Mitigating Climate Change

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Guest lecture in:
“Global Environmental Change: Science, Technology, Policy”

Profs. Eric Wood and Justin Sheffield

November 26, 2012

Outline

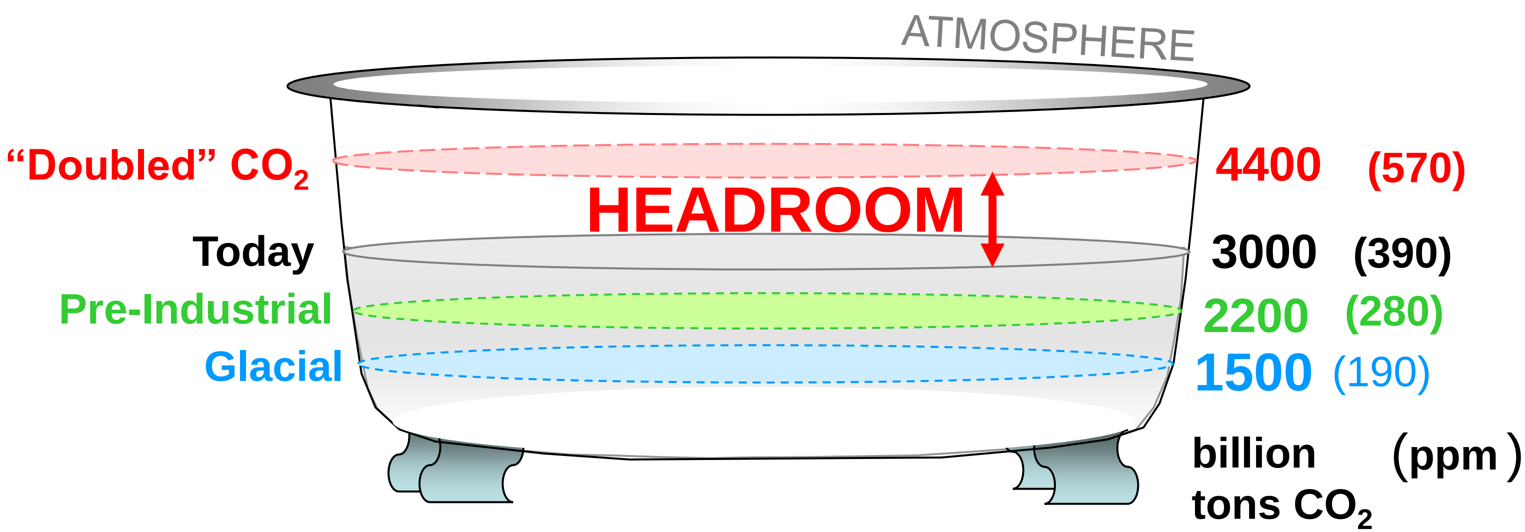
Carbon math

The wedge model

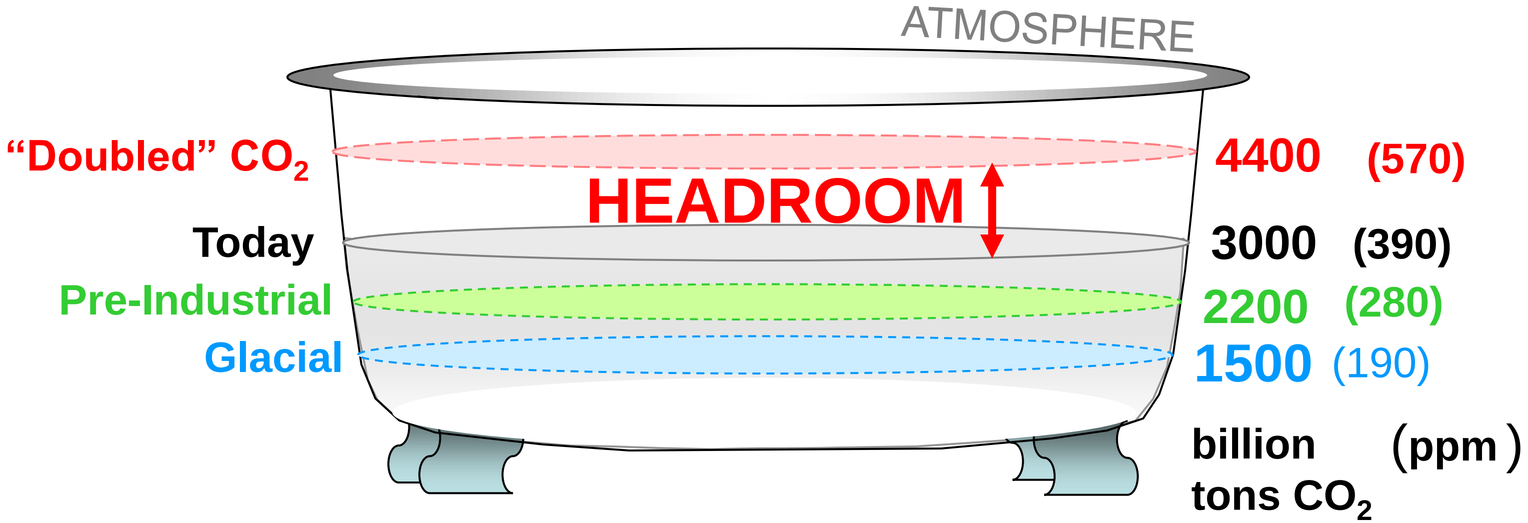
Some specific mitigation options

General thoughts

Past, present, and potential future levels of CO_2 in the atmosphere



Past, present, and potential future levels of CO_2 in the atmosphere

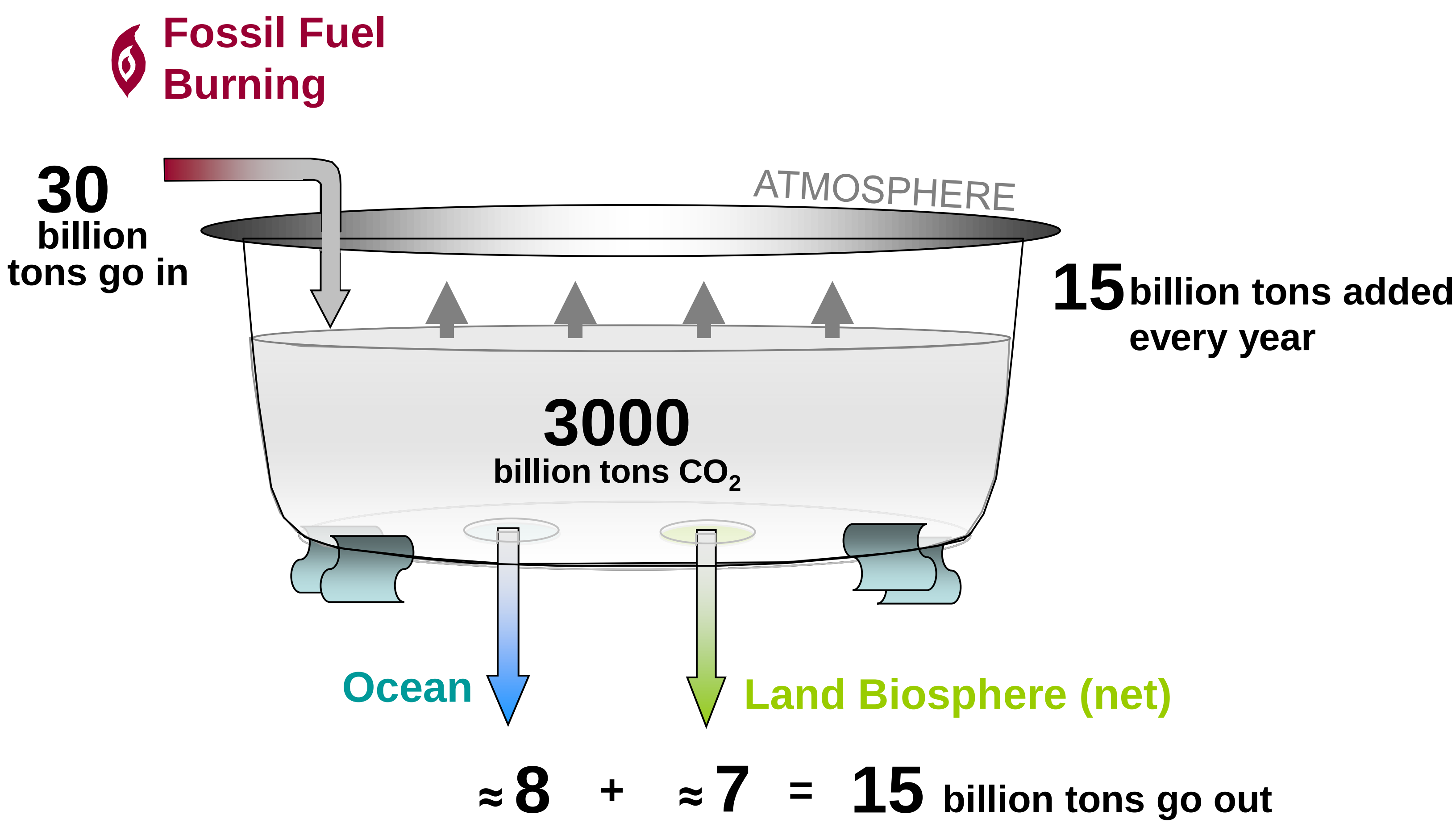


Rosetta Stone: To raise the concentration of CO_2 in the atmosphere by **one part per million:**

add **7.8 billion tons of CO_2,**

in which are **2.1 billon tons of carbon.**

About half of the CO_2 we burn stays in the atmosphere for centuries



Today, global per-capita emissions are ≈ 4 tCO_2/yr.

Four ways to emit 4 ton CO_2/yr (today's global per capita average)

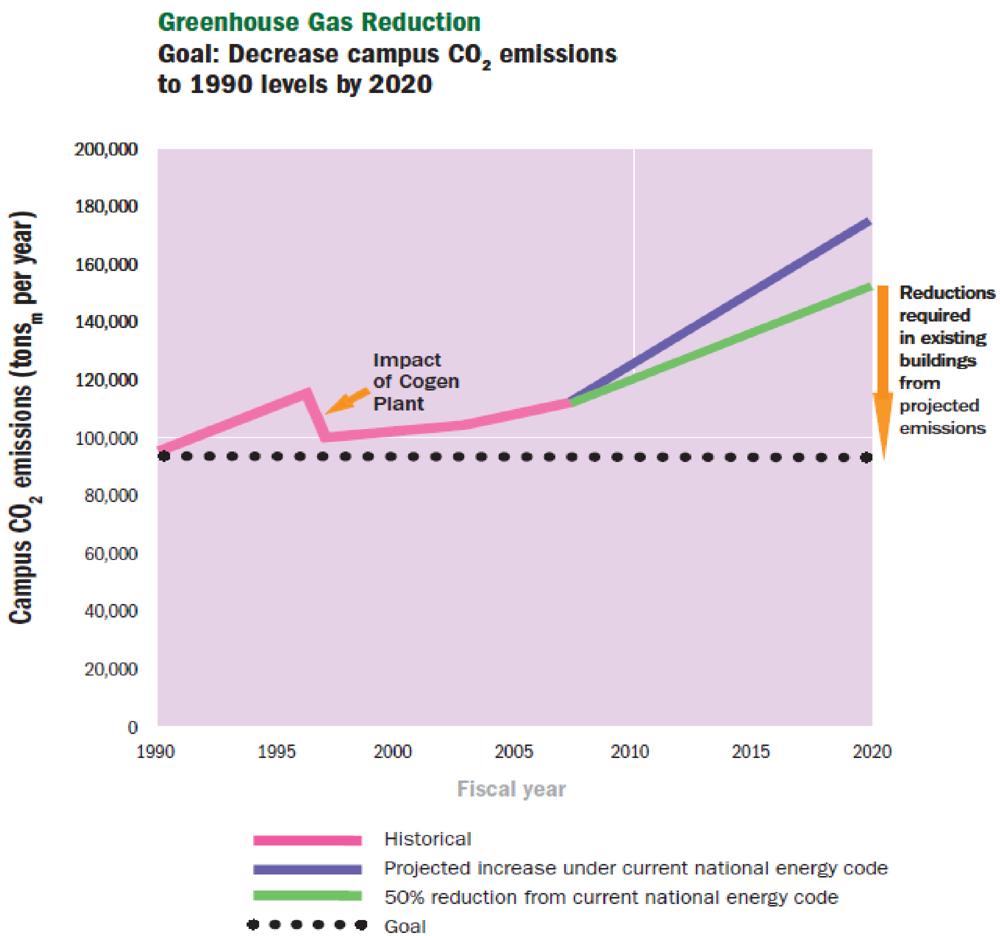
Activity	**Amount producing 4 ton CO_2/yr emissions**
a) Drive	24,000 km/yr, 5 liters/100km (45 mpg)
b) Fly	24,000 km/yr
c) Heat home	Natural gas, average house, average climate
d) Lights	300 kWh/month if all coal-power (1000 gCO_2/kWh) 600 kWh/month, natural-gas-power (500 gCO_2/kWh)

Princeton University CO_2 in 2007

University emissions*	112,000 tCO2
12,500 participants**	
Per-capita emissions	9 tCO2

