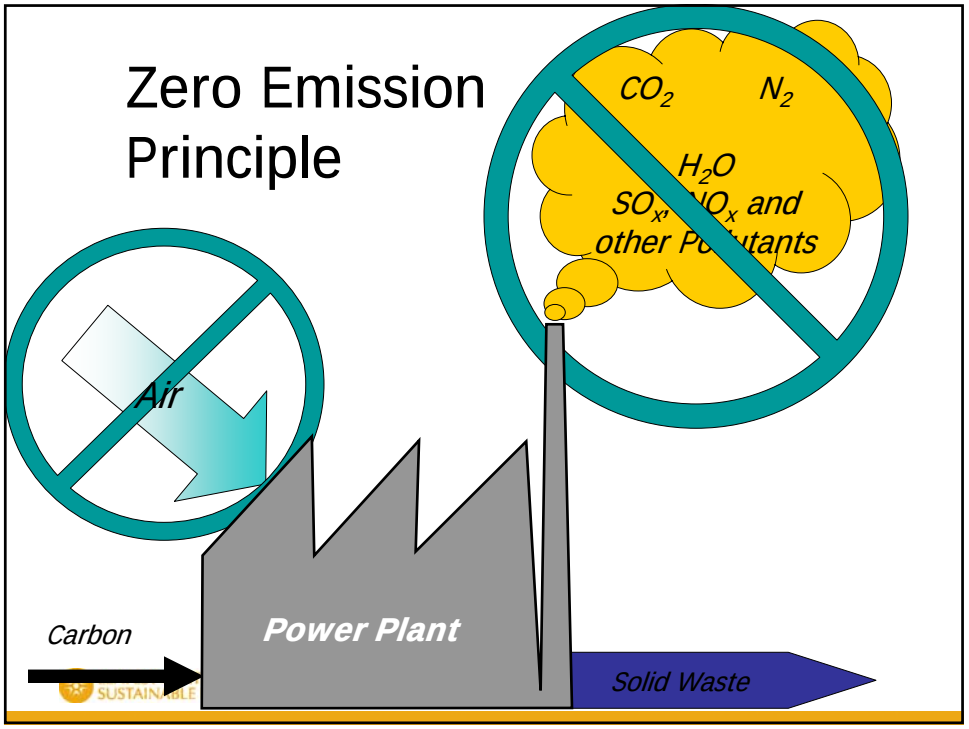

Many Different Options

- Oxyfuel Combustion
  - Naturally zero emission
- Integrated Gasification Combined Cycle
  - Difficult as zero emission
- AZEP Cycles
  - Mixed Oxide Membranes
- Fuel Cell Cycles
  - Solid Oxide Membranes

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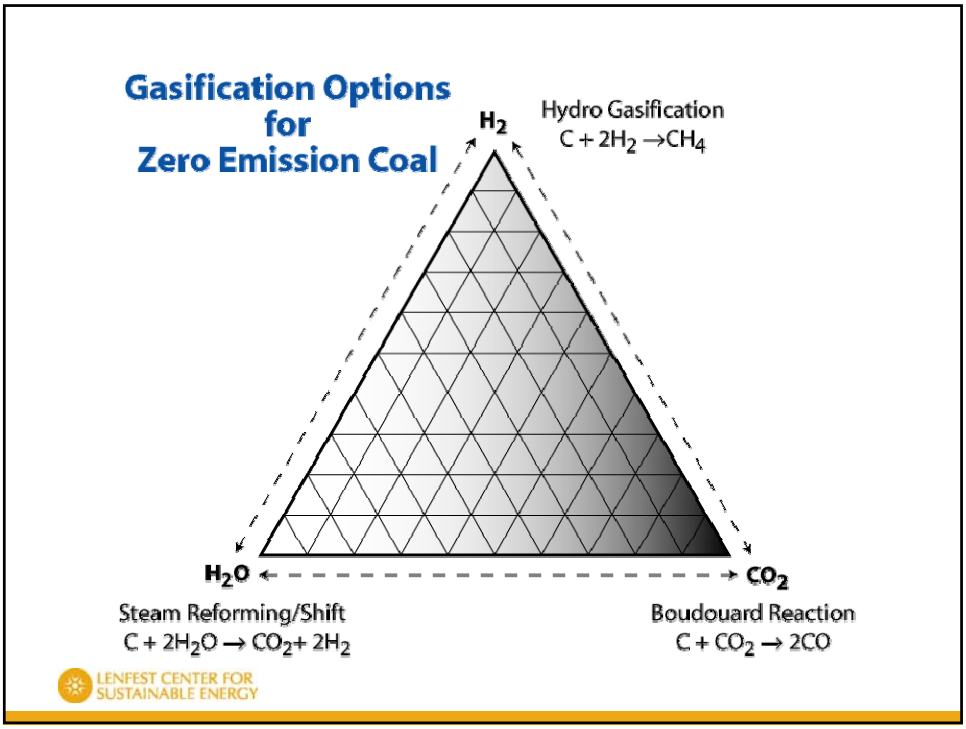


