

Truths we must tell ourselves to manage climate change

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**CLAIRE: Clusters Alpines Industry Research Energy*

Outline of talk

Overview

- Carbon math

- Truths we must tell ourselves

“Solutions”

- The end-use perspective

- Low-carbon energy

- Geoengineering

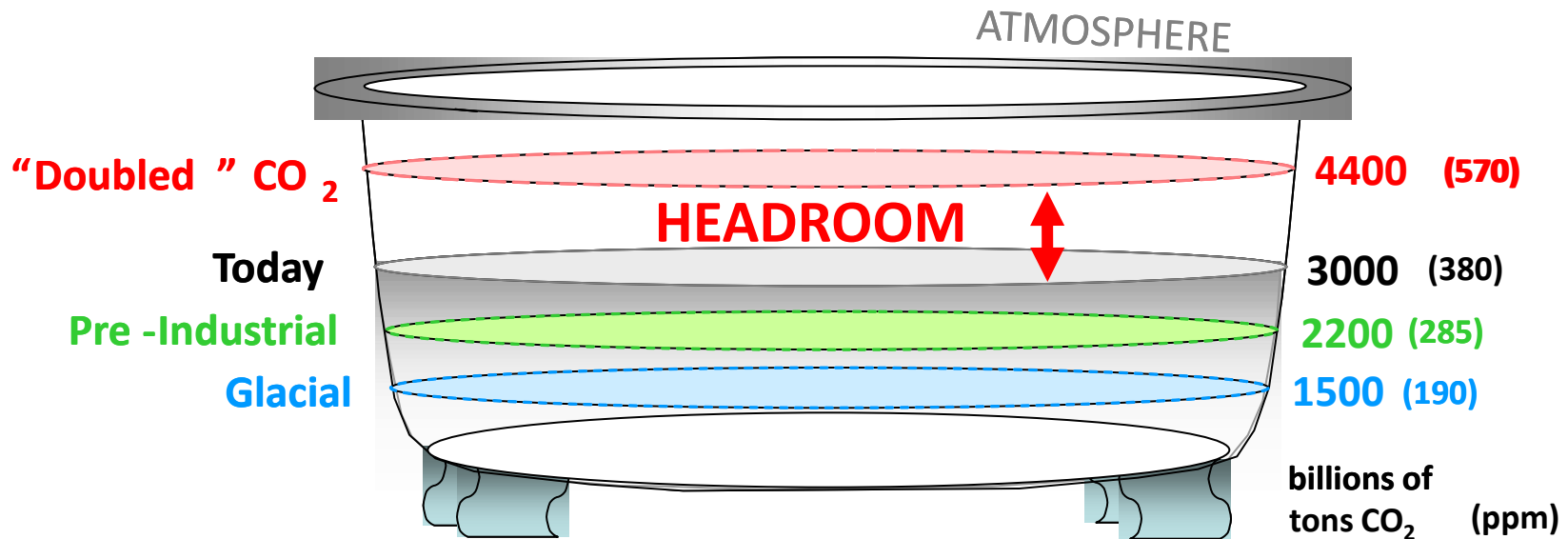
North and South

Guiding Principles

OVERVIEW

Carbon Math

Past, present, and potential future levels of CO₂ in the atmosphere

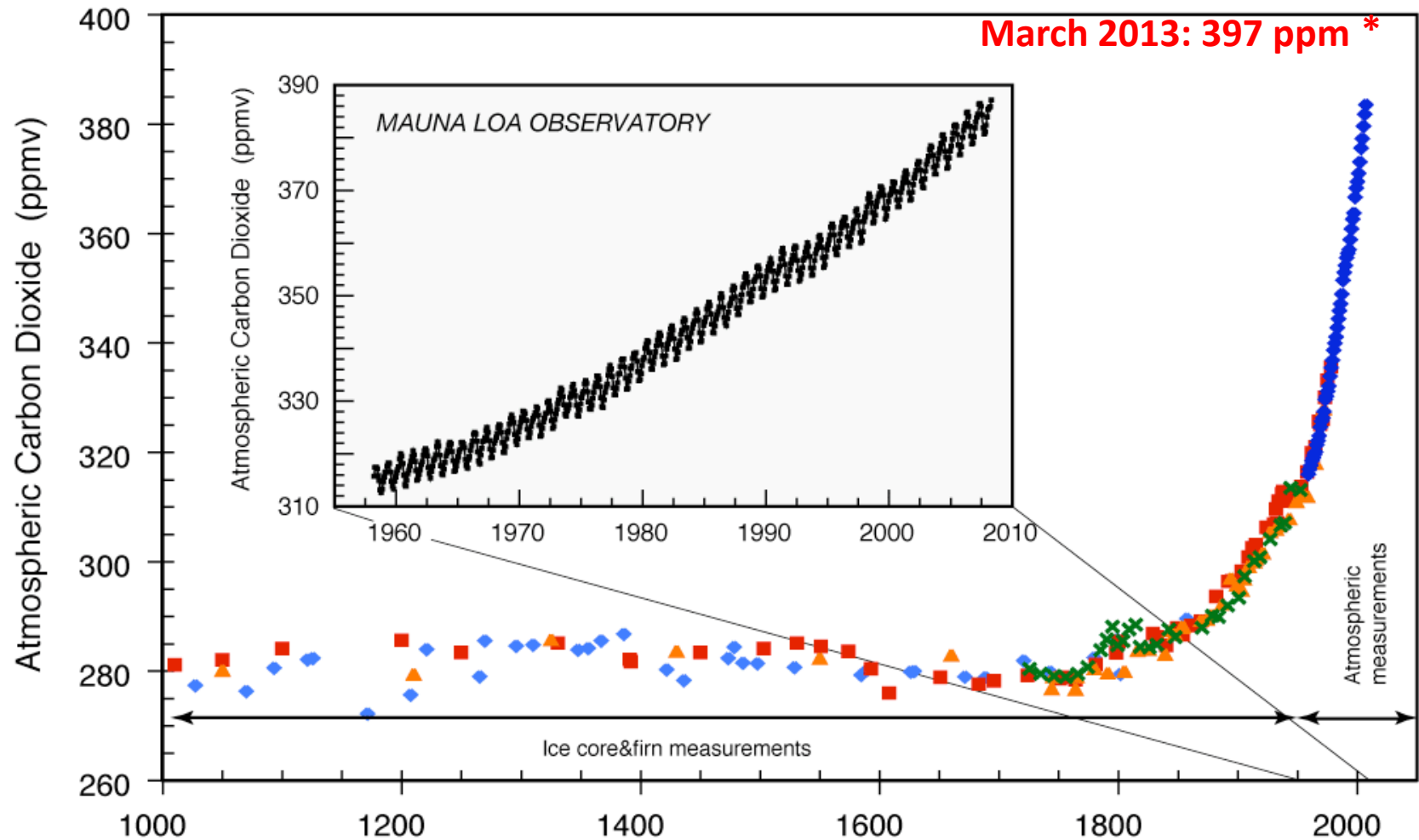


Rosetta Stone: To raise the concentration of CO₂ in the atmosphere by **one part per million**:

add **7.8 billion tons of CO₂**,

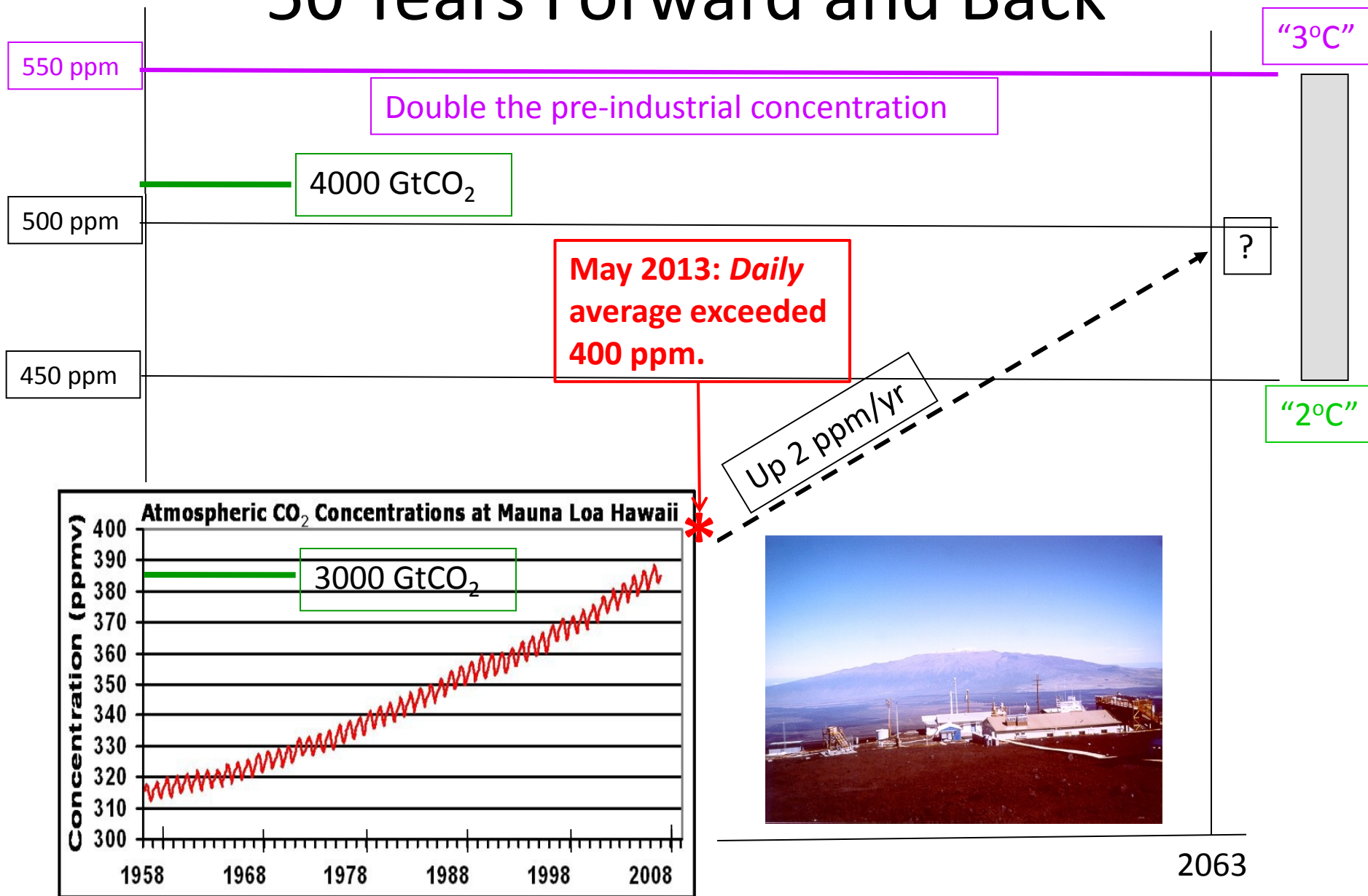
in which are **2.1 billion tons of carbon**.

Atmospheric CO₂ since 1000 AD



Source: Sarmiento. Ice core data from Barnola, 1999;
Mauna Loa data from D. Keeling & T. Whorf, 2000

50 Years Forward and Back



Monsters behind the door

Steve Pacala calls the worst credible climate outcomes “monsters behind the door.” The monsters include:

- a three-meter rise in sea level by the end of this century

- major alterations of the global hydrological cycle

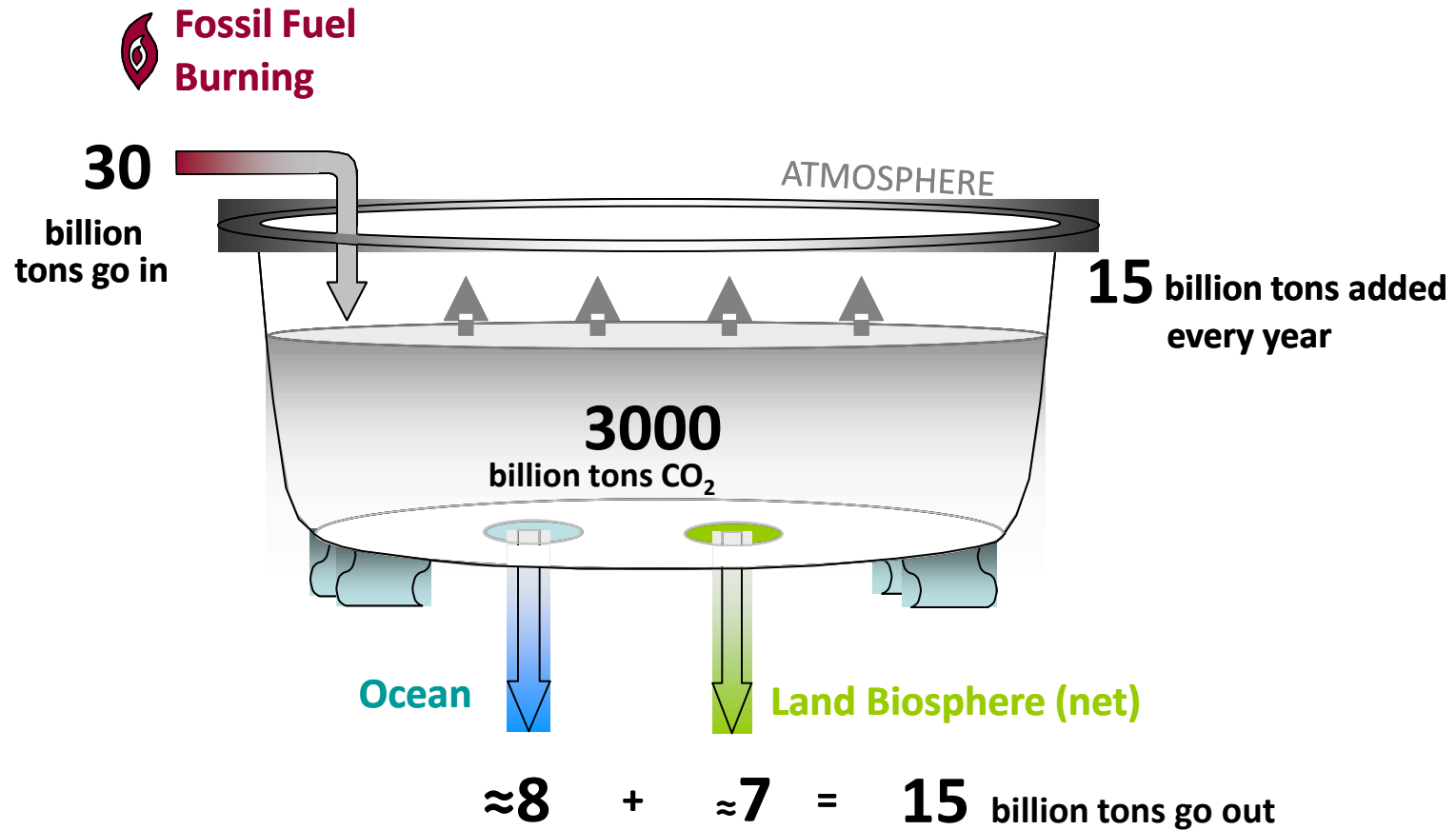
- major changes in forest cover

- major emissions of greenhouse gases from the tundra.

The monsters open their door in a world of very strong positive feedbacks, a world that spirals out of control.

Today’s science cannot predict how much atmospheric change would let these monsters in, nor how quickly they could enter.

