Stabilization Wedges: Solving the Climate Problem for the Next Half-Century with Technologies Available Today

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This talk is based on a paper of the same title, by Stephen Pacala and Robert Socolow, published in the August 13, 2004, issue of *Science*, **305** (5686), pp. 968-972, and its Supporting Online Material.

Outline of Talk

1. **The Wedges Model**

2. Some specific wedges

3. Implications for R&D

Goals of the Wedges Analysis

- Simplify the presentation of global carbon management so that quantitative analysis can be done by more people
    - Use straight lines
    - Introduce a new unit of analysis (the wedge)

- Refocus on the next 50 years, a time frame relevant to business

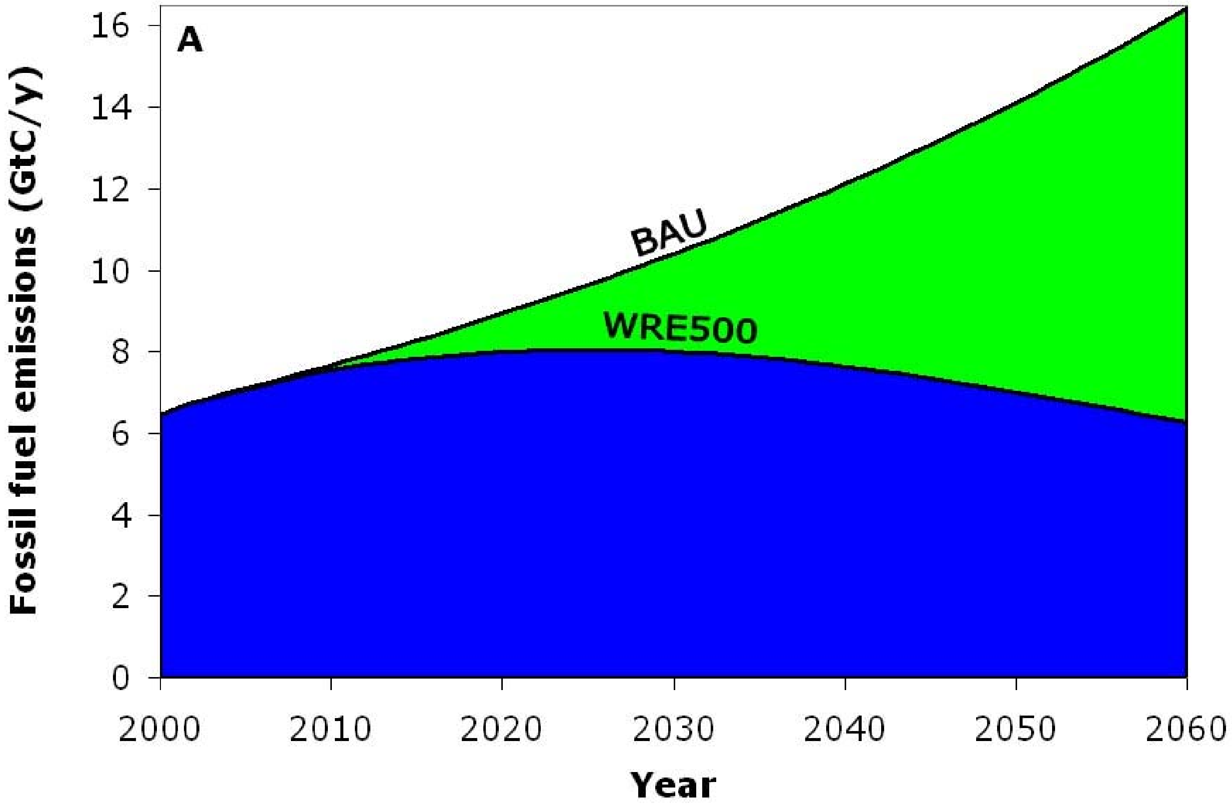
- Relate urgency to stringency of target

- Make the case for parallel campaigns

- For many campaigns based on familiar technology, quantify the level of effort required for a specific contribution to carbon emission reduction

- Highlight uncertainties

Refocus: The Next 50 Years

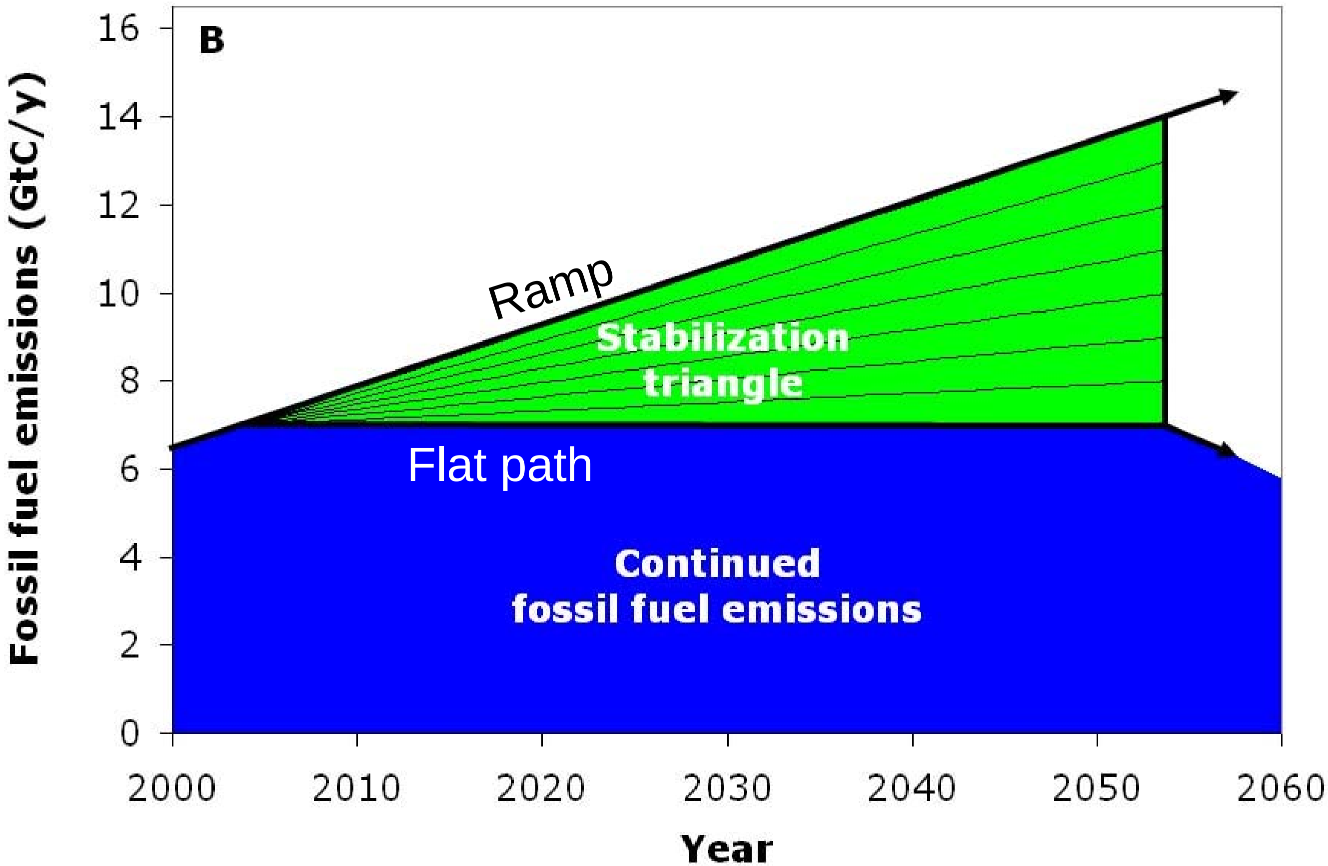


Two models of future carbon emissions:

BAU: 1.5%/yr exponential growth

WRE500: Wigley, Richels, Edmonds model for “stabilization at 500 ppm.”

The Stabilization Triangle



The Flat Trajectory as an Idealization of Stabilization below Doubling

Stabilization below doubling (450-550 ppm) is the goal for carbon management recommended by many environmental scientists.

Examination of stabilization scenarios reveals that they are broadly consistent with an *Interim goal* of having the same global emissions in 2054 as today: seven billion tons of carbon per year emitted as CO_2.

7 GtC/y in 2054, as in 2004

The interim goal changes by about 2 Gt/y with a change of stabilization target by 50 ppm.

The largest source of uncertainty in the interim goal arises from imperfect knowledge of the terrestrial carbon sink. The ocean sink is less uncertain. The combined uncertainty is about ± 3 GtC/y. A conservative view of sinks leads to an association of 500 ppm stabilization with an interim goal of 7 GtC/y.

The Ramp Trajectory as an Idealization of Business As Usual

Our Business As Usual (BAU) emissions trajectory, or "reference trajectory," rises linearly from 7 GtC/y and intersects 14 GtC/y in 2054. It is at the center of many clouds of estimates.

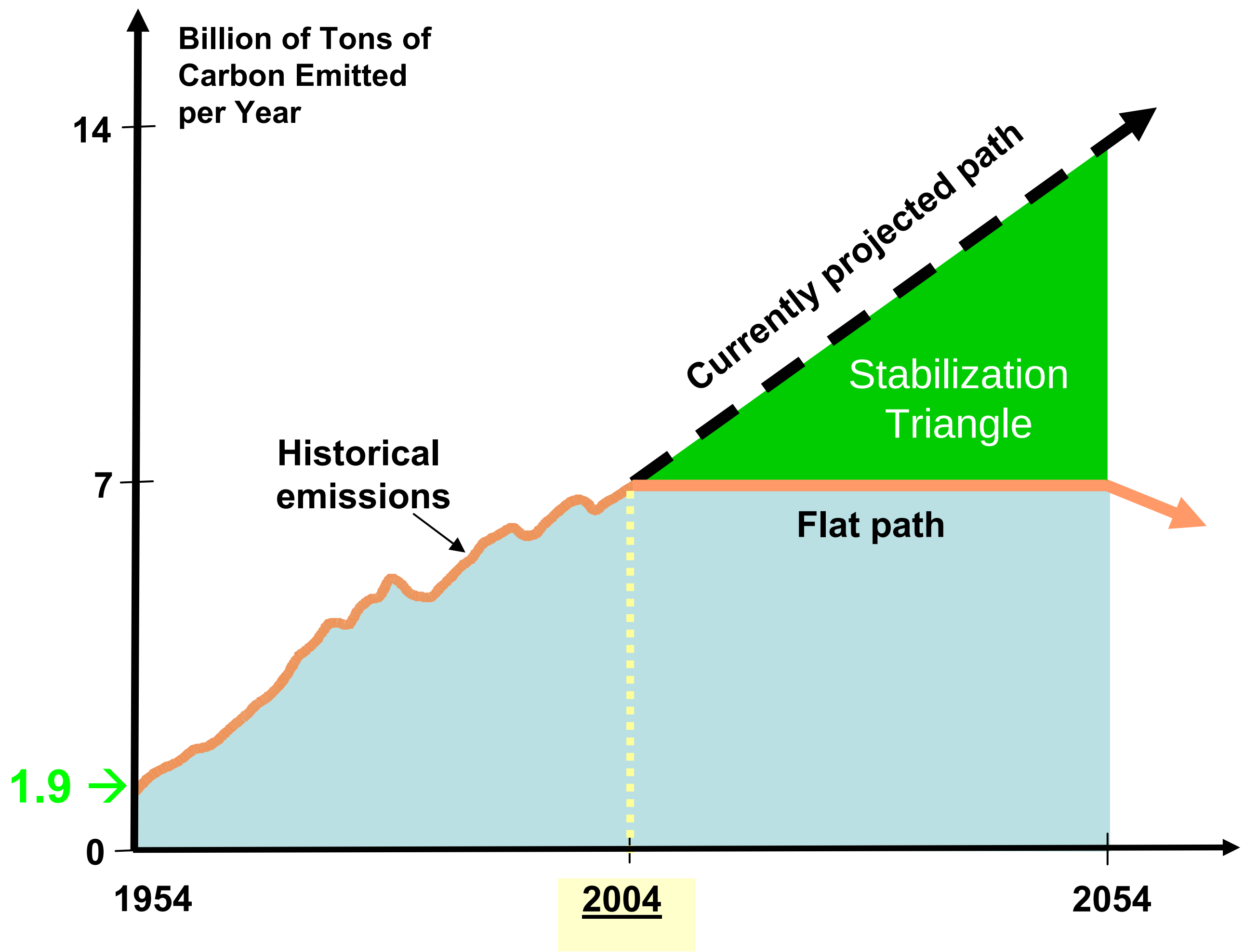
Most specific BAU trajectories "use up" a few of the wedges we discuss here.