Carbon makes a better fuel cell

$C + O_2 \rightarrow CO_2$

no change in mole volume

entropy stays constant

$\Delta G = \Delta H$

$2H_2 + O_2 \rightarrow 2H_2O$

large reduction in mole volume

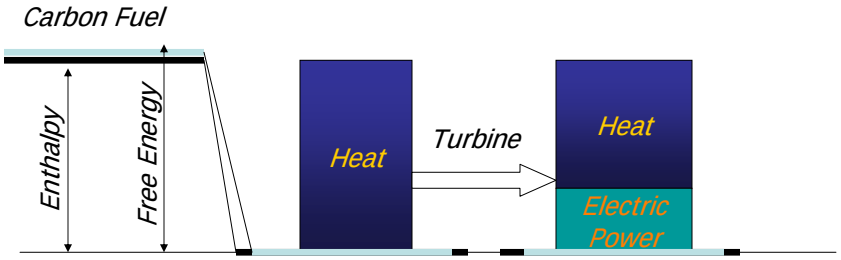
entropy decreases in reactants

made up by heat transfer to surroundings

$\Delta G < \Delta H$

The Conventional Power Plant

Carnot Limited



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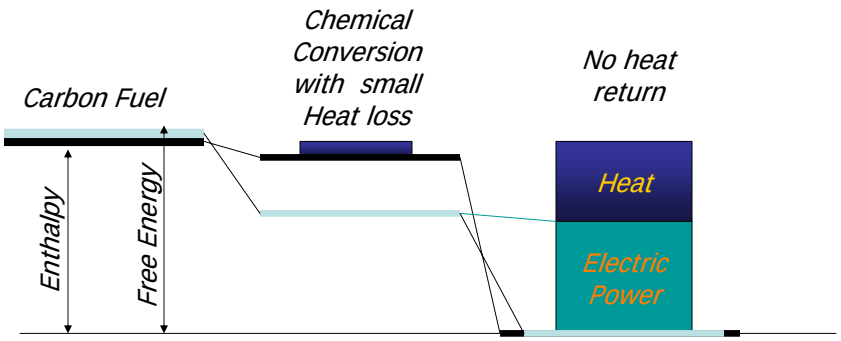
The Standard Fuel Cell

Enthalpy Limited



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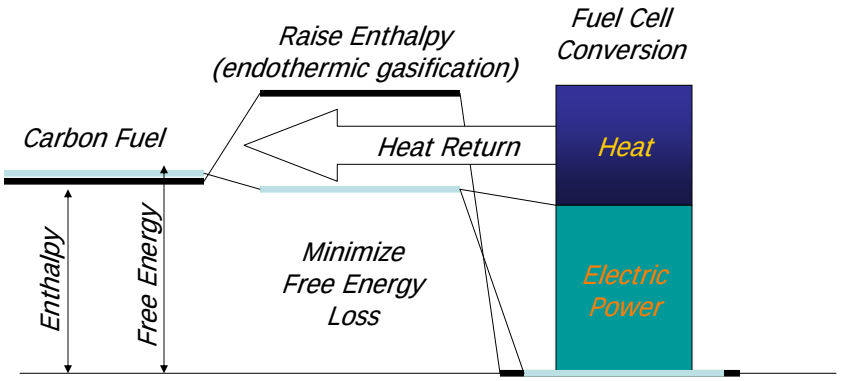
The Zero Emission Fuel Cell

Free energy limited



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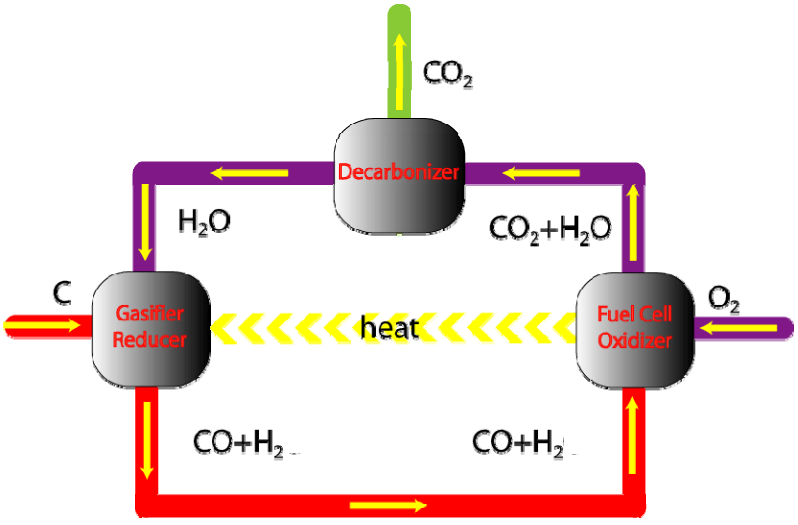
Steam Reforming



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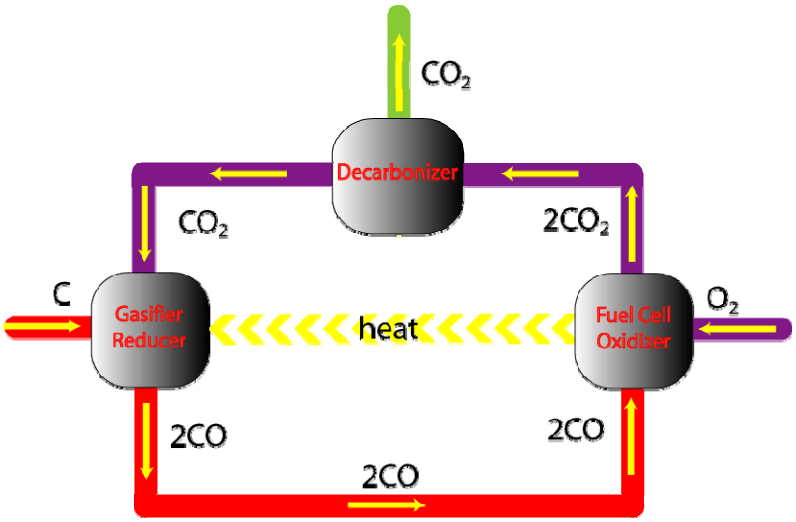
Boudouard Reaction



