

***Buttressing Sustainability
with Solid and Durable Analysis:
An Appreciation of Tom Graedel***

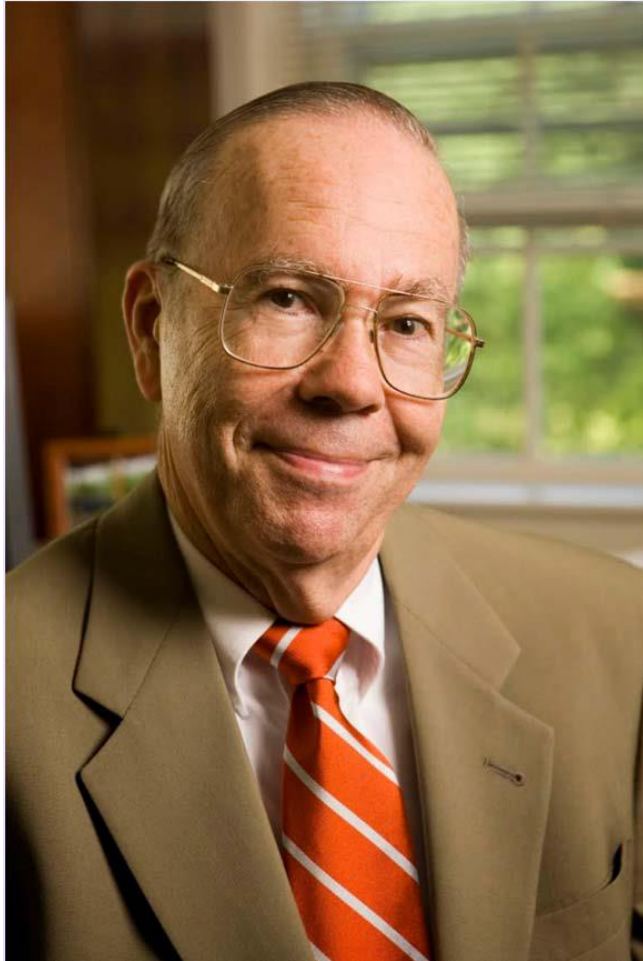
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Yale University

April 23, 2015

Tom Graedel



Beacon
Mentor
Friend

Tom and I: twinned careers

Tom and I are part of a cohort that will be giving speeches at fetes for one another over the next few years.

We studied physics and chemistry.

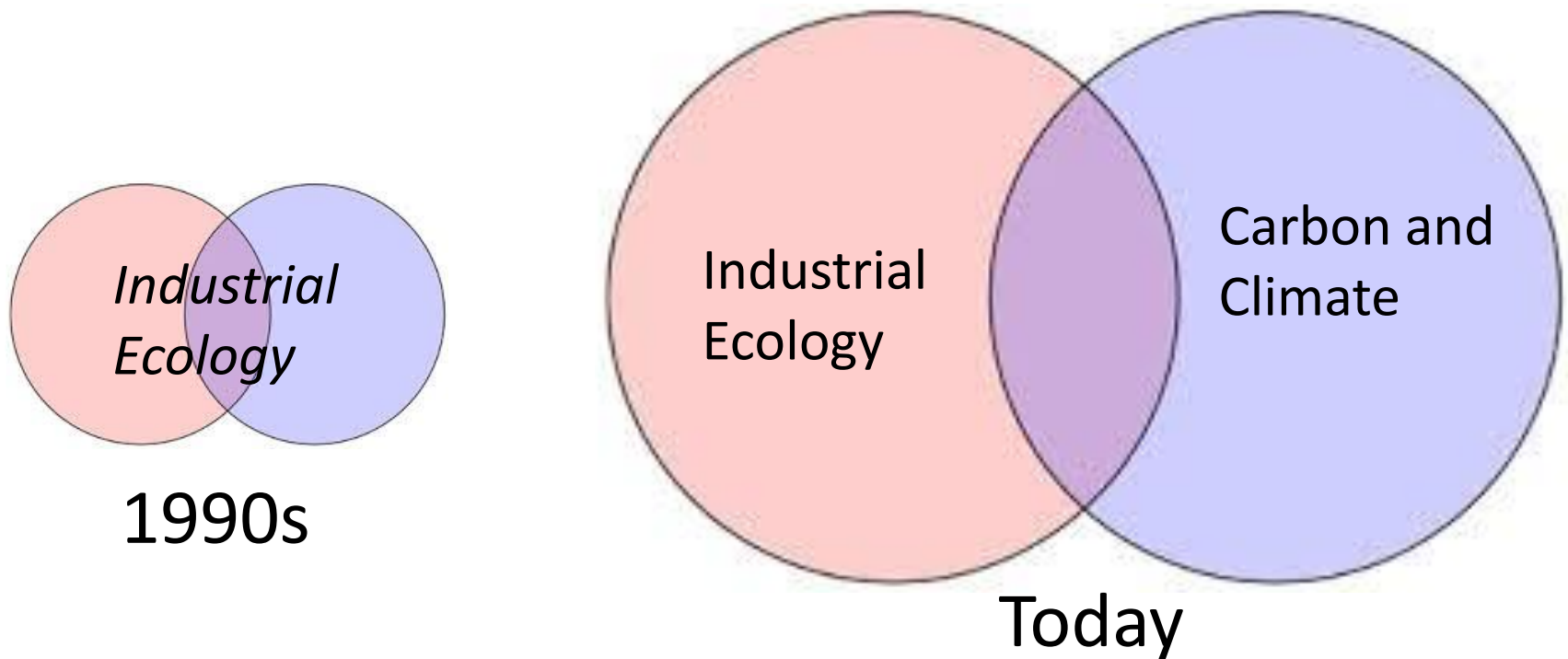
We were fascinated with multidisciplinary.

We use science to illuminate major world problems, collectively creating what Murray Gell-Mann calls “the rational underground.”

Tom and I have had the same job assignment in academia: create an innovative, interdisciplinary science and technology program in a world-class institution.

