Negative Emissions: Comprehending Scale

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International Workshop on Modeling and Policy of CO_2 Removal from the Atmosphere

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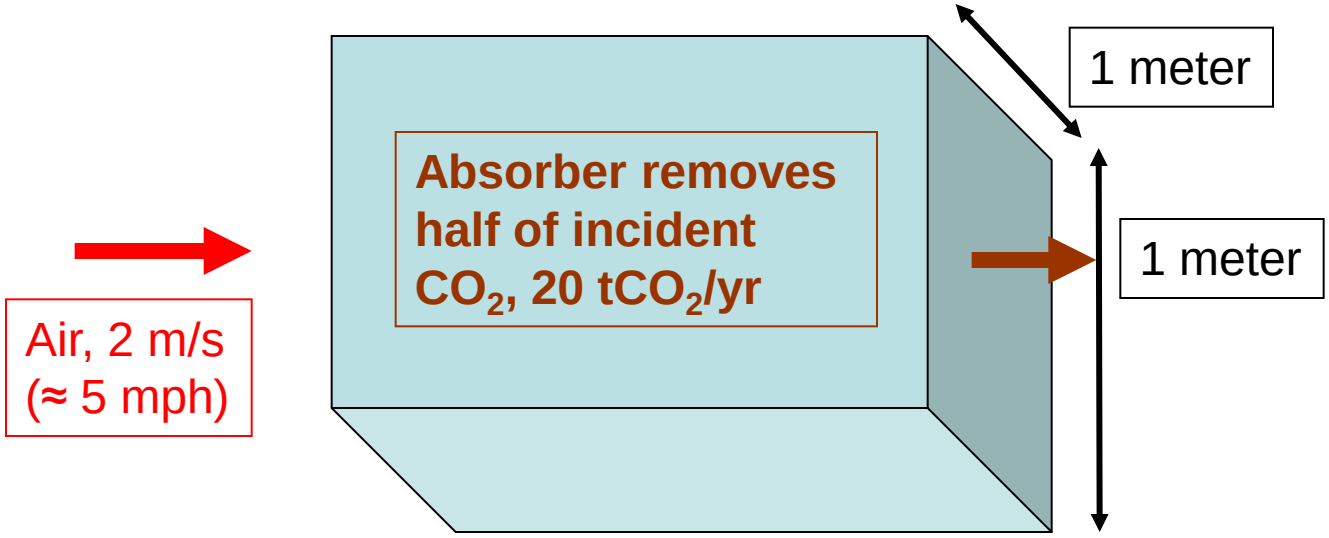
I. Where does Direct Air Capture fit?

First things first: Virtually all large-scale industrial CO_2 sources should be decarbonized before DAC is deployed.

DAC may be less expensive than both electrification and biofuels for some distributed fixed and mobile sources (home furnaces and cars)

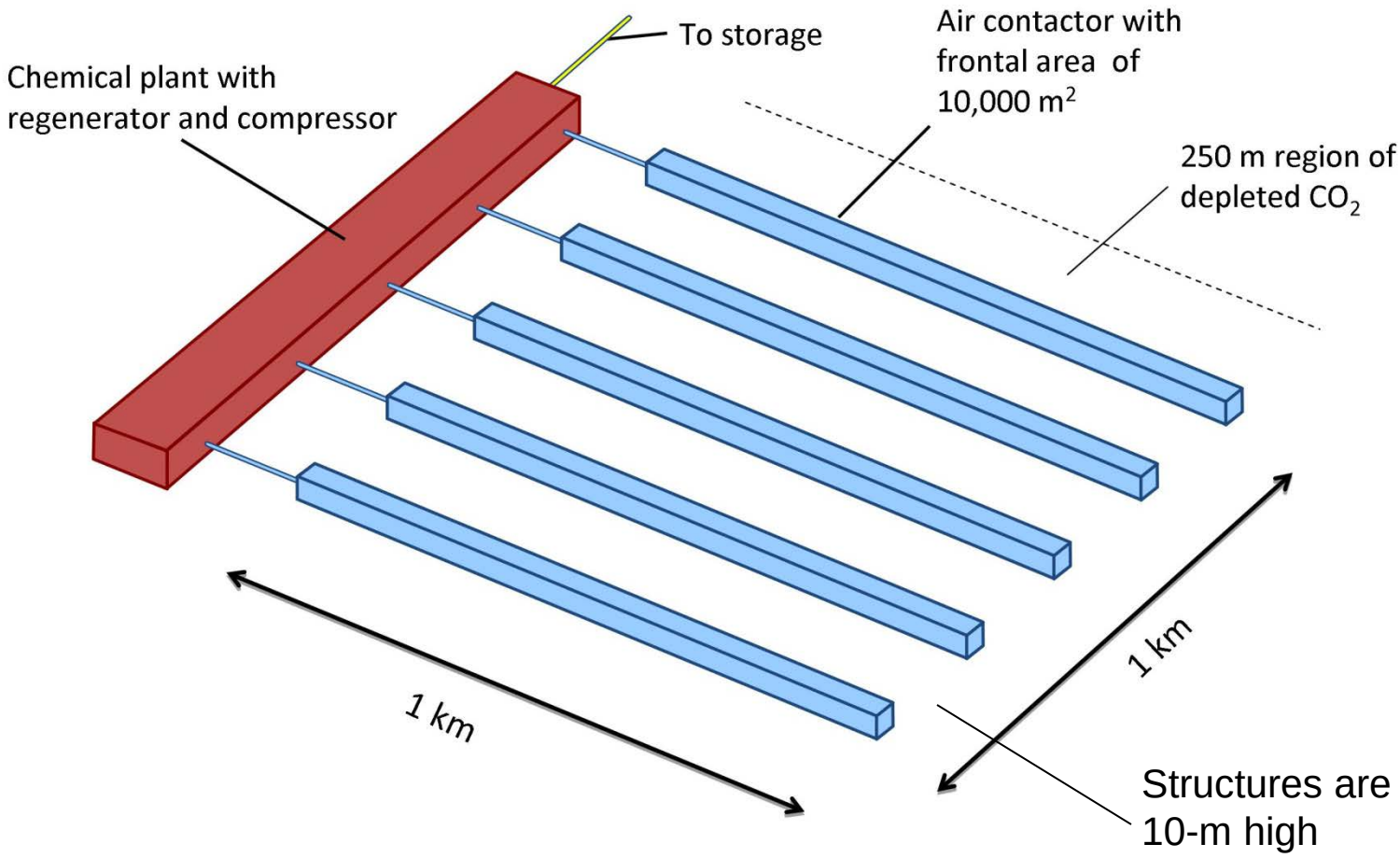
DAC may be used someday to reduce the atmospheric CO_2 concentration. It will compete with other CDR strategies.

Compensating for the average American's emissions requires a contactor with the area of a window



Ambient air flows over a chemical sorbent that selectively removes the CO_2. The CO_2 is then released as a concentrated stream for disposal or reuse, while the sorbent is regenerated and the CO_2-depleted air is returned to the atmosphere.

A 1 $MtCO_2$/yr facility



A 1000 MW coal power plant would require six of these facilities. In all, 30 km of structures 10-m high.

