Long Term Options for Reducing Physical Leakage from Carbon Dioxide Storage

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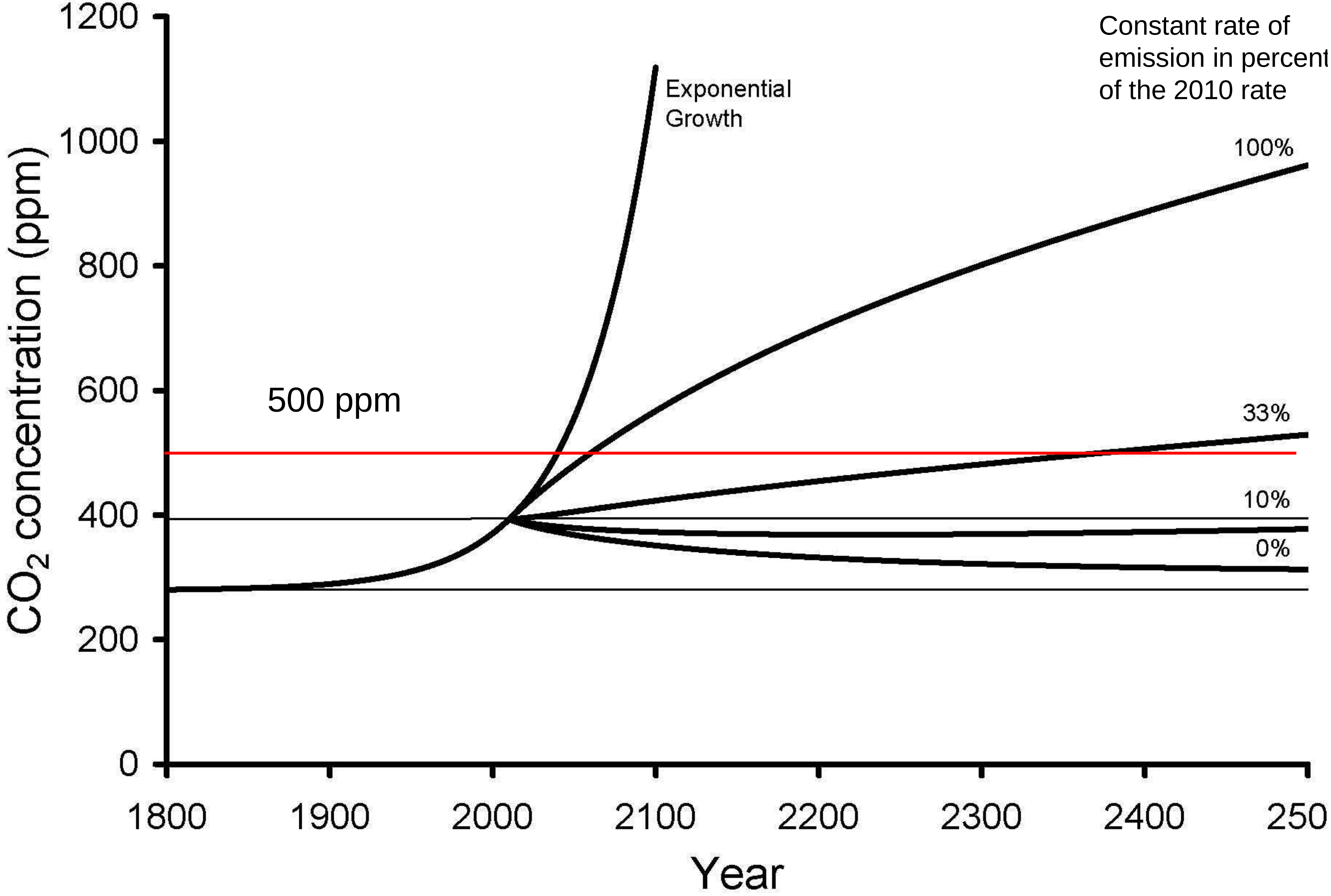
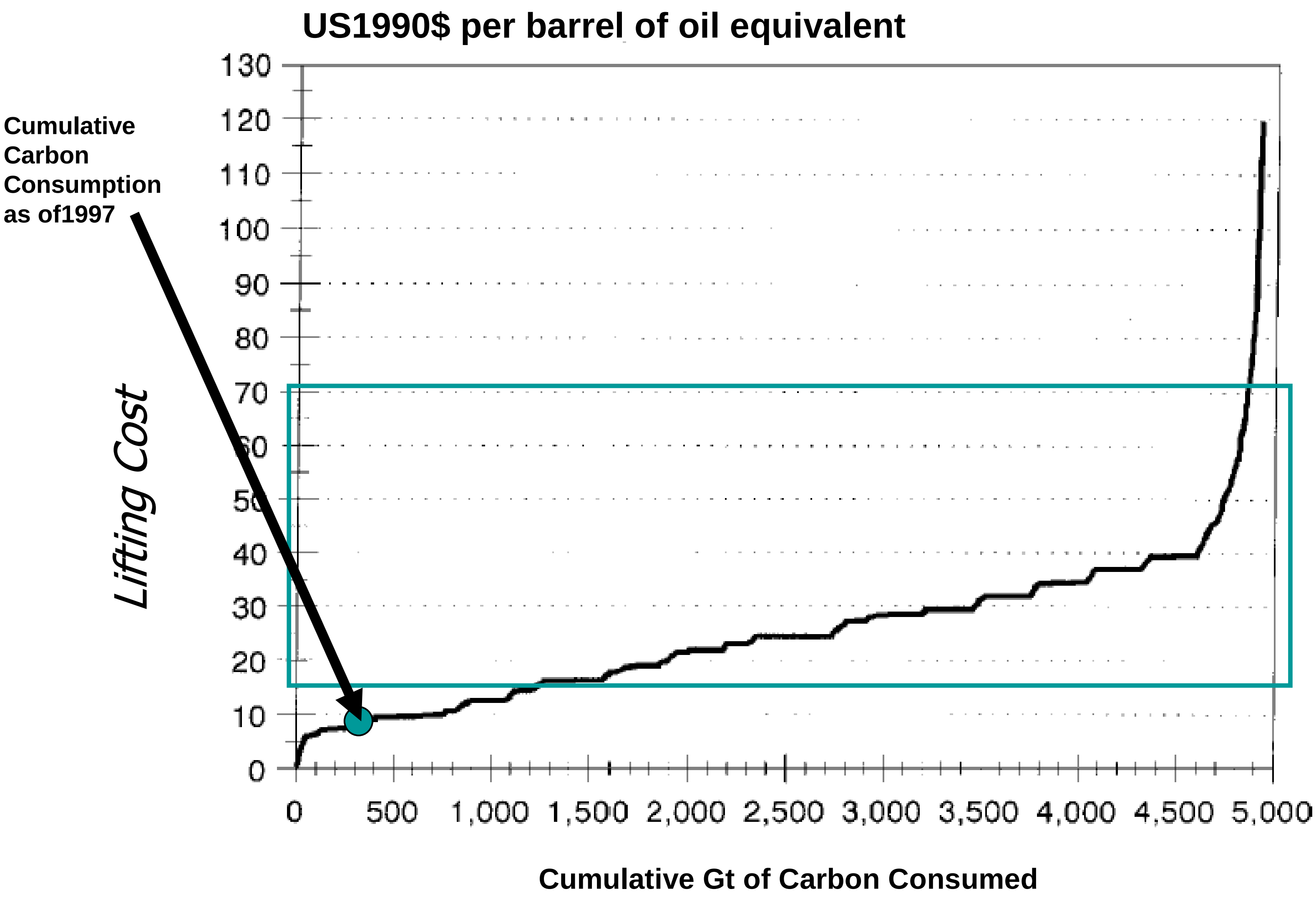
September 2007