Our philosophy: Define BAU as little as possible.

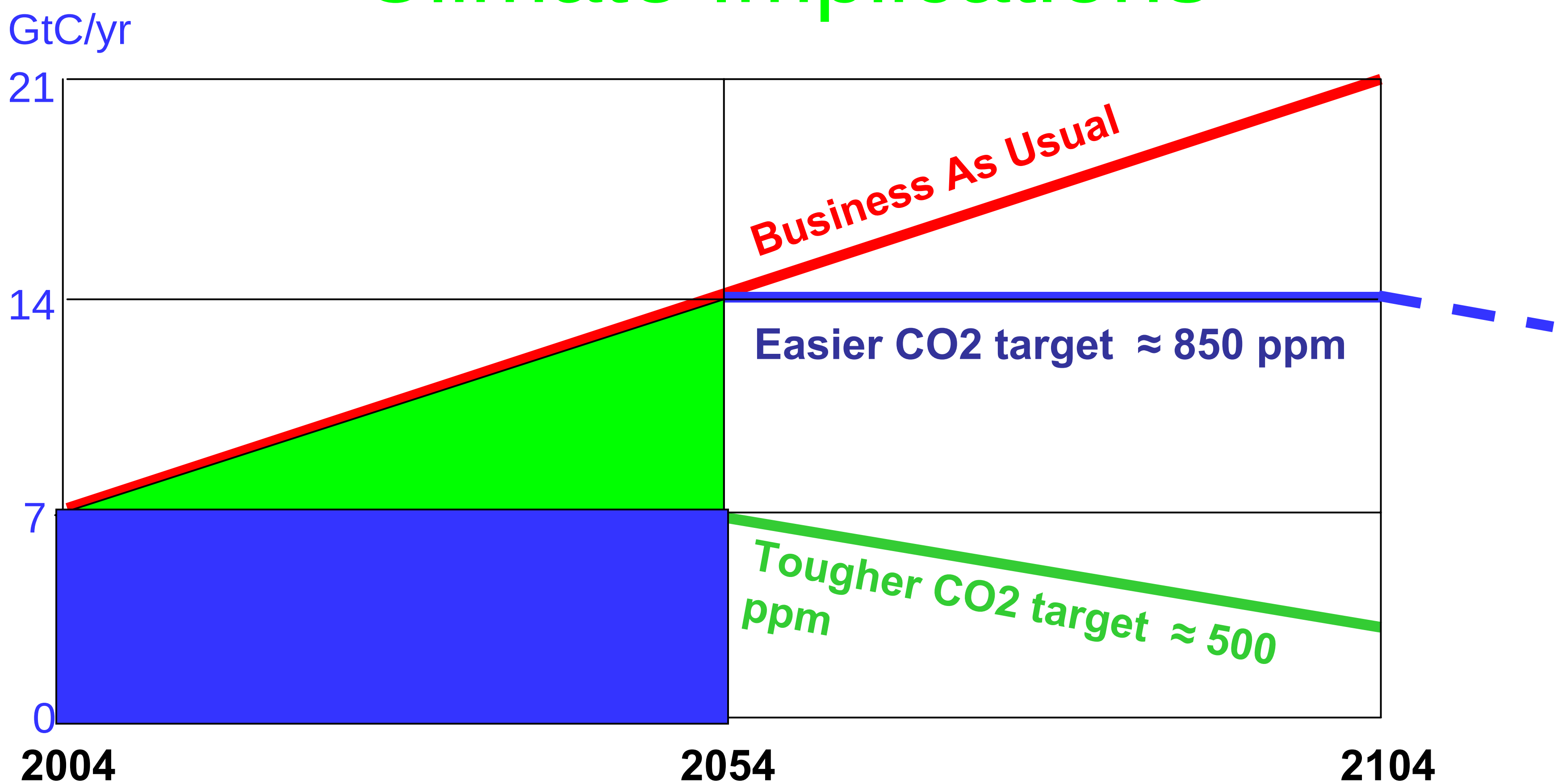
Stay focused on comparing two "stories":

1. the world is oblivious to carbon management (BAU)
2. the world is investing heavily in carbon management

The Stabilization Triangle: Historical View

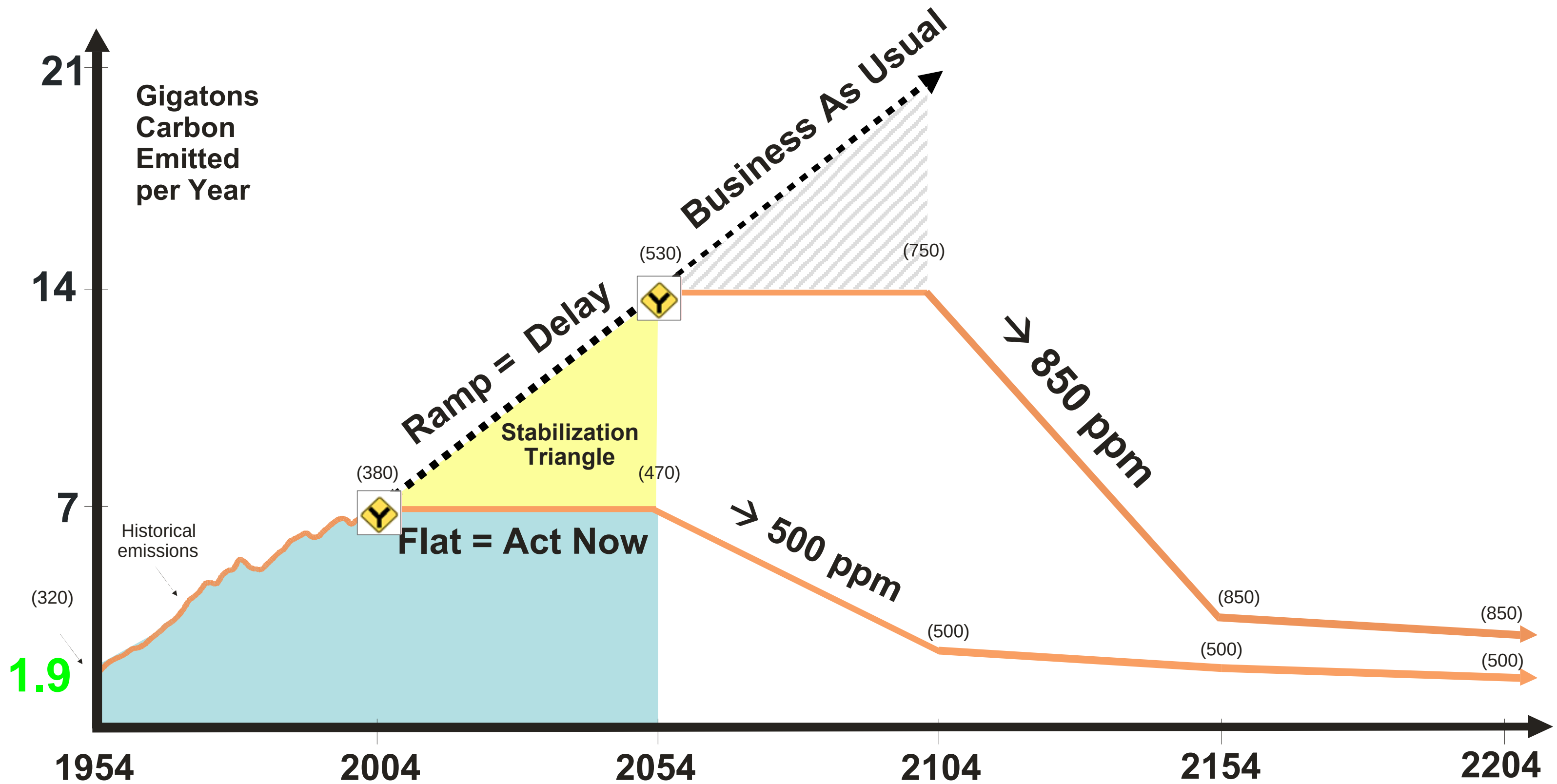


The Stabilization Triangle: Climate Implications



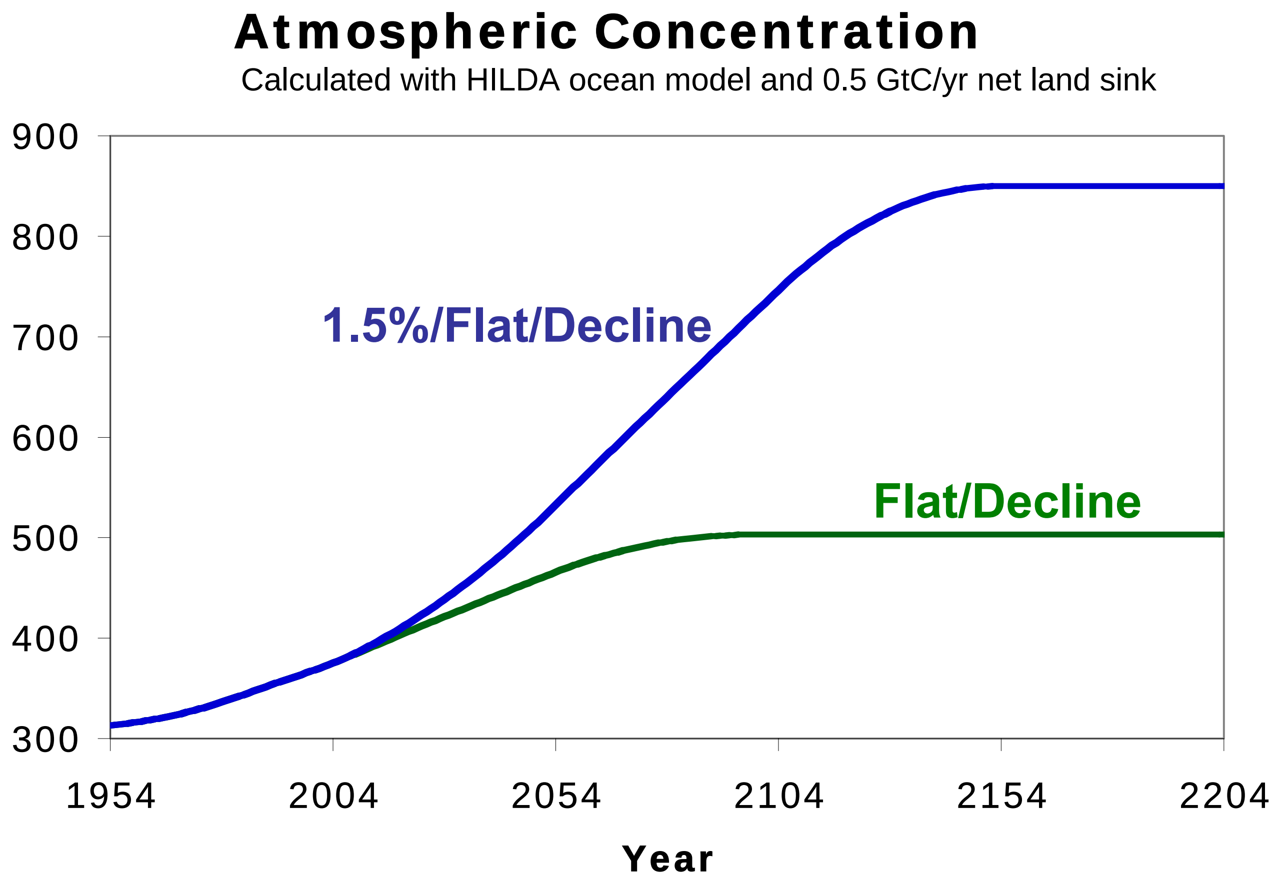
The Stabilization Triangle: Beat "doubling" or accept "tripling" of the pre-industrial 280-ppm concentration.