CO_2 captured at power plants

The 1300 MW AEP Mountaineer Plant in West Virginia, using chilled ammonia, has captured a slipstream of 100 $ktCO_2$/yr since 2009, from emissions of more than 6 $MtCO_2$/yr.

Source: Alstom via *Yale 360*, February 18, 2010

The Future Coal Power Plant

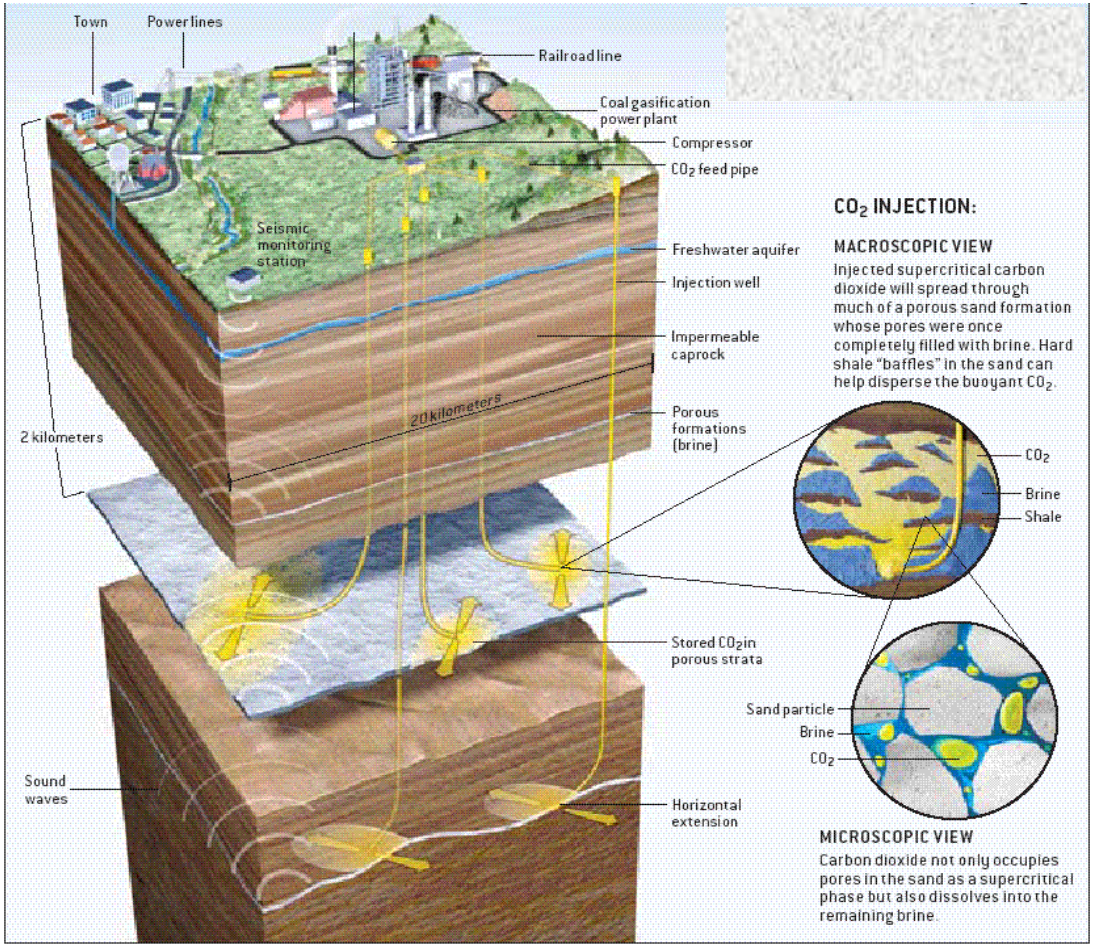


ILLUSTRATION BY DAVID FIERSTEIN; CONCEPT BY JULIO FRIEDMANN *Lawrence Livermore National Laboratories*

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.

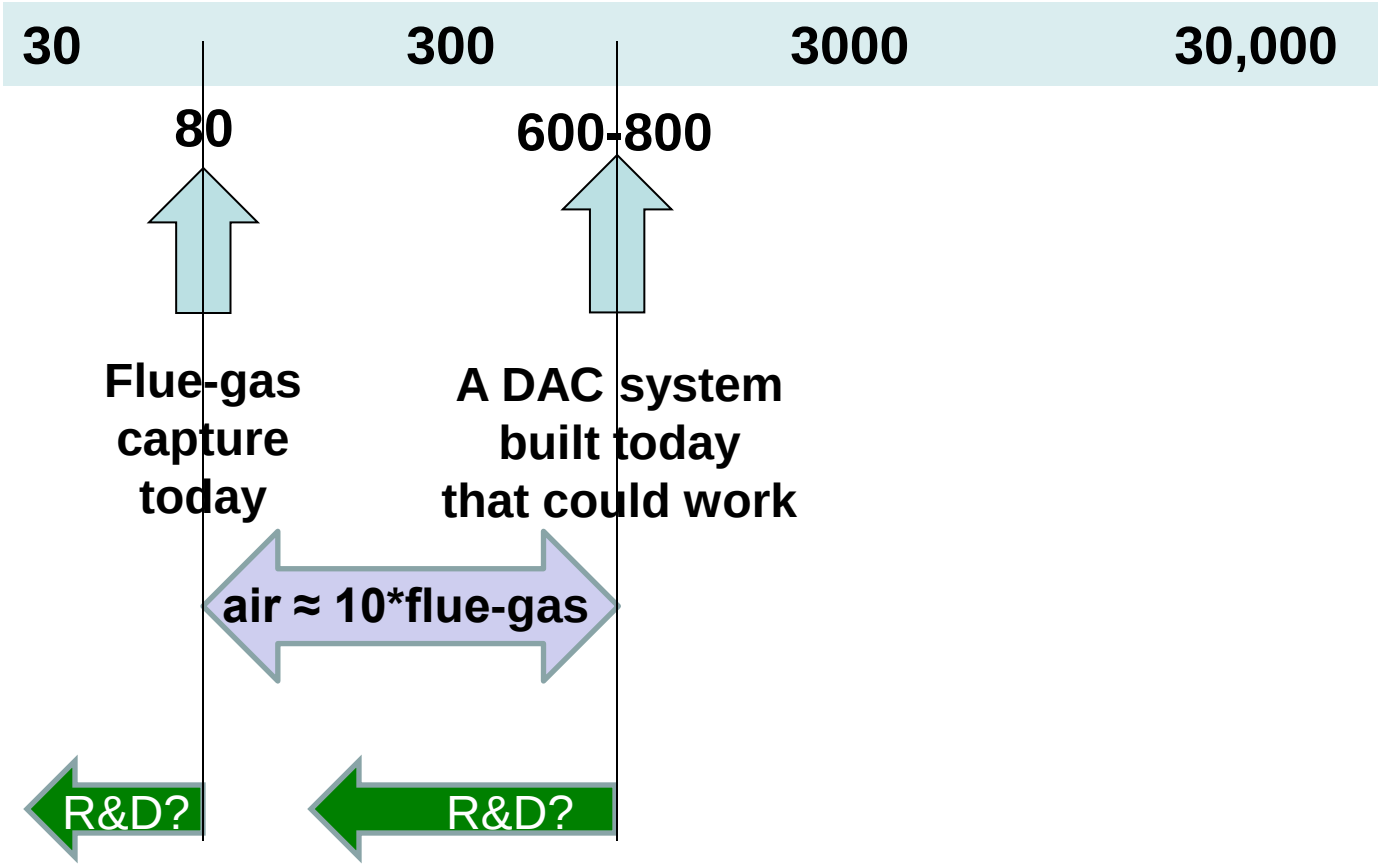
Assumptions:

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

- *Note:* Plant is still young.