As an emeritus professor, Tom intends to engage fully, with no reduction in commitment. Welcome!

Venn Diagrams, then and now



In the 1990s, Tom and I were in the same field. Today, maybe not, even though I still work in the purple overlap region.

Preparing this talk has been a trip down memory lane.

My own homage

Industrial Ecology

Robert Ayres: IE for C, N, P, S

Bill Clark and Bob Kates: “Human dimensions of global change”: albedo and IE → Snowmass 1992

Valerie Thomas: Pb and immobilization, *JIE*, Vol 1(1), 1997

Yale 1969: my escorts out of physics to “environment”

Herb Bormann and Rick Miller, School of Forestry

Charles Walker (flows through cities), Engineering

Arthur Galston (responsibility of scientists), Biology

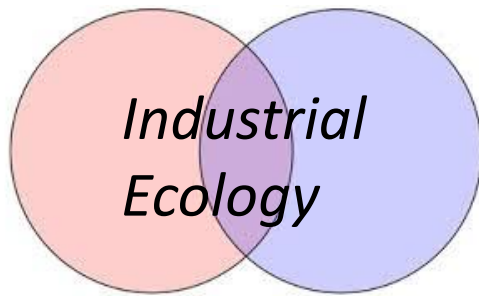
Georges May, Dean of Faculty

Yale 1996 and 2015, Deans of F&ES

Jared Cohon: championed IE, hired Tom

Peter Crane: perpetuating IE, hiring Tom’s successor

IE: A reconceptualization of environmental analysis



1990s

Design and accounting: DfE, Energy Efficiency

Cradle to grave and cradle to cradle. (Not cradle to Graedel.)

Pre-use:

Ores, co-products, reserves, “security.”

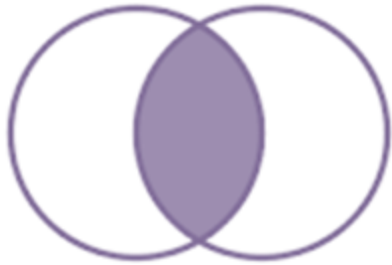
Post-use:

Damage to environment and health.

Ecology: There is no such thing as waste.

My career: Mostly C, some U and Pu. Also He, N, Pb.

IE-inspired Carbon and Climate, past 25 years



Biogeochemical stocks and flows:

Past: ice age cycles.

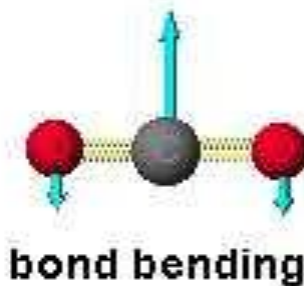
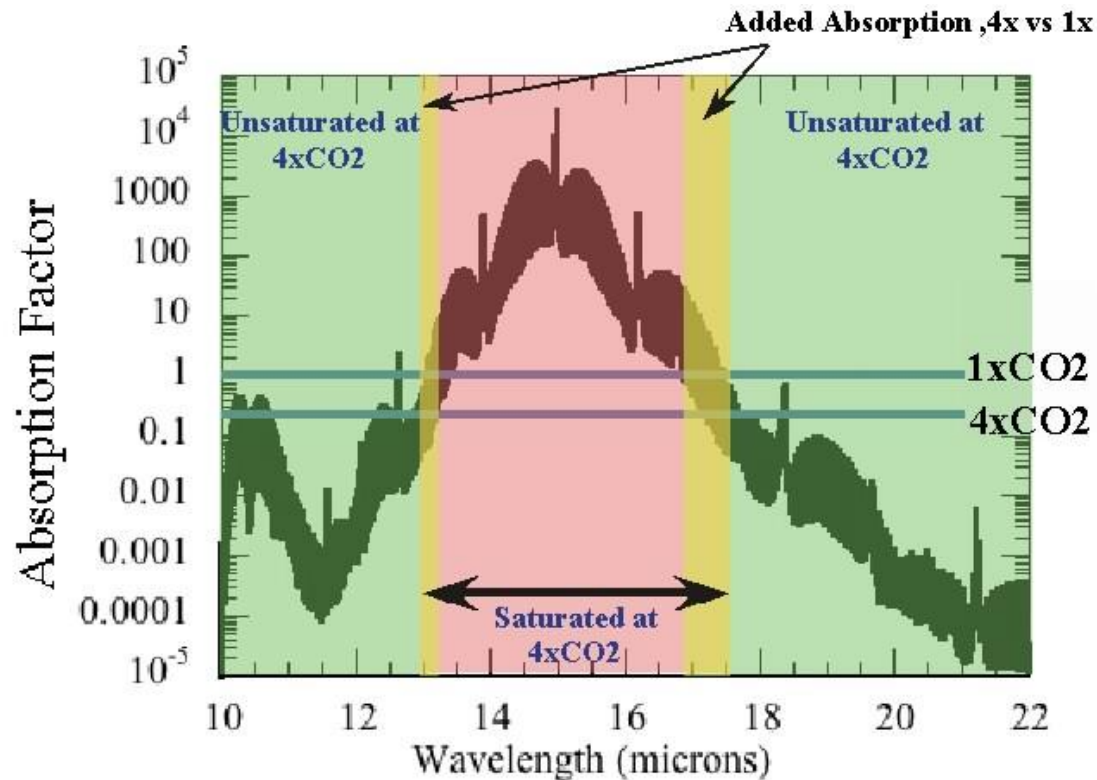
Future: land and ocean sinks.