Stopping the rise of atmospheric CO_2 concentrati



Fossil Carbon will last for centuries



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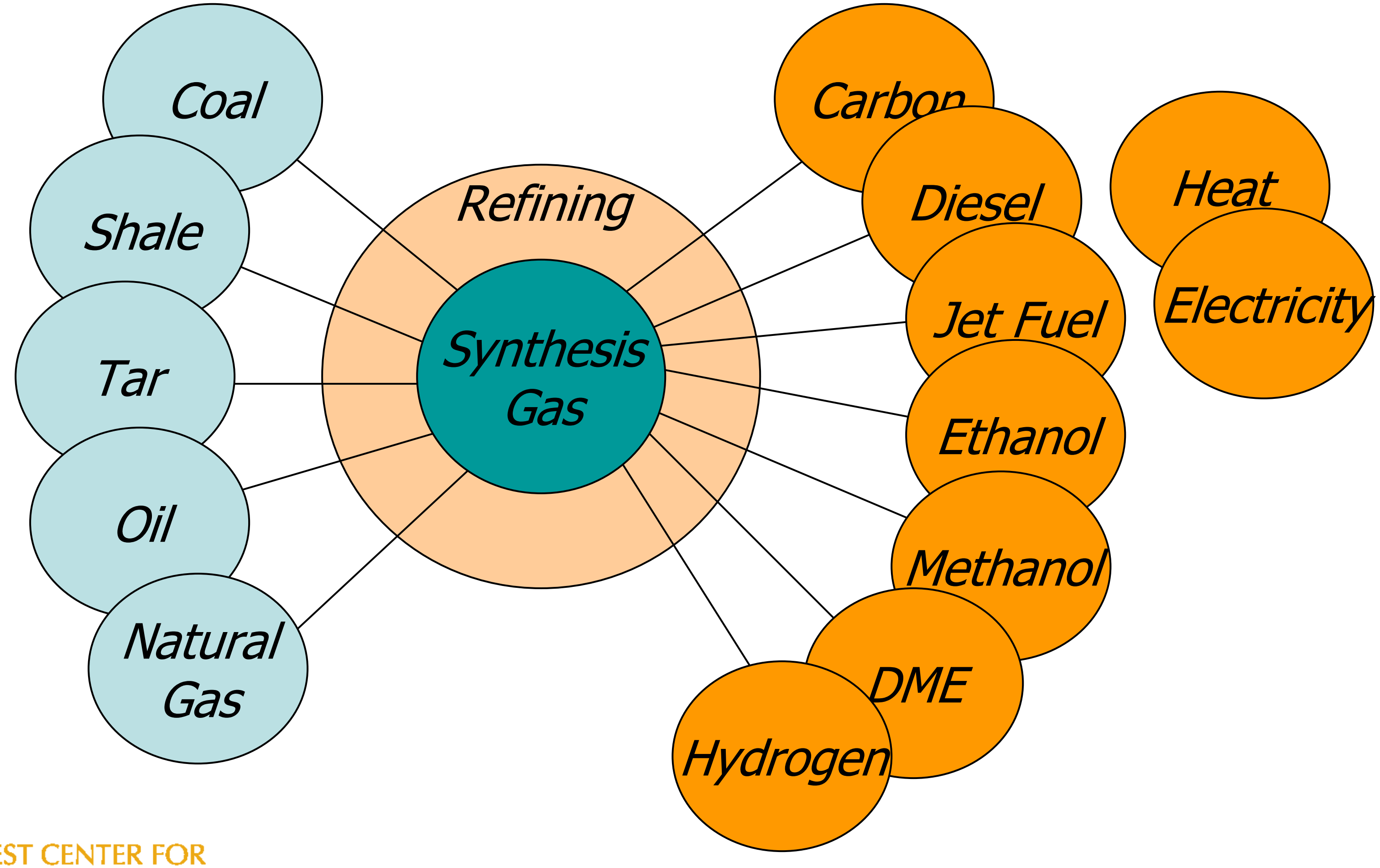
H.H. Rogner, 1997

Fossil fuels are fungible



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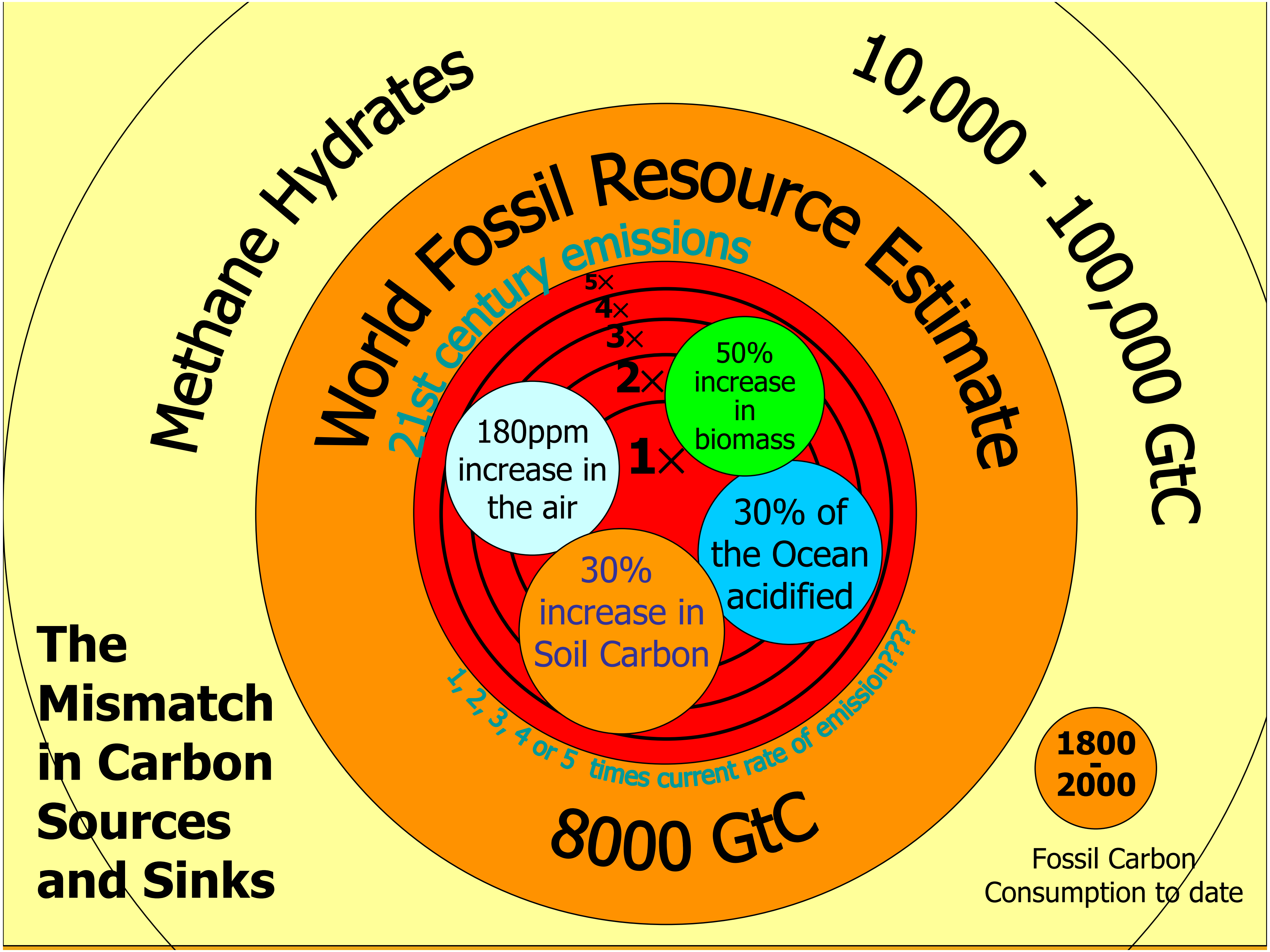
But will we use these fossil fuels?

"The stone age did not did end because we ran out of stones."

