Getting the Solutions Right:
Scoping the Risks of Mitigating Climate Change

Robert Socolow
Princeton University
socolow@Princeton.edu

Energy Seminar

Energy and Efficiency Institute

UC Davis

November 22, 2019

Abstract: Managing climate change requires two-sided reasoning, where both the risks of climate change and the risks of climate change solutions are taken into account.

Autobiographical remarks

Physics (quarks): Ph.D. and Assistant Professor, through 1971. The true and the beautiful. I became restless in 1969. “Science for the People” was in the air.

“Environment” was a new word, for a big new, widely shared insight: We could damage our small planet doing ordinary things. Why then? Moon landing, July 1969. Blue marble.

My transition 1969-71. Everglades and Miami jetport summer study 1969. *Patient Earth*, with John Harte, 1971.

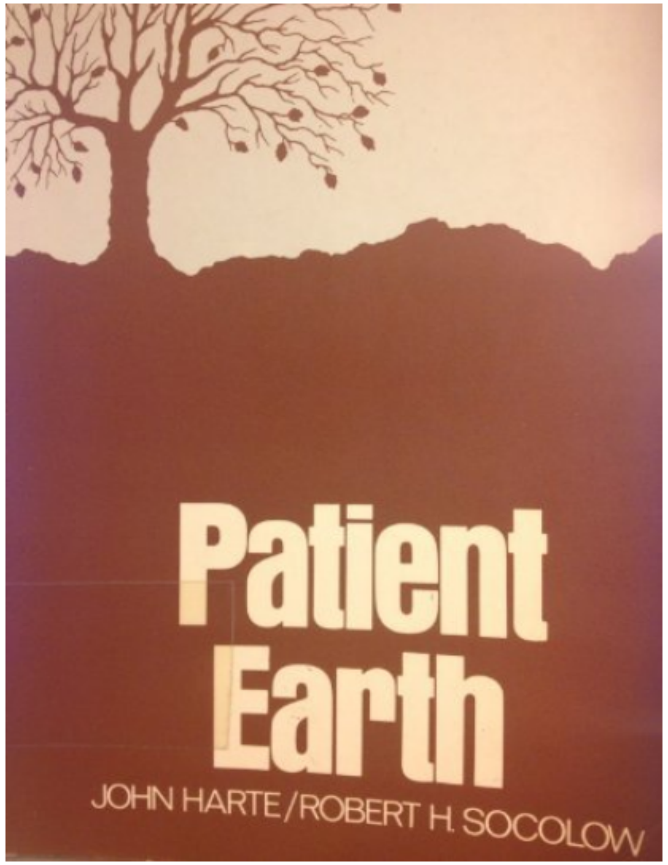
Faculty at Princeton, starting in 1971. My job has been to invent interdisciplinary environmental research. First projects addressed energy efficiency in homes and the siting of a dam on the Delaware River.

Patient Earth. John Harte & Robert Socolow, 1971

What did John and I have in mind when we chose this title?

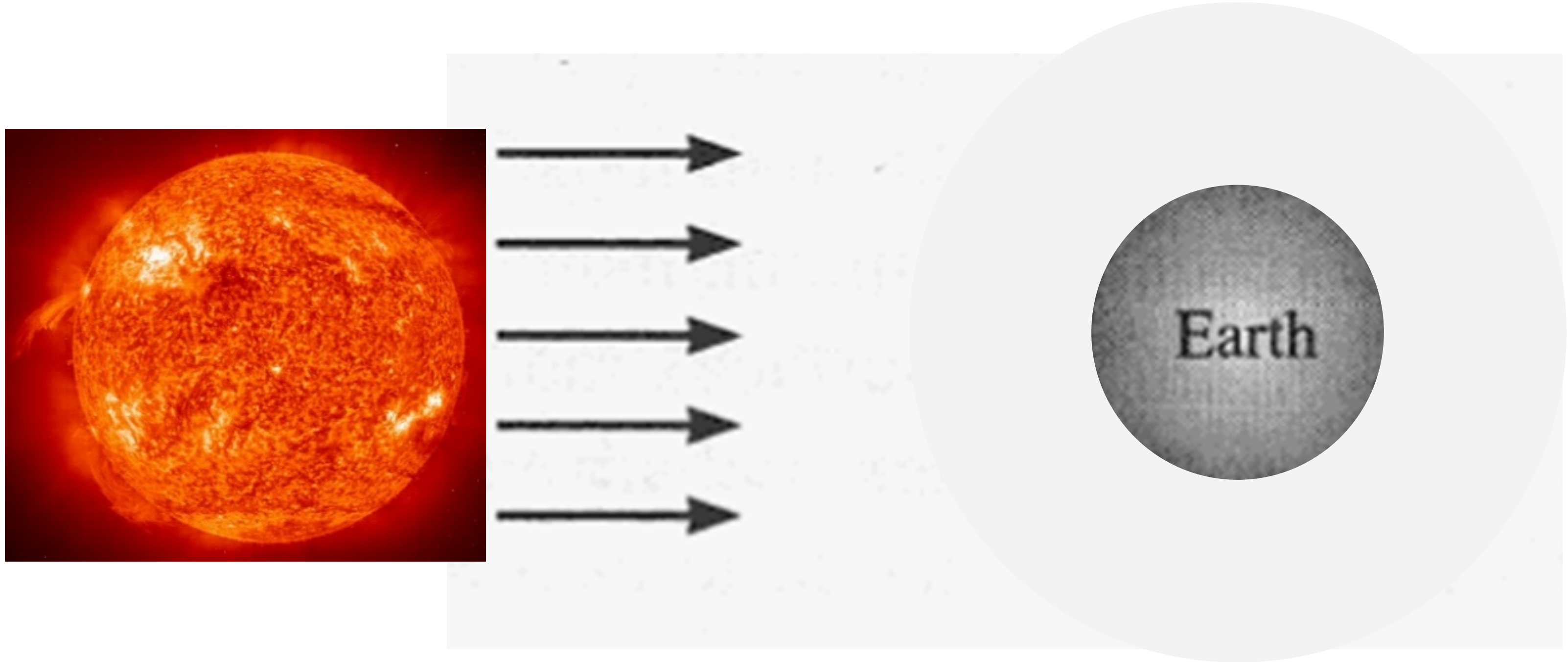
1.The planet is hurting. It has been compromised by our actions. It needs our attention.

2.We have some time. There are options that we can develop and improve. Yes, sick, but not on its deathbed. No “game over.”



I insisted that there be leaves on the tree on the cover of the paperback. The publisher originally had none.

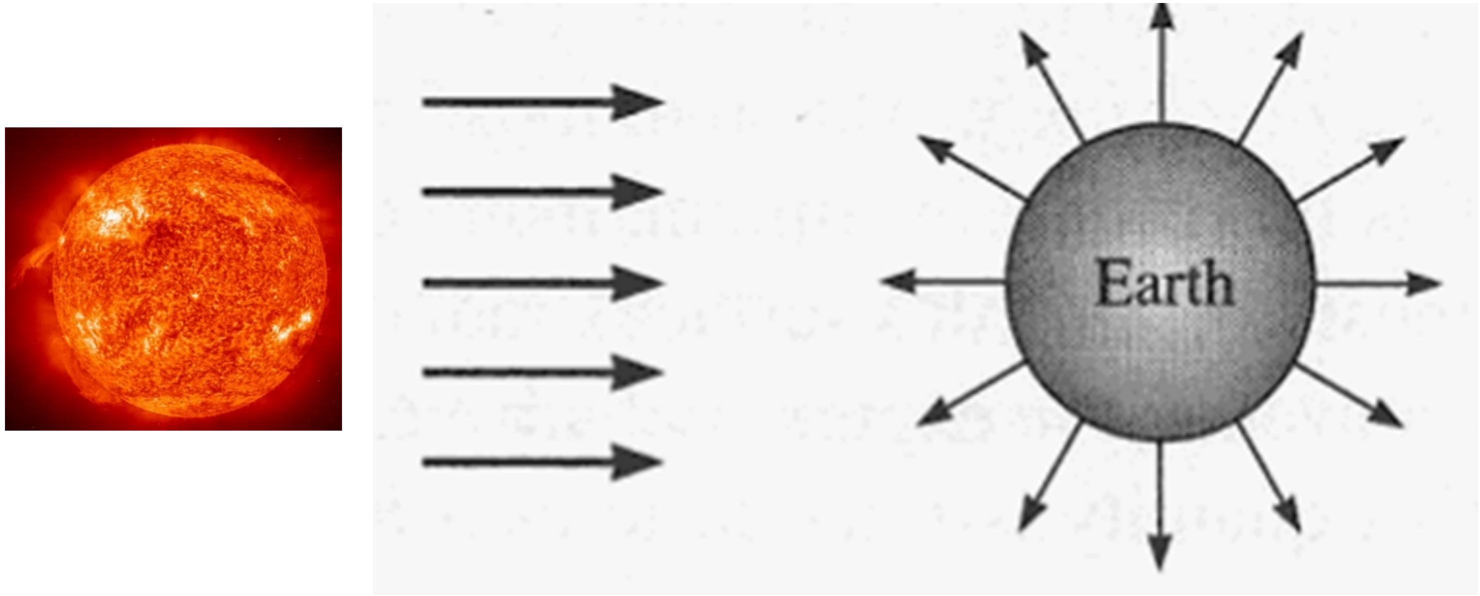
A whole-Earth calculation: Why doesn't the Earth get hotter and hotter as it is warmed by the Sun?



I'm a science teacher first!

How can we add sustainability to the curriculum?

From third grade through college, at least twice, add this question to the curriculum:



And add questions like this to the SATs.

The blue marble

Dec 7 1972, Apollo 17, 18,000 miles away, 5 hours, 6 minutes after launch.