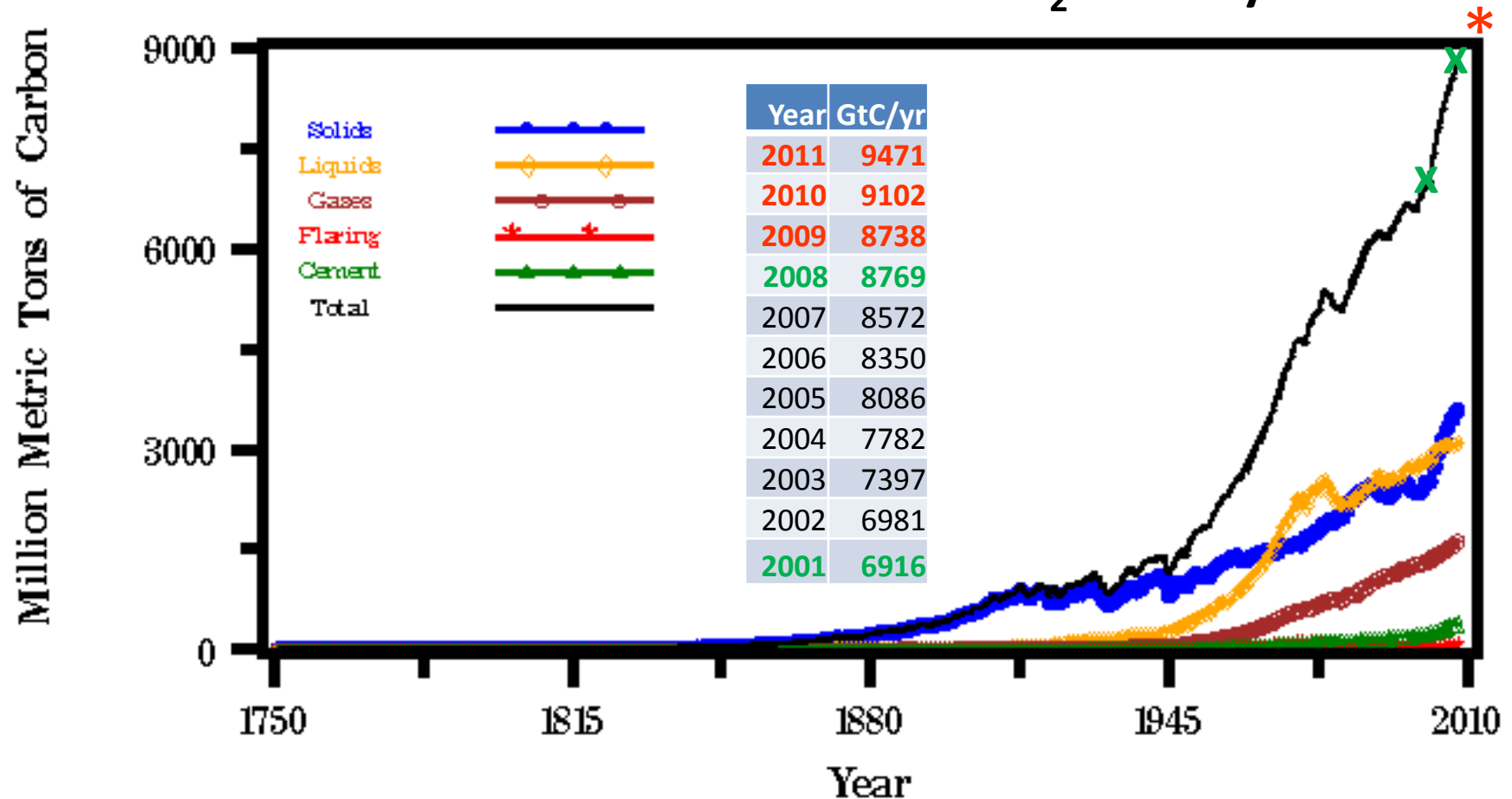
Yearly, fossil fuel burning adds 30 billion tons of CO₂ to the atmosphere, and half stays in.



Today, global per-capita fossil-fuel emissions are $\approx 4 \text{ tCO}_2/\text{yr}$.

We have lost precious time.

Annual Rate of Emissions of CO₂ Globally



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

Updated 1/5/13

Four World Views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO	A nuclear or renewables world unmotivated by climate.	Most people in the fuel industries and most of the public are here. 5°C.
	YES	Environmentalists, nuclear advocates are often here. 2°C.	OUR WORKING ASSUMPTIONS. 3°C, tough job.

How do we bend the curve?

Three ways:

Be very smart, so no policy is needed.

“ $S < C$ ” (solar is cheaper than coal).

Regulatory policy and referenda: Forbid and require.

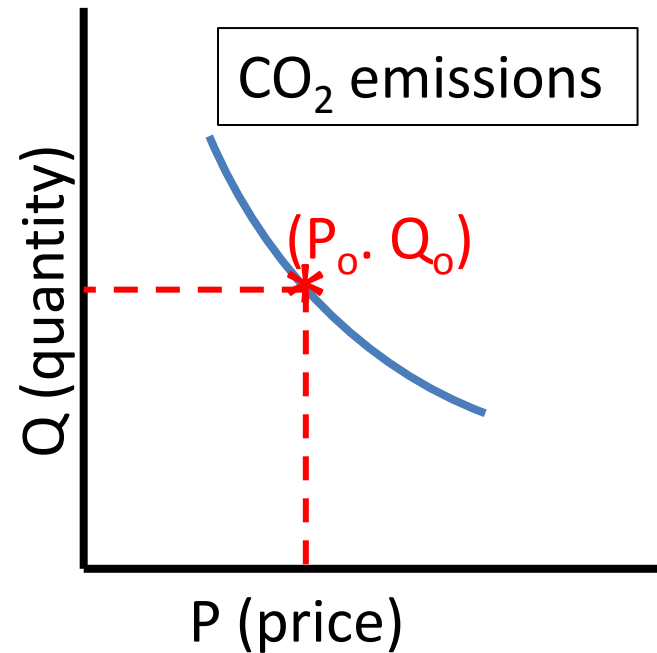
Market-based policies: Change relative prices.

**“Cap-and-trade” and “tax”
in their pure forms are identical.**

Assume $Q(P)$ exists:

Cap-and-trade: Fix Q_o , then find P_o .

Tax: Fix P_o , then find Q_o .



Truths we must tell ourselves

Admit that the news is unwelcome.

Admit that the job is hard and requires sustained focus.

Admit that we don't know how large a problem we face.

What's in the way of action?

Important factors have been beyond the control of the environmental community:

- The recent recession
- The political influence of the fossil fuel industries and the beneficiaries of low-cost power (e.g., the coal-power states)
- Economic development imperatives in countries undergoing industrialization.

However, advocates for prompt action, of whom I am one, also bear responsibility for the poor quality of the discussion and the lack of momentum.

The news is unwelcome.

The news is that our planet is small.

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 promptly and substantially.

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

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

“Shooting the messenger”? No surprise.

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 and the separate creation of Man.

But all three ideas have such appeal that they will fade away only very slowly.

The job is hard

“Stabilization”: ≈ 1 ton CO₂/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.

The science is incomplete

1. Neither slow nor rapid arrival of severe climate change can be ruled out, given our poor understanding of feedbacks.
2. The probability of very bad outcomes is poorly known.
3. Breakthroughs are not imminent. The fog is not about to lift.
4. What we don't know should motivate us as much as what we do know.

“SOLUTIONS”

The end-use perspective

Four ways to emit 4 ton CO₂/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 CO₂ in 2007

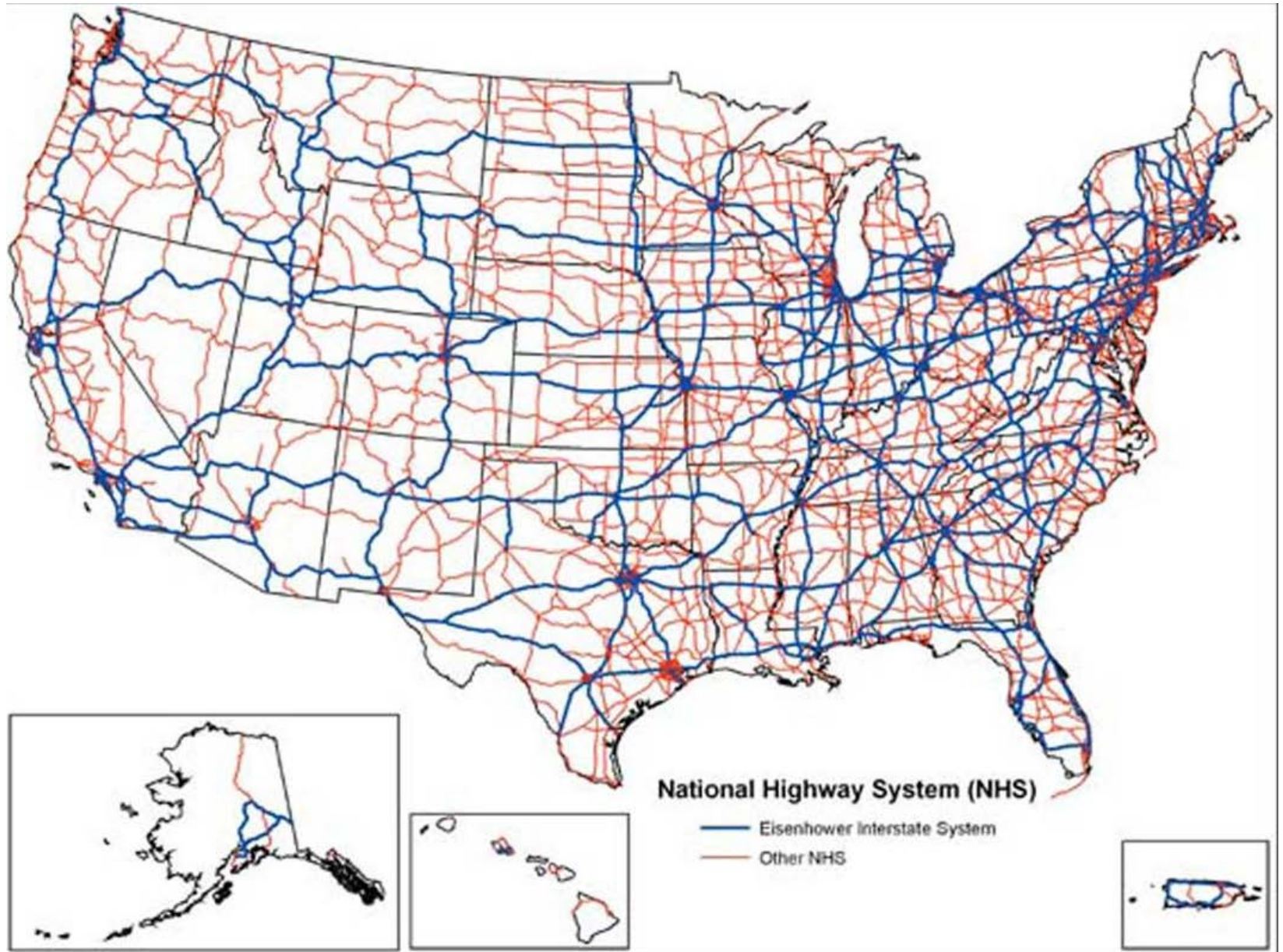
University emissions*	112,000 tCO ₂
12,500 participants**	
Per-capita emissions	9 tCO ₂

*On-site cogeneration plant, purchased electricity,
fuel for University fleet.

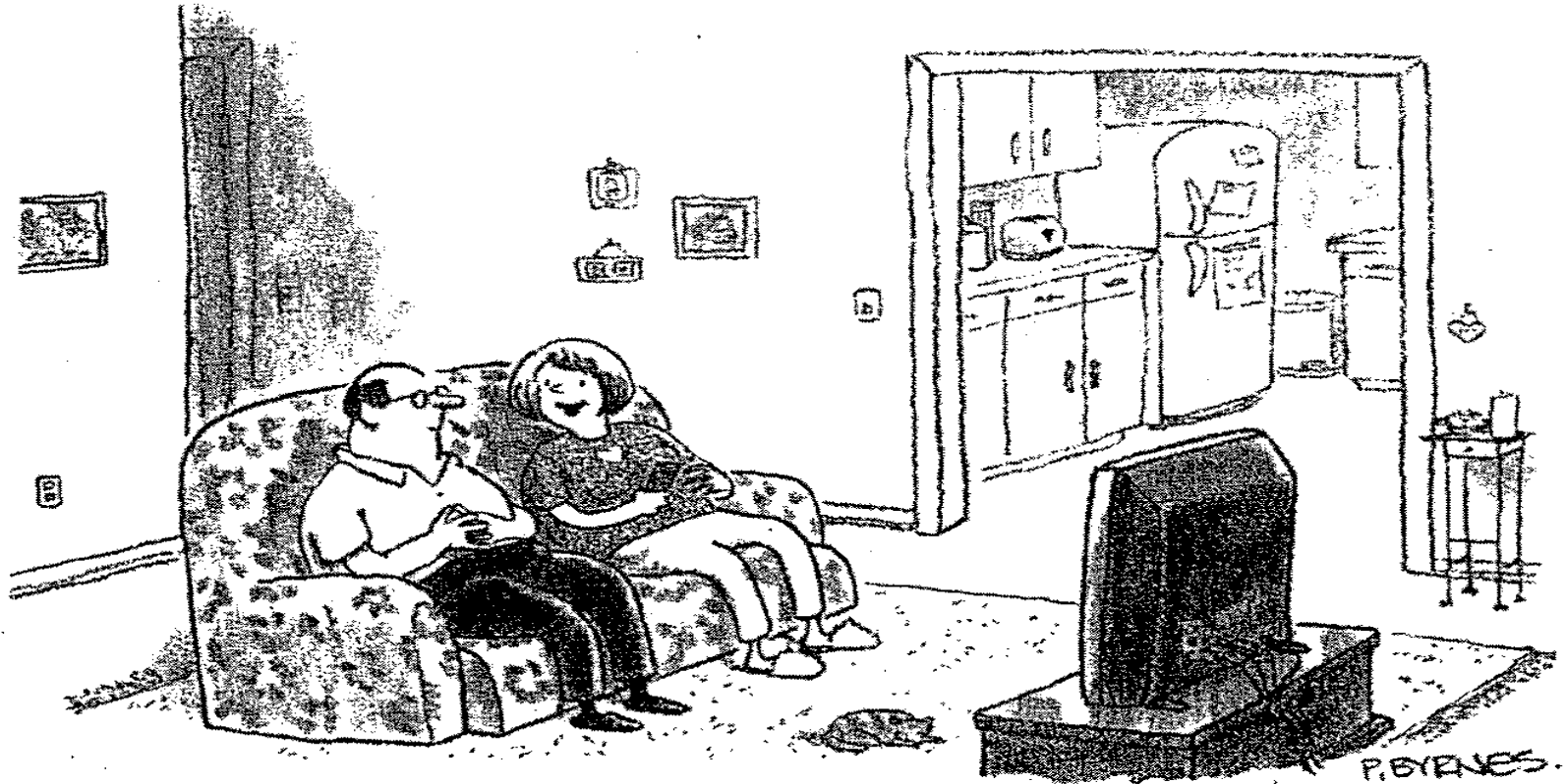
**7,100 students and 5,400 employees

What about PoliTo?

