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Stabilisation Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies

The Cambridge-MIT Institute

UNIVERSITY OF CAMBRIDGE

Based on a paper by S Pascala and R Socolow and a presentation made by Roberta Hotinski, Princeton Environmental Institute “Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies” Science 13 August 2004 vol 305, no. 5686, pp 968-972

The methodology presented here, provides a way of estimating how useful current technologies are likely to be in helping to stabilise the CO2 emissions leading to climate change. A number of quantitative estimations are presented based on current data. Although primarily focusing on technological solutions, many of these have associated social and economic effects which can also be discussed.

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Supporting on-line material at:

www.sciencemag.org/cgi/content/full/305/5686/968/

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Targets for CO_2 emissions

- Proposals to limit atmospheric CO_2 to a concentration that would prevent most damaging climate change have focused on a goal of 500 +/- 50 parts per million (ppm)
- This is less than double the pre-industrial concentration of 280 ppm.
- The current CO_2 concentration is 375 ppm.

Sources of Information:

- R. T. Watson et al., *"Climate Change 2001: Synthesis Report. Contribution to the Third Assessment Report of the Intergovernmental Panel on Climate Change"*, Cambridge Univ. Press, Cambridge, UK, 2001.
- B. C. O'Neill, M. Oppenheimer, *"Dangerous Climate Impacts and the Kyoto Protocol"* Science, June 2002, Vol **296**, No. 5575, pp 1971–1972
- Royal Commission on Environmental Pollution, *"Energy: The Changing Climate"* (2000); available on-line at RCEP
- Environmental Defense, *"Adequacy of Commitments - Avoiding "Dangerous" Climate Change: A Narrow Time Window for Reductions and a Steep Price for Delay"*, (2002); available on-line at Environmental Defense
- "Climate Options for the Long Term (COOL) synthesis report," NRP Rep. 954281 (2002); available on-line

Stabilization Wedges

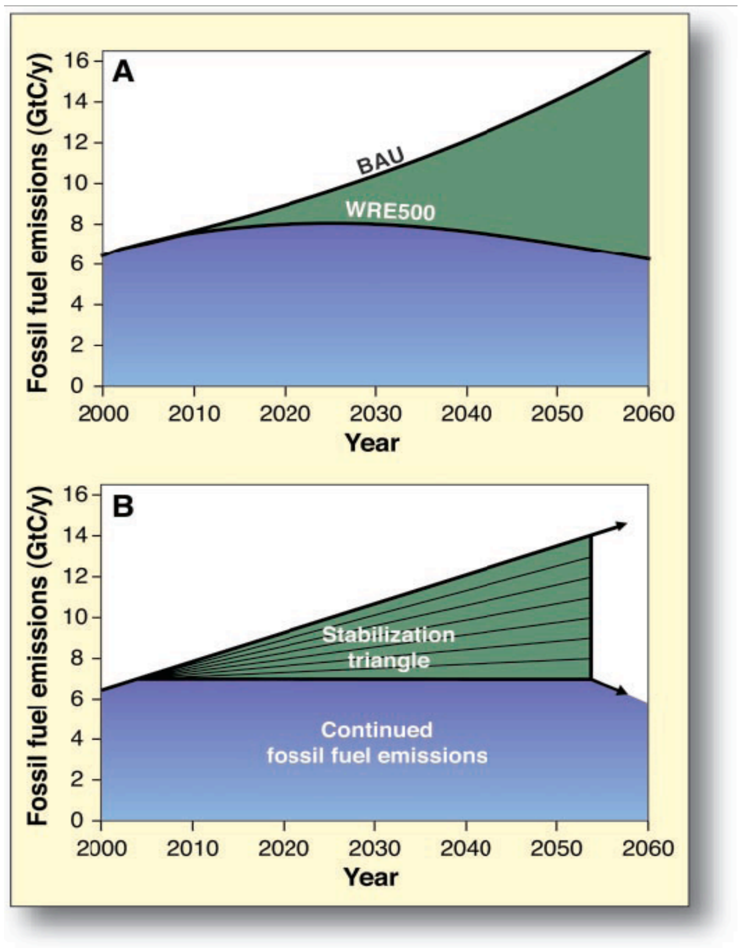
- Technologies that could be implemented to stabilise atmospheric carbon dioxide emissions within the next 50 years already exist.
- A stabilisation wedge, the focus of this presentation, represents an activity that starts at zero reduction of emissions in 2005 and increases linearly until it accounts for 1 GtC/year of reduced carbon emissions in 2055.
- Each wedge thus represents a cumulative total of 25GtC of reduced emissions over 50 years.

Notes

- The next 50 years is a sensible horizon from several perspectives: It is the length of a career, the lifetime of a power plant, and an interval for which the technology is close enough to envision.
- CO_2 emissions in 2005 have been estimated at around 7 GtC/year and are projected to increase by around 1.5%/year. Using a straight line ramp trajectory, this would give an emissions rate of around 14GtC/year in 2054, with cumulative emissions of 525GtC[1]
- A growth in carbon emissions of 1.5%/year is bracketed by the emissions forecasts of the International Energy Agency and U.S. Department of Energy, and it is similar to the mean and median of the 40 IPCC SRES future emissions scenarios over the next fifty years[1,2,3,4,5]

1. International Energy Agency, 2003. Key World Energy Statistics, 2003. Available on-line
2. Energy Information Administration, 2003. Available on-line
3. IPCC Climate Change 2001: The Scientific Basis. Available on-line
4. BP, 2003. BP Statistical Review of World Energy. Available on-line
5. IPCC, 2001, Special Report on Emissions Scenarios. Available on-line

Stabilisation Wedges



- The emissions reduction required is represented by a perfect triangle located between the flat trajectory of current fossil fuel emissions at 7 GtC/year and the 'business as usual' (BAU) trajectory ramping up to 14GtC / year in 2055