Anthrobiogeochemical stocks and flows :

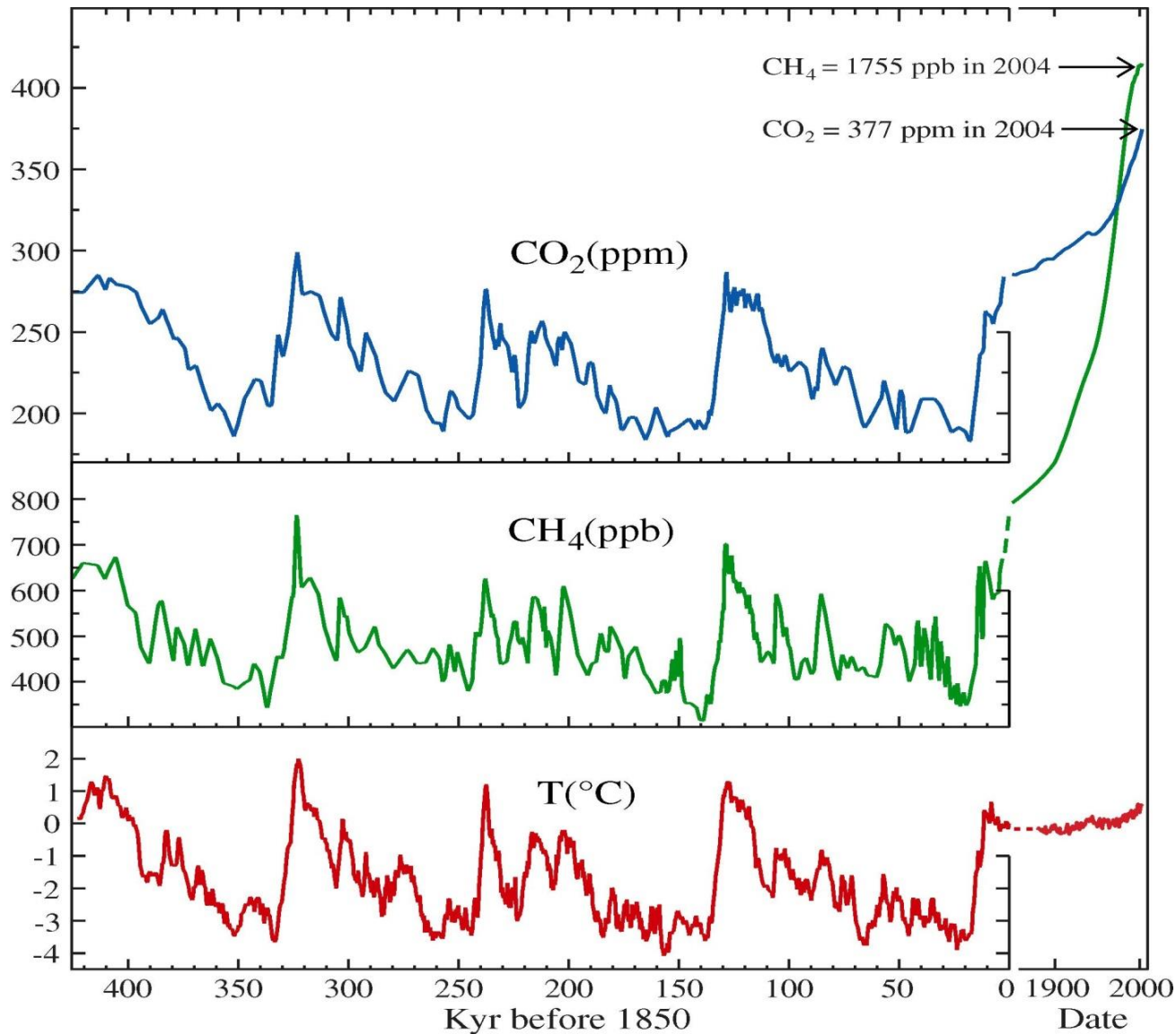
Carbon and individual consumption

CO₂ capture from waste streams, then
what? CCS, CCU, EOR.