Legacy: National Highway System



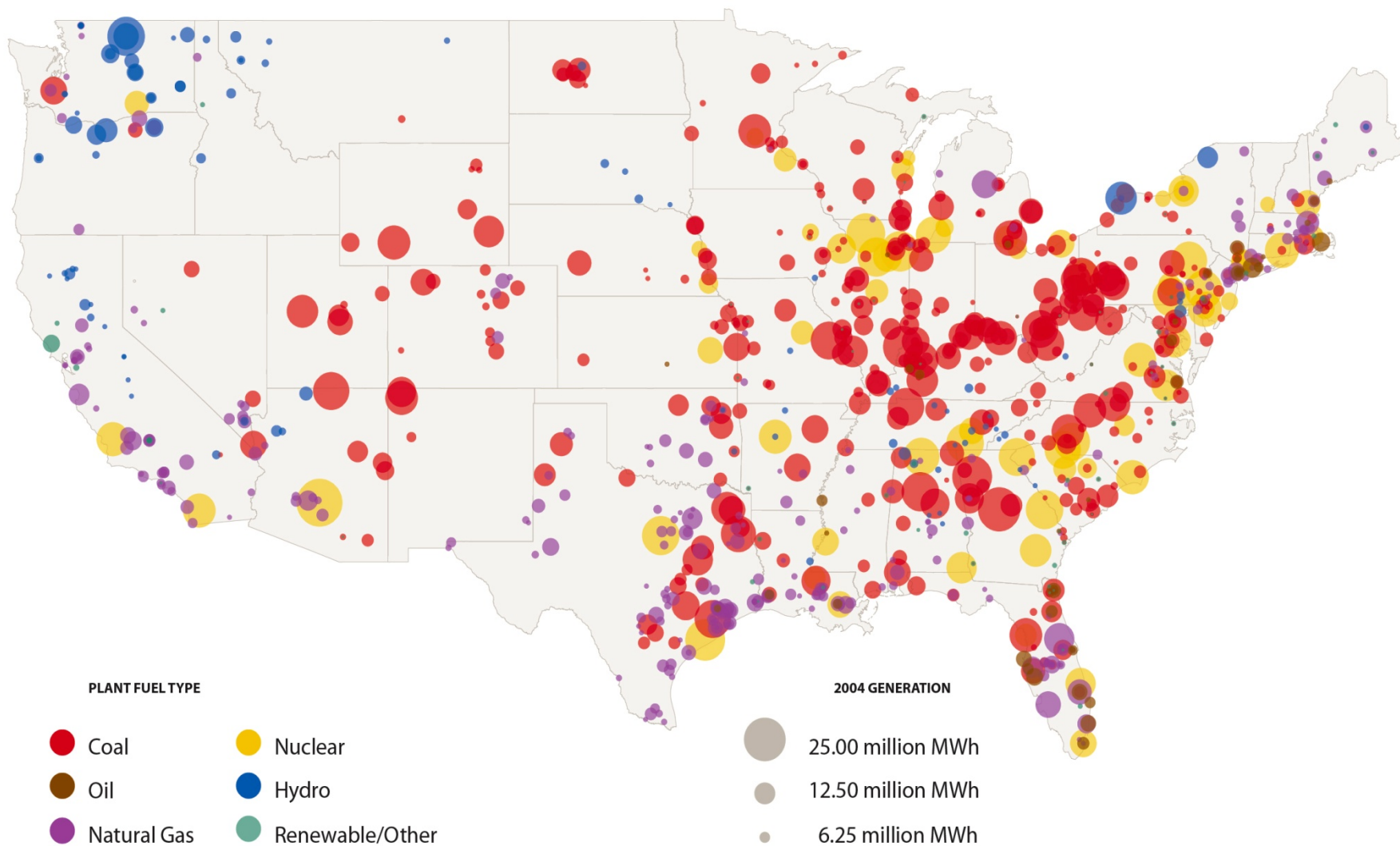
Substituting IT for travel



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

From *The New Yorker*, April 21, 2008

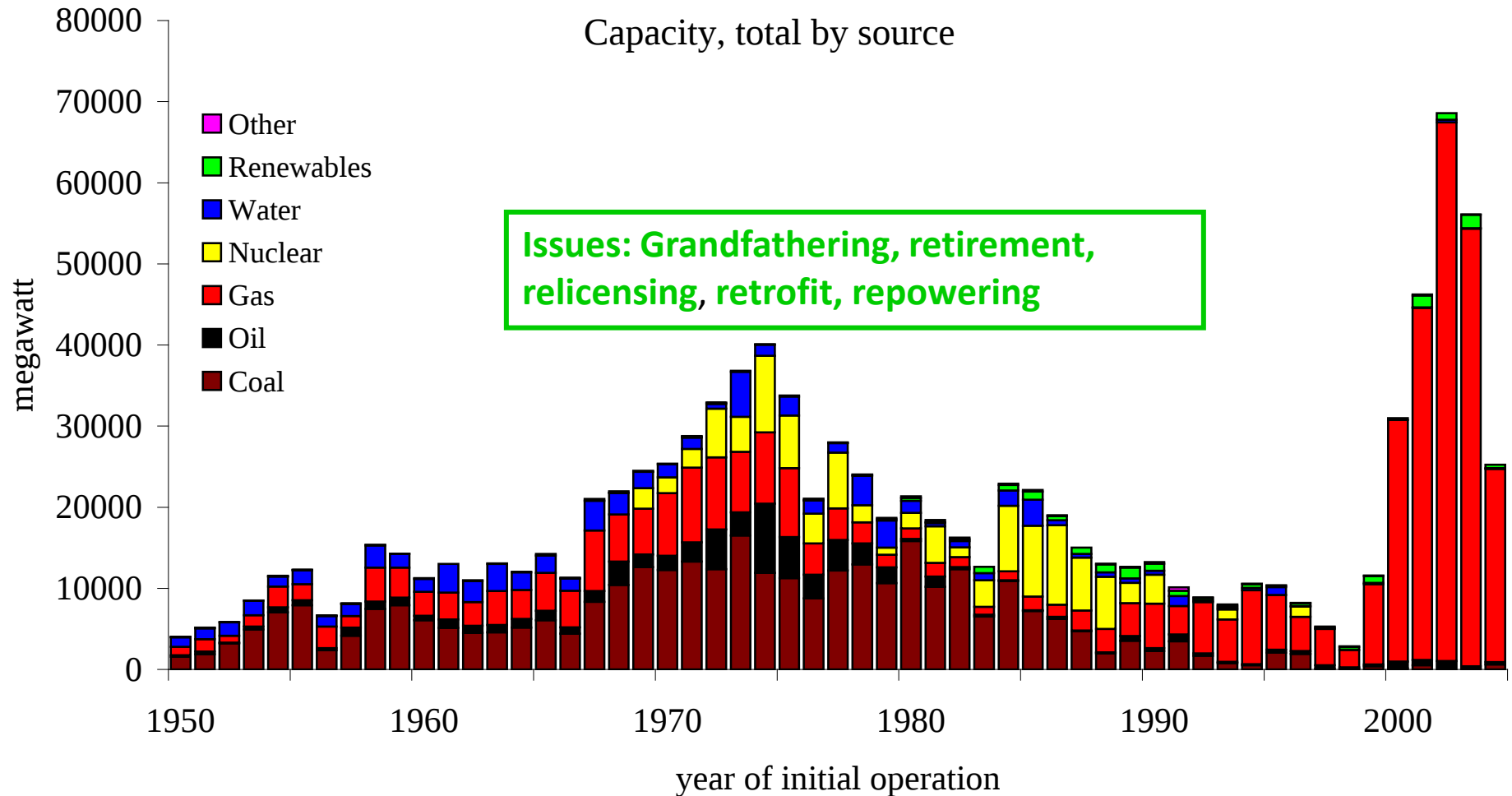
Legacy: U.S. Power Plants



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

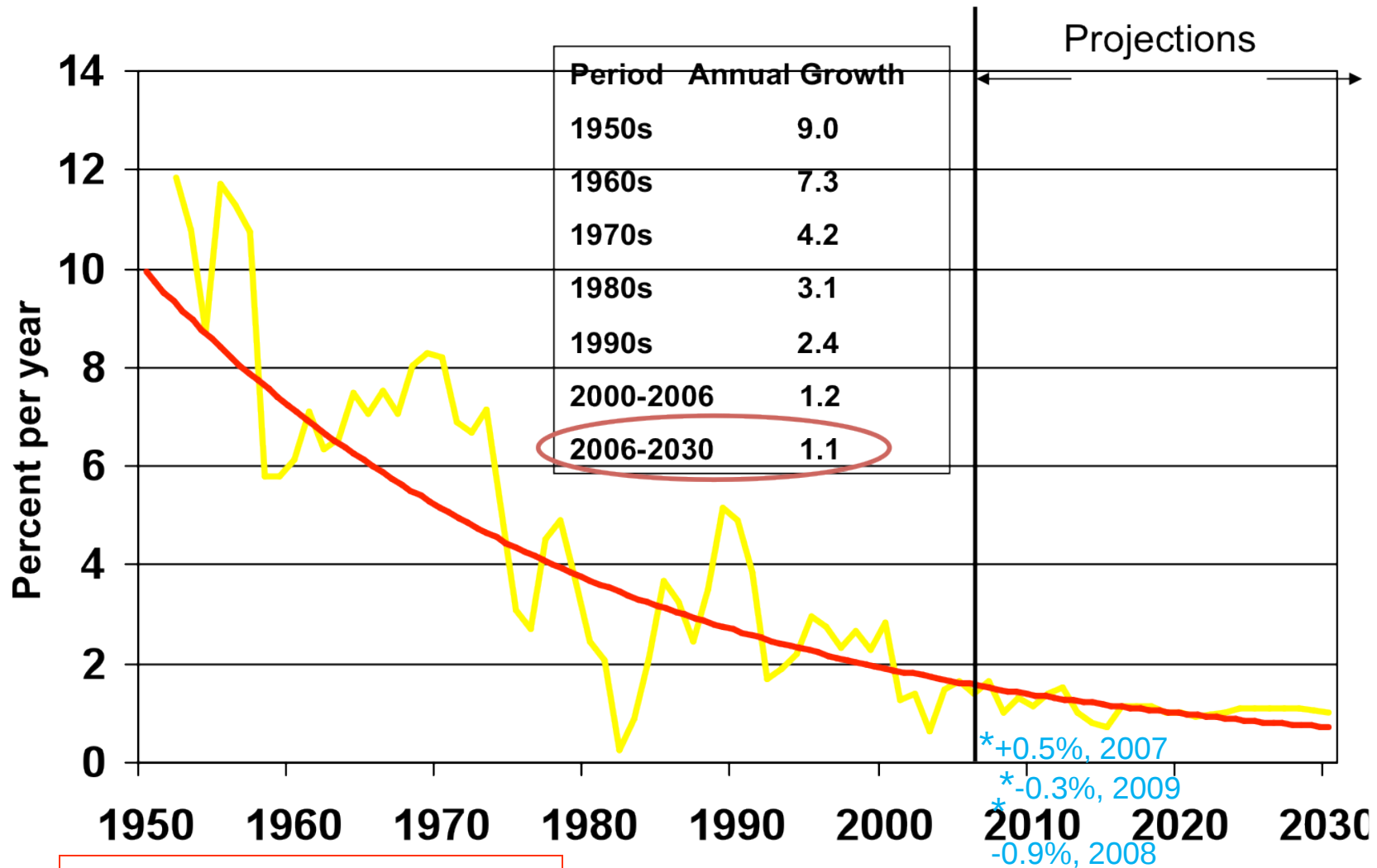
U.S. power plant capacity, by vintage

Can a group of you plot this graph for Italy?



U.S. electricity growth rate is falling

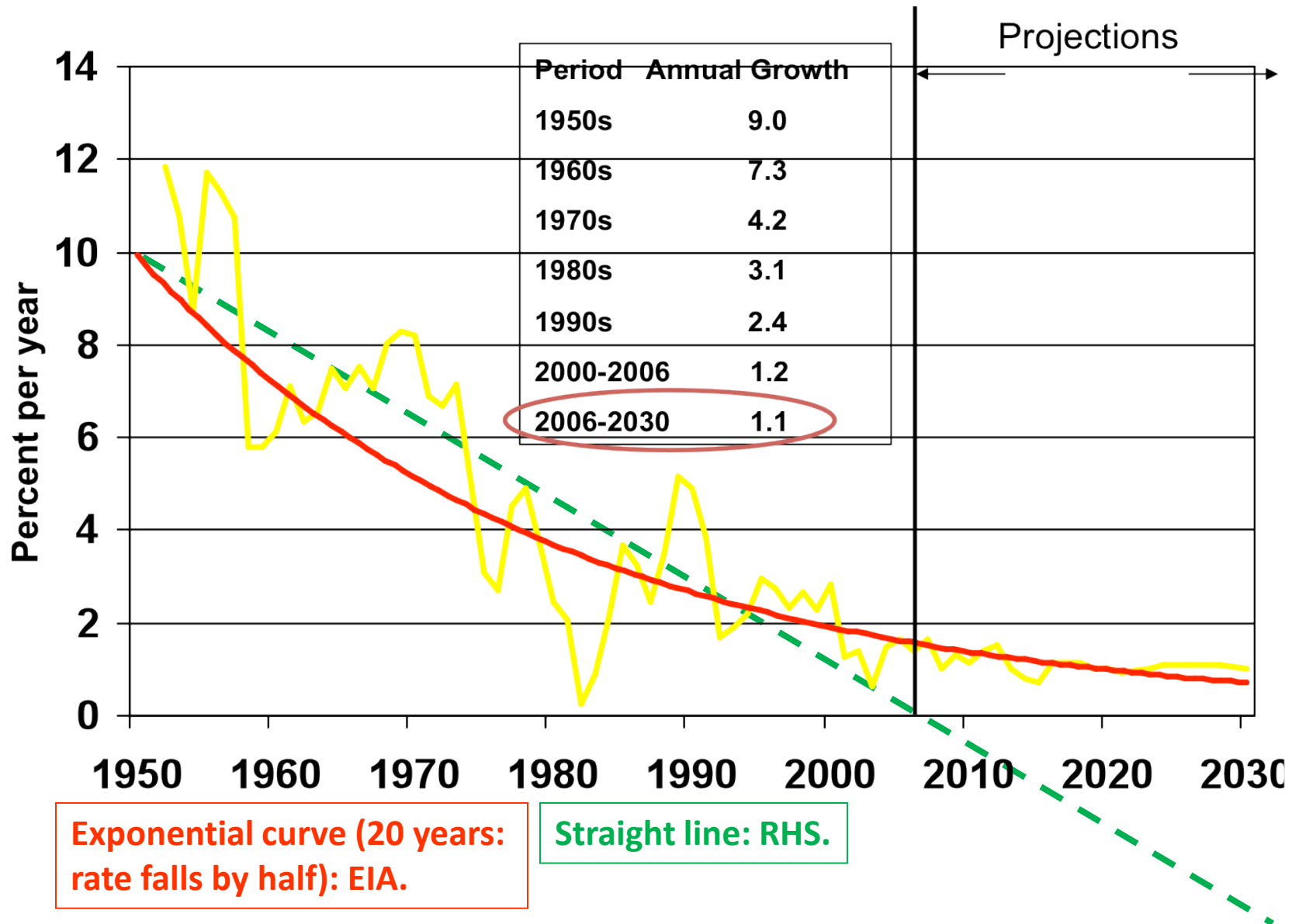
(3-year rolling average percent growth)



Exponential curve (20 years:
rate falls by half): EIA.