The Stabilization Triangle:
Beat doubling or accept tripling

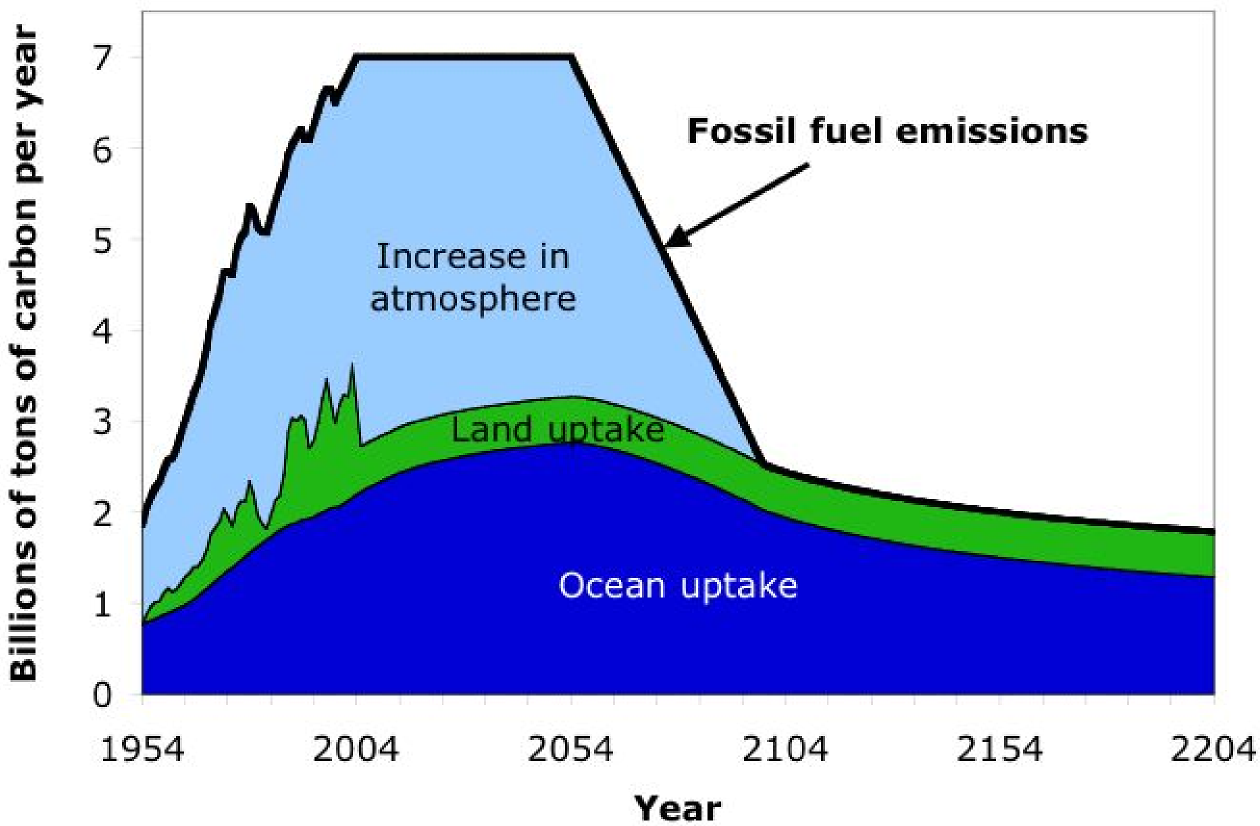


Note the identity (a fact about the size of the Earth's atmosphere): 1 ppm = 2.1 GtC.

Concentrations for the previous emission paths



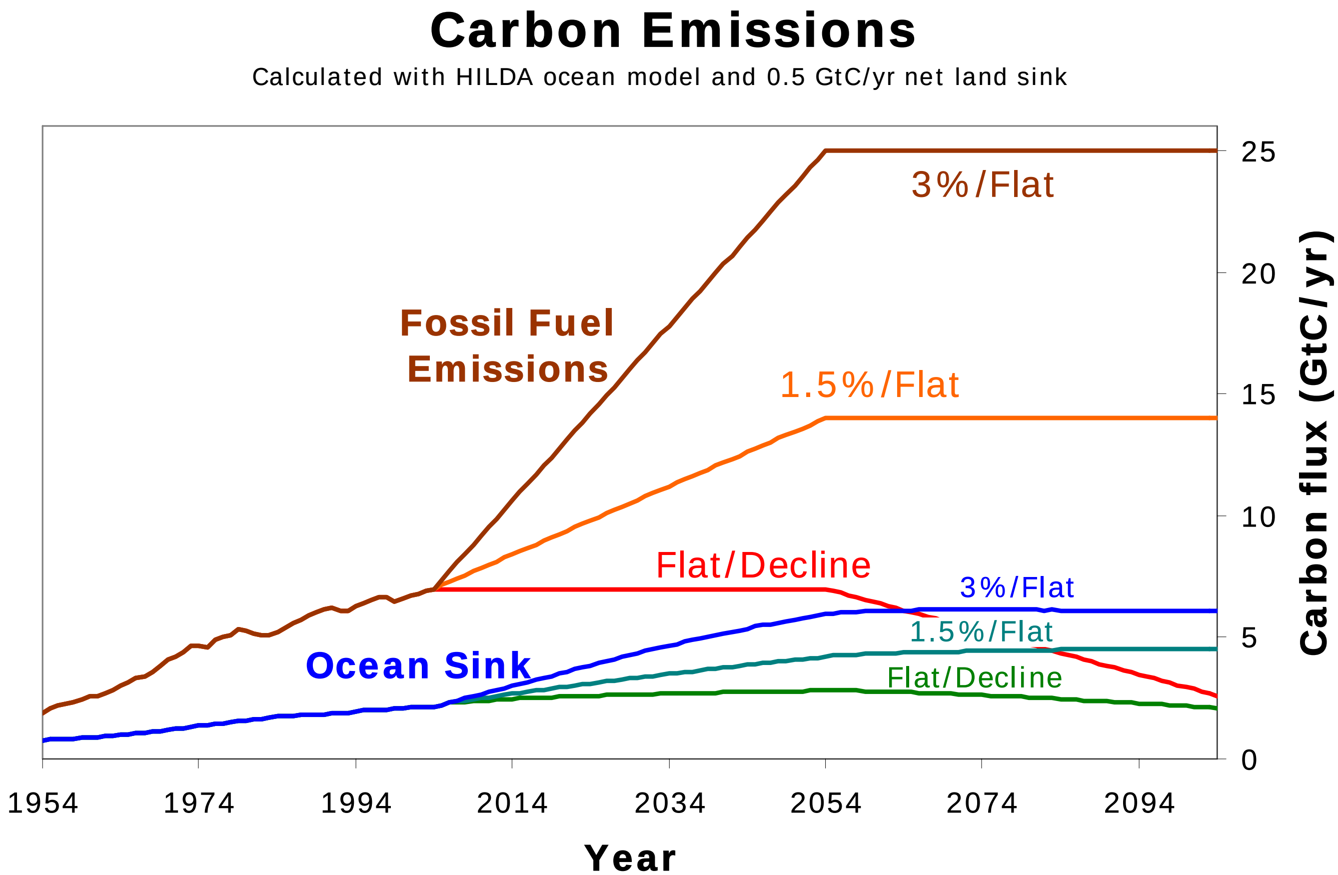
Stabilization at 500 ppm via the flat path



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

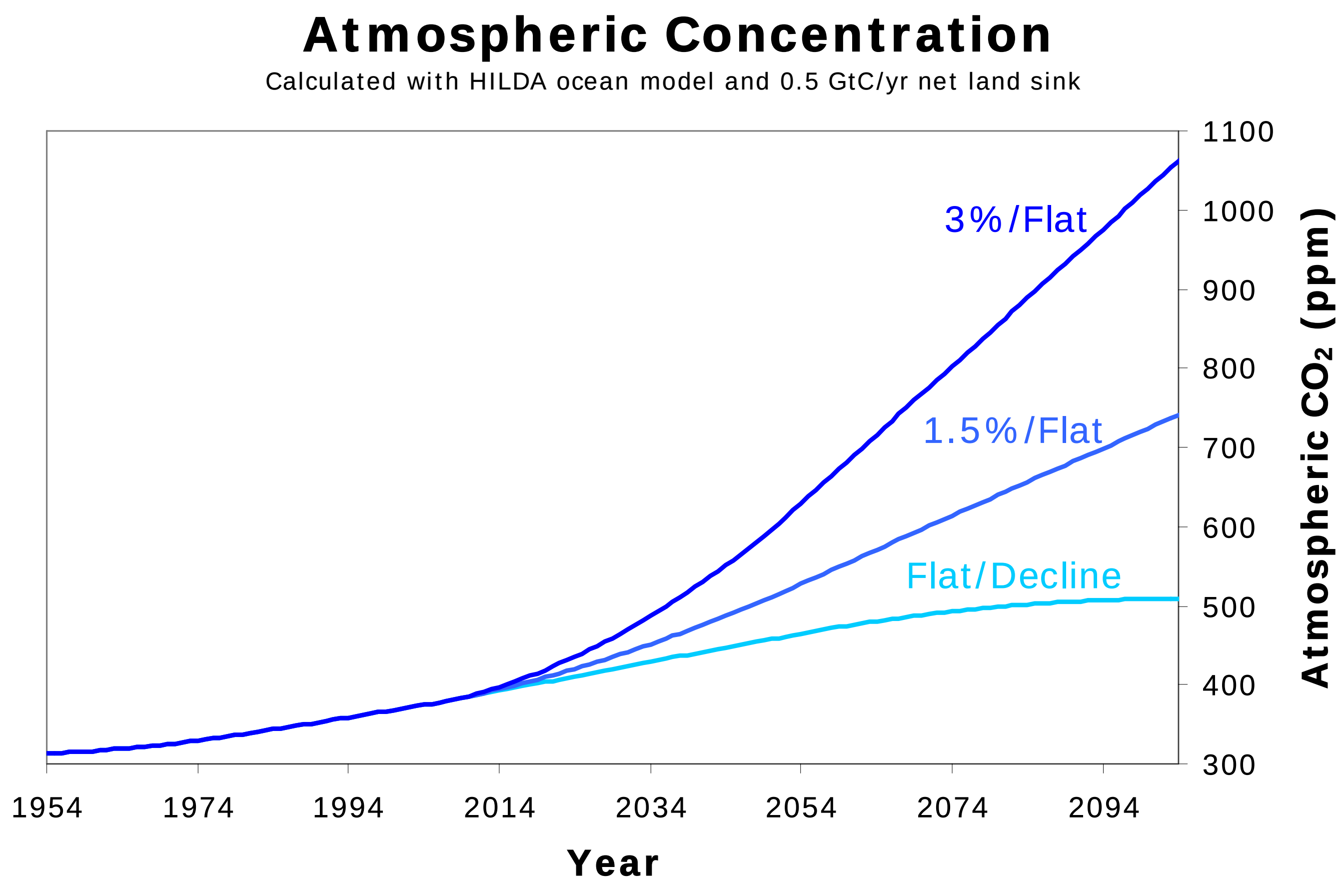
Source: Jeffery Greenblatt, Princeton University

Uncertain future



What if carbon emissions grew at 3%/yr for the next 50 years, then leveled off for 50 years?