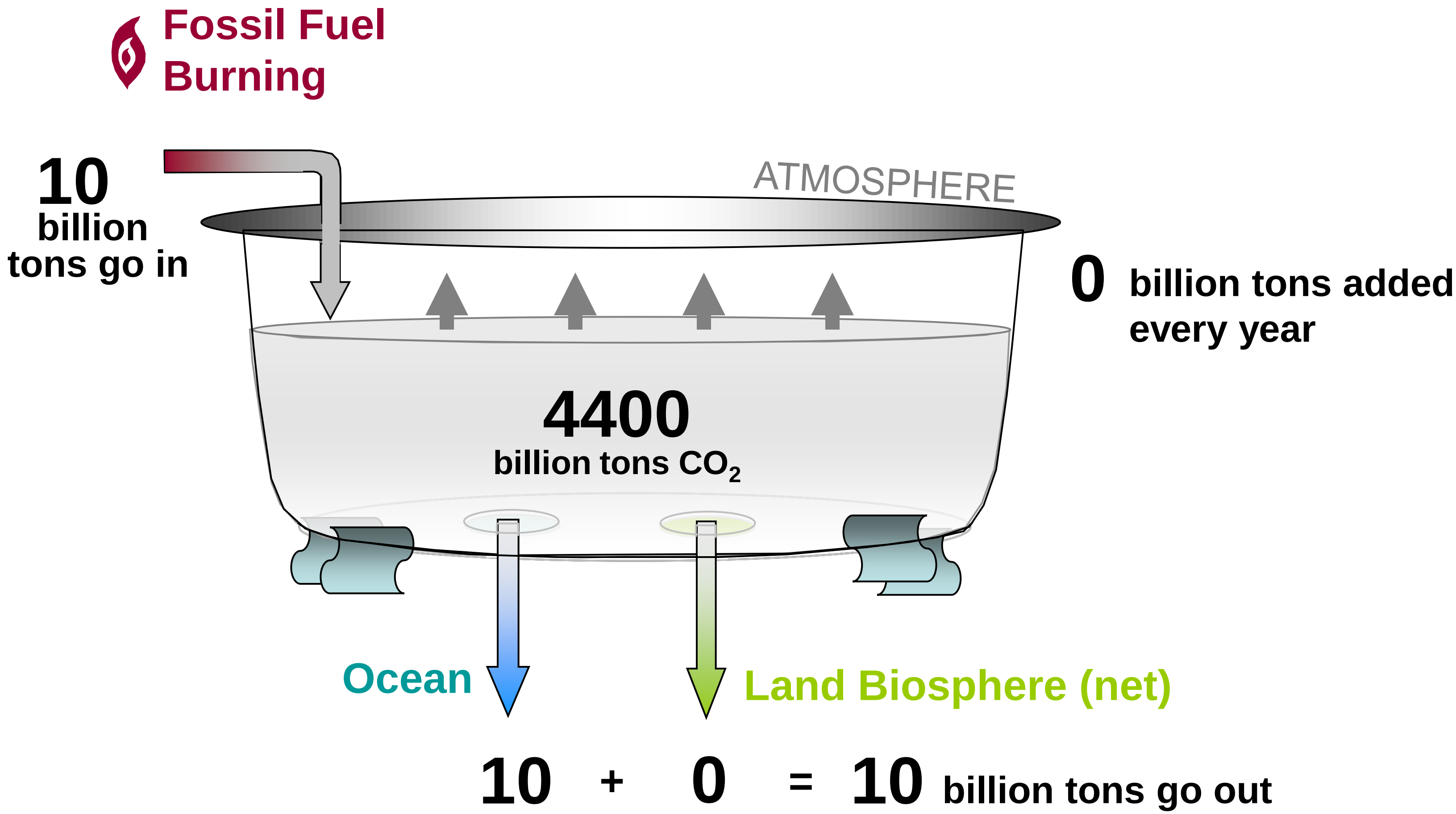
*On-site cogeneration plant, purchased electricity, fuel for University fleet.
**7,100 students and 5,400 employees

Princeton's 2020 CO_2 emissions goal



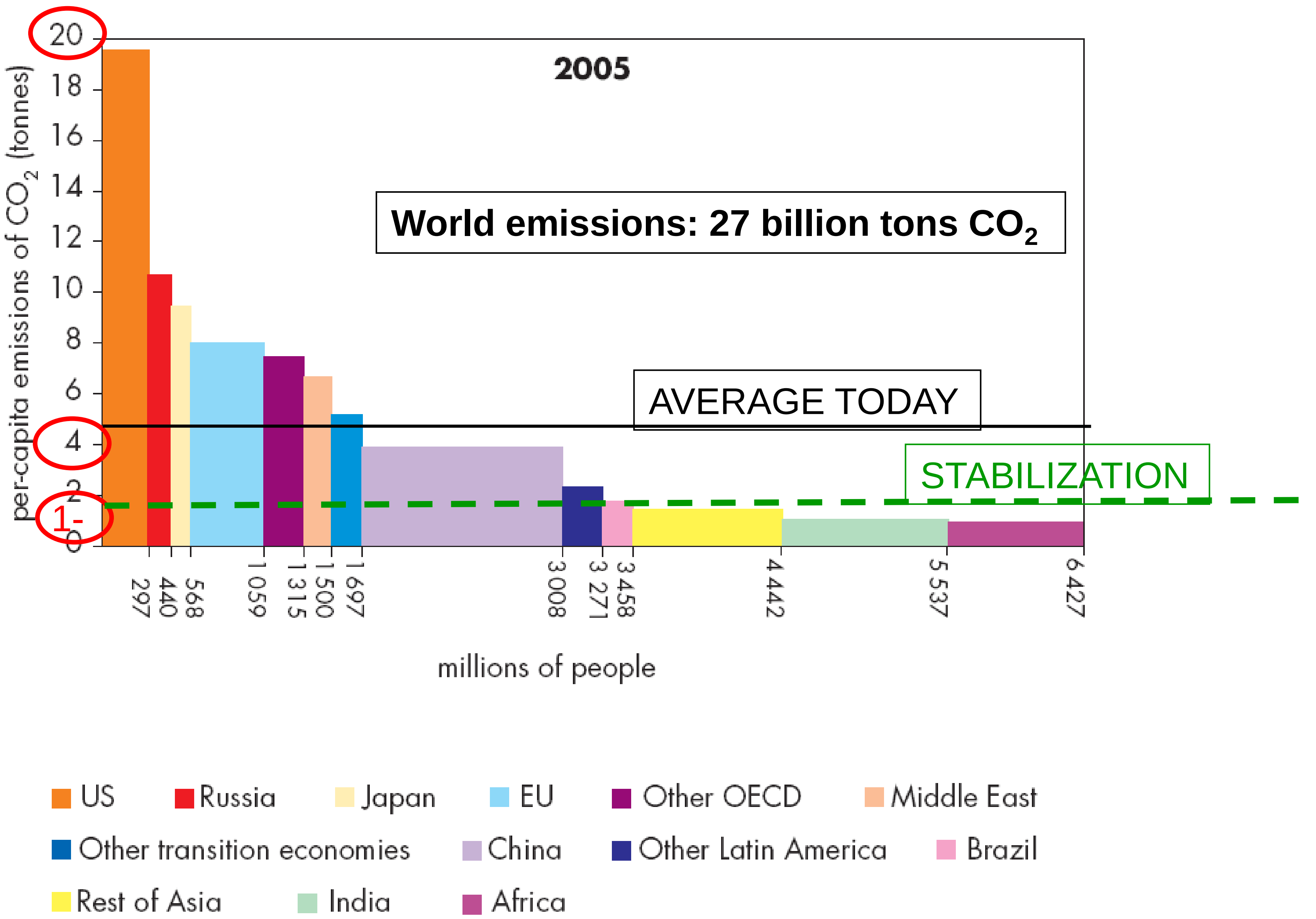
Included: On-campus and external energy for cogeneration plant, fuel for vehicle fleet, but not travel to campus. *Note*: Princeton expects to add almost 2 million square feet of building space in the next 10 years.

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_2 emissions, 2005



Source: IEA WEO 2007

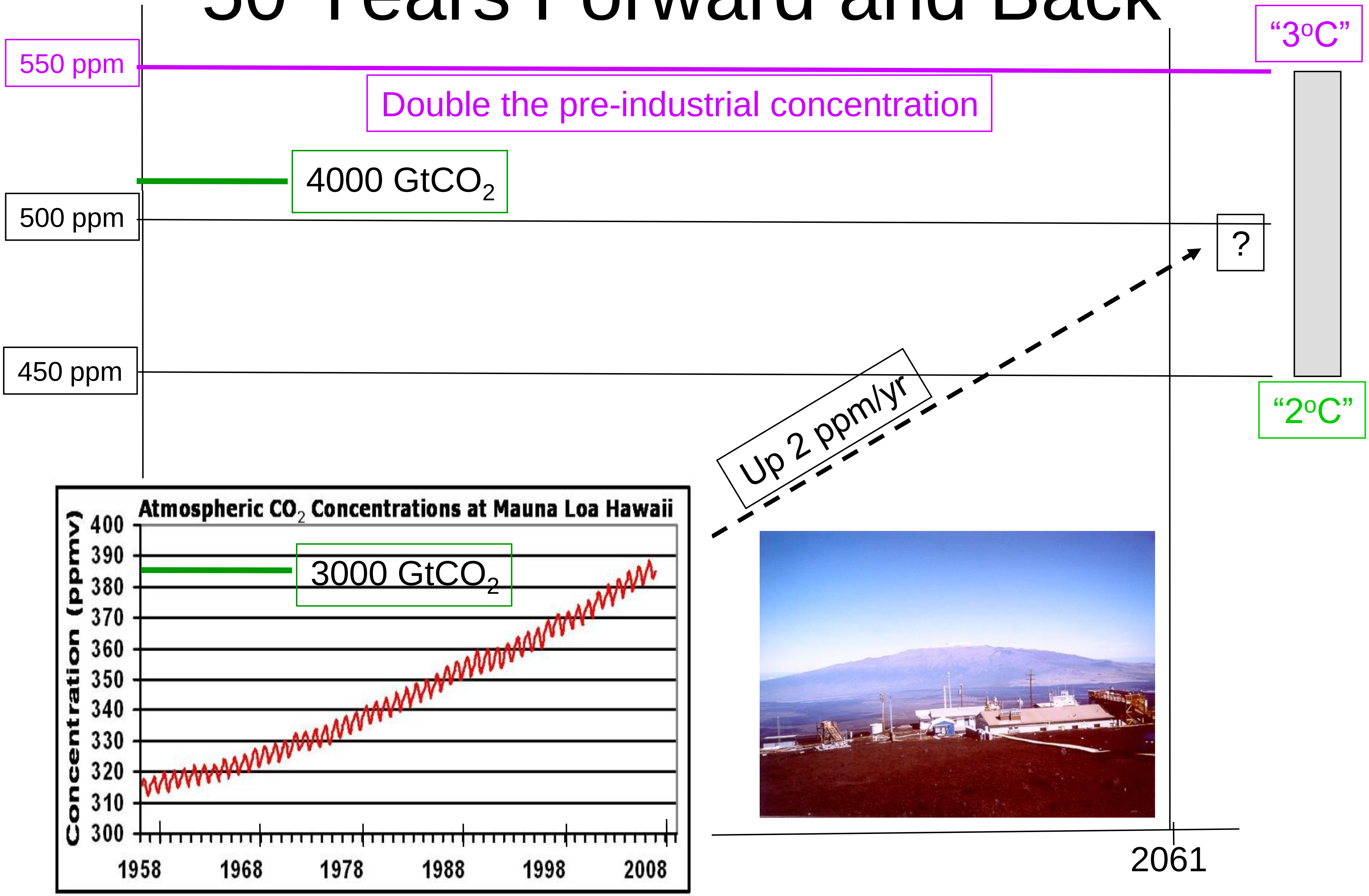
“Stabilization” ≈ 1 ton CO_2/yr per capita

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.

We are deciding only how fast to get there.

50 Years Forward and Back



http://cdiac.ornl.gov/trends/co2/sio-mlo.html

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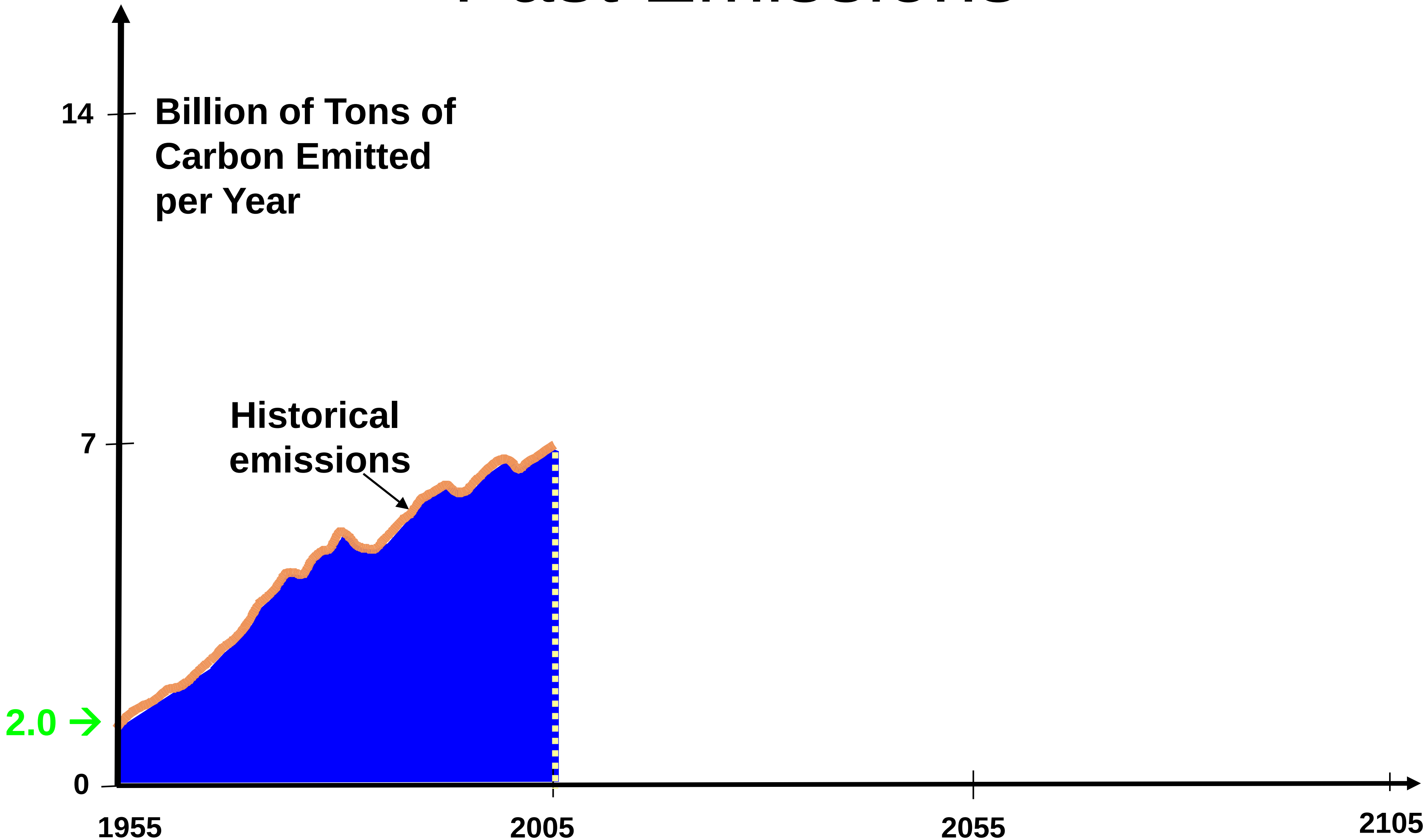
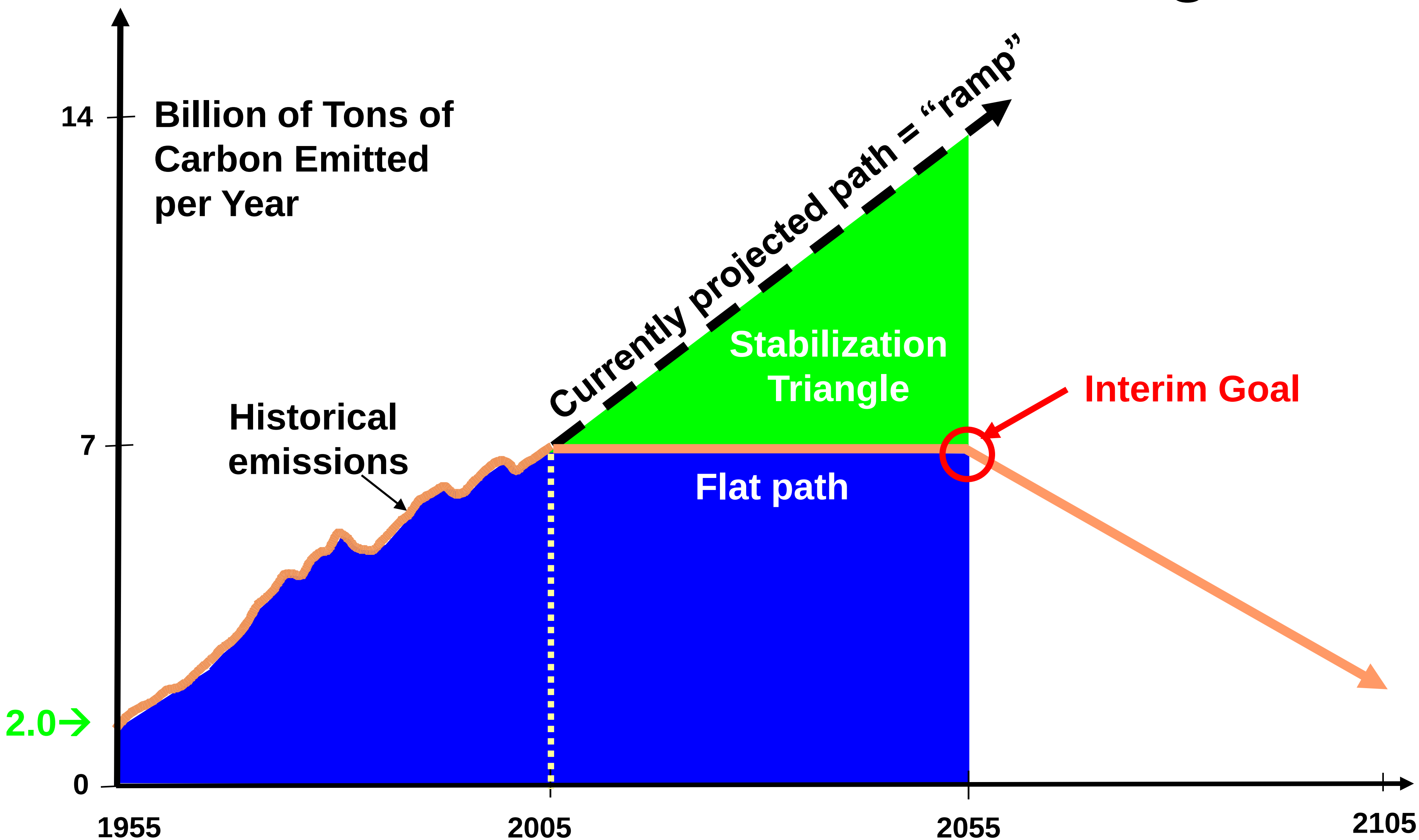
Past Emissions

