Climate Change Mitigation under Strong Carbon Constraints

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50th Anniversary of the Global CO₂ Record Symposium and Celebration, Nov. 28-30, 2007, Kona, Hawaii
A safe approach is just to remain an interested observer of the unfolding scientific evidence of man-made global climate change and its possible significance to human welfare. Without risk one can comment dispassionately… I believe, however, that a more prudent attitude would be to heed the rise in atmospheric CO$_2$ concentration as serious unless proven to be benign. (p. 76)

The mitigation thread through this symposium (1 of 2)

1. The previous session and this talk

2. Thursday, 4:30 p.m.
   “Ozone Depletion: The Story of a Successful International Agreement and Its Relevance For Climate Change” (Susan Solomon)

3. Friday
   A. Canonical mitigation
      i. Renewable energy (Charles Kutscher)
      ii. CO₂ capture and storage (Julio Friedmann)
The mitigation thread through this symposium (2 of 2)

3. Friday (continued)
   B. Geoengineering
      i. Albedo modification (David Keith)
      ii. Modification of the ocean sink (David Karl)
   C. Regional efforts
      i. California’s A.B. 32 (Fran Pavley)
      ii. Regional Greenhouse Gas Initiative (Joanne Morin)
      iii. Western Governors’ Association (David Van’t Hof)
   D. Economic tools & financial incentives (Mike Walsh)
Outline of Talk

1. Bridging the gap between stabilization targets and mitigation activity with the “wedge” model.
2. Wedges of efficiency and wedges of substitution for conventional coal.
3. A new role for environmental scientists: Assessors of the environmental consequences of “solutions.”
Rosetta Stone: To raise the concentration of CO₂ in the atmosphere by **one part per million:**

add **7.7 billion tons of CO₂**, in which are **2.1 billion tons of carbon.**
About half of the carbon we burn stays in the atmosphere for centuries.
On the heels of Mauna Loa measurements of the CO$_2$ concentration…

…came CO$_2$ emissions inventories!
Historical Emissions

GtCO$_2$/yr

Historical emissions

1950 2000 2050 2100
Today and for the interim goal, global per-capita emissions are \(\approx 4 \text{ tCO}_2/\text{yr}\).
The 2°C Variant is still tougher

Easier CO₂ target
~850 ppm

Tougher CO₂ target
~500 ppm

Interim Goal

Historical emissions

Current path = “ramp”

Flat path

Stabilization Triangle

GtCO₂/yr

2°C

3°C

The 2°C Variant is still tougher

- Easier CO₂ target (~850 ppm)
- Tougher CO₂ target (~500 ppm)
- Interim Goal

Graph showing historical emissions, current path, and future targets for CO₂ stabilization.
### Four ways to emit 4 tonCO$_2$/yr

<table>
<thead>
<tr>
<th>Activity</th>
<th>Amount producing 4tCO$_2$/yr (1tC/yr) emissions</th>
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<tbody>
<tr>
<td>a) Drive</td>
<td>10,000 miles/yr, 30 miles per gallon</td>
</tr>
<tr>
<td>b) Fly</td>
<td>10,000 miles/yr</td>
</tr>
<tr>
<td>c) Heat home</td>
<td>Natural gas, average house, average climate</td>
</tr>
<tr>
<td>d) Use lights and appliances</td>
<td>300 kWh/month when all coal-power (600 kWh/month, natural-gas-power)</td>
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</table>
Stabilization Wedges

Current path = “ramp”

Eight “wedges”

Interim Goal

16 GtC/y

GtCO₂/yr

1950 2000 2050 2100

Flat path

6 GtCO₂/yr

0 30 60
What is a “Wedge”?

A “wedge” is a strategy to reduce carbon emissions that grows in 50 years from zero to 4 GtCO₂/yr. The strategy has already been commercialized at scale somewhere.

Cumulatively, a wedge redirects the flow of 100 GtCO₂ in its first 50 years. This is three trillion dollars at $30/tCO₂.

A “solution” to the CO₂ problem should provide at least one wedge.
Global CO₂ Emissions by Sector and Fuel

Allocation of 6.2 GtC/yr (22.7 GtCO₂/yr) emitted in 2000

- Electricity: 40%
- Fuels used directly: 60%

Electricity, Transportation, Heating, other
Fill the Stabilization Triangle with Eight Wedges in six broad categories

- Energy Efficiency
- Methane Management
- Extra Carbon in Forests, Soils, Oceans
- Fuel Displacement by Low-Carbon Electricity
- Decarbonized Electricity
- Decarbonized Fuels

2007-2057
30 GtCO₂/yr - 60 GtCO₂/yr
“The Wedge Model is the iPod of climate change: You fill it with your favorite things.”