CO₂ absorption band

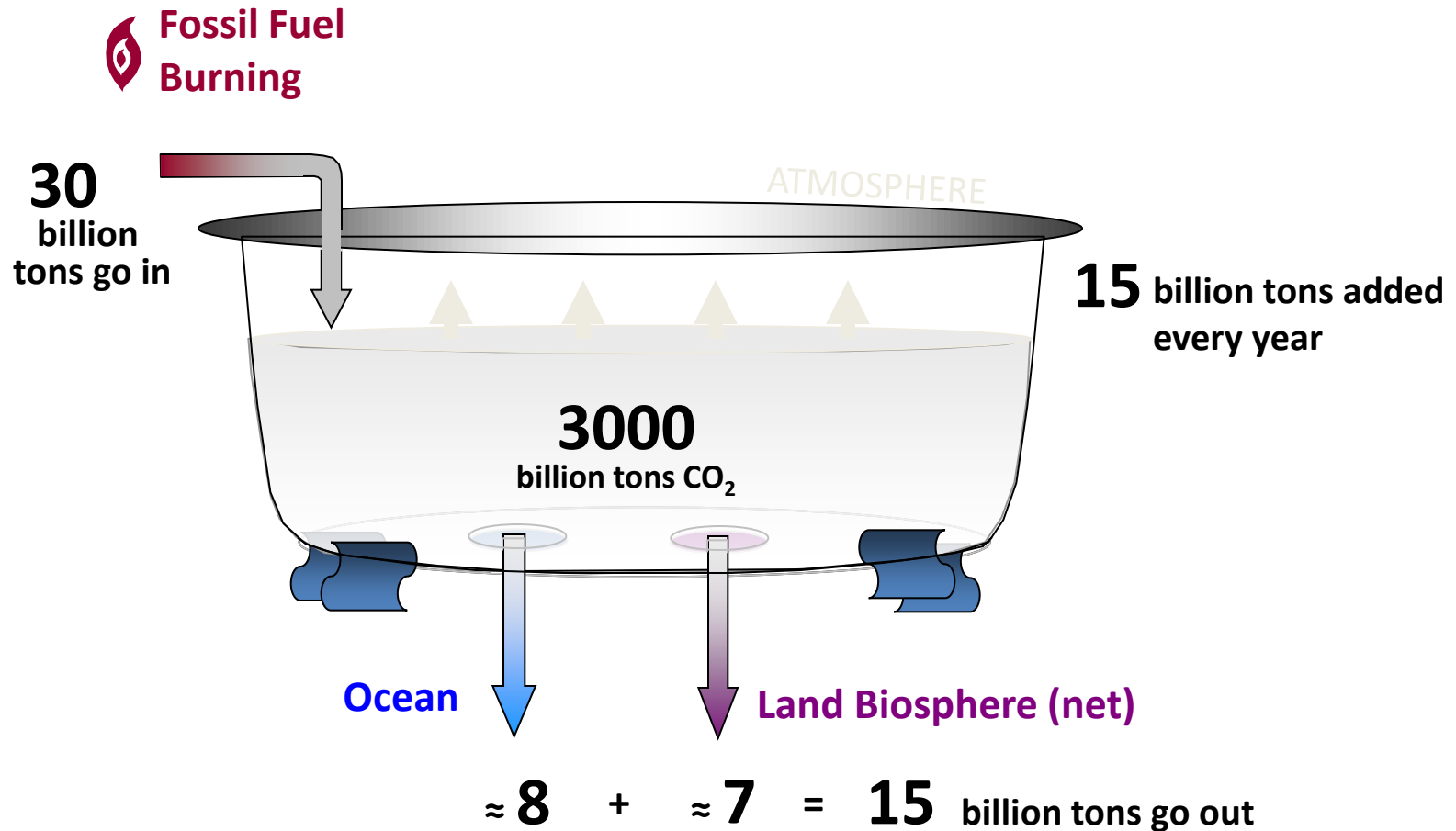


Ice-age temperature, CO₂, and CH₄ track each other



Temperature in ice-core era:
 $0.5 \times (\text{Antarctic } \Delta T)$,
0 = 1880-1899 mean.

Half of the CO₂ we put into the atmosphere doesn't stay



Today, global per-capita emissions are ≈ 5 tCO₂/yr.

Four ways to emit 5 ton CO₂/yr (today's global per capita average)

Activity	Amount producing 5 ton CO ₂ /yr emissions
a) Drive	30,000 km/yr, 5 liters/100km (45 mpg)
b) Fly	30,000 km/yr
c) Heat home	Natural gas, average house, average climate
d) Lights	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: 9 tCO₂/yr

F&ES and Yale-wide Carbon

	F&ES	Yale-wide
Cost of energy	\$400,000/yr	\$100M/yr
Carbon emissions	1200 tCO ₂ /yr	300,000 tCO ₂ /yr
Participants	600	30,000
Per-capita emissions	2 tCO ₂ /yr	10 tCO ₂ /yr

F&ES should be one of the initial “pilot units.”
Might “stuff” be traded someday?

Data in black: “Findings and Recommendations on a Carbon-Charge Program at Yale,” April 10, 2015. *Data in green: calculated.* *Data in red: Guesses.*

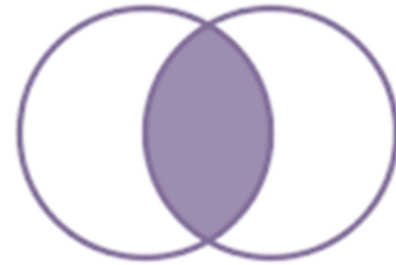
CO₂ capture from waste streams, like power plant flue gas, then what?

1. CCS: Store the CO₂ – for how long?
2. CCU: Use the CO₂ – e.g., with non-carbon energy, make a fuel. The C atom is used twice, but just twice.
3. EOR: Use *and* store it: Enhanced oil recovery: injecting CO₂ into “depleted” oil fields. Worthy?

IE-inspired Carbon and Climate: frontier

Biocarbon

Carbon budgets



Biocarbon

Biocarbon stocks:

How might managing land to maximize stored carbon affect ecological services?

Biocarbon flows:

How does using agricultural wastes (“residues”) for bioenergy affect soil productivity?

Foresters: lots to do!

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....

Conditionality for biocarbon

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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 outcomes you would decry?

Carbon budgets

The world's fourth try at framing a global climate target:

1. Emission rate at some future date
2. Concentration never to be exceeded
3. Surface temperature never to be exceeded
4. Budgets (“net cumulative emissions from now on”). IPCC, 2013.

To gain insight into budgets, extend committed emissions to “upstream” fossil fuel investments.

Budget estimates



So far:	1700 billion tons of CO ₂ have been emitted
2°C budget	1300 billion tons of CO ₂ still could be emitted)
3°C budget	another 1500 billion tons of CO ₂

The 1300 and 2800 GtCO₂ budgets correspond to 50% probability of meeting the target.

Let's simplify the bar by assuming that 1600 GtCO₂ is the size of each of its three segments.

Resource estimates



1000 billion tons of CO₂ (1000 GtCO₂) result from burning:

2 trillion barrels of oil
20,000 trillion cubic feet of gas [*factor of 1000 error in Annual Report!*]
300 billion tons of coal.

Resources in the ground, according to Rogner, in units of GtCO₂:

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.