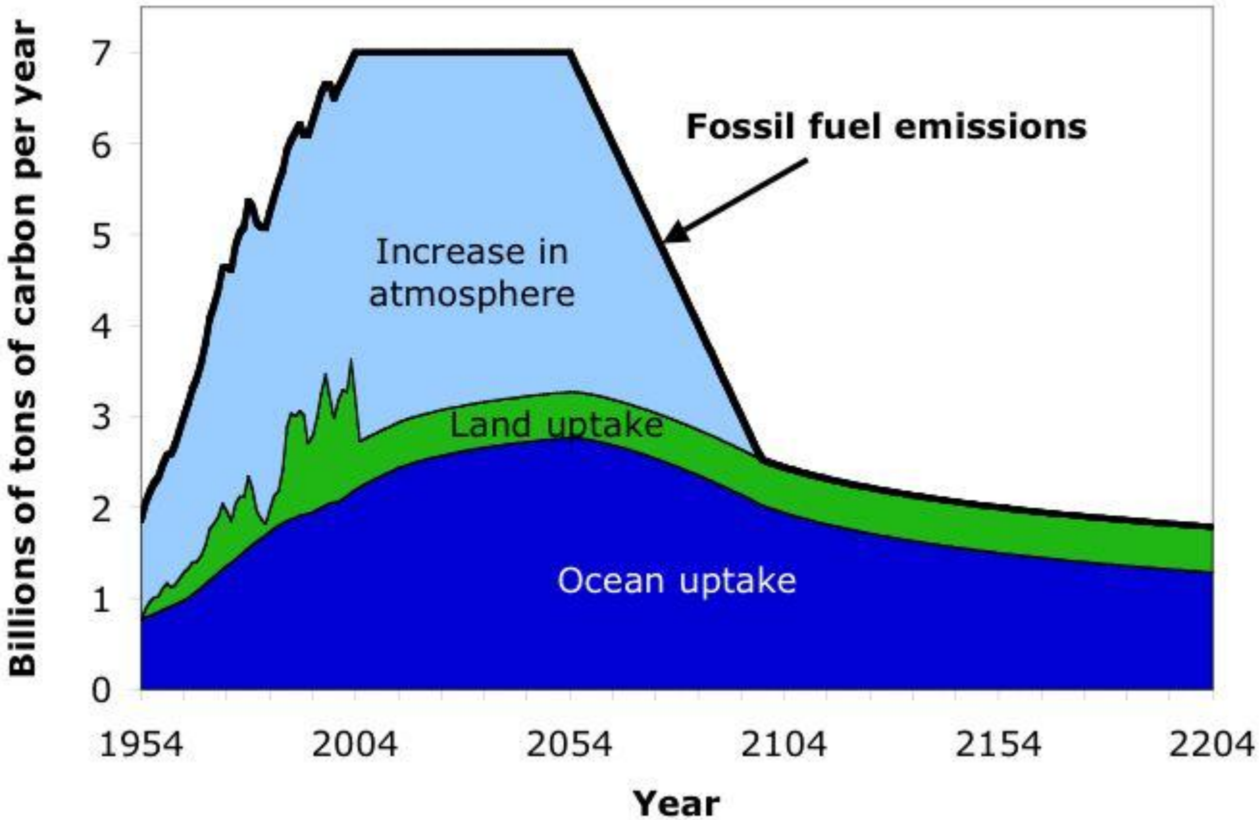


The Stabilization Triangle



Today and for the interim goal, global per-capita emissions are ≈ 1 tC/yr.

Stabilization at 500 ppm via the flat path

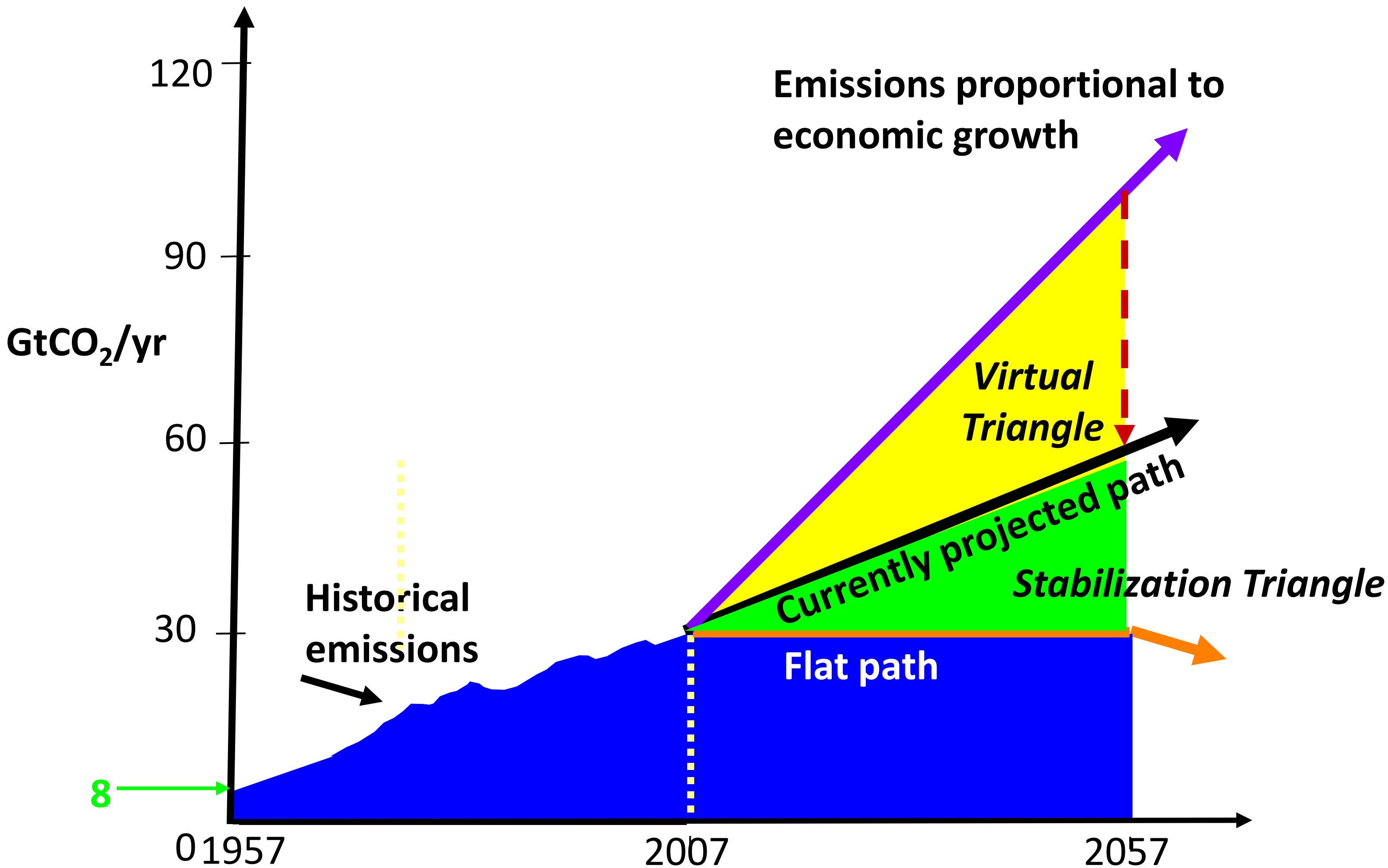


Large uncertainty in the land sink.

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

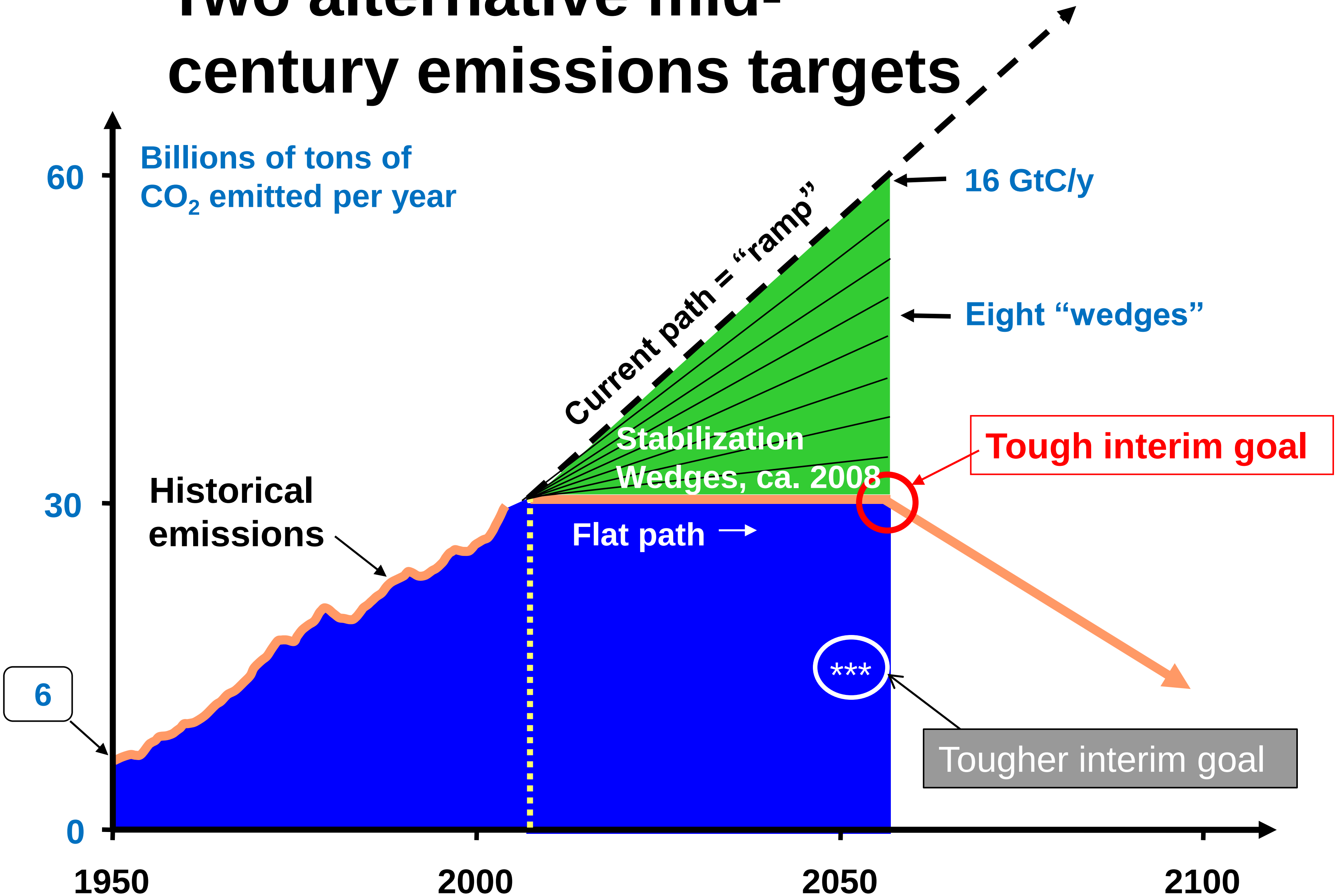
Source: Jeffery Greenblatt, Princeton University

