Stabilization Wedges:
Mitigation Tools for the Next Half-Century

Robert Socolow
Princeton University
socolow@princeton.edu

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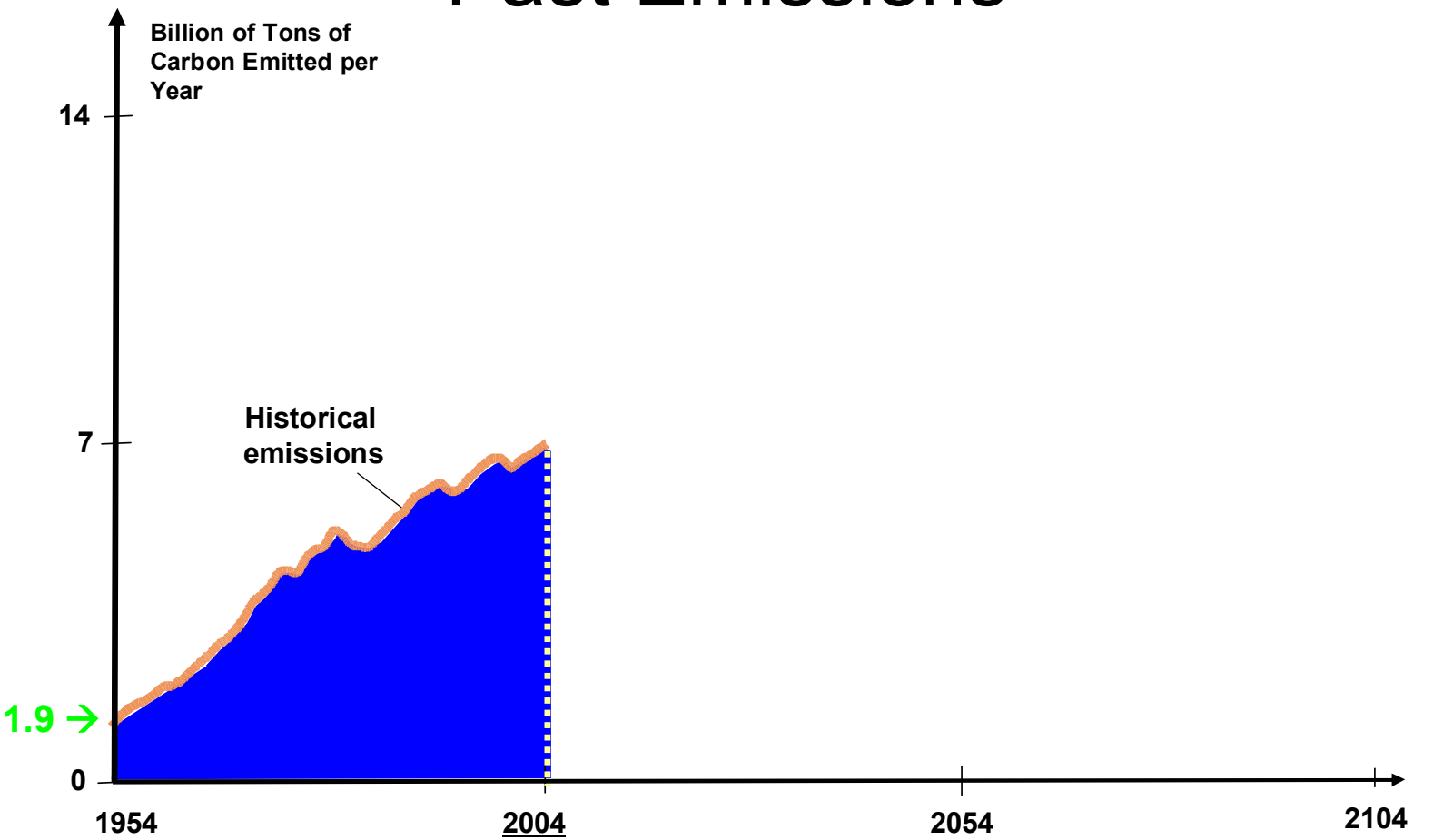
and its Supporting Online Material.