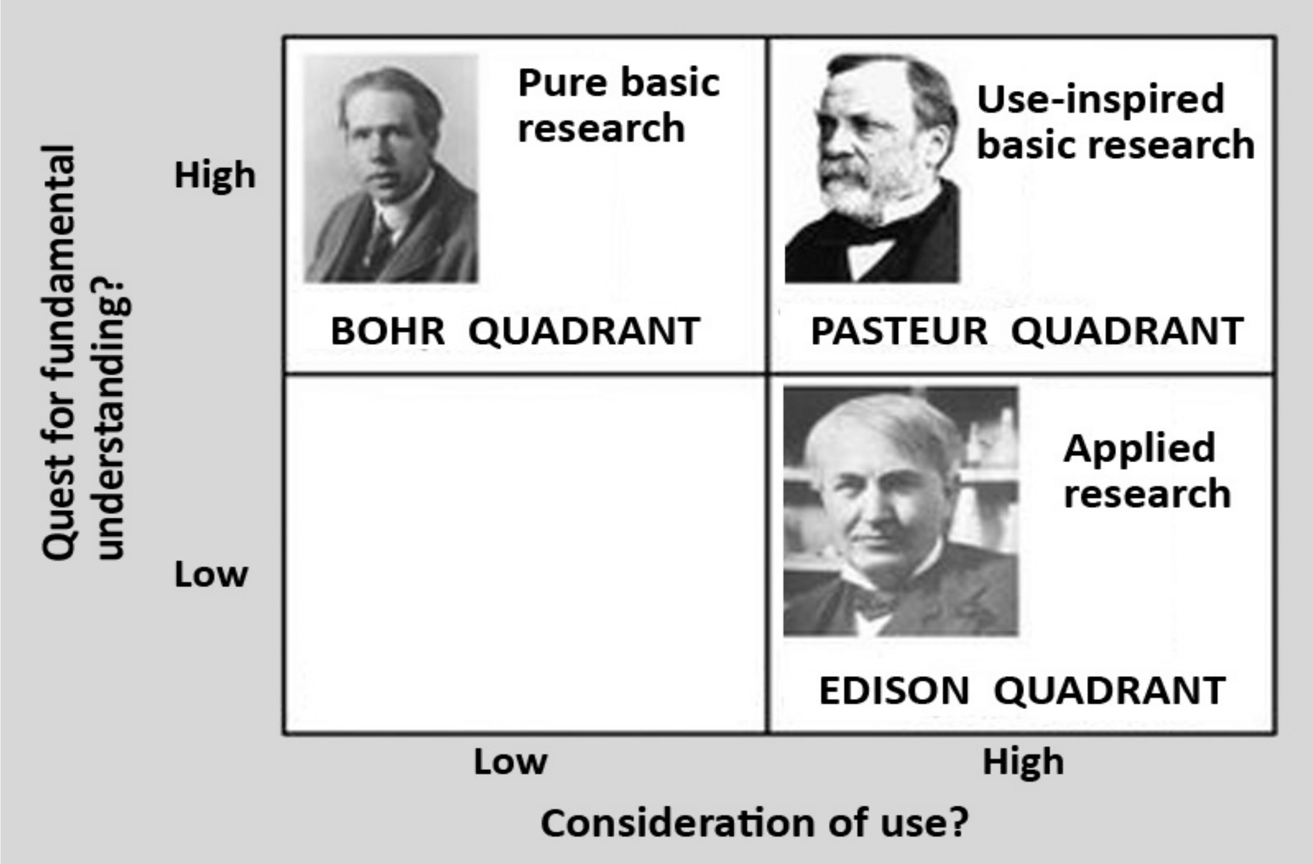
This was the last lunar mission: no human being since has been far enough from Earth to photograph a whole-earth image.

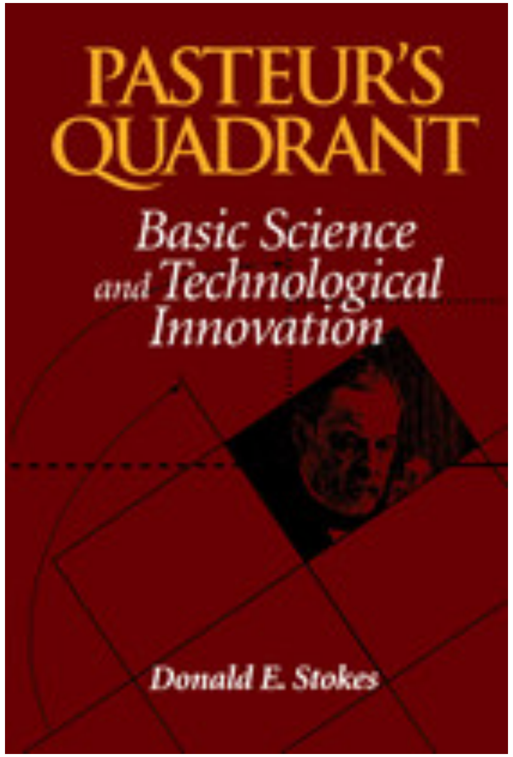
The 1972 Tamil Nadu cyclone is at top right; it brought flooding two days before.

One of the most reproduced images in human history.

https://en.wikipedia.org/wiki/The_Blue_Marble

Pasteur's Quadrant





Those working in Pasteur's Quadrant prefer to solve problems rather than to remain pure, and they seek generalizable knowledge rather than wishing to say the last word about some narrow issue, as so many academics do.

Four World Views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO		
	YES		

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.	Many people in the fuel industries and a shrinking share of the public are here. **5^{o}C**
	YES	Many of you? **1.5^{o}C and 2^{o}C**	The rest of the you. **3^{o}C**

Four promising concepts

A physicist looking at environment sees energy as a natural pursuit.

Efficiency, nuclear power, renewables,

I have been promoting four promising concepts:

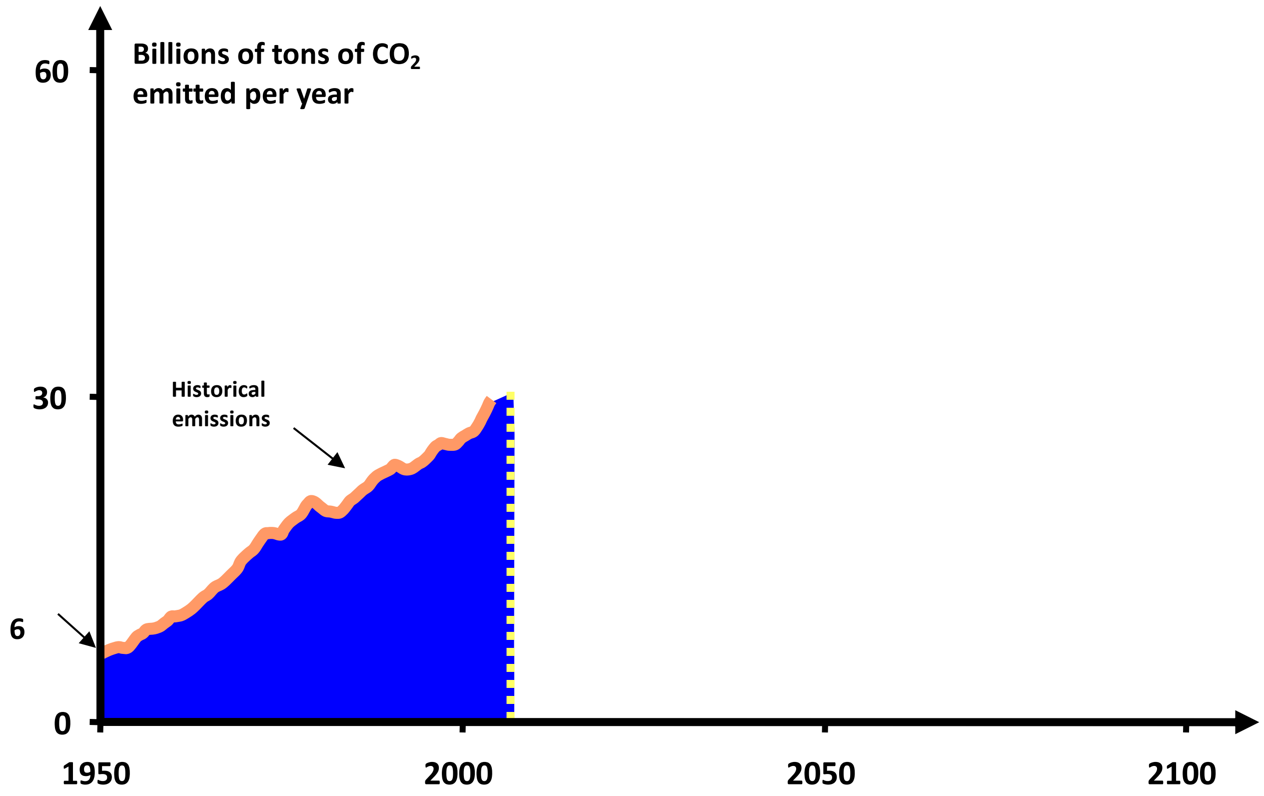
- Stabilization wedges
- One billion high emitters
- Committed emissions
- Destiny studies.

I have been problem-driven. I have spent a lot of time learning the languages of other disciplines.