- Modern society uses far more stones than the stone age ever did
- Even after the fossil fuel era ends, the world is likely to use its fossil fuel resource, unless access is made impossible



Methane Hydrates
10,000 - 100,000 GtC
World Fossil Resource Estimate
8000 GtC
21st century emissions
5×
4×
3×
2×
1×
1, 2, 3, 4 or 5 times current rate of emission????
180ppm increase in the air
50% increase in biomass
30% of the Ocean acidified
30% increase in Soil Carbon
The Mismatch in Carbon Sources and Sinks
1800 - 2000
Fossil Carbon Consumption to date

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

Net Zero Carbon Economy

CO_2 from concentrated sources

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

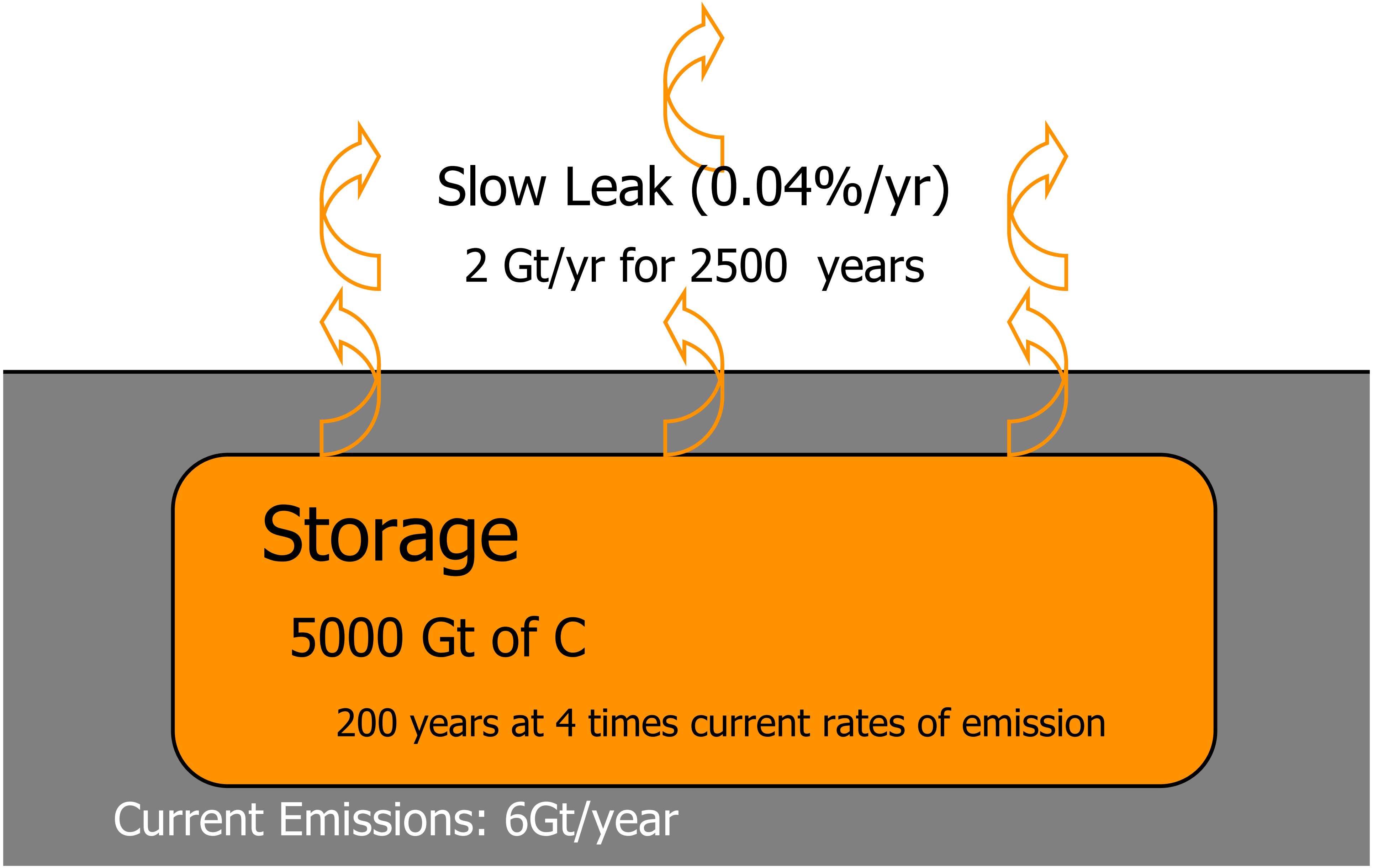
CO_2 from distributed emissions

Capture from air

Permanent & safe disposal

Geological Storage Mineral carbonate disposal

Storage Life Time



Leakage Rate

Leakage rate *R*, total carbon stored *C*, and average life time τ_s of storage are related by

$$R(t) = \frac{C(t)}{\tau_s} \quad \text{with} \quad C(t) = \int_{-\infty}^{t} E_s(t')\,dt'$$

E_s is the rate of carbon sequestration

Figure of Merit

$$f(t) \equiv \frac{R(t)}{E_s(t)} = \frac{\int_{-\infty}^{t} E_s(t')\,dt}{\tau_s E_s(t)}$$

Special Cases

- Exponential growth at rate $1/\tau_g$

$$f = \frac{\tau_g}{\tau_s} \quad \text{for} \qquad E_s(t) = E_0 e^{t/\tau_g}$$

- Constant sequestration rate

$$f(t) = \frac{t - t_0}{\tau_s} \quad \text{for} \quad E(t) = \begin{cases} 0, & t < t_0 \\ E_0, & t \geq t_0 \end{cases}$$

- Exponential decline

$$f(t) = \left(\frac{C_0}{\tau_g E_0} + 1 \right) e^{(t-t_0)/\tau_g} - 1,$$

$$\text{for} \quad C(t) = C_0 + \int_{t_0}^{t} E_0 e^{(t'-t_0)/\tau_g} dt'; \quad t \geq t_0$$

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What is the Goal of CCS?

- Give us 30 year breathing room?
- Keep today's CO_2 from rising?
- Maintain access to fossil fuels?

In all these options are we allowed to create liabilities for future generations?