Concentrations for the previous emission paths



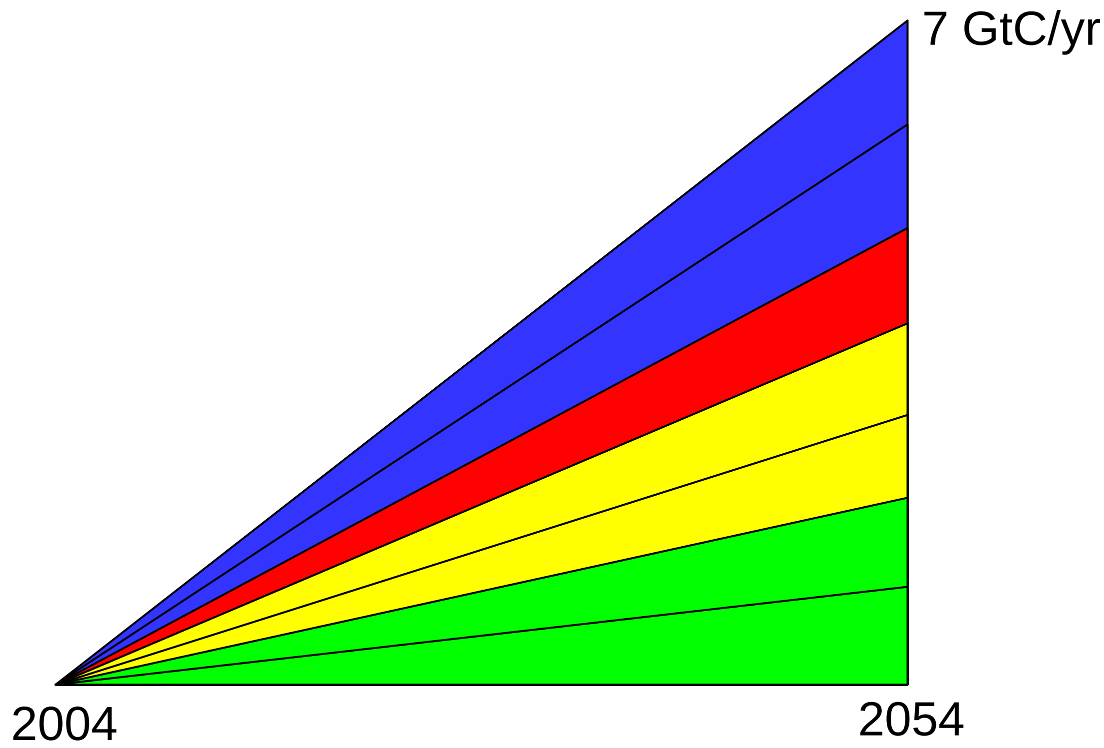
Is the interim goal beyond our reach?

I certainly do not know enough to tell the world that the interim goal is out of reach.

- The world today has a terribly inefficient energy system.
- Carbon emissions have zero economic cost
- Most energy conversion is done with capital that is replaced in no more than 50 years.

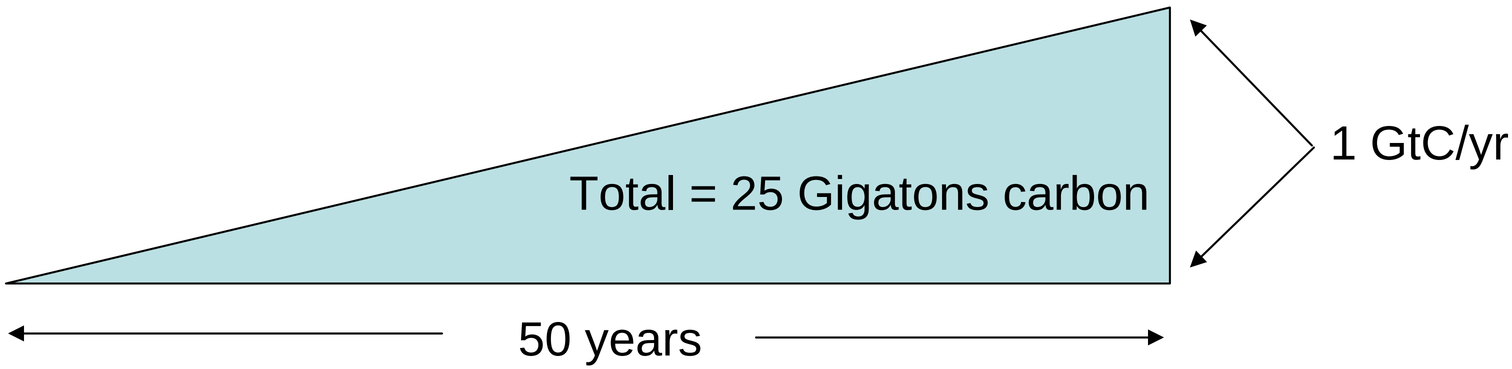
Seven "Wedges" Fill the Stabilization Triangle

It is irresistible to divide the Stabilization Triangle into seven equal parts. We call these: "wedges."



What is a "wedge"?

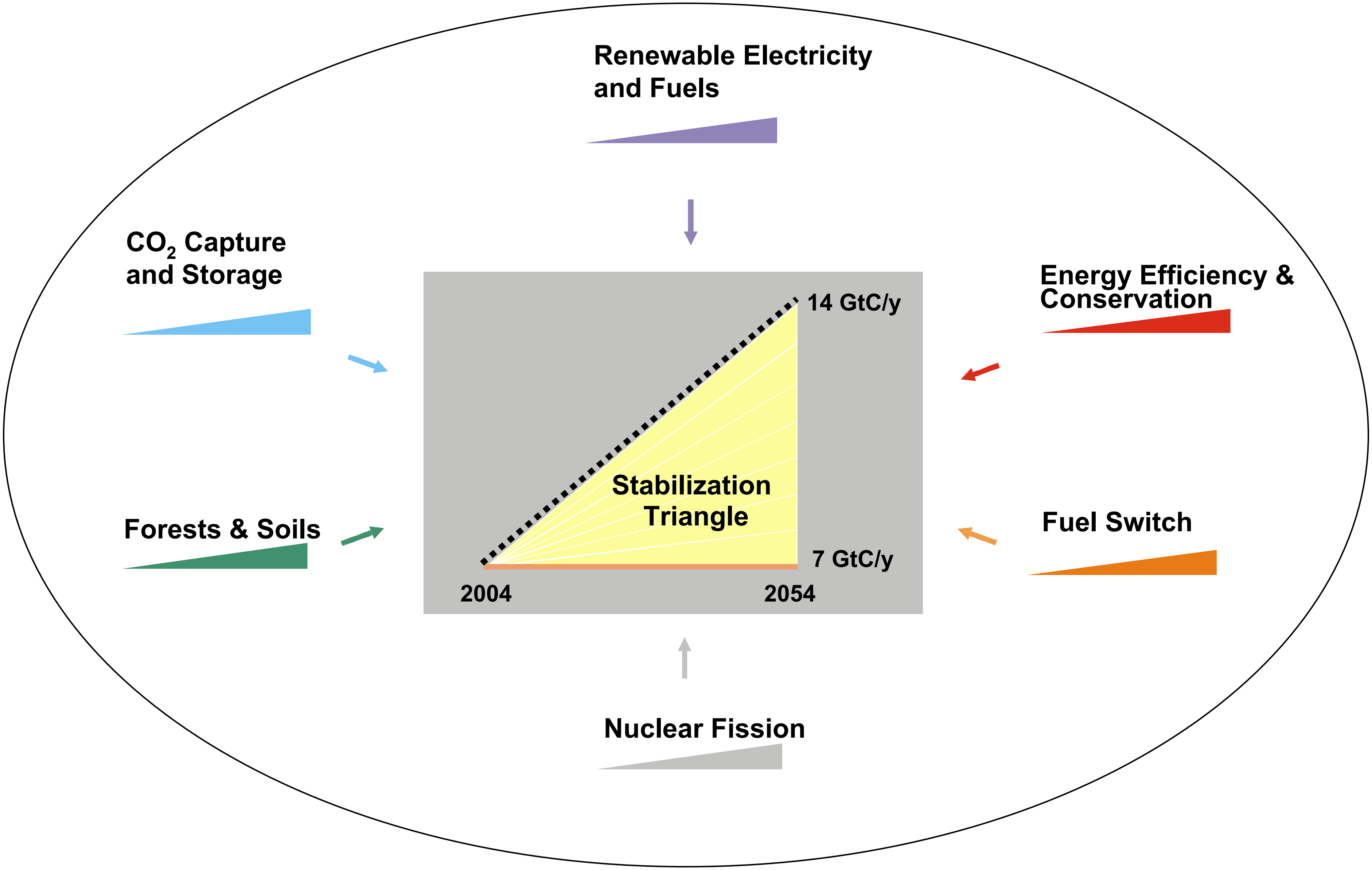
A "wedge" is an activity reducing the rate of carbon build-up in the atmosphere that grows in 50 years from zero to 1.0 Gt(C)/yr.



Cumulatively, a 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.

Filling the Stabilization Triangle with Seven Wedges



Wedges #1 - #8 (out of 15)

	Option	Effort by 2054 for one wedge, relative to 14 GtC/year BAU	Comments, issues
Energy Efficiency and Conservation	Economy-wide carbon-intensity reduction (emissions/$GDP)	Increase reduction by additional 0.15% per year (e.g., increase U.S. goal of reduction of 1.96% per year to 2.11% per year)	Can be tuned by carbon policy
	1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg	Car size, power
	2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5,000 miles per year	Urban design, mass transit, telecommuting
	3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054	Weak incentives
	4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)	Advanced high-temperature materials
Fuel shift	**5.** Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (4 times the current production of gas-based power)	Competing demands for natural gas
CO_2 Capture and Storage (CCS)	**6.** Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)	Technology already in use for H_2 production
	7. Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources)	H_2 safety, infrastructure
	8. Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels plants producing 30 million barrels per day from coal (200 times Sasol), if half of feedstock carbon is available for capture	Increased CO_2 emissions, if synfuels are produced *without* CCS
	Geological storage	Create 3500 Sleipners	Durable storage, successful permitting

Wedges #9 - #15 (out of 15)

	Option	Effort by 2054 for one wedge, relative to 14 GtC/year BAU	Comments, issues
Nuclear Fission	**9.** Nuclear power for coal power	Add 700 GW (twice the current capacity)	Nuclear proliferation, terrorism, waste
Renewable Electricity and Fuels	**10.** Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times the current capacity) “occupying” 30x10^6 ha, on land or off shore	Multiple uses of land because windmills are widely spaced
	11. PV power for coal power	Add 2000 GW-peak PV (700 times the current capacity) on 2x10^6 ha	PV production cost
	12. Wind H_2 in fuel-cell car for gasoline in hybrid car	Add 4 million 1-MW-peak windmills (100 times the current capacity)	H_2 safety, infrastructure
	13. Biomass fuel for fossil fuel	Add 100 times the current Brazil or U.S. ethanol production, with the use of 250 x10^6 ha (1/6 of world cropland)	Biodiversity, competing land use
Forests and Agricultural Soils	**14.** Reduced deforestation, plus reforestation, afforestation and new plantations.	Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)	Land demands of agriculture, benefits to biodiversity from reduced deforestation
	15. Conservation tillage	Apply to all cropland (10 times the current usage)	Reversibility, verification

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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Nuclear Electricity

Graphic courtesy of NRC

Effort needed by 2054 for 1 wedge:

Add 700 GW (twice current capacity): fourteen 1-GW plants/year.