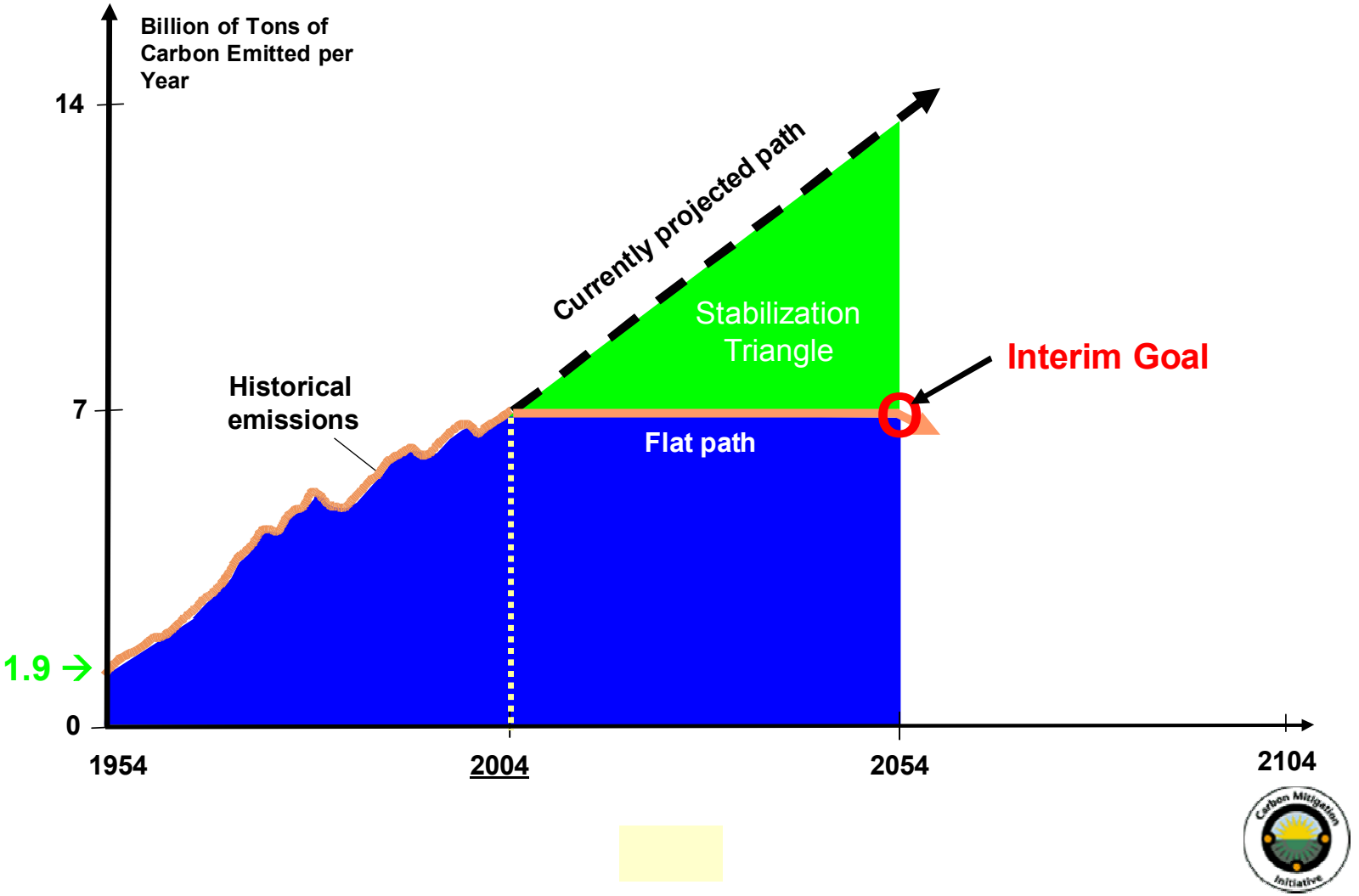
Outline of Talk

1. **The Wedges Model: A simple quantification of carbon mitigation**
2. Some specific wedges
3. Implications for policy

Past Emissions



The Stabilization Triangle



The Flat Trajectory is an Idealization of Stabilization below Doubling

Stabilization below doubling (450-550 ppm), the goal for carbon management recommended by many environmental scientists, is broadly consistent with the *Interim goal:*

7 GtC/y in 2054, as in 2004

Sensitivities:

± 3 GtC/y for the uncertainties of the land and ocean sink.

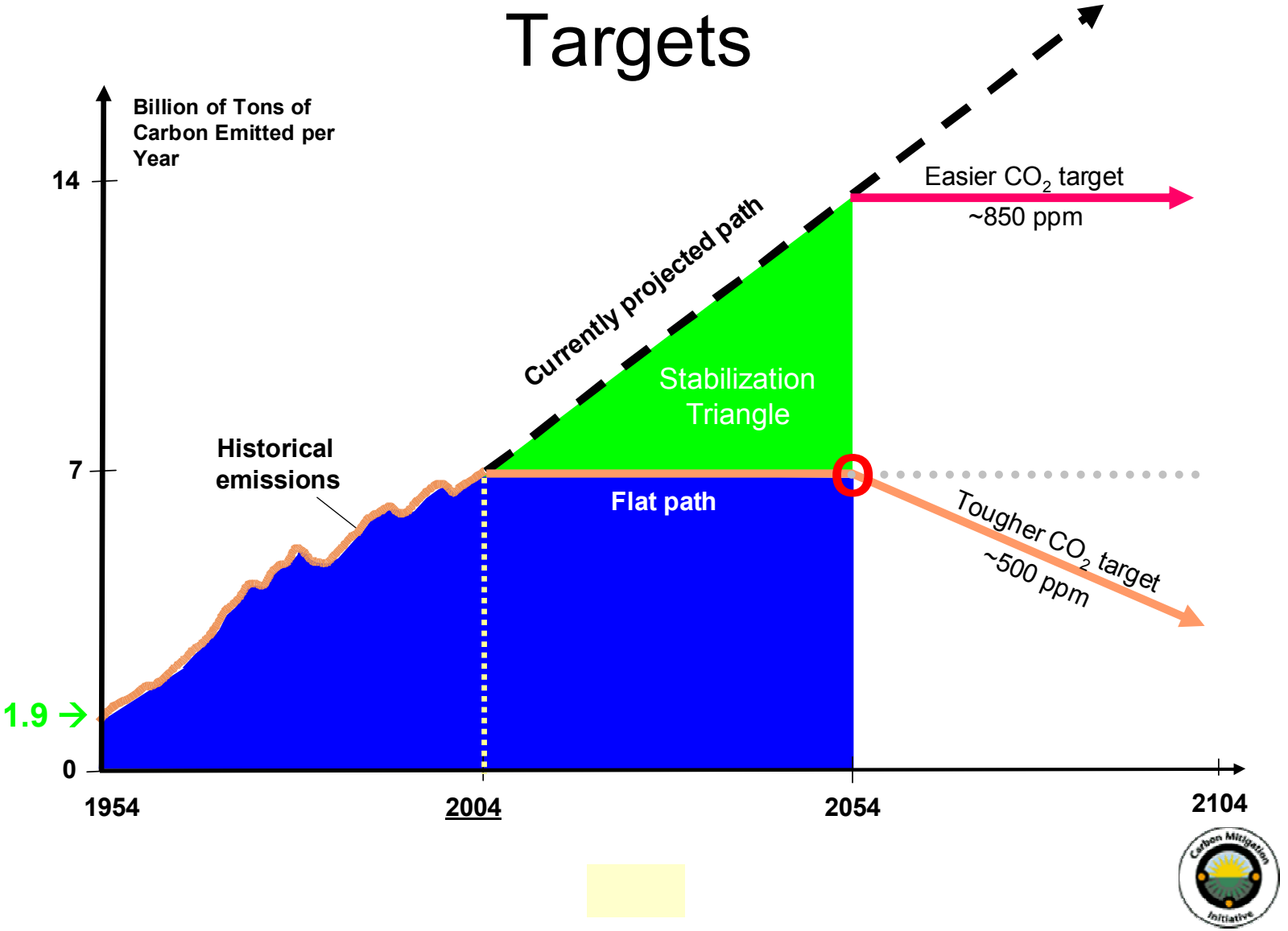
± 2 Gt/y for a change of stabilization target by 50 ppm.