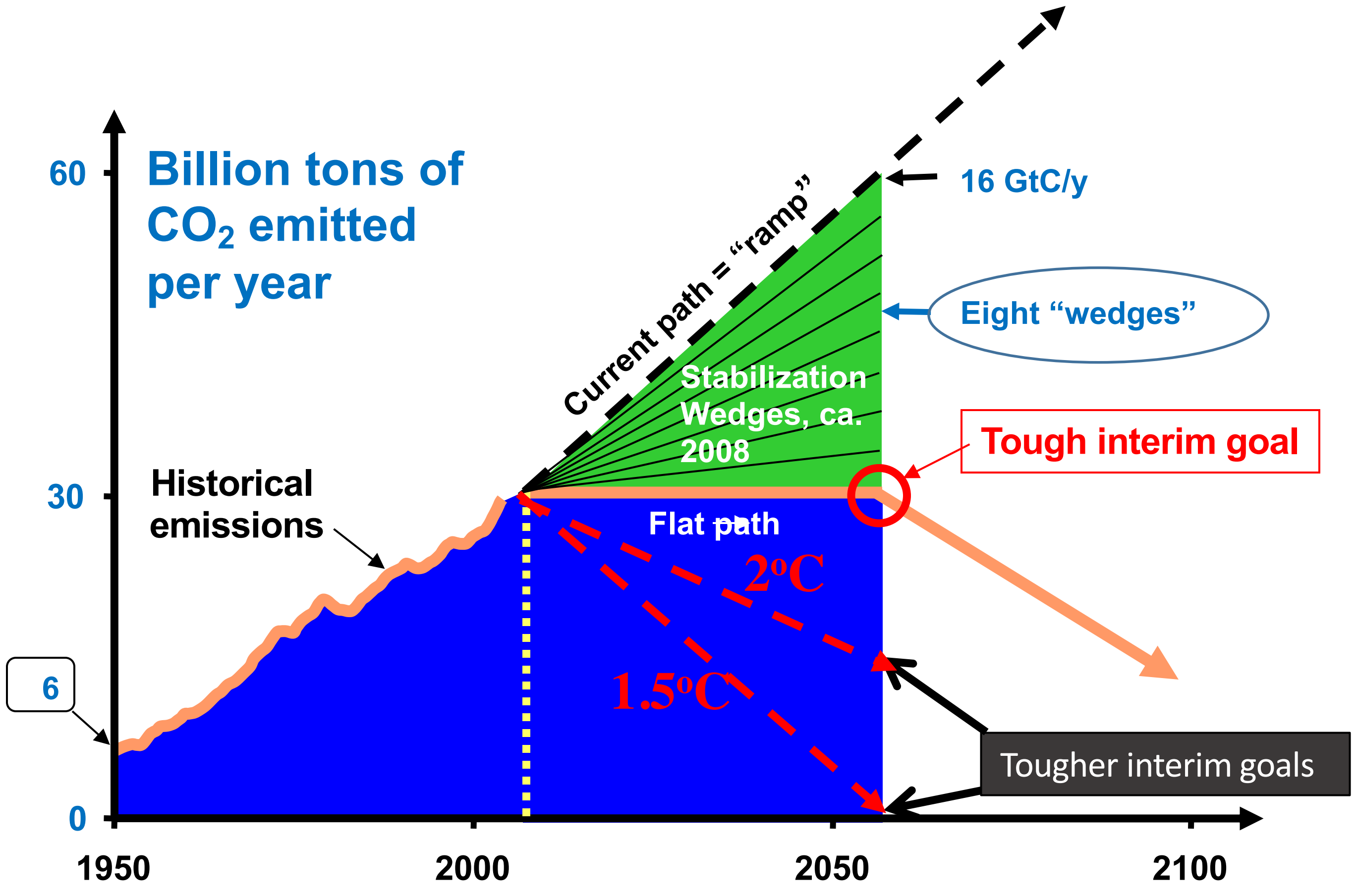
Stabilization wedges

Steve Pacala and Robert Socolow, *Science,* 2004.

Historical emissions



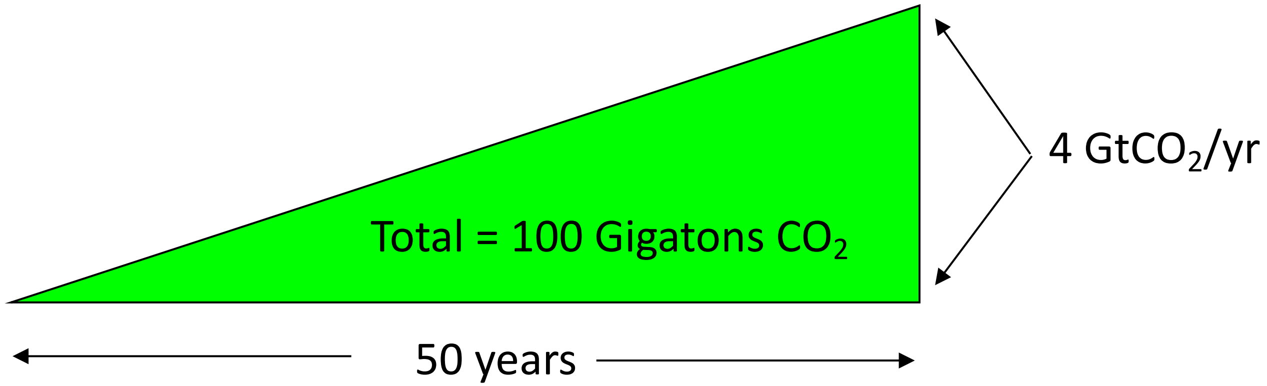
The stabilization triangle and the wedge



A “stabilization wedge” is a strategy that contributes significantly to slowing the pace of climate change, but one wedge does only part of the job.

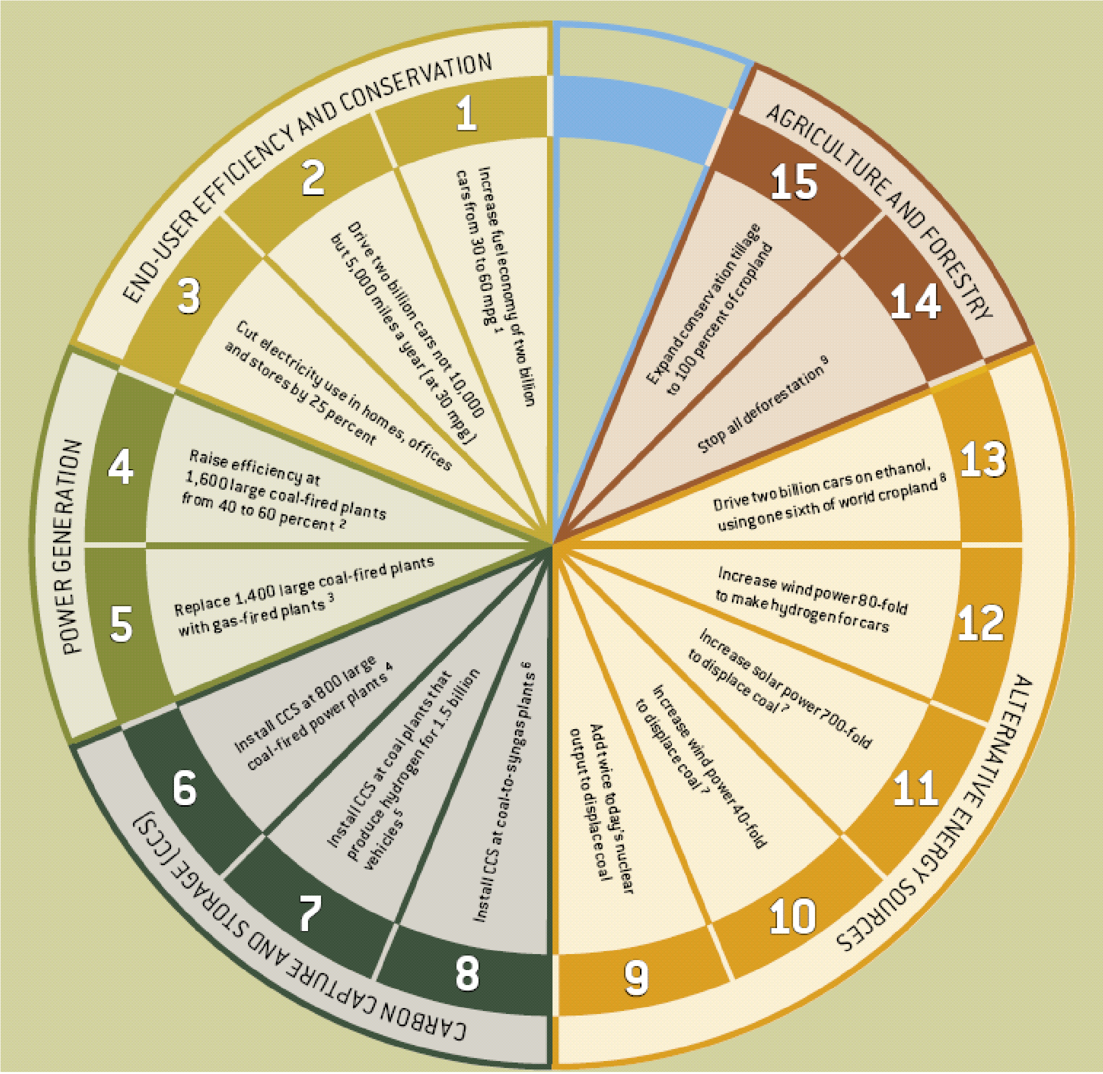
What is a "Wedge"?

A "wedge" is a strategy to reduce carbon emissions that grows in 50 years from zero to, originally, 1 GtC/yr. Now, often, rounding off, 4 $GtCO_2$/yr. The strategy has already been commercialized at scale somewhere.



Cumulatively, a wedge redirects the flow of 100 $GtCO_2$ in its first 50 years. This is ten trillion dollars at \$100/tCO_2. A "solution" should provide at least one wedge.

15 Ways to Make a Wedge



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

“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.

Stabilization wedges… in 2004

2011 Kentucky Derby, AP Photo/Matt Slocum. https://www.cbsnews.com/pictures/2011-kentucky-derby/7

Slides courtesy of Greta Shum, Andlinger Center, Princeton University

Stabilization wedges… in 2018

Melbourne Cup, The Foreign Correspondents' Club, Hong Kong. https://www.fcchk.org/event/melbourne-cup

Efficiency and Conservation

transport

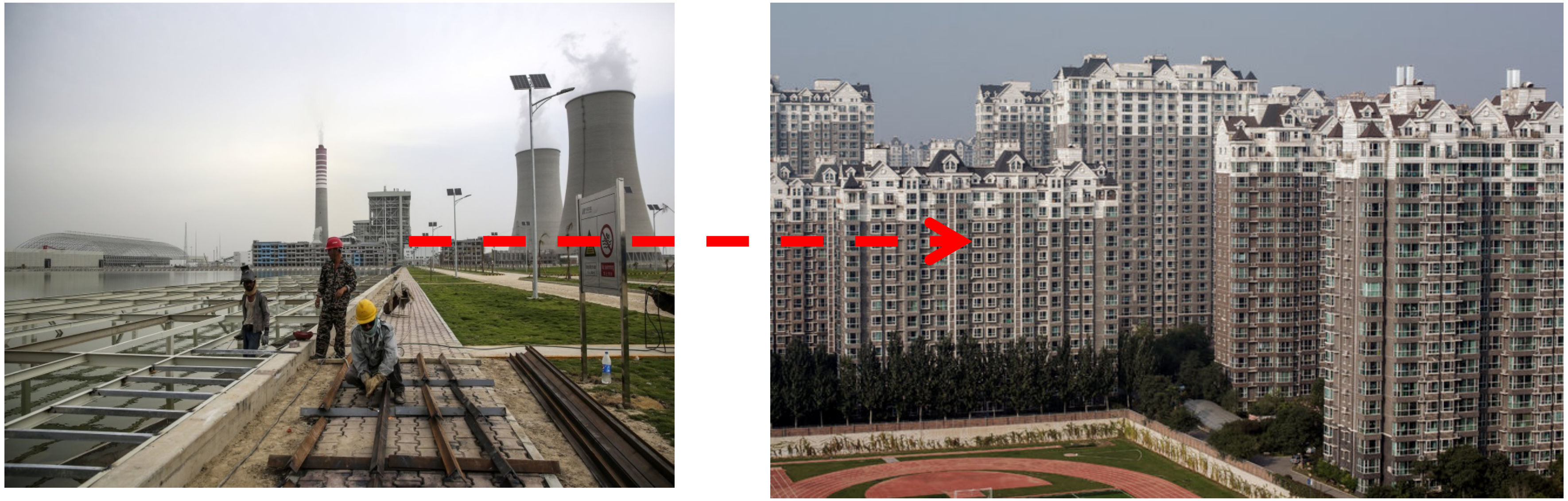
buildings

industry

information

power

In the U.S., 70% of power-plant electricity goes to buildings. Globally, 60%.