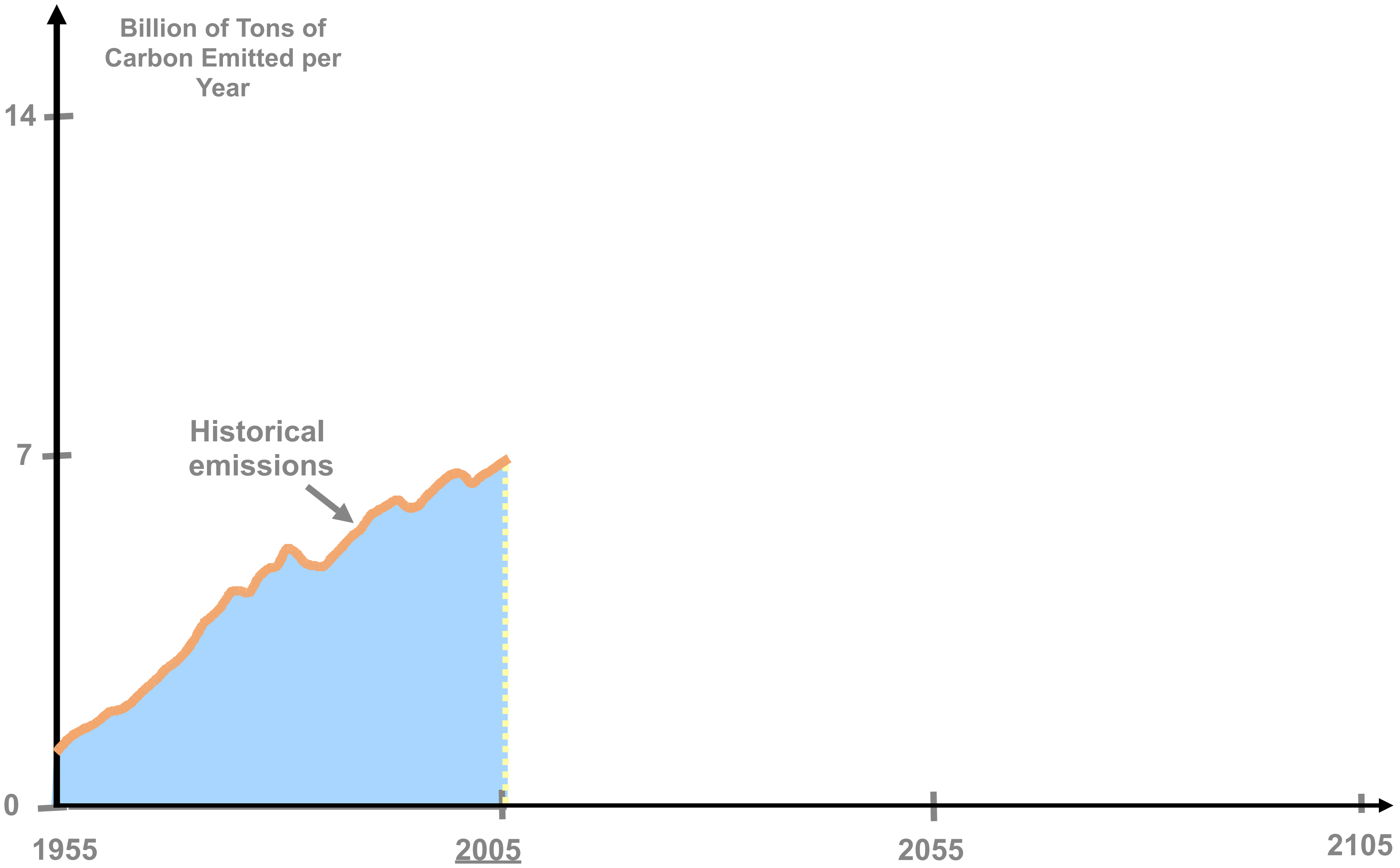
Notes

The calculations behind Fig. A are explained in Section 1 of the supporting online material (SOM) text.
The Business As Usual (BAU) and stabilization emissions in Fig. A are near the center of the cloud of variation in the large published literature.
(A) The top curve is a representative 'Business as Usual' emissions path for global carbon emissions as CO_2 from fossil fuel combustion and cement manufacture: 1.5% per year growth starting from 7.0 GtC/year in 2005. The bottom curve is a CO_2 emissions path consistent with atmospheric CO_2 stabilization at 500 ppm by 2125 akin to the Wigley, Richels, and Edmonds (WRE) family of stabilization curves described in T. M. L. Wigley in The Carbon Cycle[1]. The area between the two curves represents the avoided carbon emissions required for stabilization at around 500ppm, which is a currently recognised goal.

(B) Idealization of (A): A stabilization triangle of avoided emissions (green) and allowed emissions (blue). The allowed emissions are fixed at 7 GtC/year beginning in 2005. The stabilization triangle is divided into seven wedges, each of which reaches 1 GtC/year in 2055. With linear growth, the total avoided emissions per wedge is 25 GtC, and the total area of the stabilization triangle is 175 GtC. The arrow at the bottom right of the stabilization triangle points downward to emphasize that fossil fuel emissions must decline substantially below 7 GtC/year after 2055 to achieve stabilization at 500 ppm.