Note: Injection rate is 150,000 bbl(CO_2)/day, 3 billion barrels over 60 years.

Cost domains, in $/ton$CO_2$

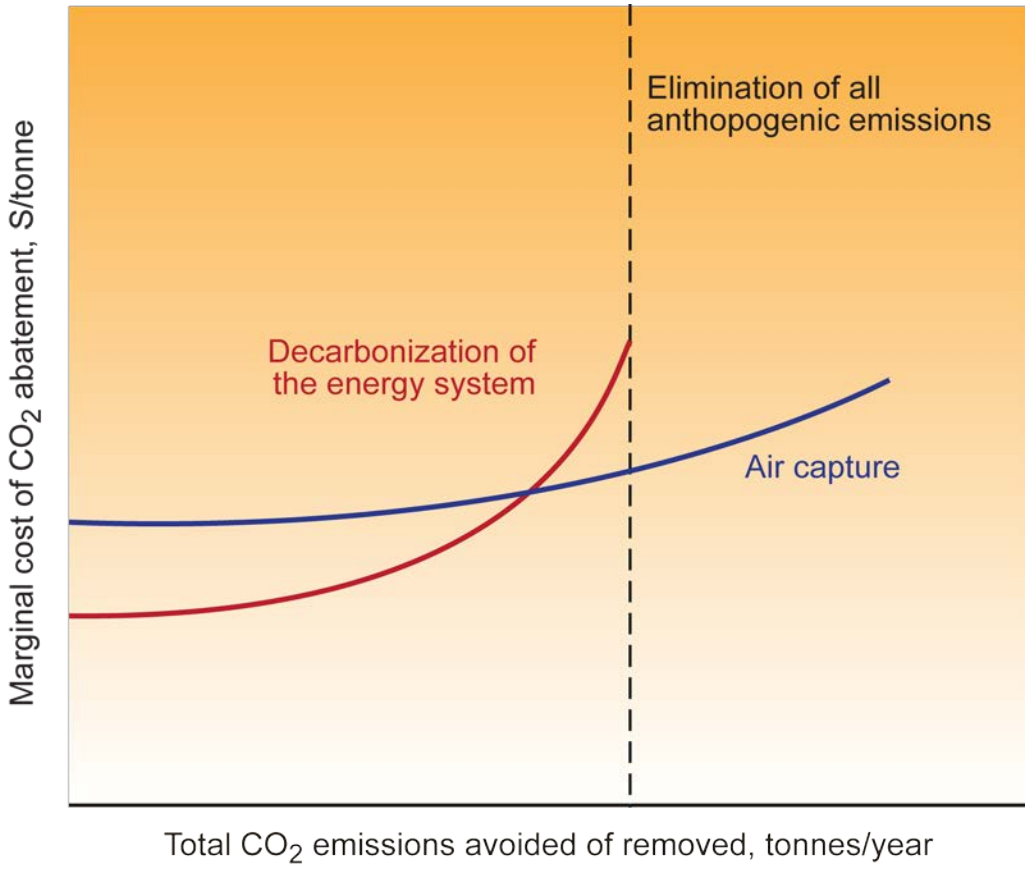


Increment from Adding \$600/tCO_2 to Fuel and Power Prices

Natural gas	**\$33/1000scf**
Crude oil	**\$260/barrel**
Coal	**\$1400/U.S. ton**
Gasoline	**\$5.20/gallon**
Electricity from coal	**48¢/kWh**
Electricity from nat. gas	**21¢/kWh**

"Indirect" CO_2 emissions associated with production, transport or transmission, and distribution are not included.

Recalcitrant emissions



Sources of CO_2 that could be costly to eliminate:

- aircraft
- natural gas infrastructure
- the last few percent of emissions

The “net-carbon” challenge

A cost-multiplier, *y*, enters this problem:

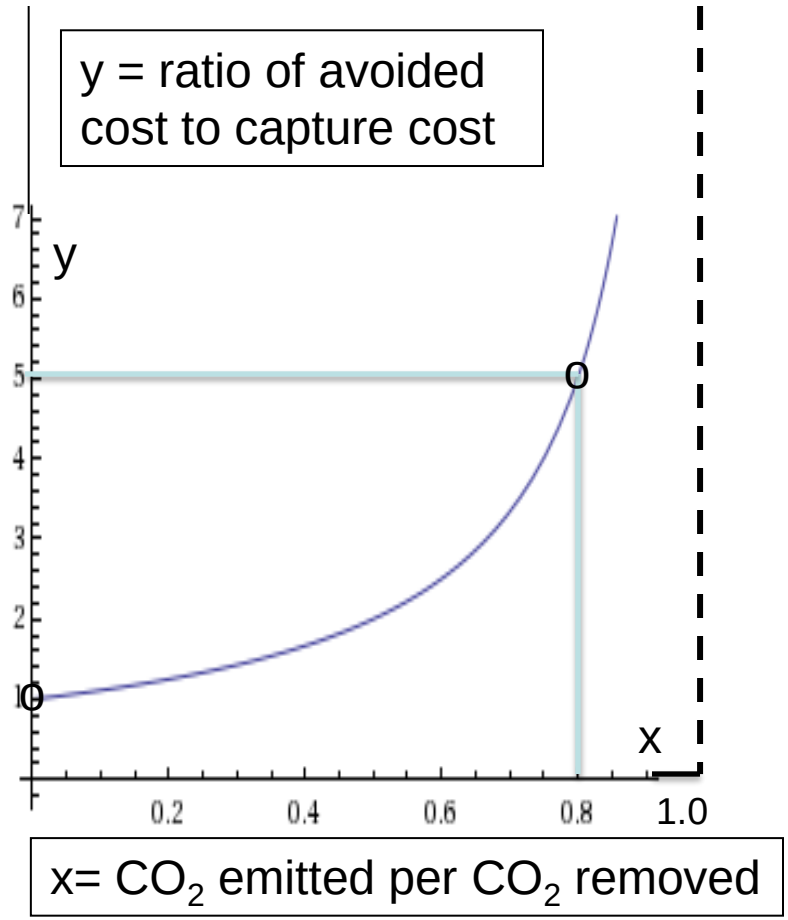
$$y = 1/(1 - x),$$

where *x* is the amount of CO_2 emitted per CO_2 captured.