Further emissions cuts are required after 2054.

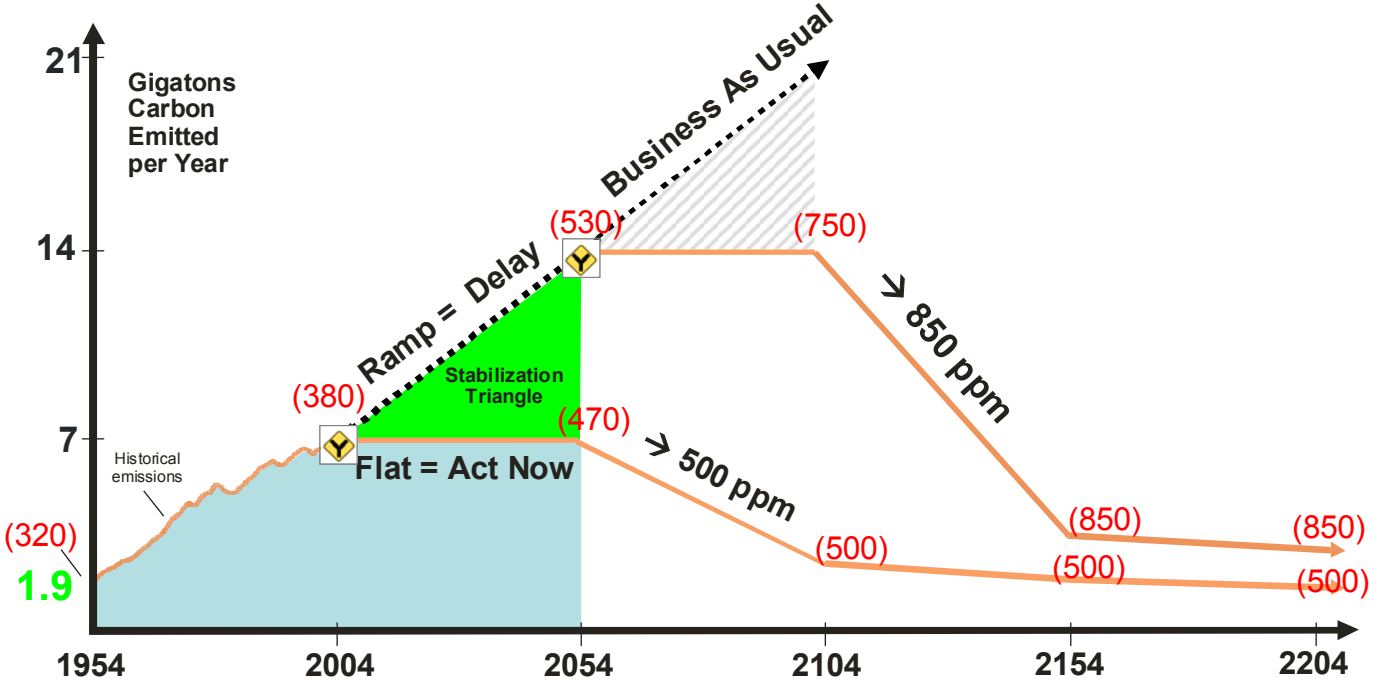
The Ramp Trajectory is an Idealization of Business As Usual

Our ramp trajectory rises linearly from 7 GtC/y and intersects 14 GtC/y in 2054. We label it the “currently projected path,” because it is near the center of many clouds of estimates of Business As Usual (BAU), a world oblivious to the issue of global carbon management.