Buried hydrocarbons: enormous resources

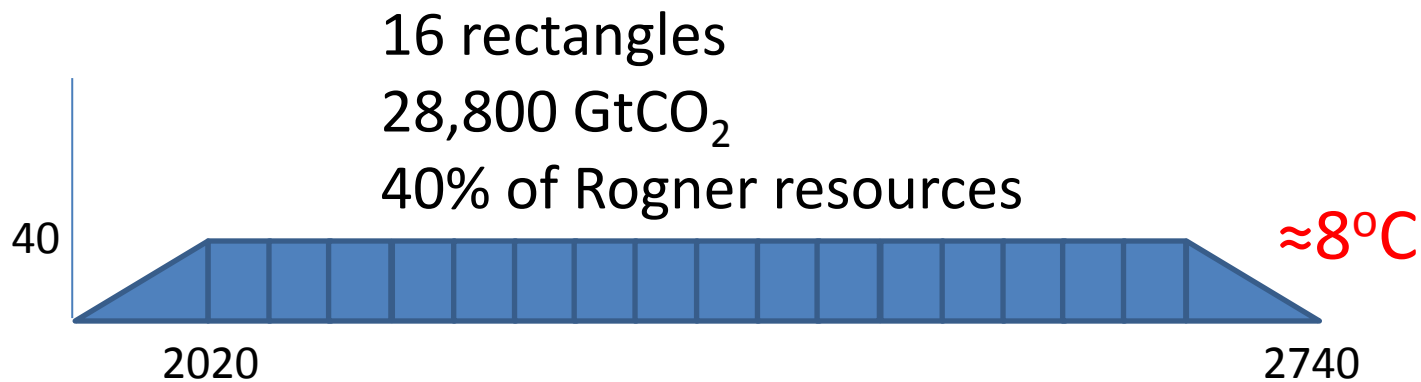
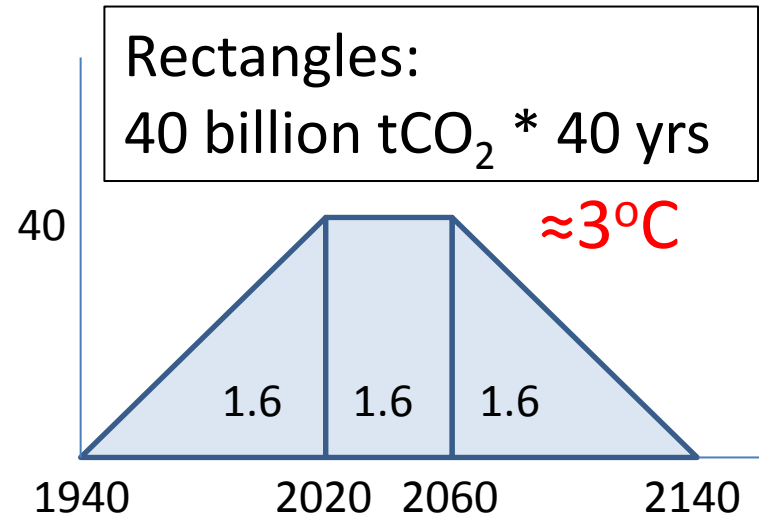
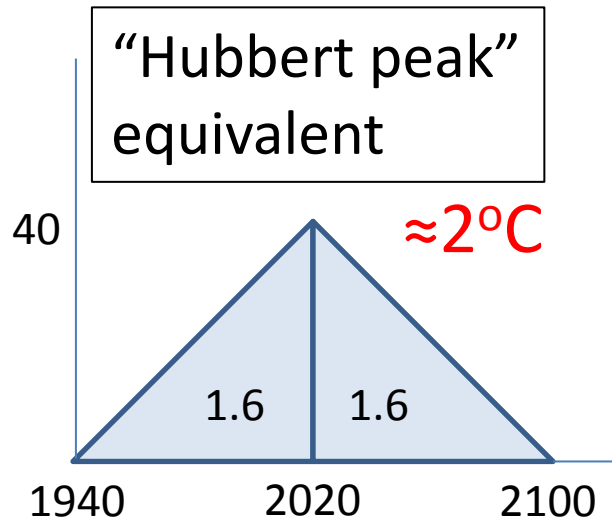
“Resources” of fossil fuels are huge. Resources become reserves over decades (not years and not centuries).

“Booked reserves” are small, in this conversation. They are not the issue. Boardroom decisions about investing in new regions like the arctic and in new countries like Oman – *are!*

Fossil fuels are so abundant that, for *any* cumulative-emissions target, even a weak one, *attractive* fossil fuel will be left in the ground.



Carbon emission trajectories



“Emissions budgets” mean choices

The budget concept leads inexorably to choices:

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?

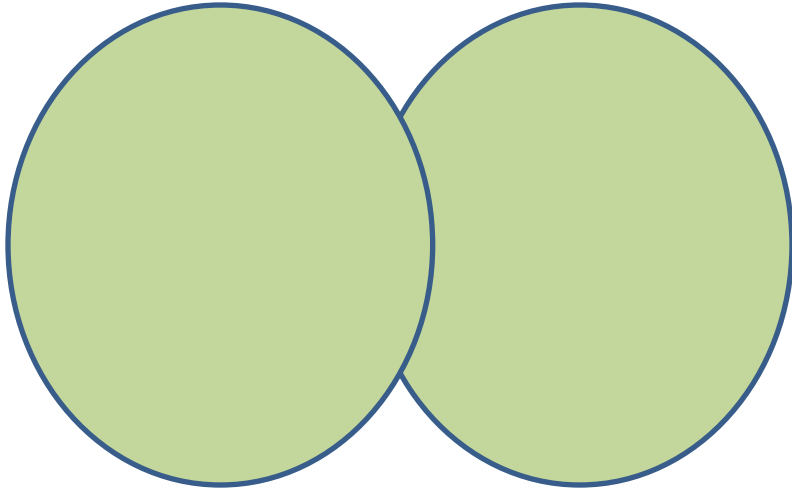
**Which fossil fuels will we judge to be “unburnable”
and leave in the ground?**

Such decision-making is unprecedented.

More scenarios and more policy in IE

“Industrial ecology will not really enter the big time until it routinely generates scenarios and discusses their policy implications.” Graedel, slide in a class lecture.