If the cost per unit of CO_2 *captured* by the system is C_{cap} , then the cost per unit of CO2 reduction in the atmospheric stock (called the avoided cost), C_{avoid}, is given by:

$$C_{avoid} = y^* C_{cap}$$

At $x = 1$, one CO_2 is emitted for every CO_2 captured.



Example: Fan-driven air flow with pressure drop, *ΔP = 100 Pa*. Assume coal power (1.0 $kgCO_2/kWh$), 400 ppm CO_2, 50% capture,100% fan efficiency. Then $\boldsymbol{x_{fan} = 0.08}$. *Lesson*: Design is tightly constrained if high-C power is required.

Low-carbon leakage

How should a *decarbonized* energy source for DAC be evaluated, while the world still has coal plants venting CO_2? The same decarbonized energy source could have reduced global CO_2 emissions by retiring the coal plant.

N → ~~C~~ + N *vs.* N → C + DAC-N

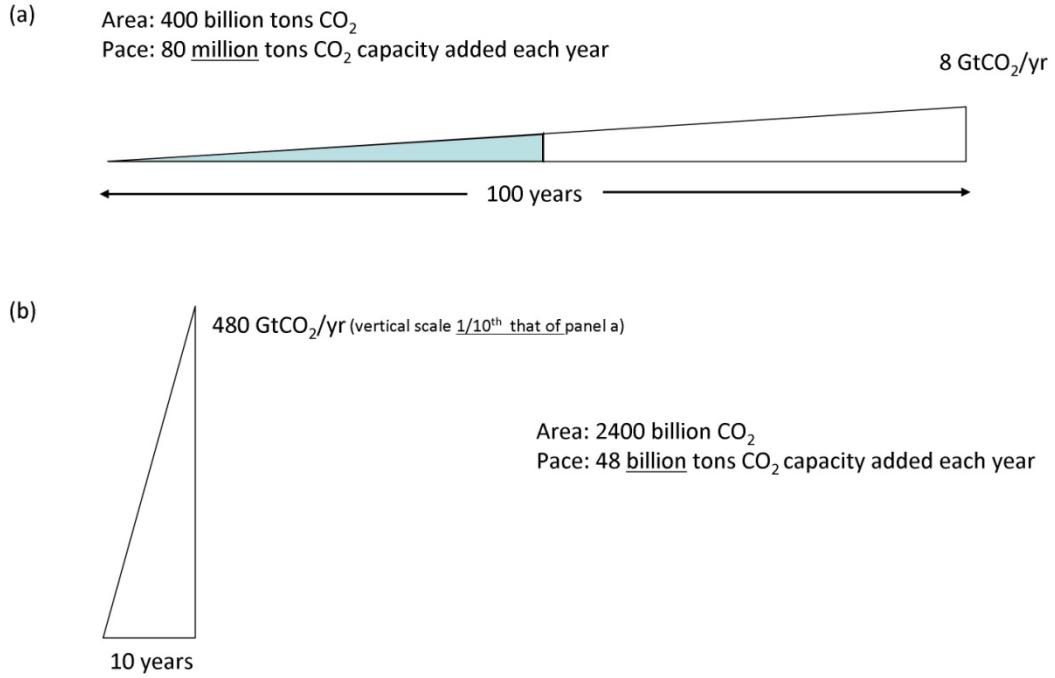
Baseline: Nuclear plant displaces coal plant. No DAC.

Alternative: Nuclear plant powers DAC, coal plant emissions continue.

Relative to baseline, DAC achieves no emissions reductions.

Special situations may show savings.

DAC is not matched to emergencies



Two CO_2 removal strategies:

(a) In 100 years, down 50 ppm (total removal ≈ 400 $GtCO_2$, reference case)
(b) In 10 years, down 300 ppm (what a crisis might require)

The "pace" (the triangle's slope) is 600 times larger for *(b)* than for *(a)*. Closing down all of the world's current power plants in three months also has a 48 $GtCO_2$/yr pace.

The land and ocean are assumed to be CO_2-neutral (not to outgas as CO_2 is removed).

II. A time for self-assessment

Scientists and environmentalists interested in getting climate change taken seriously have failed beyond their wildest imagination. Their message is being ridiculed by half the population of the U.S.

We must resist the temptation to blame everyone but ourselves: the recession, right-wind billionaires, Obama's priorities…

Reframe the challenge

Grant that the news is unwelcome.

Reveal that the job is hard and requires sustained focus.

Affirm that, because mitigation is far from risk-free, the lowest conceivable greenhouse targets are not optimal.

An unwelcome idea.

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

We have a new assignment: “Fitting on Earth.”

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

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.

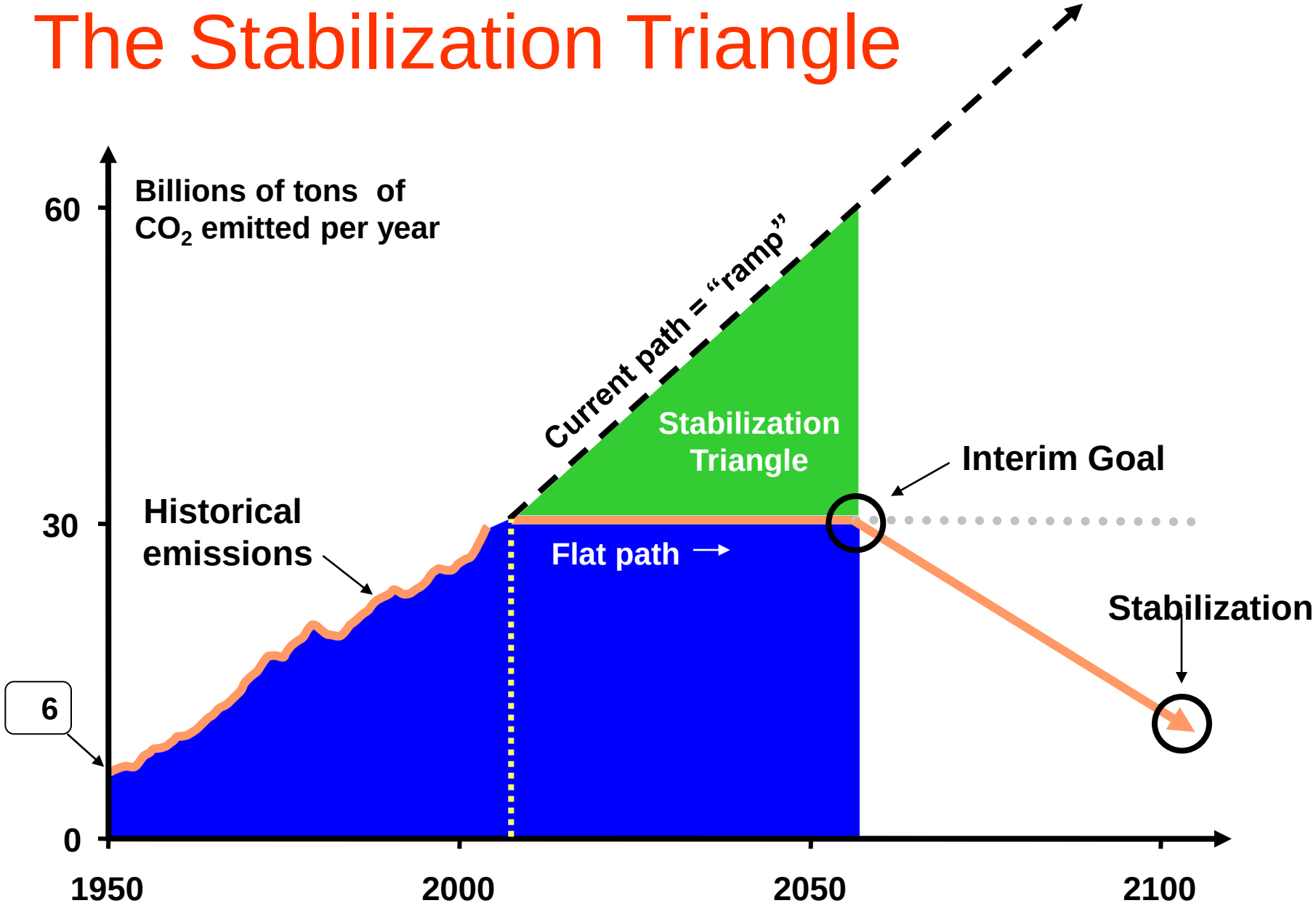
The idea that humans can’t change our planet is as out-of-date and wrong as the earth-centered universe.

