

Fall Term - 2011

**Woodrow Wilson School 585b**

**Living in a Greenhouse:  
Technology and Policy**

**Robert Socolow**

**Alex Whitworth**

**Week Five: October 19, 2011**

**The Discourse about Alternative Futures**

# Special Guest: Kristina Johnson

**TALK**  
(WOODROW WILSON SCHOOL  
ENERGY AND ENVIRONMENT SERIES)

**KRISTINA  
JOHNSON**

Former Under Secretary, U.S.  
Department of Energy  
CEO, Enduring Energy, LLC

**WHY CLEAN ENERGY  
WON'T TAKE  
OUR ECONOMY  
TO THE  
CLEANERS**

WEDNESDAY, OCTOBER 19, 2011  
4:30 P.M.

DODDS AUDITORIUM  
ROBERTSON HALL  
PRINCETON UNIVERSITY

*Woodrow Wilson*  
School of Public and International Affairs  
PRINCETON UNIVERSITY



# ENERGY UNITS: Help for “footprints”

	<b>Work Unit</b>	<b>Heat Unit</b>
<b>SI (“science”)</b> $k = 10^3$ , $M = 10^6$ , $G = 10^9$	<b>Joule</b> 1 kWh = 3.6 MJ, because 1 Watt = 1 J/second.	calorie
<b>U.S. (“British”)</b>	Foot-pound	<b>Btu</b> = 1055J
<b>Fuel-derived</b>	tce (ton of coal equivalent) = 29.3 GJ <b>toe</b> (ton of oil equivalent) = 41.9 GJ	

Industry also uses volume units: gallons, liters, barrels, cubic feet, cubic meters. E.g., the scfd, pronounced “scuff,” a standard cubic foot of natural gas per day.

# Readings for Week 5: Alternative Futures (1 of 2)

## Classic Articles (Required)

S. Pacala and R. Socolow, 2004. "Stabilization wedges: solving the climate problem for the next 50 years with current technologies," *Science*, Vol. 305, pp. 968-972, August 13, 2004.

## Required Readings

National Academy of Sciences, *America's Energy Future Report*. Look at Tables and charts on pages 17-24; pages 56-60 on costs; and pages 81-115 on technology options, especially chart on page 93.

R. Socolow and S. Pacala, 2006. "A plan to keep carbon in check," *Scientific American*, Vol. 295, No. 3, pp. 50-57.

Bezdek, R. H. and R. M. Wendling, 2002. "A Half Century of Long-Range Energy Forecasts: Errors Made, Lessons Learned, and Implications for Forecasting," *Journal of Fusion Energy* 21(3/4): 155-172.

# Readings for Week 5: Alternative Futures (2 of 2)

IEA, 2010, *World Energy Outlook 2010*. Part C: Achieving the 450 Scenario After Copenhagen. Read pages 377-387; 400-405; 415; 417-419; 420-441 and 443-448. Skim other parts of Chapters 13-15.

Philip Cafaro, 2011, Beyond business as usual: alternative wedges to avoid catastrophic climate change and create sustainable societies. Chapter 9 (pp. 192 - 215) in *The Ethics of Global Climate Change* (2011) edited by Denis G. Arnold.

## **Recommended Readings**

Resources for the Future, 2010, *Towards a New National Energy Policy: Assessing the Options*.

McKinsey and Co. Report, 2007, *Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?*

# Outline for Lecture 5

The discourse about the future

Scenarios

Targets and timetables

Available technologies and the wedge model

# WRE Stabilization Scenarios (1996)

## Illustrative CO<sub>2</sub> Emissions Profiles and Corresponding Concentrations

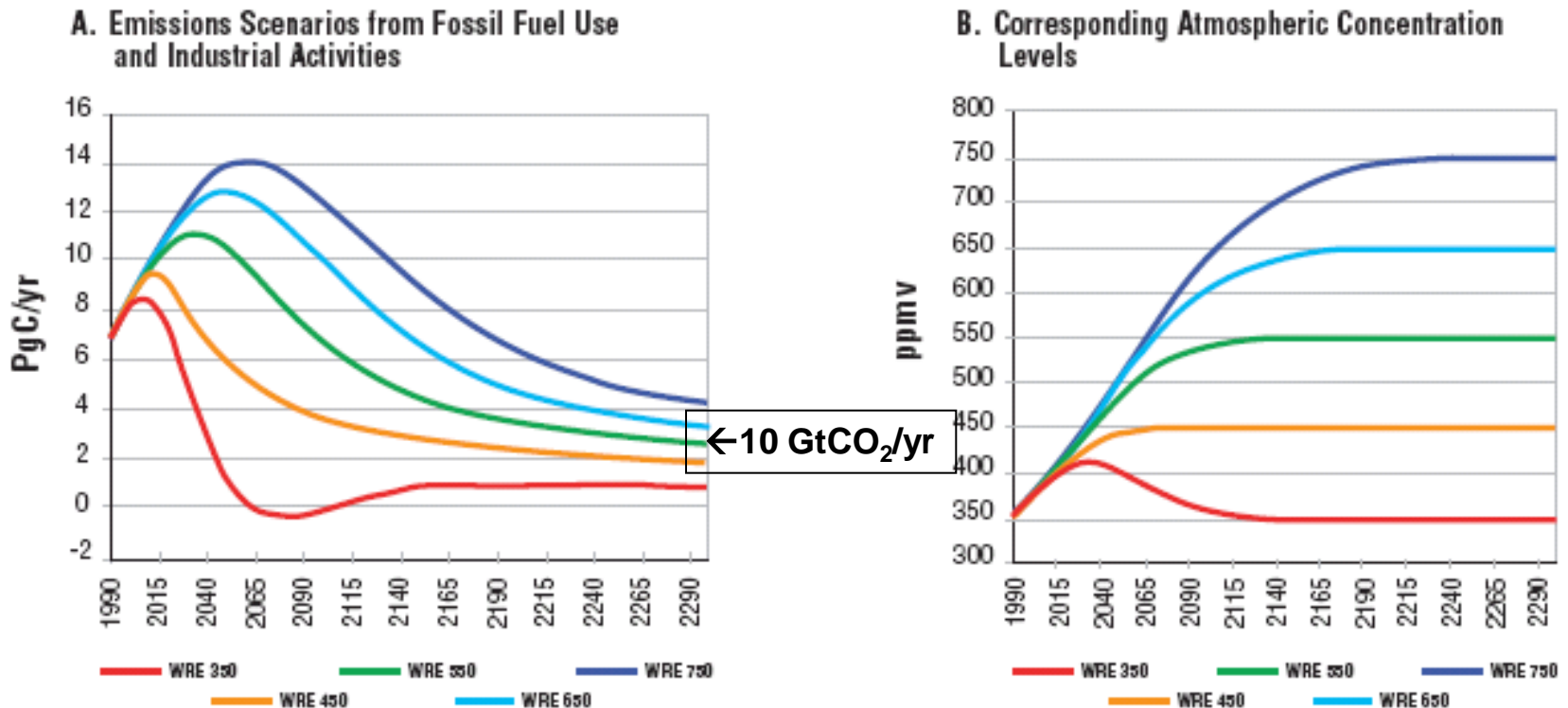
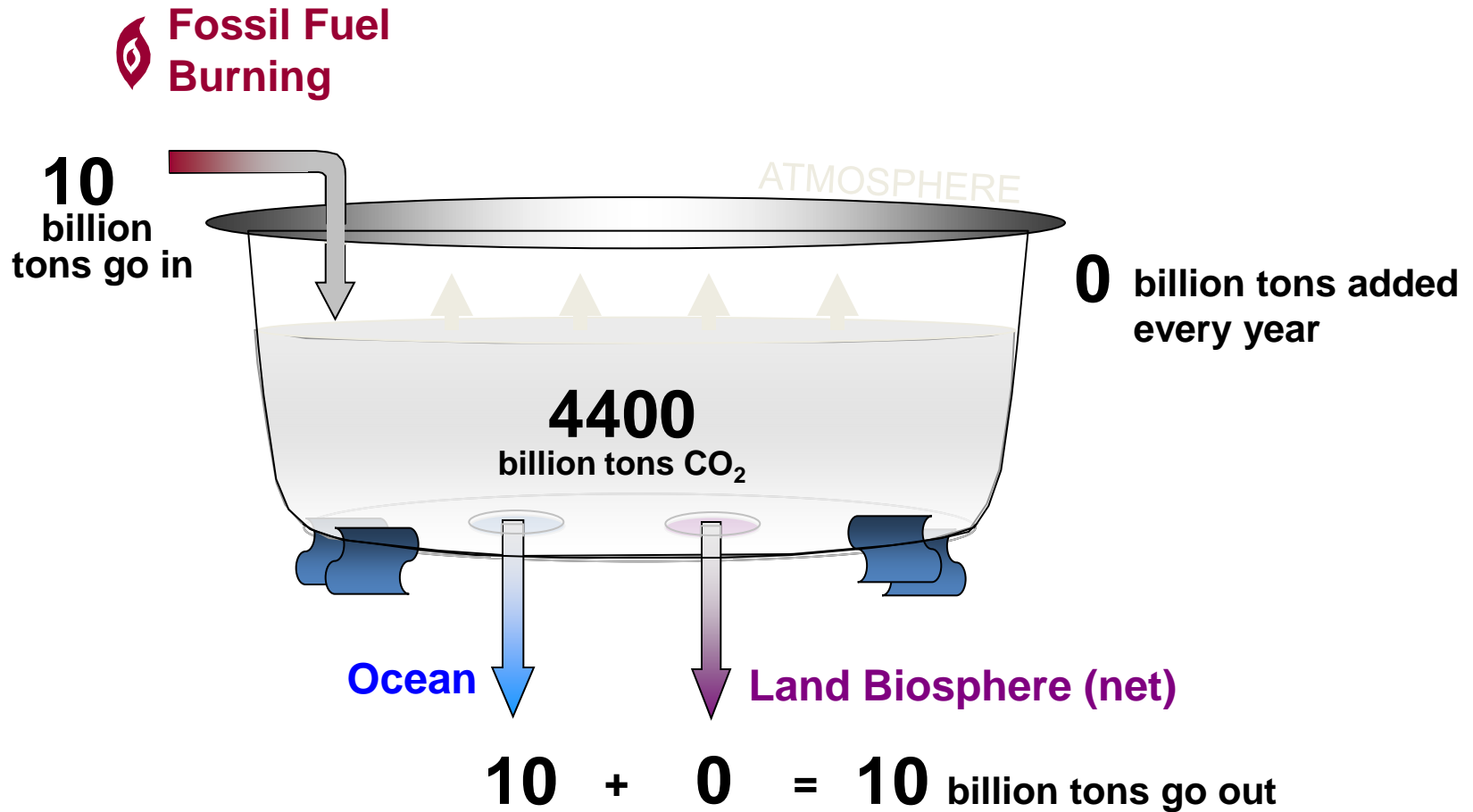


Figure 3-10. Illustrative CO<sub>2</sub> Emissions Profiles and Corresponding Concentrations

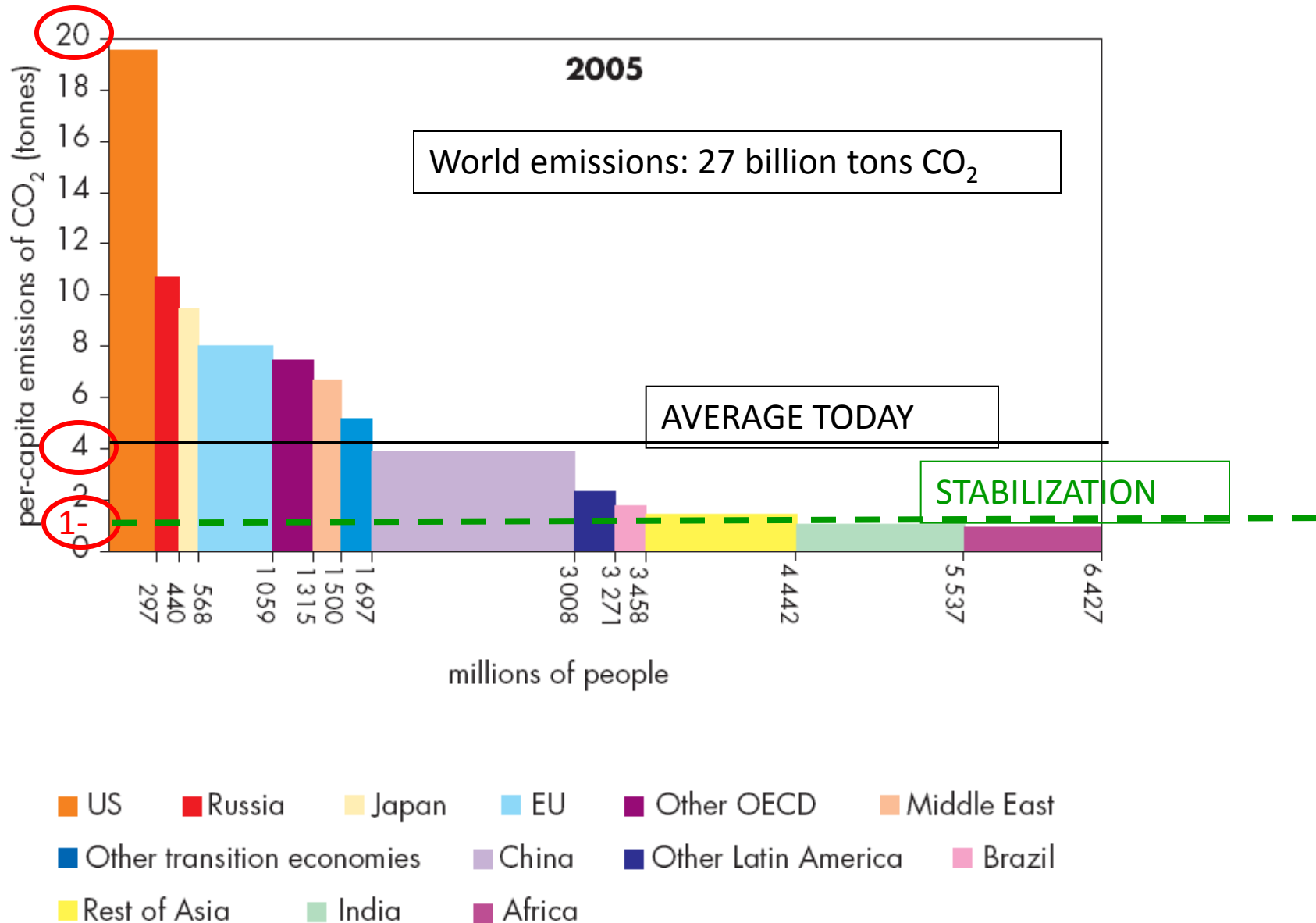
“WRE” is Wigley, Richels, and Edmonds.

At “stabilization,” allowed emissions are about one-third of today’s.



**Shown here: Stabilization at double the pre-industrial concentration.**

# Per-capita fossil-fuel CO<sub>2</sub> emissions, 2005



# “Stabilization”: 1 ton CO<sub>2</sub>/yr per capita

It is *not* sufficient to limit emissions in the prosperous parts of the world and allow the less fortunate to catch up. Such an outcome would overwhelm the planet.

The emissions of the future rich must eventually equal the emissions of today's poor, ...

...not the other way around.

# SRES and RCP emissions trajectories

SRES: *Special Report on Emissions Scenarios*, IPCC 2000

Starting point is a story. The world economy evolves in four very different directions, depending the level of coherence of global economic development and the level of priority given to environmental objectives. The end point is 2100.

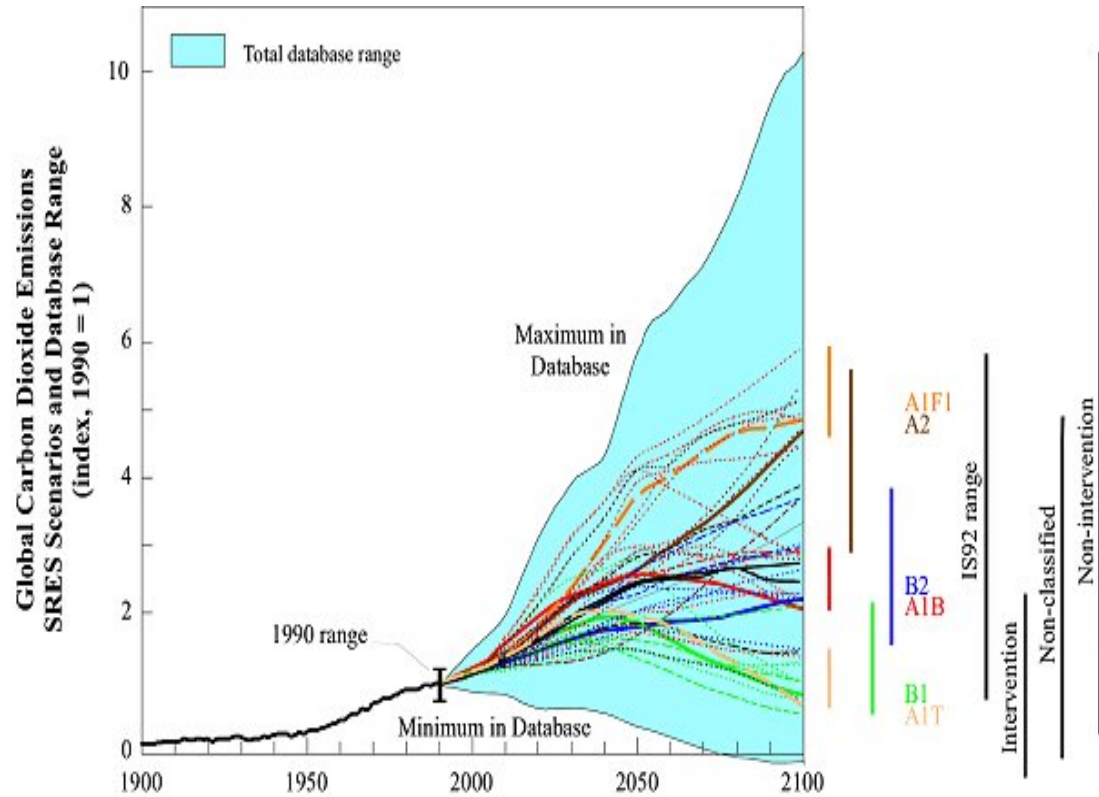
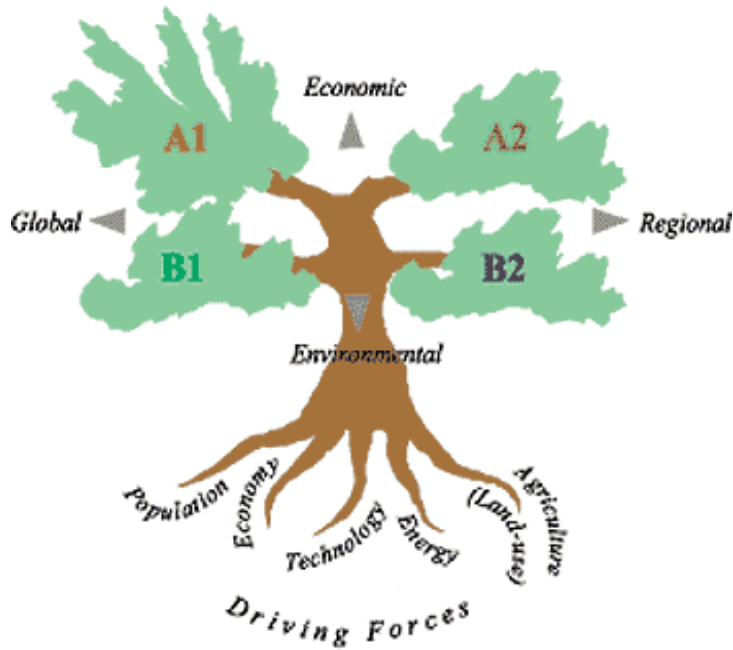
Business as Usual (BAU) is assumed in all cases, which means that climate change is not a driver of change. (“Stabilization scenarios” paired with the BAU scenarios have also been created.) Four story lines, plus alternative versions of each story (in all, 40 SRES scenarios). For the past decade, the SRES scenarios have served as inputs to climate modeling.