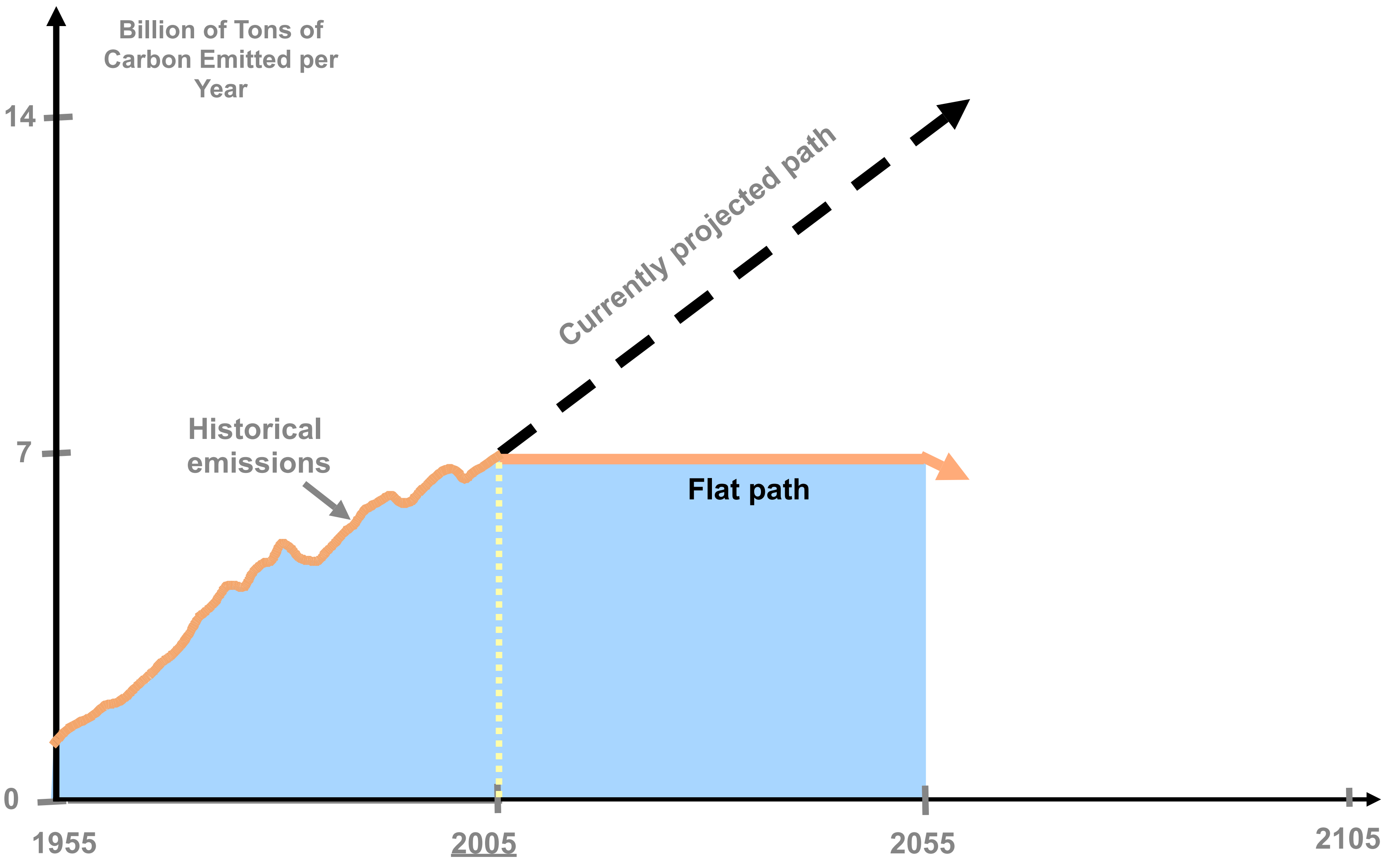
1. Wigley, T. M. L. and Schimel, D. S., Eds.*"The Carbon Cycle"*, Cambridge Univ. Press, Cambridge, 2000 , pp. 258-276.