The job went from “impossible” to “easy.”

The world, with some help from “wedges,” decided that dealing with global warming wasn’t impossible. So, it must be easy.

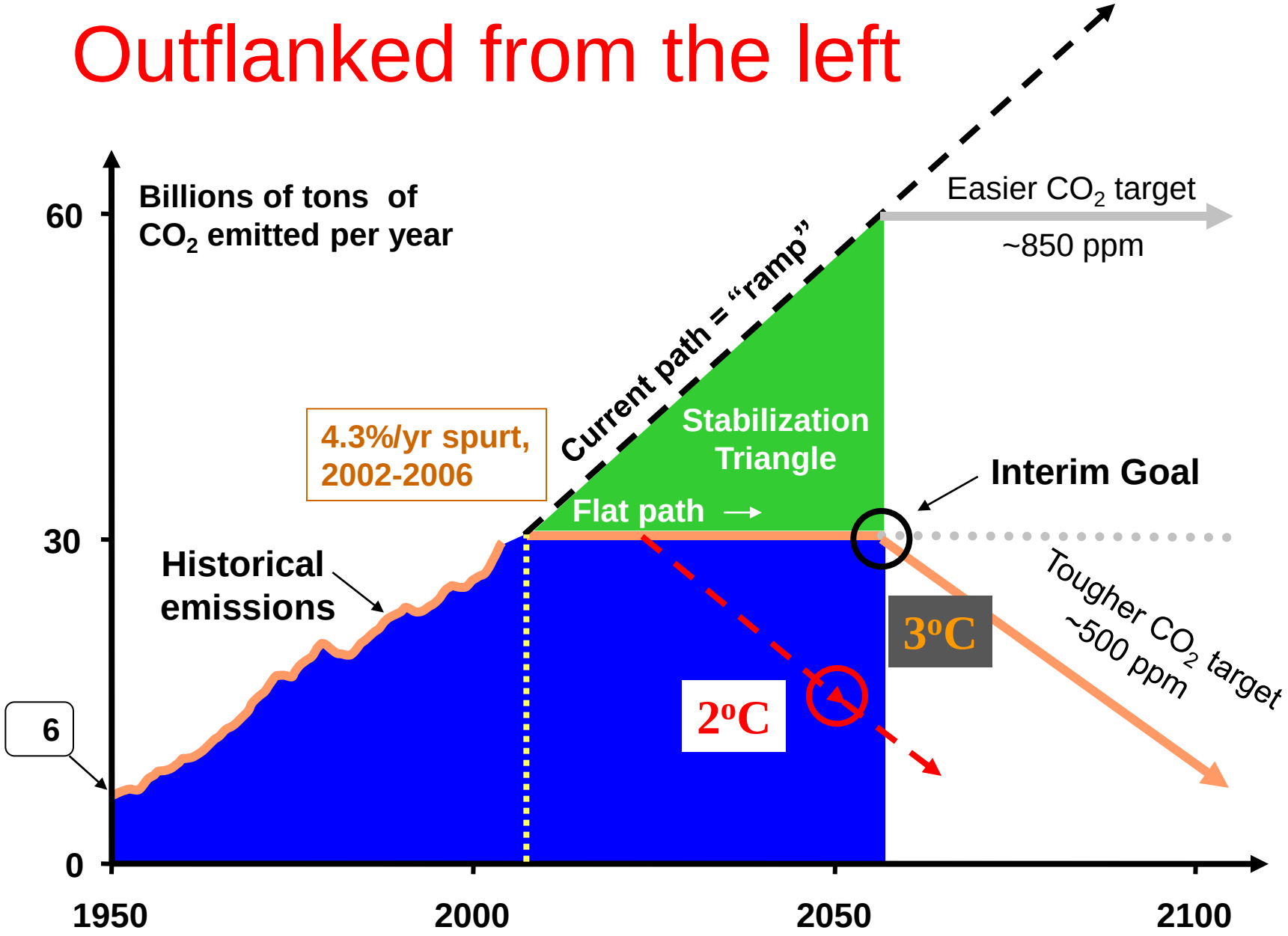
Psychologists are not surprised.

The Stabilization Triangle



Pacala's and my interim goal was the toughest I could imagine.

Outflanked from the left



Emissions in 50 years/emissions today = Two? One? One-half?

The importance of 2050

Pacala and I focused on 2050. It is within planning horizons. 2100 is not.

I developed the capacity to block out 2050-2100 on century-scale slides by holding my hand up in front of my face, a bit to the right. I was doing this yesterday.

We must keep asking: To what half century (even, to which decades) do specific mitigation strategies belong?

The job is hard

"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: *the appropriate pace.*

The appropriate pace

We must choose a pace based on what we know *and* what we don't know.

We must embrace *iterative risk management*. We must evaluate the appropriate pace frequently and anticipate revision.

This is the message of *America's Climate Choices*, just released.

Every strategy can be implemented well or poorly

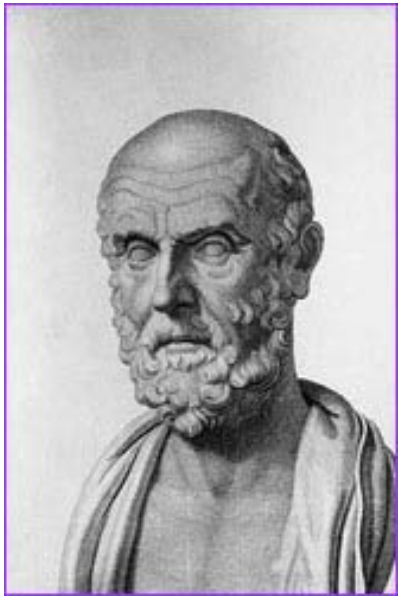
Every “solution” has a dark side.

