The Stabilization Wedge
A Concept and a Game

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The messages from CMI’s four disciplinary traditions are contradictory. On the one hand:

- **Science** (geosciences and ecology): Allowing CO₂ to double is unwise.
- **Capture** (mechanical engineering): Evolutionary technologies are ready for commercialization, if carbon has a price.
- **Storage** (environmental engineering): A permitting regime for geological storage requires field experiments (e.g., to clarify storage integrity).

On the other hand:

- **Policy** (integrated assessment -- scenarios with costs): A multi-century perspective suggests the case for action in the next few decades is weak, unless catastrophes are taken into account.

Conclusion: We should develop vocabulary that facilitates discussion of the intermediate term (next few decades) and of large-scale deployment of technologies that could avoid doubling.
The graph presumes “Stabilization” and focuses on the choice of target. But the eye moves to “2300,” and the impetus to action is desensitized. Moreover, the first quarter century is a blur.
“Baseline” emissions in 2050 are up for grabs: 10-24 GtC/yr (1½ – 3½ x present day). By stressing the unknowable consequences of inaction, the impetus to action is reduced further.
From Multiple Targets and Baselines to The Stabilization Wedge in Three Steps

Step One: Restrict attention to 50 years
Step Two: Choose one target and one baseline

Step Three: Abstracting further, take the goal to be flat emissions and the baseline to be doubling linearly in 50 years.
The Stabilization Wedge

Business As Usual

Easier CO2 target ≈ 750 ppm

Tougher CO2 target ≈ 500 ppm
Achieving the wedge will probably mean that gas’s share of the constant total CO2 emissions will grow relative to coal’s; coal’s share of energy will probably be larger than its share of carbon if CO2 from coal is captured and stored.
Seven “Slices” Fills the Wedge

It is irresistible to divide the wedge into seven equal parts. We call these “slices.”

2004 — 2054

7 GtC/yr
50 Years Back, 50 Years Forward

The Stabilization Wedge

Doubled emissions

175 gigatons carbon

Stabilization emissions

CO$_2$ released to atmosphere
565 gigatons carbon

Current emissions

Business As Usual trajectory

Stabilization trajectory
Outline of Talk

1. Potentially available slices for 2000-2050 and their challenges
2. The construction of the wedge from slices
3. Our Stabilization Wedge Game
Filling the Wedge

The strategies available to provide the slices to fill the wedge are grouped below. All strategies are based on technologies already in use.
**What is a “slice”?**

A “slice” is an activity reducing the rate of carbon build-up in the atmosphere that grows in 50 years from zero to 1.0 Gt(C)/yr.

Cumulatively, a slice redirects the flow of 25 Gt(C) in its first 50 years. This is 2.5 trillion dollars at $100/t(C).

A “solution” to the Greenhouse problem should have the potential to provide at least one slice.
Coal to Gas
**Coal to Gas Electricity**

Burning natural gas results in ~1/2 the CO₂ emissions of coal-burning, per kWh

**Effort needed for 1 slice:**
Build 28 GW of gas-fueled plant capacity per year

1400 GW of electric power fueled by gas instead of coal by 2050 (60% of current fossil-fuel electric capacity)

**Potential Pitfalls:**
Natural gas geopolitics

Cross-section of the GE MS9001H Advanced Gas Turbine
Photo courtesy of DOE

E/$/!
Coal to Gas
Heat

Burning natural gas results in ~1/2 the CO₂ emissions of coal-burning, per unit of heat.

Effort needed for 1 slice
Annually displace 2800 million tons coal with 1400 million tons gas; both quantities equal almost all current use.

Potential Pitfalls:
Natural gas geopolitics

Photo courtesy of BP

H/$/!
Carbon Capture and Storage (CCS)
CCS Electricity
(Coal or Natural Gas)

Effort needed for 1 slice:
70 Sleipner equivalents (1 Natuna equivalent) installed every year and maintained until 2054

CCS at 700 GW coal or 1400 GW natural gas

Potential Pitfalls:
Public acceptance
Global and local CO₂ leakage

E/$$/!
Fossil Fuel-based CCS $H_2$

Effort needed for 1 slice:
A volumetric flow of supercritical CO2 somewhat greater than the flow of oil today

25 billion tons of carbon stored in the next 50 years

Potential Pitfalls:
Public acceptance
Global and local CO2 leakage
$H_2$-infrastructure, $H_2$ safety

Graphics courtesy of DOE Office of Fossil Energy
Nuclear Electricity and Fuels
**Nuclear Electricity**

**Effort needed for 1 slice:**
Install fourteen 1 GW plants (4% of current capacity) every year; over 50 years, add twice current capacity.