Net Zero Carbon Economy

CO_2 from concentrated sources

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

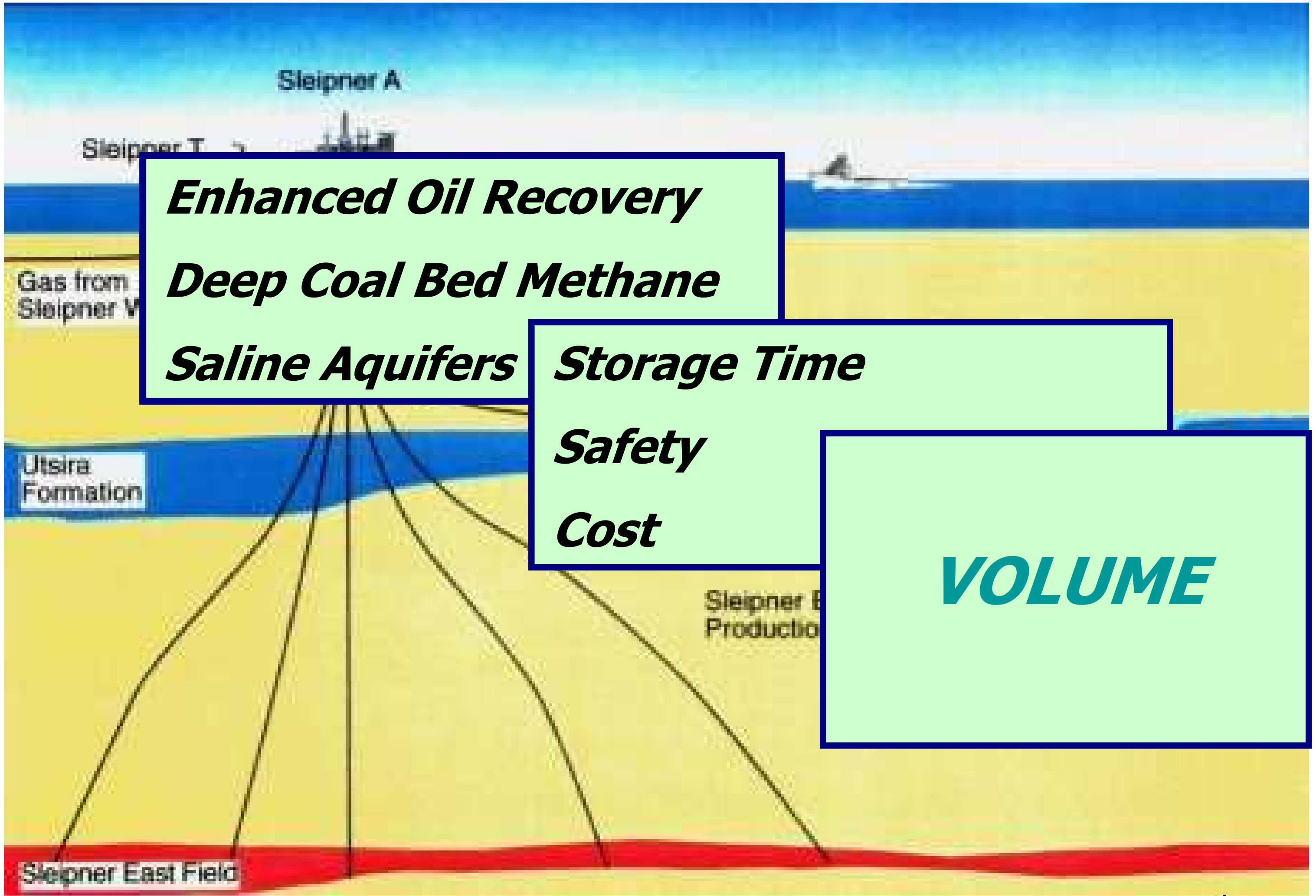
CO_2 from distributed emissions

Capture from air

Permanent & safe disposal

Geological Storage
Mineral carbonate disposal

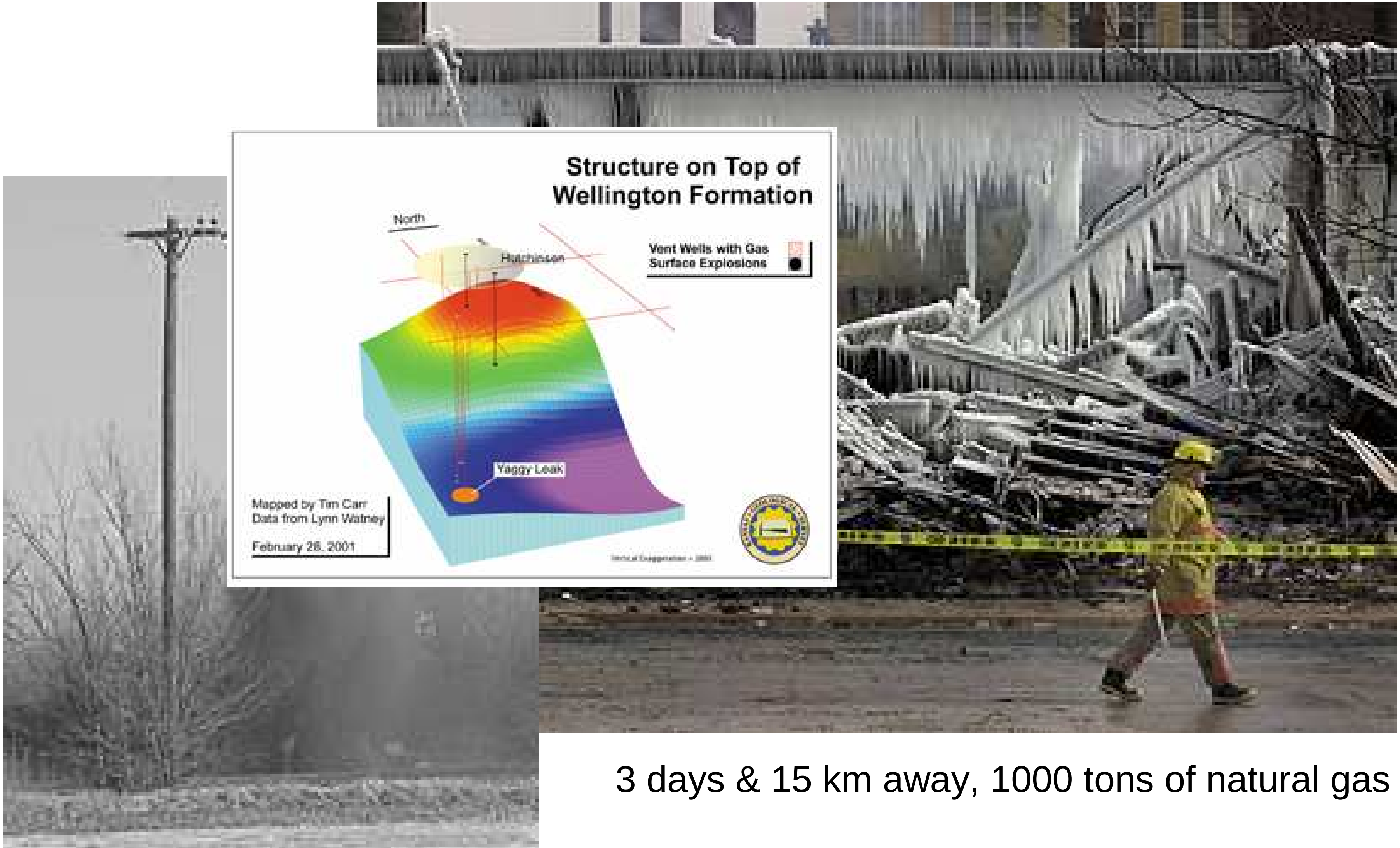
Underground Injection



statoil

Hutchinson, Kansas