Potential Pitfalls:
Nuclear proliferation and terrorism
Nuclear waste, NIMBY

Plutonium (Pu) produced by 2054, if fuel cycles are unchanged: 4000 t Pu (and another 4000 t Pu if current capacity is continued).

Compare with ~ 1000 t Pu in all current spent fuel, ~ 100 t Pu in all U.S. weapons.

10 kg ~ Pu critical mass.

Power with CCS*

The Wabash River
Coal Gasification Repowering Project

Graphics courtesy of DOE Office of Fossil Energy

*The carbon capture step of Carbon Capture and Storage (CCS)

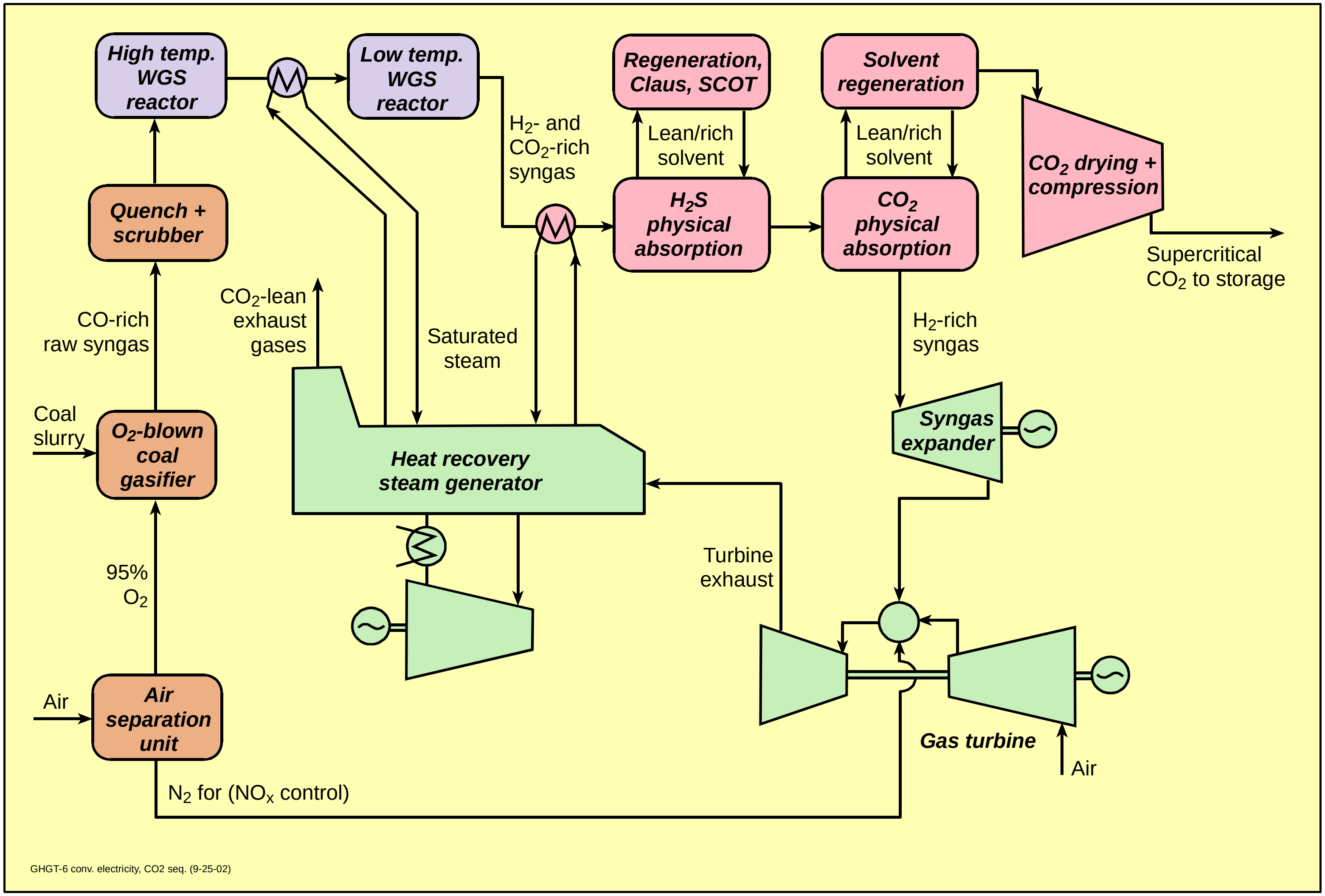
Effort needed for 1 wedge:

CCS at 800 GW coal or 1600 GW natural gas, or equivalent H_2 plants.

Potential Pitfalls:

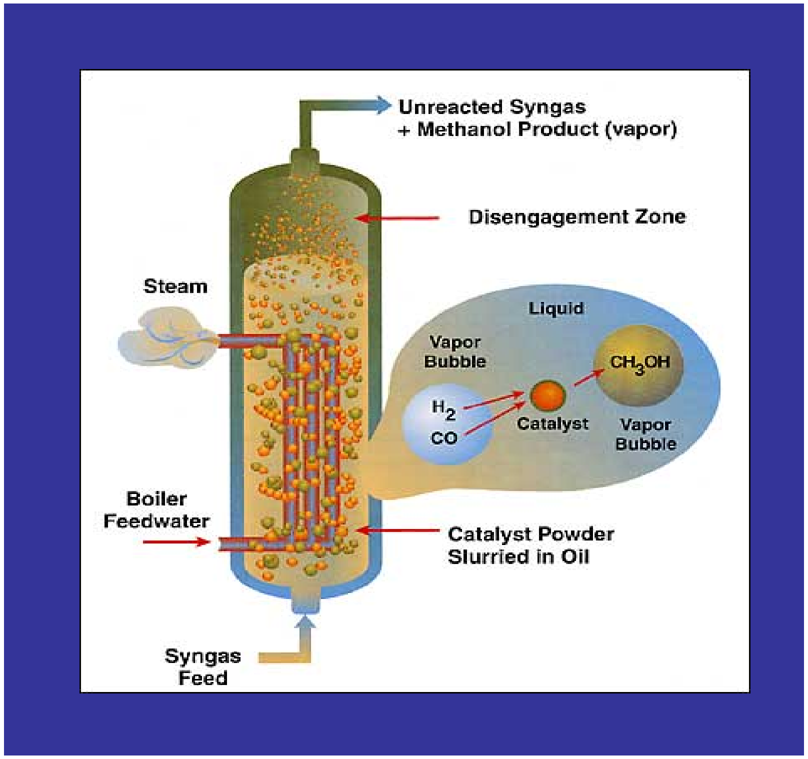
Second step, carbon storage, founders.

Benchmark: IGCC Electricity with CO_2 Capture



- Cost: 6.4 ¢/kWh (at carbon tax of 93 \$/tonne C), efficiency: 34.8% (HHV). (70 bar gasifier with quench cooling; plant scale: 368 MW_e)

Synfuels with CCS* **Carbon capture and storage*



Graphics courtesy of DOE Office of Fossil Energy

C originally in coal or tarsands: assume half captured, half in synfuels

Effort needed for 1 wedge

Annually produce synfuels from 3000 million tons coal, roughly current production; capture and store the CO_2 that would have been vented.

Potential Pitfalls:

The most carbon-intensive fuels become entrenched, because synfuel production proceeds, but CCS is thwarted.

Fossil-fuel-based H_2 with CCS

***Carbon capture and storage**

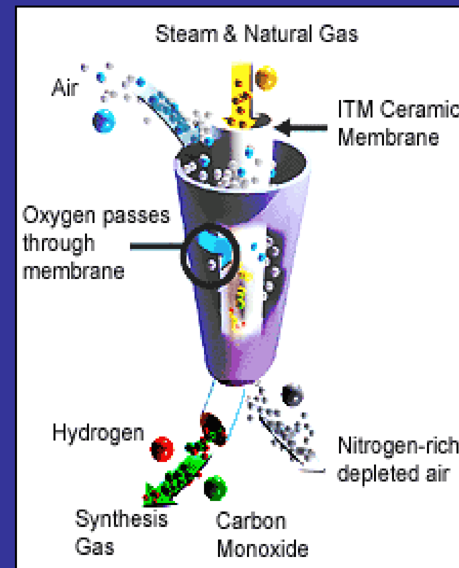
Effort needed for 1 wedge:

For both coal and natural gas, roughly the same flows as for a wedge of CCS electricity.

Today: ~40 Mt(H2)/yr produced from fossil fuels (almost all in refineries and for NH_3).

At these H_2 production sites ~0.1 GtC/yr vented as CO_2, often at high purity.

H_2 production is growing: a CCS opportunity.

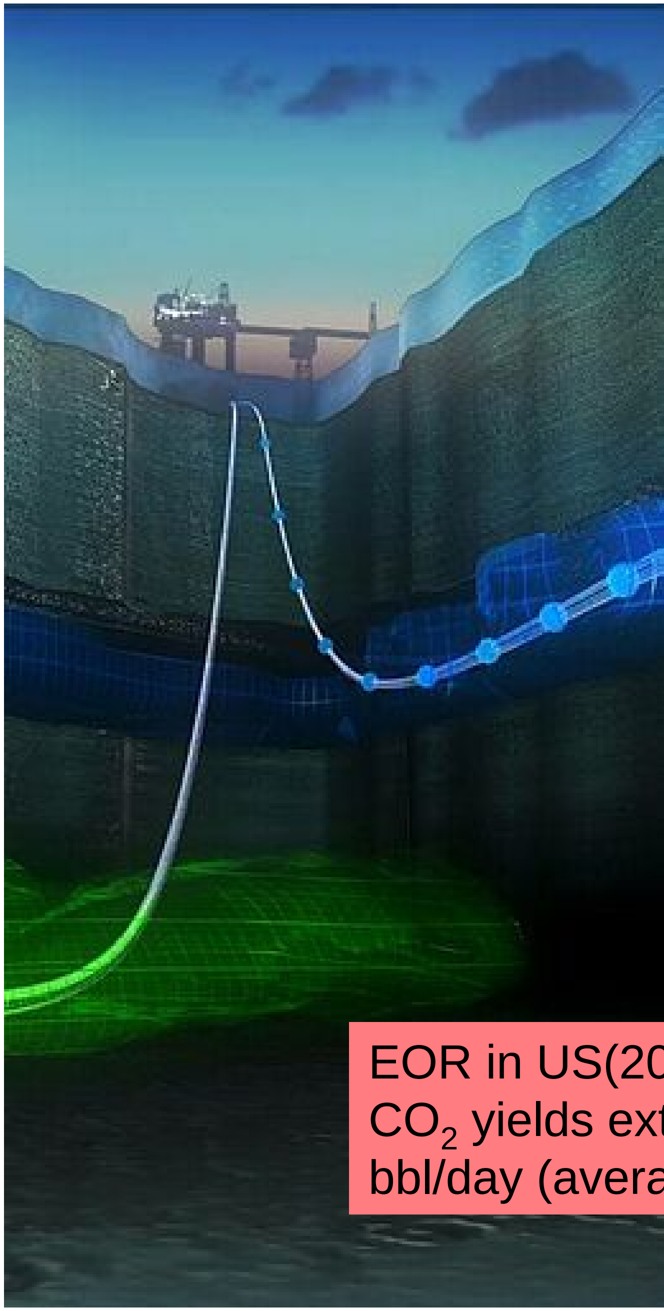


Potential Pitfalls:
H_2-infrastructure, H_2 safety

Second step, carbon storage, founders.