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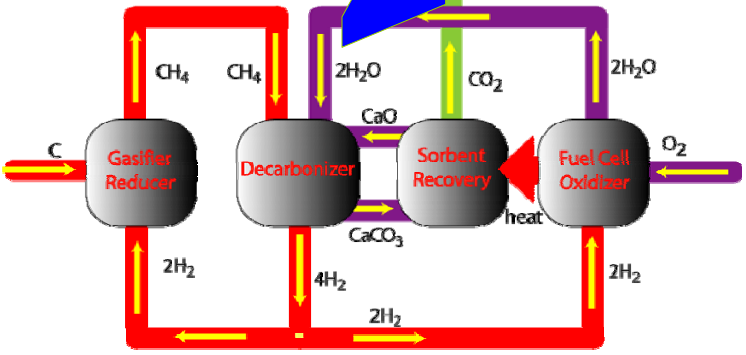
Hydrogenation

ZECA



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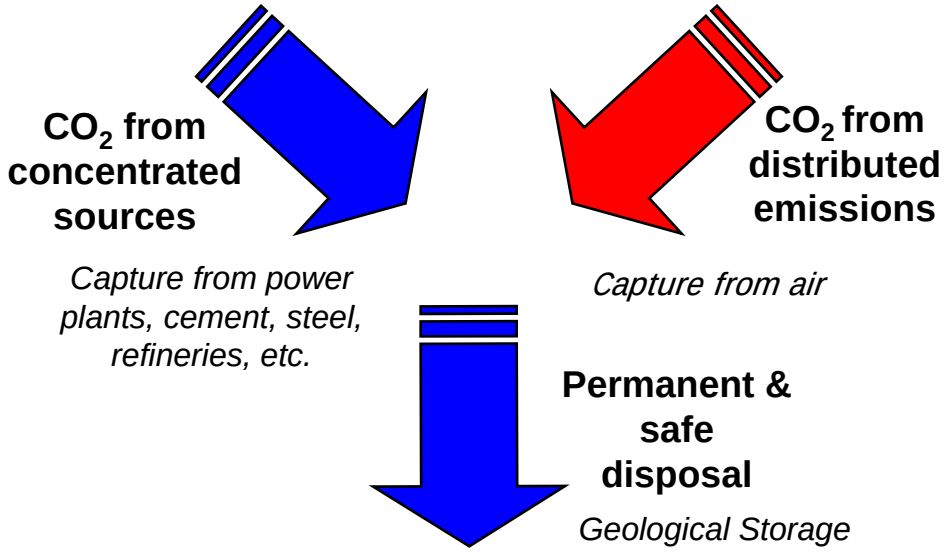
Net Zero Carbon Economy



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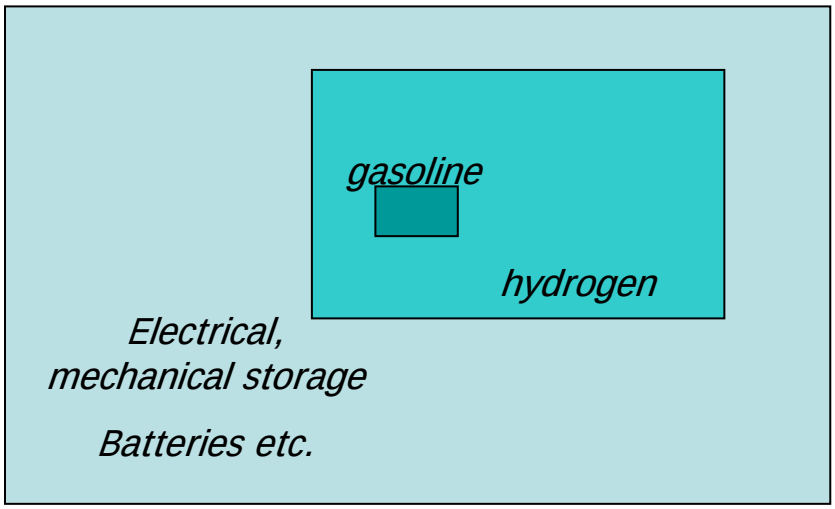
Relative size of a tank



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Biomass Fuels

- Corn Alcohol?
- Switch Grass
- "Cellulosic Alcohol"
- Biodiesel

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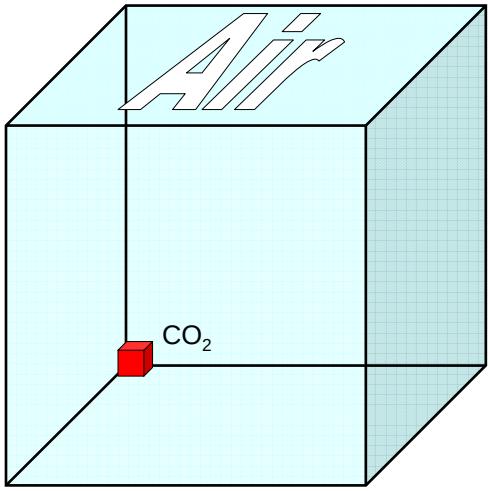
CO_2 Capture from Air



LENFEST CENTER FOR SUSTAINABLE ENERGY *Volumes are drawn to scale*

1 m^3 of Air

40 moles of gas, 1.16 kg

wind speed 6 m/s

$$\frac{mv^2}{2} = 20\ \text{J}$$

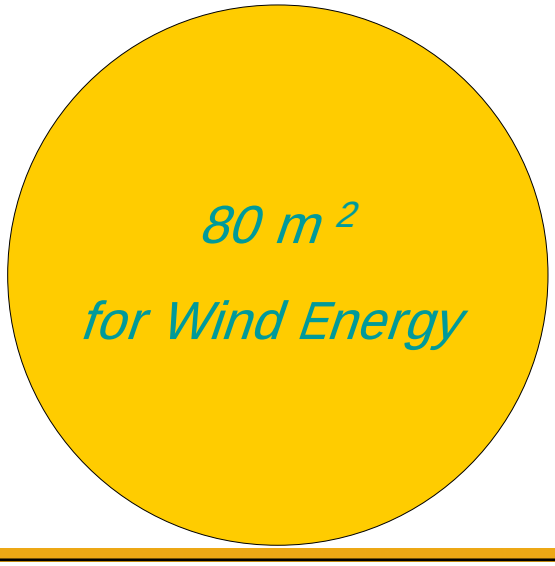
0.015 moles of CO_2

produced by 10,000 J of gasoline

How much wind?