Shown: Yanjiao, China

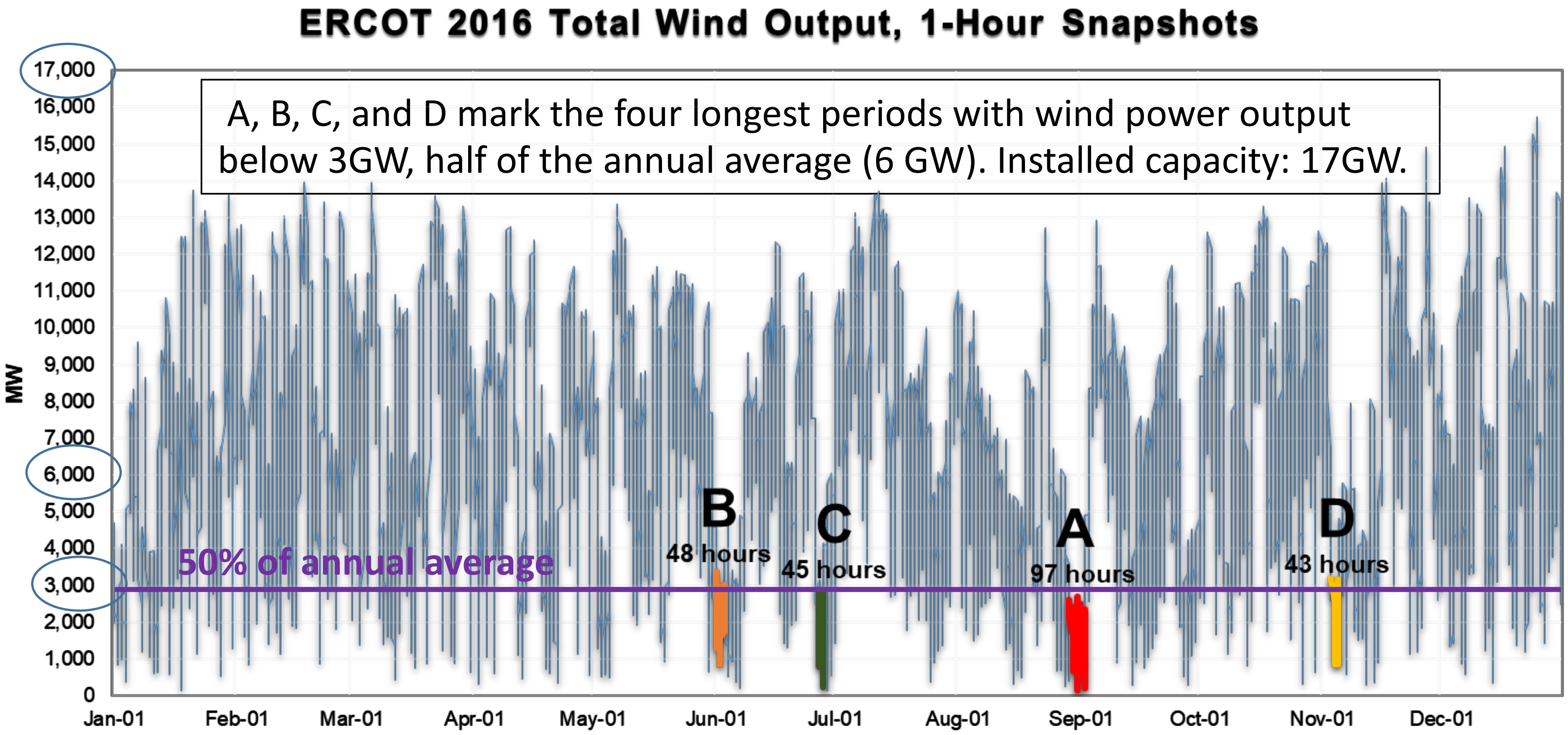
Less demand for heating, cooling, appliances – fewer power plants.

Solar power

Five questions that are key to solar power’s future:

1. Will distributed and centralized deployment both flourish?
2. How much can balance-of-system costs be reduced?
3. Will crystalline silicon remain the workhorse of solar power?
4. Will the intermittency of solar power soon throttle its expansion?
5. Will solar power subsidies disappear?

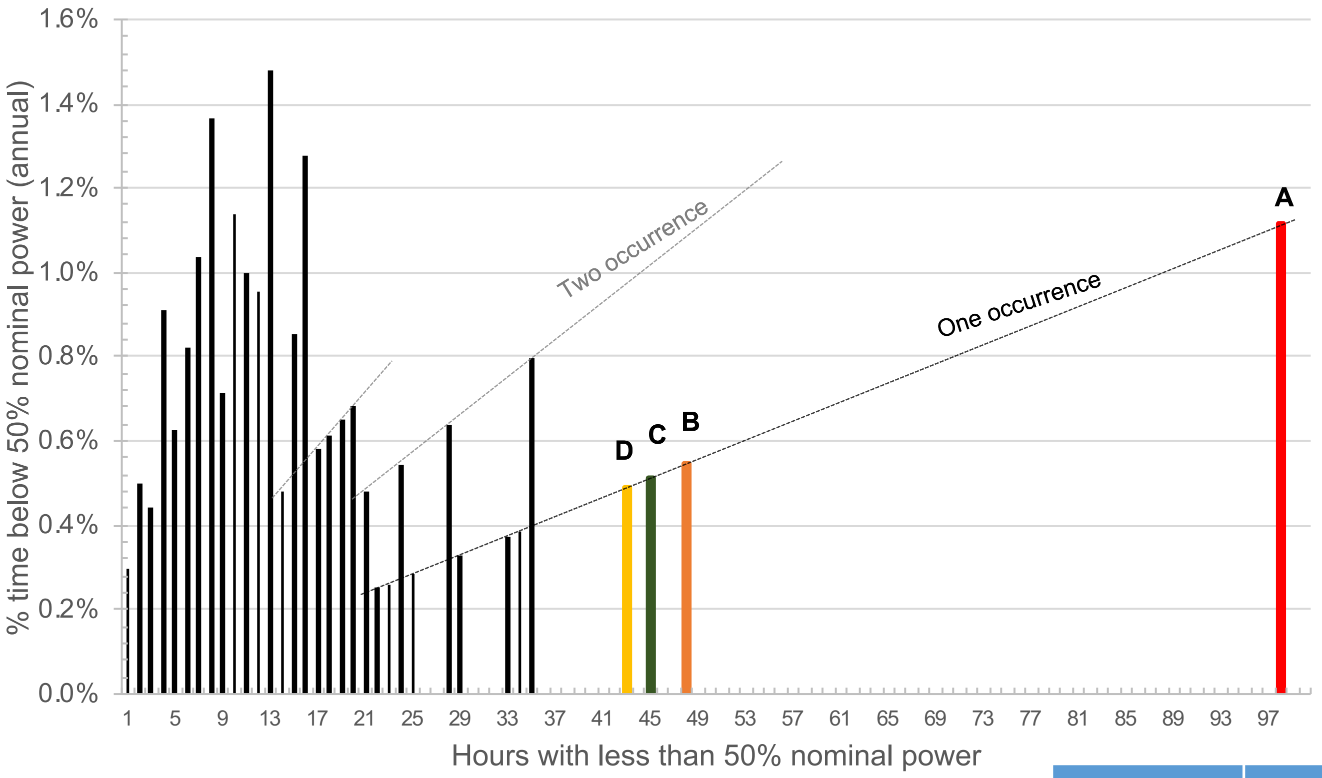
Wind power: Lull Analysis



Wind accounted for 15% of 2016 ERCOT (roughly, Texas) electricity production. Wind expansion could be thwarted by events like A-D.

Figure and analysis courtesy of Pedro Haro.

How often are long lulls?