RCP: Representative Concentration Pathways, IPCC 2010

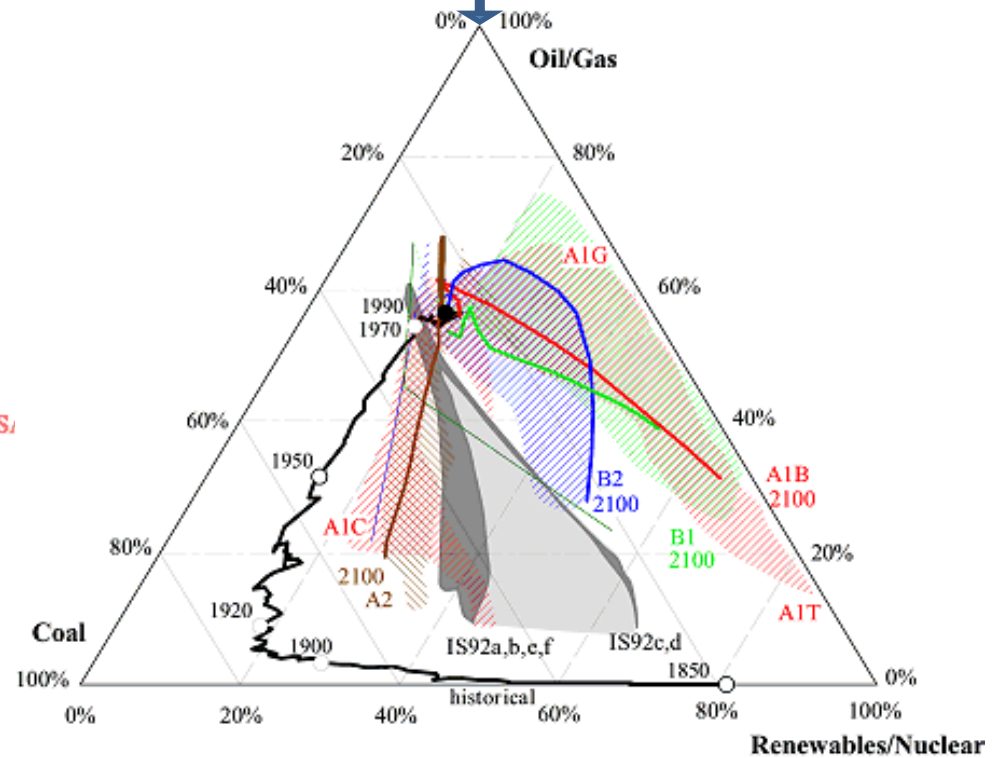
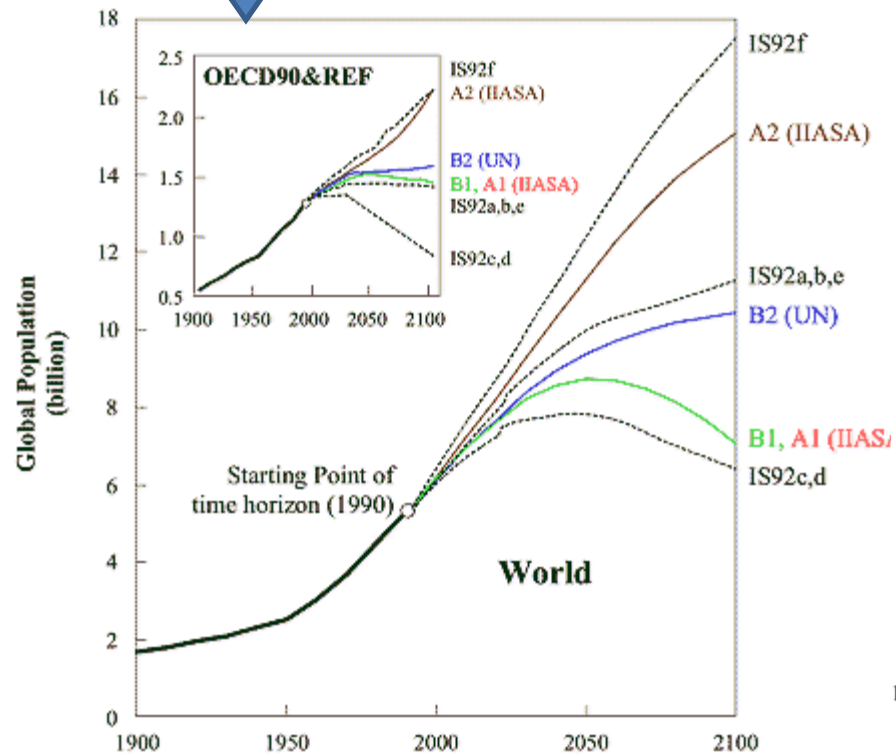
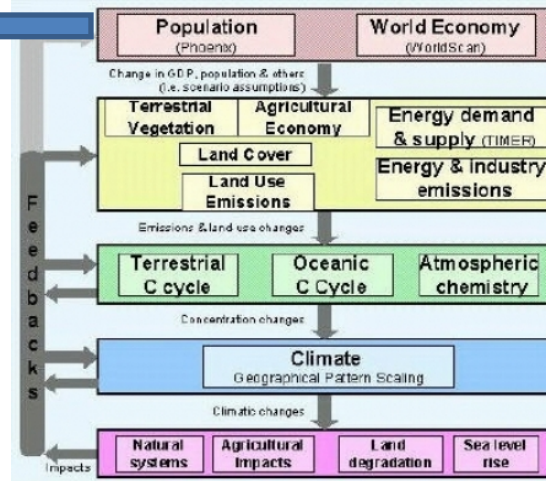
Starting point is a detailed emissions scenario: greenhouse gases, aerosols, land use. The end point is 2100, but there are extensions to 2300. SRES is dethroned. Goodbye to story lines, goodbye to Business as Usual. Just the facts, ma’am (the emissions). For now, just four RCPs.

# SRES Scenarios: Four story lines

**SRES Scenarios**

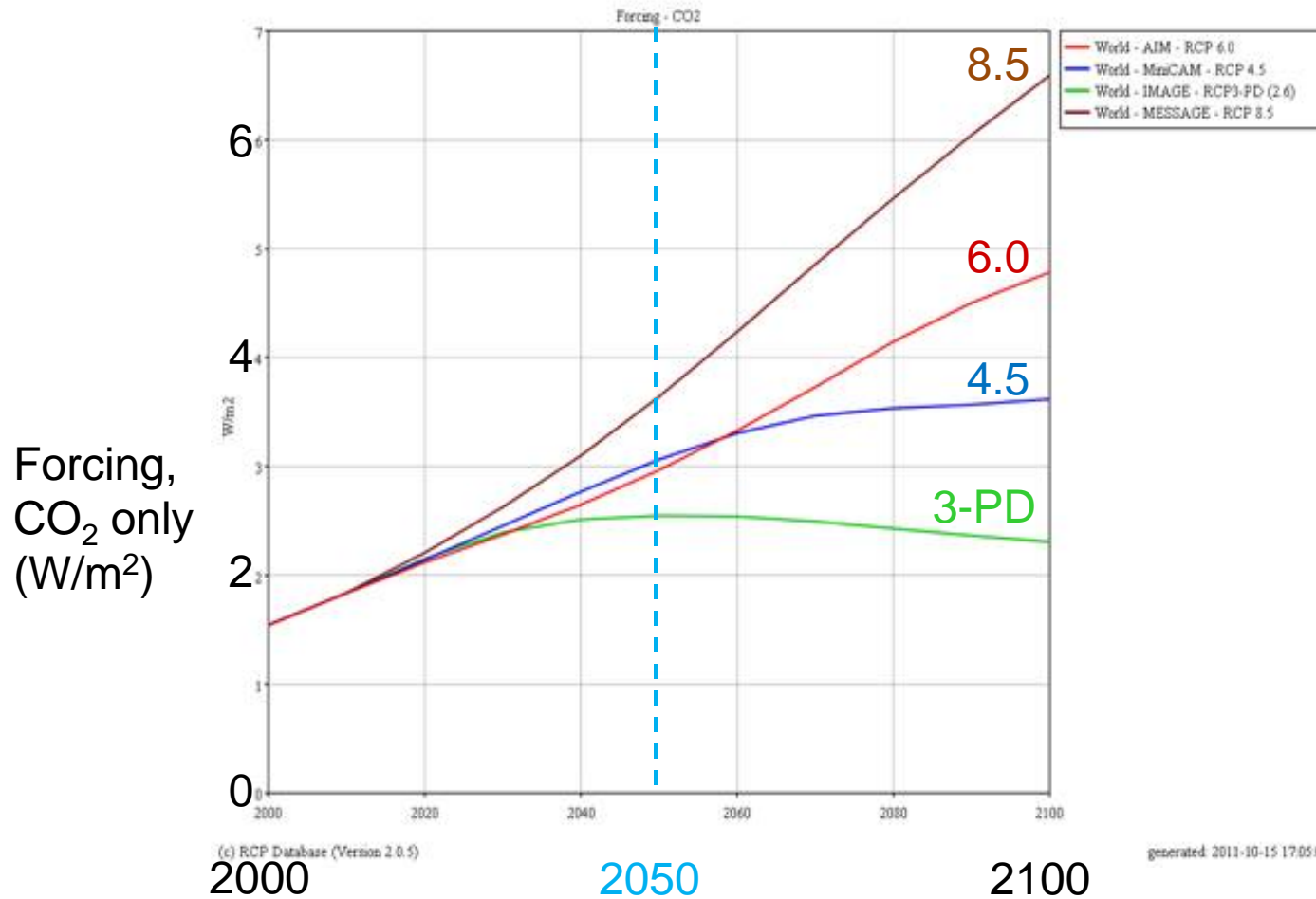


SRES: *Special Report on Emissions Scenarios*, IPCC. 2000



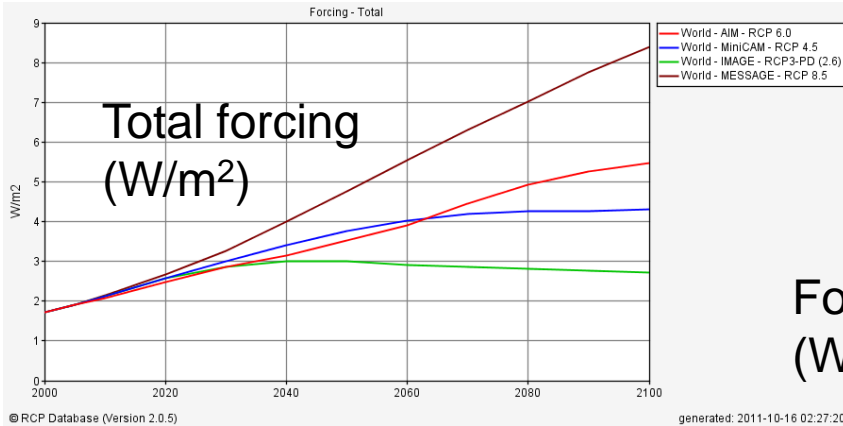
SRES: *Special Report on Emissions Scenarios*, IPCC. 2000

# Representative Concentration Pathways



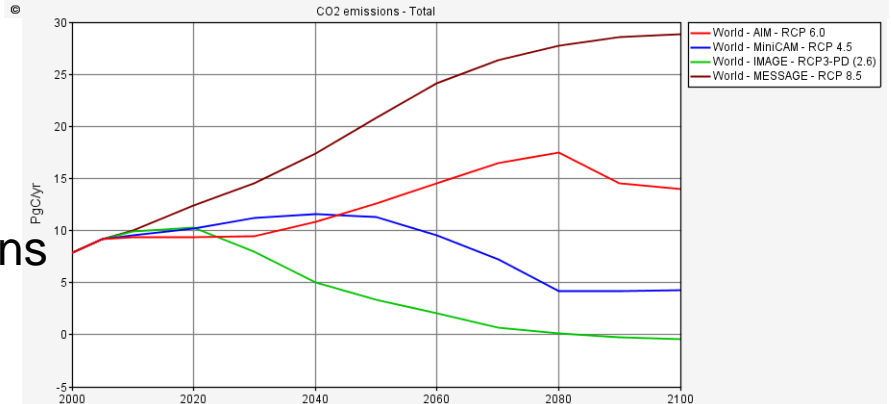
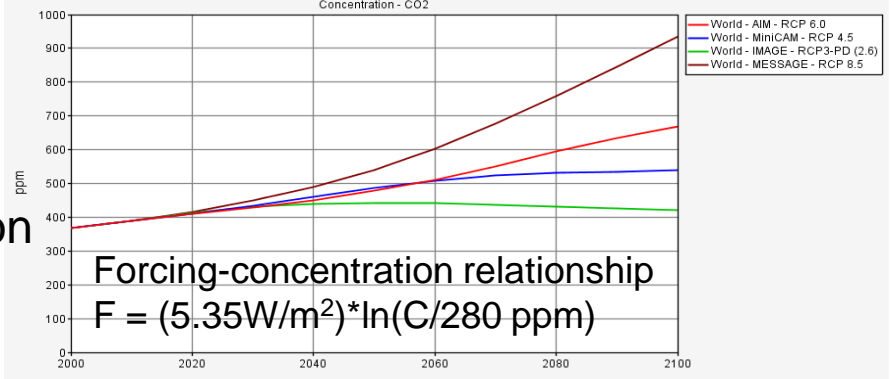
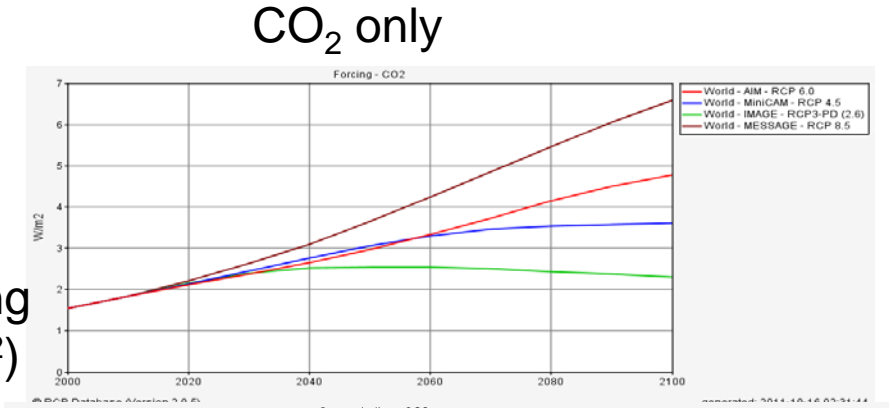
Data: <http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=about>  
Introduction: <http://www.springerlink.com/content/f296645337804p75/fulltext.pdf>

# RCPs: Forcings and CO<sub>2</sub> concentrations



Forcing (W/m<sup>2</sup>)

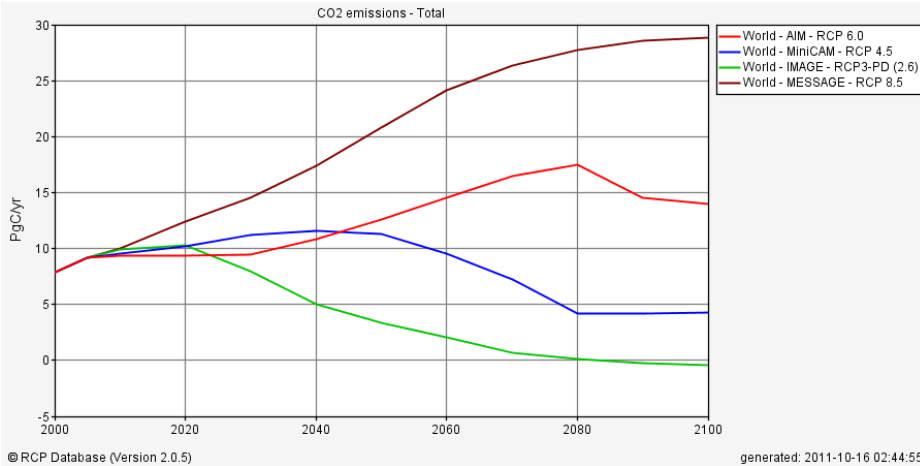
Concentration (ppm)



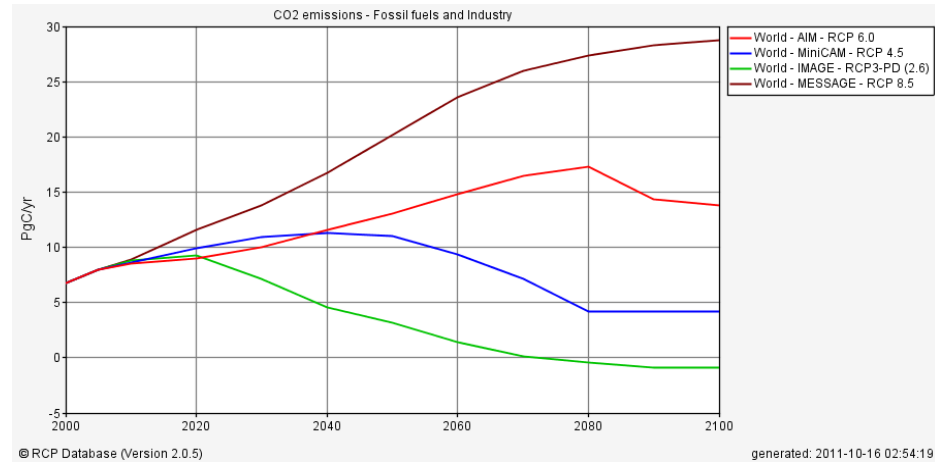
Emissions (GtC/yr)

# CO<sub>2</sub> emissions in the RCPs

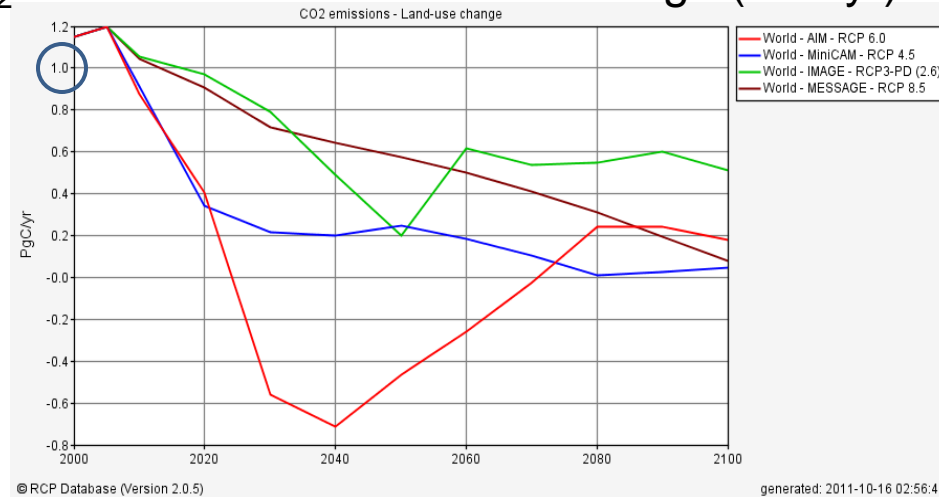
## Total CO<sub>2</sub> emissions (GtC/yr)



## CO<sub>2</sub> emissions from fossil fuels and industry (GtC/yr)



## CO<sub>2</sub> emissions from land-use change (GtC/yr)



“Total” = “Fossil fuel and industry”  
+ “Land use change”

# Representative Concentration Pathways

Pathway	RCP3.0 P-D	RCP4.5	RCP6.0	RCP8.5
Model	IMAGE	MiniCAM	AIM	MESSAGE
Group	Netherlands Environmental Assessment Agency (PBL)	Pacific Northwest National Laboratory (PNL, US): Joint Global Change Research Institute (JGCRI)	National Institute for Environmental Studies (NIES, Japan)	International Institute for Applied Systems Analysis (IAASA, Austria)
Forcing trajectory (W/m <sup>2</sup> )	“P-D” is peak-decline. Peaks midcentury at 3.1, down to 2.6 in 2100	Stabilizes before 2100	Stabilizes after 2100	Continuous increase

Five Regions: OECD-90, Reforming Economies (REF), ASIA, Middle East and Africa (MAF), Latin America (LAM).