(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

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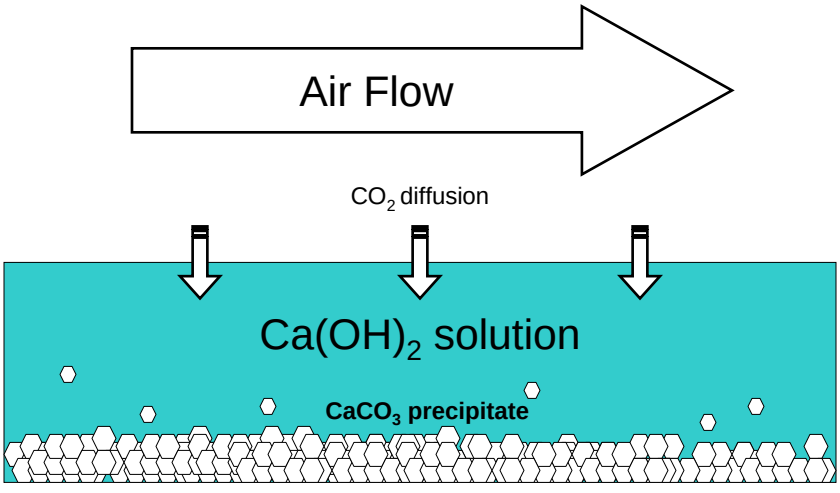
$Ca(OH)_2$ as an absorbent



CO_2 mass transfer is limited by diffusion in air boundary layer

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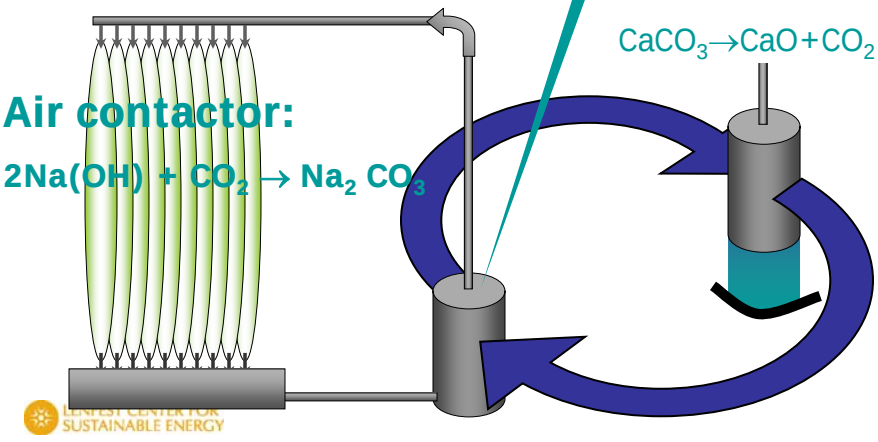
A First Attempt

Ion exchanger:

$Na_2CO_3 + Ca(OH)_2 \rightarrow 2Na(OH) + CaCO_3$

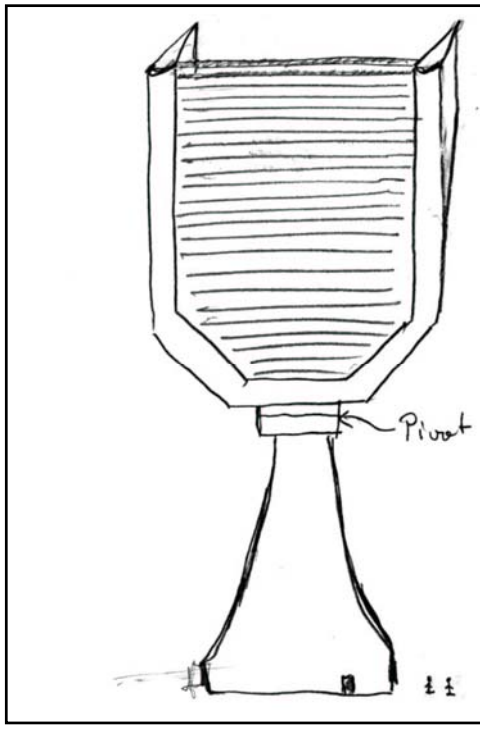
Calciner:

$CaCO_3 \rightarrow CaO + CO_2$



Air contactor:

$2Na(OH) + CO_2 \rightarrow Na_2CO_3$



60m by 50m

3kg of CO_2 per second

90,000 tons per year

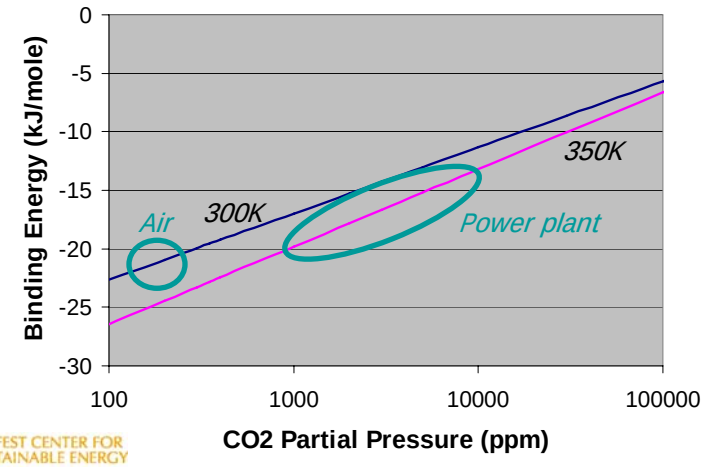
4,000 people or

15,000 cars

Would feed EOR for 800 barrels a day.