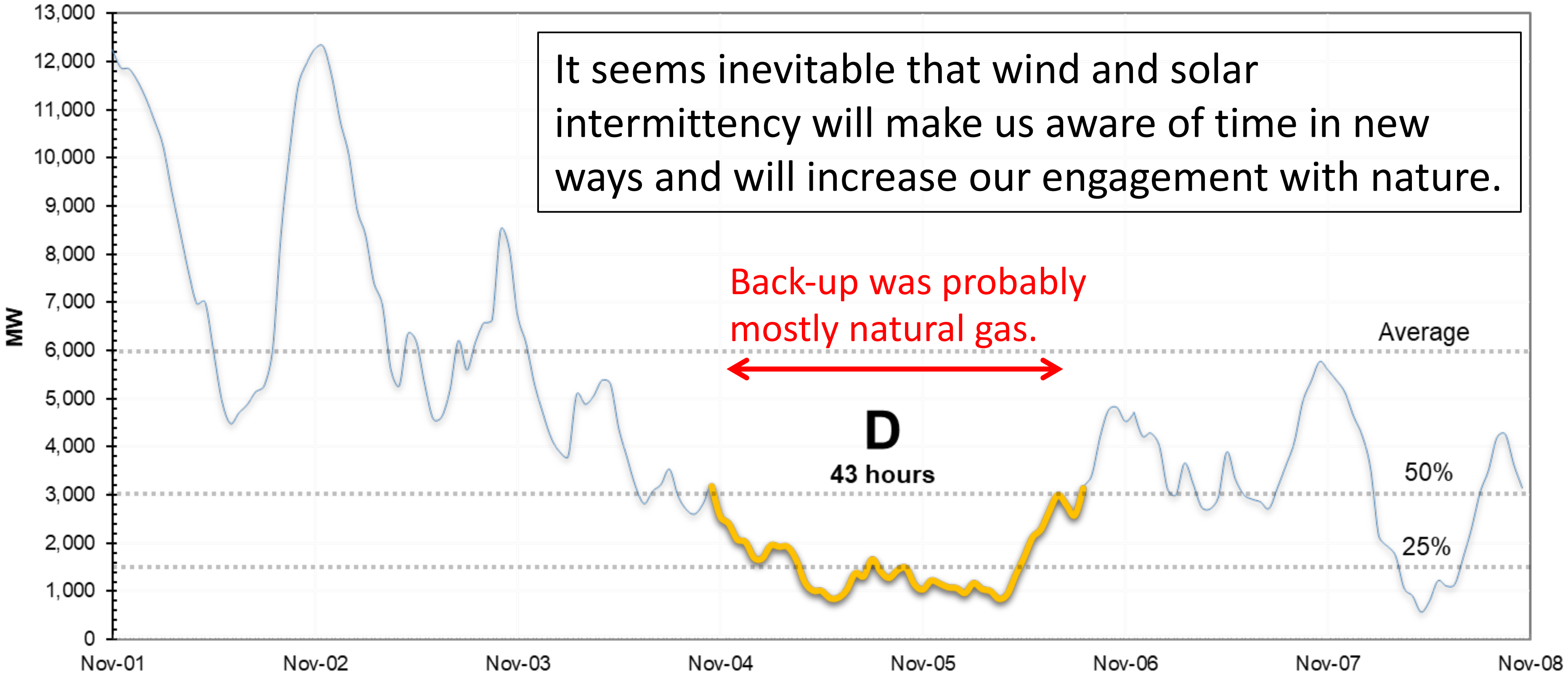


Lull (hr)	Events	Hours	% hrs
<12	164	862	42
13-24	43	716	35
25-36	8	247	12
>36	4	234	11
Total	219	2059	100

Long lulls are a new class of extreme events, needing dedicated attention and deserving names like those of hurricanes.

Figure courtesy of Pedro Haro.

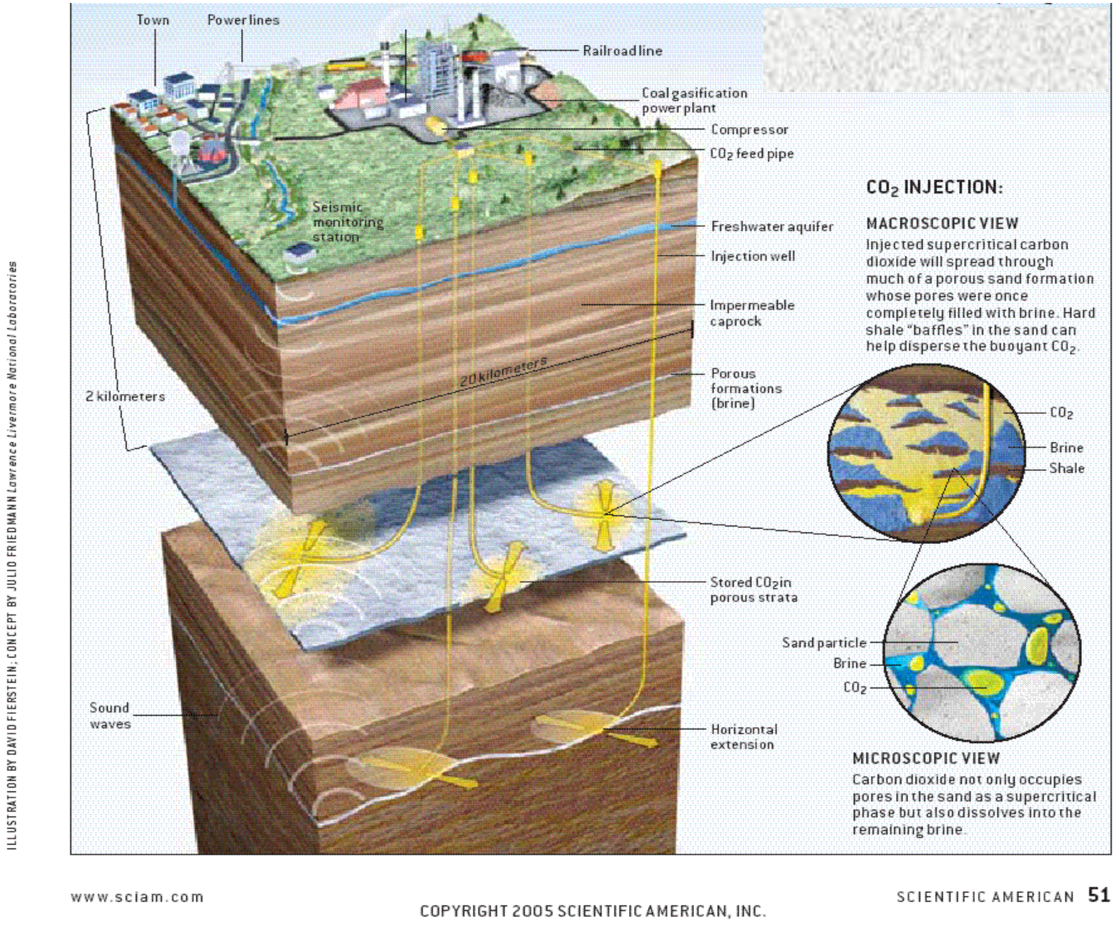
How should we back up long lulls?



Gas- solar-fossil and gas-wind packages would reduce the intermittency challenge. Zero-carbon ideology is in the way.

Figure and analysis courtesy of Pedro Haro.

All future coal and natural gas power plants?



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

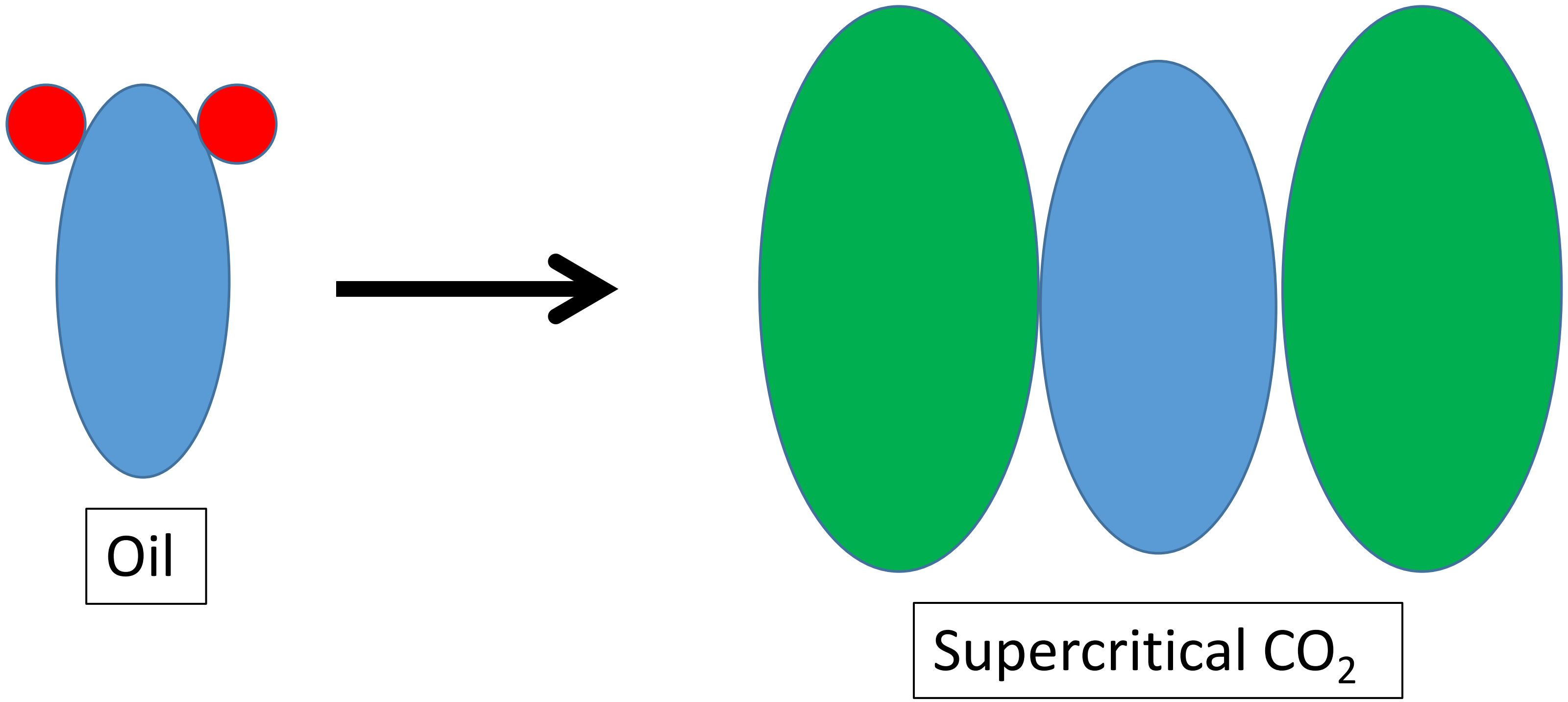
- *Note:* Plant is still young.

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

U.S. CO_2 pipelines already in place

http://www.nicholas.duke.edu/thegreengrok/co2pipeline, from *CO2 Pipelines and EOR in the US - Regulatory Issues and Opportunities,* Lawrence J. Wolfe, lwolfe@hollandhart.com. Slide 11.

Don’t kid ourselves: A huge infrastructure



Density relative to supercritical CO_2: Coal ≈ 2; Oil ≈ 1 to 1.5; natural gas (at 1000 m) ≈ 10.

One wedge at 50 years: ≈ 4 Gt(supercritical CO_2)/yr. Volume ≈ 20 billion bbl/yr, about half the volumetric flow rate of world’s oil today.

Every “solution” is dangerous.

Every strategy can be implemented well or poorly

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

It is essential to identify the “conditionalities” that make a solution less dangerous.

Risk management: It is possible to achieve some target and regret doing so. “Two-sided reasoning” weighs both the threat and the “solutions.”