Therefore, prepare to negotiate with others, who have different favorite things.
U.S. Wedges

Now we go on a hunt for wedges!

Priorities:

• Efficiency wedges
• Wedges displacing conventional coal power
Efficient Use of Fuel

Effort needed by 2055 for 1 wedge:

*Note: 1 car driven 10,000 miles at 30 mpg emits 4 tons of CO$_2$.*

2 billion cars driven 10,000 miles per year at 60 mpg instead of 30 mpg.

2 billion cars driven, at 30 mpg, 5,000 instead of 10,000 miles per year.

Property-tax systems that reinvigorate cities and discourage sprawl

Video-conferencing
Efficient Use of Electricity

Effort needed by 2055 for 1 wedge:

- 25% reduction in expected 2055 electricity use in commercial and residential buildings

Target: Commercial and multifamily buildings.
Coal-electricity Wedges

700 modern 1-GW coal plants, with CO$_2$ vented, will emit 4 GtCO$_2$ each year (6 MtCO$_2$/yr per plant).*

Electricity-carbon wedges result from not building such plants.

*For example, 90% capacity factor, 50% efficient.
Coal with Carbon Capture and Storage

Effort needed by 2055 for 1 wedge:
Carbon capture and storage (CCS) at 800 GW coal power plants.
CCS at “coal-to-liquids” plants producing 30 million barrels per day.
Natural CO₂ fields in southwest U.S.

- McElmo Dome, Colorado: 1500 MtCO₂ in place
- 800 km pipeline from McElmo Dome to Permian Basin, west Texas, built in the 1980s for enhanced oil recovery

Two conclusions:

1. CO₂ in the right place is valuable.

2. CO₂ from McElmo was a better bet than CO₂ from any nearby site of fossil fuel burning.
Already, in the middle of the Sahara!

At In Salah, Algeria, natural gas purification by CO₂ removal plus CO₂ pressurization for nearby injection

Separation at amine contactor towers
Effort needed by 2055 for 1 wedge:

One million 2-MW windmills displacing coal power.

2006: 75,000 MW (4%)
Effort Needed by 2055 for one wedge:

2000 GW_{peak} (400 x current capacity)

2 million hectares (80 x 100 miles)
Concentrating Solar Power (CSP)

Effort Needed by 2055 for one wedge:

2000 GW_{peak}

2 million hectares*
(80 x 100 miles)

*assumes same 10% site-conversion efficiency as PV

Source: Noah Kaye, SEIA, April 2007
Effort needed by 2055 for 1 wedge:
700 GW (twice current capacity) displacing coal power.

Phase out of nuclear power creates the need for another half wedge.
Retrievable Storage

The nuclear industry may soon seek to renegotiate its social contract regarding nuclear waste, asking for a change of goal: *retrievable storage* instead of irretrievable storage.
Needed: A New International Regime

*Pictured*: A cascade of centrifuges for uranium enrichment.
Every wedge strategy can be implemented well or poorly

Every wedge has a dark side, generating opposition that thwarts implementation.

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<tr>
<th>Conservation</th>
<th>Reglementation</th>
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<tbody>
<tr>
<td>Renewables</td>
<td>Competing uses of land</td>
</tr>
<tr>
<td>Nuclear power</td>
<td>Nuclear war</td>
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<tr>
<td>“Clean coal”</td>
<td>Mining: worker and land impacts</td>
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“Solution science” is emerging: the study of the environmental and social costs and benefits of stabilization strategies.
A new role for environmental scientists: Assessors of the environmental consequences of “solutions”

- Ocean fertilization
- Injection of particles into the stratosphere
- Modification of the boundary layer by large-scale deployment of wind farms
- Modification of the boundary layer and the hydrocycle by large-scale deforestation and reforestation
Parting thoughts for Bali: A new look at equitable mitigation
CO₂ emissions, OECD and non-OECD, 1860-2003

Total, 1860-2003:
OECD: 186 GtC (64%)
Non-OECD: 106 GtC (36%)
OECD and non-OECD shares

Source: Socolow and Pacala, Scientific American, September 2006, p.56
CO₂ emissions in 2030 by the world’s individuals

2030: 43 GtCO₂/yr anticipated.
Emissions are lined up from richest to poorest person

Target of 30 GtCO₂/yr (“30”) is achieved by a cap on individual emissions at 11.5 tCO₂/yr, affecting 1.0 billion people.

Cap is reduced to 10.1 tCO₂/yr (“30P”), affecting 1.2 billion people, if Millennium Development Goals are also addressed.