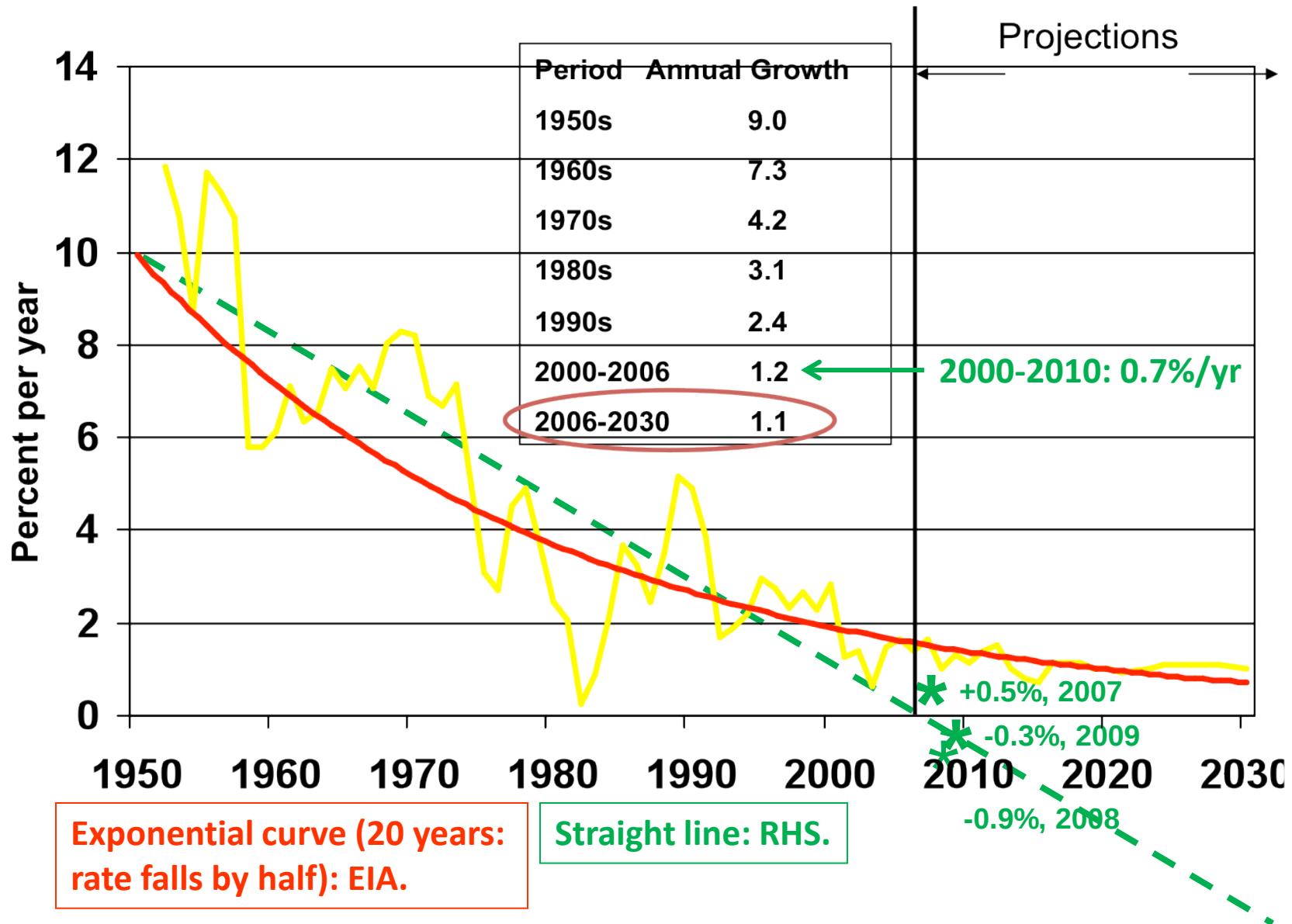
U.S. electricity growth rate is falling

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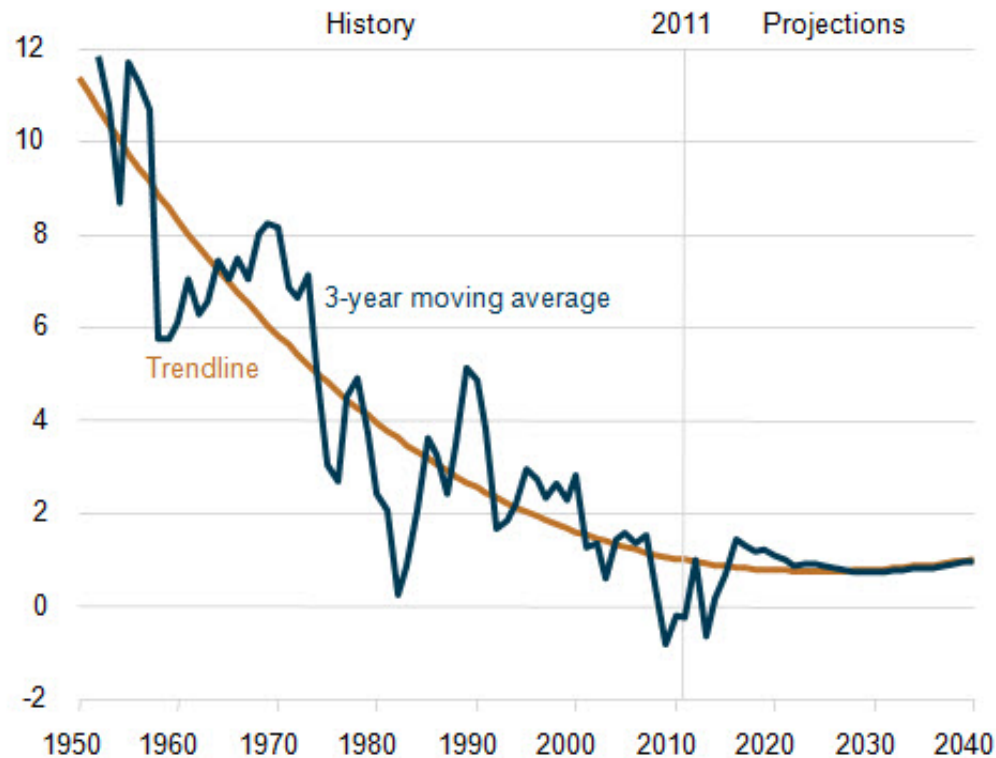
U.S. electricity growth rate is falling

(3-year rolling average percent growth)



Last month's version

Figure 75. U.S. electricity demand growth, 1950-2040
(percent, 3-year moving average)



Source: *Annual Energy Outlook, 2013*. Energy Information Agency, U.S. Dept. Energy.

Is peak energy demand behind us?

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

- oil consumption
- electric power consumption

Is it? Let me know.

Efficiency: Measure, measure, measure

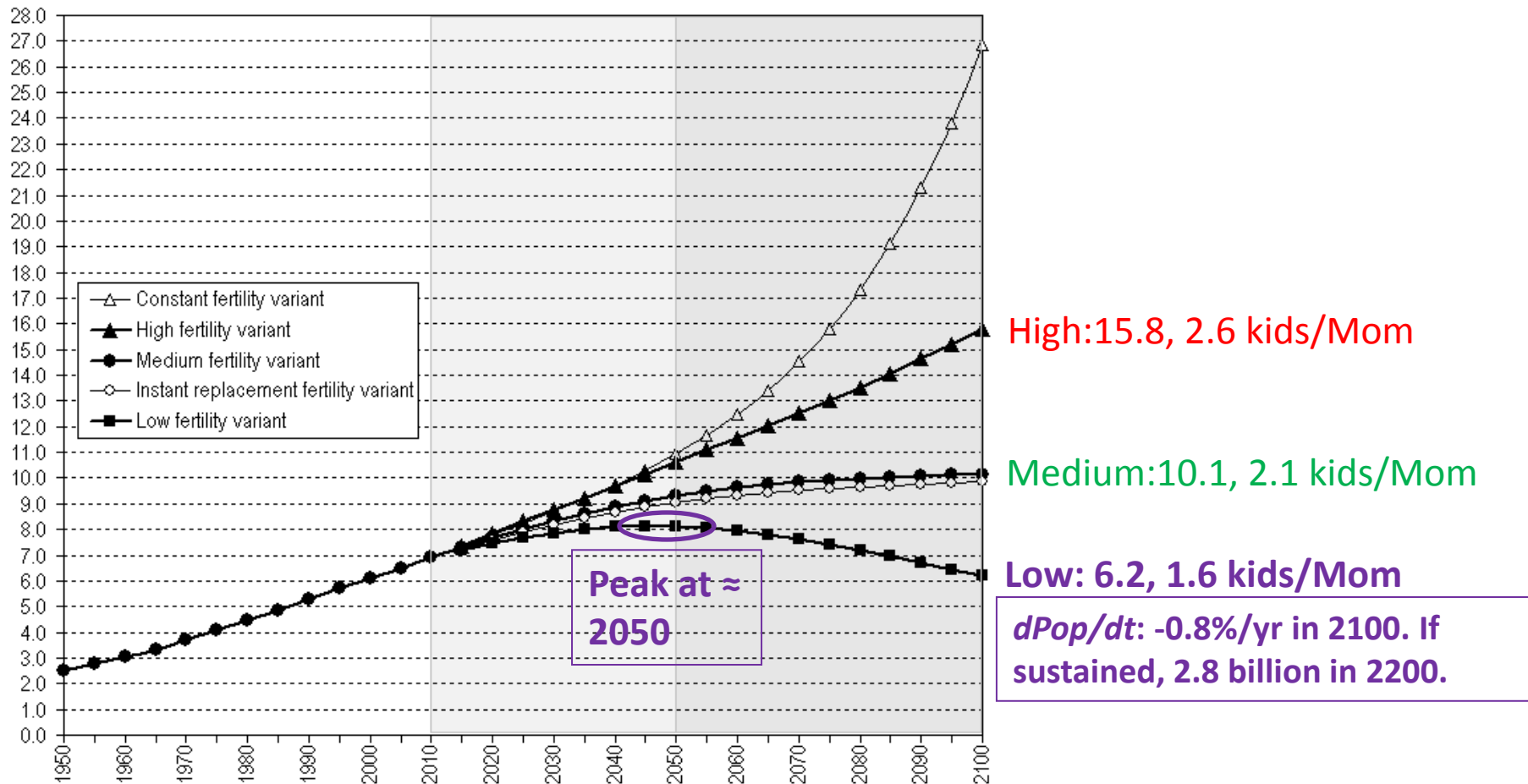
Give architecture prizes for performance, not only for design.

Trust, but verify.



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

Billion
people



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

How many children will you have?

Low-carbon energy

Photovoltaic Power



*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

Intermittency needs attention

Huge uncharted research frontier. As renewables achieve >20% penetration on grids, intermittency (non-constant, unpredictable) must be addressed.

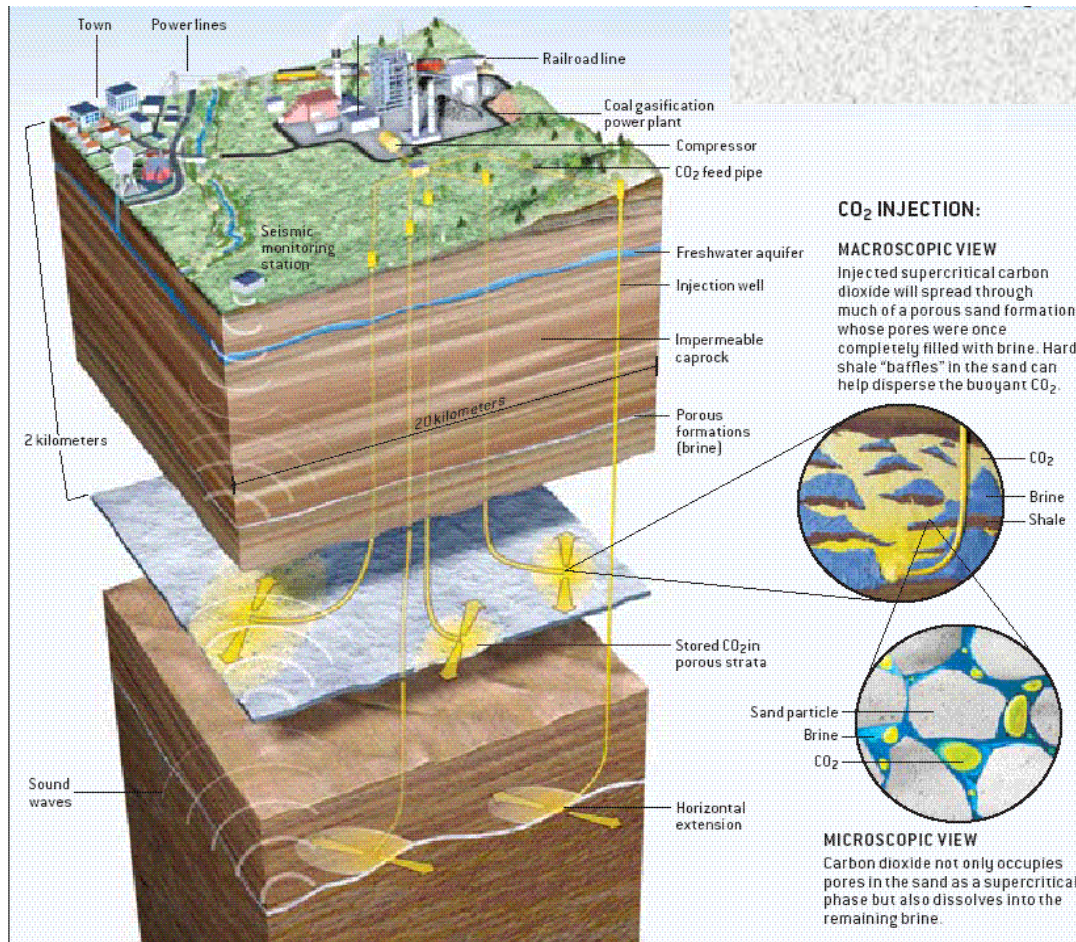
Strategies:

- Diversity of supply (wind flux is often larger at night)

- Complementary energy source (e.g., natural gas)

- Storage for various durations, from seconds to days

The future coal power plant



Shown here: After 10 years of operation of a 1000 MW coal plant, 60 Mt (90 Mm³) of CO₂ have been injected, filling a horizontal area of 40 km² in each of two formations.

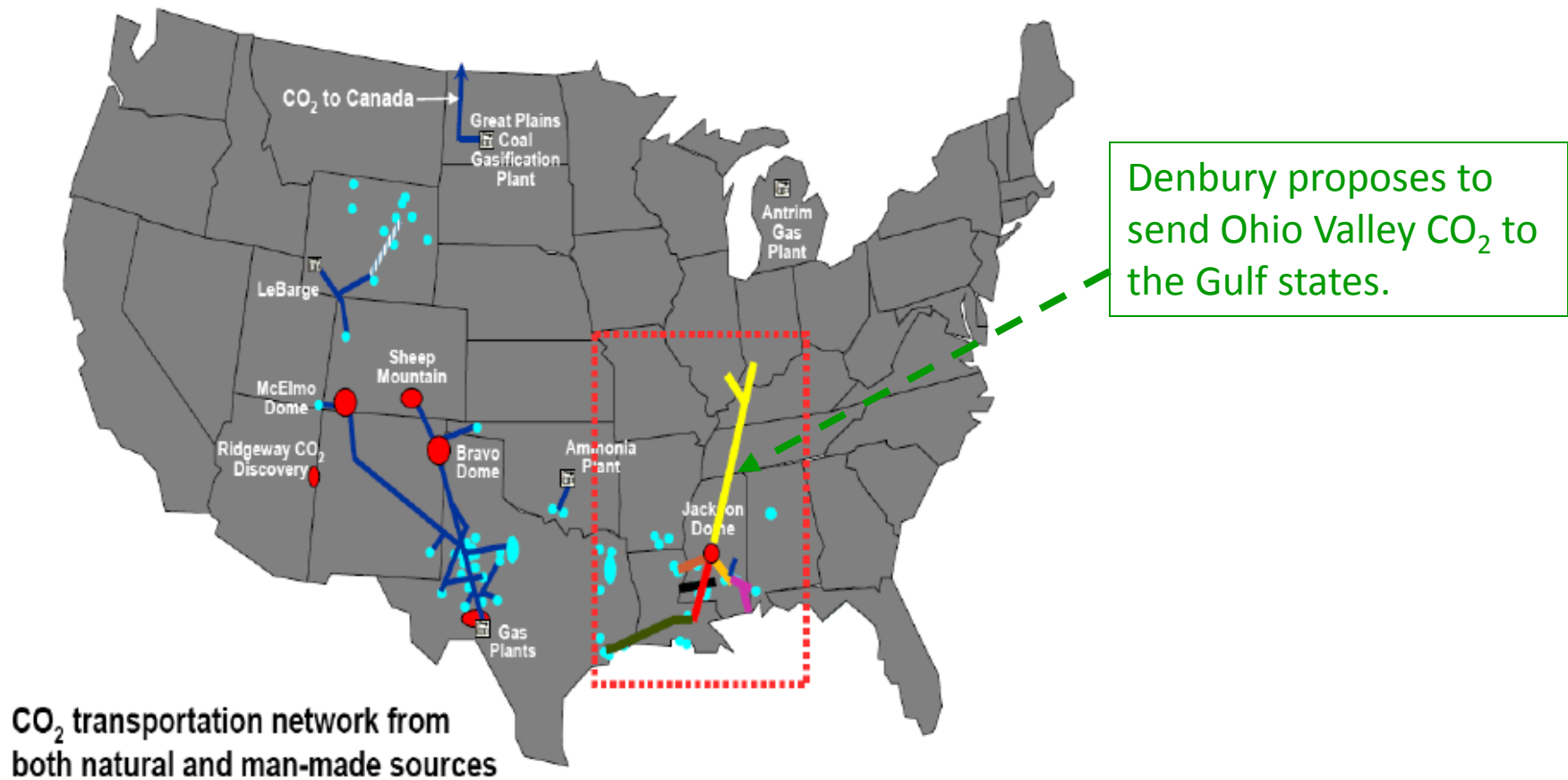
Assumptions:

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

• **Note:** Plant is still young.