Conditionality for biocarbon

What will go wrong if we move headlong to maximize global biocarbon stocks 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.…

Conditionality for biocarbon

What will go wrong if we move headlong to maximize global biocarbon stocks 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.…

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 outcomes you would decry?

"Geoengineering": cooling by blocking sunlight

On June 15, 1991, Mt. Pinatubo. injected 10 million tons of sulfur into the stratosphere.

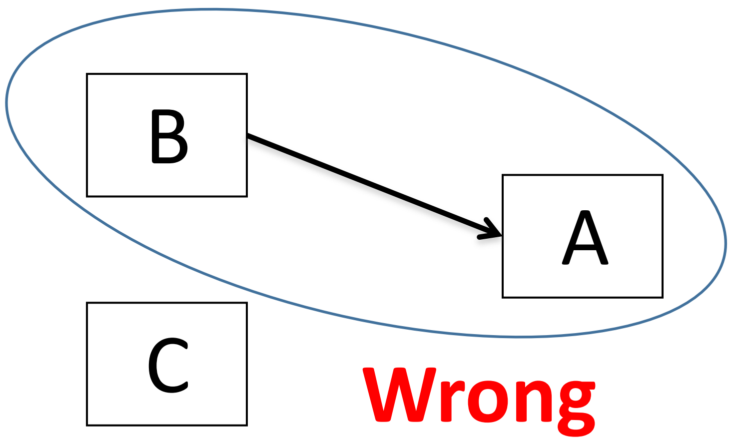
The Earth's average surface temperature was 0.5^{o}C cooler six months later, then rebounded.

One form of geoengineering mimics perpetual volcanos. Others modify clouds.

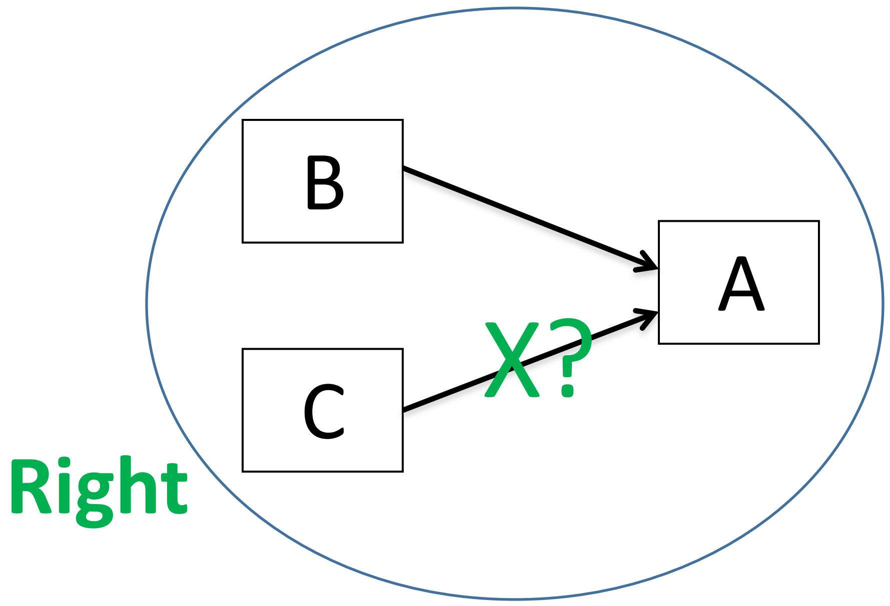
Motivation: 1) to meet tough targets. 2) to head off catastrophes.
Issues: Risks, governance, anthropocentricity, loss of randomness.

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.



Ignore C.

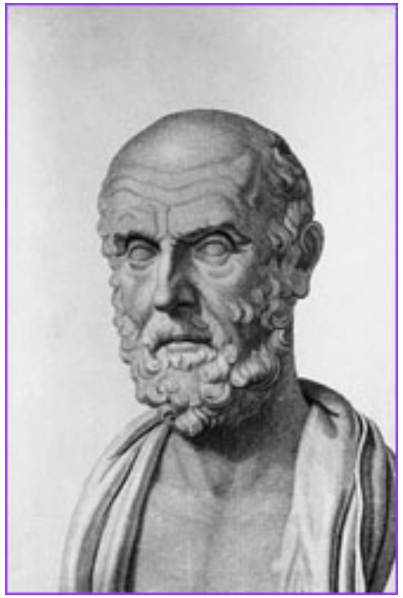


Invent and insist on conditionality for the other guy's C – and also for your B.

Harmful solutions

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

Hippocrates



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

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

One billion high emitters

Chakravarty et al., *Proceedings of the National Academy of Sciences*, 2009.

Sharing global CO_2 emission reductions among one billion high emitters

Shoibal Chakravarty[a], Ananth Chikkatur[b,1], Heleen de Coninck[c], Stephen Pacala[a,2], Robert Socolow[a], and Massimo Tavoni[a,d]

[a]Princeton Environmental Institute, Princeton University, Princeton, NJ 08540; [b]Belfer Center for Science and International Affairs, Harvard University, Cambridge, MA 02139; [c]Energy Research Centre of the Netherlands, P.O. Box 1, 1755 ZG, Petten, The Netherlands; and [d]Fondazione Eni Enrico Mattei, 20123 Milan, Italy

Contributed by Stephen Pacala, May 19, 2009 (sent for review March 16, 2009)

Four ways to emit 5 ton CO_2/year (global per capita emissions today)

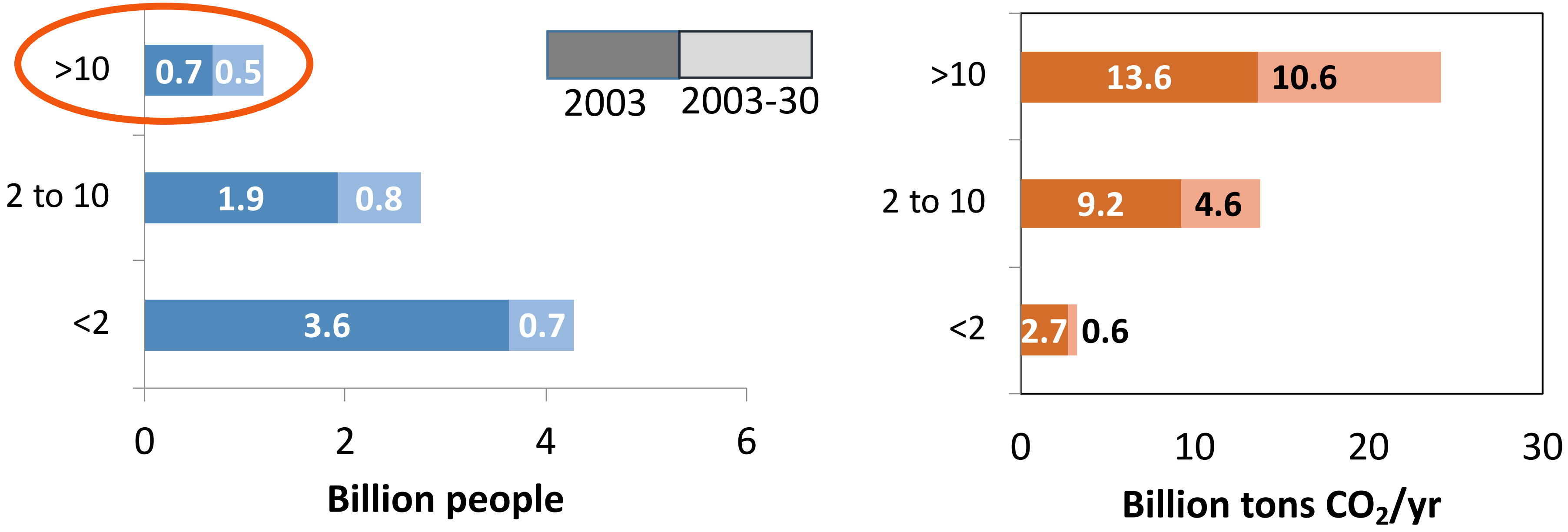
Activity	**Amount producing 5 ton CO_2/year emissions**
a) Drive	18,000 miles/year, 45 mpg
b) Fly	18,000 miles/year
c) Heat home	Natural gas, average house, average climate
d) Use electricity	400 kWh/month if all coal-power (1000 gCO_2/kWh) 800 kWh/month, natural-gas-power (500 gCO_2/kWh)

Princeton student or professor, on-campus energy: 9 tCO_2/yr.
What about Davis?

When we do ordinary things globally with current technologies, we harm ourselves.

Some *ordinary things*: eating hamburgers, commuting to work, building with concrete, going skiing.

One billion "high emitters" (>10 tCO_2/yr)



Bin boundaries at 2 tCO_2/yr and 10 tCO_2/yr are the 2003 per capita values for Brazil and EU. *Most high emitters are not "rich."*

Collaborators: Shoibal Chakravarty and Massimo Tavoni.

Source: http://www.climatescienceandpolicy.eu/2009/11/afocus-on-individuals-can-guide-nations-towards-a-low-carbon-world/

Where do the high emitters live?

More than half of the 2030 high emitters will live outside the OECD. The high-emitter lifestyle is similar world-wide.

Collaborators: Shoibal Chakravarty and Massimo Tavoni.