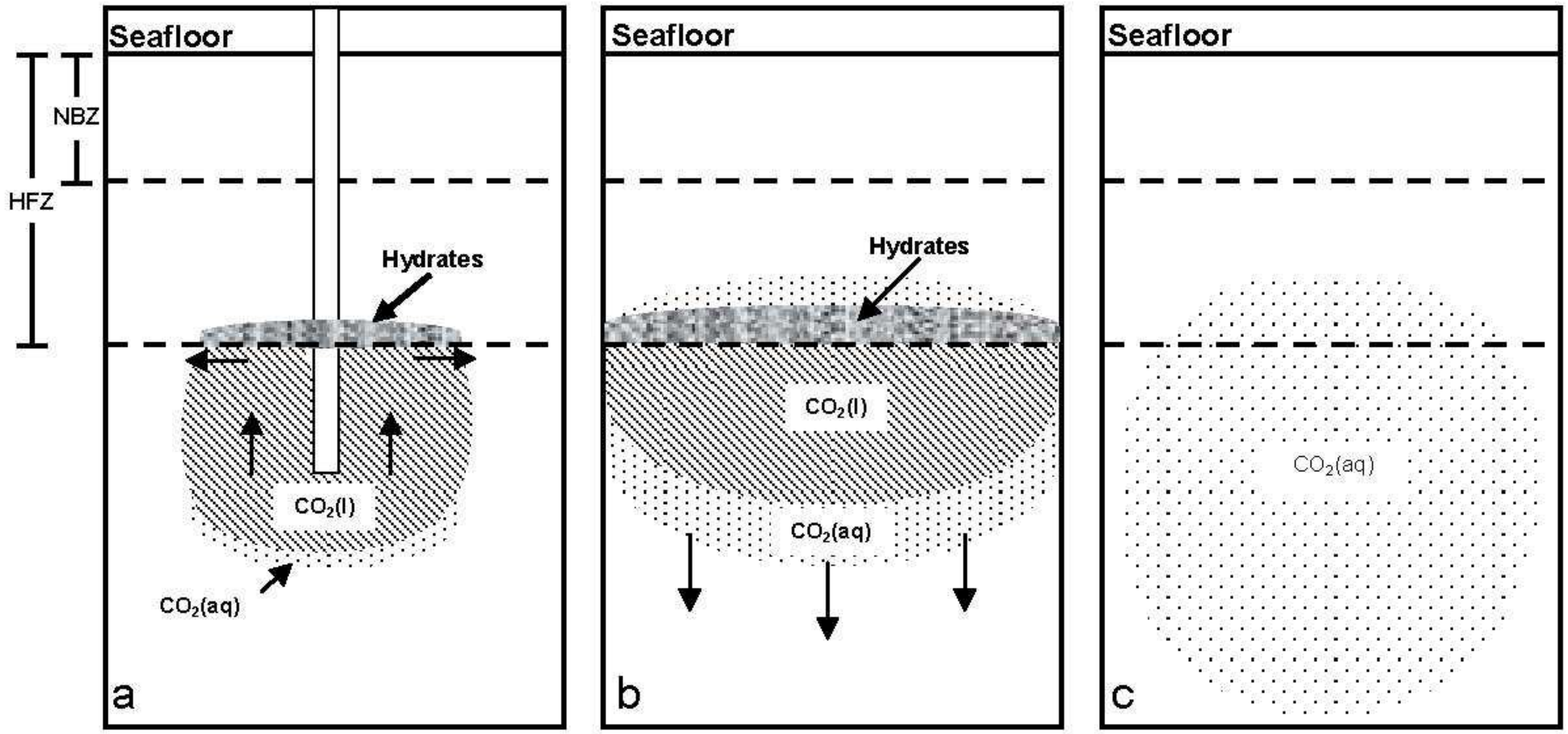
January 17, 2001



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

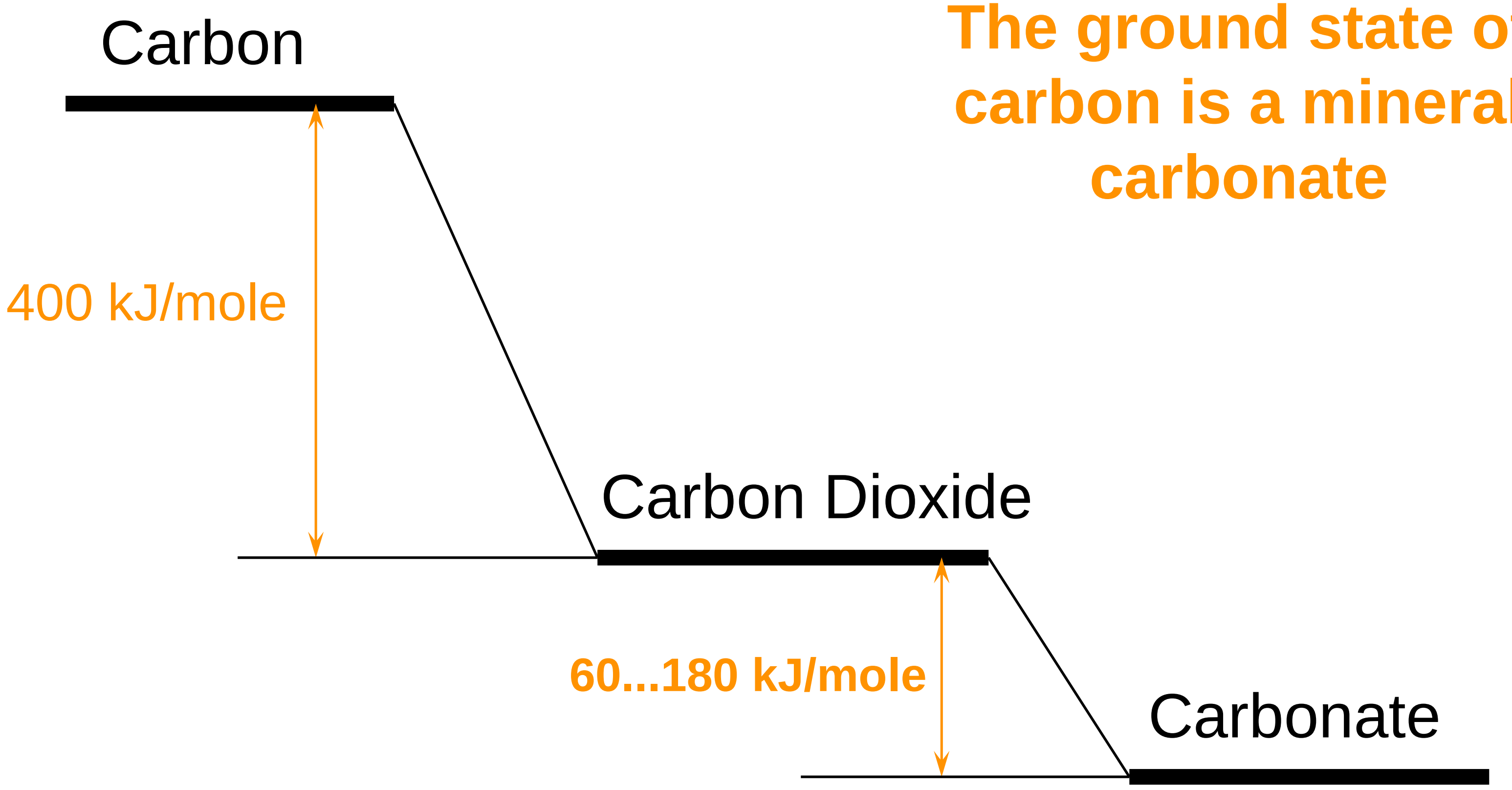
M. Lee Allison, Geotimes, October 2001

Gravitational Trapping
Subocean Floor Disposal



Energy States of Carbon

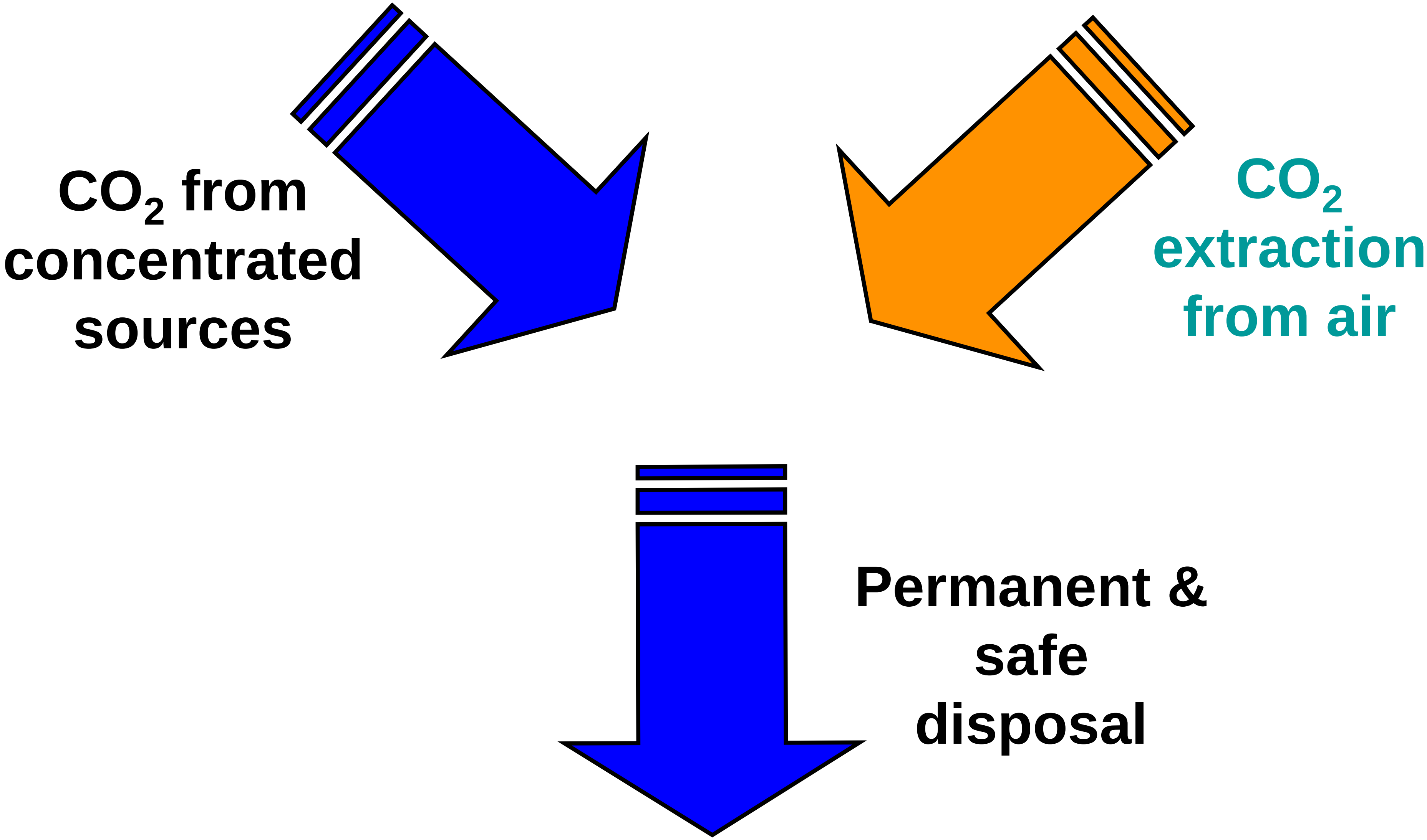
The ground state of carbon is a mineral carbonate