*Note:* OECD-90 is the 1990 membership, which includes Turkey and the Pacific island states. Joining OECD 1994-2000: Poland, Hungary, Czech Republic, Slovakia, Mexico, Republic of Korea; Joining OECD 2010: Chile, Slovenia, Israel, Estonia.

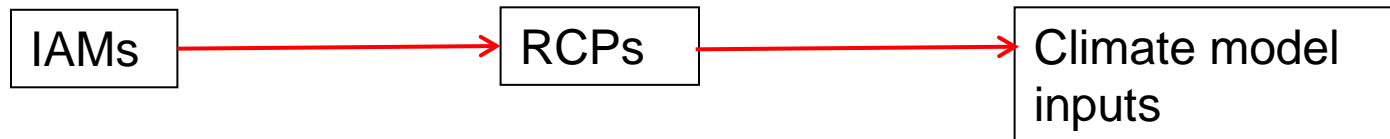
# Create the RCPs first

With RCPs in hand\*:

“Climate modelers will use the ...four RCPs in order to conduct new climate model experiments.”

“IAMs [Integrated Assessment Models] will explore a range of different technological, socio-economic and policy futures that could lead to a particular concentration pathway.”

\* See <http://www.springerlink.com/content/f296645337804p75/fulltext.pdf>.



# Outline for Lecture 5

The discourse about the future

Scenarios

Targets and timetables

Available technologies and the wedge model

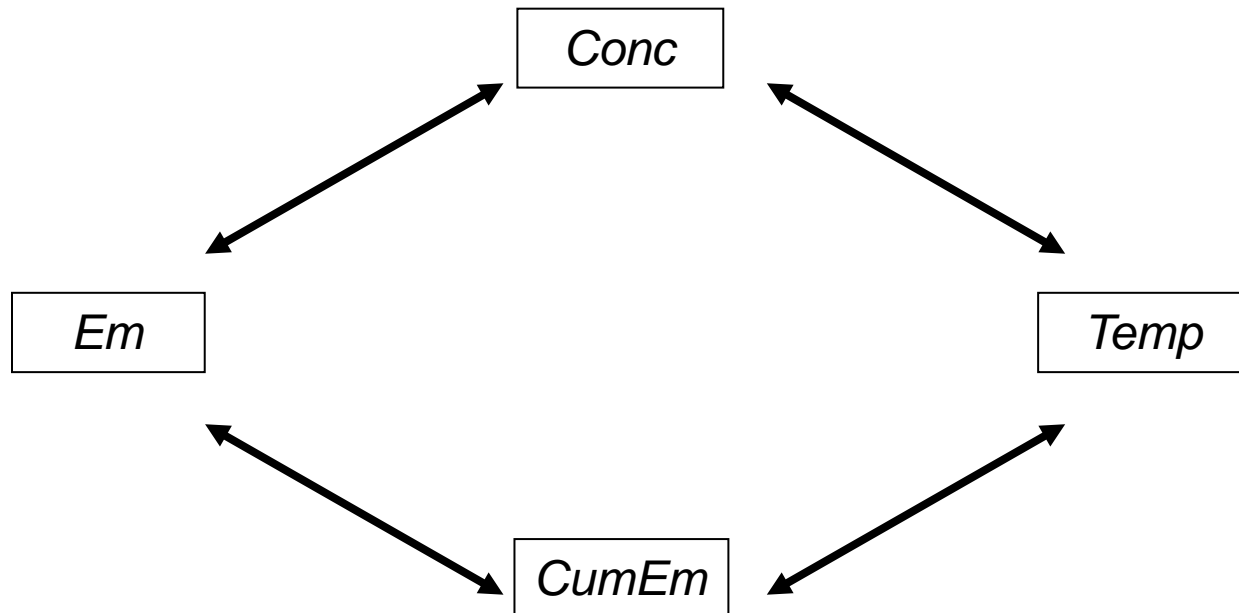
# Alternative versions of targets

*Em*: Emission rate at some future time (tCO<sub>2</sub>/yr)

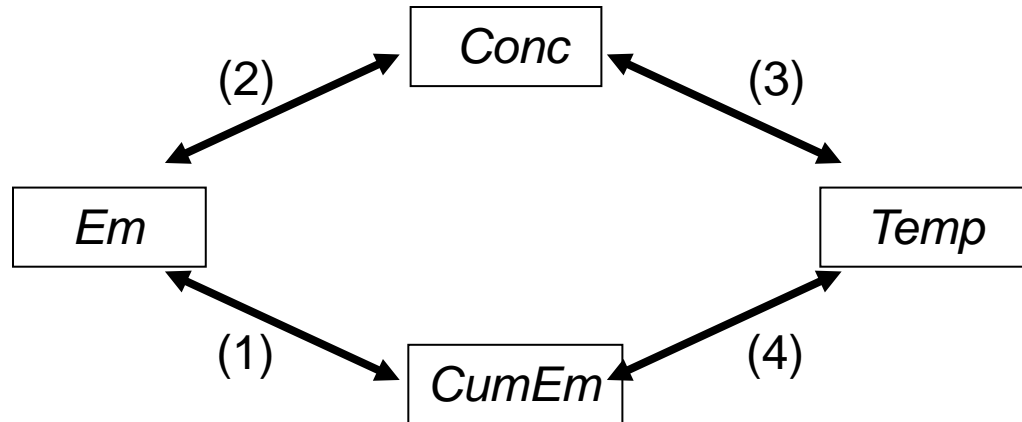
*Conc*: Maximum allowed concentration (tCO<sub>2</sub>) – often ppm.

*CumEm*: Cumulative emissions (“budget”) for an interval (tCO<sub>2</sub>)

*Temp*: Maximum allowed average surface temperature increase relative to pre-industrial times (°C)



# Relationships among global targets



(1):  $dCumEm/dt = Em$

(2):  $dConc/dt = \lambda * Em, \lambda \approx 0.5$  (“Half Stays In”)

(3):  $Temp = CS * \ln(Conc/Conc_o) / \ln 2,$

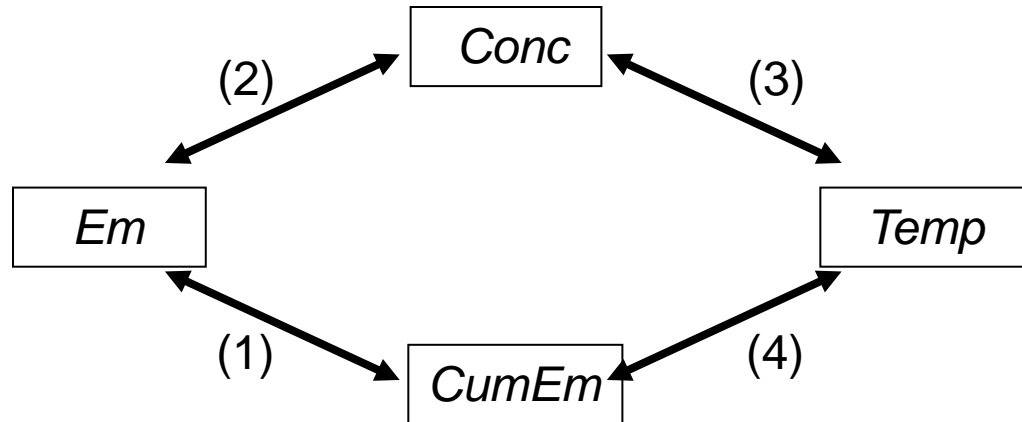
where  $Conc_o$  = pre-industrial concentration  $\approx 2200$  GtCO<sub>2</sub>  
and CS = climate sensitivity

(central value of CS is 3.0°C; 66% interval: 2.0°C < CS < 4.5°C)

(4):  $Temp = K * CumEm_{\infty},$

where  $CumEm_{\infty}$  extends from pre-industrial time to infinity  
and, in units of °C/1000GtCO<sub>2</sub>, the central value of  $K$  is 0.48:  
90% interval: 0.27 <  $K$  < 0.68.

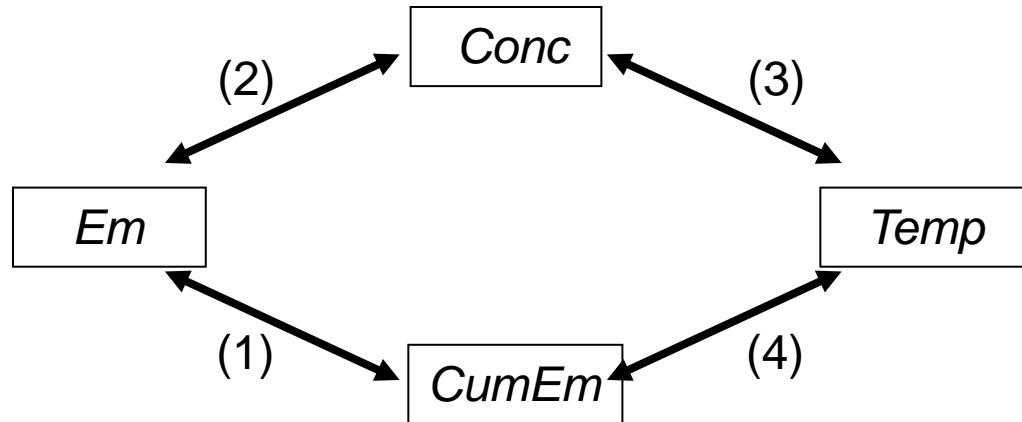
# Relationships among global targets



(1):  $dCumEm/dt = Em$

(2):  $dConc/dt = \lambda * Em, \lambda \approx 0.5$  (“Half Stays In”)

# Relationships among global targets

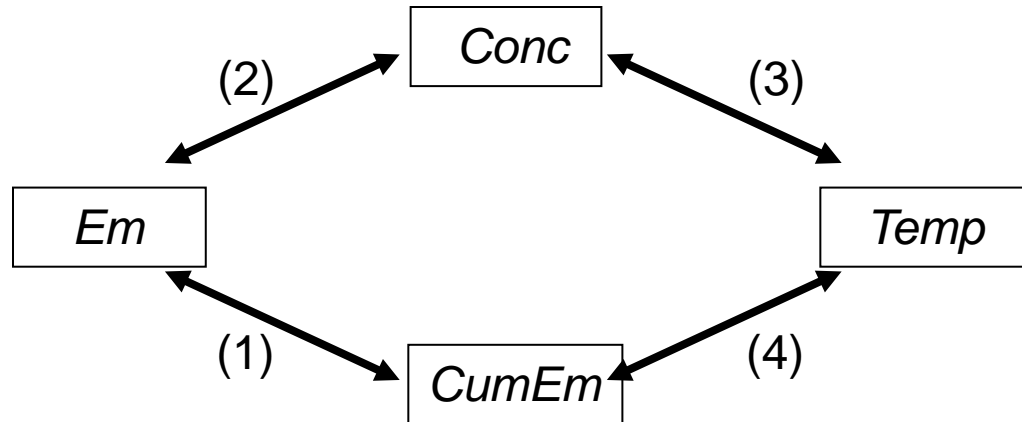


(3):  $Temp = CS * \ln(Conc / Conc_0) / \ln 2$ , where  $Temp$  is the average surface temperature,  $Conc_0$  is the pre-industrial concentration  $\approx 2200 \text{ GtCO}_2$  or 280 ppm, and  $CS$  is the climate sensitivity.

The logarithmic dependence of the temperature on the concentration derives from the dominance of line-broadening warming. A quadrupling to 1120 ppm produces a warming of  $2 * CS$ .

In *AR4*, the central value of  $CS$  is  $3.0^\circ\text{C}$  and the 66% interval:  $2.0^\circ\text{C} < CS < 4.5^\circ\text{C}$ .

# Relationships among global targets



(4):  $Temp = K * CumEm_{\infty}$ , where  $CumEm_{\infty}$  extends from pre-industrial time to infinity.

This has been newly proposed as the preferred relationship, rather than (3). The problem with (3) is that to sustain the same concentration after stabilization requires further emissions, and temperature then keeps rising. The finding from models is that  $Temp$  is insensitive to the interval over which  $CumEm$  occurs.

$K$ , of course, has its own probability distribution. In units of  $^{\circ}C/1000GtCO_2$ , the central value of  $K$  is 0.48: 90% interval:  $0.27 < K < 0.68$ . (Solomon et al., National Academy Press, 2010)

# CO<sub>2</sub>-equivalent concentration

Incremental radiative forcing (RF) for CO<sub>2</sub>, relative to pre-industrial times, is:

$$RF = \alpha \ln(C/C_o), C_o = 275 \text{ ppm}, \alpha = 5.35 \text{ W/m}^2 \quad (1)$$

For C = 385 ppm, RF = 1.80 W/m<sup>2</sup>.

Invert this equation:

$$C = C_o \exp(RF/\alpha) \quad (2)$$

Add a second gas, say CH<sub>4</sub>. Its incremental RF is found in some fashion. (For a saturated gas, like methane, perhaps from an expression like (1); for gases with unsaturated absorption lines, from a linear expression.)

Sum the RF's: RF<sub>tot</sub> = RF<sub>CO<sub>2</sub></sub> + RF<sub>CH<sub>4</sub></sub>. More generally, with *i* indexing the gases:

$$RF_{tot} = \sum RF_i \quad (3)$$

Calculate CO<sub>2e</sub> by inserting RF<sub>e</sub> into (2):

$$CO_{2e} = C_o \exp(RF_e/\alpha) \quad (4)$$

Specifically, CO<sub>2e</sub> = (275 ppm)exp[RF<sub>e</sub>/(5.35 W/m<sup>2</sup>)]. For example, if RF<sub>e</sub> = 2.2 W/m<sup>2</sup>, then CO<sub>2e</sub> = 415 ppm; and if RF<sub>e</sub> = 3.0 W/m<sup>2</sup>, then CO<sub>2e</sub> = 482 ppm.

In many definitions of CO<sub>2e</sub>, aerosols are excluded. When they are included, RF<sub>tot</sub> ≈ RF<sub>CO<sub>2</sub></sub>

# CO<sub>2e</sub> is a product of factors, one for each gas

The forcing quantities for the various gases or aerosols affecting climate forcing act additively, which is why RF<sub>tot</sub> (the total incremental radiative forcing) is a straightforward concept.

Awkward but true, the CO<sub>2</sub>-equivalent concentration, CO<sub>2e</sub> is a *product*, since RF<sub>e</sub> is a sum. Using (3) and (4), it can be written:

$$CO_{2e} = C_o * \prod \exp(RF_i/\alpha), \quad (5)$$

*where the index i runs over the various contributors to the forcing.*

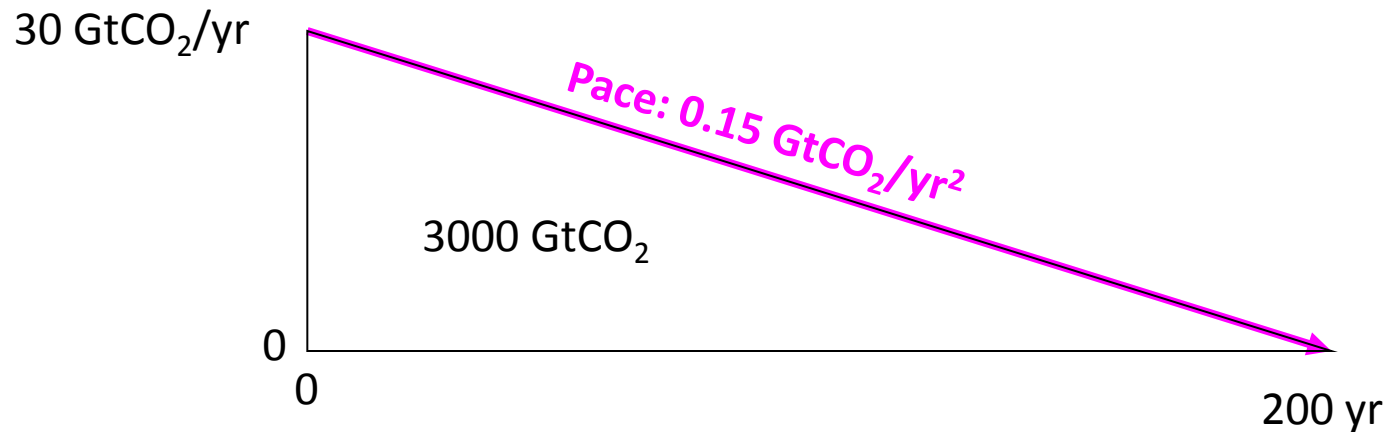
*When some RF is much less than  $\alpha$ , the multiplicative factor can be approximated by  $(1 + RF/\alpha)$ .*

*Table: Multiplicative factor,  $\exp(RF/\alpha)$ , for  $\alpha = 5.35 \text{ W/m}^2$  and various values of RF. IPCC (SFP, p.4) central values for CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O and the halocarbons are, respectively, (in W/m<sup>2</sup>): 1.66, 0.48, 0.16, and 0.34.*

RF [W/m <sup>2</sup> ]	$\exp(RF/\alpha)$
0.4	1.078
0.8	1.161
1.2	1.251
1.6	1.349
2.0	1.453

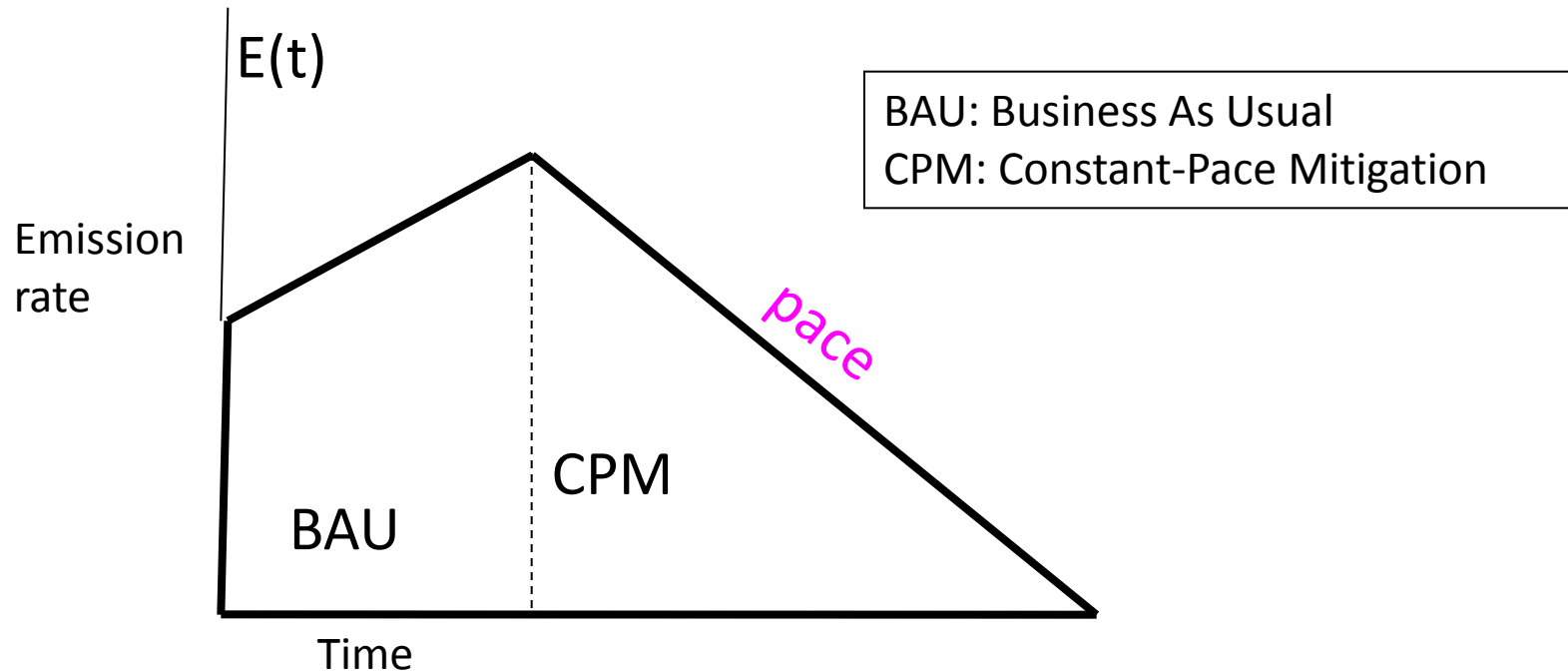
# Constant-Pace Mitigation (CPM)