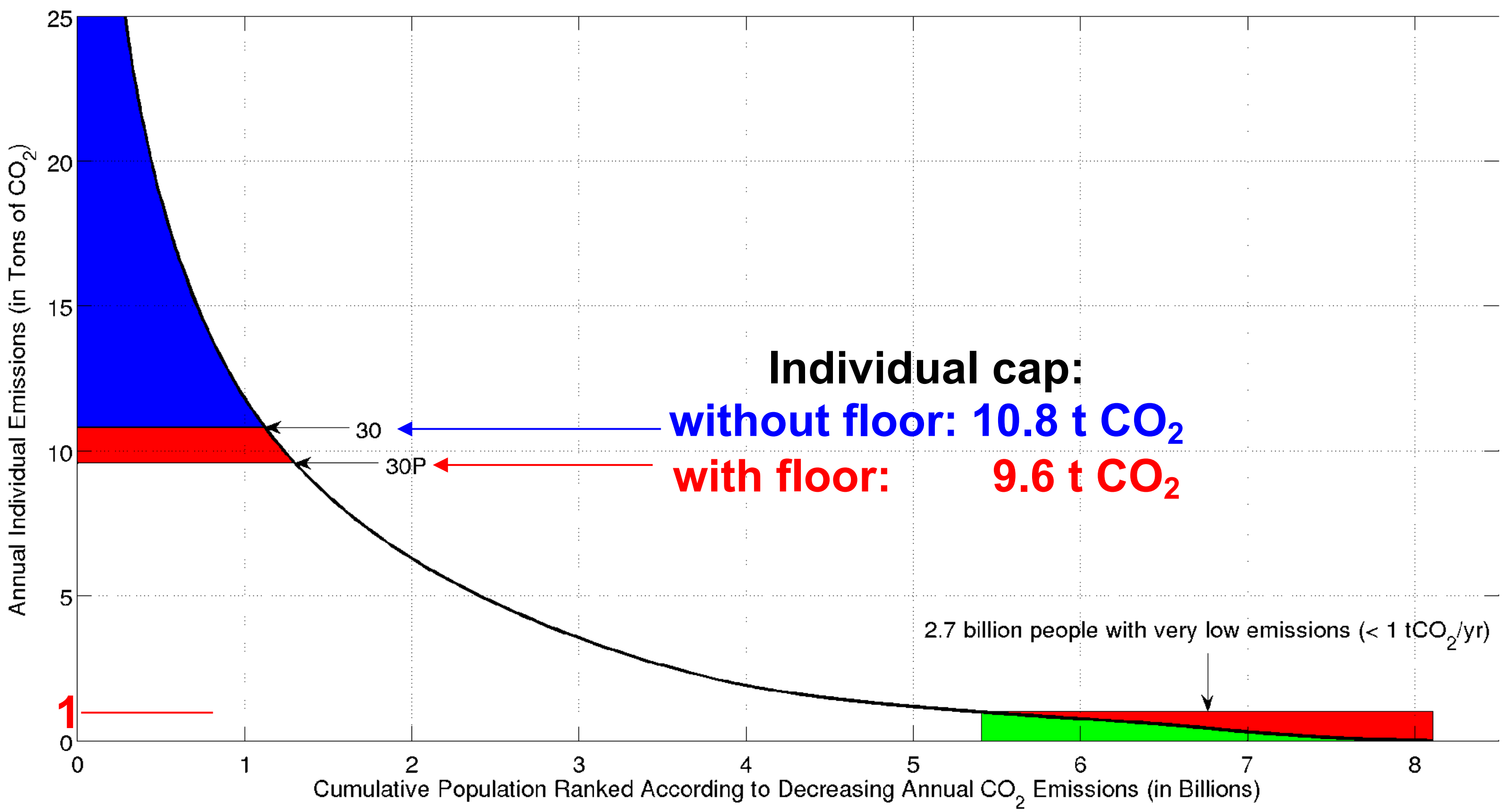
Source: http://www.climatescienceandpolicy.eu/2009/11/afocus-on-individuals-can-guide-nations-towards-a-low-carbon-world/

Low-carbon industrialization

Can the currently industrializing countries find low-carbon development paths?

China is leapfrogging over the rest of the world with high-voltage transmission, for example.

The world's poor do not need to be denied fossil fuels.



Poverty alleviation for three billion people has a negligible affect on climate change.

Committed emissions

Steve Davis and Robert Socolow, *Environmental Research Letters*, 2014.

"Rapid Switch"

Technology

Solar and wind

The power of incumbents

Electric vehicles

How quickly did automobiles displace horses?

Values

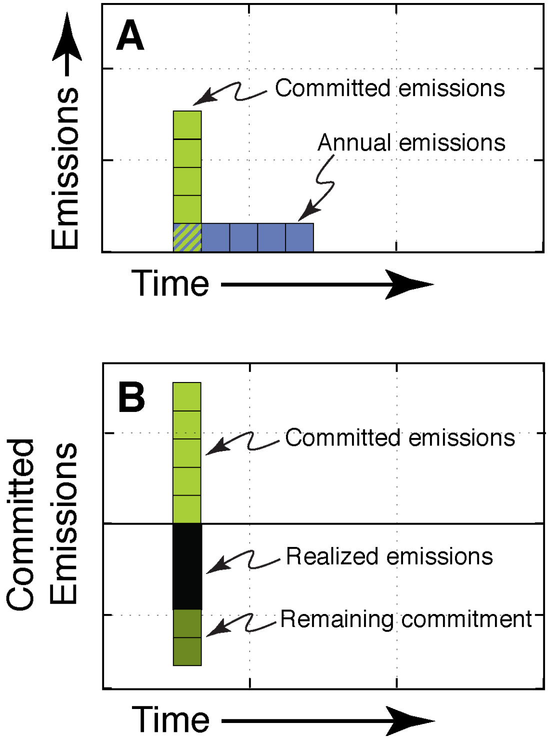
The finite planet meets the bucket list.

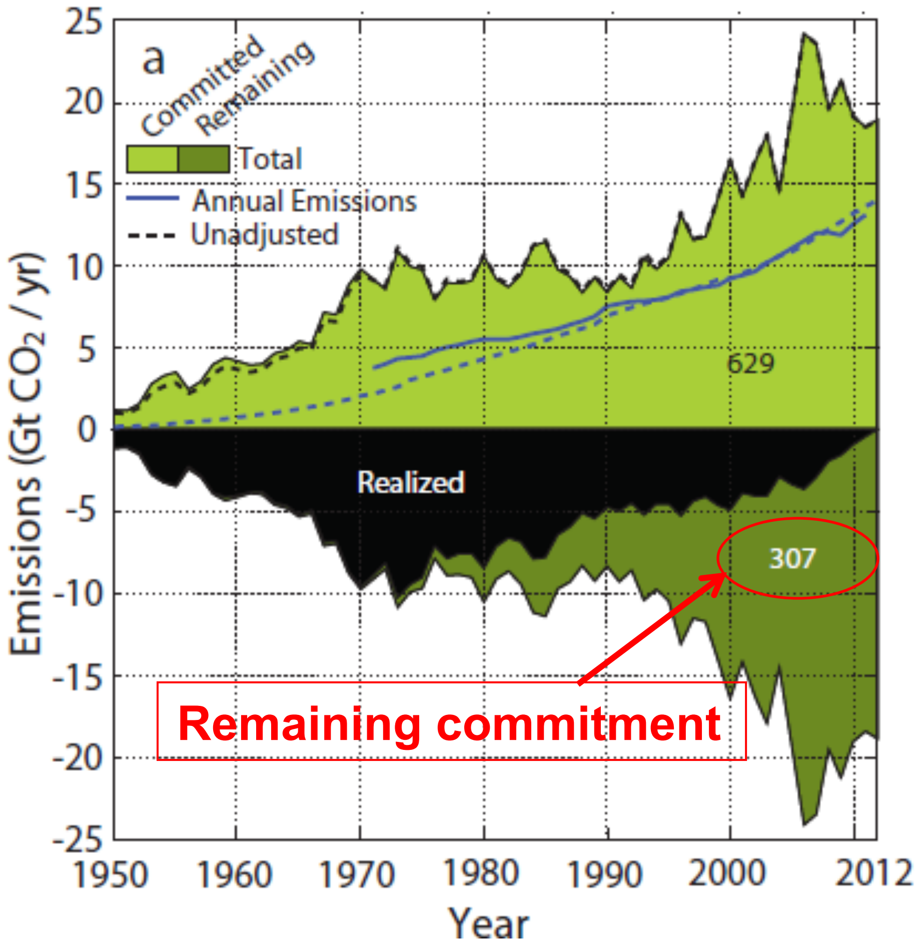
Nationalism meets planetary identity.

Now, years ahead, decades ahead, centuries ahead.

What goes wrong when change is attempted too quickly?

"Committed emissions"
Future emissions inherent in current investments

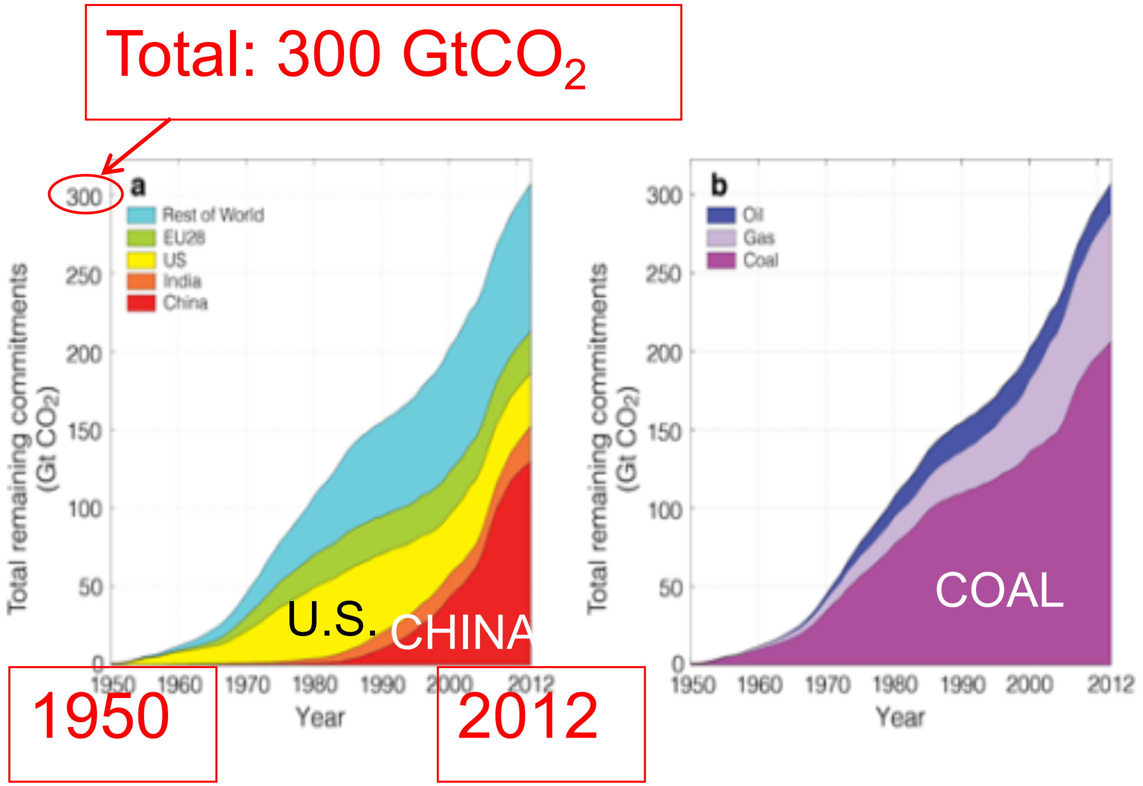




Collaborator: **Steve Davis.** *Source*: Davis and Socolow, *Env. Research Letters*, 2014

Global view of electric power from 2012. Assumes 40-year life for power plants, updated for retirements and plant-life extensions.