Targets

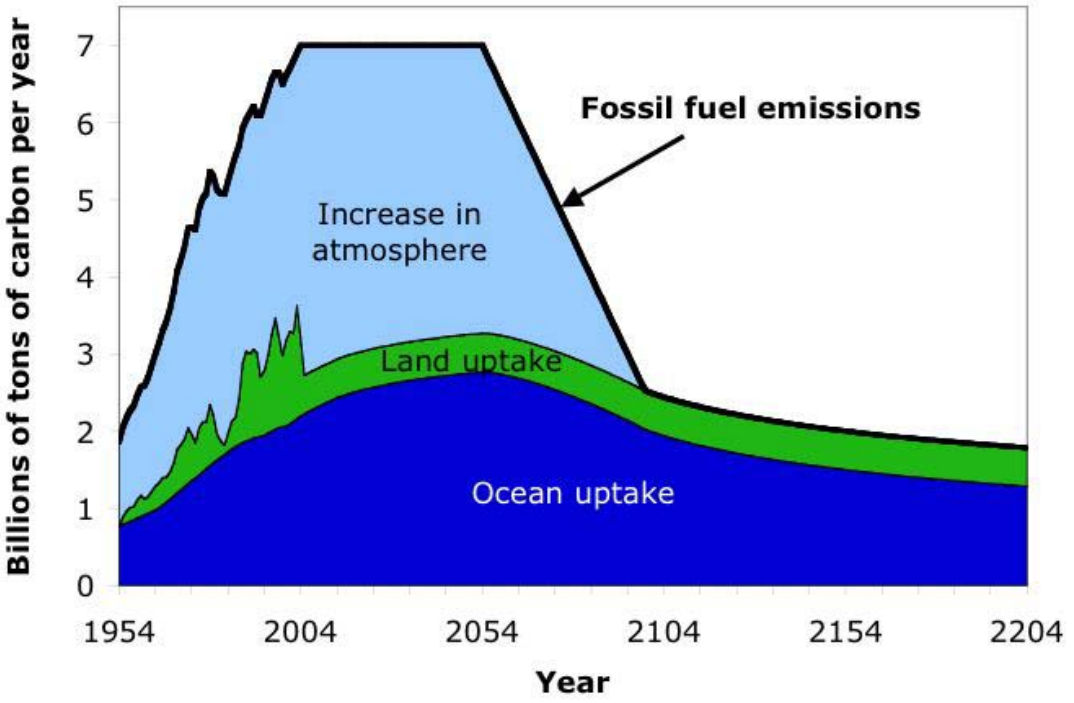

Billion of Tons of Carbon Emitted per Year
14
7
1.9
0
1954
2004
2054
2104
Historical emissions
Currently projected path
Stabilization Triangle
Flat path
Easier CO_2 target
~850 ppm
Tougher CO_2 target
~500 ppm

The Stabilization Triangle: Beat doubling or accept tripling



Values in parentheses are ppm. Note the identity (a fact about the size of the Earth's atmosphere): 1 ppm = 2.1 GtC.

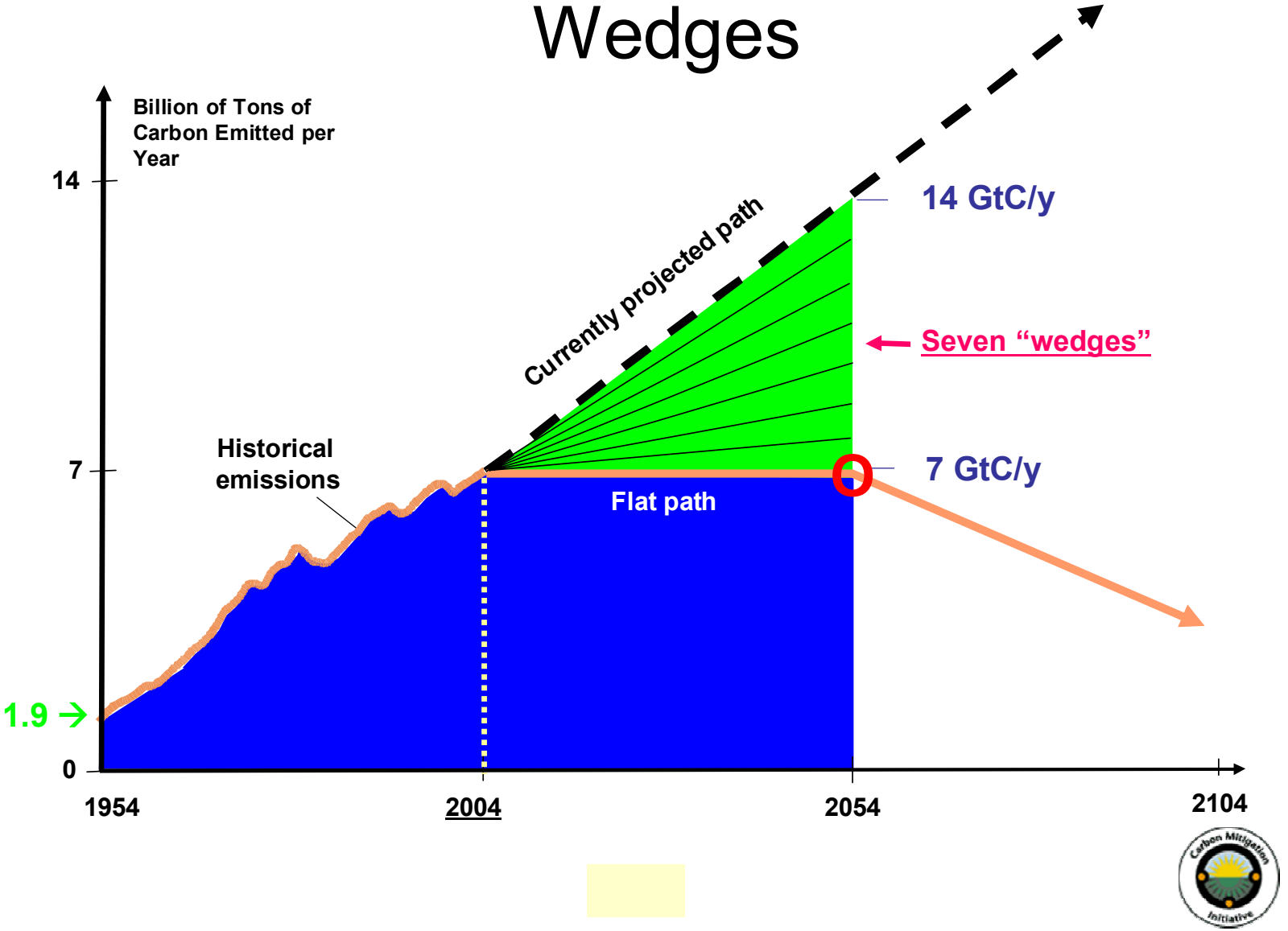
Stabilization at 500 ppm via the flat path