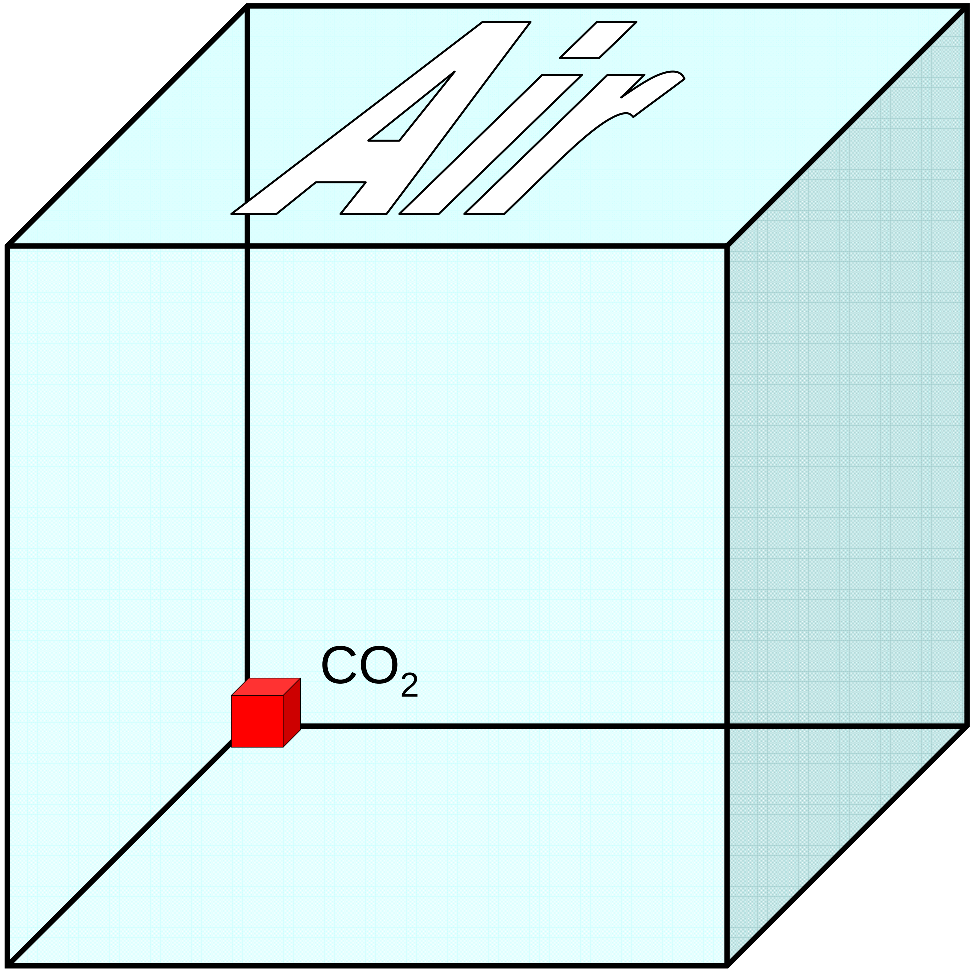
Rockville Quarry

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

Net Zero Carbon Economy



CO_2 Capture from Air



1 m^{3}of Air

40 moles of gas, 1.16 kg

wind speed 6 m/s

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

0.015 moles of CO_2

produced by 10,000 J of gasoline

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Volumes are drawn to scale

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

80 m ^{2}

for Wind Energy

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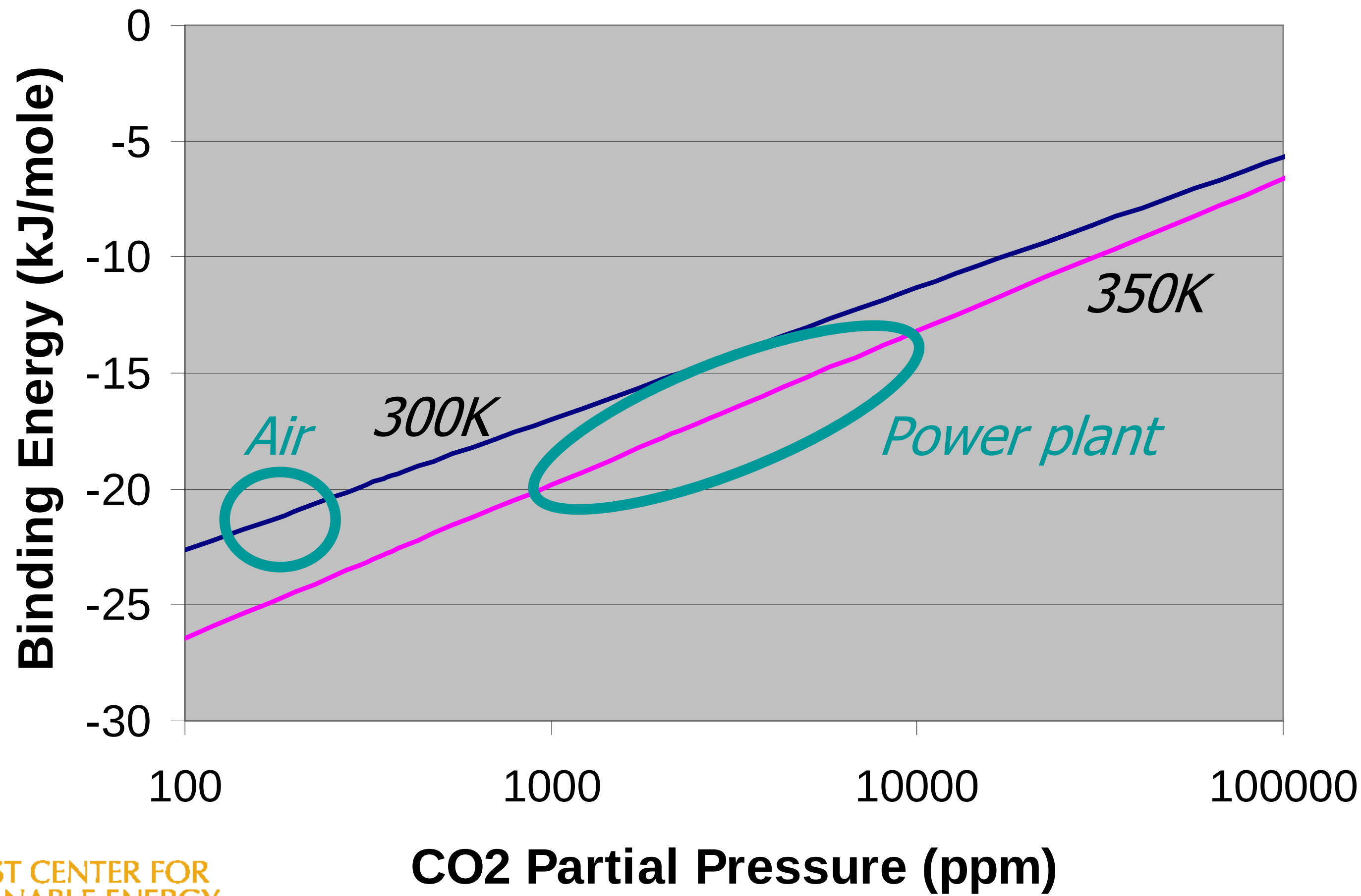
Sorbent Choices



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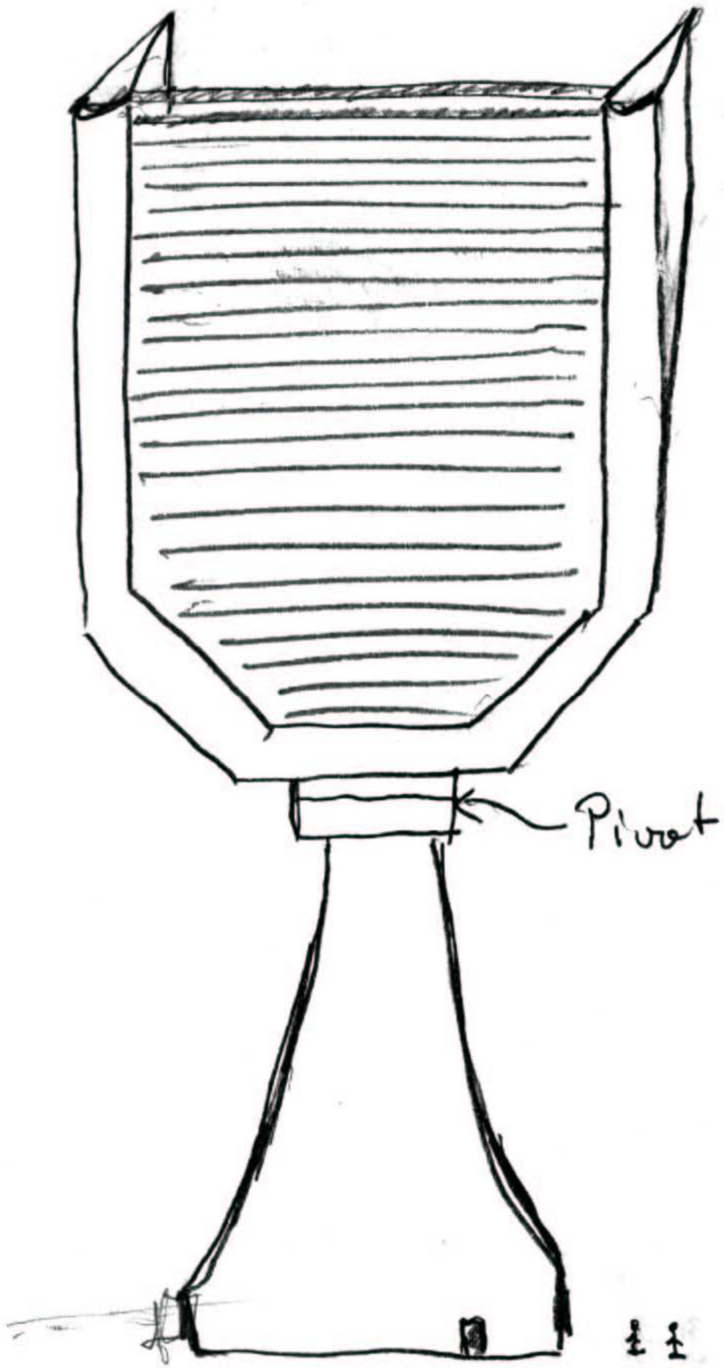