Example: Stabilize at 4500 GtCO<sub>2</sub> (double pre-industrial).  
Start today (3000 GtCO<sub>2</sub>). Assume “Half Stays In.”  
Then can emit 3000 GtCO<sub>2</sub> more.  
With CPM, emissions run for 200 years



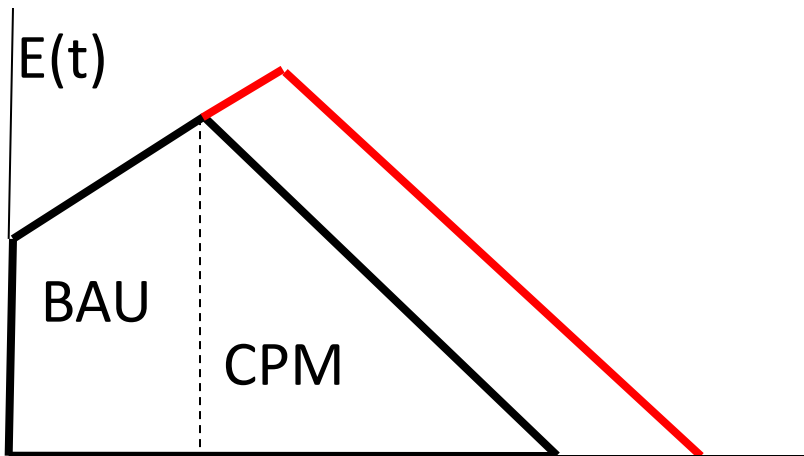
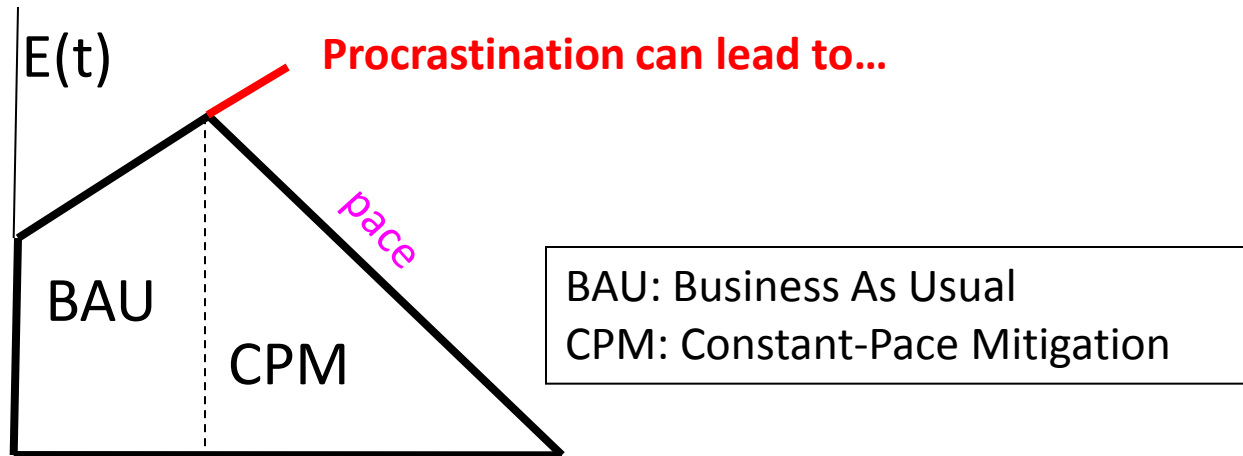
See: R.H. Socolow and S.H. Lam, “Good enough tools for global warming policy making,” *Phil. Trans. R. Soc. A* (2007) 365, 897–934

# An idealization of mitigation

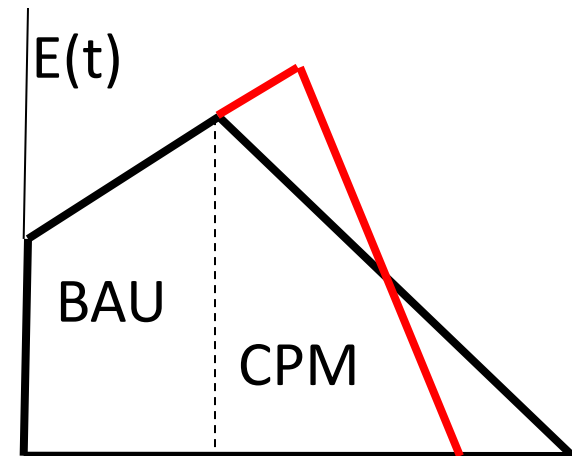


Today, approximately half of emissions are retained in the atmosphere and half move to other reservoirs.

# Procrastination and “Pace”



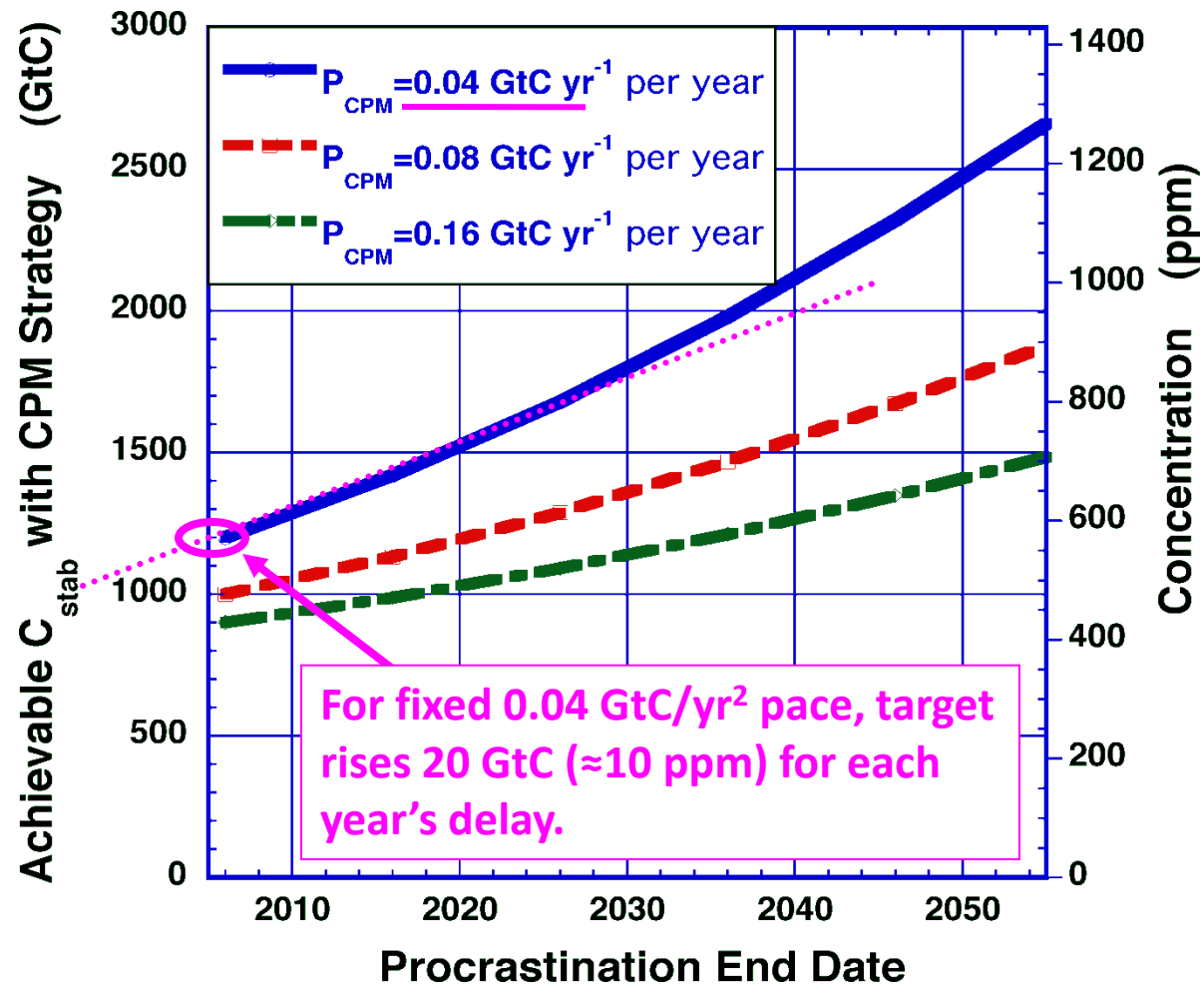
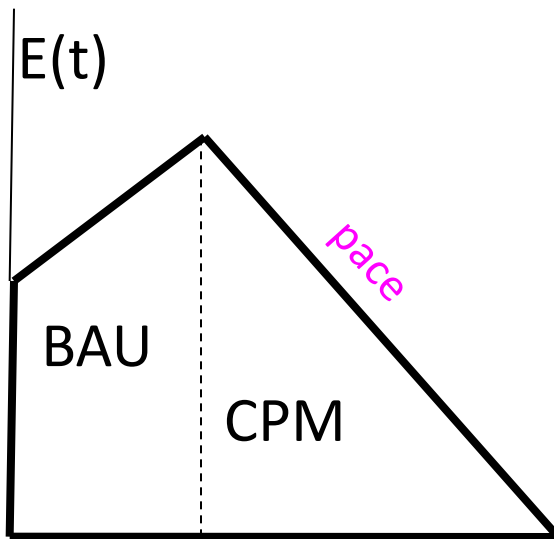
(1) Extra total emissions, because pace cannot be increased,



OR (2) Constant total emissions, with a faster pace.

# Procrastination and pace fix the target

Note: tC, not CO<sub>2</sub>!



Stabilization target ( $C_{stab}$ ) when Constant-Pace-Mitigation (CPM) follows Business as Usual (BAU) procrastination. During BAU,  $dE(t)/dt = 0.16 \text{ GtC/yr}^2$ . Throughout, half of CO<sub>2</sub> emissions stay in the atmosphere. *Source: Socolow-Lam, 2007.*

# Arguments for Delay (1 of 2)

## SCIENCE

- We don't know the science. Human activity may be having a negligible effect, swamped by natural variation.
- We may be having an effect, but the impacts are, on balance, favorable.

## TECHNOLOGY

- We do not yet have the tools to solve the problem.
- The tools to solve the problem that we have are far inferior to the tools we will have if we conduct R&D for a few decades.
- We have tools that could solve the problem, but they are too dangerous. The cures are worse than the disease.

# Arguments for Delay (2 of 2)

## POLITICS, ECONOMICS

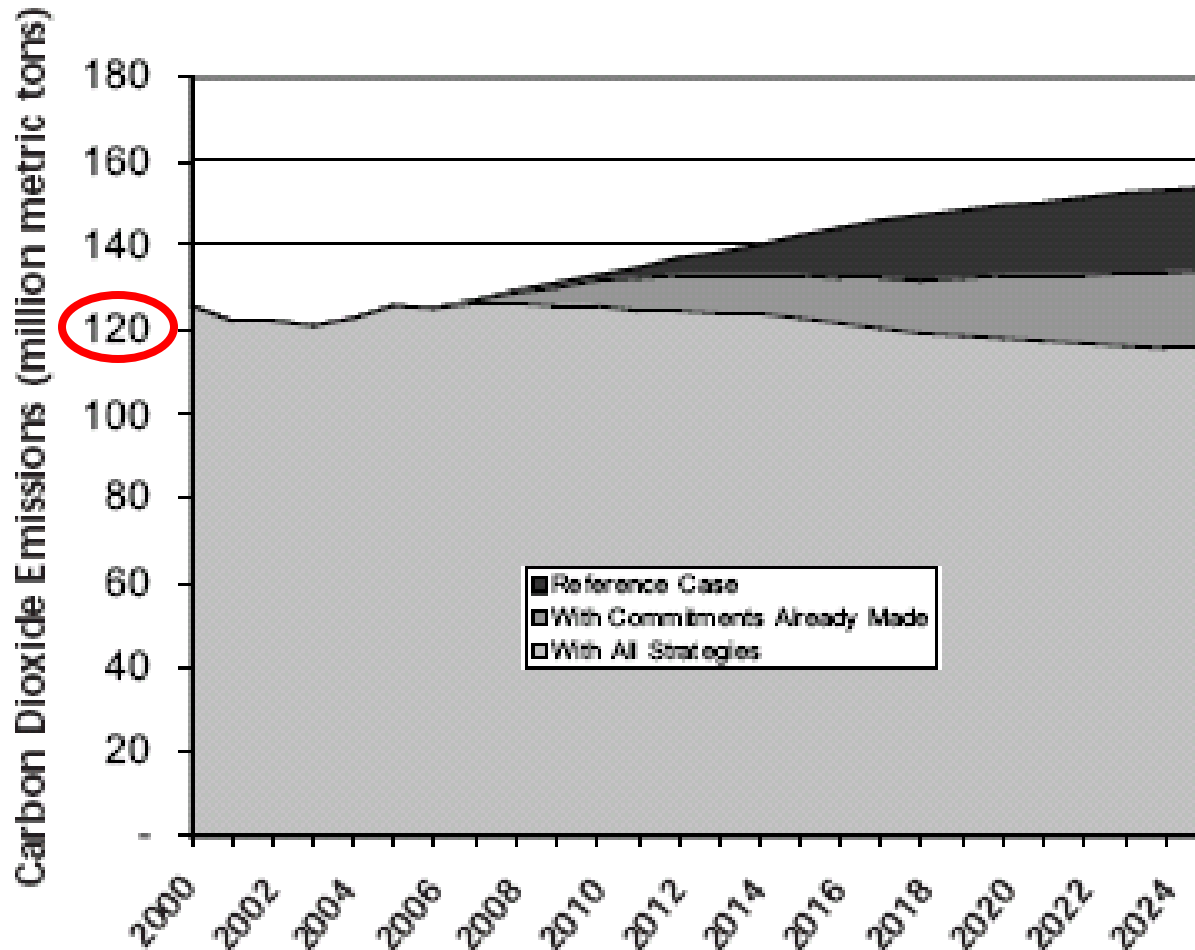
- The costs of mitigation are too high, relative to any willingness to pay.
- Government makes a mess of things when it intervenes in the economy.
- The world has more important things to do, notably to deal with world poverty.
- It is wasteful to engage developing countries in mitigation now, given that they will have much greater capacity for implementation later.
- Mitigation will hurt the poor in every country. Wait till we are richer.
- The net result will be to transfer wealth from rich to poor, not good policy.

## PHILOSOPHY

- Government should not run our lives.
- People aren't ready to tackle climate change – the issue is too abstract.
- Whatever the impacts, we can adapt to them.
- We should not play God. We should not control nature.

**BREAK**

# NJ CO<sub>2</sub> emissions goals



**Not included: CO<sub>2</sub> emissions from 28% imported power**

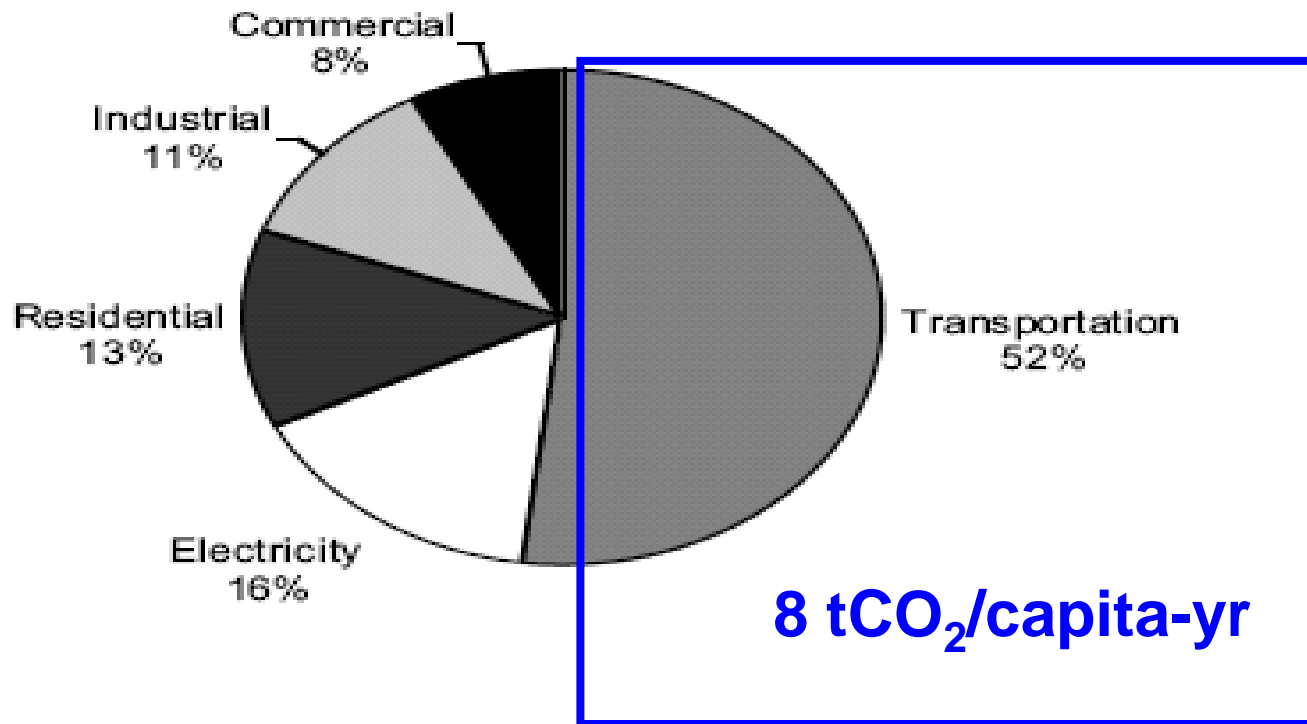
Source: *A Blueprint for Action: Policy Options to Reduce New Jersey's Contribution to Global Warming*, Environment New Jersey Research and Policy Center, September 2006.