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

The lowest conceivable greenhouse targets, achievable only by casting caution to the winds, are not optimal. Rather, we must trade the risks of disruption from climate change against the risks of disruption from mitigation.

Hippocratic oath

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

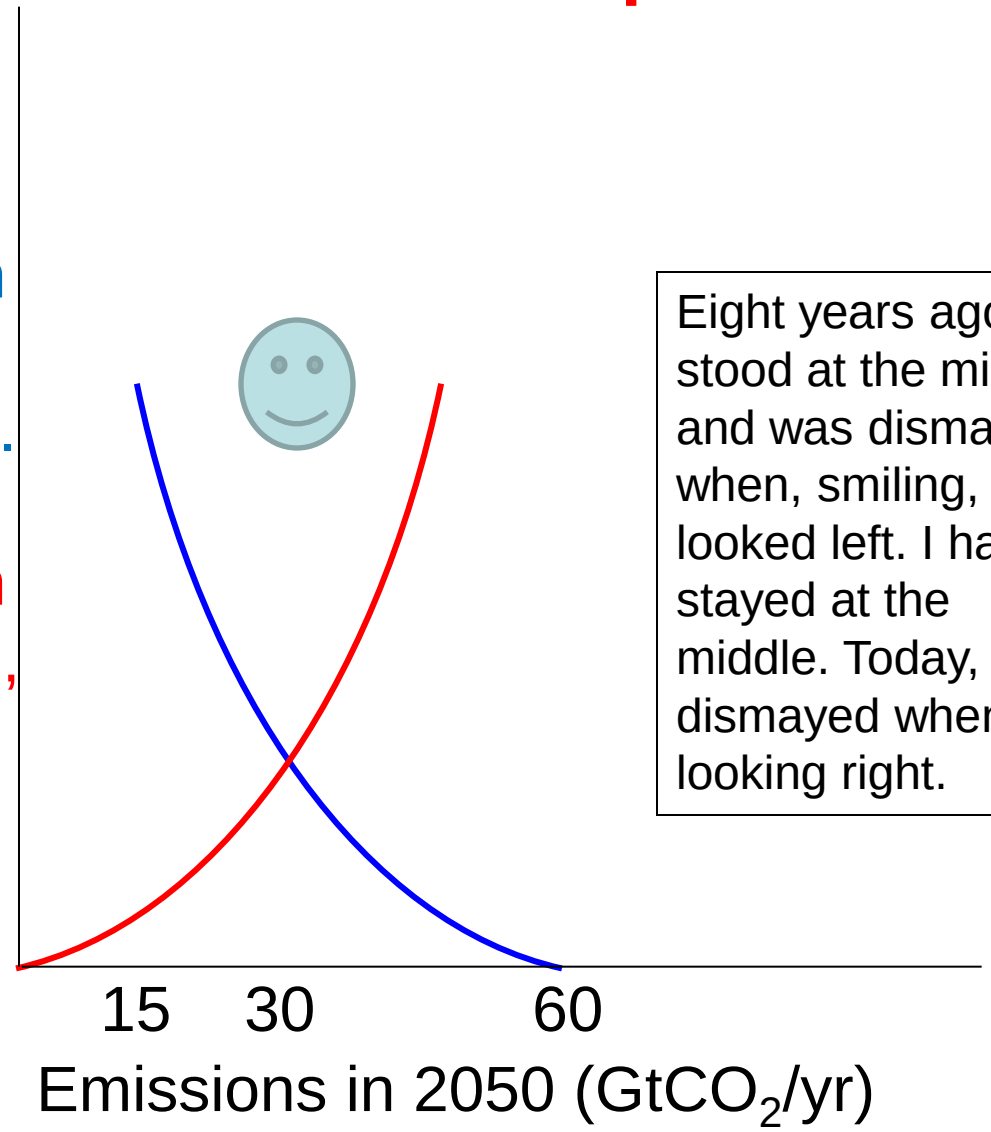


*** Modern version, Louis Lasagna, 1964,**
http://www.pbs.org/wgbh/nova/doctors/oath_modern.html

Two kinds of disruption

Disruption from mitigation, relative to BAU.

Disruption from climate change, relative to unchanged concentrations



Eight years ago, I stood at the middle and was dismayed when, smiling, I looked left. I have stayed at the middle. Today, I am dismayed when looking right.

What kind of modeling can reveal the competition between the great and the good?

We need to learn much more about transaction costs.

In particular, we need to understand what goes wrong when we go too fast.

Concluding Remarks and the Way Forward

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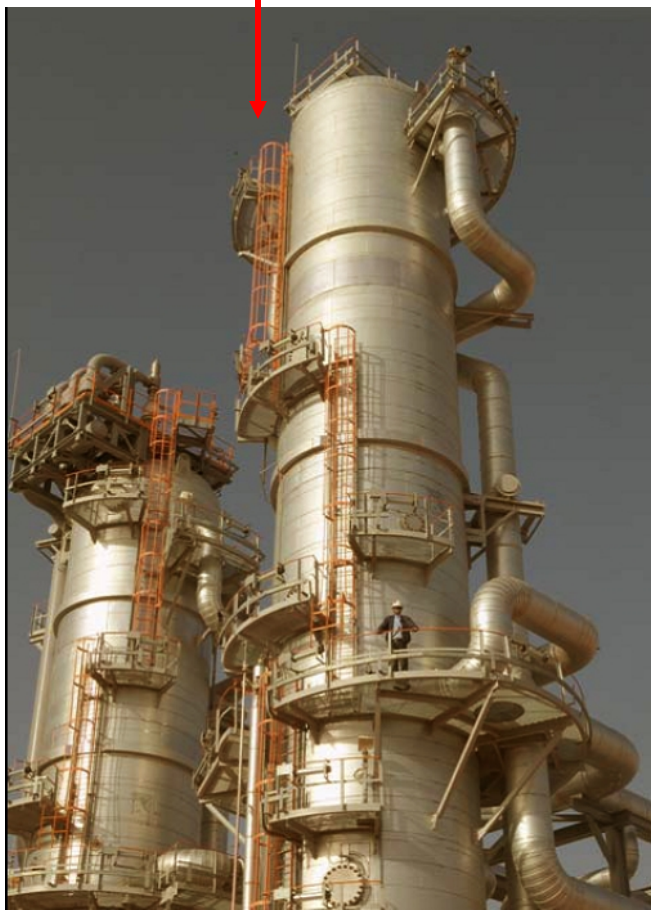
CO_2 Competitions

	CO_2 Purpose	
CO_2 Source	*Climate*	*Fuel security**
Geological	xxx	#1 now (EOR)
Industrial, various concentrations	CCS	Algae grown in flue gas
Air	**This meeting**	"Sunlight to fuels"