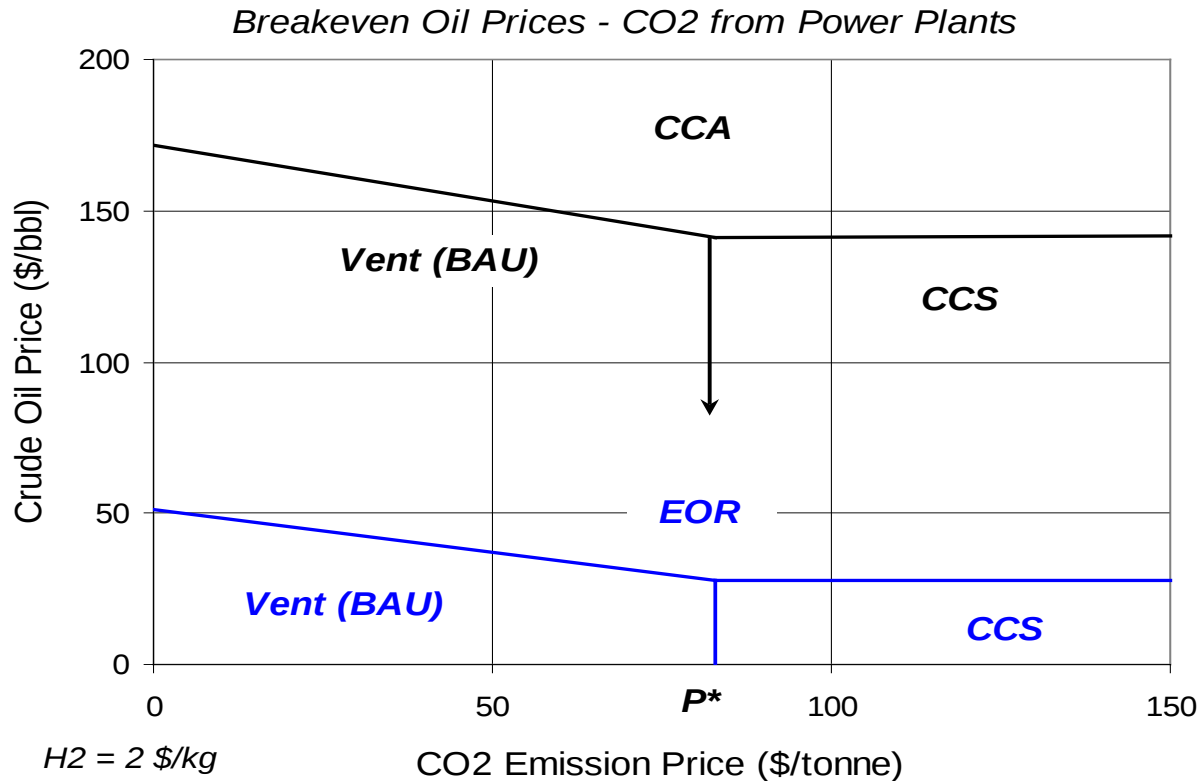
Injection rate is 150,000 bbl(CO₂)/day, or 300 million standard cubic feet/day (scfd).
Lifetime injection: 3 billion barrels, or 6 trillion standard cubic feet, over 60 years.

U.S. CO₂ pipeline infrastructure



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

CO₂ “activation” to fuels (with T. Kreutz)



One path to CO₂ activation (CCA) is a reverse shift reactor:



followed by Fischer-Tropsch synthesis.

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

Conditionality for nuclear power

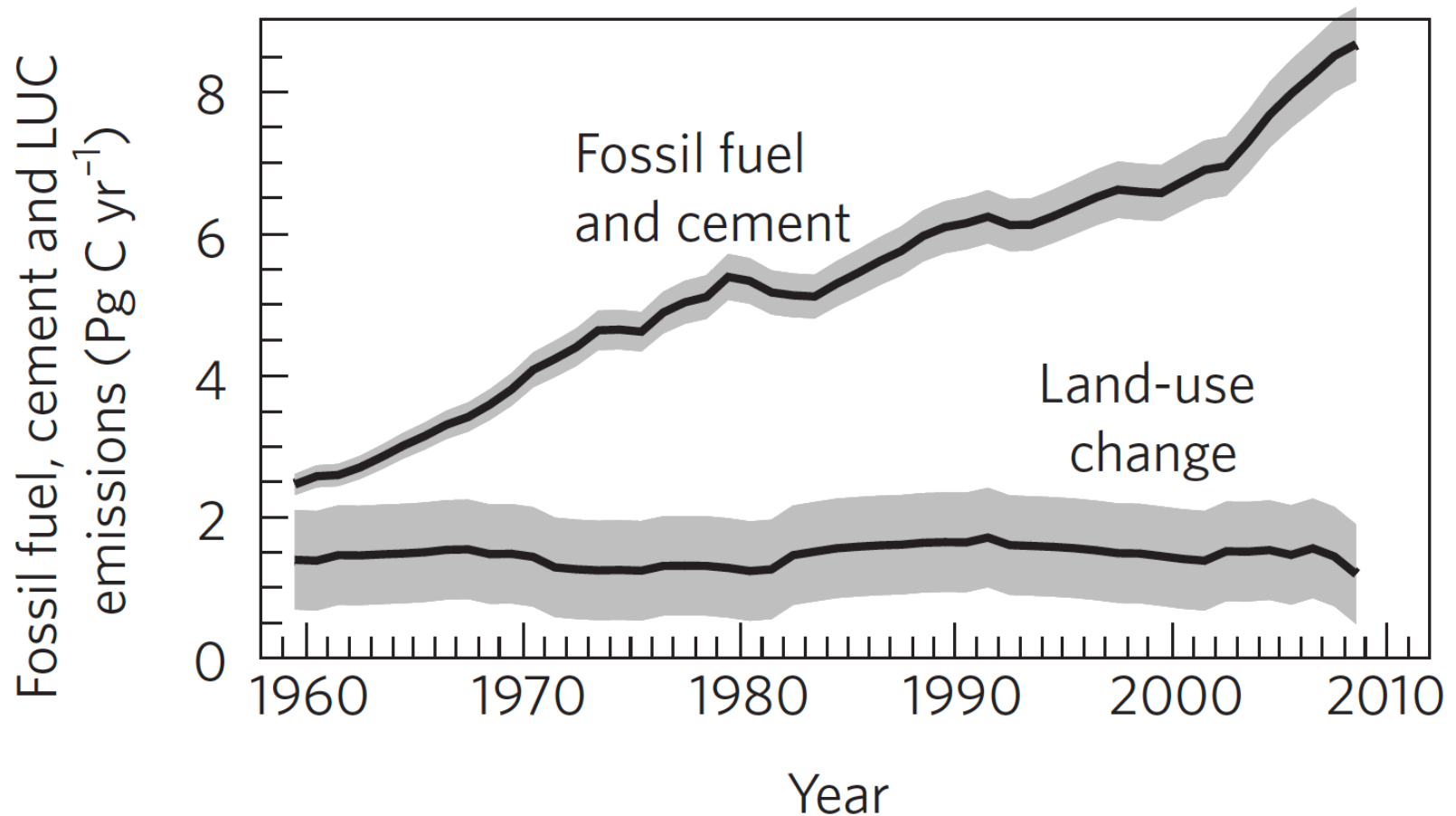
Make the use of nuclear weapons unthinkable (rather than one of the “options on the table”). Also strengthen the international institutions designed to prevent the diversion into nuclear weapons of the uranium and plutonium associated with nuclear power.

“We judge the hazard of aggressively pursuing a global expansion of nuclear power today to be worse than the hazard of slowing the attack on climate change by whatever increment such caution entails. “

Robert H. Socolow & Alexander Glaser, “Balancing risks: nuclear energy & climate change,” *Dædalus*, Fall 2009, pp. 31-44.

It would be terrible to exchange climate change for nuclear war anywhere on the planet.

Land use change emissions have remained relatively constant over time



Le Quéré et al. (2009)

Biocarbon: Biologists needed



Back of the envelope:

Yield: 10t/ha-yr

Energy content: 20 GJ/t

So 200 GJ/ha-yr

Equivalently: 200 EJ/Gha-yr

Global primary energy: 500 EJ/yr

Area of U.S. (1 Gha) yields 200 EJ/yr.

Biofuel to address oil and carbon

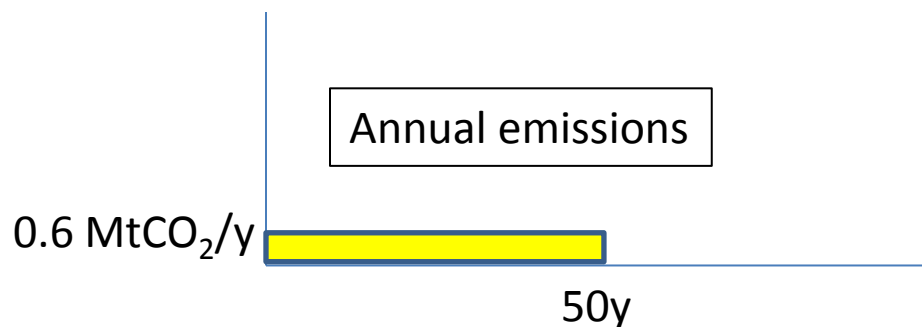
Biopower with CO₂ capture and storage to scrub the atmosphere

Biocarbon stock augmentation (afforestation) to scrub the atmosphere and provide ecosystem services

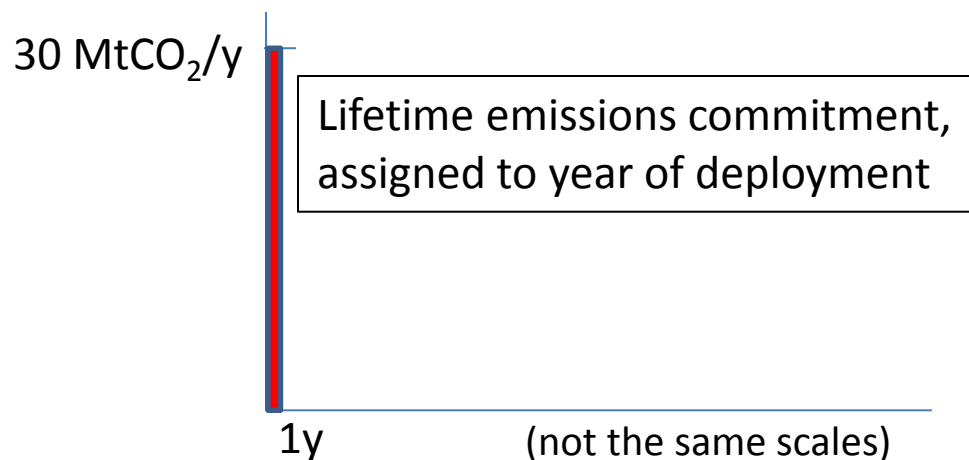
Commitment accounting (w. Steve Davis)

Imagine a 200 MW natural gas combined-cycle power plant with a plant life of 50 years and with CO₂ emissions of 3 MtCO₂/GW-year, and. There are two ways of thinking about the plant's 30 MtCO₂ of lifetime emissions.