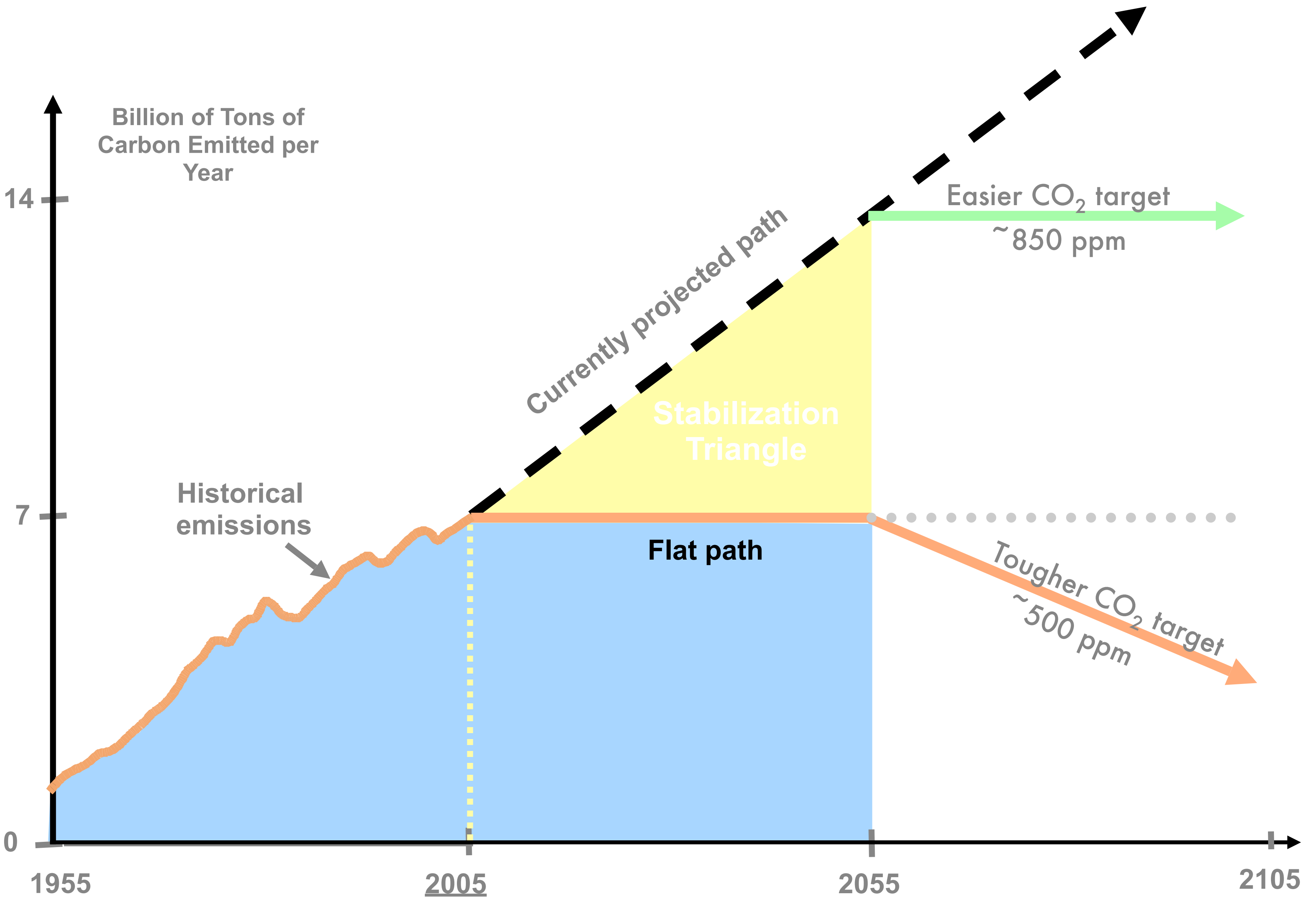
The Stabilization Wedge – Two Scenarios



Notes

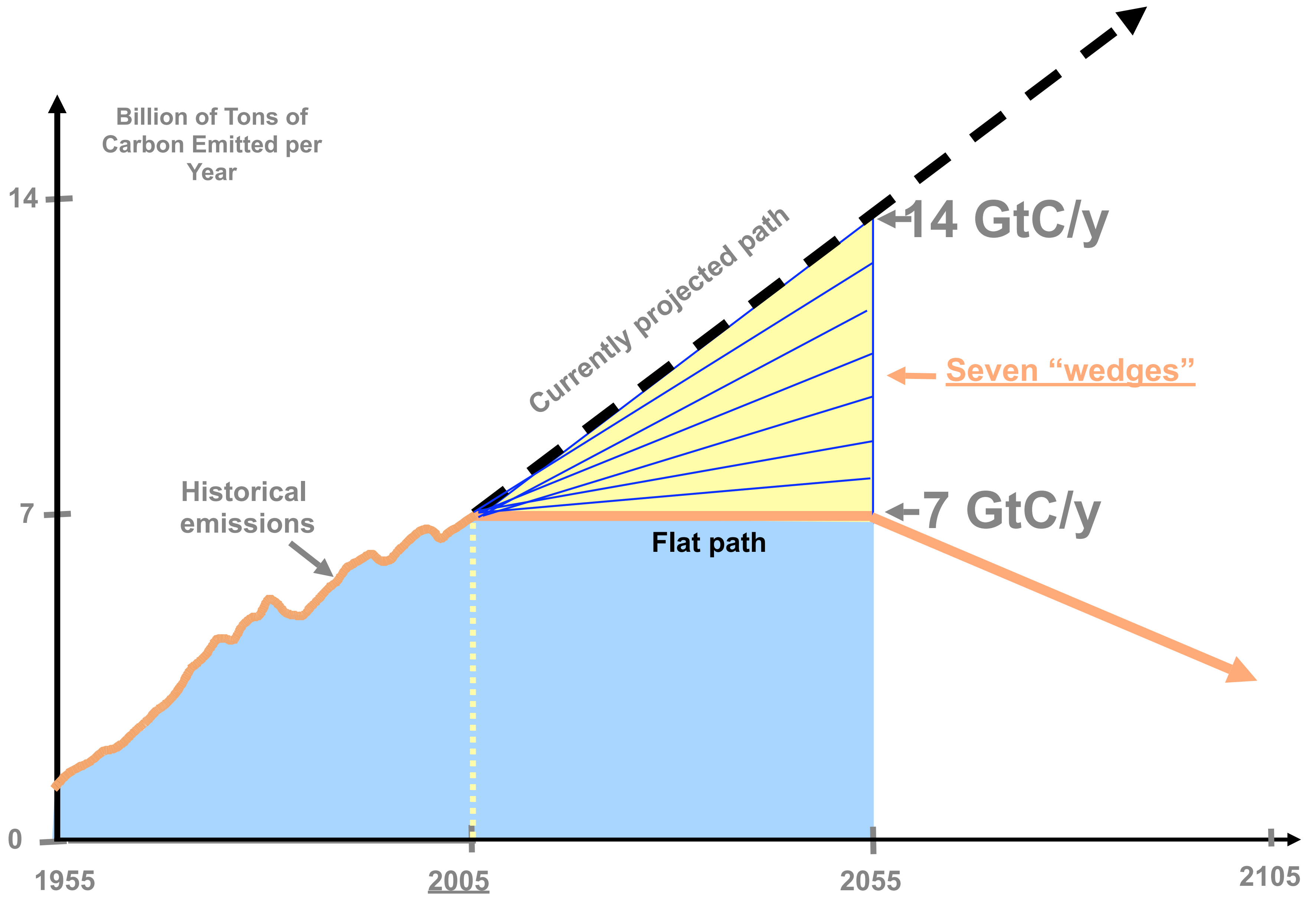
The next 4 slides build up a diagram showing how stabilisation wedges are arrived at. Animation is included in the PowerPoint and Keynote version for the slide show.


Billion of Tons of Carbon Emitted per Year
14
7
0
Currently projected path
Historical emissions
Flat path
1955
2005
2055
2105



Notes

- The flat path keeps us on track to stabilize at less than a doubling of pre-industrial CO_2 if further cuts are made post-2055. The emissions reduction required is represented by a perfect triangle located between the flat trajectory of current fossil fuel emissions at 7 GtC/year and the business as usual trajectory ramping up to 14GtC / year in 2055. If we wait another 50 years (green line), cutting seven wedges only puts us on a path toward tripling current CO_2 emissions.



