Stabilization Wedges: Mitigation Tools for the Next Half-Century

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ABSTRACT

We introduce the stabilization wedge as a useful unit for discussing climate stabilization. A wedge is 1 GtC/y of emissions savings in 2054, achieved by a single strategy that will not occur without deliberate attention to global carbon. Implementing seven wedges should place humanity, approximately, on a path to stabilizing the climate at a concentration less than double the pre-industrial concentration. We discuss wedges of energy efficiency, calling attention to the importance of avoiding investments in durable capital facilities, like power plants and apartment buildings, that are carbon-challenged. We explore wedges of capture and storage, nuclear energy, and renewable energy. The wedges framework highlights the importance of early involvement of the developing countries in mitigation activity. The wedges framework, therefore, may be able to contribute new elements to global carbon policy, related to differentiated responsibilities across countries, that promote internationally coordinated commercialization of low-carbon technology.

Stephen Pacala and I recently presented an extremely simple way of visualizing the mitigation required in the coming half century to set the world onto a path toward stabilization of the climate at a concentration less than double the pre-industrial concentration[1]. Our approach has four features:

1. *We focus on the next 50 years.* Interim targets at mid-century help divide the work among generations. A 50-year perspective is long enough to allow major changes in infrastructure and consumption patterns, but it is also short enough to be heavily influenced by decisions made today. It is a time frame, looking forward, with which many businesses are comfortable, and a time frame, looking backward, that is contained in a single human memory. It is the time-frame of a scientific career.

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[1] Pacala, S., and R. Socolow, 2004. "Stabilization wedges: Solving the climate problem for the next 50 years with current technologies." *Science* 305: 968-972. Many details are in the supporting online material.

2. *We approximate stabilization below doubling by a "flat trajectory": zero emissions growth (ZEG) for the next 50 years.* Achieving ZEG *(*a global CO_2-equivalent emissions rate in 2054 no larger than today's) delivers a far more tractable climate problem to later generations than if we postpone action for 50 years. The emission rate must fall in the second half of this century, descending to net zero emissions (emissions balanced by sinks) near the end of the century.

3. *We approximate Business As Usual (a world that pays no deliberate attention to global carbon) as a "ramp trajectory": linear growth leading to a doubling of global CO2-equivalent emissions by mid-century.* This approximation is at the center of many clouds of estimates. Thus, achieving stabilization below doubling requires, approximately, halving anticipated mid-centuries emissions. Restricting attention to fossil-fuel carbon, emissions today are 7 GtC/y and are heading for 14 GtC/y by mid-century. Between them, the flat trajectory and the ramp trajectory form the "stabilization triangle," as seen in the Figure. The interim ZEG target requires removing 7 GtC/y of emissions in 2054 by actions generated by deliberate attention to global carbon.

4. *We introduce the "wedge," as a useful unit for quantifying actions that reduce global carbon emissions.* A wedge is 1 GtC/y of emissions savings in 2054, achieved by a single strategy (*Y* displaces *X*) that will not occur without deliberate attention to global carbon. Assuming linear growth in emissions avoided, a wedge reduces emissions by 25 GtC over the half-century. Achieving ZEG requires creating, roughly, seven wedges.

There are, of course, major simplifications here. Scientific uncertainty shrouds our current understanding of carbon sinks; if carbon fertilization is a powerful effect, the land sink in 2054 could be about 3 GtC/y larger than if it is absent. Economic uncertainty shrouds the size of the future global economy and the extent to which specific wedge technologies will be adopted even in a world that has no focus on carbon. Political uncertainty shrouds the choice of stabilization target: the mid-century emissions target changes by about 2 Gt/y with a change of stabilization target by 50 ppm[2].

Accepting these uncertainties as essentially irreducible, the challenge of below-doubling stabilization reduces to an evaluation of potential wedges. Wedges come in many forms, ranging from improvements in efficiency for automobiles, appliances, and power plants, to greater shares in energy supply for nuclear energy, renewable energy, and carbon

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[2] It will be difficult to achieve stabilization below *tripling*, if the ramp trajectory is followed for the next 50 years. The same model of land and ocean sinks associates 1) 500 ppm stabilization with 50 years of the flat trajectory, followed by a 50-year descent to stabilization emissions, and 2) 850 ppm stabilization with 50 years of the ramp trajectory, followed 50 years of a flat trajectory at 14 GtC/y, followed by a 50-year descent to stabilization emissions. See R. Socolow, S. Pacala, and J. Greenblatt, "Wedges: Early Mitigation with Familiar Technology," *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies*, (GHGT-7), September 5-9, 2004, Vancouver, BC, Canada.

capture and storage, to enlargement of bio-carbon stocks through management of forests and soils. The wedge is a useful unit of action, because it permits quantitative discussion of cost, pace, risk, and trade-off. The *Science* paper has a Table, reproduced here (see final page), giving our estimates of the size of a wedge for 15 separate strategies. A wedge is two million one-megawatt windmills displacing coal power. A wedge is two billion personal vehicles achieving 60 miles per U.S. gallon (mpg) on the road instead of 30 mpg. A wedge is capturing and storing the carbon produced in 800 large modern coal plants.