* Enhanced oil recovery (EOR) or chemical activation

Pure CO_2 streams in industry

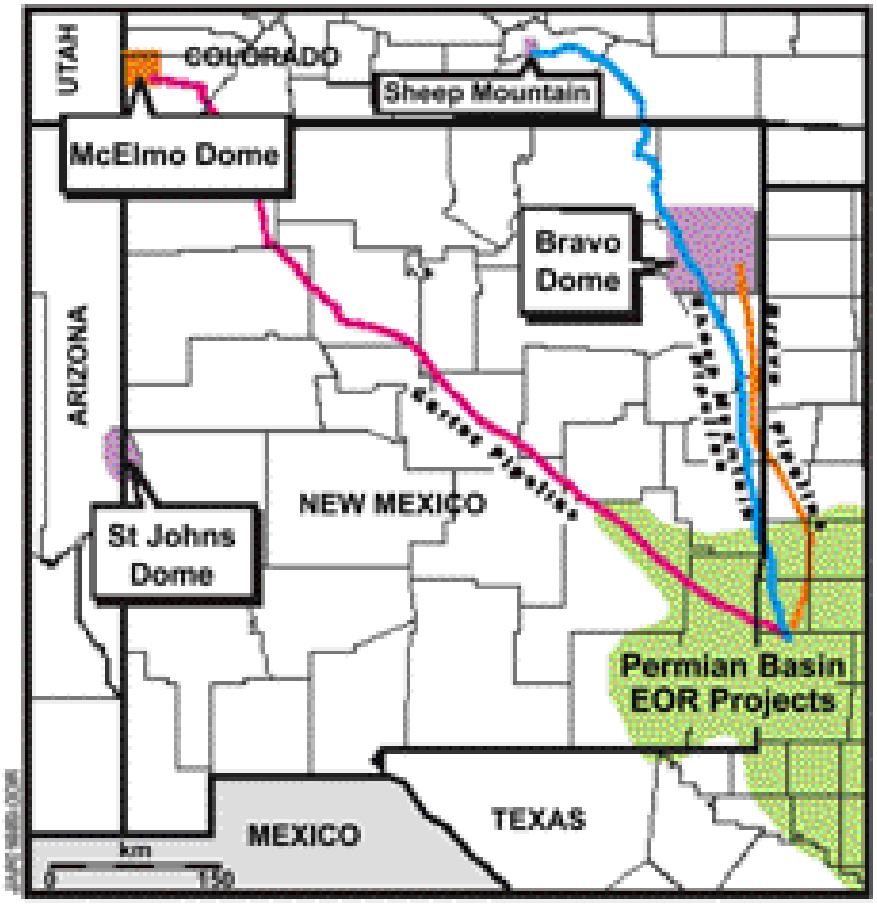


At In Salah, Algeria, natural gas purification by CO_2 removal plus CO_2 pressurization for nearby injection

Separation at amine contactor towers

Natural CO_2 fields

- McElmo Dome, Colorado: 0.4Gt(C) in place
- 800 km pipeline from McElmo Dome to Permian Basin, west Texas, built in the 1980s

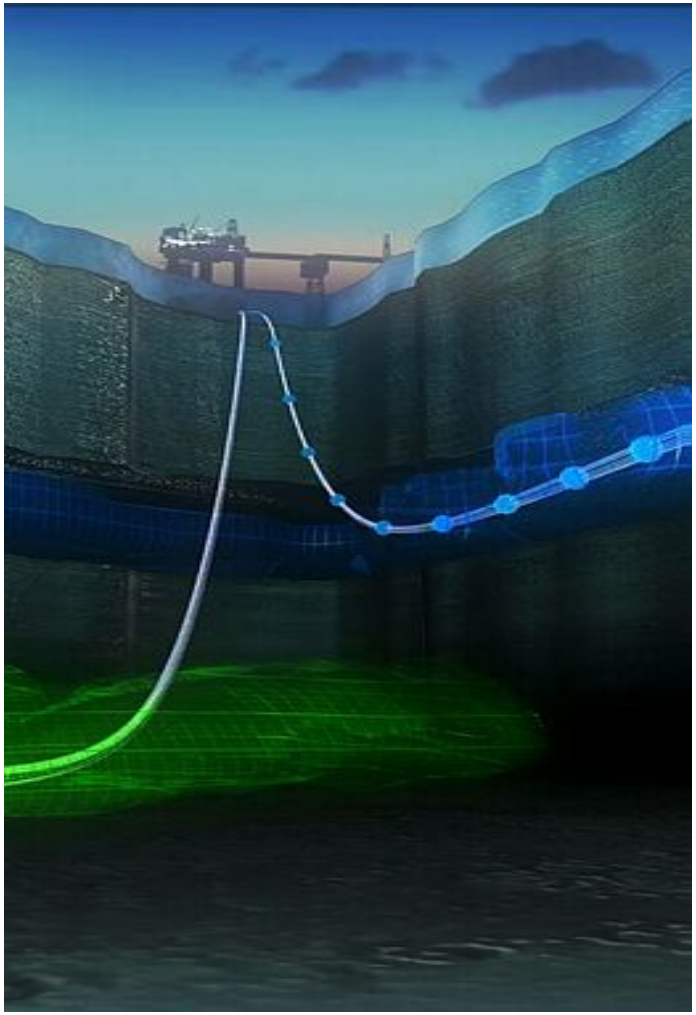


Two conclusions:

1. CO_2 in the right place is valuable.
2. CO_2 from McElmo was a better bet than CO_2 from any nearby site of fossil fuel burning.

Photo from David Hawkins

Previously sequestered CO_2



Sleipner project, offshore Norway

Graphic courtesy of Statoil ASA

Statoil has pumped 1 $MtCO_2$/yr into the Utsira formation below the North Sea since 1996 – CO_2 that has been removed from natural gas produced from the Sleipner field, offshore Norway, in order to meet the standards of the European gas grid. Retrievability has not been an objective.

What would *you* do if only carbon mattered?

My question to Margaret Torn: "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, and that you would be paid handsomely (maybe, you would be given a share of the government payment). What would you do? Establish a monocrop? Pour on fertilizer? Be inventive….

What are the right conditionalities?

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

Similarly, if your assignment were to provide a low-carbon fuel.

Who else but this group can think about such questions?

How much work was done on the global food market as biofuels policy was being developed in the U.S. and Europe?

Terrestrial CDR (1 of 2)

Afforestation

800 Mha at 500 tCO_2/ha

- reduces atmospheric CO_2 by 400 $GtCO_2$, or 50 ppm.
- is a century-scale project.
- can be compared to
  - today's forests: 1500 Mha tropical, 700 Mha temperate
  - today's tropical deforestation: 30 Mha/yr, 4 $GtCO_2$/yr.

Other versions of stock augmentation:

- Biochar (charcoal) blended into soil
- Low-till agriculture.

Fast-growing energy crops, conversion to power or hydrogen, storage of CO_2 (BECS)

These crops can remove ≈ 10 times more CO_2/ha-yr from the atmosphere than the slow-growing trees best suited for building up large stocks of standing biomass. Land requirements for equivalent quantities of CDR are less than for afforestation.

Terrestrial CDR (2 of 2)

Co-benefits

Enhancing the habitats of wildlife

Improving soil productivity

Net-carbon issues

CO_2 associated with planting, fertilizing, harvesting

“Indirect emissions”: e.g., as the land for food contracts

For BECCS: energy for energy conversion, CO_2 storage.

Research questions

Long-term sustainability of very high yields

Soil sustenance

Conditionalities to preserve forest benefits

Biodiversity protection.