**Total: 120 MtCO<sub>2</sub>/yr = 2% of U.S., 0.5% of world**

**Per capita: (120 MtCO<sub>2</sub>/yr)/8.7 M people = 13.8 tCO<sub>2</sub>/yr, 2/3 of U.S., 3x world.**

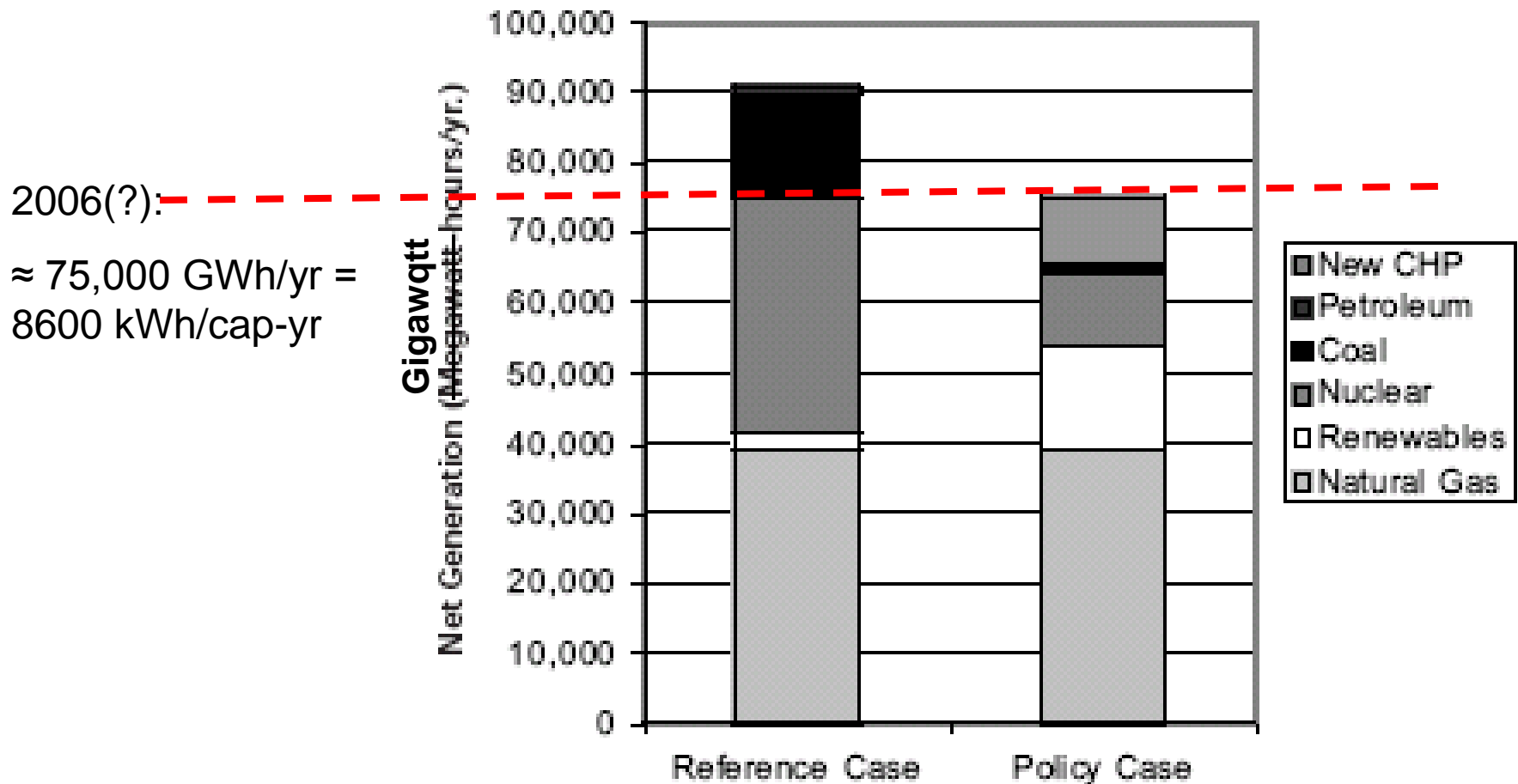
# Dominance of transport in NJ

## Sectoral CO<sub>2</sub> emissions, 2002



Source: *A Blueprint for Action: Policy Options to Reduce New Jersey's Contribution to Global Warming*, Environment New Jersey Research and Policy Center, September 2006.

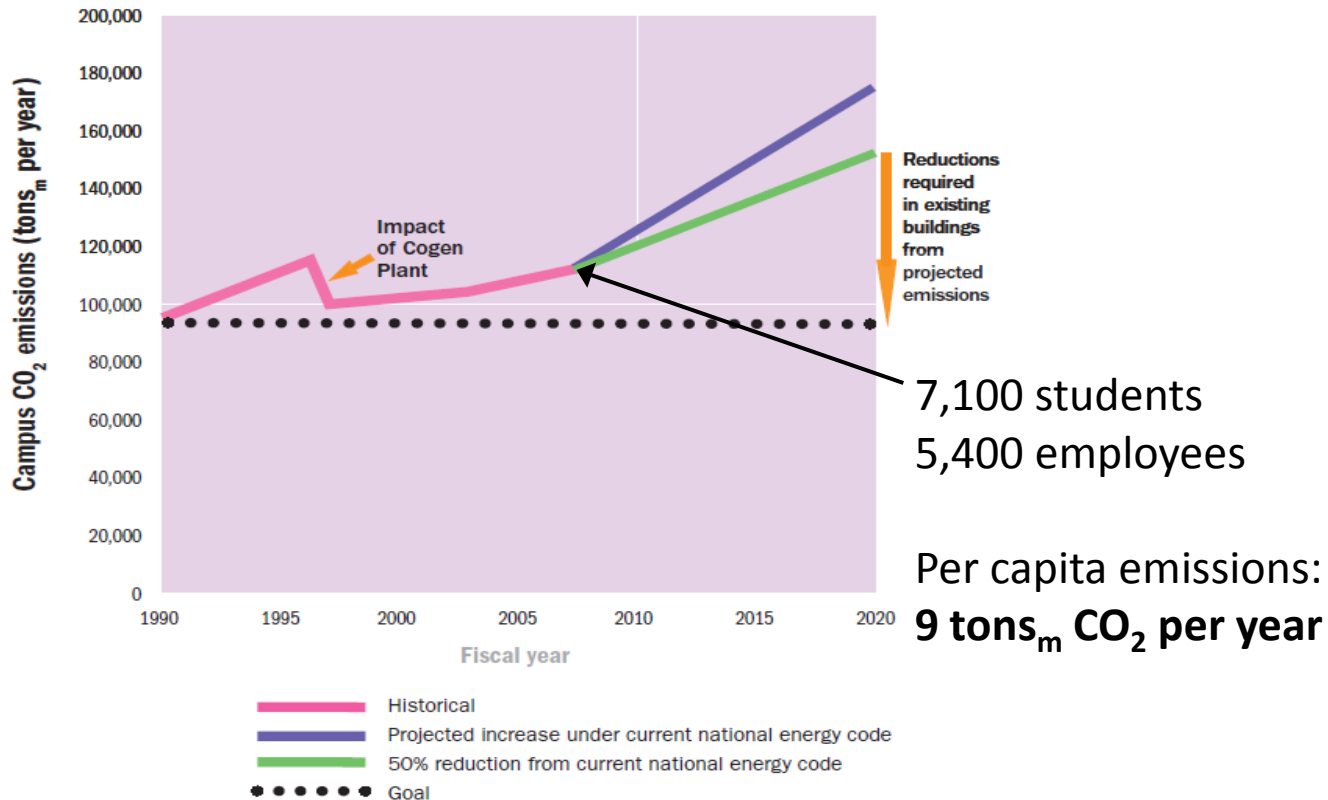
# Projected Net Generation of Electricity by Power Source, New Jersey, 2025



Source: *A Blueprint for Action: Policy Options to Reduce New Jersey's Contribution to Global Warming*, Environment New Jersey Research and Policy Center, September 2006.

# Princeton's CO<sub>2</sub> emissions goal

**Greenhouse Gas Reduction**  
Goal: Decrease campus CO<sub>2</sub> emissions to 1990 levels by 2020



Included: On-campus and external energy for cogeneration plant, fuel for vehicle fleet, but not travel to campus. *Note:* Princeton expects to add almost 2 million square feet of building space in the next 10 years.

# Goal-setting at Princeton

## GOALS

Princeton's Sustainability Plan sets ambitious goals in three areas:

1. greenhouse gas emissions reduction,
2. resource conservation,
3. research, education, and civic engagement.

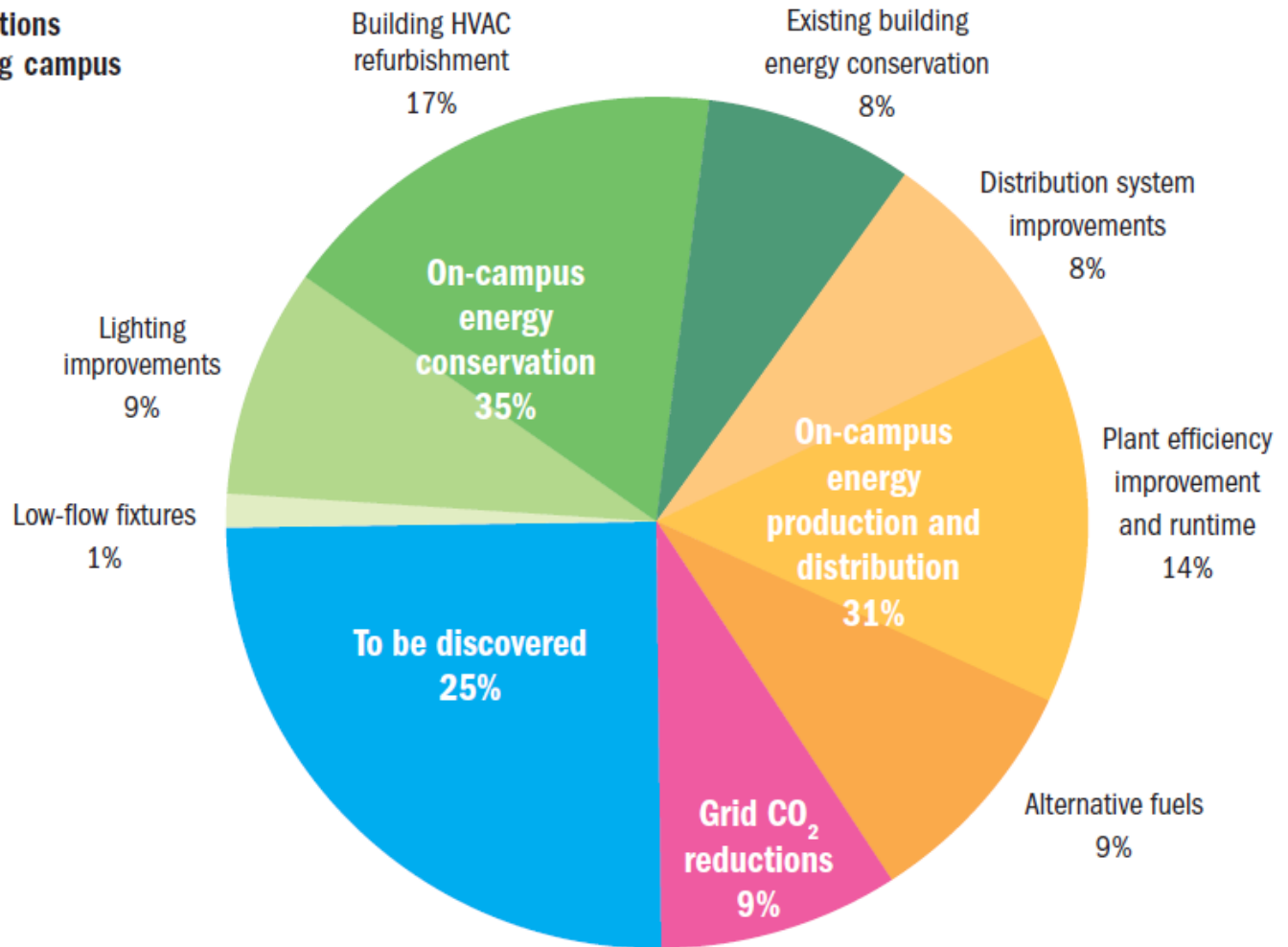
**Slides from “Examining Climate Change: the University Perspective,” in-class presentation from Matt Escarra, Matt Tilghman, and Matt Isakowitz, October 1, 2008.**

*Sources:*

Princeton sustainability brochure at  
<http://www.princeton.edu/sustainability/plan/SustainabilityBrochure.pdf>

Princeton sustainability plan at  
<http://www.princeton.edu/sustainability/plan/Sustainability-Plan-Doc.pdf>

**Greenhouse Gas Reduction**  
**Strategies to meet reductions**  
**required from the existing campus**



- Reduction of CO<sub>2</sub> emissions by 75,000 tons<sub>m</sub> per year in 2020
- No purchasing of emissions “offsets”
- Voluntary “CO<sub>2</sub> tax” when developing new building projects

# Surrogate Goals (1 of 3)

## *Definition of a surrogate goal*

A person who holds Goal A strongly and Goal B weakly, but believes that achieving Goal B will also achieve Goal A, can pursue Goal B as a *surrogate* for Goal A.

Usually, Goal A will be revealed only in special circumstances. Recognizing that a multiplicity of surrogate goals is at play has considerable explanatory power.

# Surrogate Goals (2 of 3)

## *Surrogate goals and climate change*

In the formulation of policy to deal with climate change, the general objective of slowing the rate of climate change is often a surrogate for more strongly held goals, such as:

- Augmenting financial transfers to developing countries
- Bringing the fossil fuel era to a close
- Curtailing consumerism and human centeredness
- Promoting self-sufficiency, autonomous communities
- Diminishing the power of technological elites
- Promoting environmental science
- Encouraging entrepreneurship

# Surrogate Goals (3 of 3)

A problem arises when an action in support of the surrogate goal negates the person's more strongly held goal.

Capturing and storing CO<sub>2</sub> prolongs the fossil fuel era.

Large and distant solar arrays and windfarms do not promote local self-reliance.

# Readings for Week 6:

## Energy efficiency and conservation (1 of 2)

### Classic Articles (Required)

Lovins, Amory B. 1976. "Energy strategy: The road not taken?." *Foreign Affairs*, October 1976.

Socolow, Robert, 1977. "The coming age of conservation." *Annual Review of Energy*, Vol 2: 239-289.

Socolow, Robert, 1994, Six Perspectives from Industrial Ecology. *Industrial Ecology and Global Change*. Cambridge University Press. Chapter 1.

### Required Readings

National Academy of Sciences, *America's Energy Future Report*. Chapter 4 on Energy Efficiency (pp. 135-202).

Lovins, Amory B., 2005, More Profit with Less Carbon. *Scientific American* Vol. 293 Issue 3 pg. 74-84 (September 2005).

Burton Richter, 2010, *Beyond Smoke and Mirrors: Climate Change and Energy in the 21st Century*. Cambridge University Press. Chapter 11 "Efficiency: the first priority."

# Readings for Week 6:

## Energy efficiency and conservation (2 of 2)

### **Recommended Readings**

Schumacher, E.F., 1973. *Small Is Beautiful: Economics as if People Mattered*. Perennial Library. Chapter: “Buddhist economics.”

Rybczynski, W., 1991. *Paper Heroes: Appropriate Technology: Panacea or Pipe Dream?* Penguin Books. Chapter 1: What is appropriate technology?

Tim Aldrich, Tim, 2005, ed.. *About Time: Speed, Society, People and the Environment*, Forum for the Future. Chapter 4: Living time; Chapter 6: Time and money; Chapter 9 Time and technology.