Graphics courtesy of DOE Office of Fossil Energy

Carbon storage



Graphic courtesy of Statoil ASA

Effort needed for 1 wedge:

70 Sleipner equivalents (1 Natuna equivalent) installed every year and maintained until 2054

A volumetric flow of supercritical CO_2 somewhat greater than the flow of oil today

Potential Pitfalls:
Public acceptance
Global and local CO_2 leakage

EOR in US(2001): 10 MtC/y as CO_2 yields extra 180,000 bbl/day (average: 7 bbl/tC).

Wind Hydrogen

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

Effort needed by 2054 for 1 wedge:

Displace gasoline or diesel in 2 billion 60 mpg hybrids, with 100 mpg H2 fuel cell cars, H_2 via 75% efficient electrolyzer (HHV).

Install 4,000,000 1 MW_{peak} windmills by 2054 –

twice as many windmills as for a wedge of wind electricity.

40,000 MW_{peak} in place today, rate of production growing 30%/yr

Potential Pitfalls:
NIMBY
Changes in regional climate?

Renewable H_2 vs renewable electricity

Renewable electricity (wind electricity, for example) can be used to back out carbon emissions in two ways. One can use renewable electricity:

1) to back out conventional coal-based electricity, or

2) to back out gasoline via the intermediate step of hydrogen production by electrolysis.

Displacing coal-based electricity with wind electricity provides carbon emissions reductions roughly twice as great as displacing gasoline with wind-produced hydrogen fuel. (The ratio depends on several assumptions.)

Thus, from a climate perspective, the optimal use of wind should be to provide electricity, as long as coal power (without carbon capture and storage) is still around.

Distributed H_2: One of three competing energy carriers

In a carbon-constrained world, H_2 is in many three-way competitions: with *electricity* and with *carbon-carrying secondary fuels* (gasoline and diesel, aviation fuels, distributed natural gas).

The outcomes of these competitions will depend on further competitions at the point of use:

engines *vs* fuel cells *vs* batteries for motive power

furnaces *vs* heat pumps *vs* electric resistive heating *vs* solar heating for space heating.

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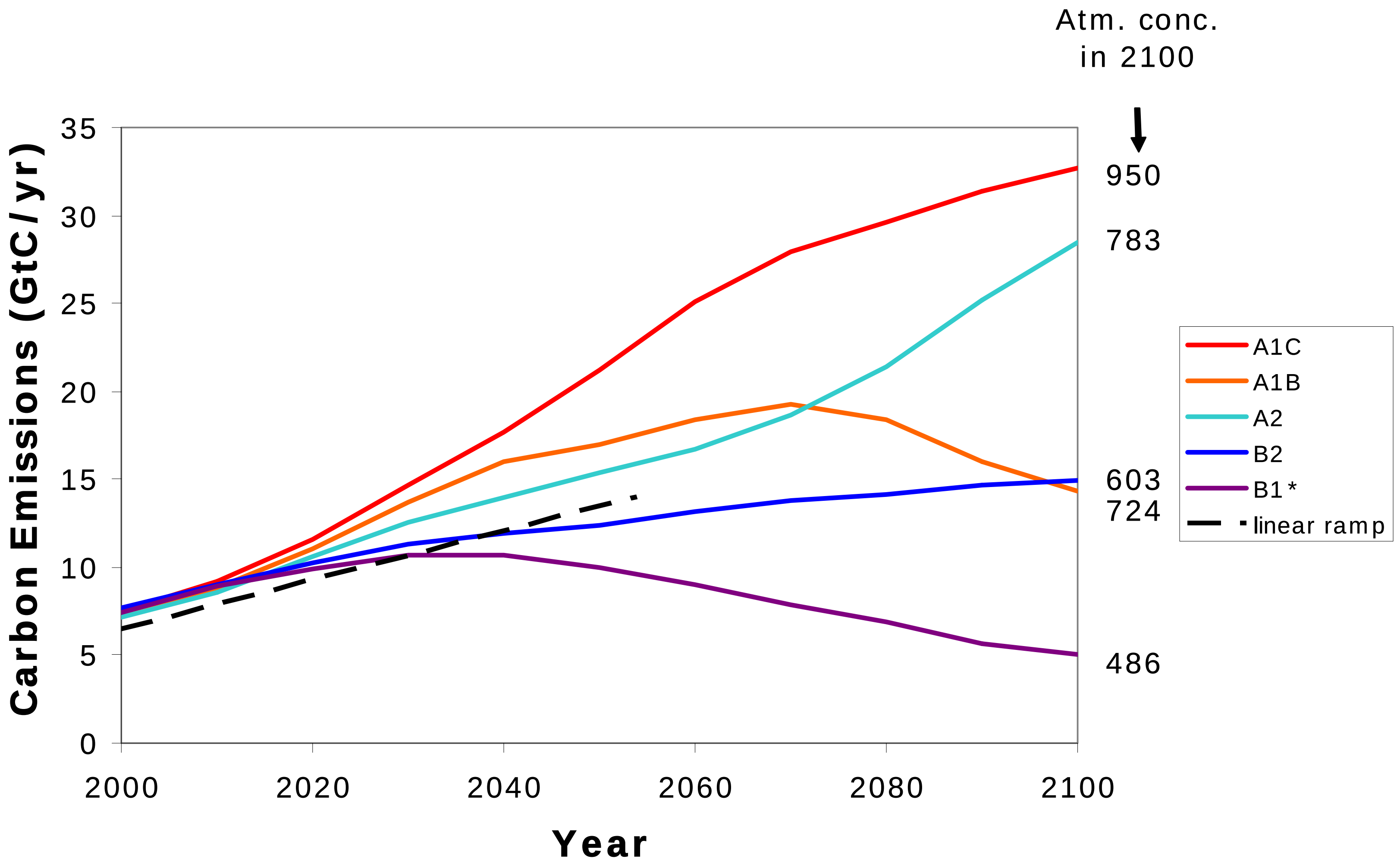
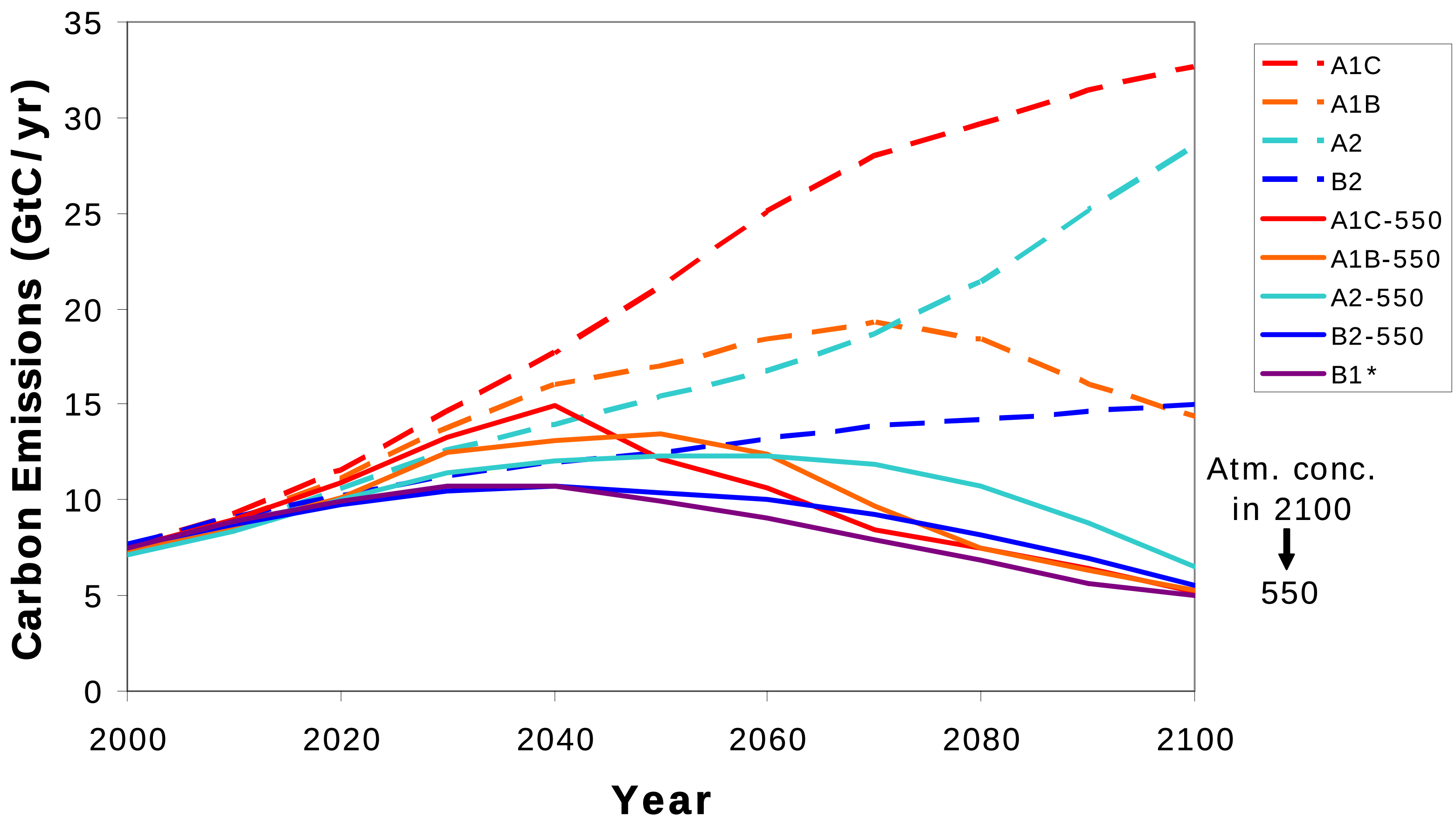
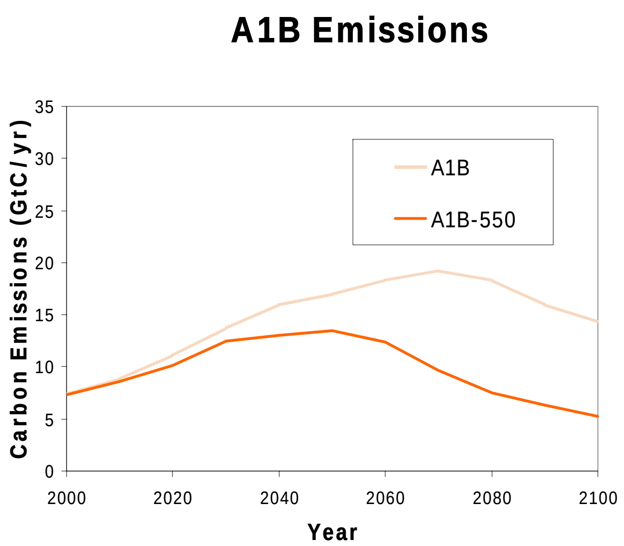
The SRES Scenarios