1. Emissions assigned to year of emission

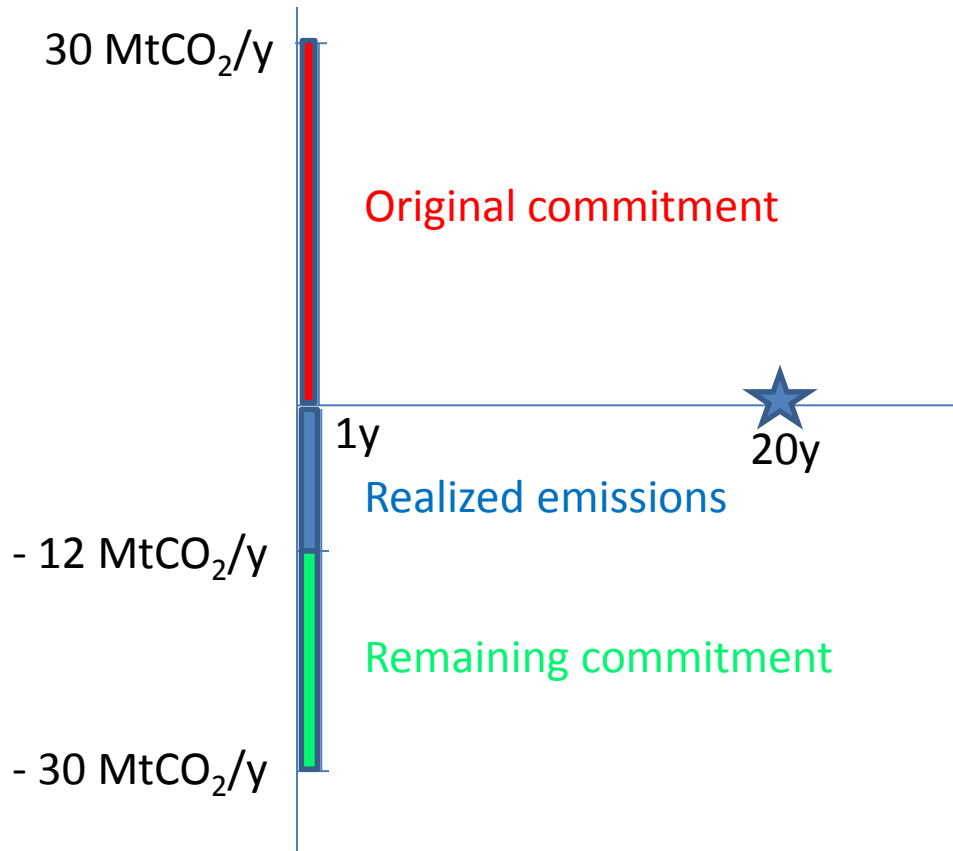


2. Emissions assigned to year of deployment.



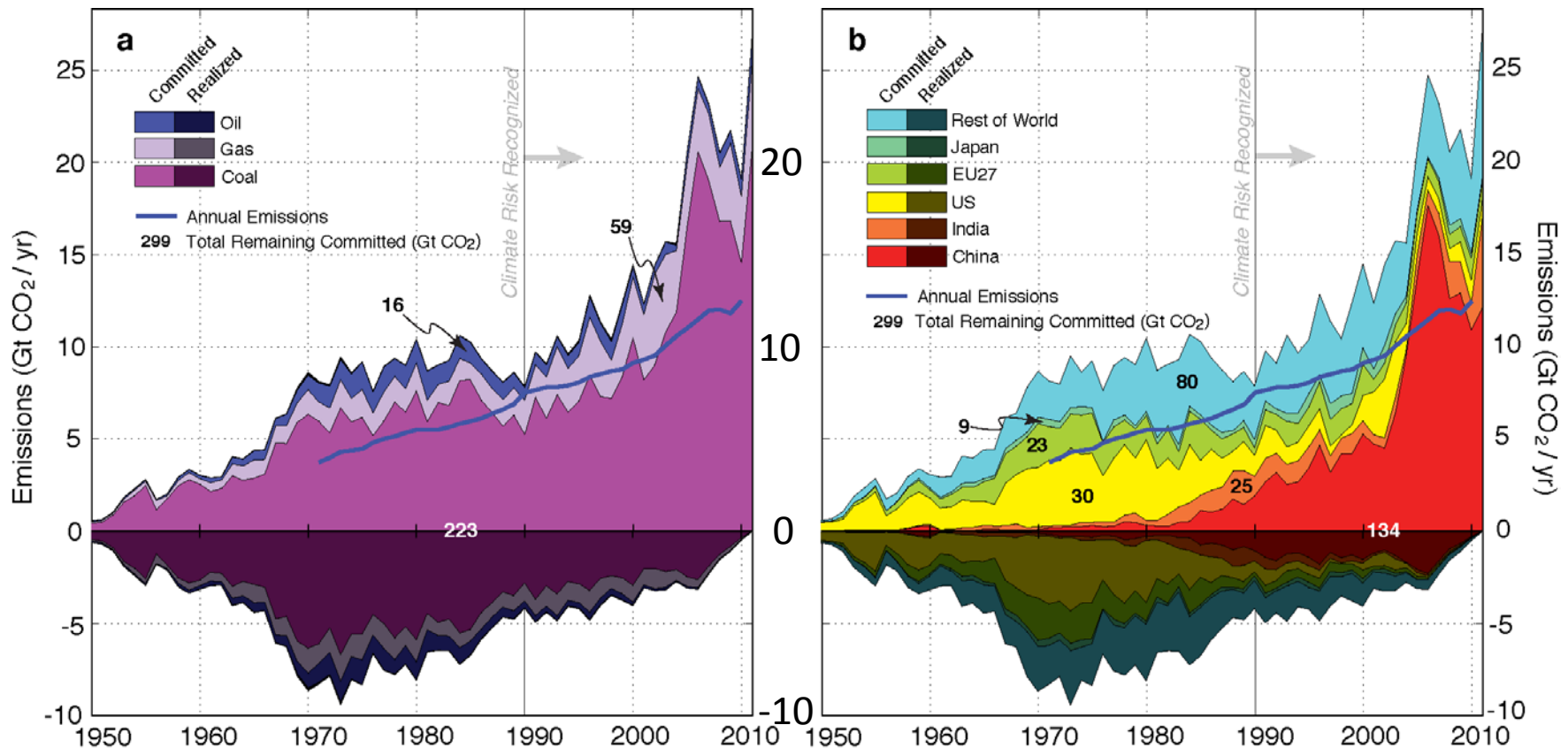
Credit David Hawkins for the original idea, ca. 2005.

Dynamic view at 20 years



Commitments from global electricity, 1950-2010

Preliminary



Geoengineering

Geoengineering by imitating volcanoes



On June 15, 1991 (three days after this photo) , Mt. Pinatubo. injected 10 million tons of sulfur into the stratosphere.

The Earth's average surface temperature was 0.5°C cooler six months later, then rebounded.

What if the current technocratic response is not sufficient?

Two possible reasons:

1. The world cannot implement the necessary changes.
 - A. Inertia and habit
 - B. Vested interests – incumbent political power
 - C. Shortcomings of the available “solutions”
2. The world *does* implement the necessary changes, but low-probability nasty outcomes arrive anyway.

The Sword of Damocles: Rapid disengagement

Rapid disengagement from S-injection might be

- a. deliberate: An adverse side-effect is discovered.
- b. unintentional: Loss of capability, political will.

In one model run, following an interruption of injection, “within a few decades, winter warming in the polar regions exceeds 10°C and summer warming in the northern temperate latitudes will be about 6°C.”

“Coming generations will have to live with the danger of this ‘Sword of Damocles’ scenario, the abruptness of which has no precedent in the geologic history of climate.”

Today's scrimmage line: Research

Research:

Slippery slope or moral imperative?

Scale: Is there a scale large enough so that research can tell us what we need to know but small enough not to trigger the hazards we must avoid. (Drug testing confronts this question too.)

Proposals for governance: Ban large-scale research, enable small-scale research.

Circumscribe the self-governance of the scientists.

Every strategy can be implemented well or poorly

Every “solution” has a dark side.

Conservation

Renewables

“Clean coal”

Nuclear power

Geoengineering

Regimentation

Competing uses of land

Mining: worker and land impacts

Nuclear war

Technological hegemony

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

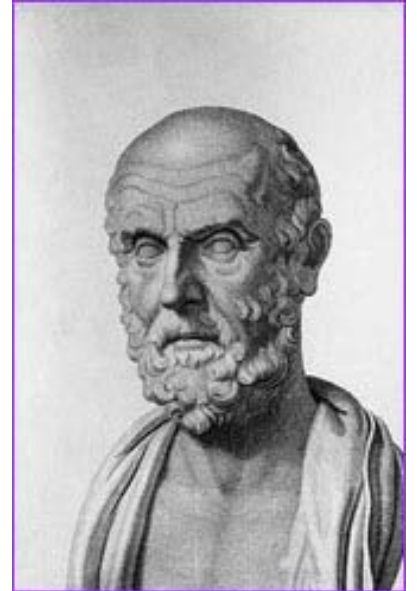
Mitigation is Not Risk-Free

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

Patient Earth

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

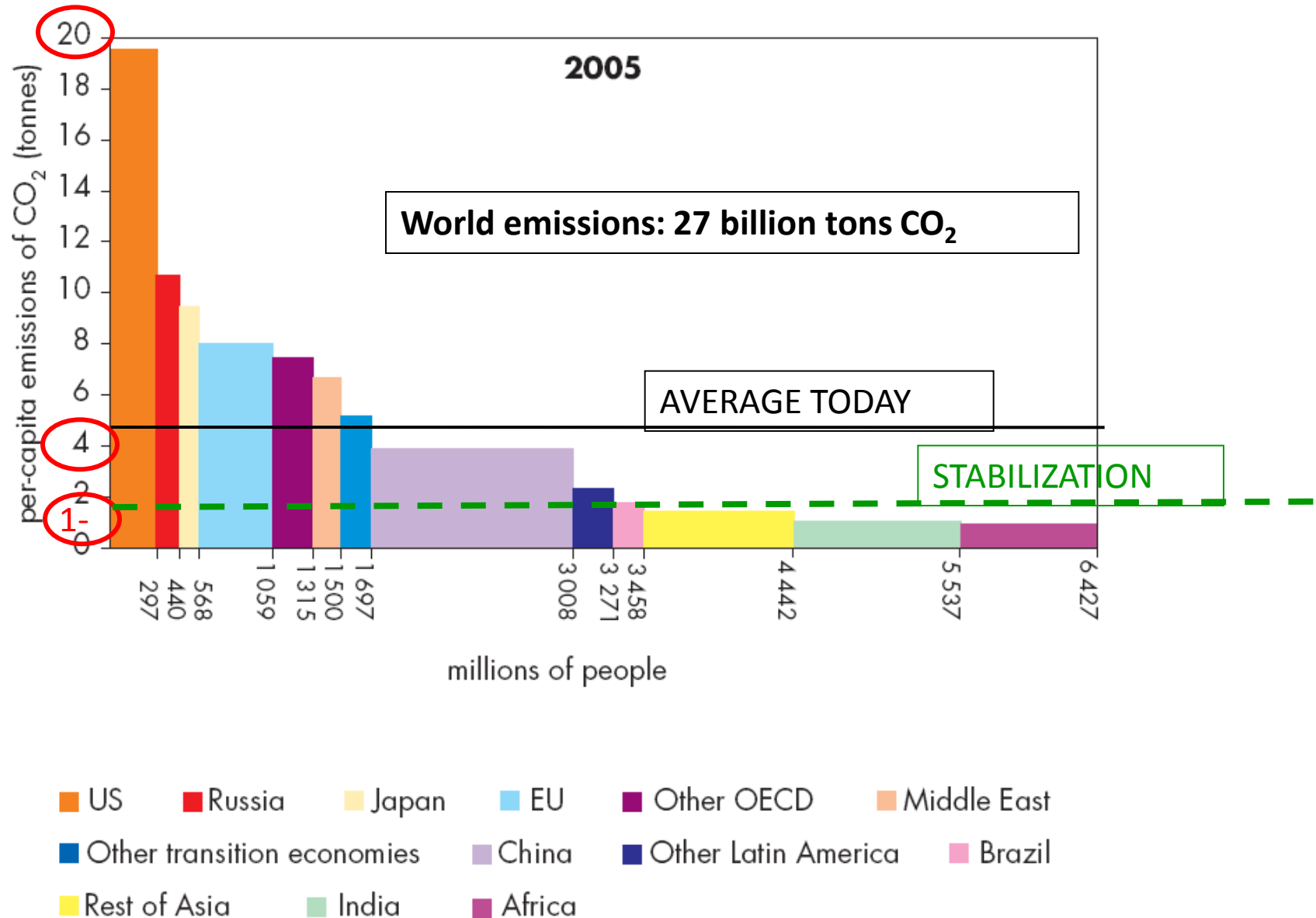
Hippocrates



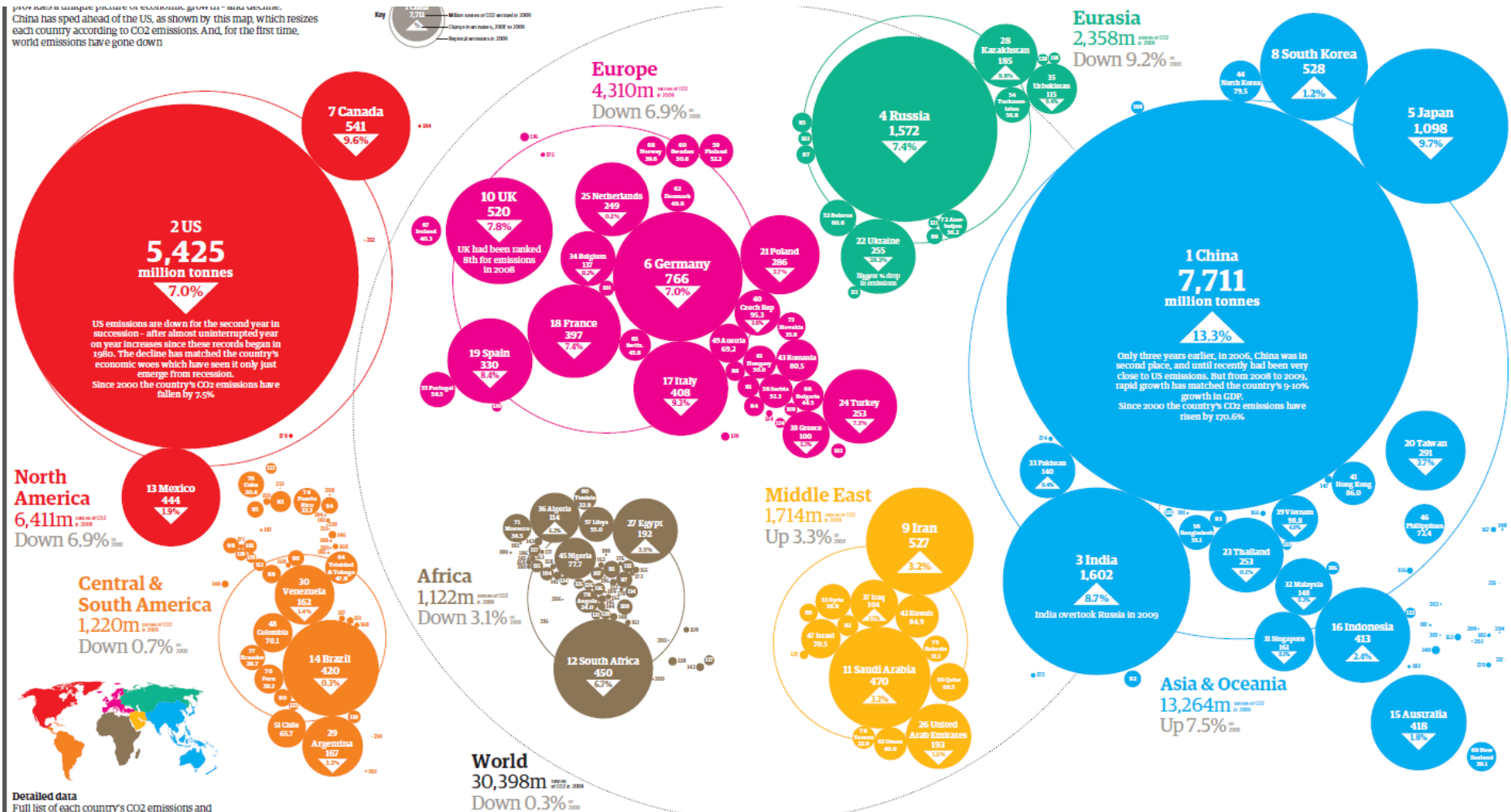
* Modern version of the Hippocratic oath, Louis Lasagna, 1964,
http://www.pbs.org/wgbh/nova/doctors/oath_modern.html

NORTH AND SOUTH

Per-capita fossil-fuel CO₂ emissions, 2005



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



Global CO₂ Emissions, 2009

Source: EIA data;
Guardian.co.uk "atlas
of pollution"

Post-post-colonialism

The UNFCCC, like many post-colonial international institutions, created two-tier behavior. The world was divided into Annex 1 and Non-Annex 1. Annex 1 is roughly the OECD plus the former Soviet Union. Non-Annex 1 is the developing world.

The two groups have “*common but differentiated responsibilities*.” This came to mean that no actions are required of Non-Annex 1 countries until Annex 1 countries have taken decisive steps to reduce their emissions.

Non-Annex 1 has half of global emissions but 80% of world population. Hence it has one fourth the per capita emissions of Annex 1. Thus, each points his finger at the other.

Beyond per capita

The Annex 1 framework expresses guilt and entitlement.