250,000 units for worldwide CO_2 emissions

Sorbent Choices



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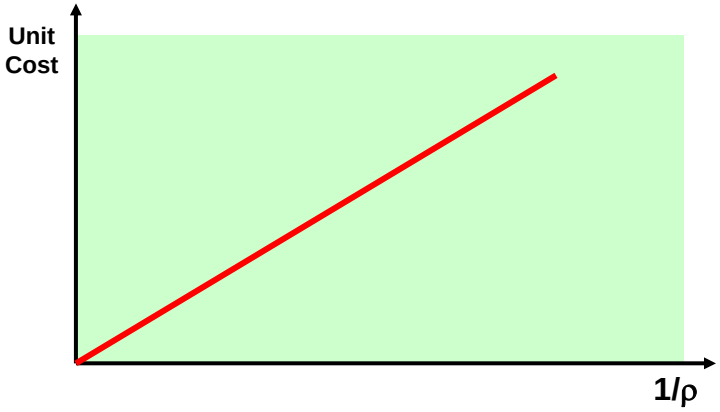
Cost of Contacting the Air



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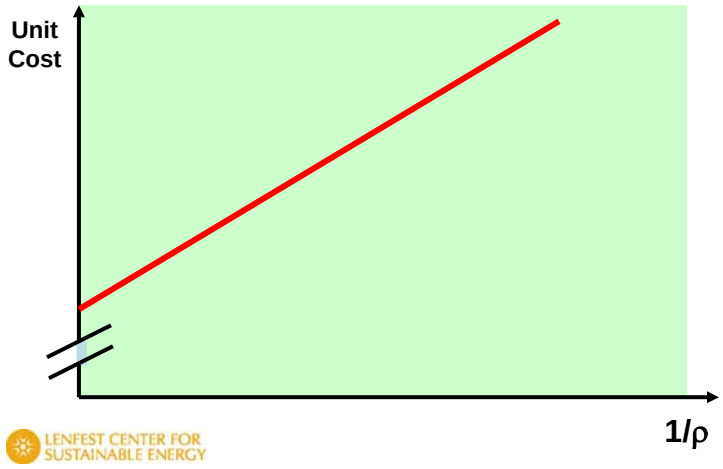
Cost of CO_2 from Air



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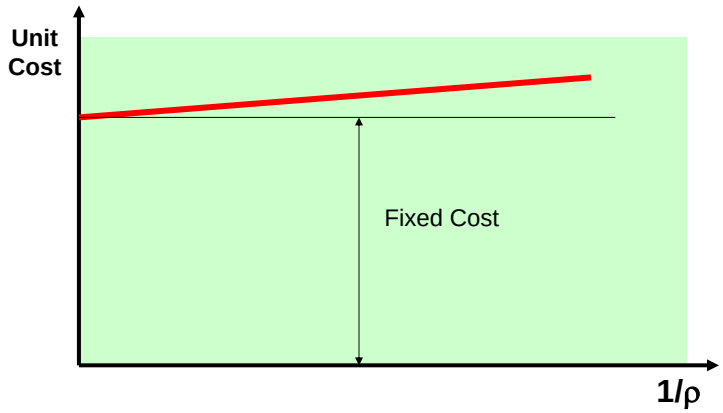
Cost of CO_2 from Air (rescaled)



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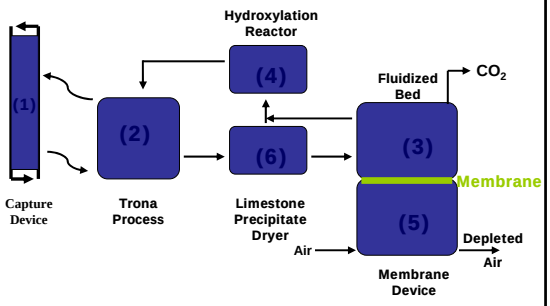
Process Reactions



(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

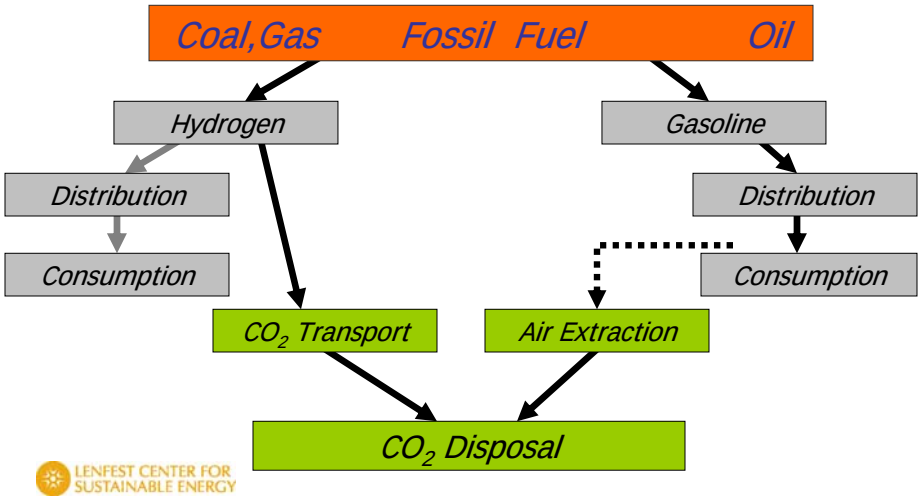
(6) H_2O (l) $\rightarrow H_2O$ (g) ΔH^o = 41. kJ/mol