The wedges listed in the Table involve technologies already deployed somewhere in the world at commercial scale. No fundamental breakthroughs are needed. However, every wedge is hard to accomplish, because huge scale-up is required, and scale-up introduces environmental and social problems not present at limited scale. (See the right hand column of the Table.) The wedge concept decomposes a heroic challenge – filling the stabilization triangle – into a limited set of monumental tasks. But an excuse for inaction based on the world's lack of technological readiness does not exist. As we write in our *Science* article: "Humanity can solve the carbon and climate problem in the first half of this century simply by scaling up what we already know how to do."

The Table shows the extent of scale-up for many of the wedges. Since there are already the equivalent of 40 thousand one-million windmills deployed globally, for example, a wedge from wind displacing coal for power requires a factor-of-50 increase. In some cases, more than one wedge may be achievable from a single strategy. In other cases, scale-up to even a single wedge may press against saturation limits: the amount of additional carbon that can be stored in soil may not be much more than one wedge, for example.

When it comes to carbon mitigation, a portfolio of strategies is required. There is no silver bullet. No single strategy can do even half the job of achieving ZEG. The list of candidates for the portfolio is sufficiently long, however, that not every strategy is needed.

A carbon-efficient global economy[3]

To achieve a carbon-efficient world, one with half the carbon emissions at mid-century now expected, requires attention to carbon flows throughout the global economy. One must confront both end-use energy consumption and energy production, all economic sectors (buildings, vehicles, factories, and farms), and economies at all levels of development. There is reason for guarded optimism that such dramatic reductions in carbon emissions are achievable: the world today has a terribly inefficient energy system, and carbon emissions today still have zero economic cost.

[3] Some of the discussion in this and later sections of this paper, including some specific language, is taken from "Solving the Climate Problem: Technologies Available to Curb CO_2 Emissions," Robert Socolow, Roberta Hotinski, Jeffery B. Greenblatt, and Stephen Pacala, *Environment*, Vol. 46, No. 10, pp. 8-19. December 2004.

Of particular concern is the turnover of physical capital. Although many of today's additions to the world's current carbon-consuming physical capital, like our new vehicle engines, have a lifetime of a decade or two, many other additions lock in carbon demand half a century from now. The new capital that will function for a half-century or more comes in all sizes: from the gas turbine or steam turbine in a power plant, to the window and furnace in an apartment building or private home. Retrofitting such physical capital after construction is generally far more costly than making the item energy-efficient in the first place. To achieve dramatic reductions in carbon emissions over the next half century, one must be vigilant about today's long-lived capital investments.

This argument for vigilance regarding new capital investments is not well appreciated. Among carbon policy analysts, there are more frequent arguments for delay than prompt action. Arguments for delay are based in an understandable concern for avoiding the costs of premature retirement of existing capital stock. But these arguments are not adequately tempered with concern for the creation of carbon-inappropriate new stock. This concern argues for the urgency of action.

One sign of this unbalanced attention to the demography of the capital stock is inadequate attention to the carbon consequences of capital formation in developing countries. At present, much of the world's addition to its capital stock (its new power plants, steel mills, and apartment buildings, for example) is taking place in the developing countries, and this is expected to remain true throughout the next 50 years. Accordingly, it makes little sense to divide the world into 1) Annex I countries whose assignment is to mitigate, and 2) non-Annex I countries whose relationship to the carbon problem is to suffer impacts and be compensated for them. Both the industrialized and the developing countries need to see mitigation in developing countries as very much in their own self-interest.

From such a perspective, the concept of "leapfrogging" rises to prominence. Leapfrogging describes the introduction of advanced technology in developing countries ahead of its introduction in industrialized countries. Today, little is done to encourage a developing country to introduce low-carbon technology, like advanced coal technology, before it is extensively tested in industrialized countries. Yet, by going first, the developing country will build fewer facilities that become a liability when a price is later put on CO_2 emissions. Leapfrogging is a path to globally coordinated learning about the potential of new carbon-responsive technology.