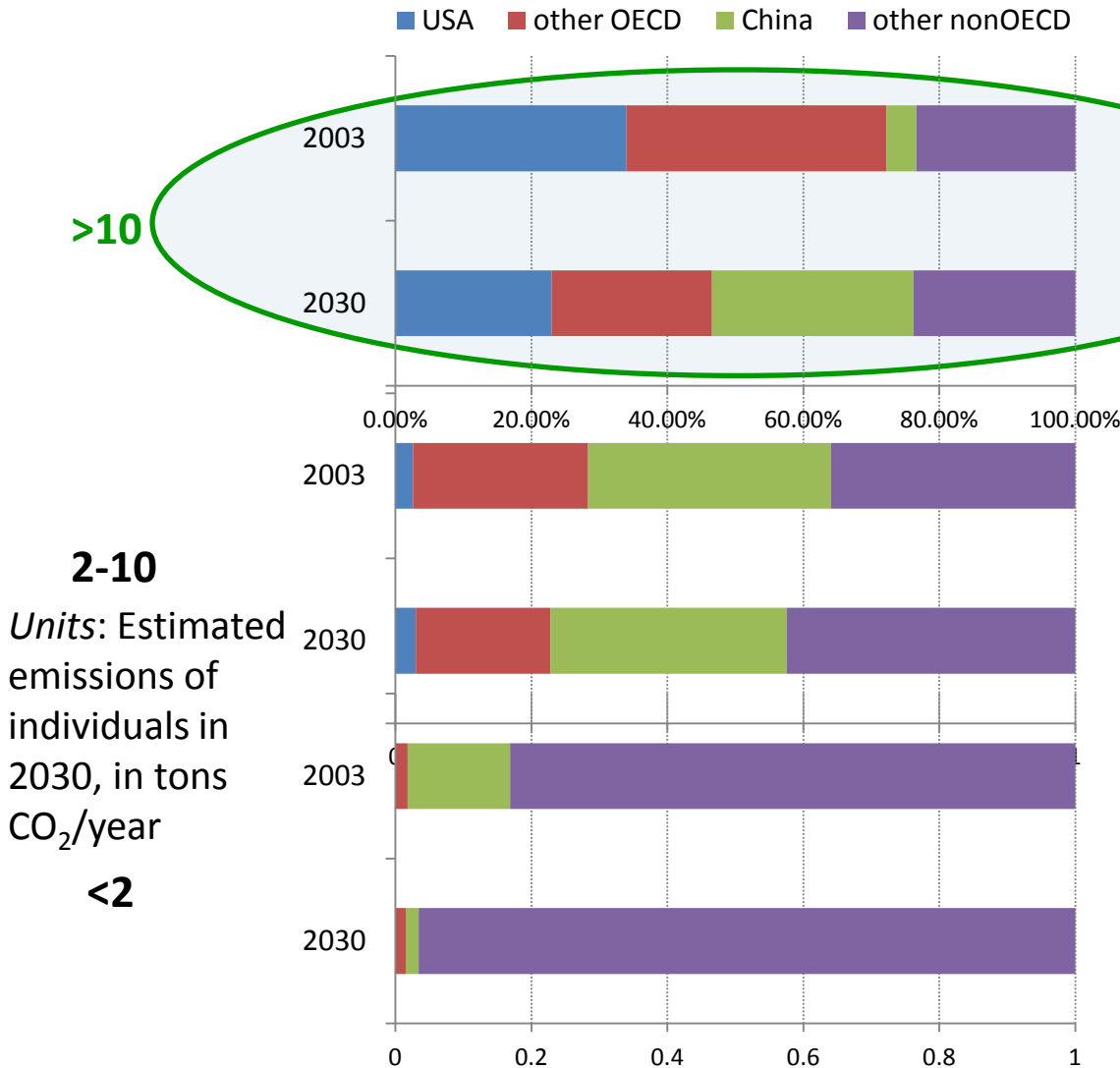
We now need to chart a path toward *post-post-colonial* institutions, where we are all in the same boat.

We can't solve the climate problem without moving beyond “per capita” – looking *inside* countries.

What if “common but differentiated responsibilities” refers to individuals instead of nations?

“One billion high emitters,” *PNAS*, 2009. *Co-authors: Shoibal Chakravarty, Ananth Chikkatur, Heleen de Coninck, Steve Pacala, Massimo Tavoni.*

One billion “high-emitters”



In 2030,
over half of the
“high-emitters”
will live outside
the OECD.

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

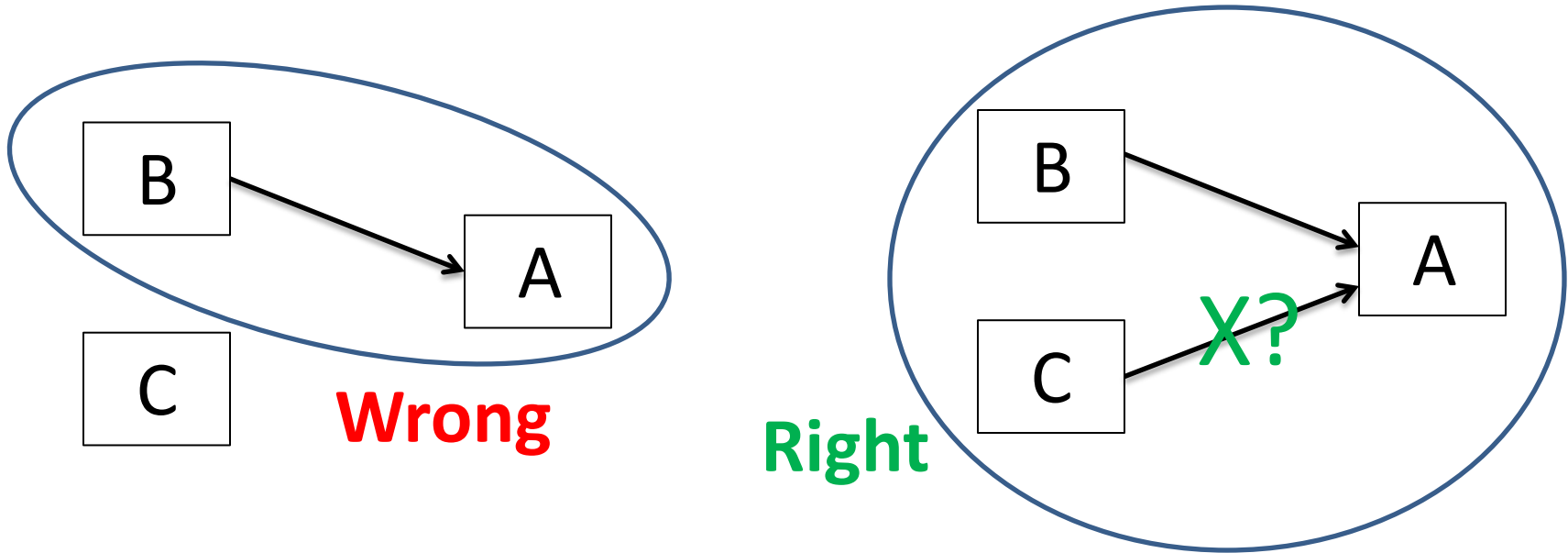


Here: a vented wood stove. Later, a gas stove – fueled by *either* biogas or fossil-gas (LPG, DME).

GUIDING PRINCIPLES

Be careful how you wish for what you wish for.

Principle: You want A. You figure out that B will get us to A, and you like B. You foster B. But *there is always a C that someone else likes and you don't like at all*, which also gets us to A. Unless you are alert, your efforts enable C.



Message: Add conditionality; bargain or walk away.

Getting to Yes

The more we fear climate change, the less we can allow ourselves to be squeamish about imperfect “solutions.”

We must remember that we want solutions to work. It can't be enough to identify what's wrong with a strategy as it is first proposed. We must ask: With what changes, would this strategy become acceptable? How might we get from here to there?

Getting to No

However, we may decide, in some situations, to forego an option.

This may be the result of a moral judgment. We will prefer enduring some amount of climate change to the compromises required to avoid it.

Planetary identity

In the process of taking climate change seriously, we develop a planetary identity.

We augment our previous loyalties to family, village, tribe, and nation.

Do *you* have a planetary identity?

Our Collective Future: Can we think systematically about it?

	PAST	FUTURE
INDIVIDUAL		
COLLECTIVE		NEGLECTED.

By “collective,” I generally mean the human species.

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 2063 physical plant is not yet built.
4. Very smart scientists and engineers now find energy problems exciting.

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.**

Extra Slides

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.

The dangerous embrace of “two degrees”

(1 of 2)

We will greatly increase the damage from climate change if we postpone action for decades.

We might well postpone action as a response to becoming disheartened.

We could become disheartened as a result of discovering that we will not achieve the currently discussed, extremely difficult goal – the only one that is widely espoused.

The dangerous embrace of “two degrees”

(2 of 2)

The extremely difficult goal espoused by many the world's diplomats and the environmentalists is “two degrees.” To achieve “two degrees,” the fossil fuel system must be shut down by mid-century.

There is no appetite for discussion of any goal that is less stringent. Yet a consensus could develop—possibly quite soon—that “two degrees” will not be attained.

It would be desirable to prepare now to discuss some relatively less difficult goal that nonetheless requires, starting immediately, major national commitments and international coordination, and that *could* be attained.

The Global Carbon Cycle

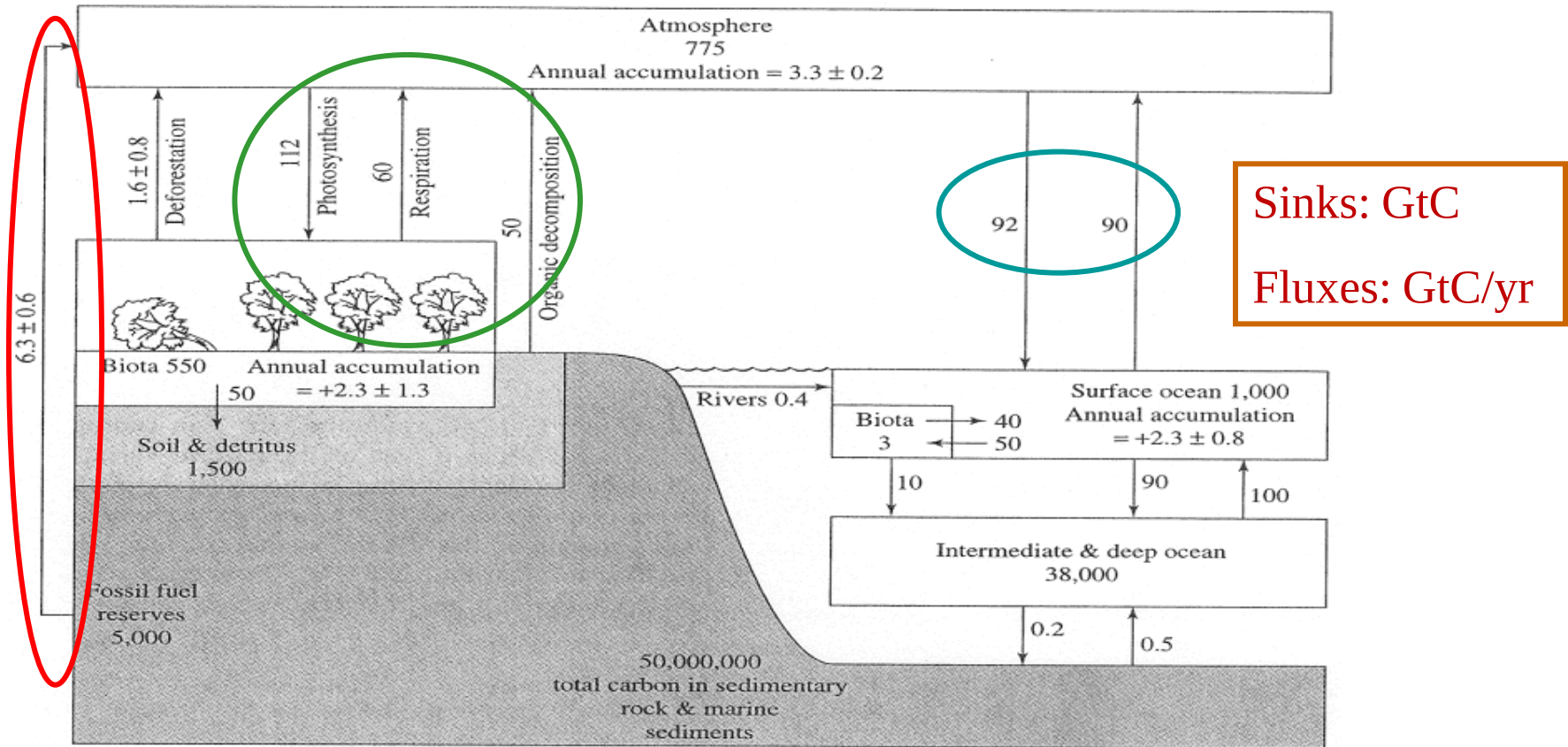
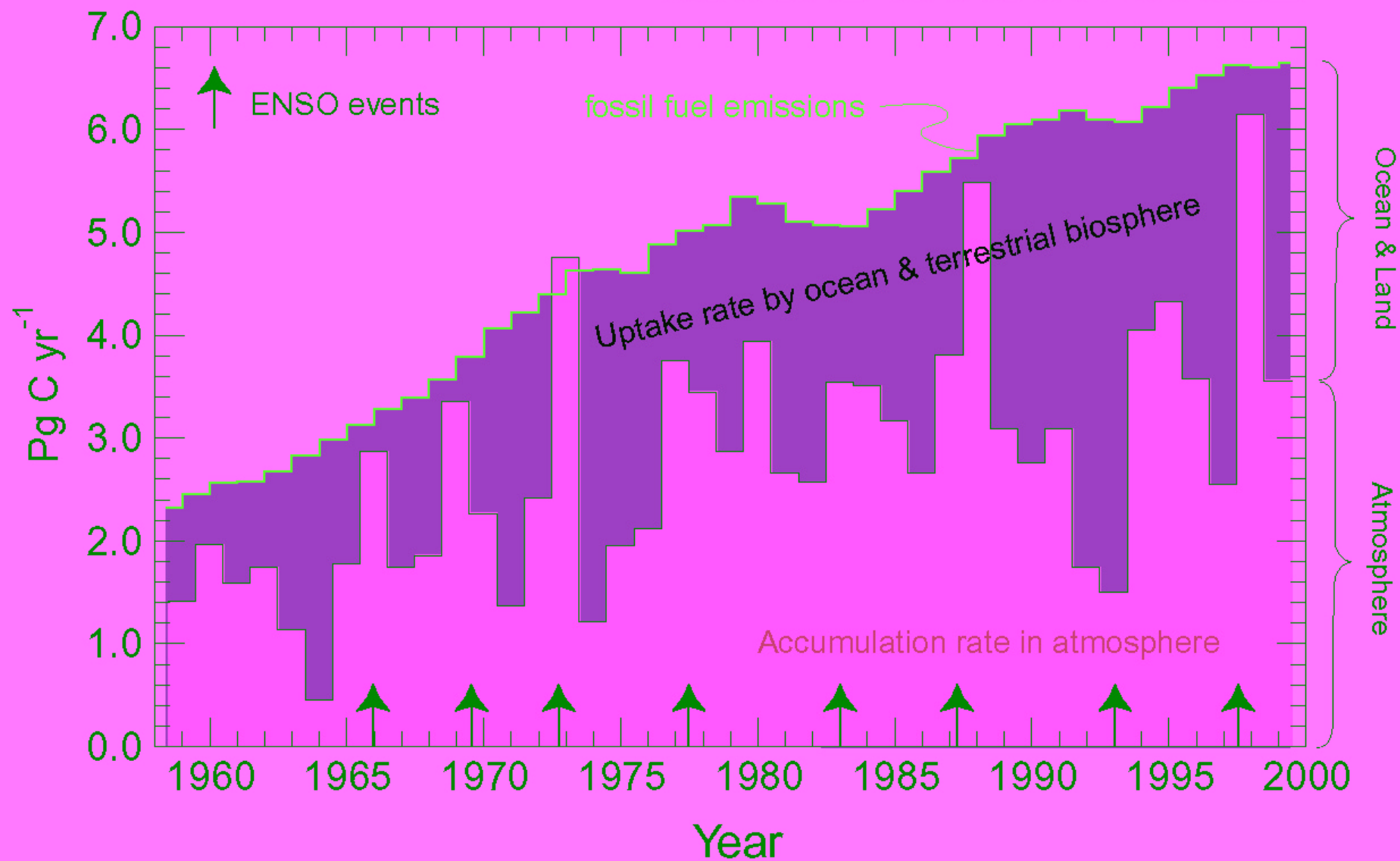