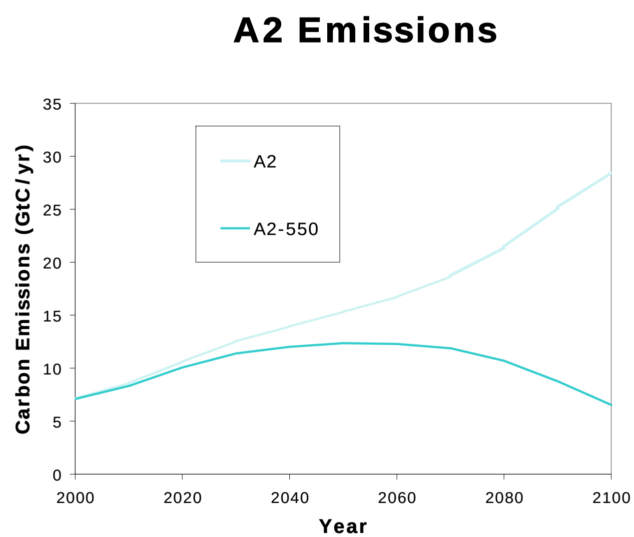


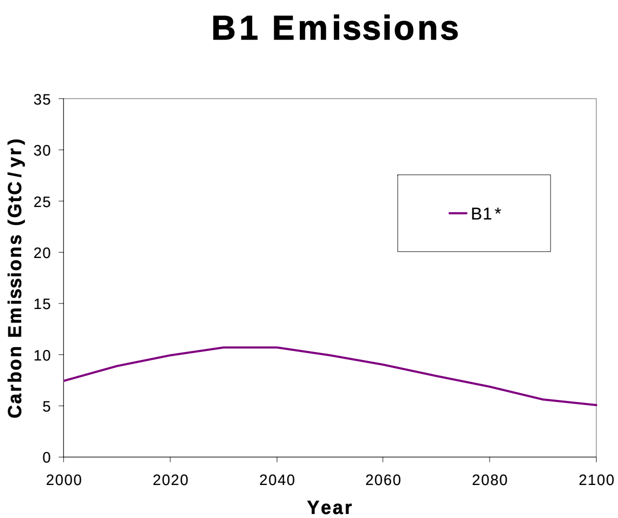
The post-SRES “550” scenarios

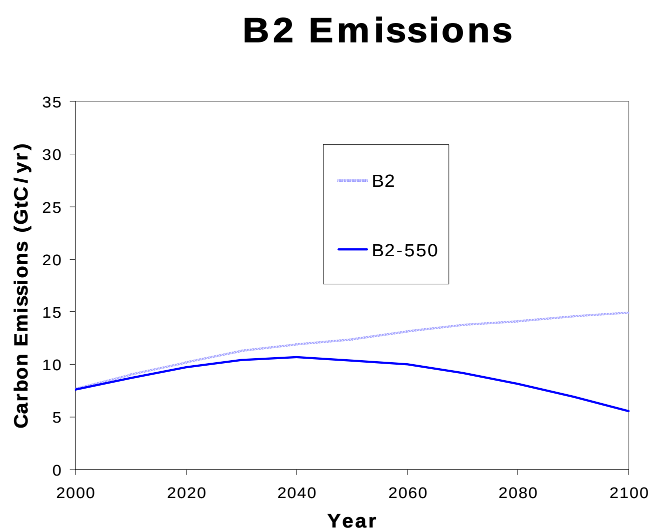


The SRES 550-Stabilization Triangles

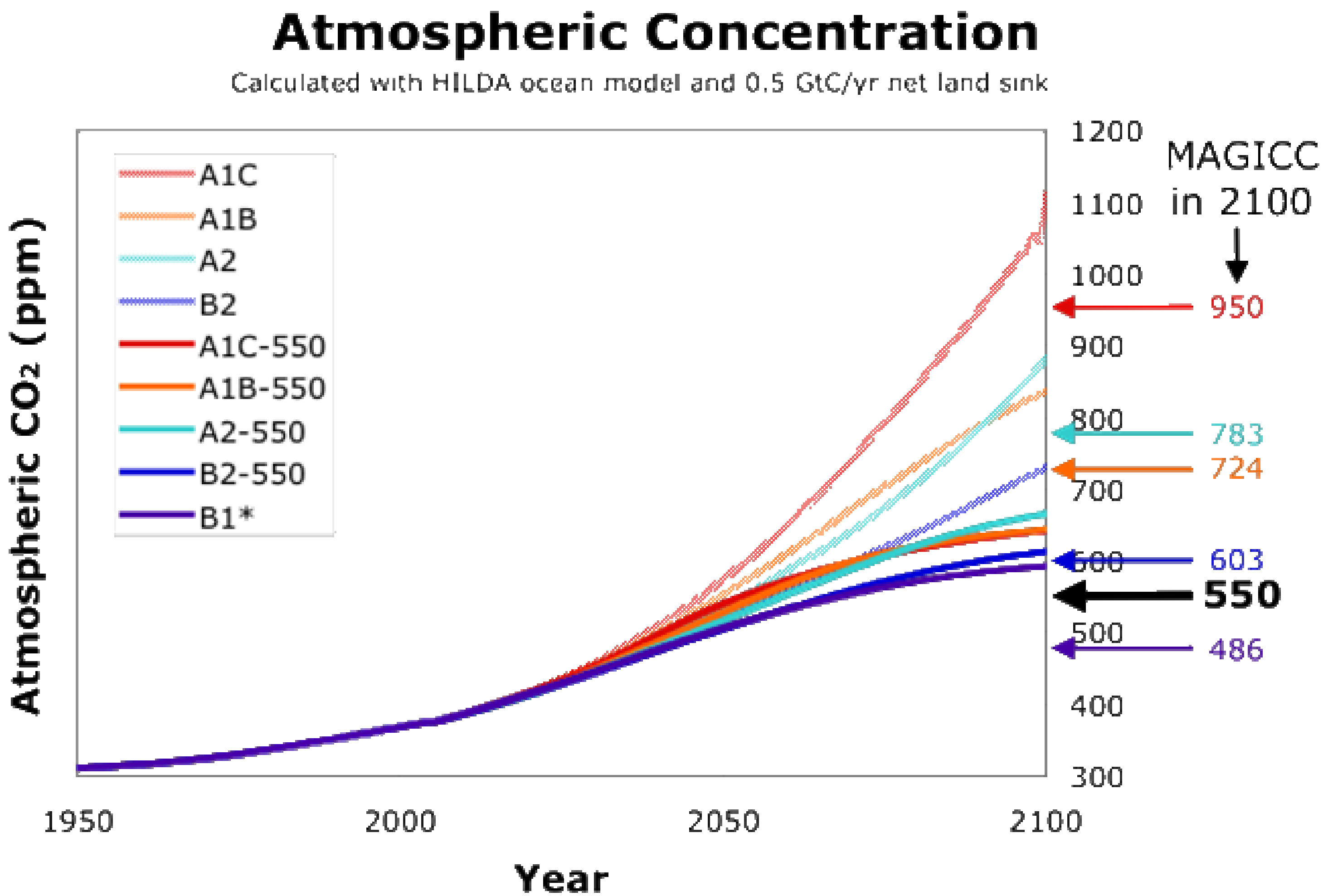








The Land and Ocean Sinks are Uncertain



The concentrations in 2100 are about 100 ppm higher with Princeton's weaker sinks than with Magicc's stronger sinks.

Virtual Wedges

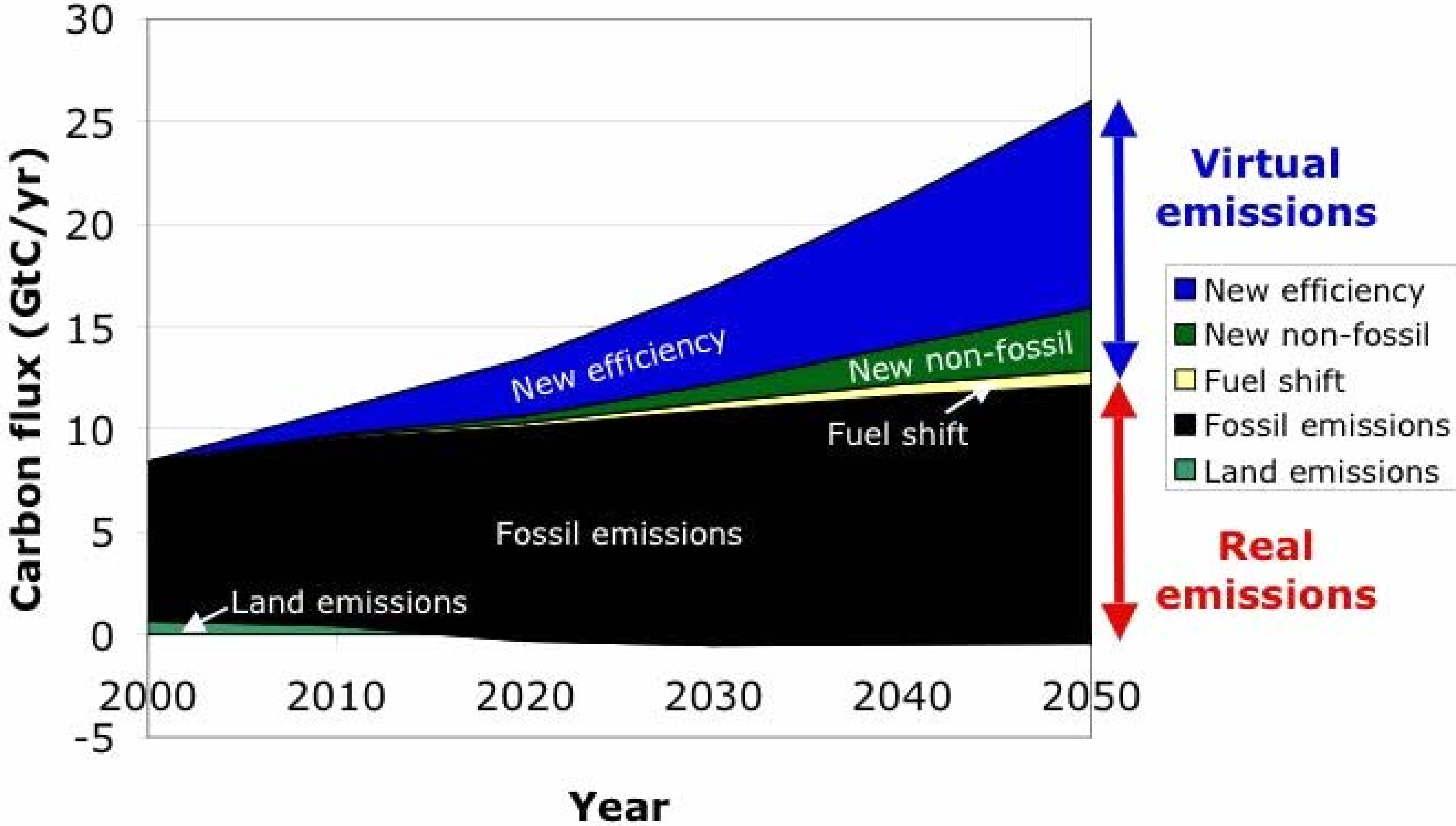
“Virtual wedges” are wedges of reductions in carbon emissions that occur in the absence of deliberate intervention.