Notes

- The stabilisation triangle is divided into seven wedges. Each 'wedge' represents an activity that reduces emissions to the atmosphere. Each activity starts at zero today and increases linearly until it accounts for 1 GtC/year of reduced carbon emissions in 50 years. Not filling the stabilisation wedge will put the 500ppm stabilisation out of reach.
- For example, in one simple model that begins with the stabilization triangle but looks beyond 2005, 500-ppm stabilization is achieved by 50 years of flat emissions, followed by a linear decline of about two-thirds in the following 50 years, and a very slow decline thereafter that matches the declining ocean sink. There will be an ocean sink of 2 GtC/y for centuries, as deep water finds its way to the surface. Having last seen the surface centuries before, it has a CO_2 concentration in equilibrium with the old atmosphere, not the new one, and is thus able to pick up CO_2 when it meets the new atmosphere.
- Another way to look at this is that stabilization (say at 500 ppm) is still a recipe for further acidification of the ocean for centuries. The goal chosen at Rio (stabilization) may not be the one we ultimately choose.
- To develop the revolutionary technologies required for such large emissions reductions in the second half of the century, enhanced research and development would have to begin immediately.

Business as Usual?

- If the 'business as usual' option is taken for the next 50 years before flat growth is achieved, then this will result in a tripling of the pre-industrialisation concentration of green house gases.

Notes

- The 'business as usual' projection reflects a continuation of the 1.5% annual carbon emissions growth of the last 30 years. If carbon emissions grow at a faster rate, then more wedges will be needed for stabilisation. e.g. for a growth rate of 2%, 10 wedges will be needed.

Current technology options to provide a wedge

- Improve fuel economy
- Reduce reliance on cars
- More efficient buildings
- Improved power plant efficiency
- Decarbonisation of Electricity and Fuels
- Substitution of Natural gas for coal
- Carbon capture and storage
- Nuclear fission
- Wind electricity
- Photovoltaic electricity
- Biofuels

Notes

- A wedge is a cumulative total of 25GtC of reduced emissions over the next 50 years.
- Some suggestions, using currently available technology are provided here, but the list is by no means exhaustive.
- Full details of all the assumptions made are given in the Science Paper[1] and the supporting on-line materials.

1. Pascala, S. and Socolow, R. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies", Science, 13 August 2004, Vol. 305, No. 5686, pp 968-972

Natural Sinks

- Forest Management
- Agricultural Soils Management

Notes

- These two options are already at large scale, and could be scaled up to provide a wedge or more without a great deal of new research.

Stabilization Wedges

- The slides that follow suggest a number of ways in which current technologies might be employed to save 'one wedge' of CO_2 emissions over the next 50 years
- One wedge provides a cumulative total of 25GtC of reduced emissions.
- A total of seven are required to stabilise emissions at 500ppm CO_2 in fifty years

Notes

- There is no body that has "recognized" any safe limit. The value of 500 may be the toughest standard still within reach and able to bring about coalitions for action, but there are many scientists who would prefer us to stop at 450.
- By not filling the stabilisation wedge, the 500 ppm stabilisation will be out of reach.

Improve fuel economy

- Increase fuel economy for 2 billion cars from 30 to 60 mpg
- A typical car emits a ton of carbon into the air each year
- If a fuel efficiency of 60 mpg was achieved, decarbonisation of the fuel would offer the potential of saving two wedges

Double the fuel efficiency of the world's cars or halve miles traveled

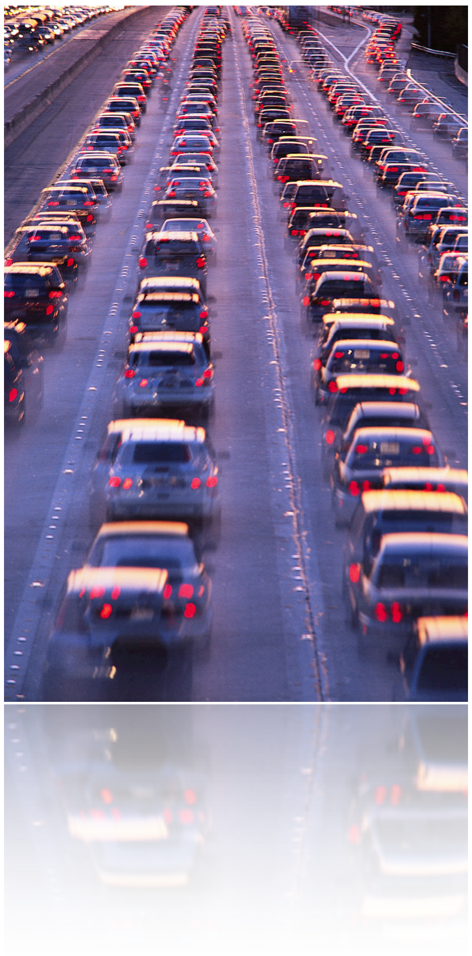
Notes

- US Energy Information Agency gives figures of 530 million cars in 1999. Growth rate is taken as 2.4% per year, giving 2 billion cars in 2054. A light-duty vehicle ("car") consumes 330 gallons of gasoline per year if it goes 10,000 miles with a fuel economy of 30 mpg. Transport statistics from the UK Department for Transport
- The carbon content of a gallon of gasoline is about 2.4 kg (specific gravity = 0.74; 85% carbon by weight), leading to 3 kg of carbon emissions per gallon of gasoline when one adds about 25% carbon "overheads" incurred at production, at the refinery and further downstream. Thus a typical car emits around one ton of carbon into the air each year.
- Therefore, if fuel efficiency is doubled, using these baseline figures, there is the potential to produce one wedge.
- The figures are strongly dependent on the average fuel economy assumed. If it is actually 24mpg, then a wedge is achieved by raising fuel efficiency to 40mpg.
- Since decarbonization of the fuel is strenuous (whether hydrogen or biofuels), it should never happen that we put decarbonized fuel into 30 mpg cars. We would want to change the cars to get 60 mpg first, whereupon one would attribute one wedge to efficiency and one wedge to decarbonization of fuels.

For more information on Road Transport, see the ImpEE Resource "Road Transport".