Ocean and land sinks permit non-zero "stabilization emissions" in the 22nd century. **But what is happening to the ocean?**

Source: Jeffery Greenblatt, Princeton University

Wedges


Billion of Tons of Carbon Emitted per Year
14
7
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1954
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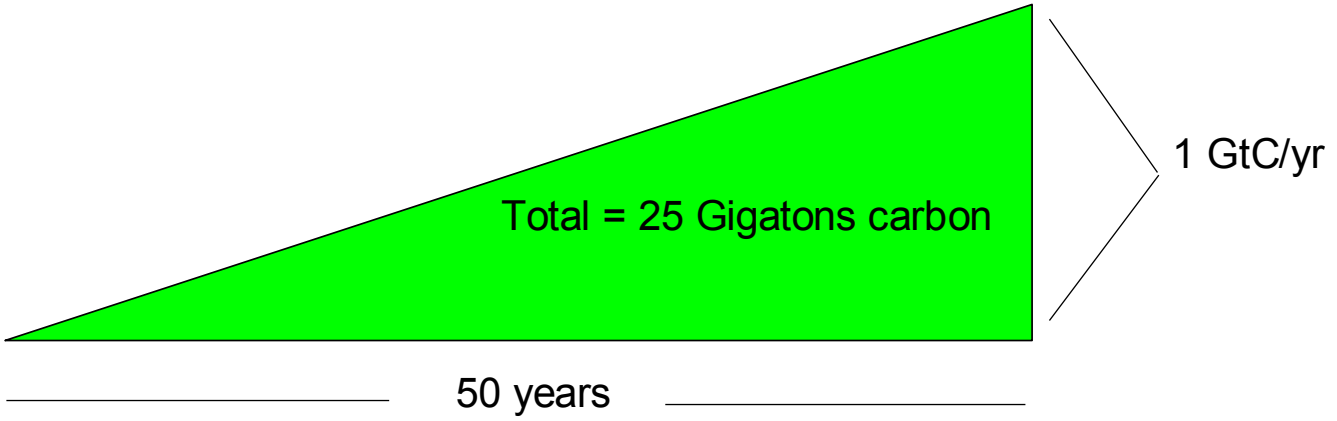
2104
Historical emissions
Currently projected path
Flat path
14 GtC/y
Seven "wedges"
7 GtC/y

What is a “Wedge”?

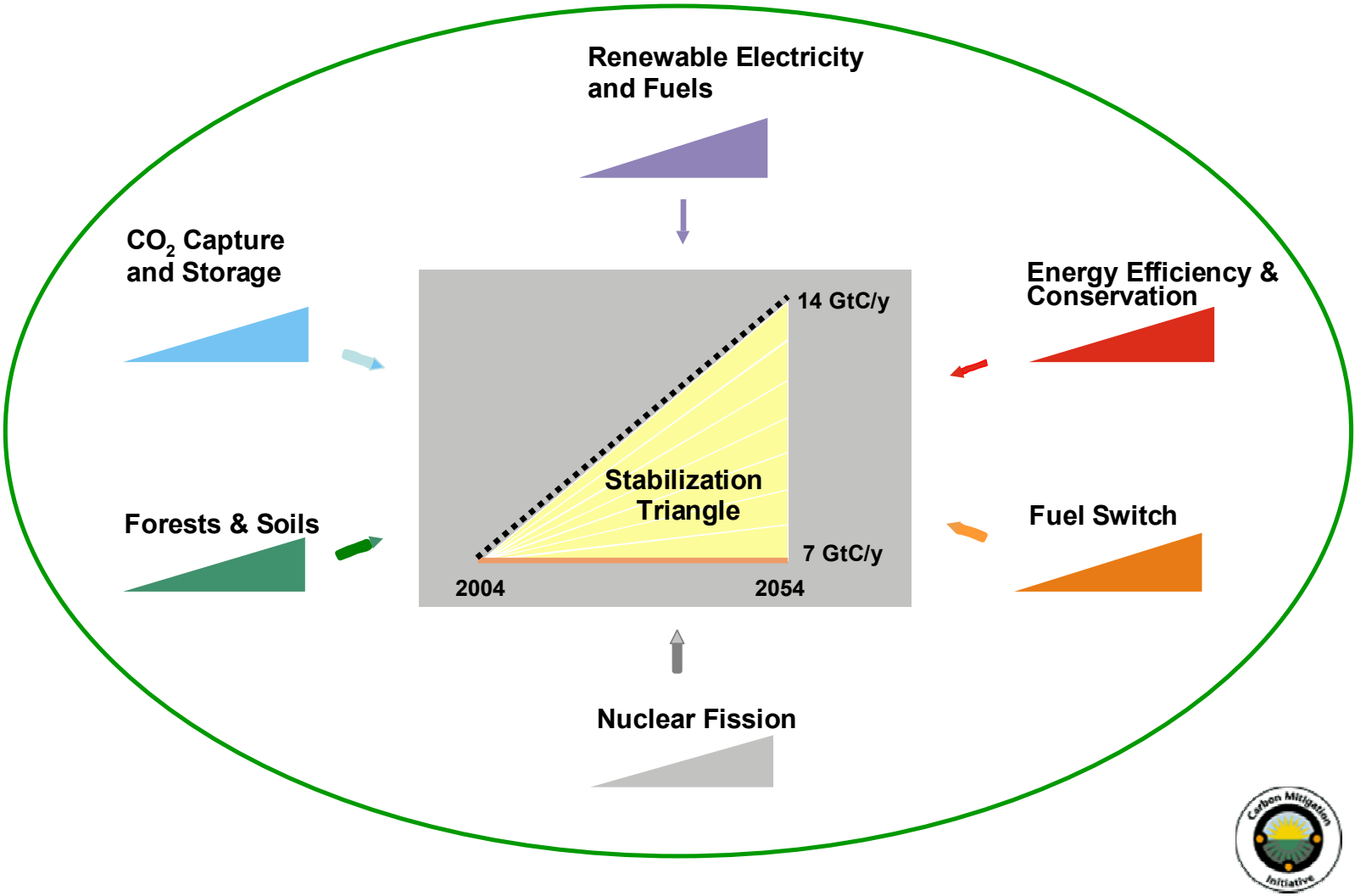
A “wedge” is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr.