60m by 50m

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

The first of a kind

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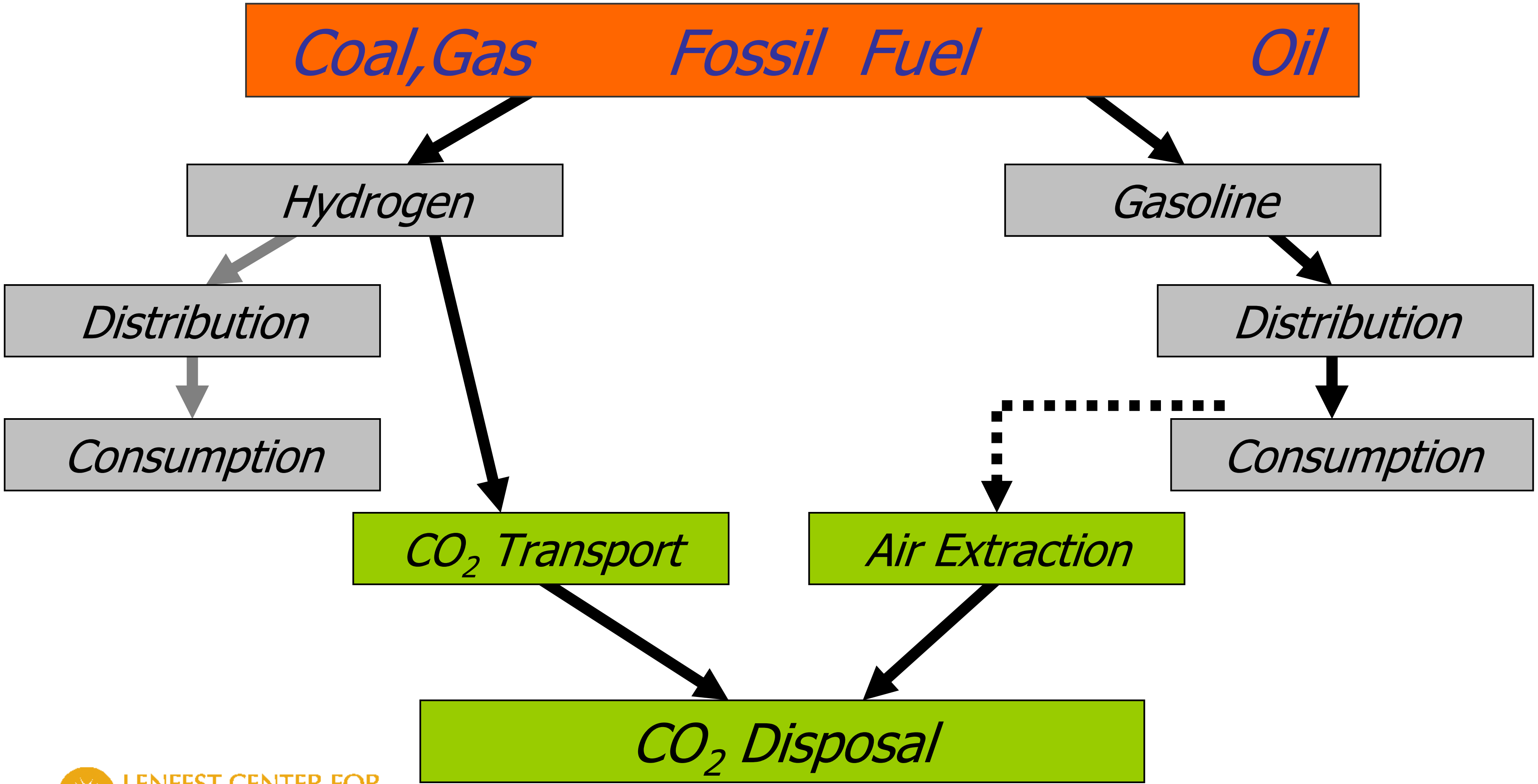
Hydrogen or Air Extraction?



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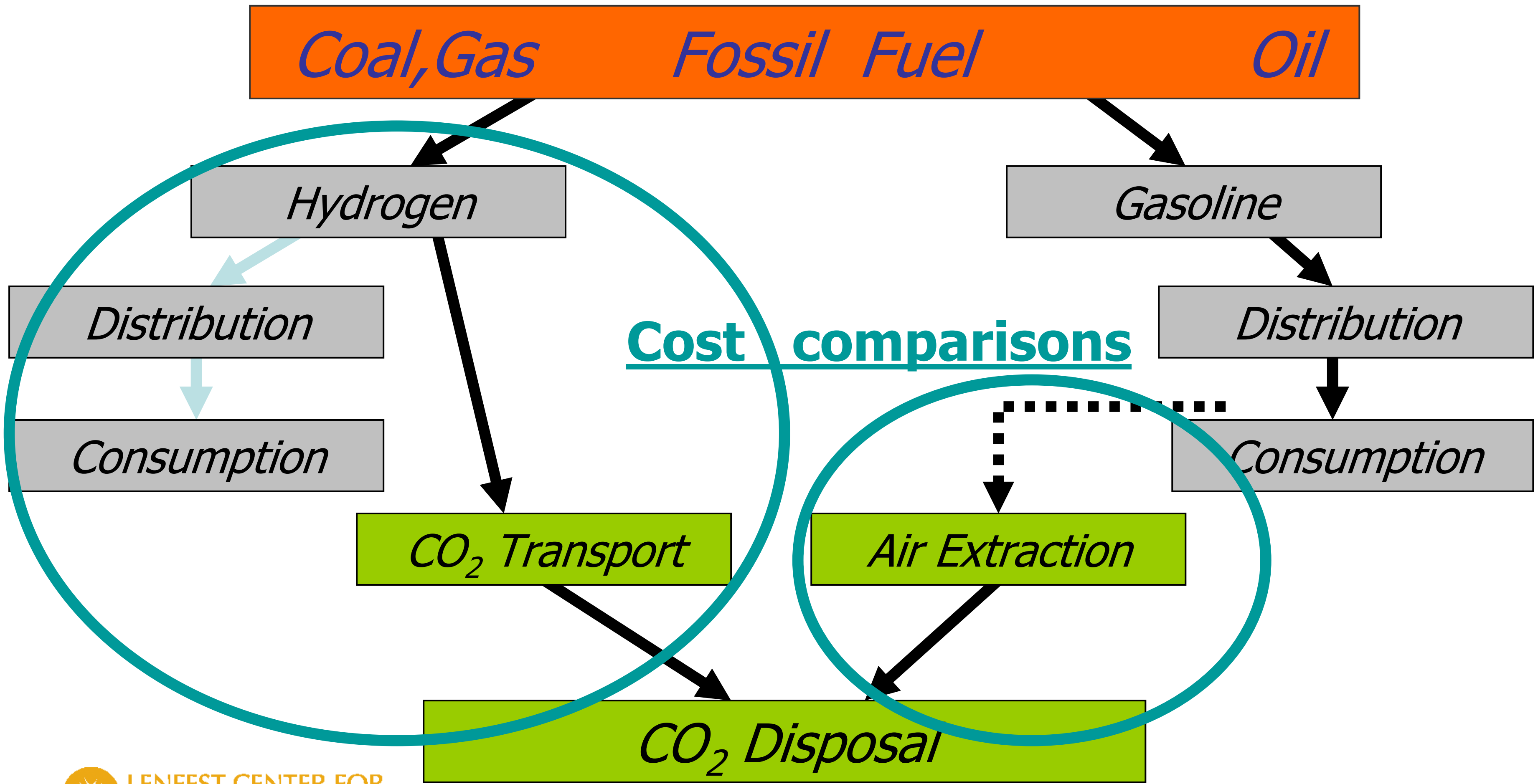
Hydrogen or Air Extraction?