Reduced Use of vehicles

- Decrease car travel for 2 billion 30 mpg cars from 10,000 to 5000 miles per year
- Issues for implementation include urban design, mass transit, telecommuting



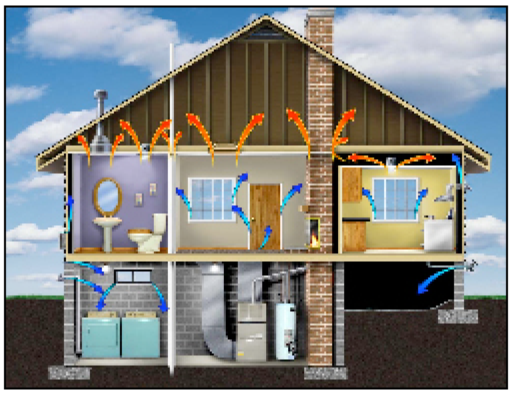
Notes

- Travel statistics from the UK department for transport shows that the distance travelled per car in 2005 was around 9000 miles per year in the UK.
- A light-duty vehicle ("car") consumes 330 gallons of gasoline per year if it goes 10,000 miles with a fuel economy of 30 mpg. The carbon content of a gallon of gasoline is about 2.4 kg (specific gravity = 0.74; 85% carbon by weight), leading to 3 kg of carbon emissions per gallon of gasoline when one adds about 25% carbon "overheads" incurred at production, at the refinery and further downstream . Thus, a typical car emits a ton of carbon into the air each year.

For more information on Road Transport, see the ImpEE Resource "Road Transport".

More efficient buildings

- Need to cut the carbon emissions from buildings by 25% by 2055
- This can be achieved using known and established approaches to energy efficiency
- The largest savings are in space heating and cooling, water heating, lighting, and electric appliances.



Replacing all the world's incandescent bulbs with compact fluorescent lights would provide 1/4 of one wedge

Notes

- Two of the most important uses of fuel, from the standpoint of carbon emissions, are heating of living spaces and heating of water, and both involve supplying heat at a temperature not very different from nearby "ambient" temperatures (the temperatures of nearby outside air or ground water, for example). Here we note that one strategy is to pursue passive and active solar energy management, the domain of solar architecture, to heat buildings in winter and to heat water year round. A full wedge is probably available from judicious combinations of solar design, careful construction, substantial insulation, and broad use of efficient heat pumps.
- The jobs of space heating and water heating rarely involve boosting the temperature, relative to ambient temperature, more than 50 degrees C. Thermodynamics identifies the combustion of fuels for such purposes as intrinsically inefficient[1].

For more information, see the ImpEE Resource on "Domestic Energy ".

1. Ford, K.W., et al., eds. 1975. *"Efficient Use of Energy"*. New York: American Institute of Physics. Part I – A Physics Perspective.

Improved power plant efficiency

- A wedge is achieved if, in 2055, roughly twice today's output of coal-power is produced at 60% instead of 40% efficiency.
- Emissions from power plants can be reduced both by changing the fuel and by converting the fuel to electricity more efficiently at the power plant.
- More efficient conversion results at the plant level, for example, from better turbines, from high temperature fuel cells, and from combining fuel cells and turbines.

Average coal plant efficiency is 32% today

Notes

- To develop a wedge from the efficiency of coal power, it is noted that 40% and 60% efficient coal plants have carbon intensities of 232 gC/kWh and 155 gC/kWh, respectively, and thus a difference in carbon emissions of 77 gC/kWh. Hence, a wedge is achieved when 13,000 TWh (13 trillion kWh) are produced per year in 2054 at 60% instead of 40% efficiency. By comparison, global electricity output from coal in 2000 was 6000 TWh, according to the World Energy Outlook
- See original paper for source of calculations[1].

1. Pascala, S. and Socolow, R. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies", Science, 13 August 2004, Vol. 305, No. 5686, pp 968-972

Decarbonisation of Electricity and Fuels: from coal to gas

- Carbon emissions per unit of electricity are half as large for natural gas power plants than from coal
- A wedge would be achieved by displacing 1400GW of baseload coal with baseload gas by 2055

Photo by J.C. Willett (U.S. Geological Survey).

A wedge requires an amount of natural gas equal to that used for all purposes today

A wedge worth of gas would require 50 LNG tanker deliveries every day, or the equivalent of 50 Alaska pipelines

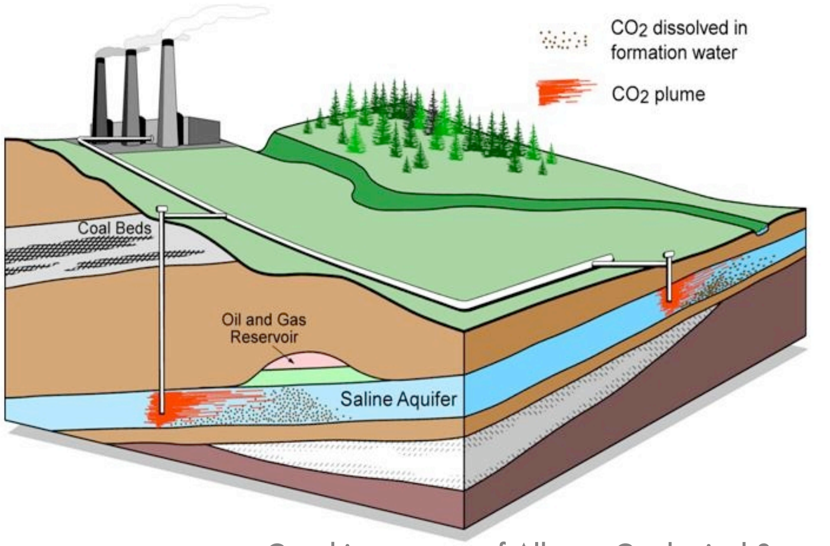
otes

- This estimation assumes that the capacity factor of the average base load coal plant in 2055 has increase to 90% and that its efficiency has improved to 50%. Because 700 GW of such plants emit carbon at a rate of 1 GtC/year, a wedge would be achieved by displacing 1400GWof base load coal by base load gas by 2055.The power shifted to gas for this wedge is four times as large as the total current gas-based power. See the on-line supporting material for full details of the calculation.
- Unless otherwise noted, we use CO_2 emissions data from the International Energy Agency's World Energy Outlook 2002[1]
- We also use the energy-to-carbon conversion ratios recommended at the BP website[2]. These are lower heating values, for natural gas, oil, and coal, in units of kgC /GJ, these are, respectively: 15.29, 20.07, and 25.806.
- Capacity factor net: The ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period.
- The amount of carbon emitted for a given amount of energy is known as the carbon intensity.