By 2050, manage the production of 200 tons/yr of plutonium (20% of the Pu in all current spent fuel, and approximately twice the Pu in all U.S. weapons).

**Potential Pitfalls:**
- Nuclear proliferation and terrorism
- Nuclear waste, NIMBY

Graphic courtesy of NRC
Effort needed for 1 slice:

Electrolytic hydrogen: 1000 1 GW reactors backing out petroleum fuels.

Thermal hydrogen (gleam in the eye): 600 1 GW high-temperature reactors backing out petroleum fuels.

Potential Pitfalls:
Nuclear proliferation and terrorism
Nuclear waste, NIMBY
H2-infrastructure, H2 safety
Efficiency
Effort needed for 1 slice:

7% across-the-board reduction of 2050 “baseline” energy use

Carbon/GDP falls 0.15% faster than “baseline” for 50 years

2 billion gasoline and diesel cars (10,000 miles/car-yr) at 60 mpg instead of 30 mpg

Potential Pitfalls:
Electricity: Air conditioning in tropics
Transportation: Suburban sprawl
Buildings: House size

Renewable Electricity and Fuels
Wind Electricity

Effort needed for 1 slice:

Install $40,000 \times 1 \text{ MW}_{\text{peak}}$ windmills each year (roughly, current capacity)

By 2050, two million $1 \text{ MW}_{\text{peak}}$ windmills

Backing out coal.

60 million hectares (7% of U.S.): multiple use

Potential Pitfalls:

NIMBY
Changes in regional climate?

Prototype of 80 m tall Nordex 2.5 MW wind turbine located in Grevenbroich, Germany (Danish Wind Industry Association)

E/$-$$/!
**Wind $H_2$**

**Effort needed for 1 slice:**
Provide hydrogen to heat as many buildings as are heated today in all ways.
By 2050, three million $1 \text{ MW}_{\text{peak}}$ windmills.

**Potential Pitfalls:**
NIMBY attitudes
Changes in regional climate?

T&H/$$$/!
Solar Electricity

Effort needed for 1 slice:

Install 40 GW\textsubscript{peak} (20x current capacity) each year

By 2050, 2000 GW\textsubscript{peak}

2 million hectares

Potential Pitfalls:

Minimal: Scarce minerals for some semiconductors (CdTe?)

E/$$$/$!
**Biofuels**

**Effort needed for 1 slice:**

Plant and sustain 4 million hectares of crops every year, to back out petroleum fuels used in conventional (30 mpg) cars.

By 2050, have planted area equal to U.S. cropland (200 million hectares)

**Potential Pitfalls:**

Competing land use, biodiversity

*Photos courtesy of NREL*
Natural Sinks
Natural Sinks

Effort needed for 1 slice:
Rehabilitate 14 million hectares every year
By 2050: global area equal to coterminous 48 U.S. states (700 million hectares)

Potential Pitfalls:
Competing land use, biodiversity

Photo courtesy of NREL, SUNY Stonybrook
Outline of Talk

1. Potentially available slices for 2000-2050 and their challenges
2. The construction of the wedge from slices
3. Our Stabilization Wedge Game
The discussion moves to choosing among alternate ways of filling the wedge.
Two of a Kind vs One plus One

One strategy can be used for more than one slice. Will the second slice be harder than the first?

Yes: Externalities usually grow with scale. Best options (wind locations, efficiency opportunities) are used first.

No: Costs are continually driven down by learning by doing.
Non-carbon energy and energy conservation still must be specified

The task of “filling the wedge” remains incompletely specified, even after one declares that “Business as Usual” is a linear path to the doubling of carbon emissions in 50 years.

– Non-carbon energy (nuclear, hydro, wind, PV) in 2054 could be large or small.

– Conservation (size of homes and efficiency of lighting, amount of driving and mpg of cars) could be large or small.
Carbon Growth and Replacement in IS92a

Like all scenarios, lots of assumptions, idiosyncrasies. Here, strong economic growth, strong substitution away from oil and gas.
Double-counting

One can displace the emissions of a coal-based power plant only once!

Building a natural-gas-fired plant, a nuclear plant, and a windfarm are competitive strategies.

Carbon emissions today arise about equally from providing electricity, transportation, and heat (for industry and buildings). To cut 2050 carbon by half, all three uses must be decarbonized.
Summary: What’s appealing about Wedges and Slices?

The stabilization wedge:
  Does not concede doubling is inevitable.
  Shortens the time frame to within business horizons.