2.84 Billion Poor Emitters Allowed 1 tCO₂ per head
Four comparable assignments!

Emission Profiles and Cuts for a 30 Billion Tons CO$_2$ target in 2030

- USA
- Rest of the OECD
- China
- Rest of the World
- 30 Billion Tons Cap
- 30 Billion Tons Cap with Poverty Headroom

Cumulative Population Ranked According to Annual CO$_2$ Emissions (in Millions)

Annual Individual Emissions (in Tons of CO$_2$)

30
30P
USA
China
Rest of OECD
Rest of the world
A world transformed by deliberate attention to carbon

A world with the same total CO$_2$ emissions in 2057 as in 2007 will also have:

1. Institutions for carbon management that reliably communicate the price of carbon.
2. If wedges of *nuclear power* are achieved, strong international enforcement mechanisms to control nuclear proliferation.
3. If wedges of *CO$_2$ capture and storage* are achieved, widespread permitting of geological storage.
4. If wedges of *renewable energy* and *enhanced storage in forests and soils* are achieved, extensive land reclamation and rural development.
5. A planetary consciousness.

Not an unhappy prospect!
Never in history has the work of so few led to so much being asked of so many!

The warnings about global climate change from the climate scientists have launched a deep reexamination of the energy system and other resource-intensive aspects of ordinary living.

It is crucial that these scientists convey, as carefully as possible, what they know and how well or poorly they know it.

You have been doing this very well. Now, the stakes are rising.
From Dave Keeling’s autobiography

Perhaps my success in sustaining time-series measurements will eventually raise the general scientific regard for making repetitive but important environmental measurements. Also, I hope that there will always be opportunity for individual scientists to pursue scientific leads not anticipated by committees or agencies. (p. 79)

Extra Slides
[In 1956] Wexler invited me to Washington. There I showed him my data suggesting that the amount of CO$_2$ in the open atmosphere might be far less variable than was generally believed…  (p. 36)

[In March 1958] to our great surprise on the first day of operation [the air sampler] delivered within 1 ppm the CO$_2$ concentration that I had told [Ben] Harlan to expect…  (p. 39)

[In November 1958] I was allowed to visit Mauna Loa and restart the analyzer. As new data emerged without further interruption, the concentration rose steadily. Then, in May, it started to decline. A regular seasonal pattern began to emerge…  (p. 40)

$30/tCO_2 \approx 2\$\text{/kWh} \text{ induces CCS. Three views.}

A coal-gasification power plant can capture CO\textsubscript{2} for an added 2\$\text{/kWh} ($30/tCO\textsubscript{2}$). This:

- triples the price of delivered coal;
- adds 50% to the busbar price of electricity from coal;
- adds 20% to the household price of electricity from coal.
Carbon emission charges in the neighborhood of $30/tCO_2$ can enable scale-up of most of the wedges, if supplemented with sectoral policy to facilitate transition.

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<tr>
<th>Form of Energy</th>
<th>Equivalent to $30/tCO_2 (≈ $100/tC)</th>
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<tr>
<td>Gasoline</td>
<td>25¢/gallon (ethanol subsidy: 50¢/gallon)</td>
</tr>
<tr>
<td>Electricity from coal</td>
<td>2.4¢/kWh (wind and nuclear subsidies: 1.8 ¢/kWh)</td>
</tr>
<tr>
<td>Electricity from natural gas</td>
<td>1.1¢/kWh</td>
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$30/tCO_2$ is the current European Trading System price for 2008 emissions. At this price, current global emissions (30 GtCO_2/yr) cost $900 billion/yr, 2% of GWP.
Mitigation Lite: The right words but the wrong numbers. Companies’ investments are unchanged: the emissions price is a cost of business. Individuals change few practices.

For specificity, consider a price ramp that is not “lite,” one rising from zero to $30/tCO₂ over 10 years.
Some carbon policy principles

- Establish a CO$_2$ price schedule forceful enough to drive investment decisions.
- Make the price salient as far upstream as possible (best, when C comes out of the ground or across a border).
- Supplement the price with sectoral policies (RPS, CCS, CAFE, appliance mandates).
- Stimulate international coordination.
- Allow a teething period.
An equity-based CO₂ strategy

1. Meet Basic Human Needs without considering carbon.
   Don’t discourage diesel engines for village-scale power or LPG for cooking.
   Expect a poor family to respond to a better insulated home by raising the indoor temperature (“takeback”).

2. Attain all savings from the largest emitters

3. Mitigate uniformly for the same income level across all countries.
   Coordinated development and deployment of efficient appliances, urban mass transit, videoconferencing, CO₂ capture and storage, renewables, and nuclear power.