Anticipate conflict over setting the thermostat

Imagine that nations are coordinating their mitigation actions: who owns negative emissions?

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

There will be some bias toward retrieving the pre-industrial world. 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.

The engineered earth

At times over these two days, we have had glimpses of a fully engineered world:

Every landscape is simplified

The well-being of every non-human species is subordinated

Instrumental values completely dominate.

Anticipate push-back here too.

Earth enhancement

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
cooler summers where people want them
less severe storms and droughts

} sweet spots

See Michael Sandel, T*he Case Against Perfection*. Enhancement can be pursued to excess. The ability to savor the life we have been "gifted" can be lost, as wel as the random, the "unbidden."

Climate science today sends a difficult message

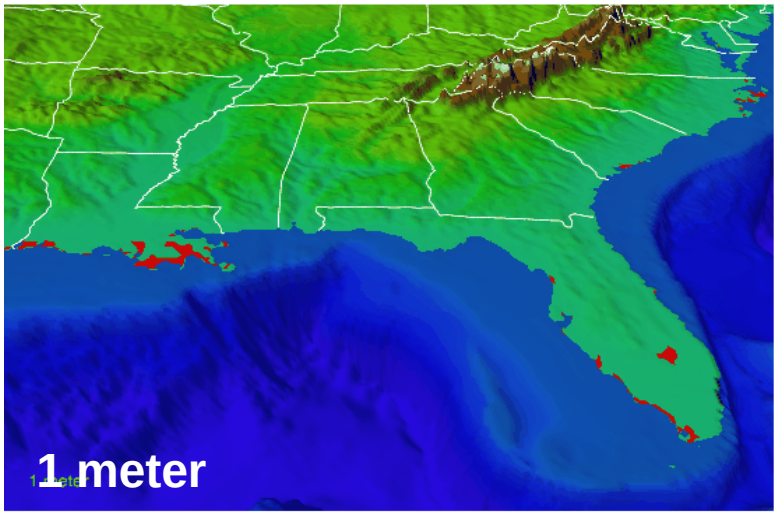
1. Neither mild nor severe climate change can be ruled out, given our poor understanding of feedbacks.
2. The probability of very bad outcomes is poorly known.
3. Breakthroughs are not imminent. The fog is not about to lift.

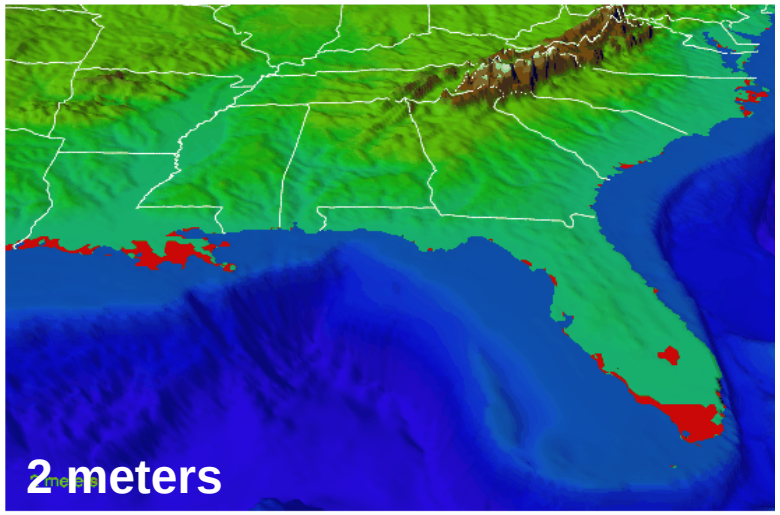
"High-consequence outcomes and internal disagreements: Tell us more, please."

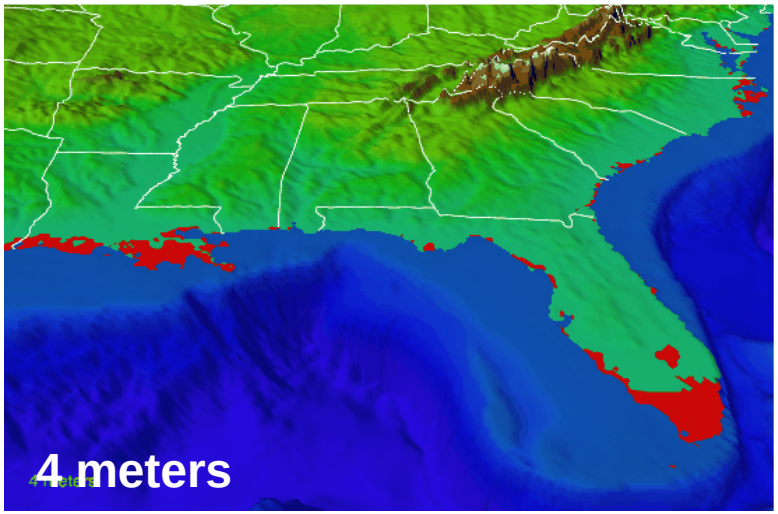
To be published in *Climatic Change.T*wo points:

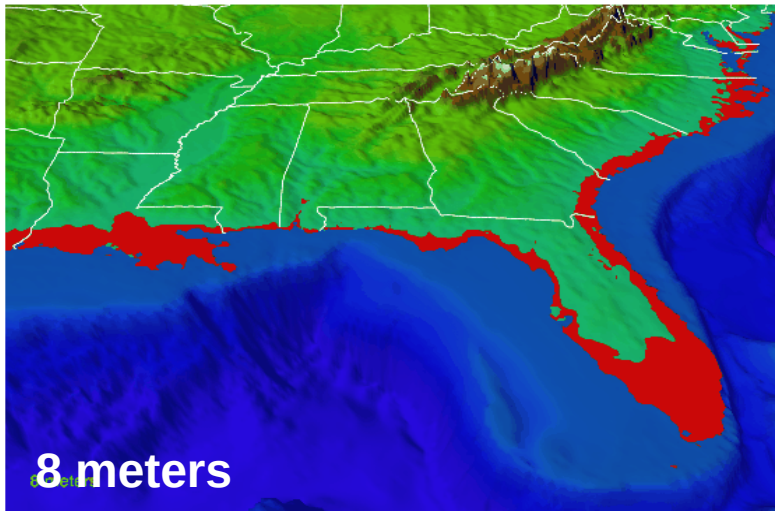
1. The tails of distributions of outcomes are disproportionately important and deserve disproportionate attention.
2. Dissonance across individual views must be reported. Currently, there is much disagreement about the tails. In AR4, the presentation of this dissonance was faulty.

Sea Level Rise









Greenland ice sheet:	7 meters
West Antarctic Ice Sheet:	5 meters

Source: T. Knutson, Geophysical Fluid Dynamics Laboratory, NOAA. See:
http://www.gfdl.noaa.gov/~tk/climate_dynamics/climate_impact_webpage.html#section4

Grounds for optimism

- The world today has a terribly inefficient energy system.
- Carbon emissions have just begun to be priced.
- Most of the 2061 physical plant is not yet built.
- Very smart scientists and engineers now find energy problems exciting.