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

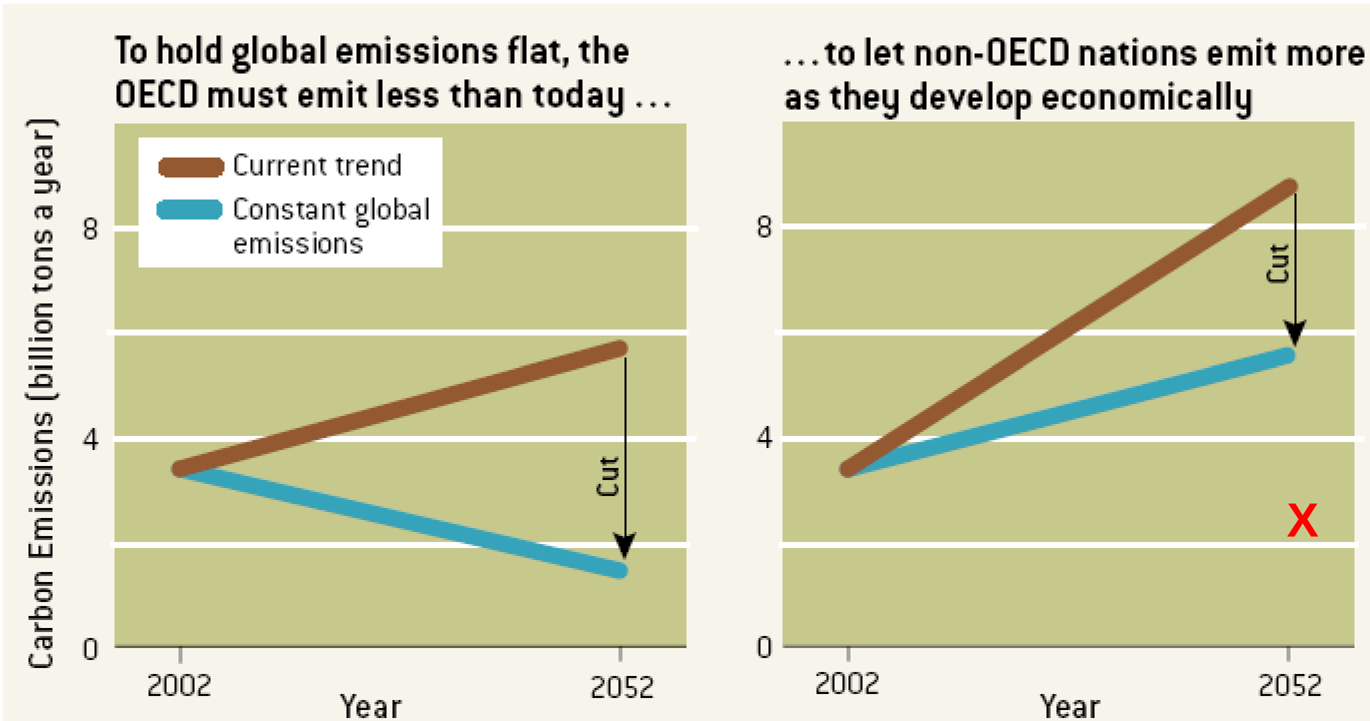


Models differ widely in their estimates of contributions to the virtual triangle from structural shifts (toward services), energy efficiency, and carbon-free energy.

Two alternative mid-century emissions targets



"Flat" vs. "down 50%" is about the developing world's emissions



Up 60% or down 60%

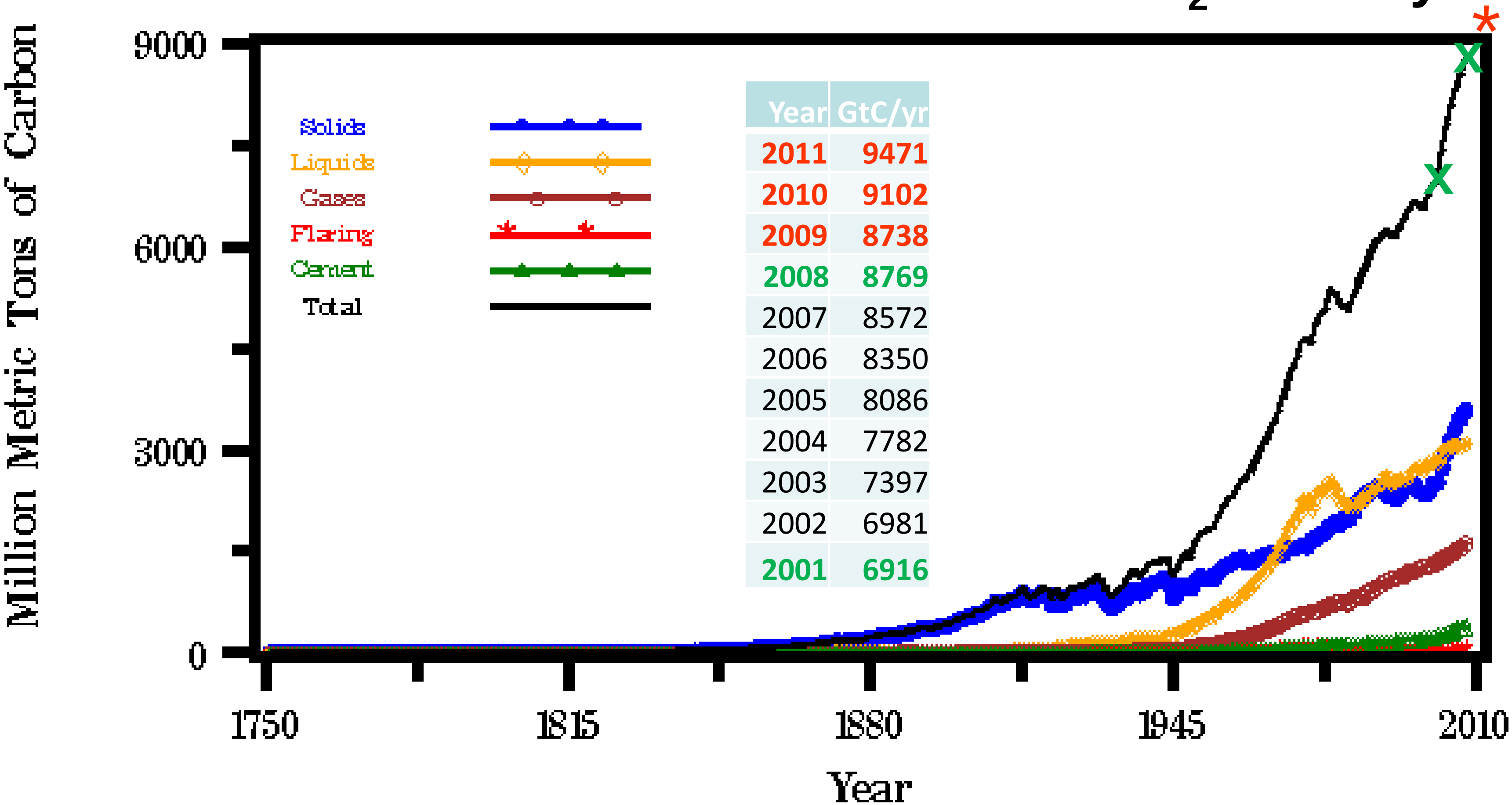
Up 140% or up 60%, *or down 40%*

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

Source of Figure: Socolow and Pacala, "A plan to keep carbon in check," *Scientific American*, Sept . 2006.

We have lost precious time.

Annual Rate of Emissions of CO_2 Globally



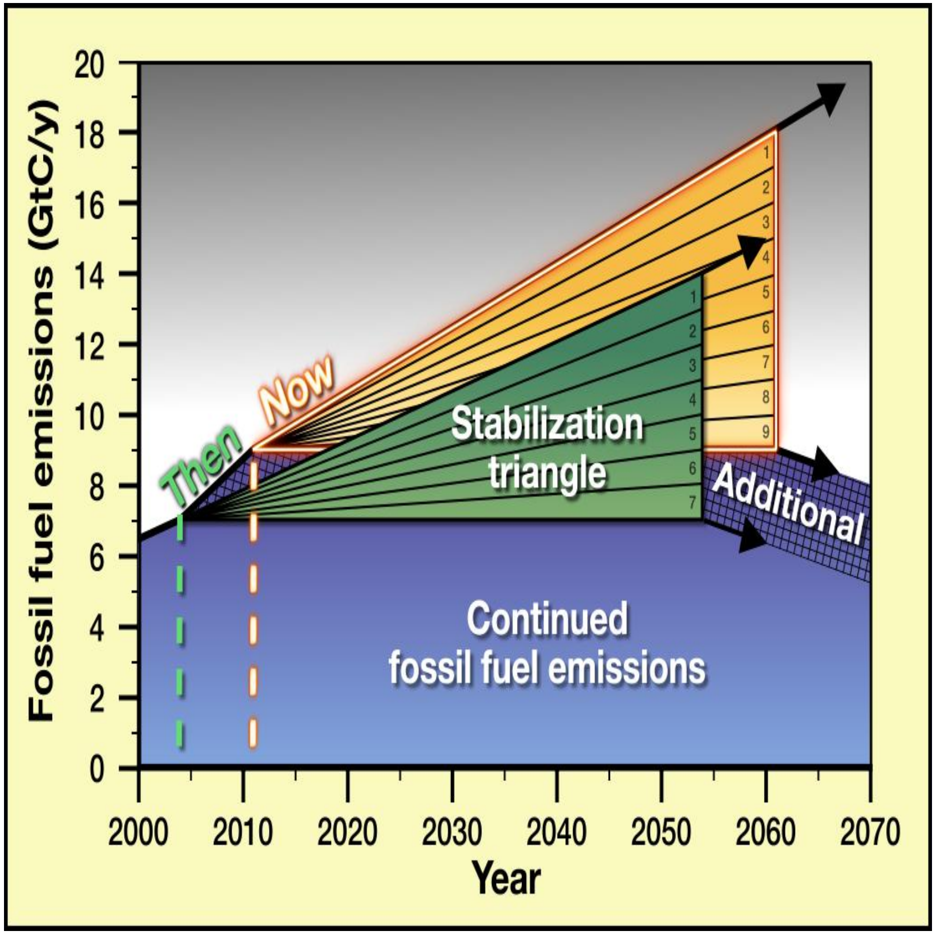
Year	GtC/yr
2011	9471
2010	9102
2009	8738
2008	8769
2007	8572
2006	8350
2005	8086
2004	7782
2003	7397
2002	6981
2001	6916

Source (accessed 10/1/11): http://cdiac.ornl.gov/trends/emis/glo.html.

Updated 1/5/13

"Wedges reaffirmed,"

a short essay released on Sept 27, 2011



The essay was accompanied by comments from:

Carter Bales
Ralph Cicerone
Freeman Dyson
Christopher Field
Robert Fri
David Hawkins
Rush Holt
Robert May
Phil Sharp
Nicholas Stern

Released at www.thebulletin.org and www.climatecentral.org.
Commenting is continuing at www.dotearth.blogs.nytimes.com.

With what wedges will you fill your stabilization triangle?

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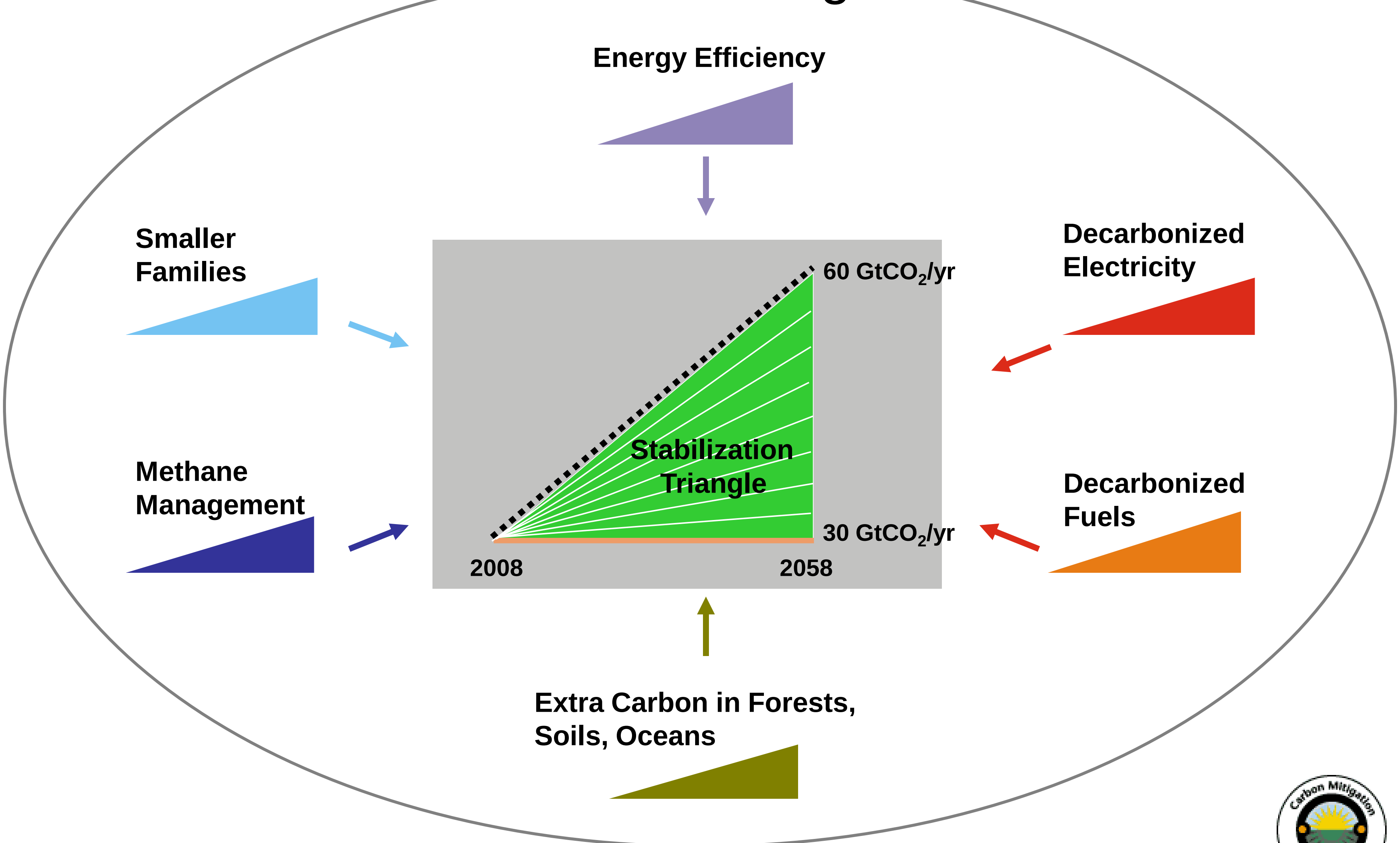
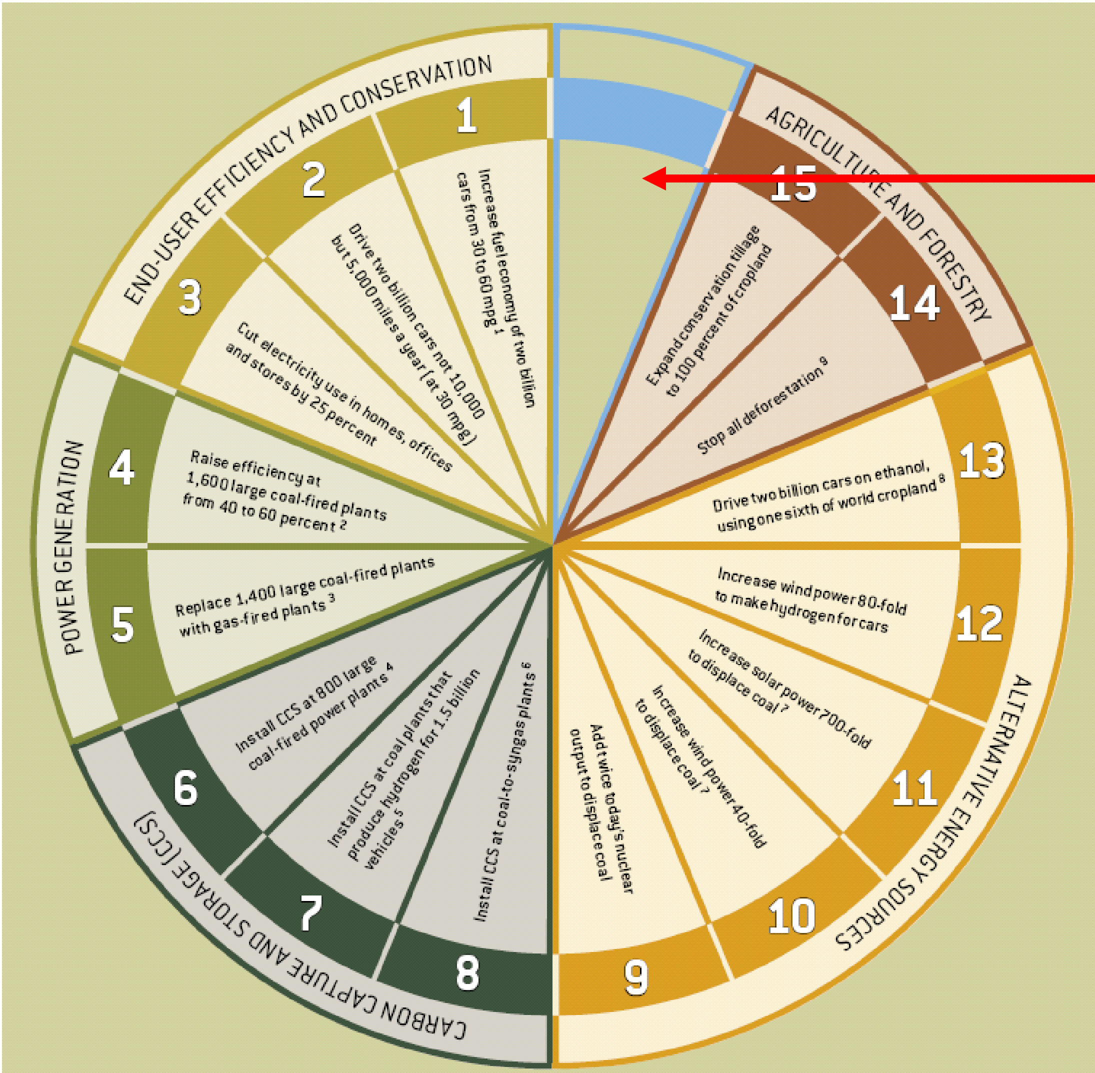
Fill the Stabilization Triangle with Wedges in six broad categories



