How to Solve the Problem of Greenhouse Warming

• How serious is the problem and what is a safe level for greenhouse gasses in the atmosphere?

• How much must emissions be reduced to achieve a safe stable level, and how confidently can we compute the required cuts?

• **How can we best achieve the required cuts through the year 2050?**
Carbon Mitigation Initiative at Princeton, 2001-2010

Carbon Capture  Carbon Storage

Carbon Science  Carbon Policy

Socolow, Bradford, Oppenheimer, Celia, Williams, Sarmiento, etc
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5600 GT carbon consumed = 80% of FF reserves.
Surface Air Warming (°F)

2xCO₂ Climate

4xCO₂ Climate

GFDL Model (Manabe & Stouffer)
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Growth Rate of Carbon Reservoirs
Emission Cuts Required for Stabilization at 500 ppm

Emission Cuts for Stabilization VS IPCC CO2 Fertilization

- IS92A to S450
- IS92A to S550
Yearly Emissions of Carbon

Emissions (GT Carbon)

Year

Emissions (GT Carbon)

Year

IS92A BAU
S500
(IPCC Third Assessment)
Uncertainty About the Future of the Land Sink Compared to Stabilization Emissions

![Graph showing the relationship between years and billions of tons of carbon per year. The graph includes two lines: one for reduction in net land emissions required for 500 ppm stabilization and another for the strength of CO2 fertilization in IPCC Third Assessment Models.](image-url)
Down-Regulation
Sampling Distribution For Change in Growth Rate

Observed Mean = -0.085 ft² acre⁻¹ = -0.020 m² ha⁻¹

0.36-Beta Expected Mean = 0.064 ft² acre⁻¹ = 0.015 m² ha⁻¹

Number of Observations

Observed Change in Growth Rate Divided By Square Root of Sample Size
Cumulative Emissions Reductions Necessary to Stabilize at 500 PPM

Year

Fossil Carbon Emissions Reductions (Gt/y)

CO2 Fertilization Sink
Land Use Sink
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A Slice Grows From Zero Today to 1 GtC/y in 50 Years
Strategy #1: Initiate seven “slices” now. Forego R&D

Risk arises if current slices cannot be enlarged.
Strategy #2: Initiate seven “slices” in 2050. Defer action now.

Risk arises from costs of a later decision that a tough target is preferred.
31 Slices?

- Pessimistic BAU
- BAU (IS92 A)
- Tripling
- < Doubling
Evolutionary and revolutionary solutions

Examples of evolutionary solutions

Efficiency
Coal gasification with CO$_2$ capture and geological storage
Wind, photovoltaics
Biofuels and biological storage

Examples of revolutionary solutions

Fusion
Inorganic photosynthesis
Direct capture from air
Storage as carbonates
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Capture the Carbon in Fossil Fuels
Separate the energy content from the carbon content
Produce two C-free secondary energy carriers: electricity and H₂
The Wabash River
Coal Gasification Repowering Project
Pd/Cu Membrane-Based $H_2$ Separation

Cost of $H_2$ via Pd/Cu membrane very close to conventional technology.

- Includes $\text{CO}_2 = \sim 0.5 \$/GJ HHV sequestration cost

Bar chart showing:
- CO2 venting
- Pure CO2 sequestration
- Co-sequestration

Comparison of:
- Conv. tech. base case
- Fuel grade H2
- Membrane base case

Cost ($/GJ HHV)$
Hydrogen System (Joan Ogden)

**Fossil Energy Complex**
- **Fossil Feedstock**: NG, coal
- **Plant design, scale, P,T, purity of H₂, CO₂**

**H₂ Demand Center**
- (Local Pipeline network and refueling stations serving H₂ vehicles)

**CO₂ Sequestration Site**
- injection wells and assoc. piping
- Well depth, reservoir permeability, layer thickness, pressure, capacity, CO₂ purity

**Electricity**
- amount, price

**H₂**
- length

**CO₂**
Sleipner CO₂ Injection Seismic Monitoring

E-W Section

1994

October 1999

after injecting ~ 2 mill. tons CO₂ since 1996

no change above this level

top Utsira Fm.

100 m%

1000 m

injection point
Near McElmo Dome, Colorado (from David Hawkins, NRDC)

“A sign about every quarter-mile” in the Canyons of the Ancients National Monument, Southwest Colorado.
Existing Wells (“Artificial Penetrations”) are Critical Leakage Pathways

ABANDONED WELLS: ALBERTA BASIN

number of wells

year abandoned

0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000

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NCAR Difference in Annual Means (TREFHT_09w1-6 - c108)
GFDL Difference in Annual Means (TREFHT_09g2 - gcont)
Climate Change From Wind Power

• 1. Globally, changes are small in magnitude (i.e. from negligible to 1/10) compared to the changes induced by CO2 for equivalent fossil fuel energy.

• 2. Locally, changes are of the same order but still smaller than equivalent CO2 effects. But there are winners and losers. Some places warm, others cool. Some have increased precip., others decreased.

• 3. The results imply that new engineering might mitigate the impact of wind farms on climate.
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Tropospheric ozone formation for dummies

Isoprene

Monoterpenes

Anthropogenic

VOC

\[
\text{HO}_2 \xrightarrow{hv} \text{OH} \quad \text{NO} \xrightarrow{hv} \text{RO}^* \quad \text{NO} \xrightarrow{hv} \text{RO}_2^* \quad \text{HO}_2 \xrightarrow{hv} \text{OH}
\]

Ozone

\text{NOx}
(d) Implications for air quality control

Combined effect

In broad agreement with observed changes (Lin et al)
My Arithmetic of Available Slices

1  Fuel Switching
3  Sequestration
3  Increased Efficiency
2  Wind Power/ Solar
2  Biological Fuels and Sequestration
2  Nuclear

_________________________________________________________________

13  Total
Conclusions

• To prevent damaging climate change, we must stabilize atmospheric CO$_2$ at ~ 500 ppm.
• For anyone $\geq$ college age, stabilization at a safe level means that humanity must freeze emissions at roughly current levels for the rest of our lives.
• Those who claim that we need fundamental scientific and technical breakthroughs to solve the greenhouse warming problem are simply stalling. Cost-effective technology already exits to freeze global emissions through mid-century.