Slices:
  Decomposes a heroic challenge (the wedge) into a limited set of monumental tasks
  Establishes a unit of action that permits quantitative discussion of cost, pace, risk.
  Establishes a unit of action that facilitates quantitative comparisons and trade-offs
Outline of Talk

1. Potentially available slices for 2000-2050 and their challenges
2. The construction of the wedge from slices
3. Our Stabilization Wedge Game
Game structure

You are on one of six teams.
Each team works on its own for half an hour
    (six parallel games, duplicate bridge).
Each team has a coach.
You play yourselves: No need to role-play.
The output is your team’s proposed wedge.
We reconvene in plenary to compare wedges.
There is a jury. Each team will have five minutes to
    present its wedge to the jury.
Game Scenario

• It is the spring of 2004. You are in Bonn to attend a meeting of stakeholders, convened by the Secretariat of the U.N. Framework Convention. The purpose of the meeting is to plan the post-Kyoto world. Its premise is that the world response will be some “stabilization wedge.”

• You are at the meeting to affect the choice of the wedge that the attendees recommend. You have your own preferences, but, to be influential, you must be responsive to the interests of others.
How to Win

Six jurors, representing important perspectives, will hear your presentation. Each juror will award points (1-5, 5 is best), based on how well he judges your team’s wedge to be consistent with the interests of his constituency.

The Jury:
Tom Heller: U.S. administration  
Li Zheng: China  
Tariq Banuri: Developing countries (except China)  
Michael Oppenheimer: An environmental ngo  
Ken Hass: An auto company  
Chris Mottershead: An energy company
The 2050 Baseline

More about the 2050 baseline:

Coal, oil, n.g. emissions (GtC/yr): $5 + 4 + 5 = 14$.

Non-carbon electricity: 50% more nuclear and hydro than today; renewables match nuclear.

Non-carbon fuels: None.

Efficiency: 40 mpg car, emblematic of efficiency throughout the economy.

At least 14 strategies are available

Fossil Fuel
- Coal->Gas Elec
- Coal->Gas Heat
- CCS Elec
- CCS H2

Nuclear
- Nuclear Elec
- Nuclear H2

Efficiency
- Electricity Eff.
- Transport Eff.
- Heat Eff.

Renewables and Sinks
- Wind Elec
- Wind H2
- Solar Elec
- Biofuels
- Natural Sinks
- Other

Use “Other” as you wish.
The 14 Strategies: Scale, Cost, Risk (1 of 2)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Use</th>
<th>Description</th>
<th>Effort Required in 2050 for a Slice</th>
<th>Cost</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal to Gas</td>
<td>E</td>
<td>Replace coal-burning electric plants with natural gas plants</td>
<td>Use gas at a rate almost equal to rate for all purposes today</td>
<td>$</td>
<td>Natural gas, geopolitics !</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
<td>Displace 2800 million tons coal per year, a rate almost equal to the rate at which coal used today.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal to Gas Heat</td>
<td>H</td>
<td>Replace coal with natural gas in heating &amp; cooking</td>
<td></td>
<td>$</td>
<td>Natural gas, geopolitics !</td>
</tr>
<tr>
<td>CCS Electricity</td>
<td>E</td>
<td>Capture and store CO$_2$ from fossil fuel power plants</td>
<td>Inject a greater volumetric flow of supercritical CO$_2$ than the flow of oil today; CCS at 700 GW coal, 1400 GW n.g.</td>
<td>$$</td>
<td>CO$_2$ leakage !</td>
</tr>
<tr>
<td>Coal or NG</td>
<td></td>
<td></td>
<td>Displace half the world's conventional cars with CCS-H$_2$ cars</td>
<td>$$$</td>
<td>Infrastructure; H$_2$ safety ! !</td>
</tr>
<tr>
<td>CCS H$_2$</td>
<td>H,T</td>
<td>Use hydrogen from decarbonized fossil fuels as automotive fuel or heat source</td>
<td>Displace half the world's conventional cars with CCS-H$_2$ cars</td>
<td>$$$</td>
<td>Infrastructure; H$_2$ safety ! !</td>
</tr>
<tr>
<td>Nuclear Electricity</td>
<td>E</td>
<td>Displace coal-burning electric plants with nuclear plants</td>
<td>Add twice current nuclear capacity, all displacing coal</td>
<td>$$</td>
<td>Proliferation, nuclear waste, NIMBY ! ! !</td>
</tr>
<tr>
<td>Nuclear H$_2$</td>
<td>H,T</td>
<td>Displace petroleum fuels with nuclear hydrogen</td>
<td>Operate reactors built throughout 50 years at ~5 times France’s rate of nuclear construction during the 1980’s</td>
<td>$$$</td>
<td>Proliferation, nuclear waste, NIMBY ! ! !</td>
</tr>
</tbody>
</table>

* Strategy becomes increasingly expensive with increasing number of slices: 1st slice = $ or !, 2 slices = $$ or !!, 3 slices = $$$ or !!!