Cumulatively, a wedge 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 wedge.

Fill the Stabilization Triangle with Seven Wedges



Humanity Already has the Tools

- READINESS: All wedge technologies are already deployed somewhere at commercial scale.
- PORTFOLIO: No single wedge technology can do the whole job, or even half the job.
- CHOICE: Not every wedge technology is needed.

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Wedges

EFFICIENCY
- Buildings, ground transport, *industrial processing, lighting*, electric power plants.

DECARBONIZED ELECTRICITY
- Natural gas for coal
- Power from coal or gas with CCS
- Nuclear power
- Power from renewables: wind, photovoltaics, *solar concentrators (troughs and dishes), hydropower, geothermal.*

DECARBONIZED FUELS
- Synthetic fuel from coal, natural gas, and biofuels, with carbon capture and storage
- Biofuels
- Hydrogen
  - from coal and natural gas, with carbon capture and storage
  - from nuclear energy
  - from renewable energy (hydro, wind, PV, etc.)

FUEL DISPLACEMENT BY LOW-CARBON ELECTRICITY
- *Grid-charged batteries for transport*
- *Heat pumps for furnaces and boilers*

NATURAL SINKS
- Forestry (reduced deforestation, afforestation, new plantations)
- Agricultural soils

METHANE MANAGEMENT
- *landfill gas, cattle, rice, natural gas*

Italics: Not on list in *Science*

Efficiency and Conservation

transport

buildings

industry

Effort needed by 2054 for 1 wedge:

2 billion cars at 60 mpg instead of 30 mpg.

power

lifestyle

Power with Carbon Capture and Storage

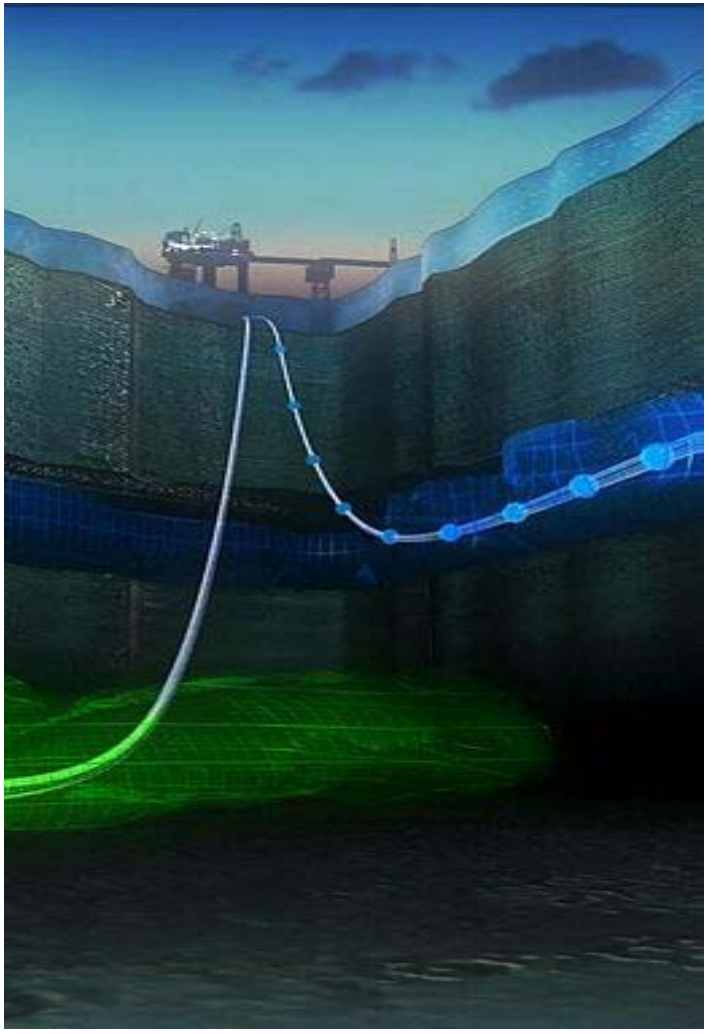
The Wabash River
Coal Gasification Repowering Project

Effort needed by 2054 for 1 wedge:

Carbon capture and storage at 800 GW coal power plants.