# Outline for Lecture 5

The discourse about the future

Scenarios

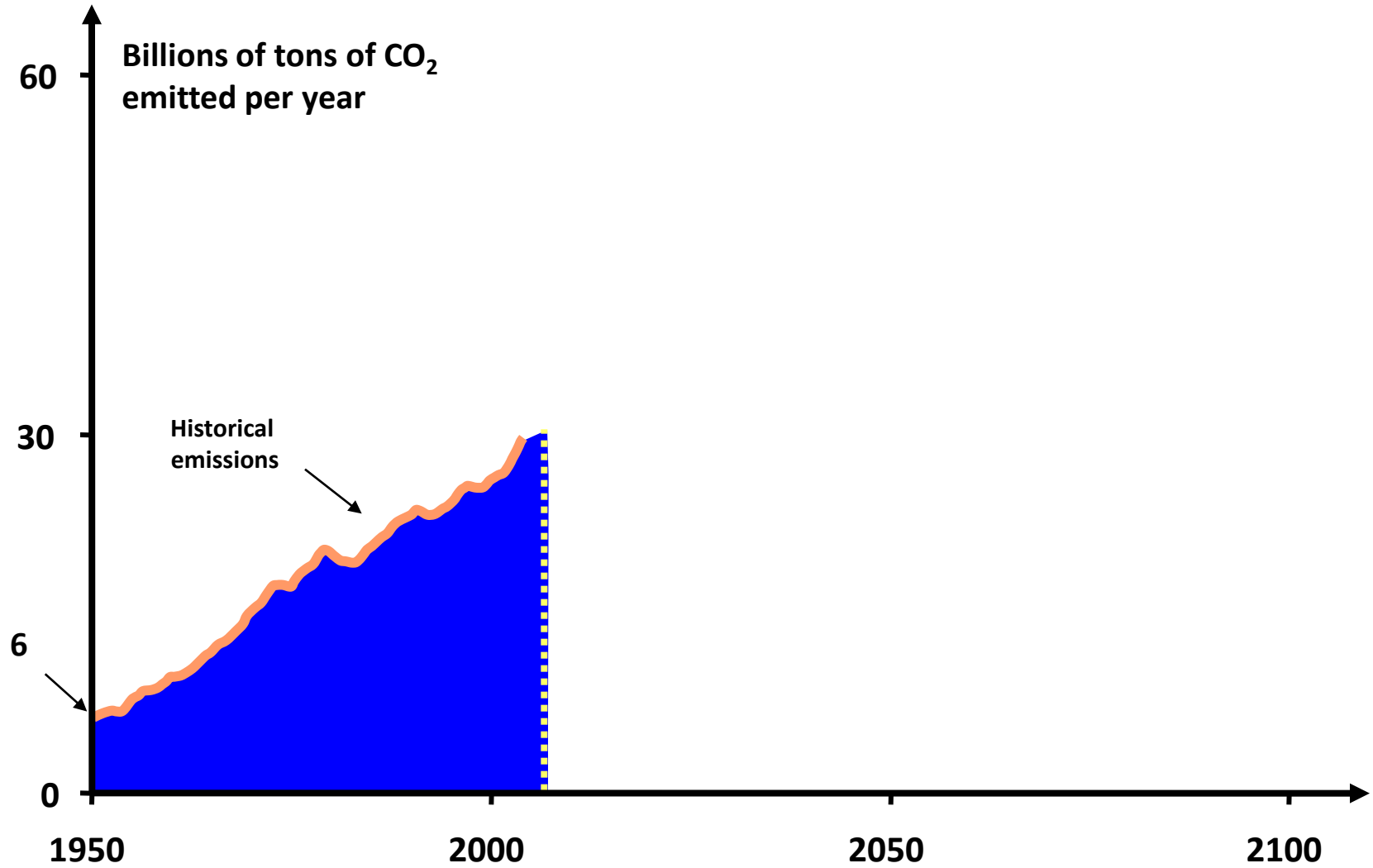
Targets and timetables

Available technologies and the wedge model

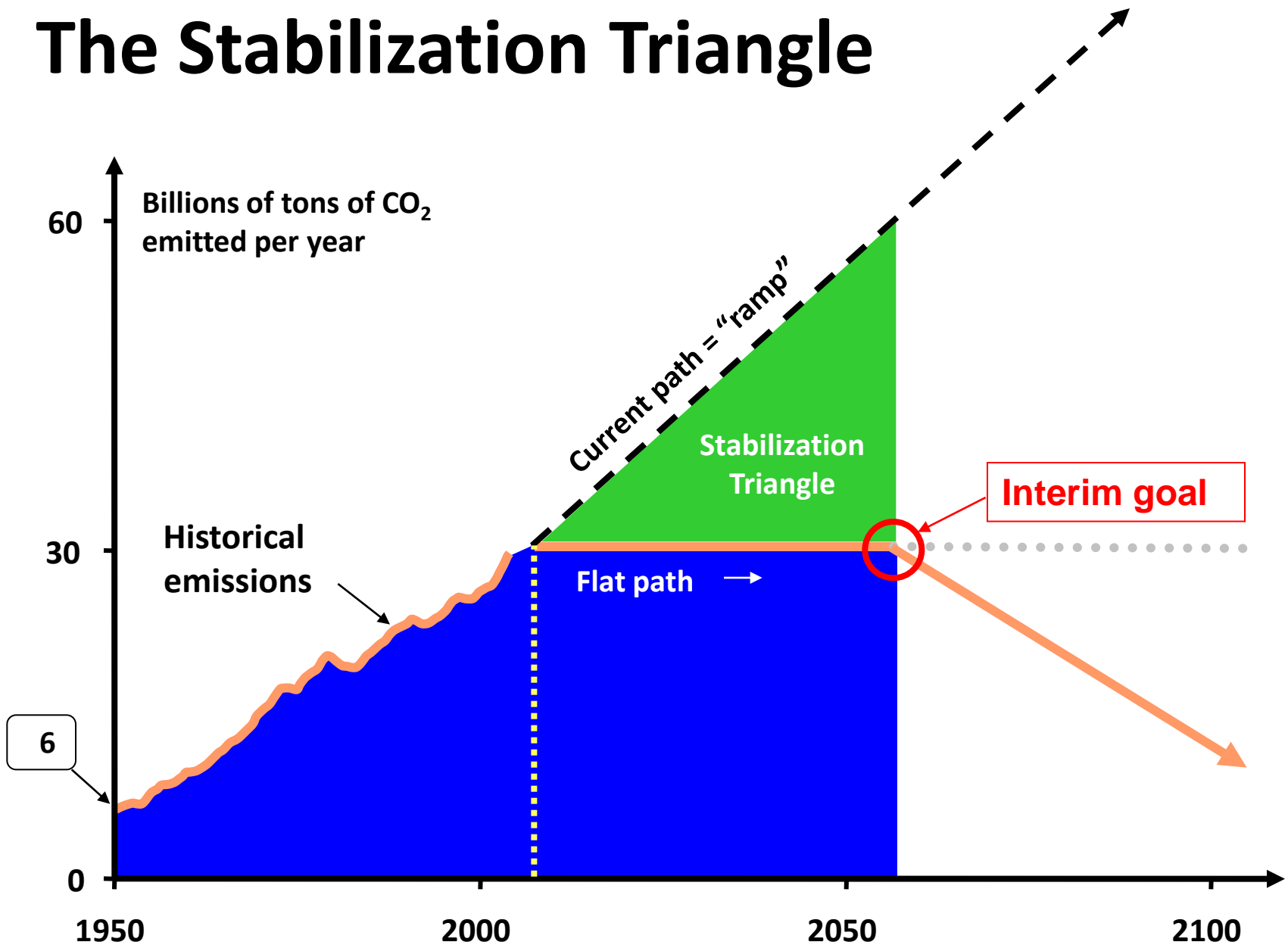
# Einstein's advice

“Make everything as simple as possible, but no simpler.”

# Historical Emissions

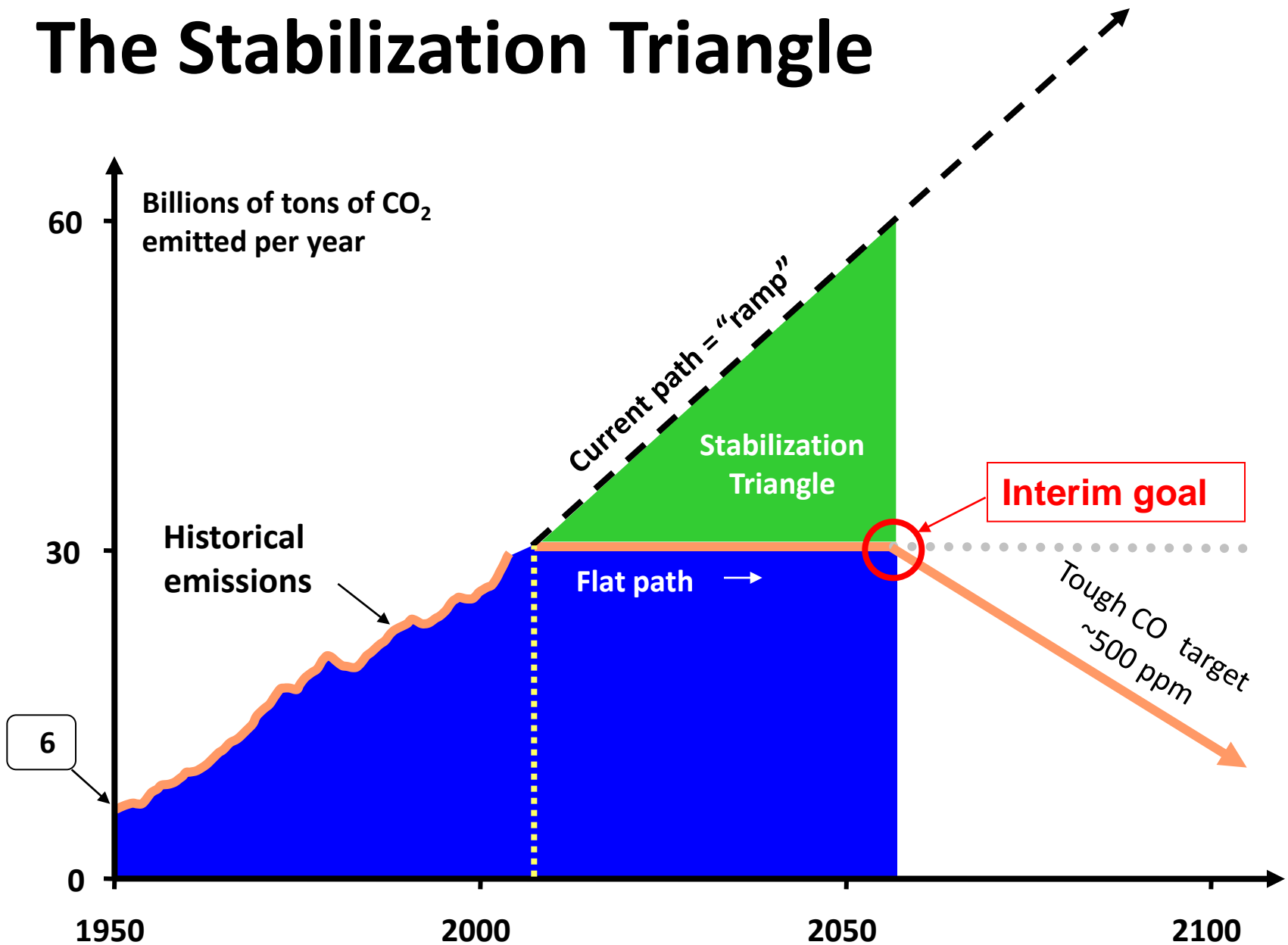


# The Stabilization Triangle



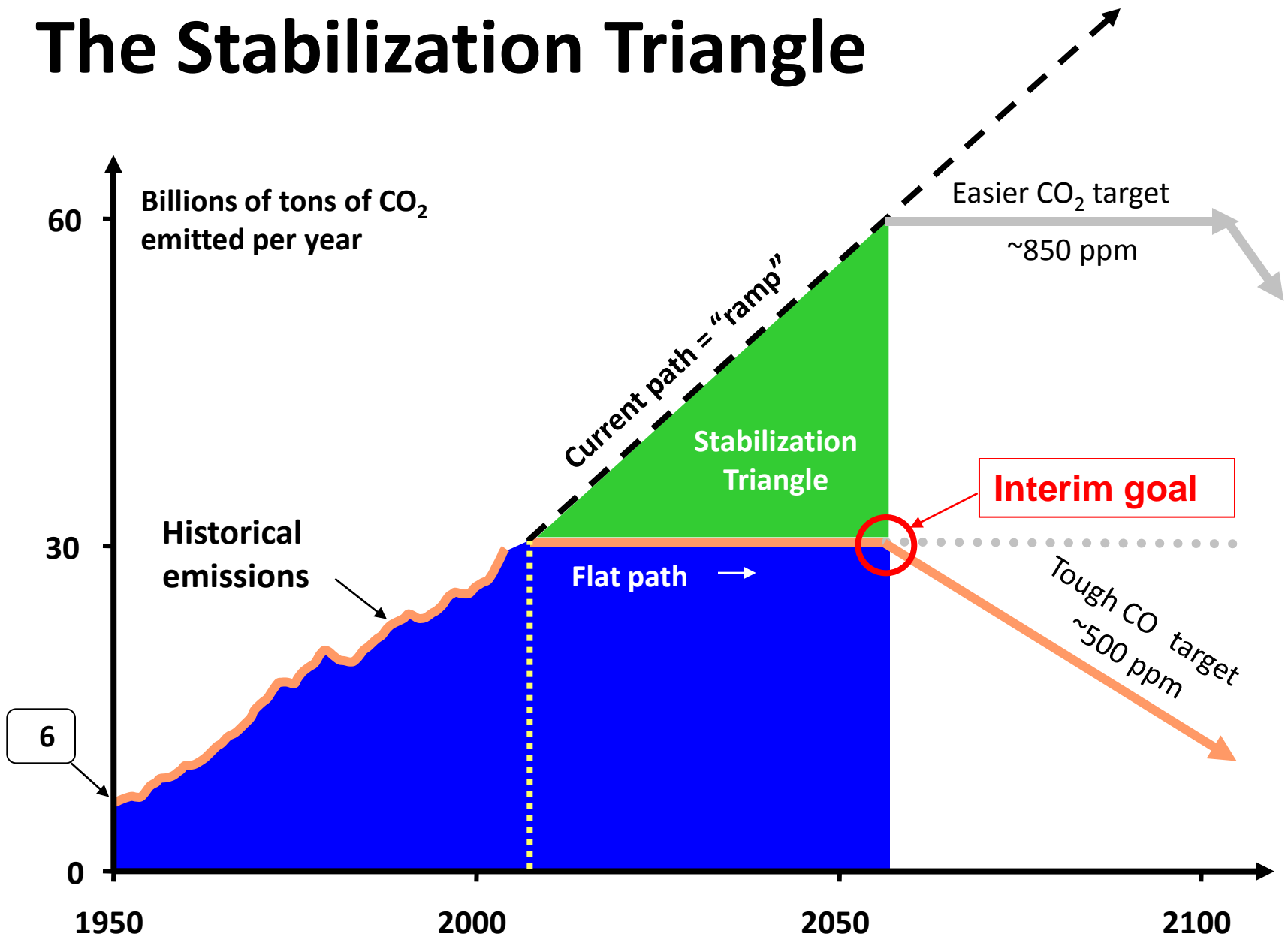
Today and for the interim goal, global per-capita emissions are  $\approx 4$  to  $5$  tCO<sub>2</sub>/yr.

# The Stabilization Triangle

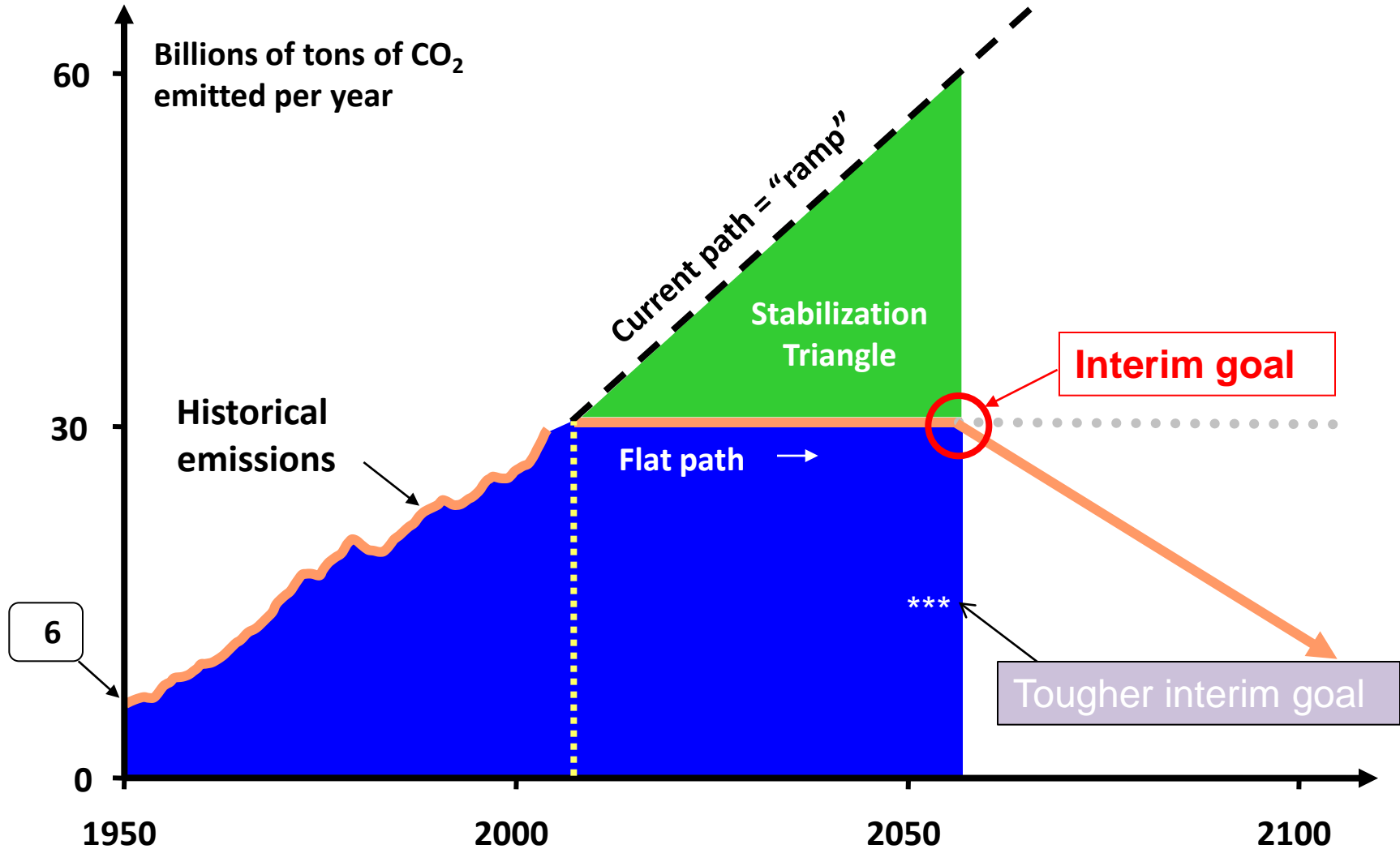


Today and for the interim goal, global per-capita emissions are  $\approx 4$  to  $5$  tCO<sub>2</sub>/yr.

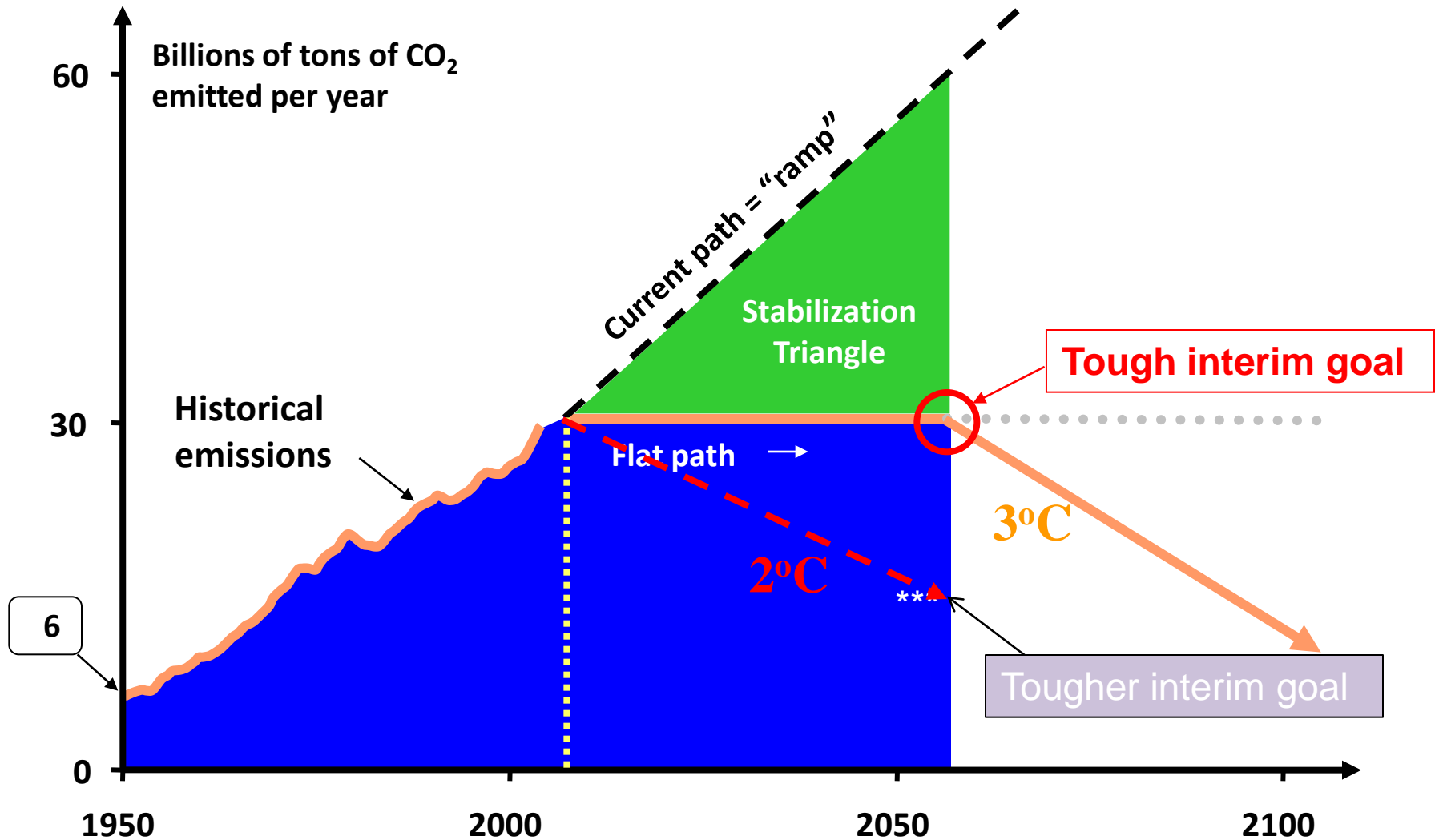
# The Stabilization Triangle



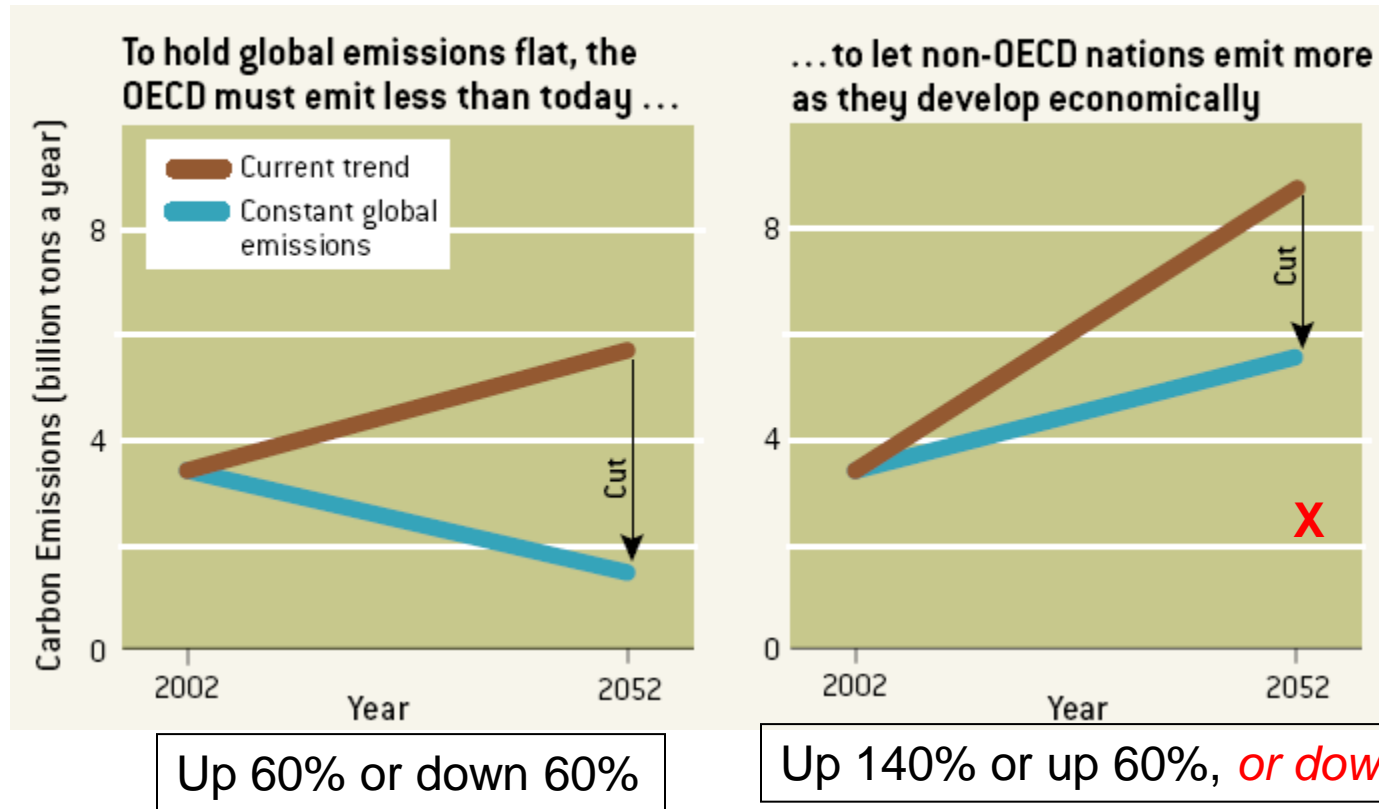
# “The target isn’t tough enough”