Common frontiers



Beyond per capita

Poverty

Demography

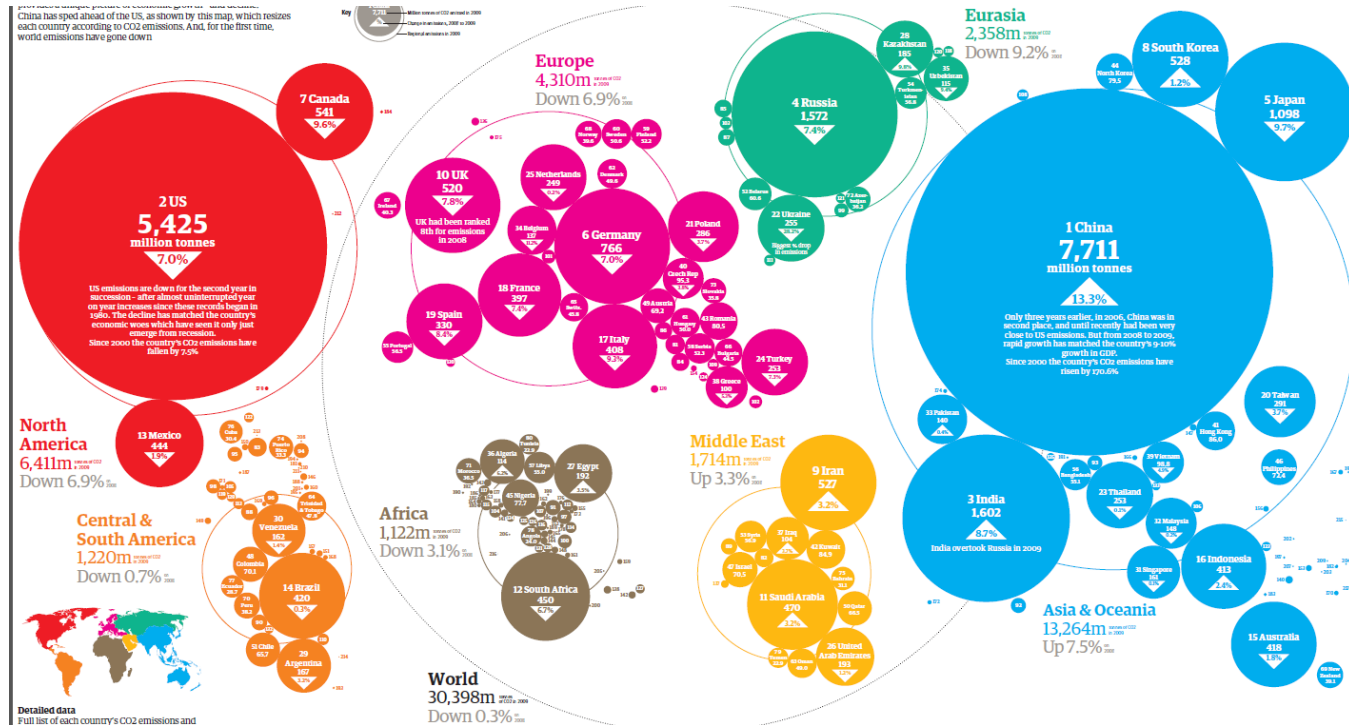
Pace of change

Extraction and Entropy

Destiny Studies

Beyond per capita

“Per capita” hides too much. We must look *inside* countries.



The North-South Impasse

Five sixths of the world population are in the “South,” *and* half of the world’s emissions are in the South.

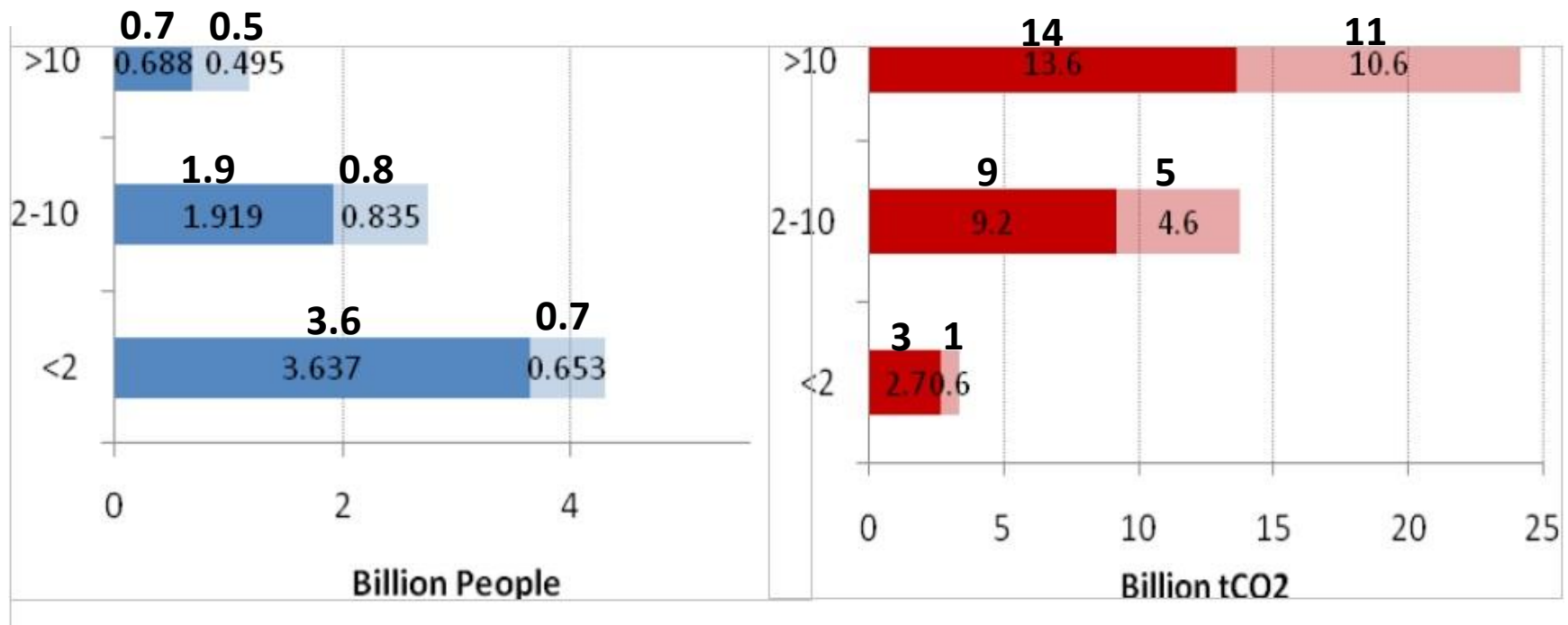
Says the South: “Our per capita emissions are negligible!”