15 Ways to Make a Wedge



Industrial energy efficiency
“Upstream” investment
Concentrated solar power
Methane mitigation
Population

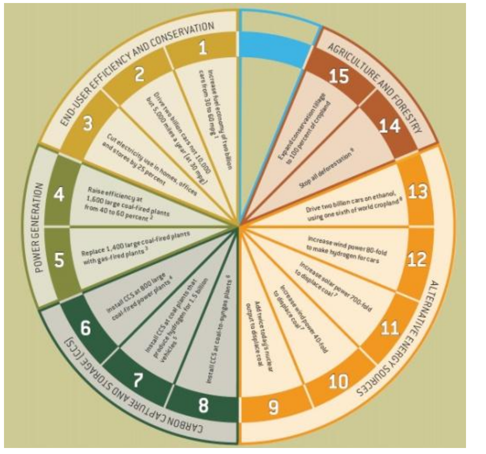
Not commercial, so not included:

Fusion

Capture of CO_2 from air

Source; Socolow and Pacala, *Scientific American*, September 2006, p.54

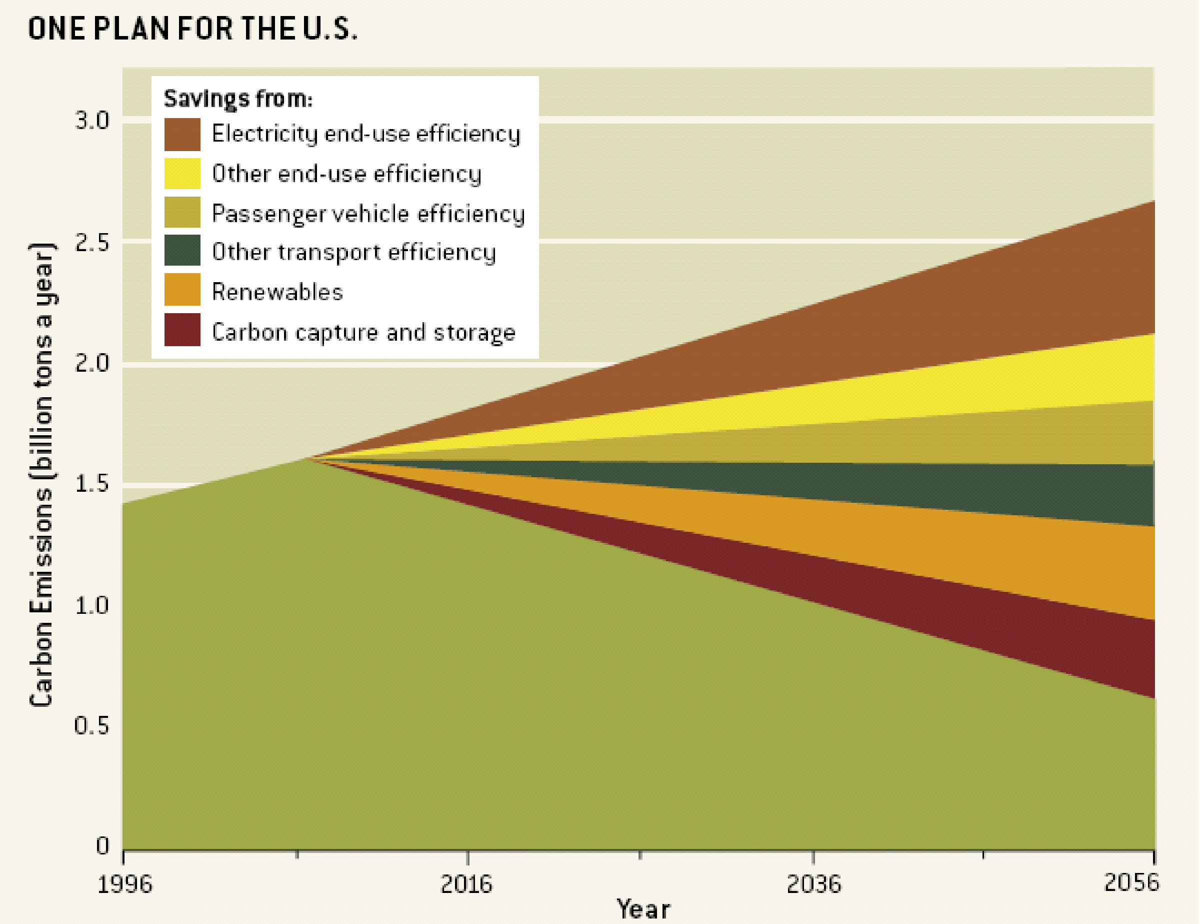
Dartboard notes



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_2 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.

Source; Socolow and Pacala, *Scientific American*, September 2006, p.54

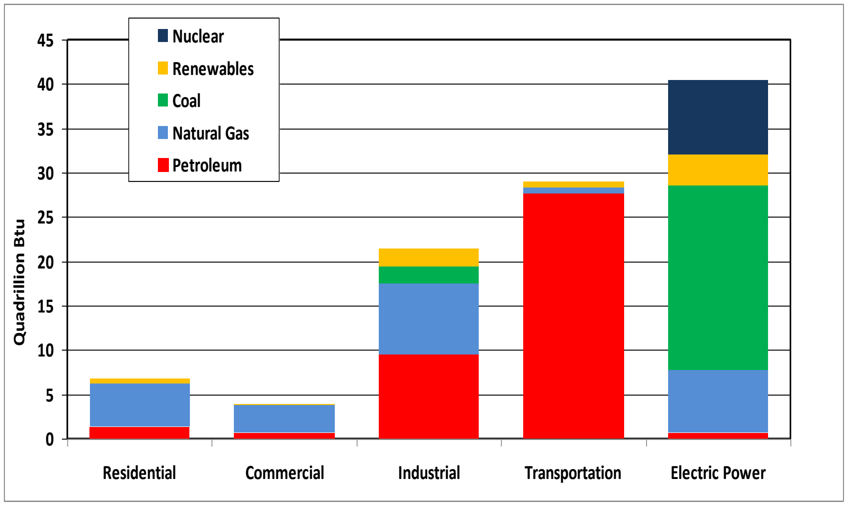
U.S. Wedges

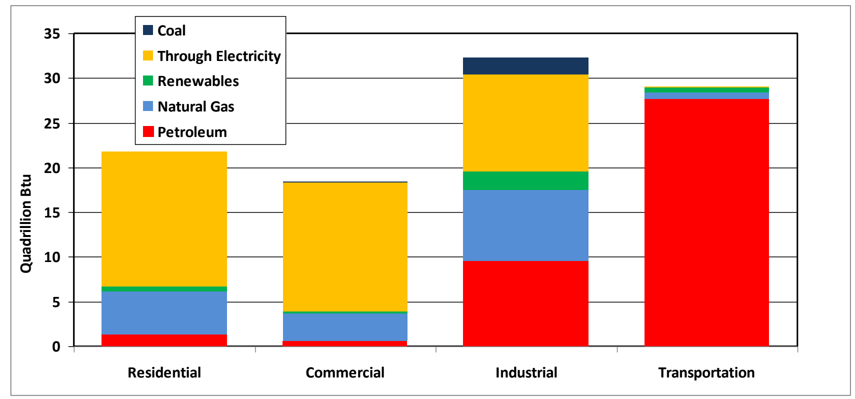


▲ U.S. share of emissions reductions could, in this Natural Resources Defense Council scenario, be achieved by efficiency gains, renewable energy and clean coal.