LENFEST CENTER FOR SUSTAINABLE ENERGY

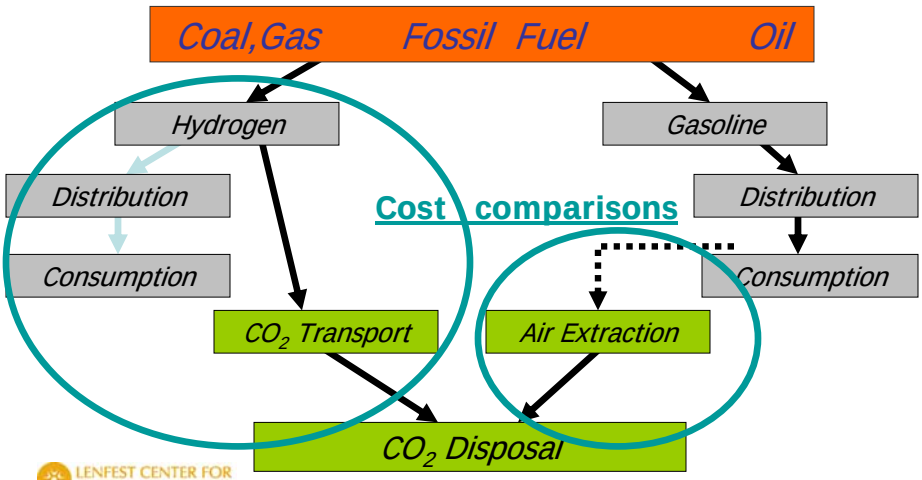
Source: Frank Zeman

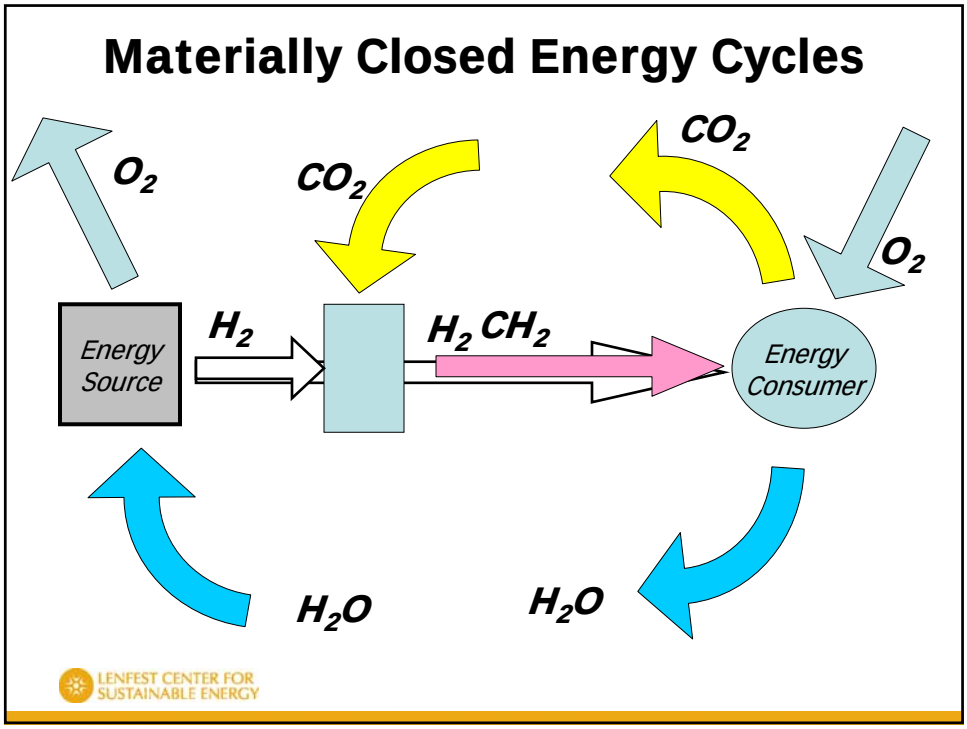
Art Courtesy Stonehaven CCS, Montreal

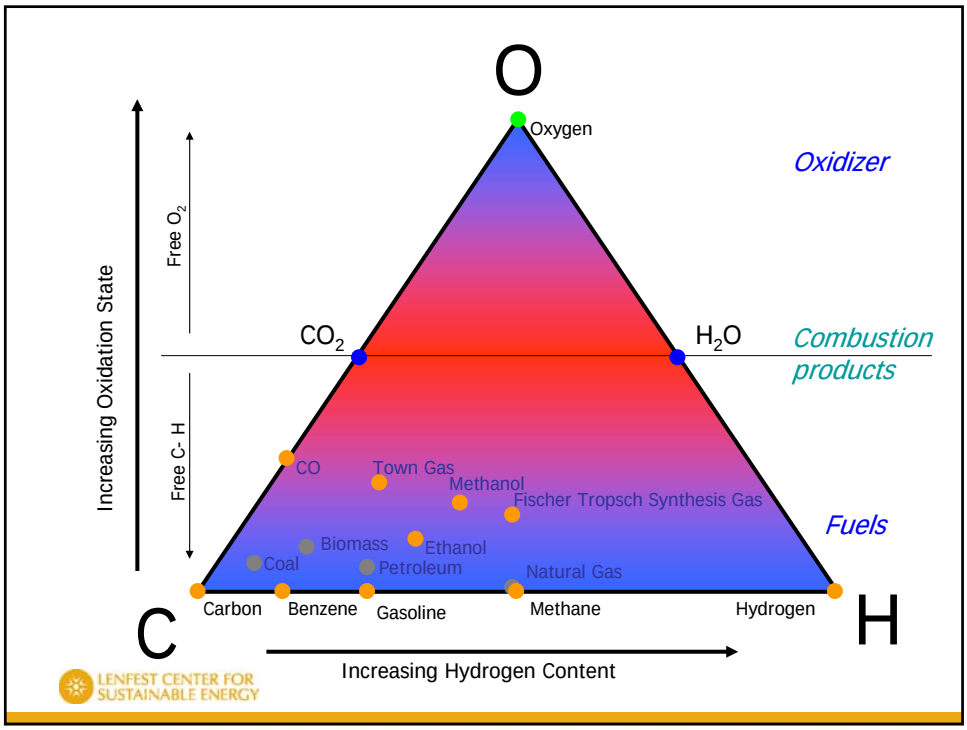
Hydrogen or Air Extraction?