1. International Energy Agency, 2003. *"Key World Energy Statistics"*. 2003. Available on-line.
2. BP website, 2005. *"BP Statistical Review of World Energy"*.

Decarbonisation of Electricity and Fuels:CCS

- Carbon Capture and Storage
- One wedge is achieved by providing CCS at 800GW of baseload coal plants or 1600GW of natural gas plants



Graphic courtesy of Alberta Geological Survey

A wedge will require injecting a volume of CO_2 equal to the amount of oil extracted every year

There are currently three storage projects that each inject 1 million tons of CO_2 per year – by 2055 need 3500.

Notes

- The capture part of this wedge would require a tenfold expansion of today's large hydrogen plants.
- CO_2 injection into geological reservoirs is already used to spur enhanced oil recovery. If this were scaled up by a factor of 100 over the next 50 years, this would give us a wedge.
- Likewise CO_2 storage is practised in Norway at the Sleipner reservoir. A wedge would be 3500 more similar projects (or fewer larger ones) over the next 50 year.
- Useful link for info on CCS

Decarbonisation of Electricity and Fuels:Nuclear Fission

- Add 700 GW (twice the current capacity)
- Issues are nuclear proliferation, terrorism and waste

Graphic courtesy of NRC

The rate of installation required for a wedge from electricity is equal to the global rate of nuclear expansion from 1975-1990.

Phasing out of nuclear electric power would create the need for another half wedge of emissions cuts

Notes

- Issues concerning nuclear power generation as outlined above are always worthy of discussion. Myths abound and public perception is a major issue providing value for consideration by engineers. Here is an issue where there are no 'right answers'.
- The global pace of nuclear power construction from 1975 to 1990 would yield a wedge.

Decarbonisation of Electricity and Fuels:Wind Energy

- Installed wind capacity has been growing at about 30% per year for more than 10 years
- It is currently about 50 GWp.
- A wedge of wind electricity would thus require 40 times today's deployment.
- The wind turbines would "occupy" about 30 million hectares (about 3% of the area of the United
- States), some on land and some offshore.
- Because windmills are widely spaced, land with windmills can have multiple uses.

Photo courtesy of DOE

An electricity wedge would require a combined land area the size of Germany

Notes

- For both wind and PV, deployment can be measured in peak watts (Wp), a measure of the power output at the cut-off wind speed for wind and in direct sun normal to the surface for PV. A simple way to estimate intermittency is to match peak watts to baseload watts by dividing by three. (A typical capacity factor for wind or PV is about one quarter, as compared to somewhat more than three-quarters for a baseload plant).
- In 2055, we imagine a 30% capacity factor for PV and wind and a 90% capacity factor for baseload plants. Thus, a wedge is achieved by about 2000 GWp of peak wind or PV power displacing coal by 2055, or 4000 GWp displacing natural gas. The rate of deployment, for a linear ramp, is 40 GWp per year if coal is displaced and 80 GWp per year if natural gas is displaced. The current global deployment of PV is about 3 GWp.
- To estimate the spatial demands of future wind farms on land or in the sea, we use data for Denmark's new 160 MW Horns Rev wind farm off the west coast of Jutland. This offshore wind farm has 80 turbines in an 8x10 rectangular array, each with 80m-diameter blades and 2 MWp output. The turbines are seven blade-diameters apart both in the prevailing wind direction and transverse to it. Thus, each of the inner 2-MWp turbines "occupies" 310,000 m2, and its power density is 6 Wp/m2, from the perspective of surface area required. A wedge in the form of 2000 GWp of wind-for-coal would then require 30 million hectares of surface. If all were on land, this would be between one and two percent of the world's 1800 million hectares of land estimated to have winds of Class 4 and above. Thirty million hectares is also 3% of the land area of the United States. Land from which wind is harvested can be used for many other purposes, notably for crops or pasture.

Decarbonisation of Electricity and Fuels:photovoltaic electricity

- The current global deployment of PV is about 3GWp
- The growth factor is around 30% per year
- To save 1GtC per year would require an increase in the deployment of PV by a factor of 700 by 2054 giving 2000 GWp
- This requires 2 million hectares assuming an output of 100Wp/m^2 for peak power or 2 to 3 m^2 per person

Photos courtesy of DOE Photovoltaics Program

A wedge would require an array of photovoltaic panels with an combined area about 12 times that of metropolitan London

Notes

- For both wind and PV, deployment is measured in peak watts (Wp), a measure of the power output at the cut-off wind speed for wind and in direct sun normal to the surface for PV. A simple way to estimate intermittency is to match peak watts to baseload watts by dividing by three. (A typical capacity factor for wind or PV is about one quarter, as compared to somewhat more than three-quarters for a baseload plant.)
- For the past several years, installed global PV capacity, like wind capacity, has been growing at 30% per year (say, 0.7 GWp/y). Thus, a wedge of PV-for-coal requires increasing the deployment of PV by a factor of 700 by 2054, or increasing the current deployment rate by a factor of 60.
- The land demand for PV is inversely related to the conversion efficiency of sunlight. Here we choose 100 Wp/m^2 for the peak power output from PV divided by the area of the collection site,15 times greater than for wind. Then, a wedge in the form of 2000 GWp of PV-for-coal requires two million hectares, or 20,000 km^2, of site surface, either dedicated land or multiple-use surfaces such as the roofs and walls of buildings.