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

U.S. primary energy, 2007





Electricity explicit

Electricity allocated

Source: Jim Sweeney, 2009

Efficiency and Conservation

transport

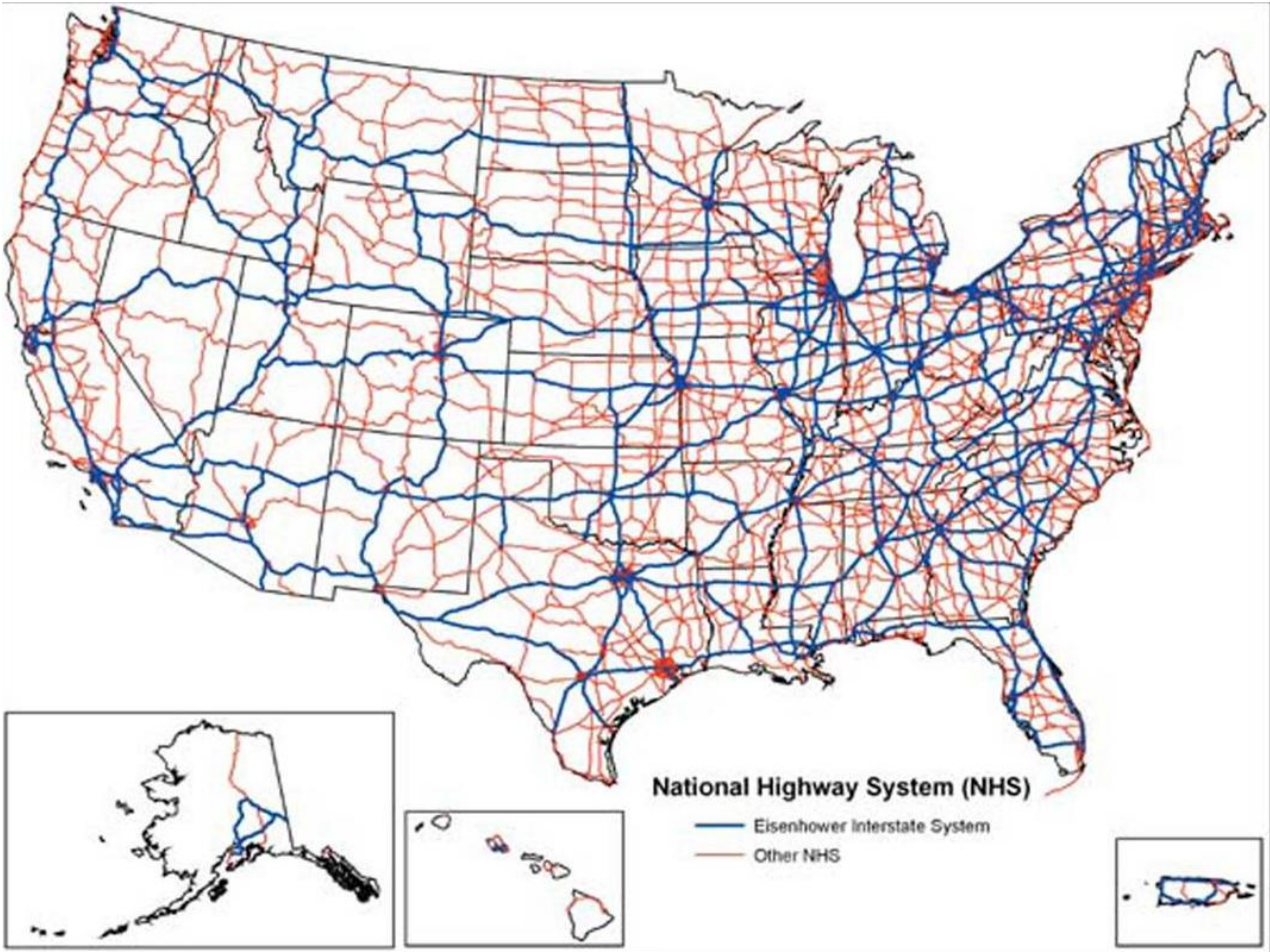
buildings

industry

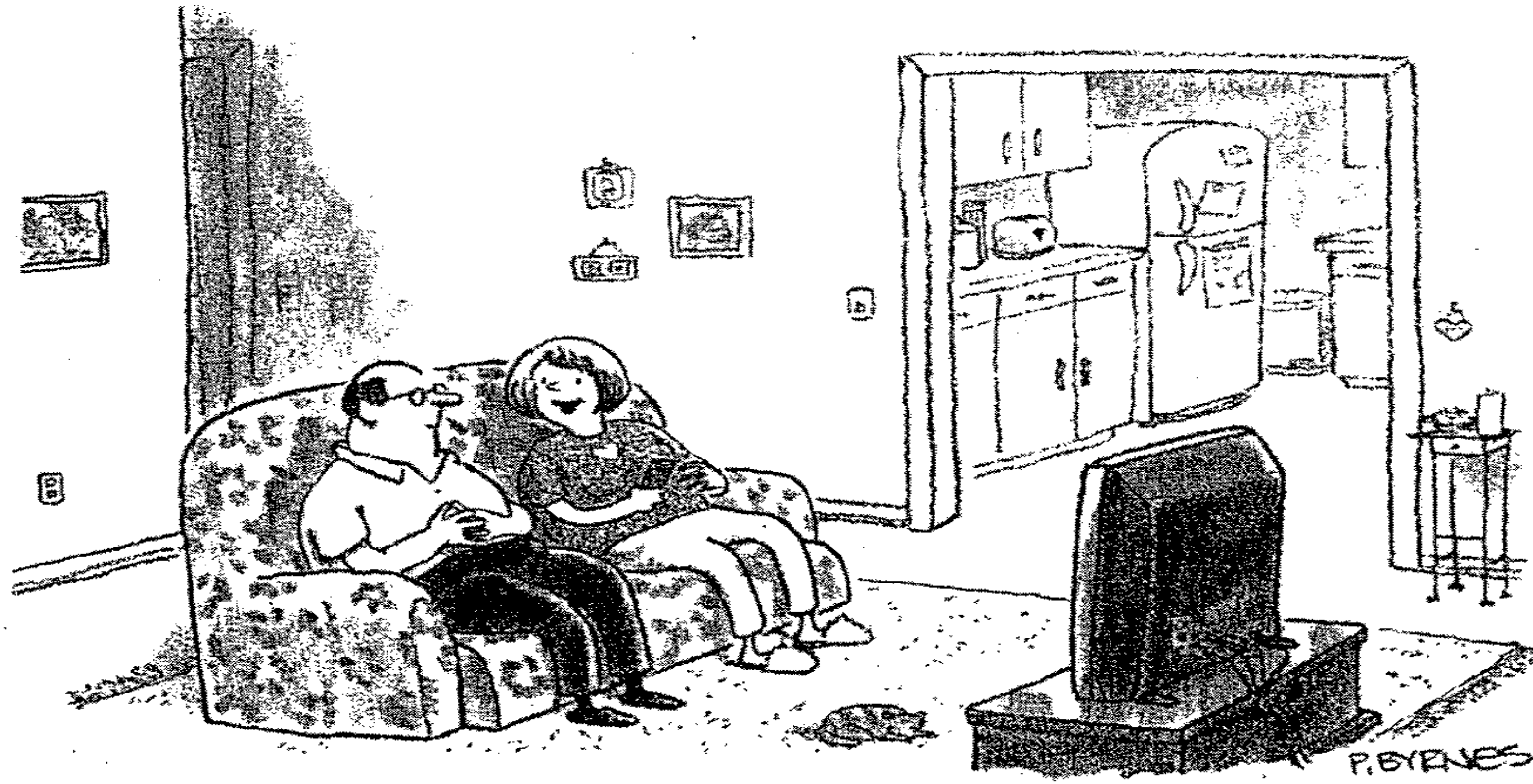
lifestyle

power

Legacy: National Highway System



Substituting IT for travel

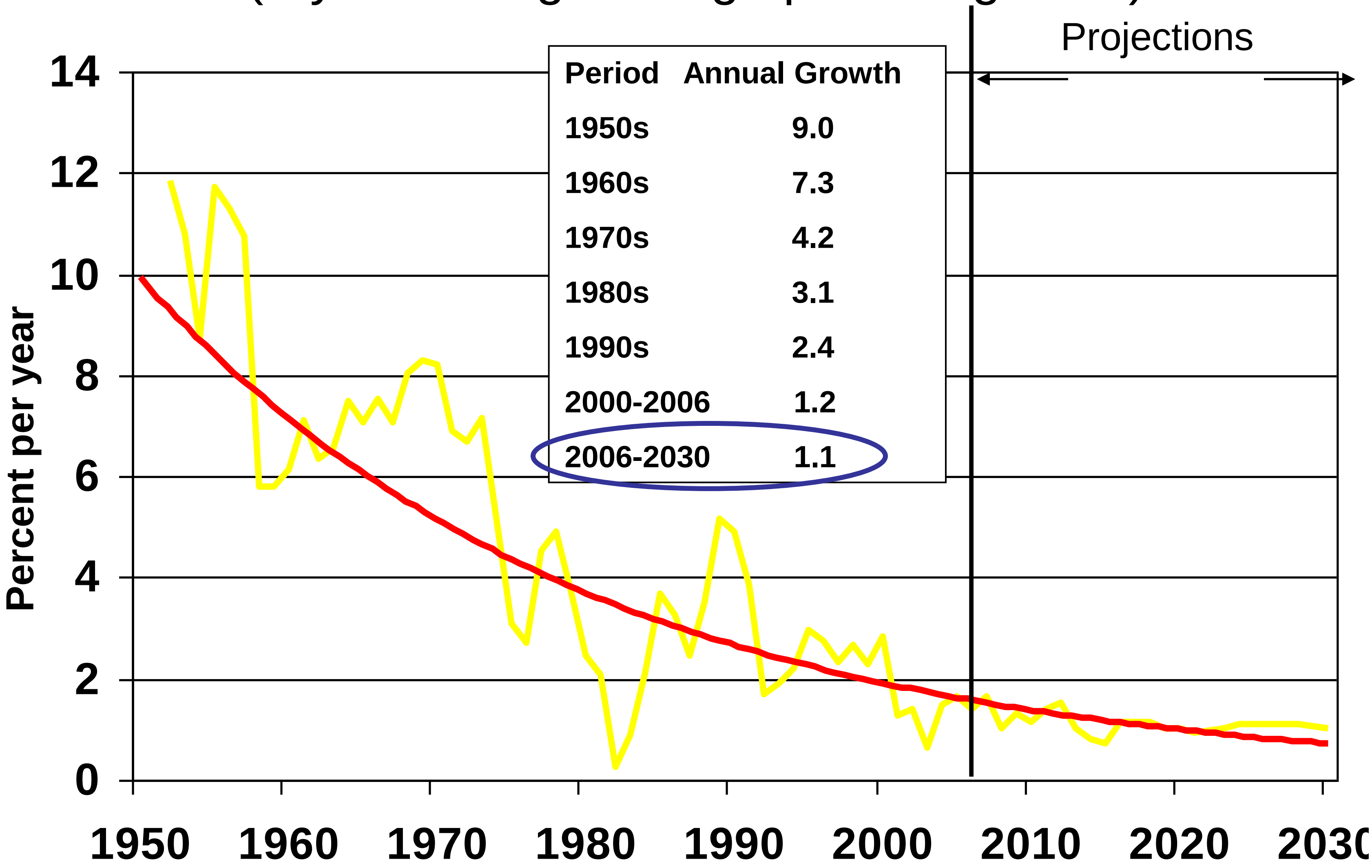


"When we retire, I want to watch travel videos."

From *The New Yorker*, April 21, 2008

U.S. electricity growth rate is falling

(3-year rolling average percent growth)



Period	Annual Growth
1950s	9.0
1960s	7.3
1970s	4.2
1980s	3.1
1990s	2.4
2000-2006	1.2
2006-2030	1.1

Exponential curve (20 years for rate to fall by half): EIA

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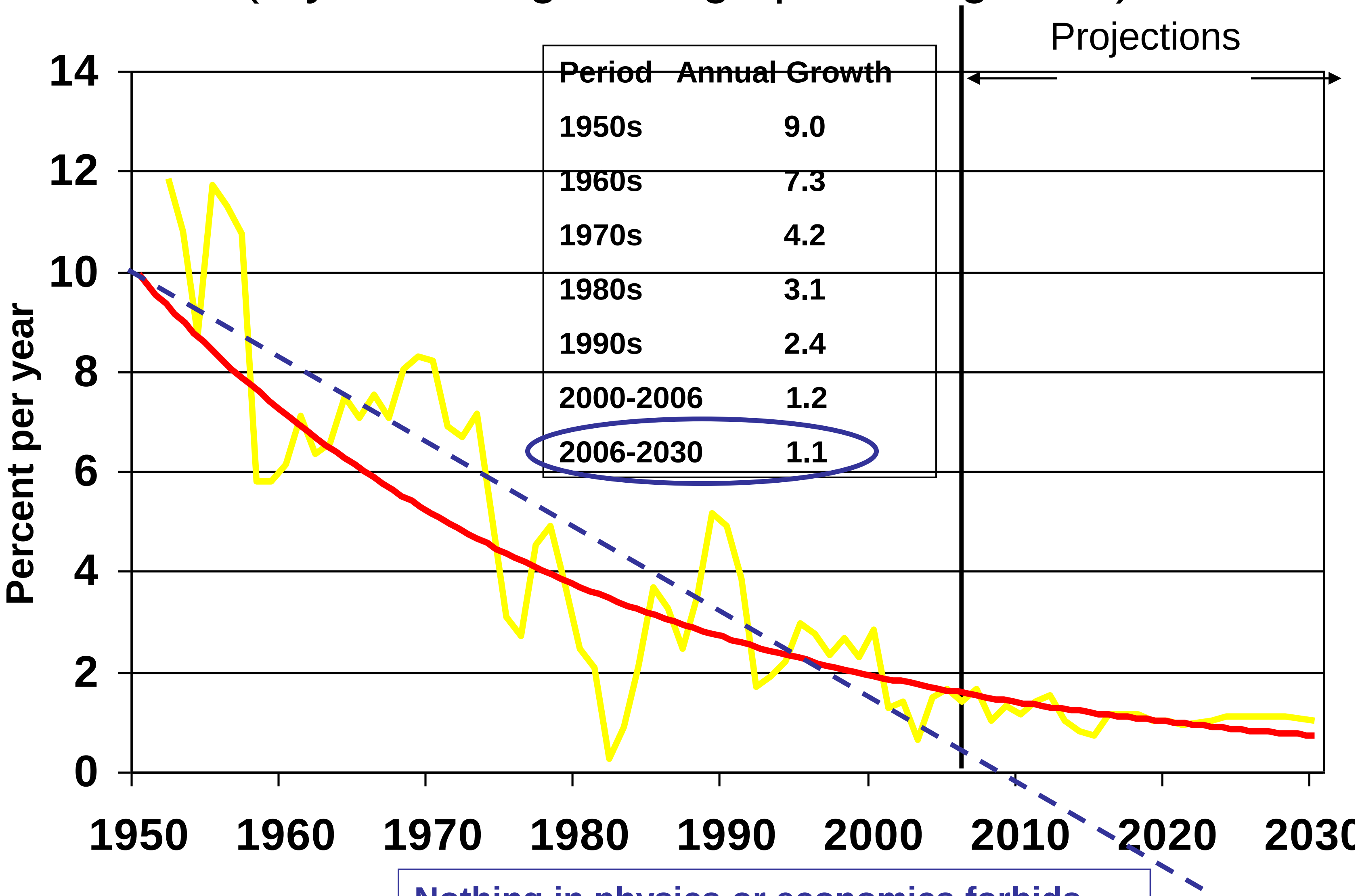
(3-year rolling average percent growth)



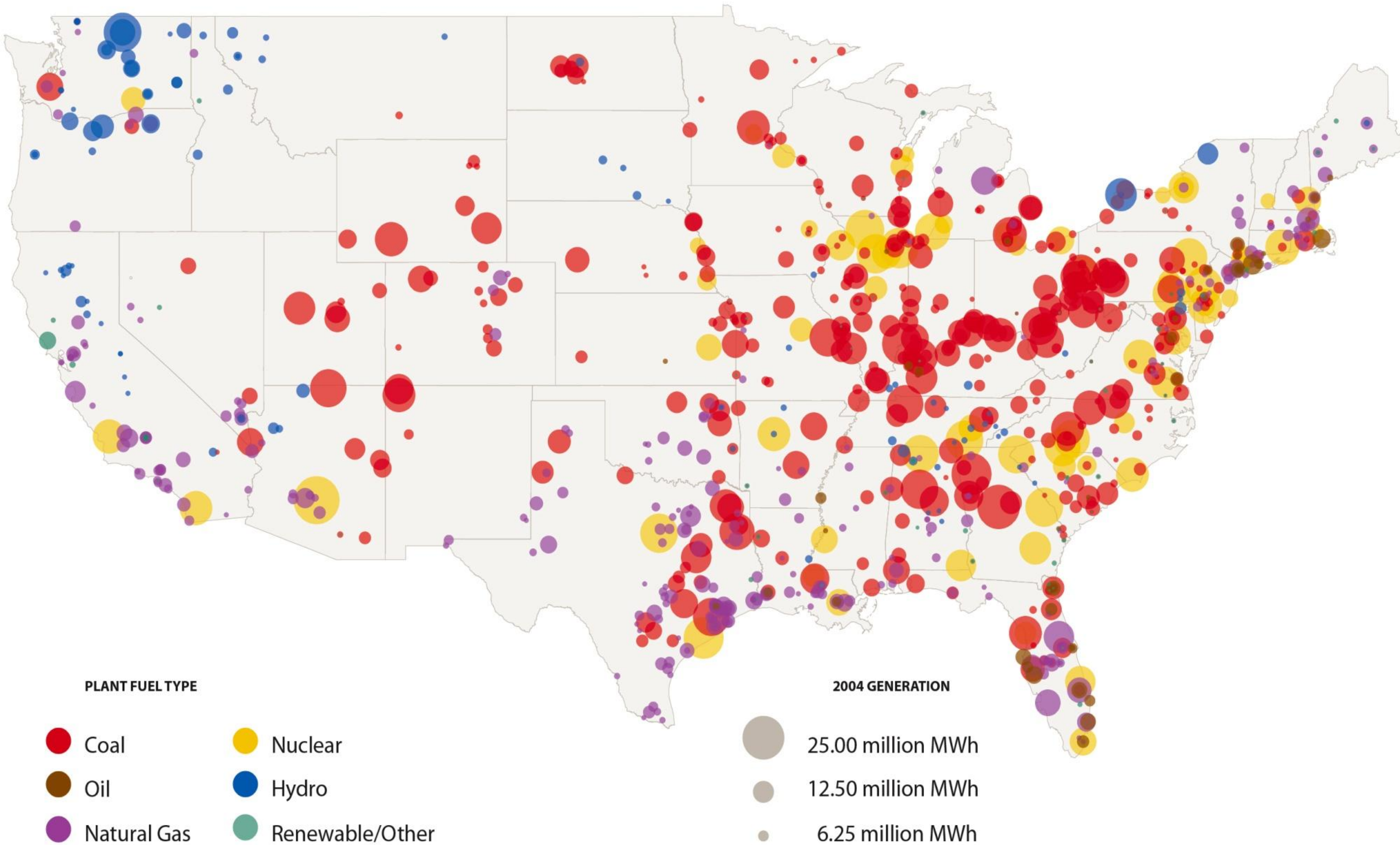
Nothing in physics or economics forbids negative values! Blue dashed line: RHS.