Carbon capture and storage

In the Figure, fossil fuels hardly disappear in 2054. Carbon emissions from fossil fuel use are as large in 2054 as today. Moreover, the Figure is consistent with the extraction from the earth of even greater amounts of carbon in 2054 than today. The rate of extraction of carbon in fossil fuels from the earth may grow, even though CO_2 emissions to the atmosphere stay constant, if some of the CO_2 released as energy is produced is prevented from reaching the atmosphere.

Interfering with CO_2 emission in this way requires a two-step process known as "carbon capture and storage." The first step, carbon capture, typically creates a pure, concentrated stream of CO_2, separated from the other products of combustion. The second step, carbon storage, sends the concentrated CO_2 to a destination other than the atmosphere.

Opportunities for CO_2 capture are abundant. The natural gas industry routinely generates capturable streams of CO_2 when natural gas, after coming out of the ground, is scrubbed of CO_2 before shipment by pipeline or tanker. Refineries making hydrogen for internal use are generating, as a byproduct, capturable streams of CO_2. Capturable streams of CO_2 will also be generated where technologies are deployed to convert coal or natural gas into hydrogen or synthetic hydrocarbon fuels. In a world focused on CO_2, all of these streams are candidates for capture, instead of venting to the atmosphere.

The most promising storage idea is "geological storage," where the CO_2 is placed in deep sedimentary formations. (Alternate carbon storage ideas include storage of CO_2 deep in the ocean and storage of carbon in solid form as carbonates.) Carbon capture and storage has the potential to be implemented wherever there are large point sources of CO_2, such as at power plants and refineries. The storage space available below ground is probably large enough to make carbon capture and storage a compelling carbon mitigation option.

In all situations where CO_2 capture and storage is under consideration, there may be opportunities to "co-capture and co-store" other pollutants, like sulfur, with the CO_2. With co-capture, the costs of above-ground pollution control will be reduced, and perhaps total pollution control costs and total environmental emissions as well.

Non-carbon energy supply

Non-carbon energy supply comes in two principal varieties: nuclear energy and renewable energy. Both, in principle, can produce wedges of electricity by backing out coal electricity and wedges of fuel by backing out hydrocarbon fuels used directly. An example of the latter is the production of electrolytic hydrogen and its use in vehicles. However, it turns out that the same non-carbon electricity can save about twice as much carbon when used to displace coal-based electricity than when used to produce hydrogen that displaces gasoline[4]. A wedge of wind power can be either two million one-megawatt windmills backing out efficient coal power plants or four million one-megawatt windmills making hydrogen for cars and backing out efficient gasoline cars. Thus, from a climate perspective, in most parts of the world, the optimal use of nuclear energy, hydro-energy (falling water), wind or wave energy, solar thermal energy, geothermal energy, and photovoltaic energy, will be to provide electricity, as long as coal power (without carbon capture and storage) is still around. There will, of course, be special situations, such as Iceland, where the case for electrolytic hydrogen as a carbon emission reduction strategy may be compelling.

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[4] The factor of two here, of course, depends on several assumptions. See the supporting online material for Pacala and Socolow, *op. cit*.

A wedge of nuclear power is its displacement of 700 modern, large (1 million kilowatt) coal plants. Today's stock of nuclear power plants is about half this large. Thus, if, over the next 50 years, today's global fleet of nuclear power plants were to be phased out in favor of modern coal plants, about half a wedge of additional CO_2 emissions reductions would be required to compensate. This half-wedge would not be required if current nuclear reactors were replaced with new ones, one-for-one.

Policy

Do the wedges have policy relevance? Can ideas based on wedges supplement the targets, trading, international assistance mechanisms, and other already identified elements of global carbon management? The wedges encourage thinking about multiple parallel campaigns. Perhaps the Framework Convention's call for differentiated responsibilities across countries can be met in part by differentiated assignments for the commercialization of wedge technologies. In particular, wedge-based global carbon policy could reapportion some of the initiative in global carbon agreements in favor of a greater early role for developing countries. For example, a developing country already investing heavily in new capital stock could assume responsibility for commercializing the first stages of certain specific wedges. Compensation for first movers would be a collective responsibility.

Although champions of particular wedges are often unenthusiastic about other wedges, there is actually much common ground. Advocates of particular wedges, for example, might all agree on the following six principles:

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.

Each specific wedge has benefits beyond its effect on climate. Rural development is positively affected by harnessing renewable energy, for example. Co-benefits may be crucial in eliciting the collaborations and coalitions necessary to achieve agreement on early action.