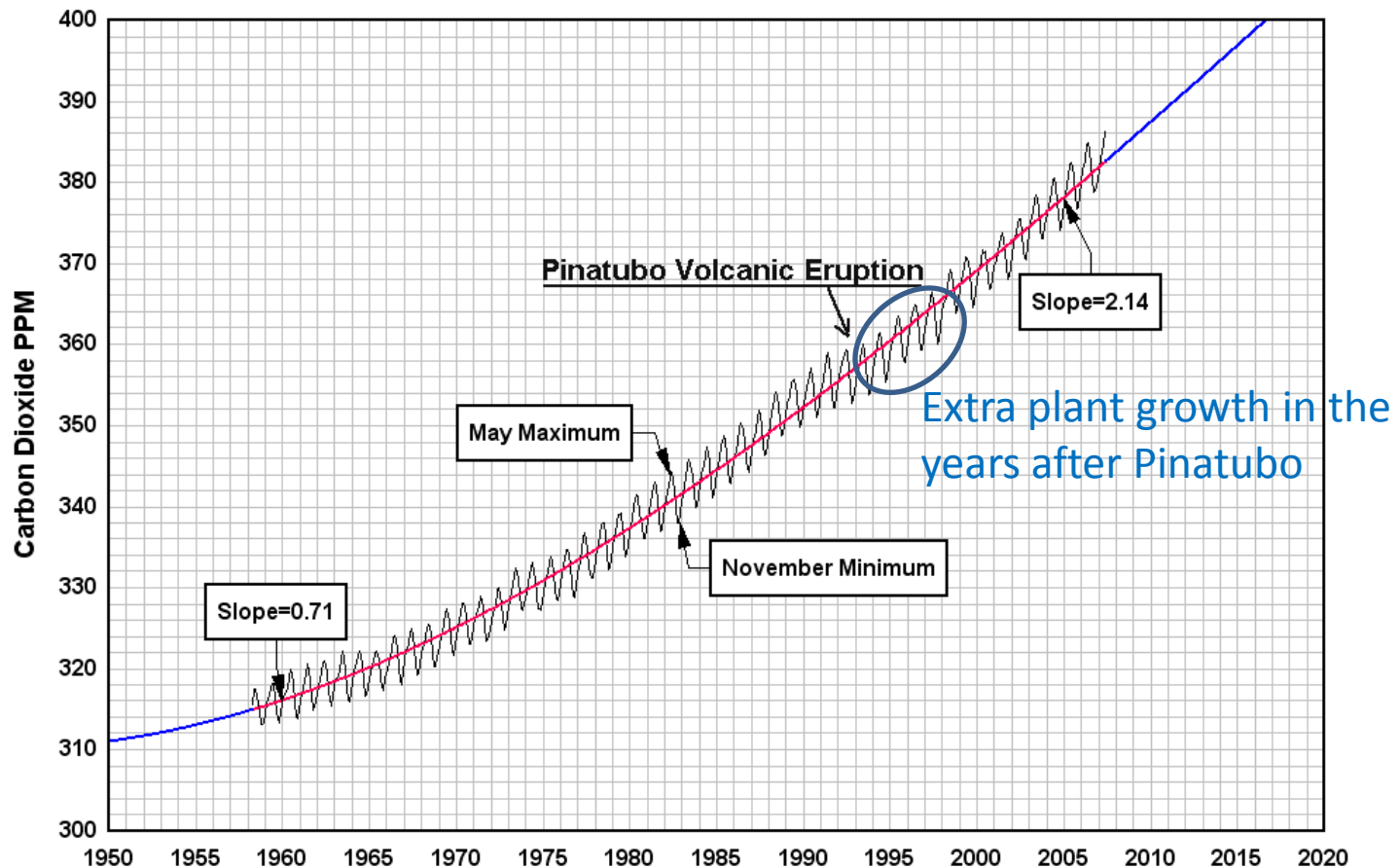
Figure 6.18 The carbon cycle (in Gt C for pools; Gt C/yr for fluxes). Net annual accumulation in biota is the difference between enhanced biomass accumulation (2.3 ± 1.3 Gt C/yr) and deforestation (1.6 ± 0.8 Gt C/yr), which equals about $+0.7$ Gt C/yr. *Sources:* Adapted from the Carbon Dioxide Information Analysis Center (2000). *Global Carbon Cycle (1992–1997)* (Oak Ridge National Laboratory, U.S. Department of Energy) (<http://cdiac.esd.ornl.gov>); Intergovernmental Panel on Climate Change (IPCC) (2000). *Summary for Policymakers, Land Use, Land-Use Change, and Forestry* (Geneva, Switzerland: World Meteorological Organization/United Nations Environment Programme).

Growth Rate of Carbon Reservoirs



Variations in fraction of emissions remaining in the atmosphere

Atmospheric Carbon Dioxide During the Past 50 Years

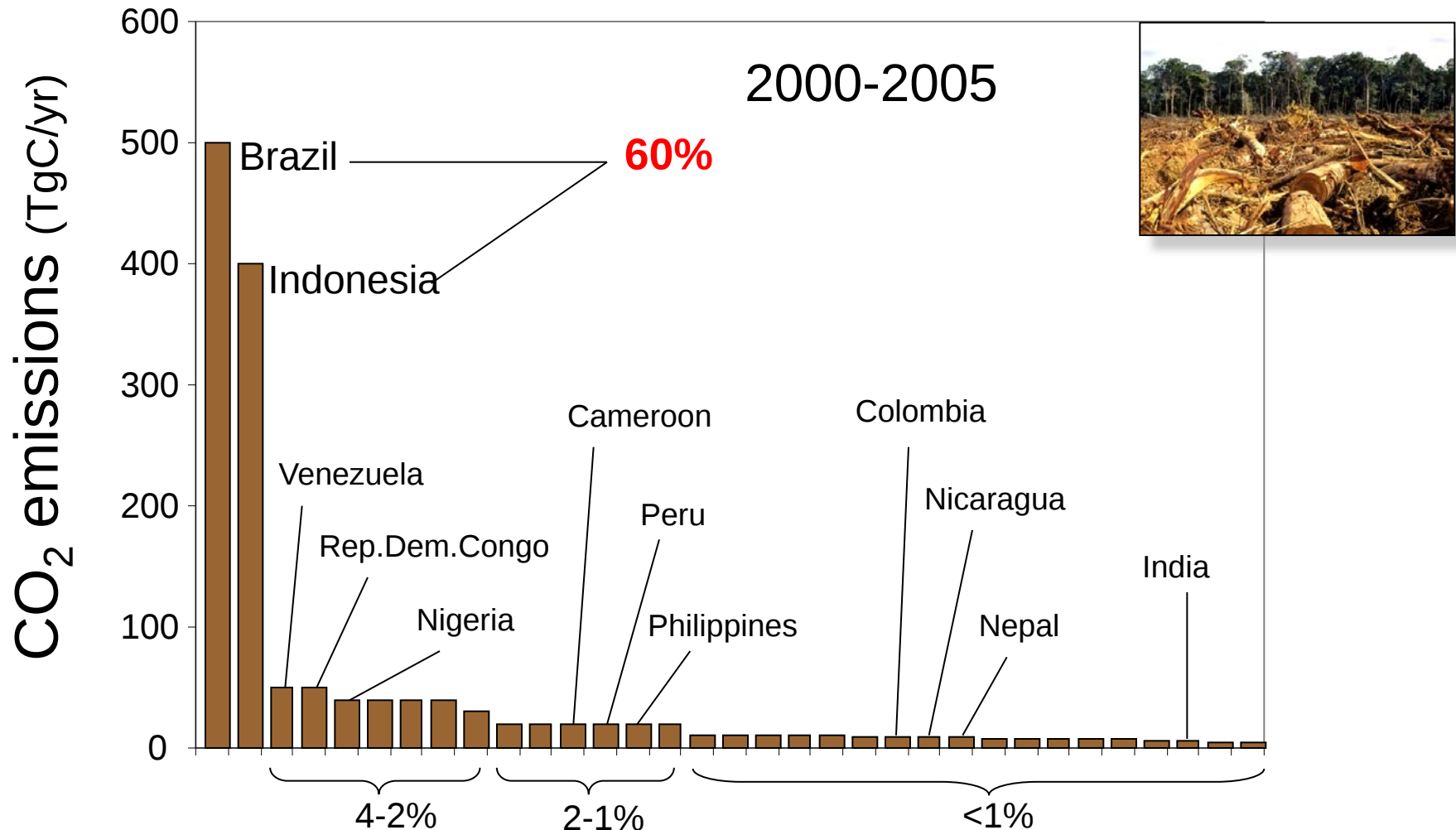


Global CO₂ budget

	2000-2008	
Sources (Pg C/yr)		
Fossil fuel + cement	7.7 ± 0.4 (85%)	
Land use	1.4 ± 0.7 (15%)	
Sinks (Pg C y ⁻¹)		
Atmospheric growth	4.1 ± 0.1 (45%)	
Ocean sink (models)	2.3 ± 0.4 (26%)	
Land sink (models)	3.0 ± 0.9 (29%)	
Residual (imbalance)	-0.3 ± 1.3	

Source: Sarmiento, from Le Quéré et al. (2009)

Net CO₂ emissions from land use change in tropical countries



Source: Sarmiento (privately), from RA Houghton 2009, unpublished, based on FAO land use change statistics

Biomass for CO₂ removal (CDR)

Two bio strategies for CDR

Biopower with CCS (BECCS)

Afforestation

Land for afforestation, removing 1 ppm/yr from the atmosphere

Inputs:

10 t biomass/ha-yr (for 50 years)

0.5 tC/t biomass.

1 ppm = 2 GtC

Result: **400 Mha.**

Conditionality for biocarbon

What will go wrong if we move headlong to maximize either global biostocks or global biofuels without conditionalities?

Suppose you were a forester or an agronomist in a world where the carbon price was very high. You were told that storing carbon was your only objective. What would you do? Establish a monocrop? Pour on fertilizer? Be inventive....

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Now, change roles. You are the policy maker in the same world. What conditionalities would you place on the carbon market for biostocks in the interest of eliciting actions you would welcome and deterring out comes you would decry?

Geoengineering

Response to an emergency

We may someday need “fast geoengineering,” matched to the sudden onset of a crisis. S injection acts quickly.

The analogy here is to the use of epinephrine to treat an acute allergic reaction. It is considered irresponsible for a doctor not to have epinephrine in his or her medicine cabinet.

But geoengineering today is “comparable with 19th century medicine.” (James Lovelock).

Moral hazard

Geoengineering and traditional mitigation compete, if costs of geoengineering are low enough.

Is geoengineering qualitatively different? (Scale?? Reversibility?? Something else??) If so, geoengineering needs special attention.

If not, and given that all responses to climate change are fraught, shouldn't geoengineering be welcomed as allowing reduced effort on other alternatives?

Conservatives like Geoengineering

Watermelon greens [green on the outside, “red” on the inside] reject geoengineering because it does not result in reduction of human appetites for natural resources.

Source: David Schnare, Thomas Jefferson Institute; A Presentation at the Research Triangle Institute, International. November 18, 2008.

On what grounds will geoengineering be resisted?

Rejection will be energized by:

- belief in Murphy's Law

- unwillingness to cede authority to experts

- religious outrage at the prospect of unconstrained human self-determination.

But will rejection dominate?

Global thermostat – set where?

The deployment of geoengineering will present choices among end-points.

There will be some bias toward retrieving the pre-industrial world (the *status quo ante*). We planted crops where the rain fell and built our cities near rivers and coasts. Sea-level rise means moving inland. Sea-level fall means cities without access to the sea.

Nonetheless, neither the pre-industrial world nor any other world will be universally desired.

Can the world conceivably negotiate its temperatures and sea level?

Earth enhancement

If we succeed in developing geoengineering for insurance, it will allow us to enhance the planet.

The analogy is genetic engineering, valuable for the treatment of many diseases, and also providing a capability to enhance the human species.

What will Earth-enhancement look like?

Genetic engineering now allows enhancement of the human species (prettier, taller, smarter,...)

Geoengineering will allow enhancement of the planet – notably, the moderation of extreme events:

warmer winters where people want them	} sweet spots
cooler summers where people want them	
less severe storms and droughts	

Every valley shall be exalted and every mountain and hill made low, the crooked straight and the rough places plain.

As for the well-being of non-human species?

Enhancement *is* problematic

Michael Sandel sets up a dichotomy to explore modern medicine:

Cure or restore vs. enhance or perfect.

Fertility and sex selection

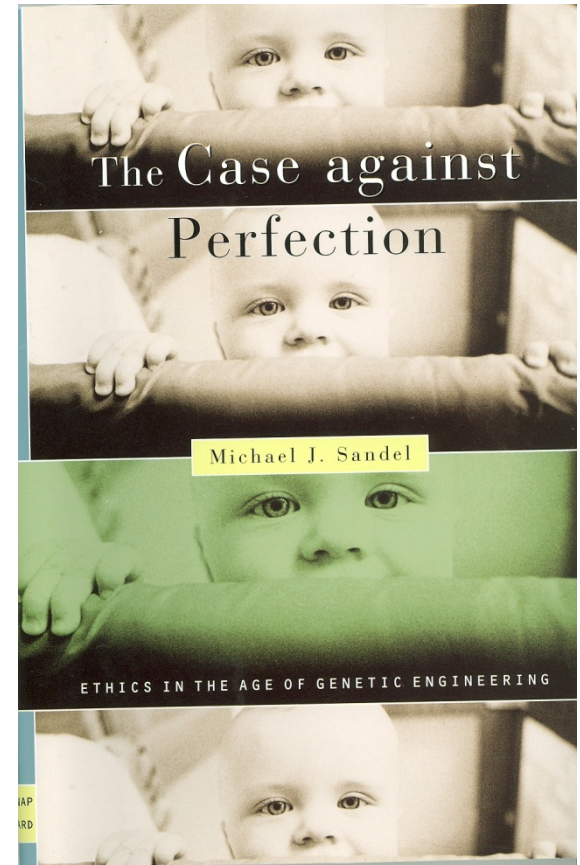
Eugenics

Steroids and sports

Cosmetic surgery

Hyper-parenting

He argues that enhancement can be pursued to excess. He sees a loss of the ability to savor the life we have been “gifted.” He sees value in randomness, the “unbidden.”



“When science moves faster than moral understanding, as it does today, men and women struggle to articulate their unease.”

Three boxes, I presume, are well mapped.

	PAST	FUTURE
INDIVIDUAL	Memory Morality and law (accountability, statutes of limitation)	Death, plain and simple vs. after-life stories.
COLLECTIVE	Myth vs. science. (Science is not just another myth.)	

Three boxes, I presume, are well mapped.

	PAST	FUTURE
INDIVIDUAL	Memory Morality and law (accountability, statutes of limitation)	Death, plain and simple vs. after-life stories.
COLLECTIVE	Myth vs. science. (Science is not just another myth.)	Do we even know what the questions are?

Evidence that we are confused

	PAST	FUTURE
INDIVIDUAL	Memory Morality and law (accountability, statutes of limitation)	Death, plain and simple vs. after-life stories.
COLLECTIVE	Myth vs. science. (Science is not just another myth.)	Discount rate. Rules for nuclear waste. Infrastructure and climate change

Questions we need to ask (1 of 2)

	PAST	FUTURE
INDIVIDUAL	Memory Morality and law (accountability, statutes of limitation)	Death, plain and simple vs. after-life stories.
COLLECTIVE	Myth vs. science. (Science is not just another myth.)	A → B. How quickly, looking ahead, do we become ignorant of what future generations will know and desire? A – B → C How much can we say about how future generations will view future time?

Questions we need to ask (2 of 2)

	PAST	FUTURE
INDIVIDUAL	Memory Morality and law (accountability, statutes of limitation)	Death, plain and simple vs. after-life stories.
COLLECTIVE	Myth vs. science. (Science is not just another myth.)	Does our collective future matter at all? What are we on earth to do?

Will universities some day have Destiny Studies departments?

Destiny

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?

Cherish the scientific method

It's worth at least 0.1C.*

*At 2000 GtCO₂/°C, 200 GtCO₂ (seven years of emissions).

Imagine dealing with climate change without it.

Co-authors, recent papers

Wedges

Steve Pacala

Roberta Hotinski

Jeff Greenblatt (now, Lawrence Berkeley Laboratory)

Nuclear power

Alex Glaser

One-billion high emitters

Shoibal Chakravarty

Massimo Tavoni (FEEM, Milan)

Steve Pacala

Ananth Chikkatur (then, Harvard; now ICF in D.C.)

Heleen de Coninck (ECN, Netherlands)