Says the North: “Even if we go to zero, if you ignore carbon you will wreck our common planet!”

What if “common but differentiated responsibilities” were to refer to individuals instead of nations?*

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

Binning the world's individual emitters

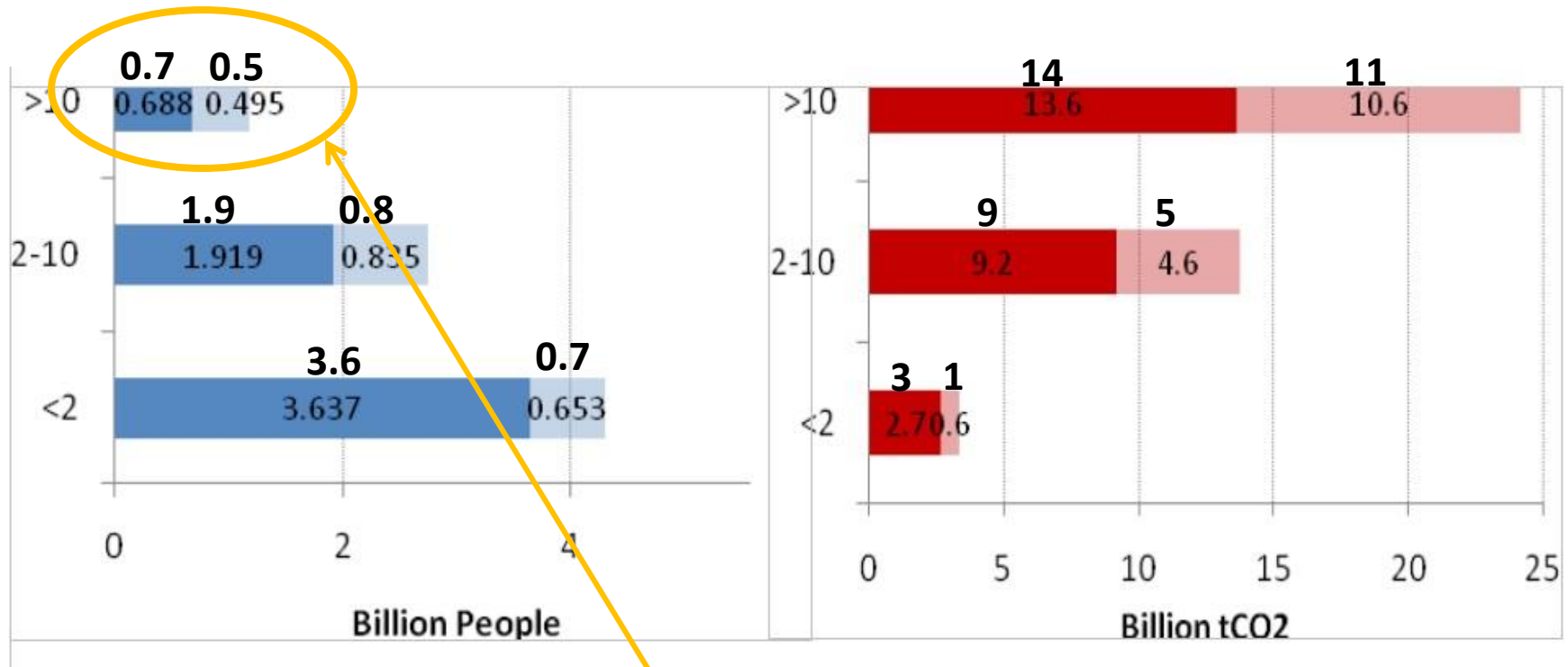


Darker parts of the bars: 2003; lighter parts, additions from 2003 to 2030. Bin boundaries at 2 tCO₂/yr and 10 tCO₂/yr are approximately the 2003 per capita values for Brazil and the EU, respectively.

Source: Chakravarty, Socolow, and Tavoni, 2009. Figure 1.

<http://www.climate-science-and-policy.eu/2009/11/a-focus-on-individuals-can-guide-nations-towards-a-low-carbon-world/>

One billion high emitters



More than half of the 1.2 billion high emitters in 2030 are projected to live outside the OECD.

Source: Chakravarty, Socolow, and Tavoni, 2009. Figure 1.