# “The target isn't tough enough”



# “Flat” vs. “down 50%” is about the developing world’s emissions



Analysis of low-carbon industrialization has been far too casual for me to be comfortable endorsing the lower fifty-year target at this time.

The developing world will decide what  
kind of planet we live on.

For a while longer, the industrialized  
countries will lead.

# *Iterative* risk management: the basis for a renewed commitment

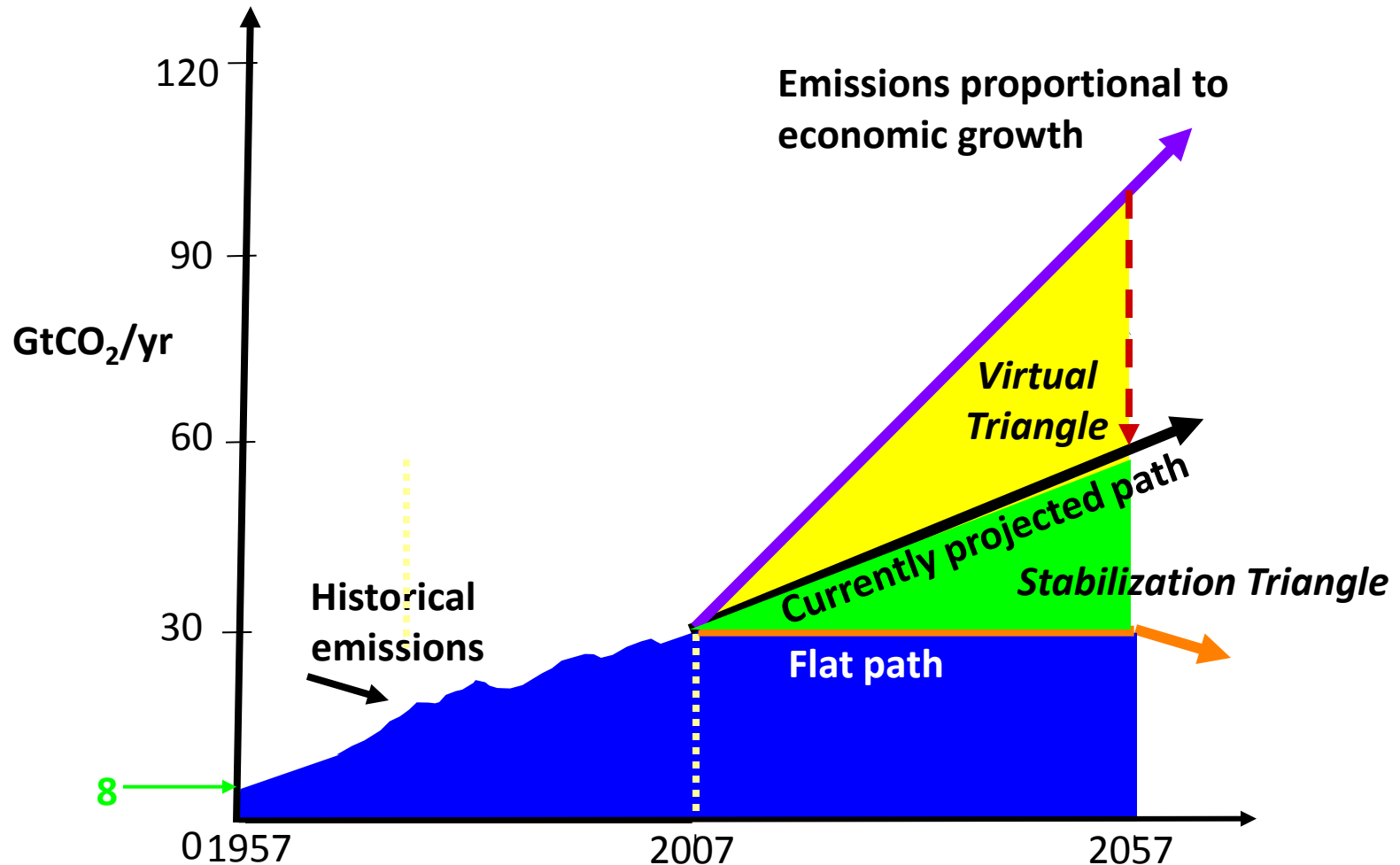
In another decade we'll know a lot more about the earth, both because of new climate science and because of what the earth tells us about itself.

We'll also know more about the solutions themselves, thanks to both R&D and field experience.

All this argues for making decisions *iteratively*.

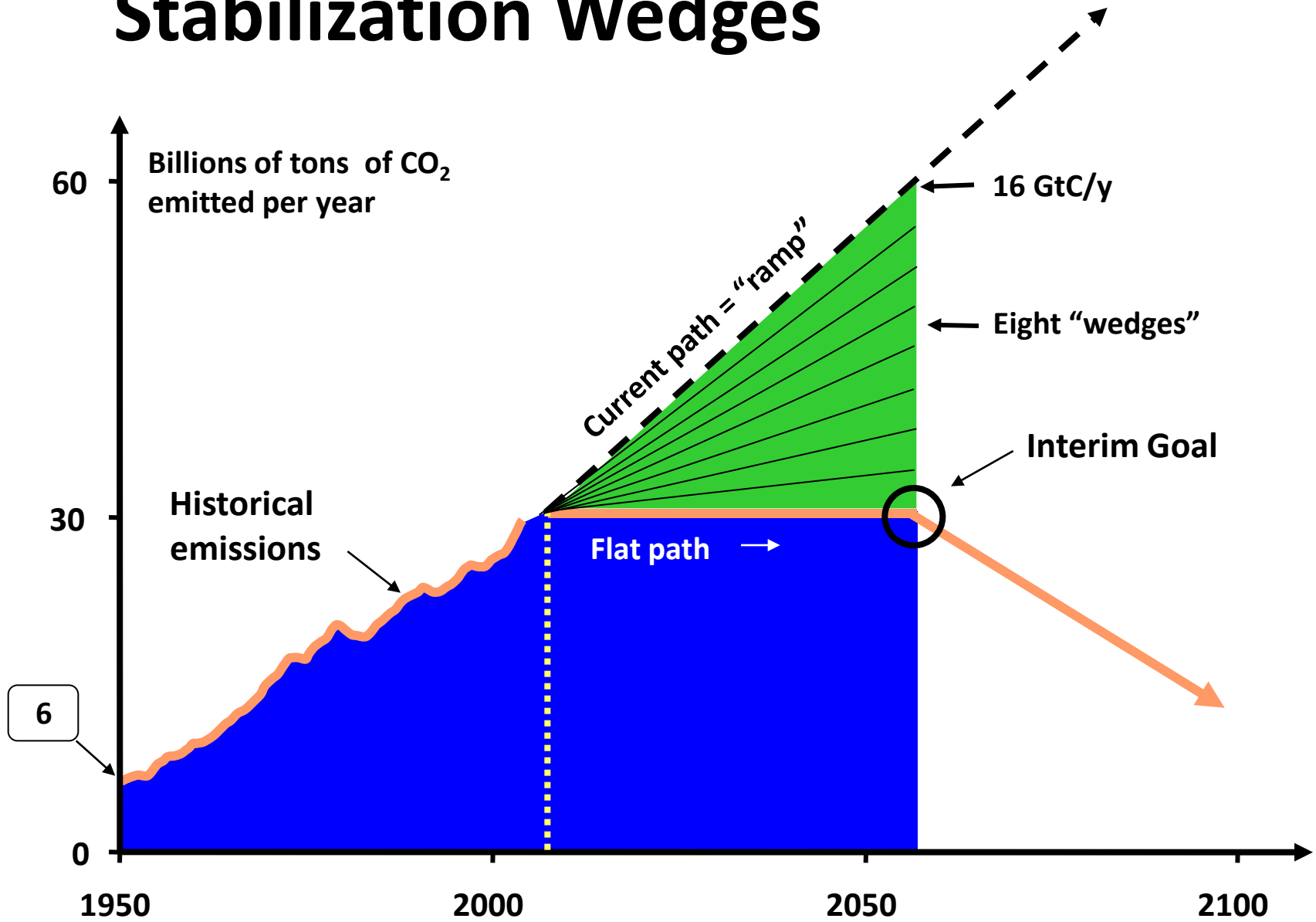
Specifically, we can wait at least a decade before deciding whether 1) flat emissions are as heroic an outcome as we can achieve safely and equitably, or 2) whether we can achieve still more.

# The Virtual Triangle: Large Carbon Savings Are Already in the Baseline



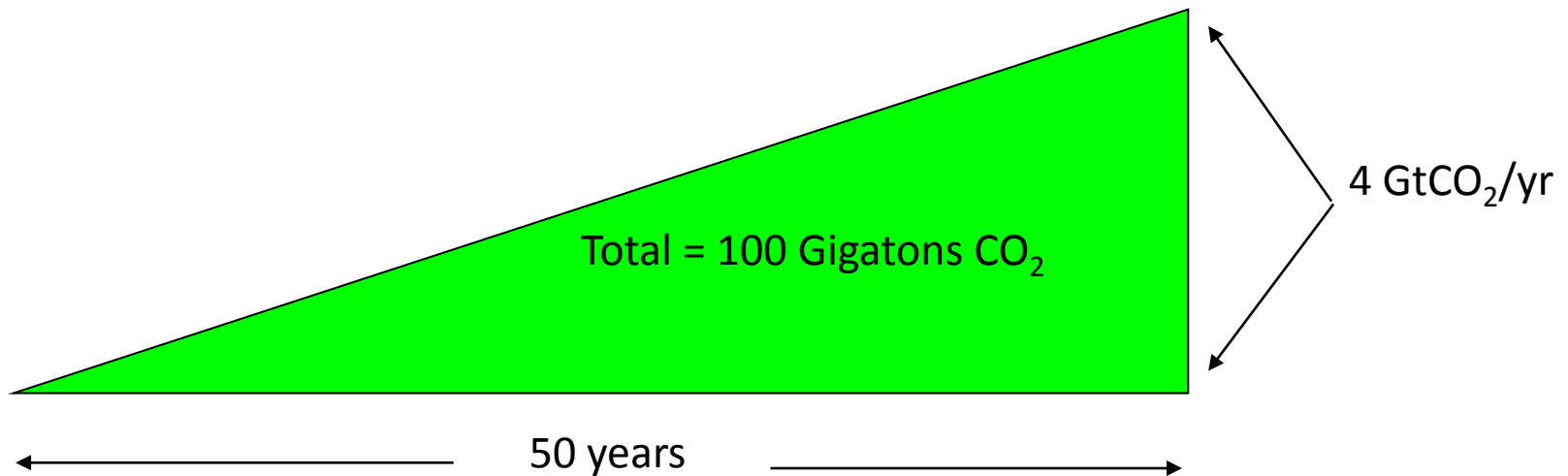
Models differ widely in their estimates of contributions to the virtual triangle from structural shifts (toward services), energy efficiency, and carbon-free energy.

# Stabilization Wedges



# What is a “Wedge”?

A “wedge” is a strategy to reduce carbon emissions that grows in 50 years from zero to 4 GtCO<sub>2</sub>/yr. The strategy has already been commercialized at scale somewhere.

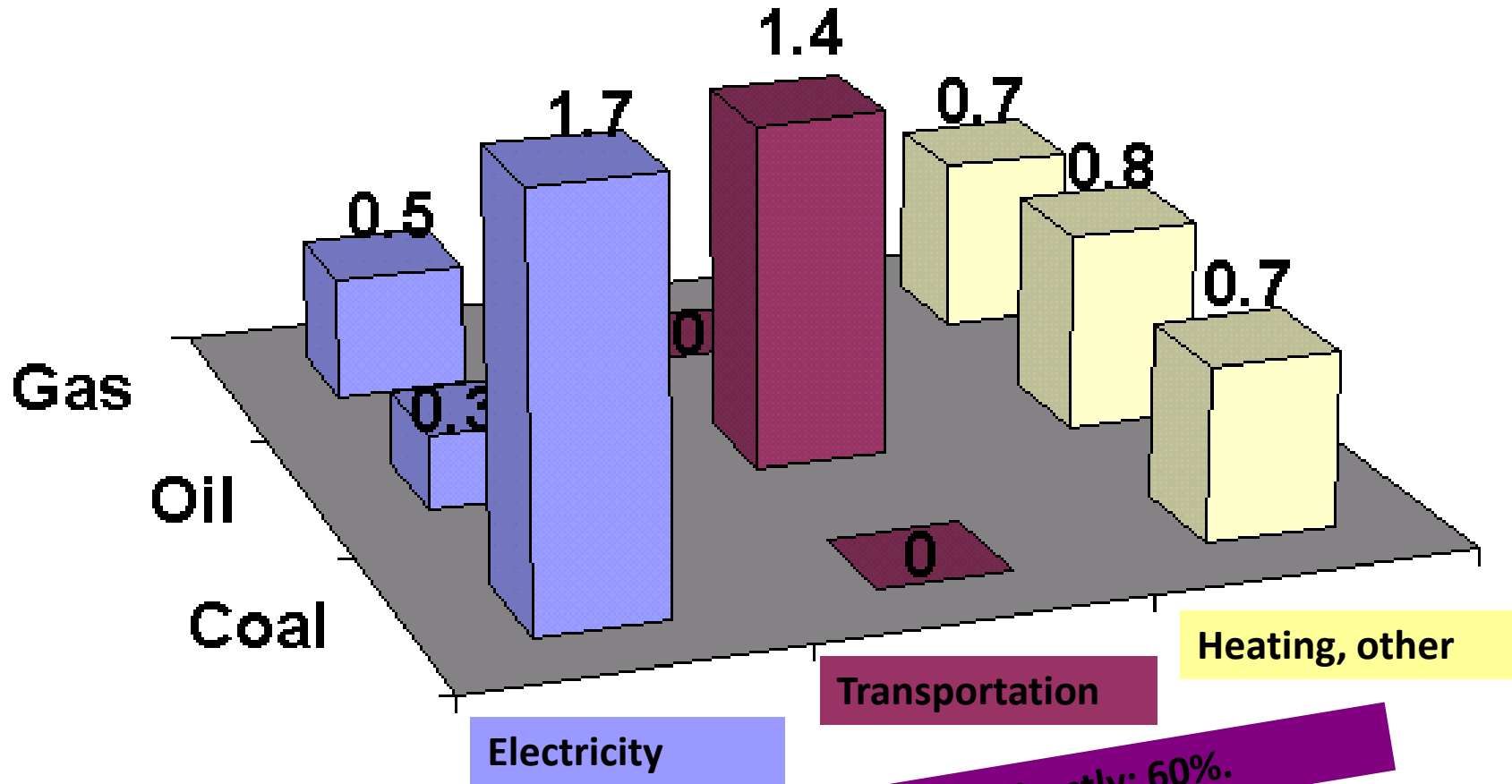


Cumulatively, a wedge redirects the flow of 100 GtCO<sub>2</sub> in its first 50 years. This is **six trillion dollars** at \$60/tCO<sub>2</sub>.

A “solution” to the CO<sub>2</sub> problem should provide at least one wedge.

# Global CO<sub>2</sub> Emissions by Sector and Fuel

Allocation of 6.2 GtC/yr (22.7 GtCO<sub>2</sub>/yr) emitted in 2000

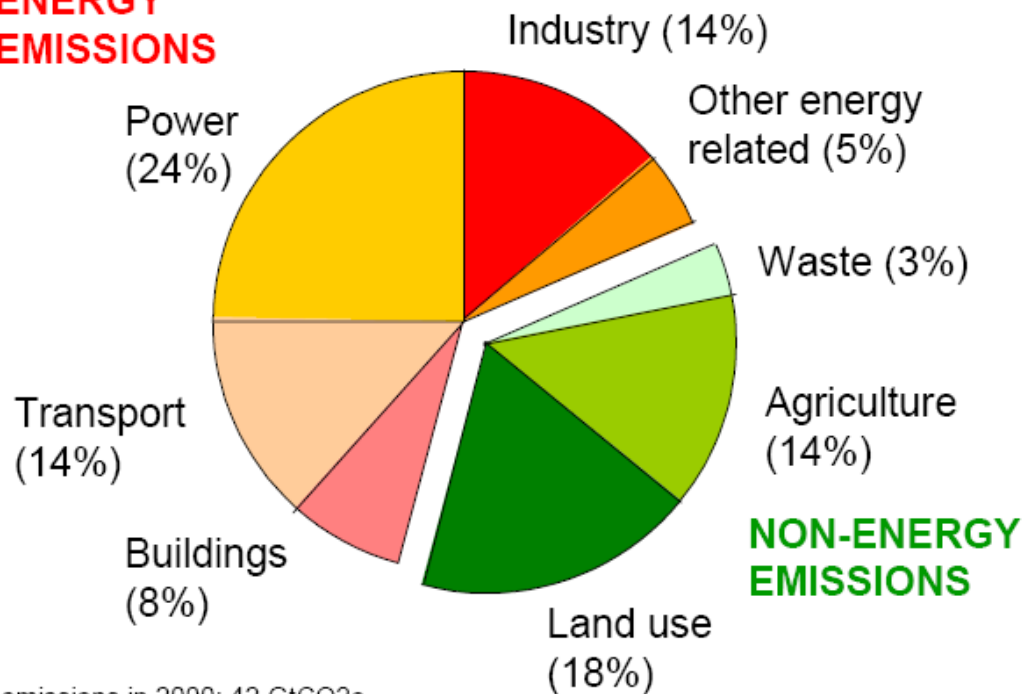


Electricity: 40%; fuels used directly: 60%.