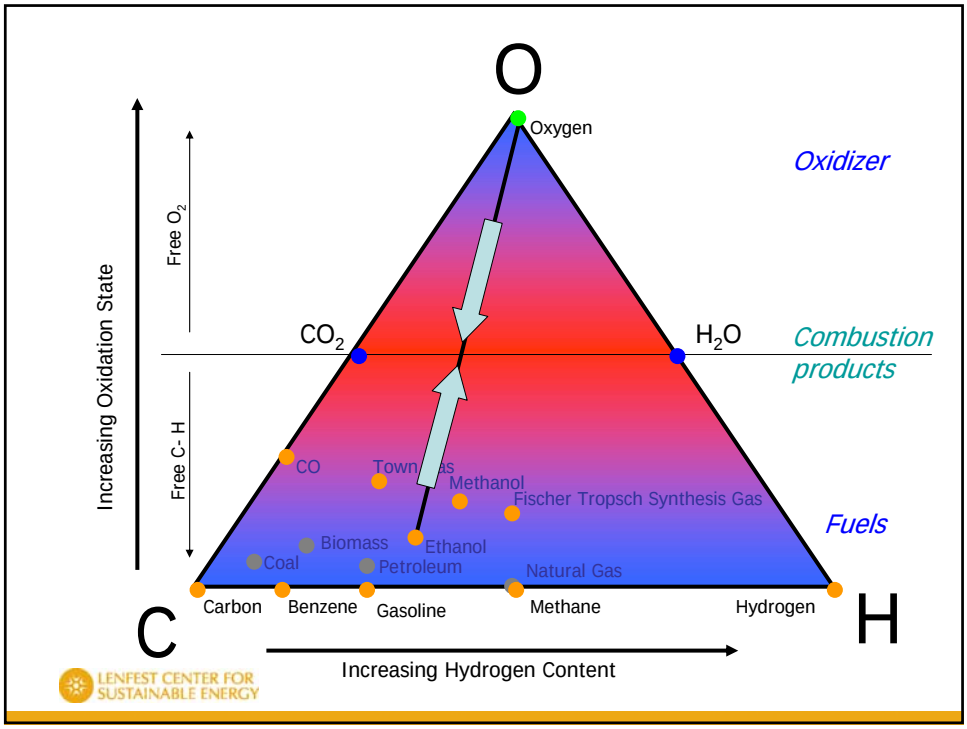


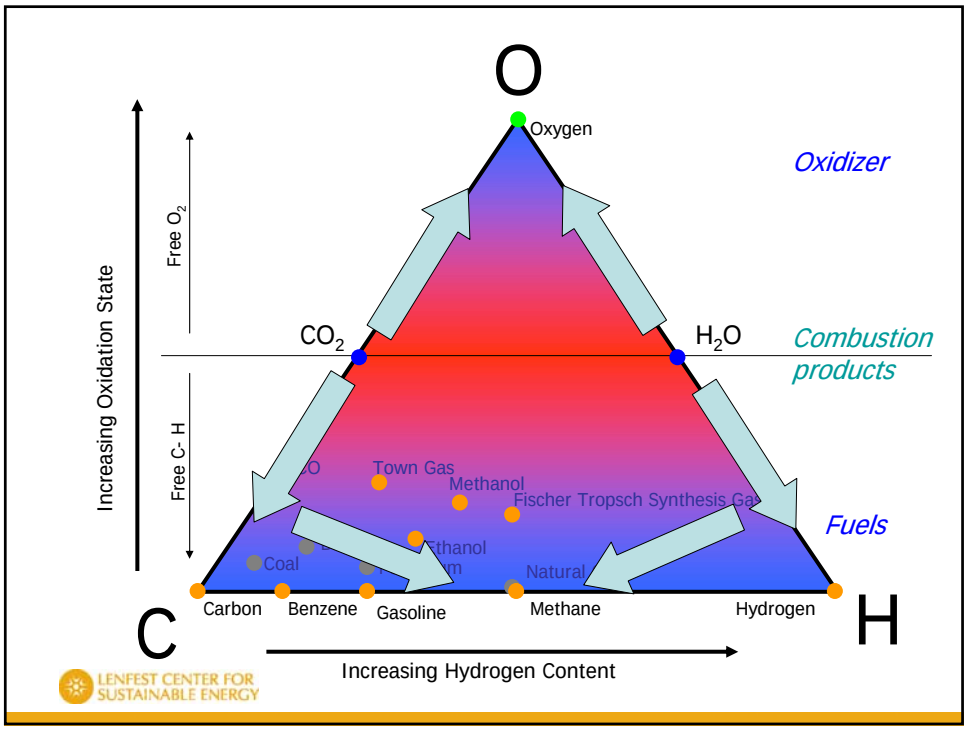
Hydrogen or Air Extraction?