Is peak energy demand behind us?

Annual US and OECD consumption from now on could be less than in any past year – for both:

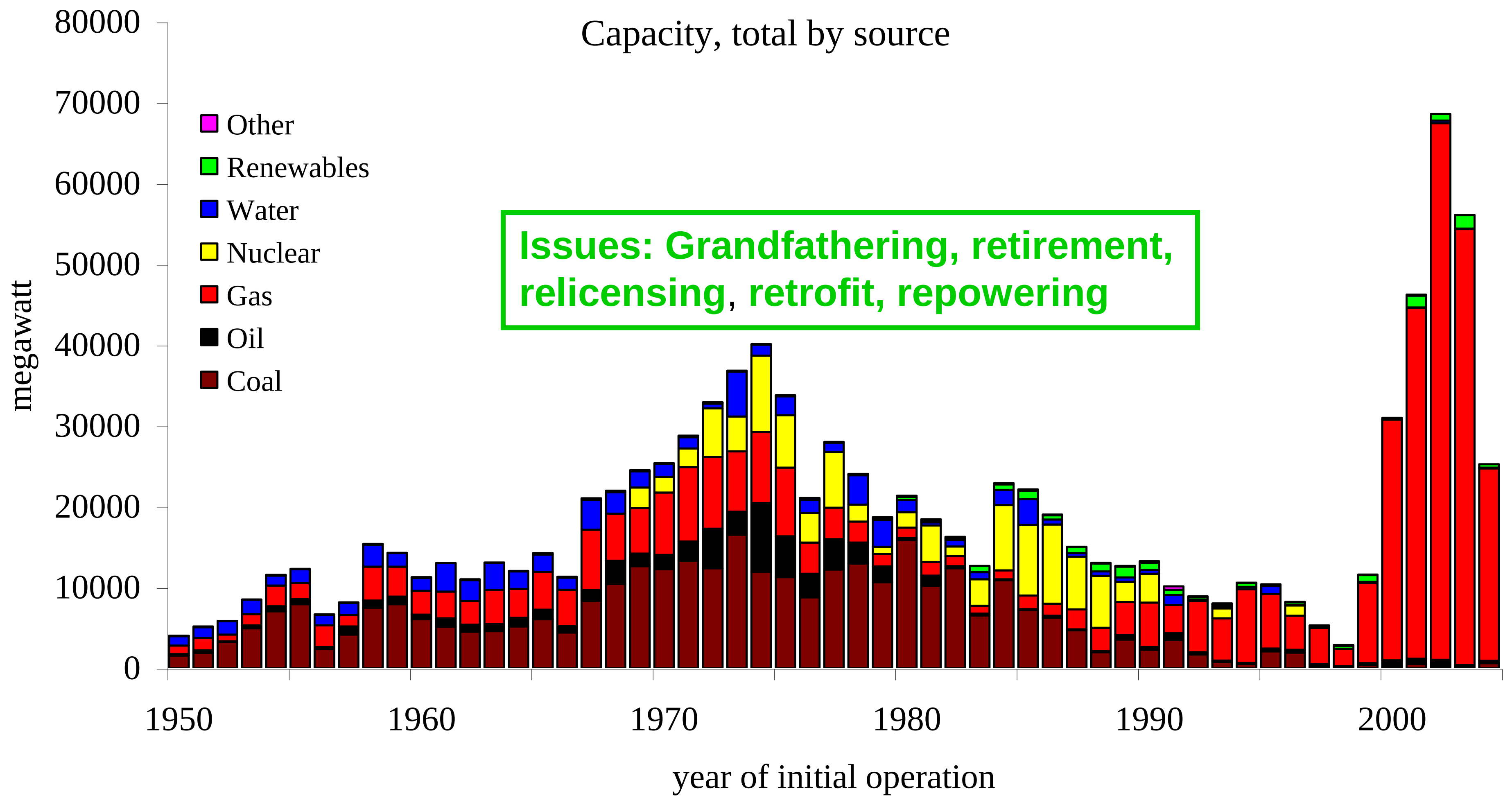
- oil consumption
- electric power consumption

Legacy: U.S. Power Plants



Source: *Benchmarking Air Emissions*, April 2006. The report was co-sponsored by CERES, NRDC and PSEG.

U.S. power plant capacity, by vintage



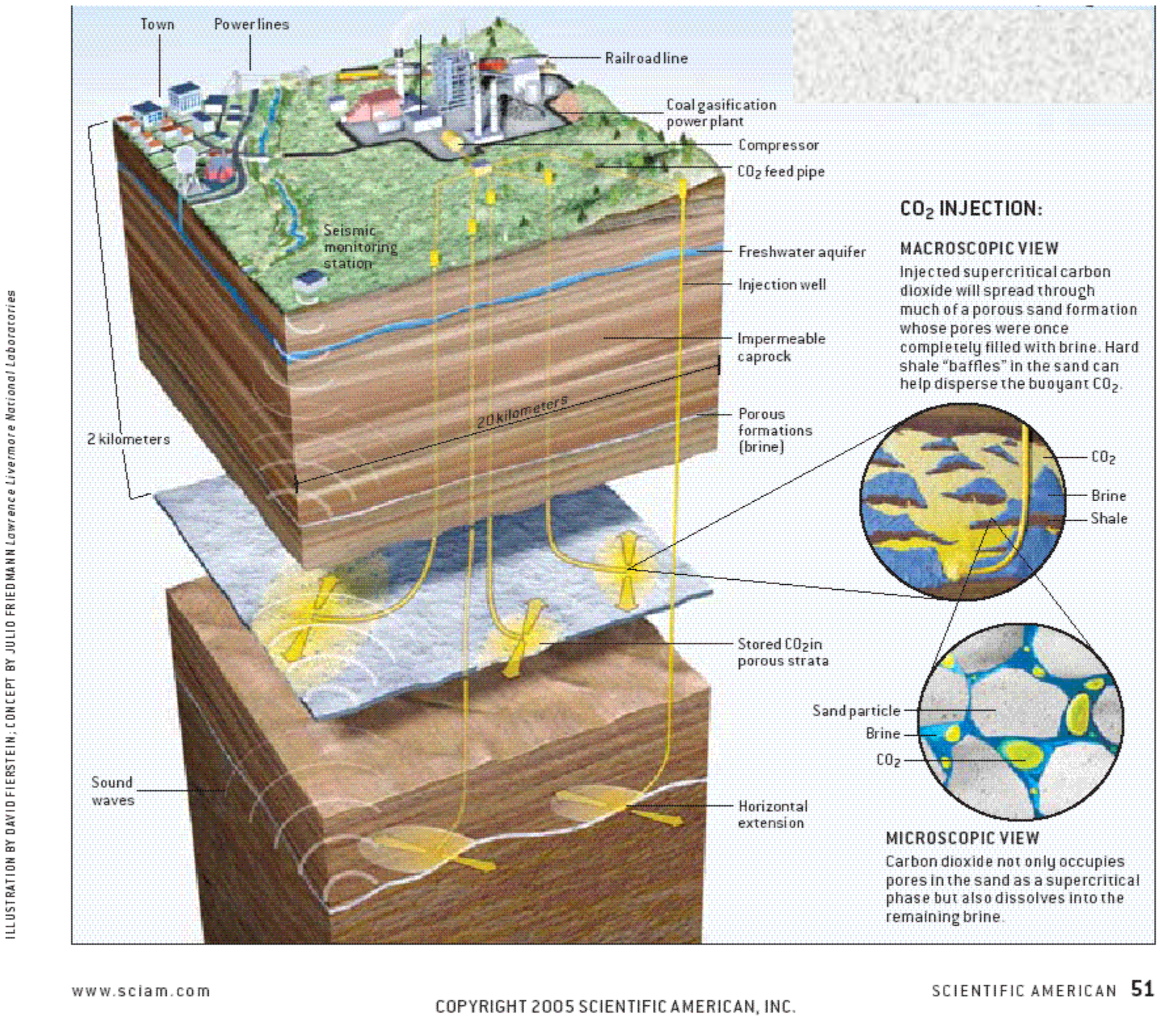
Source: EIA. Joseph.Beamon@eia.doe.gov

Zero minus zero equals zero

Where there is no load growth and there are no retirements, nothing new needs to be built.

Note: Demand can grow in some regions, fall in others.

The future coal power plant



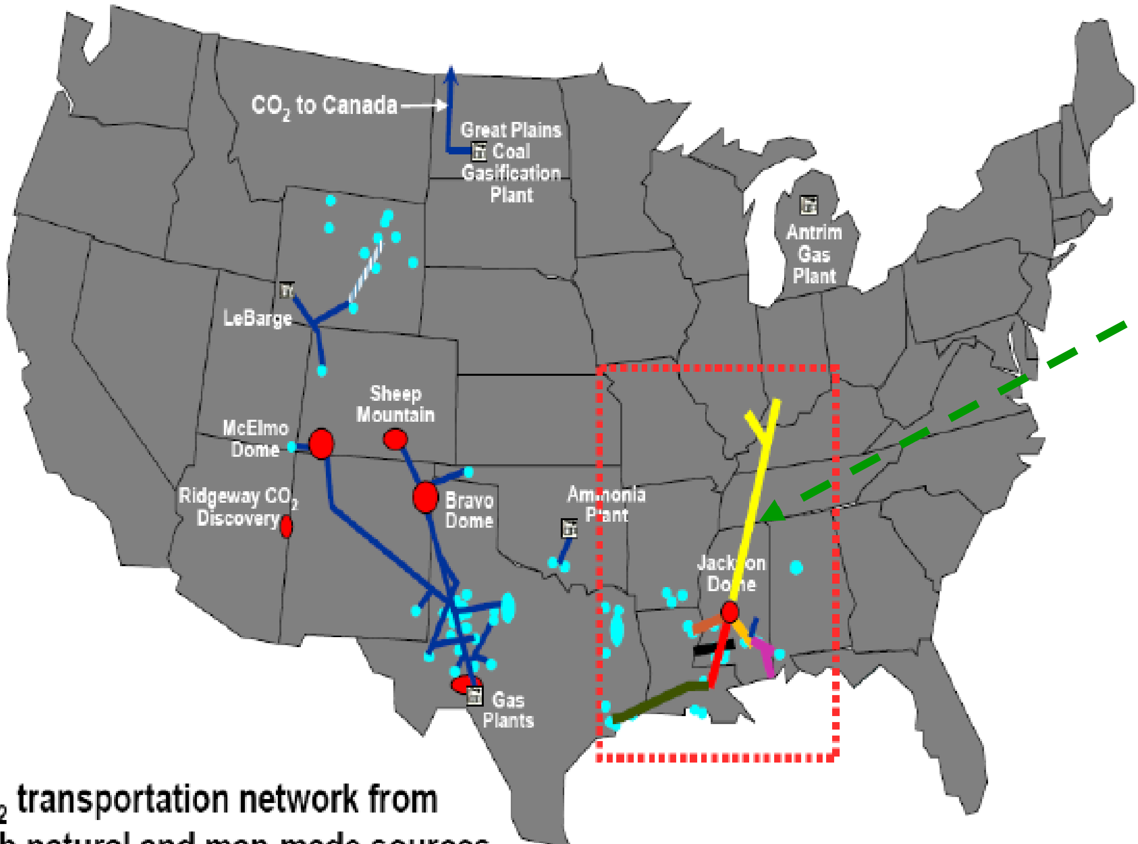
Shown here: After 10 years of operation of a 1000 MW coal plant, 60 Mt (90 Mm^3) of CO_2 have been injected, filling a horizontal area of 40 km^2 in each of two formations.

Assumptions:
- 10% porosity
- **1/3 of pore space accessed**
- 60 m total vertical height for the two formations.

- *Note:* Plant is still young.

Injection rate is 150,000 bbl(CO_2)/day, or 300 million standard cubic feet/day (scfd).
Lifetime injection: 3 billion barrels, or 6 trillion standard cubic feet, over 60 years.

U.S. CO_2 pipeline infrastructure



Denbury proposes to send Ohio Valley CO_2 to the Gulf states.

CO_2 transportation network from both natural and man-made sources

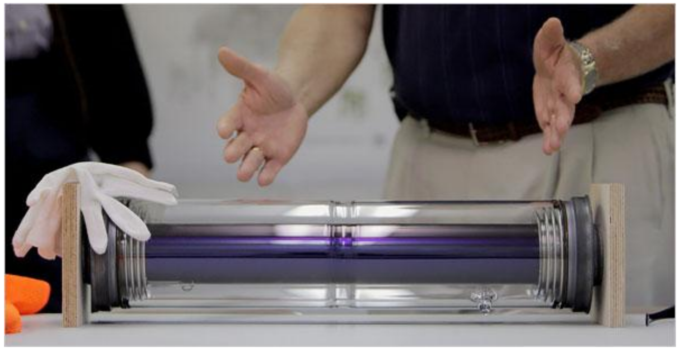
Source: "Reducing CO2 Emissions from Coal-Fired Power Plants," John Wheeldon, EPRI, presented at the CCTR Advisory Panel Meeting, Vincennes University, Vincennes IN, September 10, 2009. Reproduced in Science Applications International Corporation, *Indiana and Coal: Keeping Indiana Energy Cost Competitive,* June 2010, Fig. 2-15, submitted to Indiana Center for Coal Technology Research

Photovoltaic Power

5 MW have been installed by Princeton University south of the canal, east of the Dinky.

Graphics courtesy of DOE Photovoltaics Program

Concentrating Solar Power (CSP)



Florida Power and Light's "Next Generation Solar Energy Center," Martin County: 75 MW, 500 acres, 190,000 mirrors.