A world transformed by deliberate attention to carbon

If those alive today bring about the dramatic changes that appear to be our assignment for the next 50 years, the world will be so transformed that the options for the following 50 years will be myriad. Institutions for carbon management that reliably communicate the price of carbon will have become well entrenched. If wedges of nuclear power are achieved, strong international enforcement mechanisms to control nuclear proliferation will have emerged. If wedges of carbon capture and storage are achieved, a well-accepted permitting regime will have been created, governing the conversion of coal, oil sands, and, perhaps, methane clathrates to electricity and fuels. If wedges of renewable energy and carbon sink management are achieved, land use will have been transformed. If hydrogen is widely used at small scale, in buildings and vehicles, ways to handle hydrogen safely will have been devised and the chicken-and-egg-like problems of establishing a hydrogen infrastructure will have been solved. If energy efficiency gains are large, urban space will have been used in new ways, and advanced technologies for buildings and vehicles will have been widely deployed. A planetary consciousness will be much more widespread.

Not an unhappy prospect!

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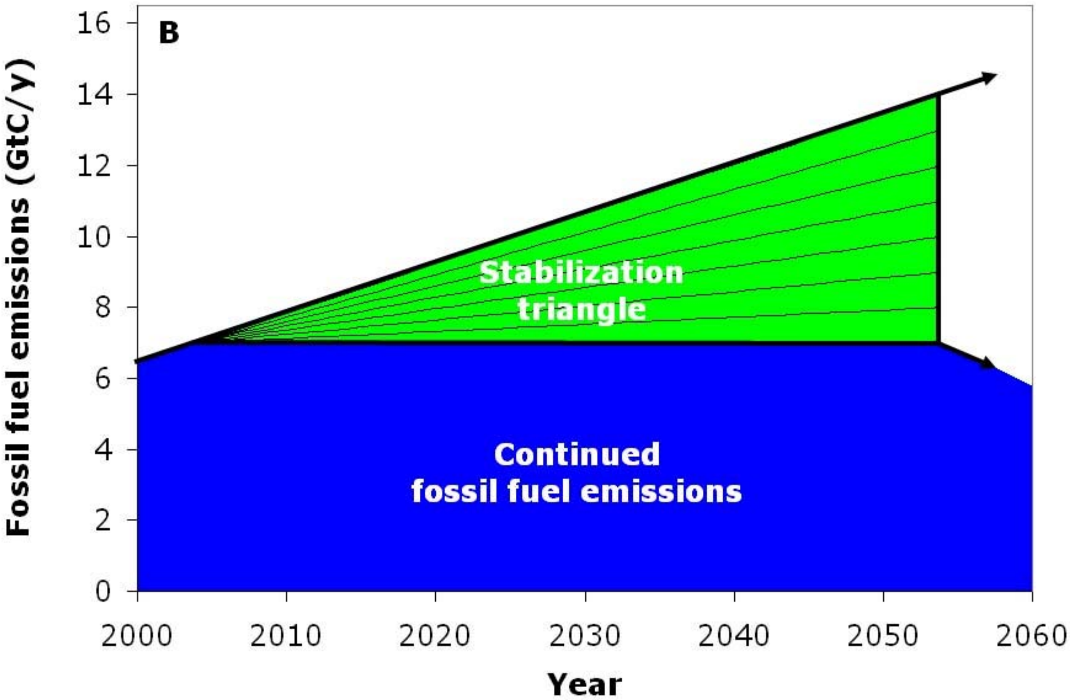

Figure: The “stabilization triangle” is an idealization of the first 50 years of action required to achieve stabilization of the atmospheric CO_2 concentration below double the pre-industrial concentration. The triangle is bounded by 1) the Year 2054; 2) a “flat trajectory” of constant global carbon emissions at the current rate of 7 GtC/y, intended to approximate the first 50 years of a 500 ppm stabilization trajectory; and 3) a “ramp trajectory,” where emissions climb linearly to twice current rates, intended to approximate Business As Usual, i.e., a world inattentive to global carbon. The stabilization triangle is divided into seven “wedges” of avoided emissions, each of which grows linearly from zero today to 1 GtC/y in 2054.

Table 1. Potential wedges: Strategies available to reduce the carbon emission rate in 2054 by 1 GtC/year, or to reduce carbon emissions from 2004 to 2054 by 25 GtC.

	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
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" 30×10^6 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 2×10^6 ha	PV production cost
	12. Wind H_2 in fuel-cell car for gasoline in hybrid	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 $\times 10^6$ 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