* Strategy becomes increasingly expensive with increasing number of slices: 1st slice = $ or !, 2 slices = $$ or !!, 3 slices = $$$ or !!!
# The 14 Strategies: Scale, Cost, Risk (2 of 2)

<table>
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<tr>
<th>Strategy</th>
<th>Use</th>
<th>Description</th>
<th>Effort Required in 2050 for a Slice</th>
<th>Cost</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Efficiency – Electricity</strong></td>
<td>E</td>
<td>Increase efficiency of lighting, motors, power generation</td>
<td>Chimera: Displace ~50 billion incandescent bulbs (60W, 25% use) with fluorescents (coal power)</td>
<td>$*</td>
<td>Tropical A.C ! *</td>
</tr>
<tr>
<td><strong>Efficiency – Transport</strong></td>
<td>T</td>
<td>Increase automobile fuel efficiency</td>
<td>Double the efficiency of the all world’s cars from 30 to 60 mpg</td>
<td>$*</td>
<td>Car size &amp; power, Urban design ! *</td>
</tr>
<tr>
<td><strong>Efficiency – Heat</strong></td>
<td>H</td>
<td>Increase insulation, passive solar heat, district heating (?)</td>
<td>Cut by half the anticipated fuel use in all buildings</td>
<td>$*</td>
<td>House size ! *</td>
</tr>
<tr>
<td><strong>Wind Electricity</strong></td>
<td>E</td>
<td>Displace coal power by wind power</td>
<td>Operate 70 x current capacity Lease land with ~7% U.S. land area</td>
<td>$$</td>
<td>Regional climate change, NIMBY !</td>
</tr>
<tr>
<td><strong>Wind H₂</strong></td>
<td>T,H</td>
<td>Produce H₂ with wind electricity, displace carbon fuels</td>
<td>Power half the world’s cars predicted for 2050 by wind-H₂</td>
<td>$$</td>
<td>Same as wind Electricity !</td>
</tr>
<tr>
<td><strong>Solar Electricity</strong></td>
<td>E</td>
<td>Displace coal power by solar power (PV, solar thermal, etc..)</td>
<td>Operate 1000 x current capacity Dedicate to solar collection an area equal to 0.2% of U.S</td>
<td>$$$</td>
<td>PV cell materials !</td>
</tr>
<tr>
<td><strong>Biofuels</strong></td>
<td>T,H</td>
<td>Displace petroleum fuels with biomass fuels</td>
<td>Dedicate to plantations an area equal to all US cropland</td>
<td>$$</td>
<td>Biodiversity, scarce land ! *</td>
</tr>
<tr>
<td><strong>Natural Sinks</strong></td>
<td>n/a</td>
<td>Store carbon in forests, soils</td>
<td>Intensify biological storage on an area equal to the U.S. (lower 48)</td>
<td>$*</td>
<td>Biodiversity, scarce land ! *</td>
</tr>
</tbody>
</table>

* Strategy becomes increasingly expensive with increasing number of slices: 1$ slice = $ or !, 2 slices = $$ or !!, 3 slices = $$$ or !!!
# Worksheet: Part One

**Rules**
- You may use a strategy more than once
- Use only whole numbers of slices
- You may use at most:
  - 5 “E” slices (Electricity)
  - 4 “T” slices (Transportation)
  - 5 “H” slices (Heat)

<table>
<thead>
<tr>
<th>Slice #</th>
<th>Strategy</th>
<th>E, T, or H</th>
<th>Cost ($)</th>
<th>Challenges (!)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>E=___ (5 max)</td>
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<tr>
<td>2</td>
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<td>T=___ (4 max)</td>
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<tr>
<td>3</td>
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<td>H=___ (5 max)</td>
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<td>7</td>
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**Totals**
- E=___ (5 max)
- T=___ (4 max)
- H=___ (5 max)
Worksheet: Part Two

Guess the score each judge will give your team’s wedge on a scale of 1 to 5 (5 = best).

<table>
<thead>
<tr>
<th>U.S.</th>
<th>China</th>
<th>LDC’s (other than China)</th>
<th>Green NGO</th>
<th>Auto Company</th>
<th>Energy Company</th>
</tr>
</thead>
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Missing from This Game

You are not assigning responsibility for slices to particular parts of the world: e.g., industrialized vs developing countries.

You are not proposing any financial mechanisms.
What Have We Learned So Far

The game is a promising teaching tool. It highlights:
– The structure of the problem
– The magnitudes
– The centrality of politics, interests, values

The game is a promising communications tool. It helps battle the stovepipe problem.

Please keep track of questions and suggestions. Enjoy yourselves.