“Real wedges” are reductions in carbon emissions that result only when interventions directed specifically at carbon emission reductions are introduced.

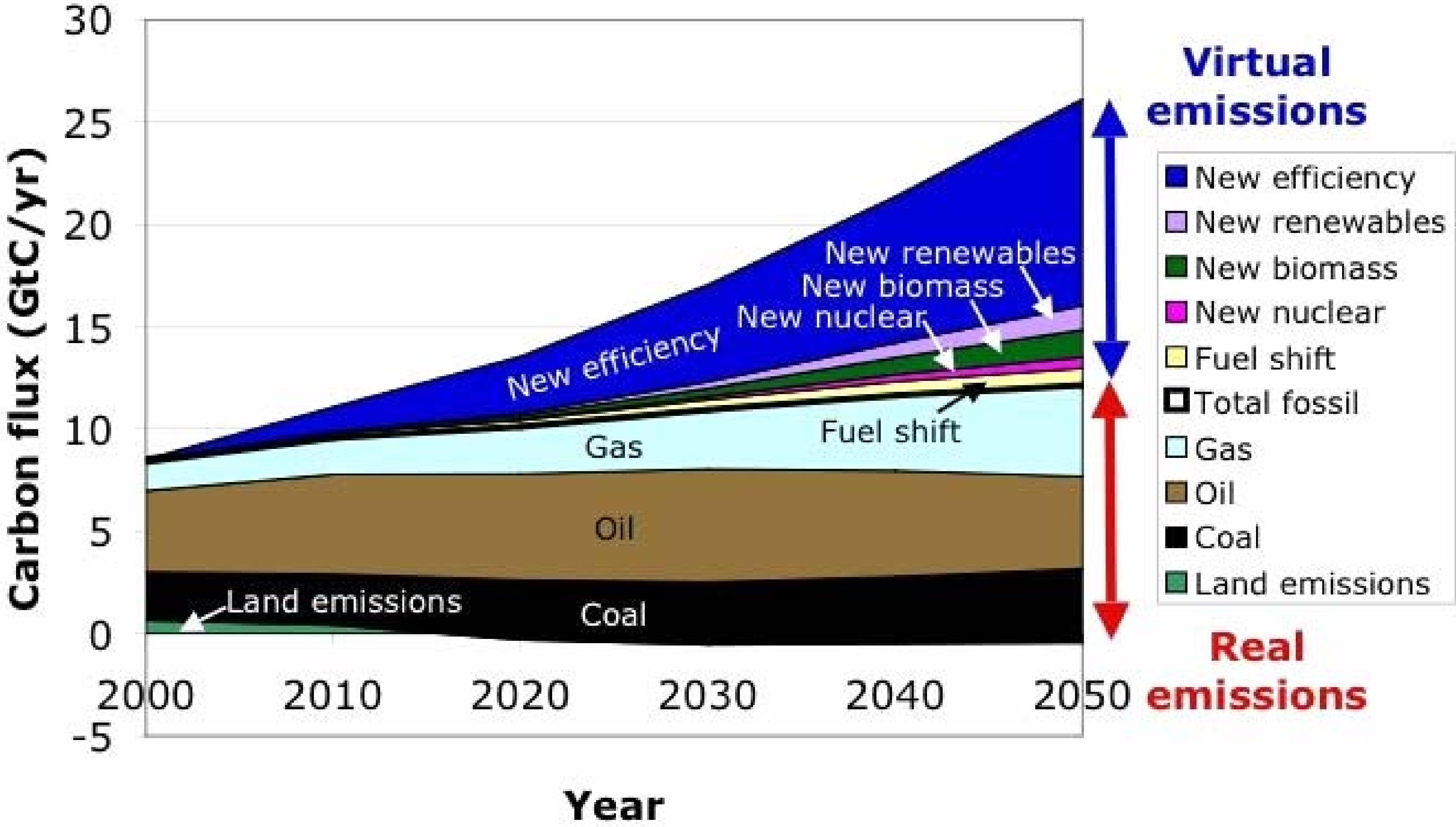
One way to imagine this distinction is to equate the absence of deliberate intervention with no carbon tax and its presence with a hefty carbon tax. Since there are many carbon-motivated policies other than carbon taxes, this is, of course, an oversimplification.

The history of the energy system leads one to expect a considerable number of virtual wedges from energy efficiency and decarbonization.

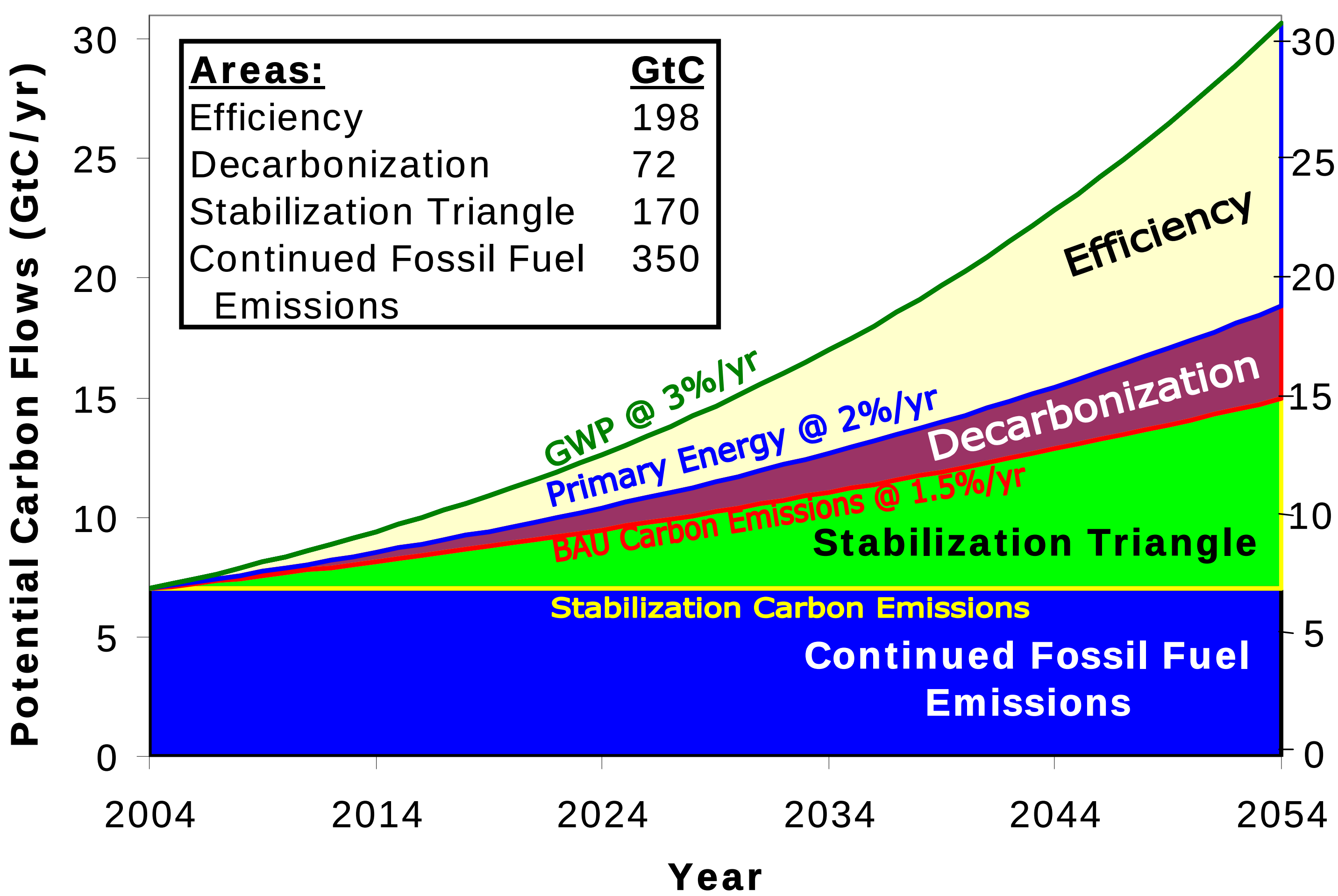
B2: Real and Virtual Emissions



B2: Real and Virtual Emissions



Carbon growth rates may be reduced by efficiency and decarbonization



All wedges are hard to make happen

Advocates of any one wedge should take a clear-eyed look at the difficulties inherent in cutting 1 billion tons of carbon emissions per year using that strategy.

- Deep patterns in the energy system limit the rate of introduction of energy efficiency.
- Land-use constraints limit the roles of renewable energy and natural sinks.
- Deep fear and distrust, as well as nuclear weapons proliferation, hobble nuclear power.
- The long record of resistance to pro-environment initiatives by the fossil fuel industries compromises their credibility.
- Aesthetic considerations limit the penetration of several renewable options, including wind and hydropower.

Evolutionary and Revolutionary Technology

My concern: Asserting, without qualification, that revolutionary technology is indispensable is almost guaranteed to generate a kind of paralysis. The general public and decision makers will decide to wait for the revolutionary technology before proceeding.

The Bush administration reads the message this way. (Secretary Abraham: “It will take a discovery like the discovery of electricity…,” May, 2004.)

If this is not the intended message, forceful writing with the contrary message is required. Hoffert’s note to Socolow, 11/3/04, has it right:

> *Revolutionary change in the technology of the global energy system [should not be used to] justify inaction on emission-reducing measures that can be implemented promptly.”*

My example of a useful revolutionary technology is commercially competitive fusion power in 2054. If the world does nothing explicit to affect carbon emissions in the next 50 years, fusion will arrive too late.

Making the case for more R&D

In the *Science* article, Pacala and I advocate vigorous R&D today to have new options for the period beyond 2054, when stabilization below doubling requires that global emissions drop to about half of current emissions in, presumably, a still richer world. There are many other good reasons:

We must understand the Earth better: cf., uncertainties about sinks

We must understand the scale-up of “solutions” better (solution science).

We must develop new end-use technologies: Well known examples are new materials for building shells, fuel cells, and H_2 storage.

The U.S. program in carbon capture and storage (CCS) is a good example of R&D launching an entirely new thrust in carbon management.

It seems to me that it will be much harder to secure the commitments that enable a greatly expanded R&D program for long-term carbon management in a world that is postponing direct engagement with carbon than in one that has engaged.

Consensus

A multiple-wedge approach to CO_2 policy will provide common ground and foster consensus on mitigation policy. Most advocates of particular wedges agree that:

- it is too early now to settle on just a few “winner” strategies,
- the relative attractiveness of strategies will differ from one region to another,
- environmental problems associated with scale-up ought to be investigated,
- subsidy of early stages is often merited,
- choices among mature alternatives should be determined mostly by market mechanisms.

Framing the climate problem as one requiring the parallel exploration of many stabilization wedges may help broaden the political consensus for early action.

Does humanity already have the tools to “solve” the global carbon problem for the next half century? We conclude: Yes.

- We formulate the challenge as one of halving the global CO2 emissions rate in 2050, relative to what would happen in a world with no interest in carbon management.
- The job is described in terms of parallel 50-year campaigns. Candidate strategies include energy efficiency, carbon capture and storage, fuel shifts among the fossil fuels, decarbonization of fuels, and decarbonization of electricity.
- Many of these strategies involve already commercialized technologies that can be scaled up.
- Although in no case is this scaling up easy to achieve or free of environmental and social costs, its achievement in a supportive policy environment is plausible.
- An excuse for inaction based on the world’s lack of technological readiness does not exist.