Decarbonisation of Electricity and Fuels:Biofuels

- Fossil-carbon fuels can be replaced by biofuels such as ethanol
- A wedge of biofuel could be achieved by the production of 34 million barrels per day of ethanol to replace gasoline in 2055, provided the ethanol is fossil carbon free
- This is 50 times larger than current ethanol production rate
- Would require 250 million hectares of high yield plantations equivalent to one sixth of the world's cropland

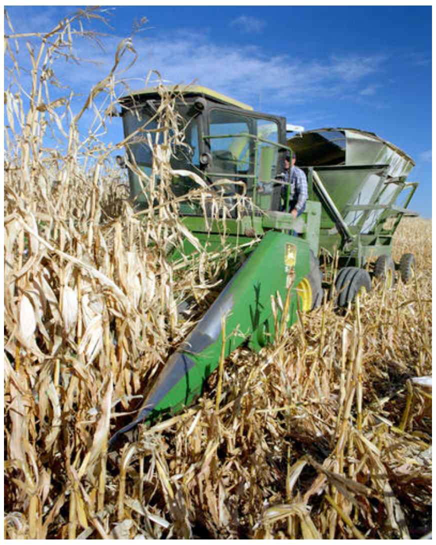


Photo courtesy of NREL

Using current practices, one wedge requires planting an area the size of India with biofuels crops

Notes

- A sustainable biofuel is one obtained from plants that are replaced by new plants at the same rate as they are used. A hectare of land dedicated to biofuels can produce these fuels indefinitely, displacing a stream of fossil carbon indefinitely, whereas a hectare of land used as a carbon sink has a certain capacity to store carbon and then its contribution to carbon accounts "saturates."
- Examples of biofuels crops include switchgrass, sugarcane, and corn. A good yield from such annually harvested species is 15 dry tons (dt) per hectare per year. Dry biomass is about 50% carbon by weight, so the carbon yield is 7.5 tC/ha-y, and the yield from 130 million hectares (Mha) dedicated to such biofuels (biofuels plantations) is 1 GtC/y. This is 10 percent of today's 1500 Mha of total cropland.
- The energy content of biomass fuel is between 15 and 20 GJ/dt (dt=dry tons). (The lower value is appropriate for crops, the higher value for wood.) Thus, a good energy harvest is about 200 to 300 GJ/ha-y. This harvest may be restated as 0.7 W/m^2 to 1.0 W/m^2. Comparing this harvest with annually averaged incident sunlight, typically 250 W/m^2, the harvest is seen to convert 0.3 to 0.4 percent of incident sunlight. Such a low conversion rate, even for a high-yield species, is confirmation that the conversion of incident sunlight via photosynthesis has been only one of many objectives of green-plant evolution. Accordingly, there is considerable headroom for genetic engineering to improve substantially on such yields with organisms designed to convert sunlight efficiently into fuel (artificial photosynthesis), greatly reducing the land demands for a future wedge from artificial biofuels, relative to biofuels from nature's plants.
- How are biofuels likely to be used? The current energy economy demonstrates clearly that liquid and gaseous fuels that contain carbon are the most valuable forms of energy. Biomass is therefore likely be transformed preferentially into biofuels, rather than into electricity or hydrogen. Assuming an average value of 250 GJ biomass yield per hectare, one-eighth of a hectare of dedicated land will be required for each car.

Natural sinks:Reduced Tropical Deforestation

- Estimates of tropical forest lost per year in the 1990s vary from 6 to 12 million hectares
- This leads to a factor of two difference in emissions to the atmosphere: ~1 vs. ~2GtC/y
- At least half a wedge could be obtained by eliminating deforestation
- Another half could be created by reforesting 250 million hectares in the tropics or 400 million in the temperate zone

One wedge would require new forests over an area the size of the continental U.S.

Notes

- The 1.5 billion hectares of tropical forests contain 7-10 wedges worth of carbon in living trees and another 5-9 wedges in soils .When primary forest (forest that has never been logged) is converted to permanent cropland, all of the 120-165 tC/ha in living trees and up to one third of the 83-150 tC/ha in the top 1 meter of soil is emitted to the atmosphere.
- Conversion to pasture emits the carbon in trees, but may actually increase soil carbon by up to 10%. Details can be found on-line in the IPCC Special Report on land use, land use change and forestry.
- See the supporting on line material for full details of this estimate.

Natural sinks:agricultural soils management

- About 55 GtC (2 wedges worth) of CO_2 has been lost through annual tilling of land converted to cropland
- Adopting the practice of "conservation tilling" could make considerable savings in CO_2 emissions

Photo courtesy of NREL, SUNY Stonybrook, United Nations, FAO

Conservation tillage is currently practiced on less than 10% of global cropland

Notes

- When forest or natural grassland is converted to cropland, up to one-half of the soil carbon is lost, primarily because annual tilling increases the rate of decomposition by aerating un-decomposed organic matter.
- About 55 GtC, or two wedges' worth, has been lost historically in this way. Practices such as conservation tillage (e.g., seeds are drilled into the soil without plowing), the use of cover crops, and erosion control can reverse the losses. By 1995, conservation tillage practices had been adopted on 110 million hectares of the world's 1600 million hectares of cropland. If conservation tillage could be extended to all cropland, accompanied by a verification program that enforces the adoption of soil conservation practices that actually work as advertised, a good case could be made for the IPCC's estimate that an additional half to one wedge could be stored in this way.

Choices: a case for action

- The choice we have in facing the problem of climate change is between action and delay.
- The technologies presented here make a case for action.
- All of these technologies **exist today** and could be scaled up over 50 years to help stabilisation the rise in CO_2 emissions.

Notes

- The slides have indicated various ways by which large scale decarbonisation might be achieved. How and whether this happens will be as a result of industrial structures, carbon policies, targeted subsidies, international relationships, geophysical realities, R&D priorities, changes in behaviour and values and other crucial factors.

Things to think about

- In order to avoid a doubling of atmospheric CO_2, we need to **rapidly** deploy low-carbon energy technologies and/or enhance natural sinks
- We already have an adequate portfolio of technologies to make large cuts in emissions
- No one technology can do the whole job – a variety of strategies will need to be used to stay on a path that avoids a CO_2 doubling
- Every "wedge" has associated impacts and costs

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