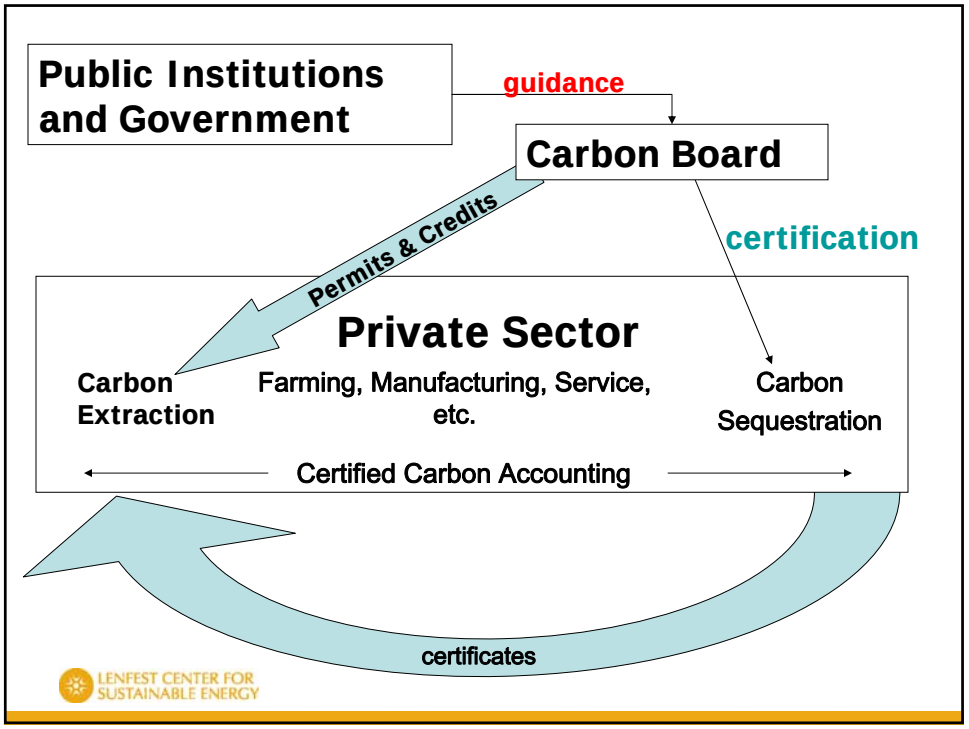


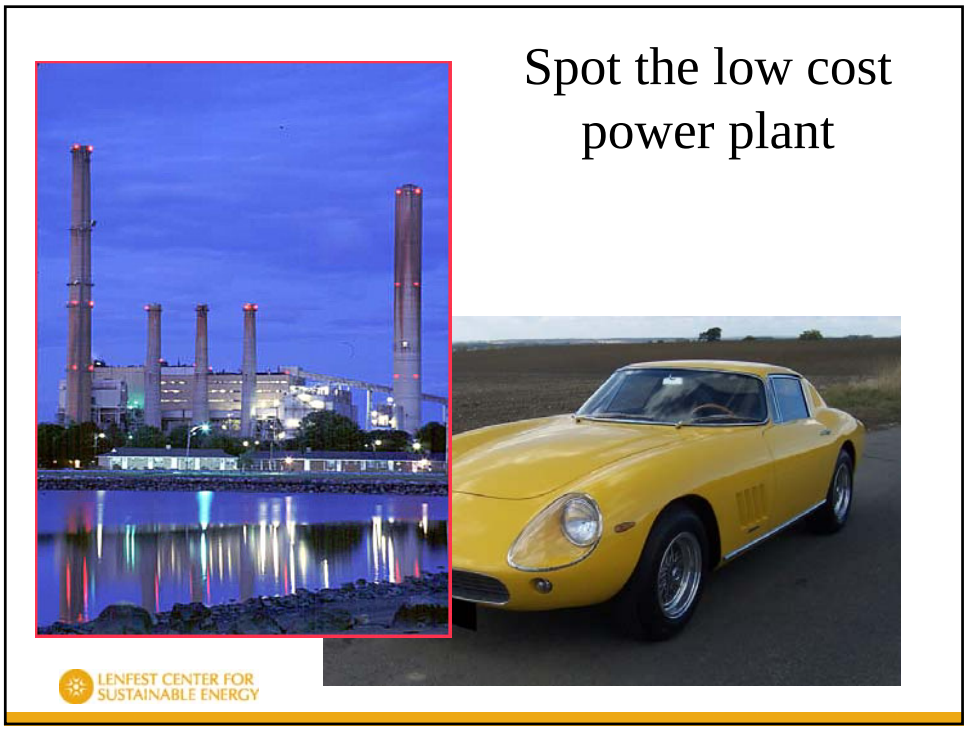

Materially Closed Energy Cycles
O_2
CO_2
CO_2
O_2
Energy Source
H_2
H_2 CH_2
Energy Consumer
H_2O
H_2O
LENFEST CENTER FOR SUSTAINABLE ENERGY


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


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


O
Oxygen
Oxidizer
Free O_2
Increasing Oxidation State
CO_2
H_2O
Combustion products
Free C- H
Town Gas
Methanol
Fischer Tropsch Synthesis Gas
Fuels
Coal
Natural
Carbon
Benzene
Gasoline
Methane
Hydrogen
C
H
Increasing Hydrogen Content
LENFEST CENTER FOR SUSTAINABLE ENERGY


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


Spot the low cost power plant
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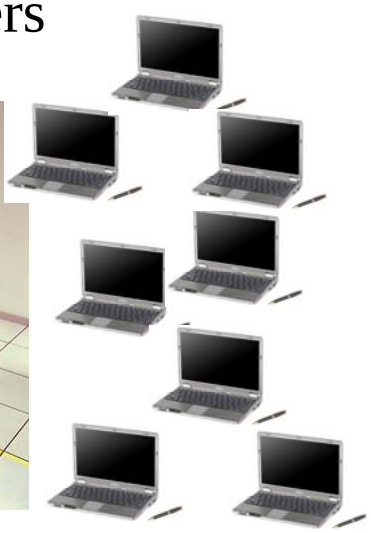
Computers



Cray supercomputer (from NASA)

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