# Global GHG emissions, by source

Figure 1 Greenhouse-gas emissions in 2000, by source

## ENERGY EMISSIONS



Total emissions in 2000: 42 GtCO<sub>2</sub>e.

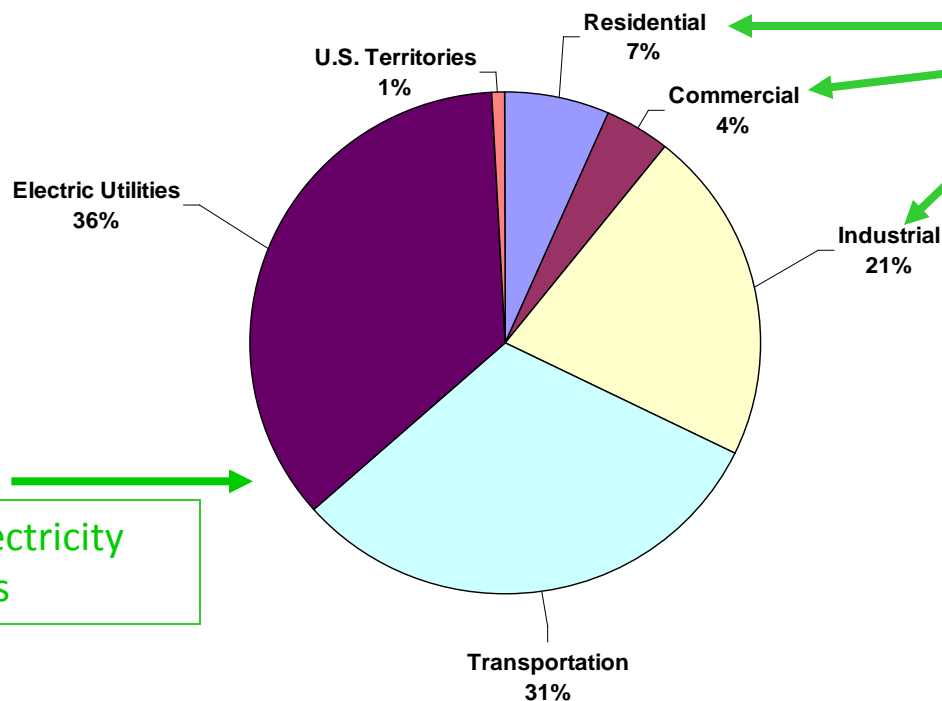
Energy emissions are mostly CO<sub>2</sub> (some non-CO<sub>2</sub> in industry and other energy related).

Non-energy emissions are CO<sub>2</sub> (land use) and non-CO<sub>2</sub> (agriculture and waste).

## NON-ENERGY EMISSIONS

**Source:** Prepared by Stern Review, from data drawn from World Resources Institute Climate Analysis Indicators Tool (CAIT) on-line database version 3.0.

# Sources of U.S. CO<sub>2</sub> Emissions, 1999

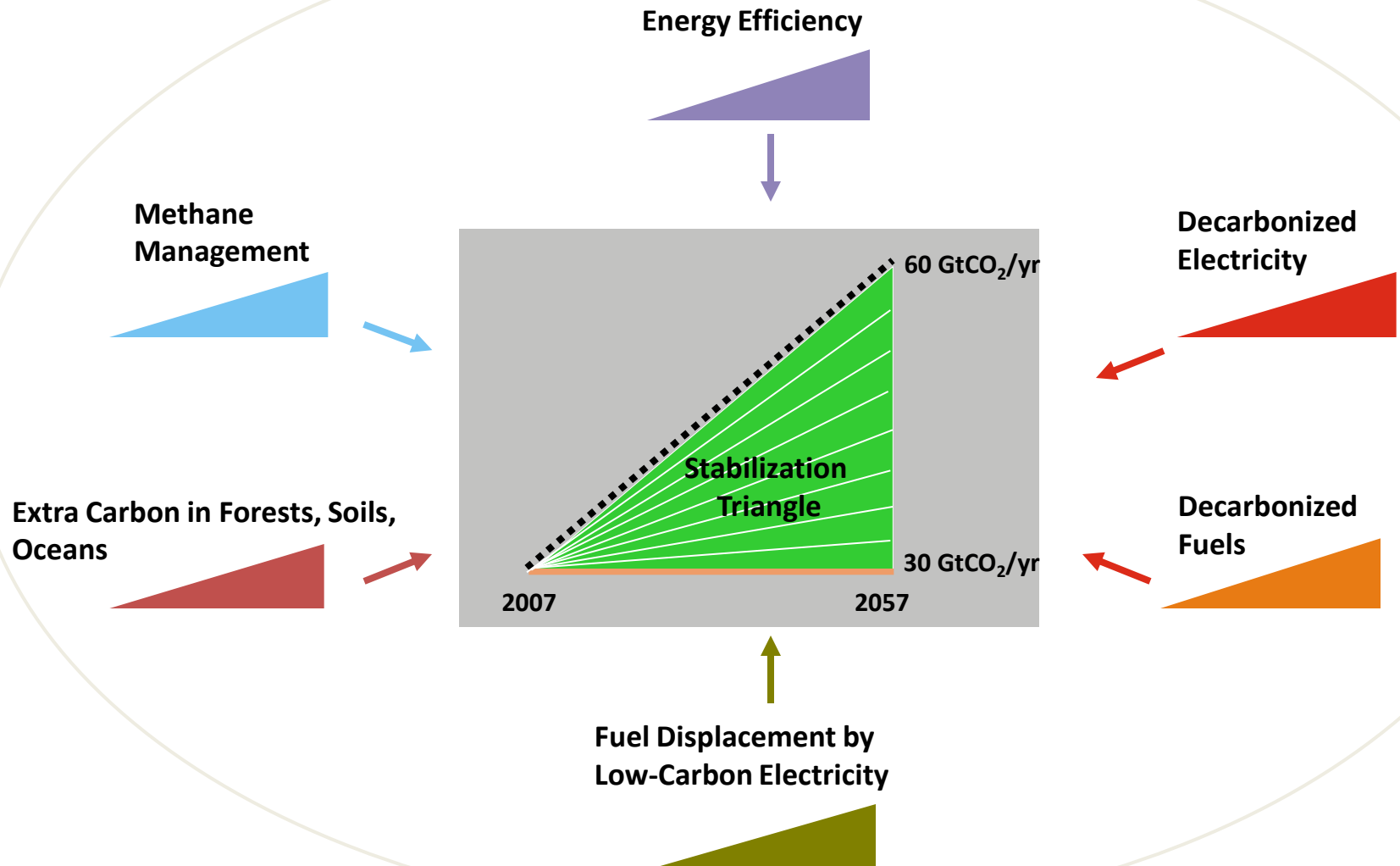


Note: 70% of electricity goes to buildings

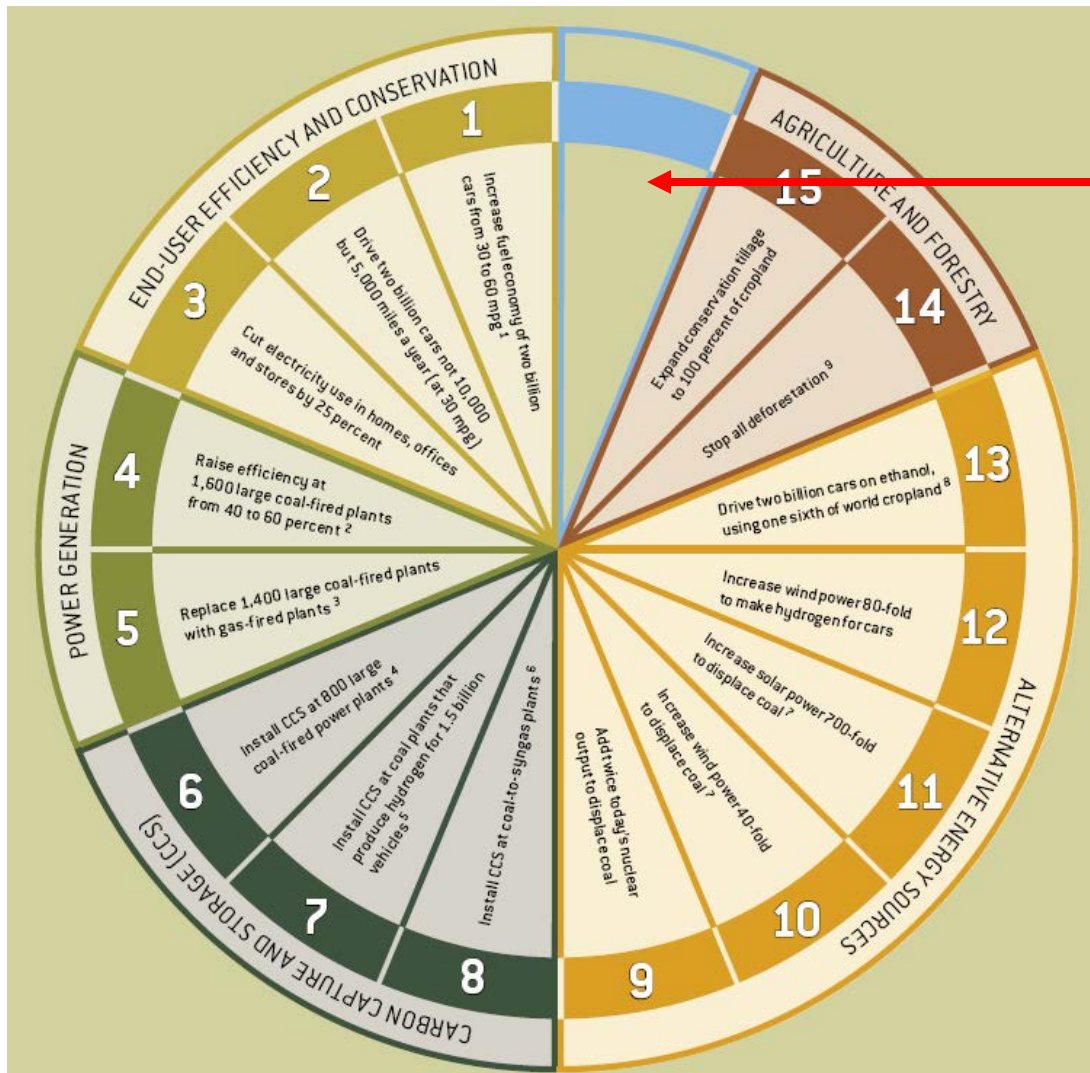
Direct use of fuel in stationary applications

U.S. total in 1999, 4600 MtCO<sub>2</sub>  
(U.S. fractional use) – (World fractional use):  
Electricity: -5%  
Transportation: +8%  
Direct fuel use in stationary applications: -3%

# Fill the Stabilization Triangle with Eight Wedges in six broad categories



# 15 Ways to Make a Wedge



Industrial energy efficiency  
 "Upstream" investment  
 Concentrated solar power  
 Methane mitigation  
 Population

*Not commercial, so not included:*

Fusion  
 Capture of CO<sub>2</sub> from air

# Dartboard notes



## Notes:

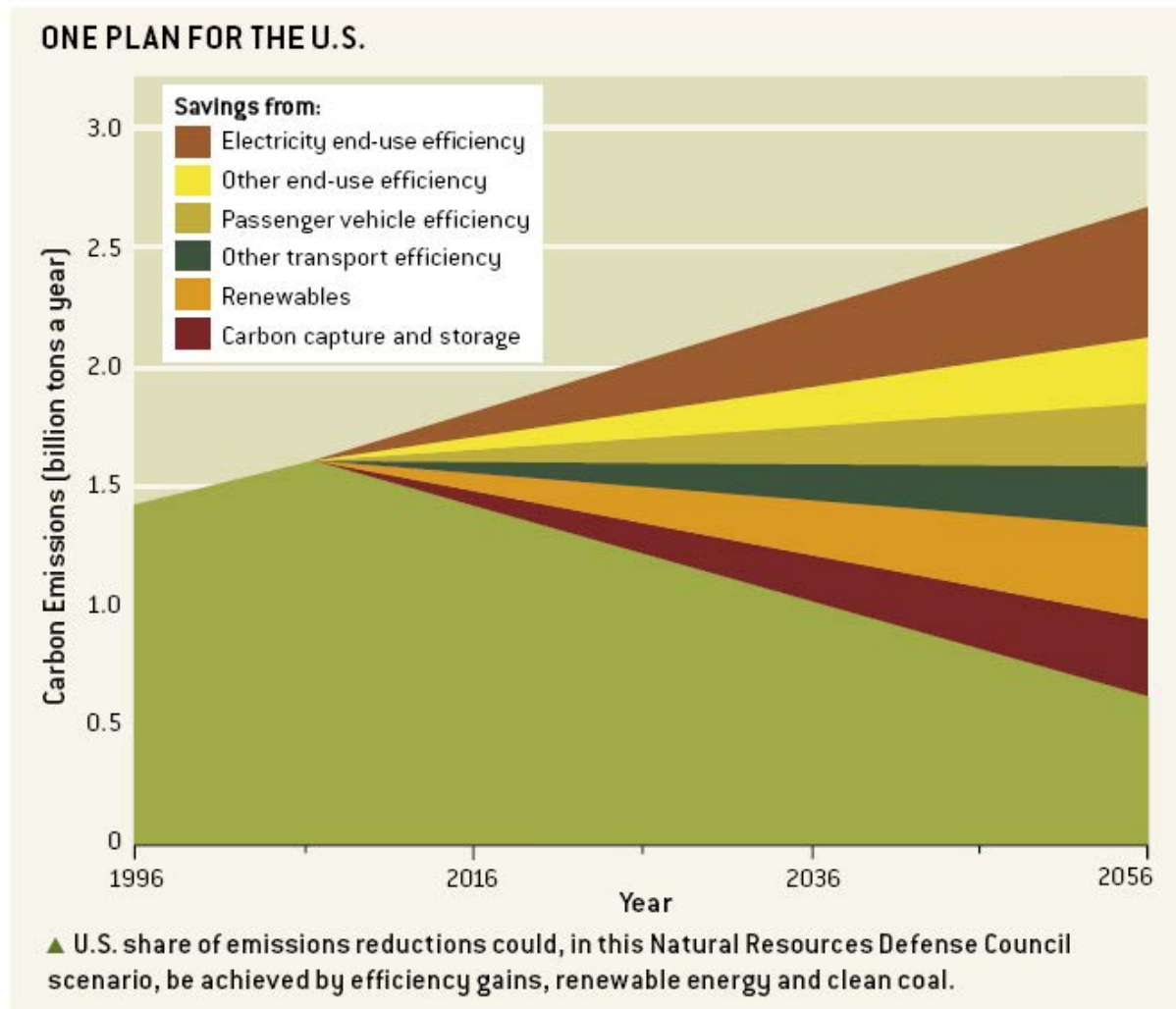
- 1 World fleet size in 2056 could well be two billion cars. Assume they average 10,000 miles a year.
- 2 "Large" is one-gigawatt (GW) capacity. Plants run 90 percent of the time.
- 3 Here and below, assume coal plants run 90 percent of the time at 50 percent efficiency. Present coal power output is equivalent to 800 such plants.
- 4 Assume 90 percent of CO<sub>2</sub> is captured.
- 5 Assume a car (10,000 miles a year, 60 miles per gallon equivalent) requires 170 kilograms of hydrogen a year.
- 6 Assume 30 million barrels of synfuels a day, about a third of today's total oil production. Assume half of carbon originally in the coal is captured.
- 7 Assume wind and solar produce, on average, 30 percent of peak power. Thus replace 2,100 GW of 90-percent-time coal power with 2,100 GW (peak) wind or solar plus 1,400 GW of load-following coal power, for net displacement of 700 GW.
- 8 Assume 60-mpg cars, 10,000 miles a year, biomass yield of 15 tons a hectare, and negligible fossil-fuel inputs. World cropland is 1,500 million hectares.
- 9 Carbon emissions from deforestation are currently about two billion tons a year. Assume that by 2056 the rate falls by half in the business-as-usual projection and to zero in the flat path.

“The Wedge Model is the iPod of climate change: You fill it with your favorite things.”

David Hawkins, NRDC, 2007.

Therefore, prepare to negotiate with others, who have different favorite things.

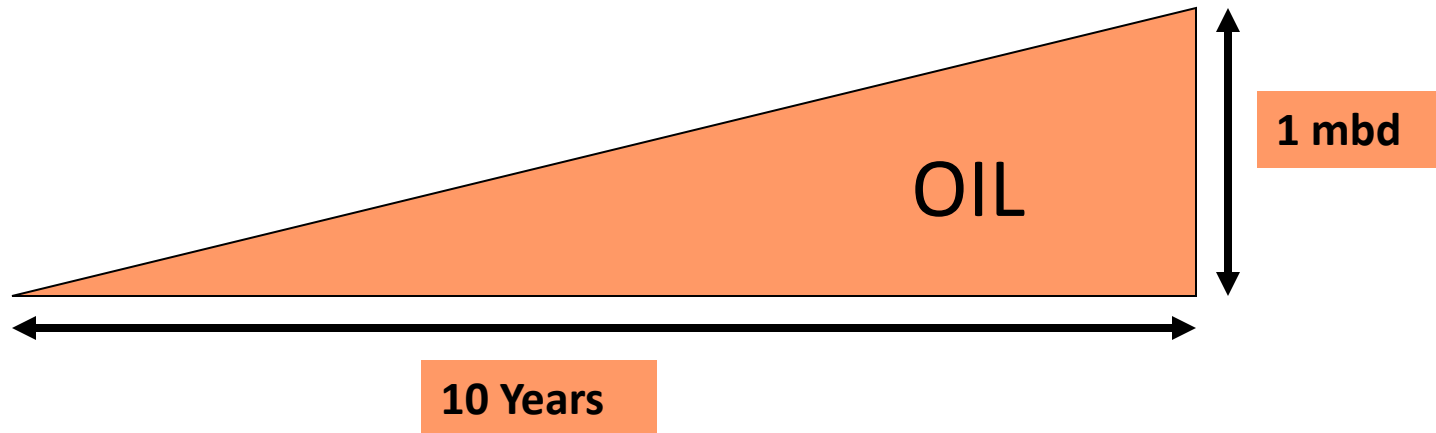
# U.S. Wedges



Source: Lashof and Hawkins, NRDC, in Socolow and Pacala, *Scientific American*, September 2006, p. 57

# The Analogous Oil Wedge

1 oil wedge is a strategy or campaign that results in the reduction of pressure on oil markets (by either supply augmentation or demand reduction) by 1 million barrels per day after 10 years.



This is a much smaller wedge than the carbon stabilization wedge:

Much smaller vertical dimension:  $26 \times (1 \text{ mbd}) = 4 \text{ GtCO}_2/\text{yr}$ .

Smaller slope:  $5.2^* (1 \text{ mbd}/10 \text{ yr}) = (4 \text{ GtCO}_2/\text{yr})/50 \text{ yr}$

At \$55/bbl, area of oil wedge is \$100 billion (30 times smaller).

For the next few lectures  
we go on a hunt for wedges