Wind electricity

2.5 MW Nordex wind turbine (80-m tall)
Grevenbroich, Germany

Source: Danish Wind Industry Association

Source: Hal Harvey, TPG talk, Aspen, CO, July 2007

Fukushima #1 in better times

***Source*: "After the Deluge: Short and Medium-term Impacts of the Reactor Damage Caused by the Japan Earthquake and Tsunami." Nautilus Institute for Security and Sustainability, March 17, 2011. *Figure 4* : Fukushima Number 1 Nuclear Power Plant**

After-heat: A fire you can't put out.

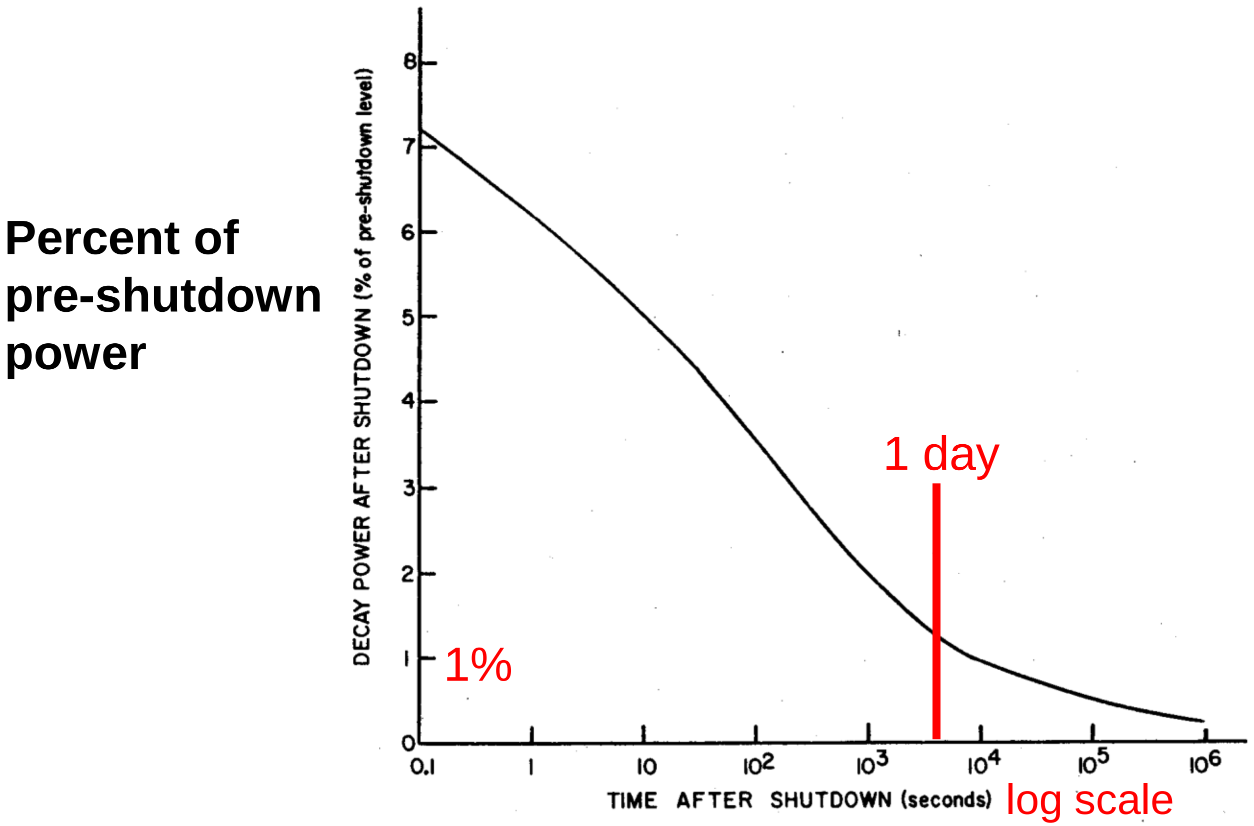
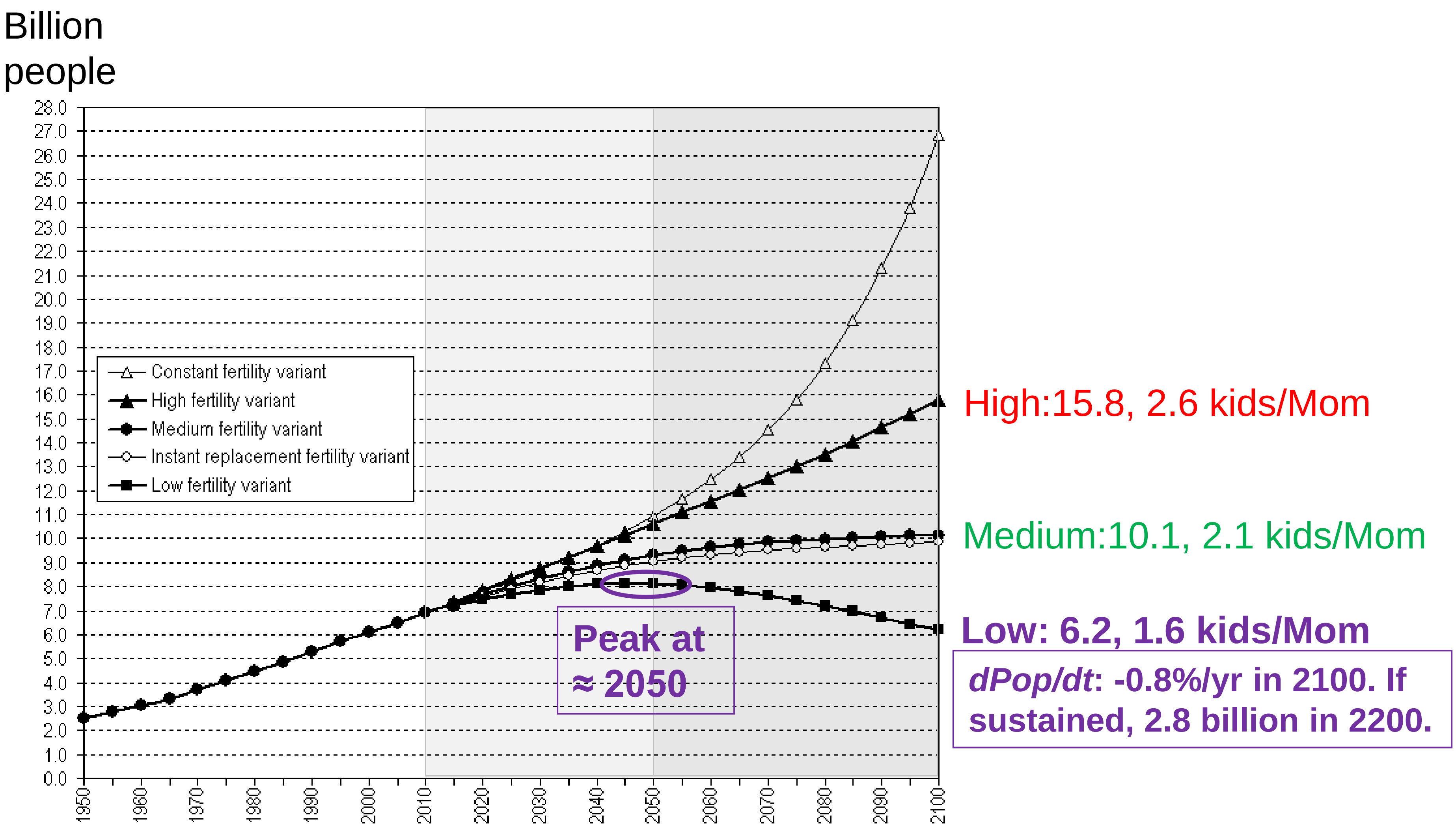


Figure 4-1. THERMAL POWER AFTER REACTOR SHUTDOWN.
After the nuclear chain reaction ceases, radioactivity remaining in the fuel will generate heat as a result of radioactive decay. Assuming that the reactor had been operating for a substantial period, the power generated immediately after shutdown will be approximately 7% of the level before shutdown. For a 3000 MWth reactor, with 1000 MWe capacity, this implies an initial decay power level of about 200 MWth. Due to the rapid decay of short-lived species, this decay heat level decreases rapidly, but is is this heat that imposes the requirement that, in a light-water reactor, cooling water remain available to prevent damage to the fuel.

Source: A. Nero. Jr., *The Guidebook to Nuclear Reactors*, p. 54

The UN's "low"population projection has almost 10 billion fewer people in 2100 than its "high" projection.



Source: United Nations. http://esa.un.org/unpd/wpp/unpp/panel_population.htm

Every strategy can be implemented well or poorly

Every “solution” has a dark side.

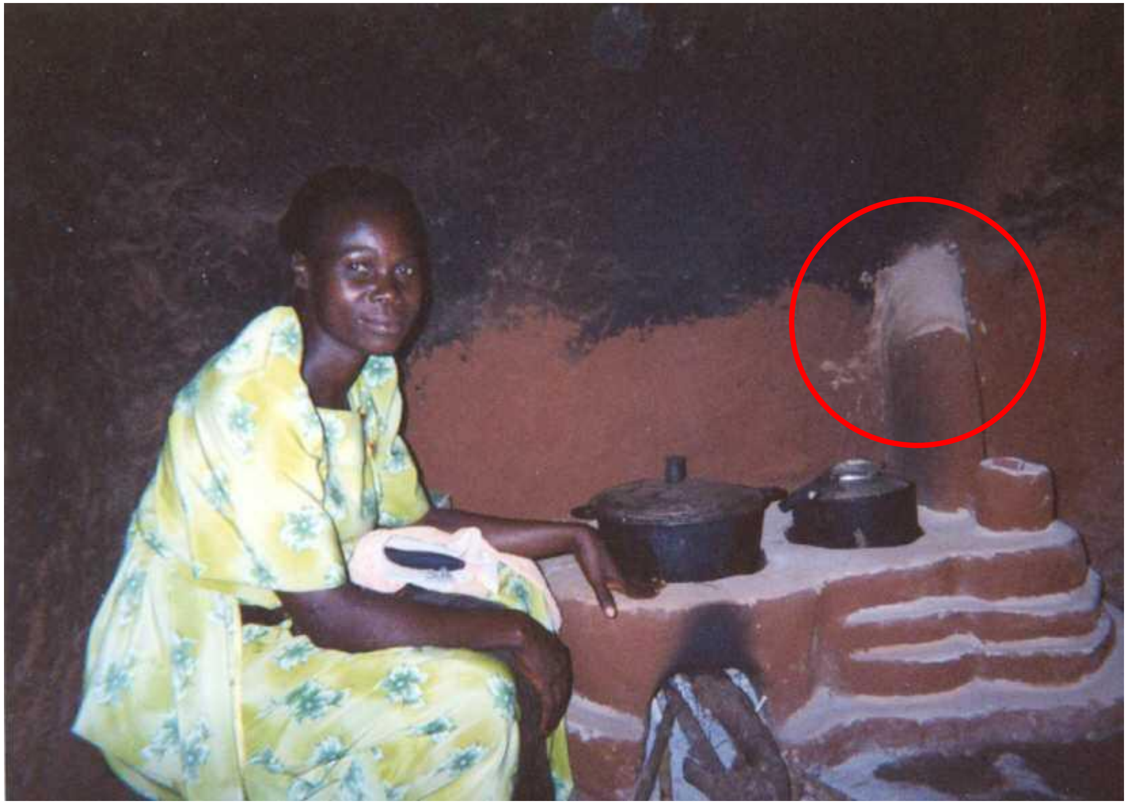
Conservation	Regimentation
Renewables	Competing uses of land
“Clean coal”	Mining: worker and land impacts
Nuclear power	Nuclear war
Geoengineering	Technological hegemony

Risk management: We must trade the risks of disruption from climate change against the risks of disruption from mitigation.

Mitigation is Not Risk-Free

Therefore, the lowest conceivable greenhouse targets, achievable only by casting caution to the winds, are not optimal.

Mitigation can have co-benefits



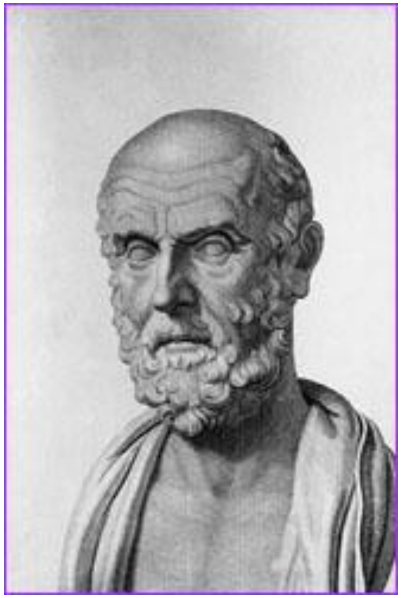
Indoor air pollution: No. 1 adverse health impact of energy

Here: a vented wood stove. Later, a gas stove – fueled by *either* biogas or fossil-gas (LPG, DME).

Iterative risk management

“I will apply, for the benefit of the sick, all measures that are required, avoiding those twin traps of overtreatment and therapeutic nihilism.”

Hippocrates



*** Modern version of the Hippocratic oath, Louis Lasagna, 1964, http://www.pbs.org/wgbh/nova/doctors/oath_modern.html**

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A big new idea

Science has introduced a big, counterintuitive idea: *Human beings are able to change the planet at global scale.*

Forests have been cleared and fisheries have been depleted on a global scale. Most of the low-cost oil has been found. The surface oceans are already more acidic.

That we are changing the climate is just another example.

An unwelcome idea.

We would much rather live on a larger planet, where all our actions mattered less.

Our new assignment: “*Fitting on Earth.*”

Never in history has the work of so few led to so much being asked of so many!

The “few” are today’s climate science researchers.

The “many” are the rest of us.

We are asked to reduce our emissions.

Don’t shoot the messenger

The messenger has been shot before.

Galileo argued that the earth wasn’t at the center of the universe and was excommunicated.

Darwin argued that human beings were part of the animal kingdom and was cruelly mocked.

The idea that humans can’t change our planet is as out-of-date and wrong as the earth-centered universe.

Grounds for optimism

1. The world today has a terribly inefficient energy system.
2. Carbon emissions have just begun to be priced.
3. Most of the 2062 physical plant is not yet built.
4. Very smart scientists and engineers now find energy problems exciting.

Prospicience

Prospicience: "The art [and science] of looking ahead."

In the past 50 years we have become aware of the history of our Universe, our Earth, and life.

Can we achieve a comparable understanding of human civilization at various future times: 50 years ahead – *vs.* 500 years and *vs.* 5000 years? Prospicience is needed to address planning horizons, infrastructure, waste management….

We have scarcely begun to ask: What are we on Earth to do?

Fitting on the Earth

Fortunately:

Our science has discovered threats fairly early;

We can identify a myriad of helpful technologies;

We have a moral compass that tells us to care not only about those alive today but also about the collective future of our species.

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