Graphics courtesy of DOE Office of Fossil Energy

Carbon Storage



Sleipner project, offshore Norway

Graphic courtesy of Statoil ASA

Effort needed by 2054 for 1 wedge:

3500 Sleipners @1 $MtCO_2$/yr

100 x U.S. CO_2 injection rate for EOR

A flow of CO_2 into the Earth equal to the flow of oil out of the Earth today

Graphic courtesy of David Hawkins

Wind Electricity

Effort needed by 2054 for 1 wedge:

Two million 1 MW windmills displacing coal power.

Today: 40,000 MW (2%)

Prototype of 80 m tall Nordex 2,5 MW wind turbine located in Grevenbroich, Germany (Danish Wind Industry Association)

Pholtovoltaic Power

Effort Needed by 2054:

2000 GW_{peak} (700 times current capacity)

2 million hectares

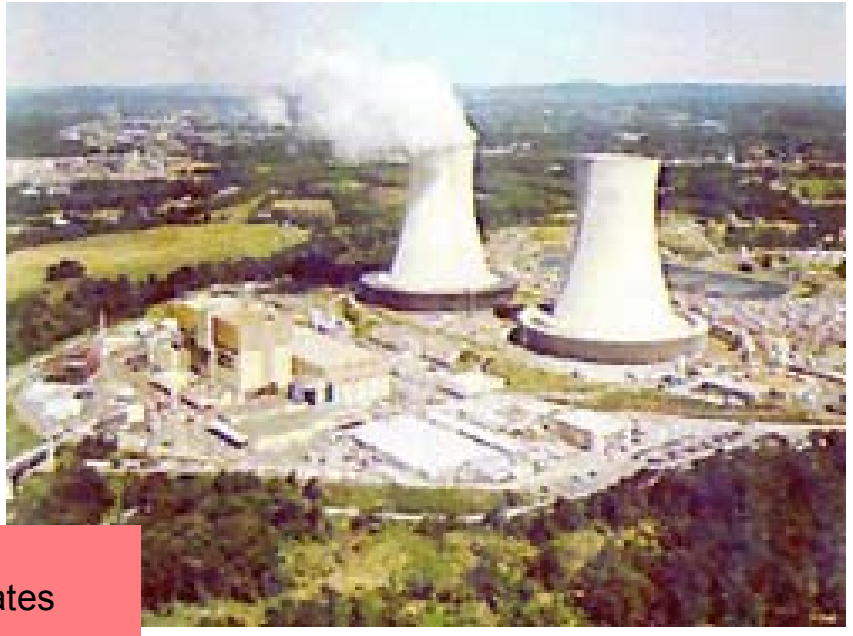
Solar thermal power via concentrators (troughs and dishes) is produced at high efficiency, like PV.

Graphics courtesy of DOE Photovoltaics Program

Nuclear Electricity

Effort needed by 2054 for 1 wedge:

700 GW (twice current capacity) displacing coal power.



Graphic courtesy of NRC

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

Biofuels

Usina Santa Elisa mill in Sertaozinho, Brazil
(http://www.nrel.gov/data/pix/searchpix.cgi?getrec=5691971&display_type=verbose&search_reverse=1_

Effort needed by 2054 for 1 wedge:

Two billion 60 mpg cars running on biofuels

250 million hectares of high-yield crops (one sixth of world cropland)

Fossil-fuel-based H_2 with CCS

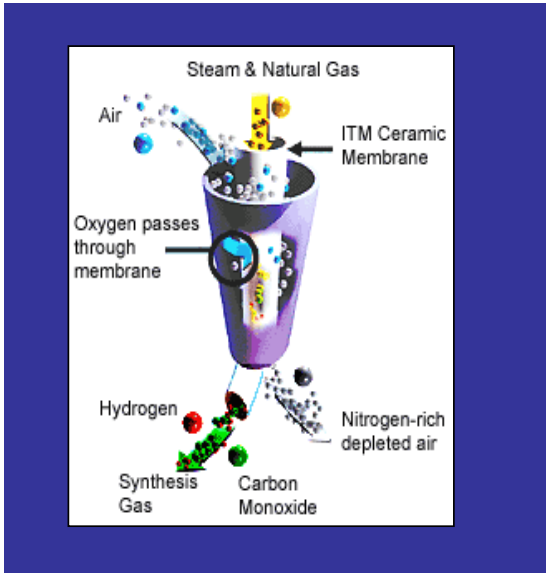
***Carbon capture and storage**

Effort needed by 2054 for 1 wedge:

Use: H_2 instead of gasoline or diesel in 2 billion 60 mpg vehicles

Production: Capture and store, instead of venting, the CO_2 byproduct of 250 MtH_2/year produced from coal

Today: 40 MtH_2/year is produced from all sources.



Graphics courtesy of DOE Office of Fossil Energy

Prototype of 80 m tall Nordex 2,5 MW wind turbine located in Grevenbroich, Germany

(Danish Wind Industry Association)

Wind Hydrogen

Effort needed by 2054 for 1 wedge:

H_2 instead of gasoline or diesel in 2 billion 60 mpg vehicles

Four million 1 MW windmills

Twice as many windmills as for a wedge of wind electricity

Today: 40,000 MW (1%)