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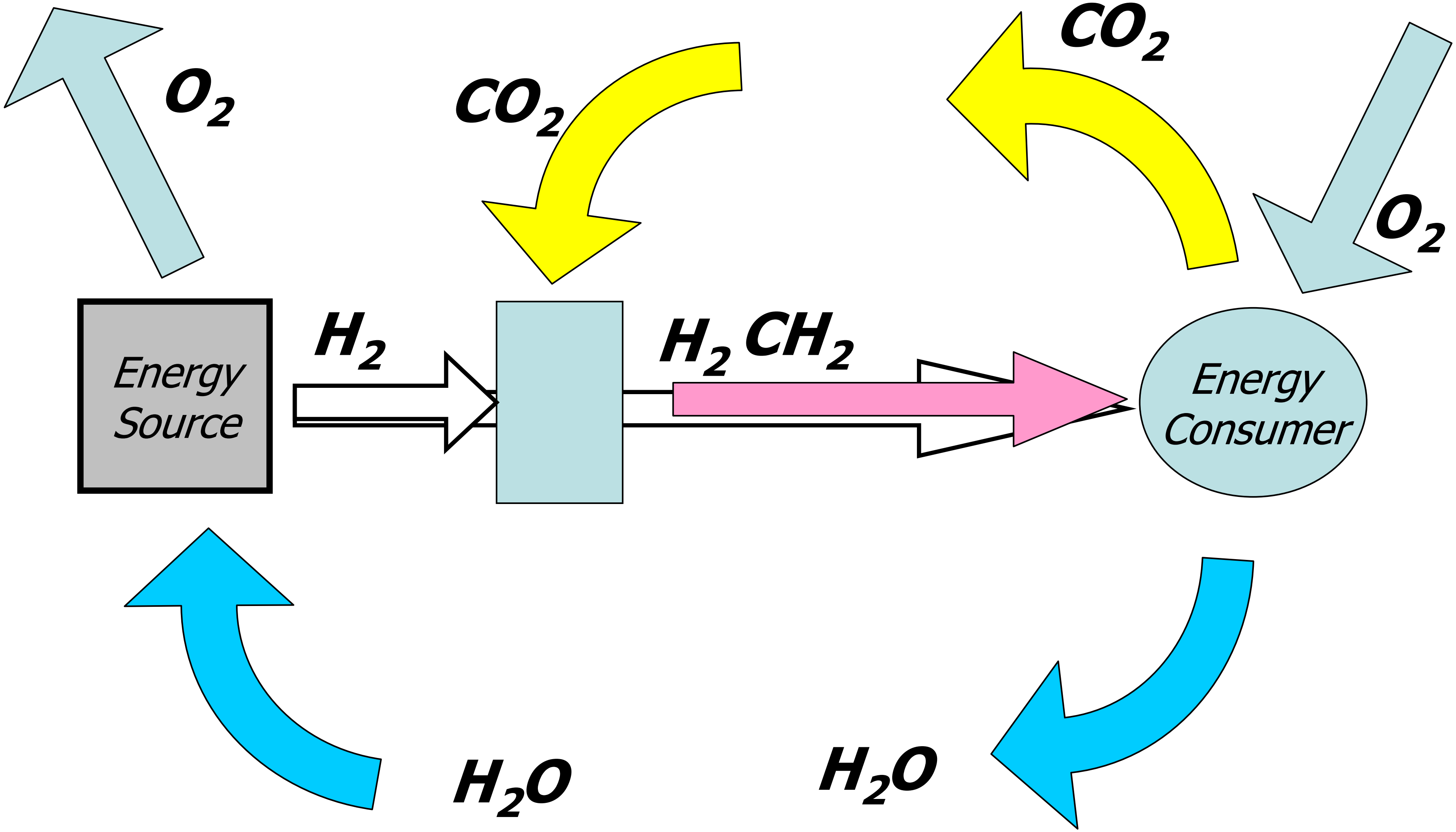
Materially Closed Energy Cycles



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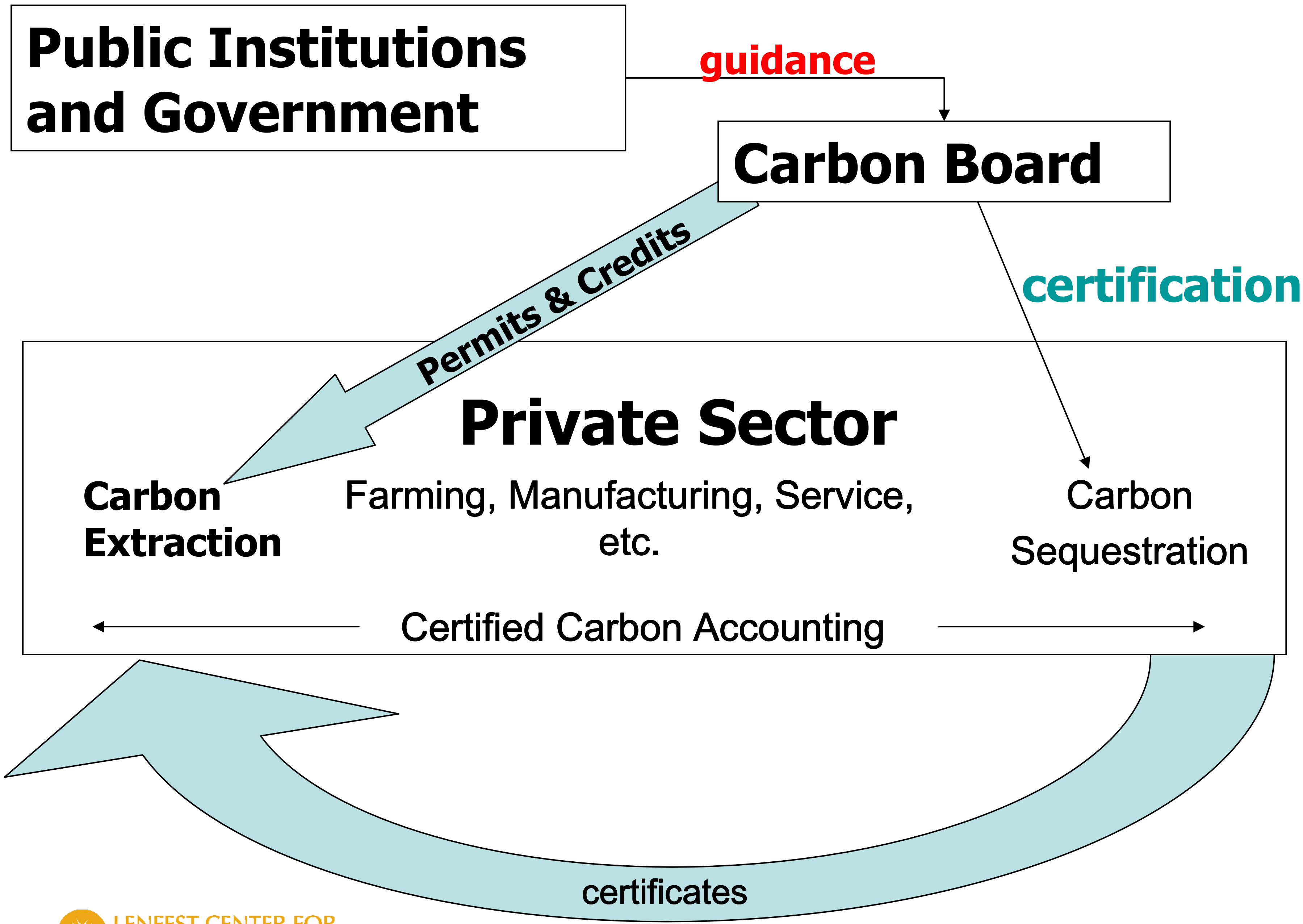
Air Capture Can Compensate for Leakage

- At what rate?
- At what price?
- Who pays?

Conclusion

- Leakage is a long term issue
  - Not an excuse to delay CCS
  - Demands for low leakage will grow with accumulated storage
- Long term leakage constraints derive from geological weathering
  - Time constant $\tau_s > 10{,}000$ years
- Safe and permanent storage can solve this problem
  - For example, mineral sequestration
- Air capture makes recapture feasible
  - But creates a moral hazard by allowing sloppiness
  - Air capture should address mobile sources rather than leaks



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