Remaining emissions, year by year



Global remaining "committed emissions" from then-operating power plants, 1950 – 2012. Assumes a 40-year lifetime.

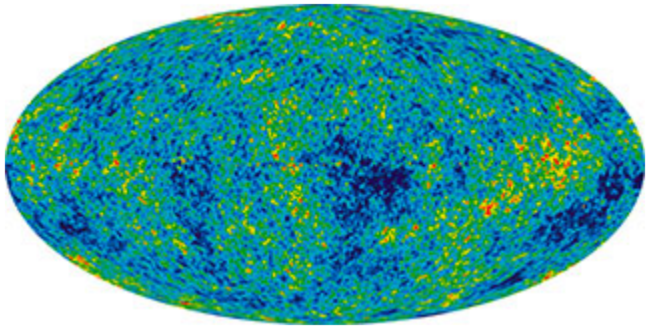
***Collaborator:* Steve Davis.** *Source*: Davis and Socolow, *Env. Research Letters*, 2014

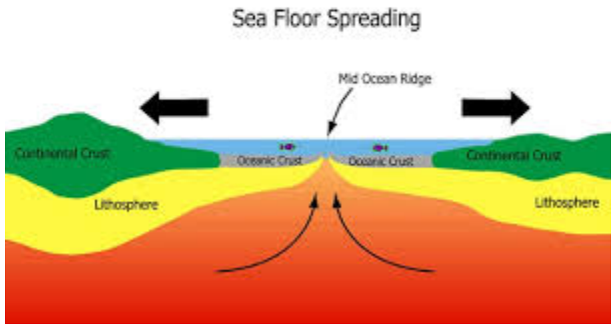
Destiny Studies

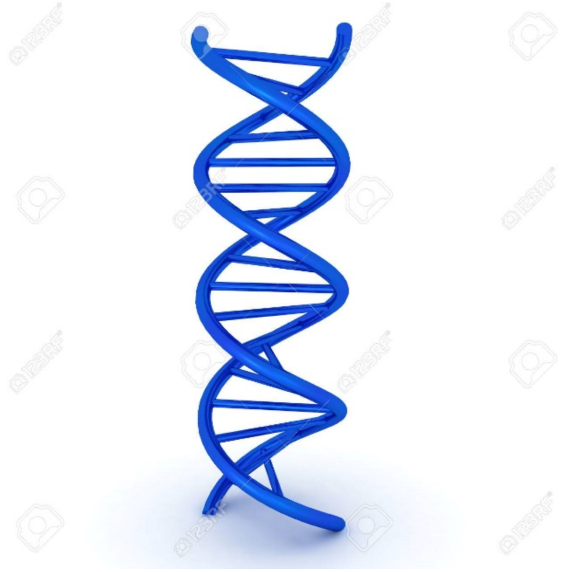
Robert Socolow, *Bulletin of the Atomic Scientists*, 2015.

Destiny Studies

In my lifetime we have gained a qualitatively better understanding of the histories of our Universe, our Earth, and life: the Big Bang, seafloor spreading, and DNA.







The task of the next decades is to achieve a qualitatively better understanding of our collective future. This is the domain of Destiny Studies.

Citations:
https://map.gsfc.nasa.gov/media/121238/index.html;
https://www.lee.k12.nc.us/cms/lib/NC01001912/Centricity/Domain/2042/sea-floor-spreading-diagram-kids.jpg:

Disciplining future time

At present, we have little capacity to distinguish between what we owe our grandchildren's generation and what we owe more distant future generations. Destiny Studies will provide disciplined analysis of our collective future for various time frames.

In particular, it will distinguish our 50-year future from our 500-year future.

How soon will Davis have a major in Destiny Studies?

Alternate goals

Set no target at all; let the future take care of itself.

Set a target which accepts that we will not turn the clock back but will establish a new normal.

Restore some characteristics of the Earth at some earlier time: e.g., some previous atmosphere.

Compensate for our changing atmosphere with other changes.

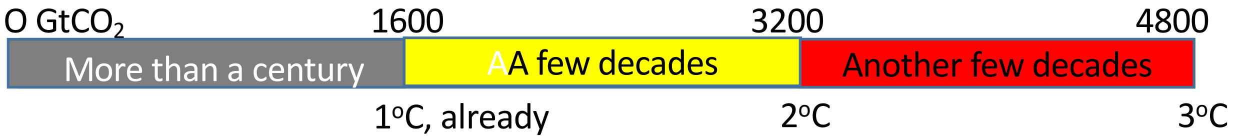
“Manifest destiny” for the developing world

John Gast, American Progress, 1872.
Chromolithograph published by George A. Crofutt.
Source: Prints and Photographs Division, Library of Congress.

American Progress, 1872, is an iconic painting by John Gast. The central figure brings light, and darkness recedes. A large coil of telegraph wire is on her right arm, and she is threading it through the fingers of her left hand.

Native Americans and bison flee.

Cumulative emissions and temperature



1°C will result from anthropogenic CO_2 emissions to date.

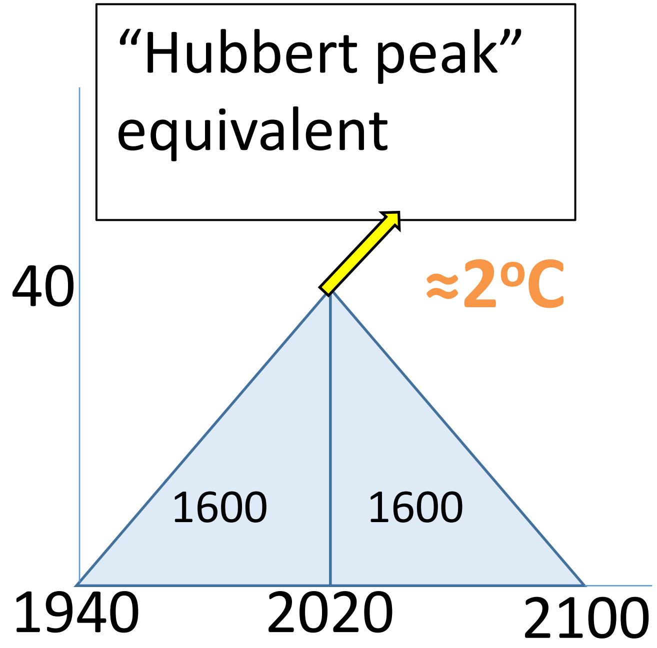
2°C results from future emissions equaling historic emissions.

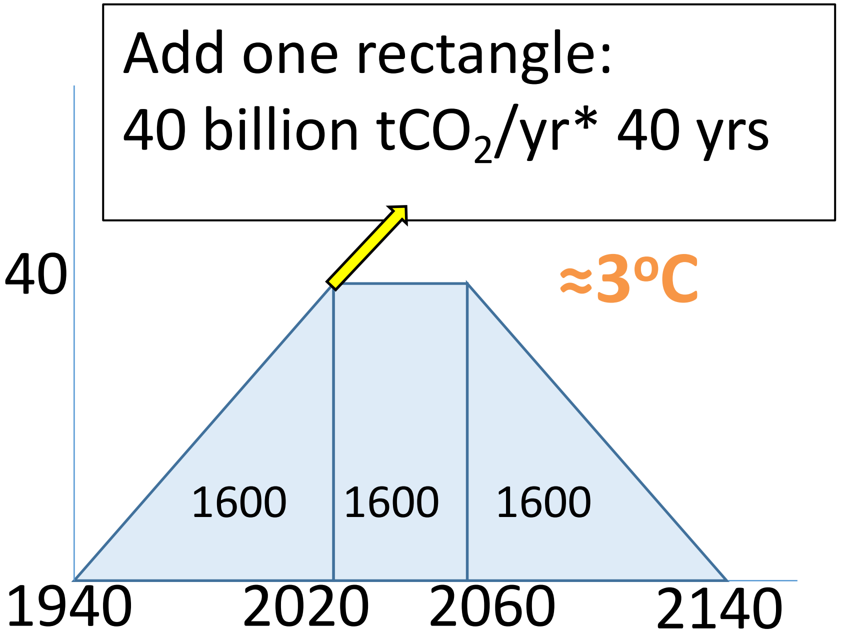
3°C will result from roughly a tripling the historical total.

The probability is about 1/6 for both:

getting 3°C while aiming for 2°C (being unlucky)
getting 2°C while aiming for 3°C (being lucky).

Targets





If we were not confronting climate change, the era of fossil fuels (coal, oil, and gas) could last hundreds of years.

“Unburnable” fossil fuels

1000 billion tons of CO_2 (1000 $GtCO_2$):

2 trillion barrels of oil
20,000 trillion cubic feet of gas
300 billion tons of coal

Resources in the ground ($GtCO_2$):

Oil	8,000
Gas excluding clathrates	3,000
Clathrates	40,000
Coal	20,000
Total	**70,000**

Source: Rogner, H-H, 1997. “An assessment of world hydrocarbon resources,” *Ann. Rev. Energy and Env. 22*, pp. 217-262. The table reworked here is on p. 249. Estimates include “additional” resources.

Budgets demand choices

The budget concept leads inexorably to choices about which fossil fuels to extract and which to leave in the ground:

When?	Better options someday?
Whose?	Geopolitical stability
Used where?	“Fairness”
For what purpose?	Who judges?
Which fossil fuels?	Those with the highest H/C ratio?

Judgments about which fossil fuels are “unburnable” have no precedents.

Grounds for optimism

1. The world today has a terribly inefficient energy system.
2. The costs for solar power and wind power have fallen precipitously.
3. Most of the 2069 physical plant is not yet built.
4. Very smart young people now find carbon and 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 about everybody alive today… and about the collective future of our species.

Yours is the generation that will figure out how to fit on this small planet.