Assumes the H_2 fuels 100-mpg cars

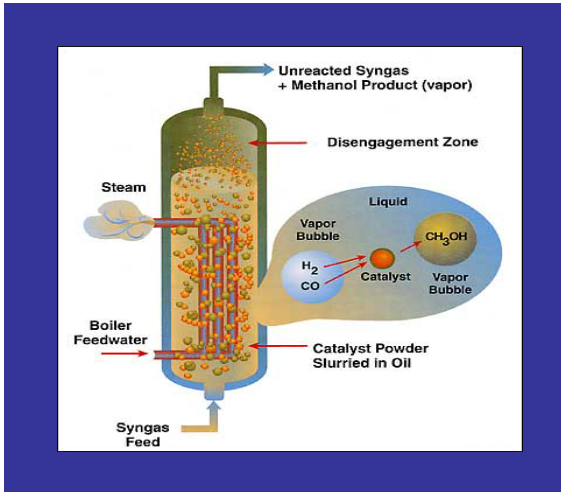
*Coal-based Synfuels with CCS**

Carbon capture and storage

Effort needed for 1 wedge by 2054

Capture and storage of the CO_2 byproduct at plants producing 34 million barrels per day of coal-based synfuels

Assumption: half of C originally in the coal is captured, half goes into synfuels.



Graphics courtesy of DOE Office of Fossil Energy

Result: Coal-based synfuels have no worse CO_2 emissions than petroleum fuels, instead of doubled emissions.

Natural Stocks

Forests

Effort needed by 2054 for 1 wedge:

Elimination of tropical deforestation

and

Rehabilitation of 400 million hectares (Mha) temperate *or* 300 Mha tropical forest

Photo: SUNY Stonybrook

Soils

Effort needed by 2054 for 1 wedge:

Conservation tillage on *all* cropland

Photo: Brazil: Planting with a jab planter. FAO

Summary: What's appealing stabilization wedges?

The stabilization triangle:

- Does not concede doubling is inevitable.
- Shortens the time frame to within business horizons.

The wedge:

- Decomposes a heroic challenge (the Stabilization Triangle) 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

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Consensus Building via Wedges?

Advocates of particular wedges agree:

1. It is already time to act.
2. It is too soon to pick “winners.”
3. Subsidy of early stages is often desirable.
4. At later stages, markets help to choose the best wedges.
5. The best wedges for one country may not be the best for another.
6. The environmental and social costs of scale-up need attention.

Can a consensus in favor of early action be built on stabilization wedges?

$100/tC

Carbon emission charges in the neighborhood of $100/tC can enable commercialization of most of the wedges. (PV is an exception.)

Form of Energy	**Equivalent to $100/tC**
Gasoline	25¢/gallon
Crude oil	$12/barrel
Coal	$65/U.S. ton
Natural gas	$1.50/1000 scf
Electricity from coal	2.2¢/kWh
Electricity from natural gas	1.0¢/kWh
Today's global energy system	$700 billion/year (2% of GWP)

Learning-by-doing should reduce the cost of every wedge.

Can wedges costs be estimated from successful subsidies?

Focused subsidies by specific countries have already enabled deployment at significant scale. Most subsidies were motivated by energy security, not climate.

Wedges Technology	**Subsidy**
CO_2 transport	EOR (U.S.)
CO_2 geological storage	EOR (U.S.), Sleipner (Norway)
Wind	Wind electricity (Germany, Denmark, U.K.)
Nuclear power	Nuclear power (U.S., Russia, France)
Coal-to-H_2	Fertilizer (China)
Biofuels	Sugarcane ethanol (Brazil)
Coal-to-liquids (negative wedges)	*Synfuels (South Africa)*

The Demography of Capital

Long-lived capital stock (lifetime >50 years) is the source of a significant fraction of global CO_2 emissions.

Examples: power plants, residential and commercial buildings, fuels infrastructure

Retrofitting after construction is usually very costly.

Two messages:

Avoid premature retirement: DELAY

Avoid new high-carbon stock: ACT NOW

One must heed both messages.

Mitigation *now* in Developing Countries

Unless buildings and power plants are built energy efficiently and carbon efficiently *now*, they will become a liability when a price is later put on CO_2 emissions.

Currently, much of the world's construction of long-lived capital stock is in developing countries.

Attending to the carbon efficiency of new long-lived capital is urgent EVERYWHERE.

Leapfrogging and Wedges

"Leapfrogging": introducing advanced technology in developing countries *first*, industrialized countries *later*. Examples:

energy-efficient buildings
advanced coal technology
carbon capture and storage
biofuels.

Consider *differentiated responsibilities:* Specific developing countries can commercialize the early stages of several wedges.

Compensation for first movers would be a collective responsibility.

Leapfrogging is a path to globally coordinated mitigation.

A world transformed by deliberate attention to carbon (1 of 2)

Achieving zero global CO_2 emissions growth for 50 years will bring:

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 *carbon capture and storage* are achieved, widespread permitting of geological storage.

The list continues…

A world transformed by deliberate attention to carbon (2 of 2)

The list continues…

4. If wedges of *renewable energy* and *carbon sink management* are achieved, extensive land reclamation.

5. If *hydrogen* is widely used, ways of handling hydrogen safely.

6. If wedges of energy-efficient *vehicles* are achieved, solutions to congestion.

7. A planetary consciousness.

Not an unhappy prospect!

The Interim Goal is Within Reach

Reasons for optimism that global emissions in 2054 need not exceed today's emissions:

- The world today has a terribly inefficient energy system.
- Carbon emissions have zero economic cost.
- Most of the 2054 physical plant is not yet built

Can We Do It?

To stabilize below doubling will be disruptive.

But people are becoming increasingly anxious about our limited understanding of the experiments we are performing on the only Earth we have…

…and are learning that there are ways to live more cautiously.

We should anticipate a discontinuity:

What has seemed too hard becomes what simply must be done.

Precedents include abolishing child labor, addressing the needs of the disabled, and mitigating air pollution.