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Post-post-colonialism

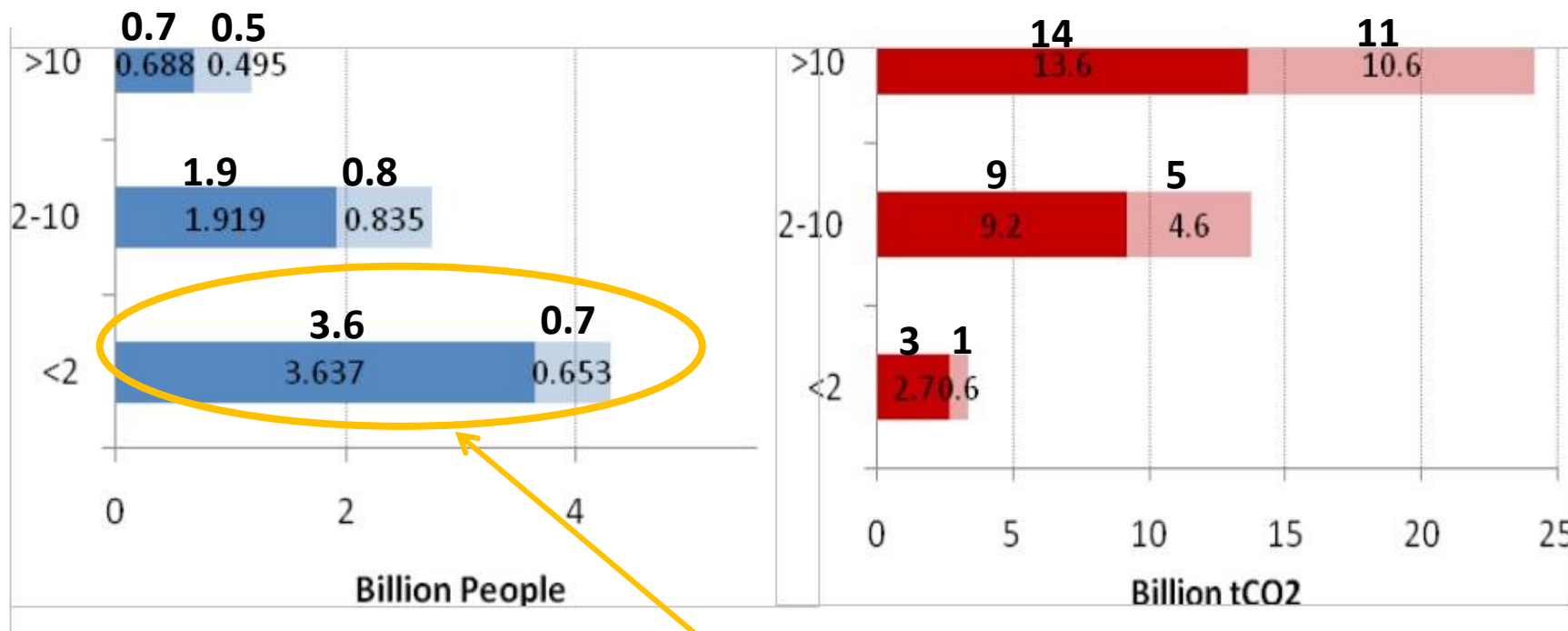
The UNFCCC, like many post-colonial international institutions, created two-tier behavior. Annex I expresses guilt and entitlement.

In the preparations for COP-21 in Paris in Dec 2015, the world is struggling to invent *post-post-colonial* institutions, where we are all in the same boat.

To what extent does IE confront similar issues?

Coinciding with the birth of IE was the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, 1989. *How well is it working?*

Poverty and Complacency



4.3 billion low emitters in 2030, 0.7 billion more than in 2003. Acceptable?

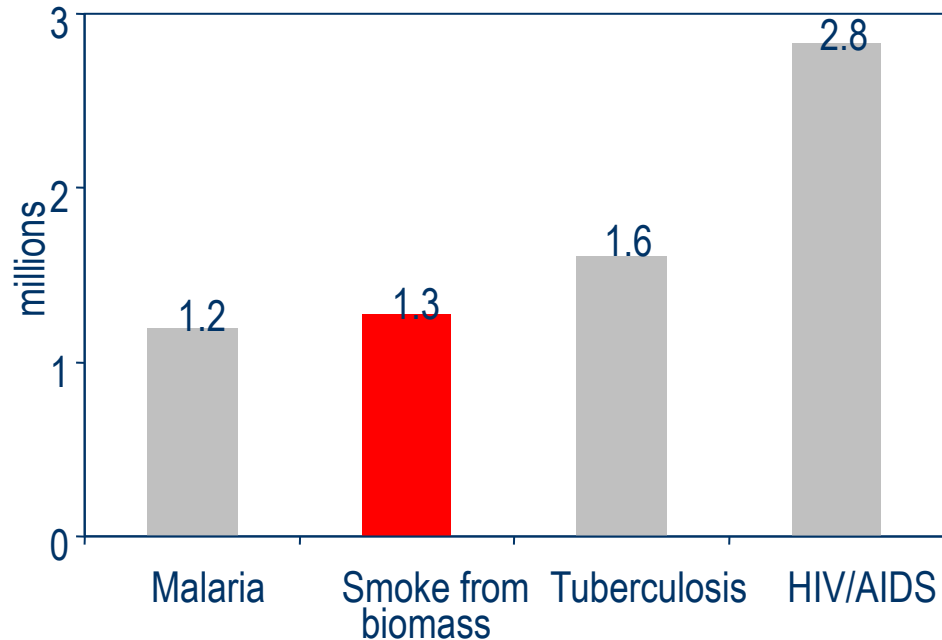
Source: Chakravarty, Socolow, and Tavoni, 2009. Figure 1.

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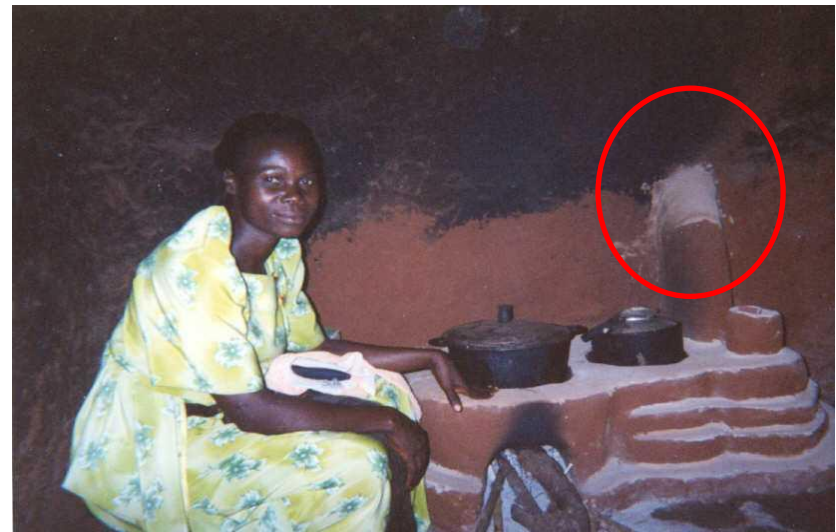
Poverty and traditional biofuels



Poverty and death from indoor air pollution

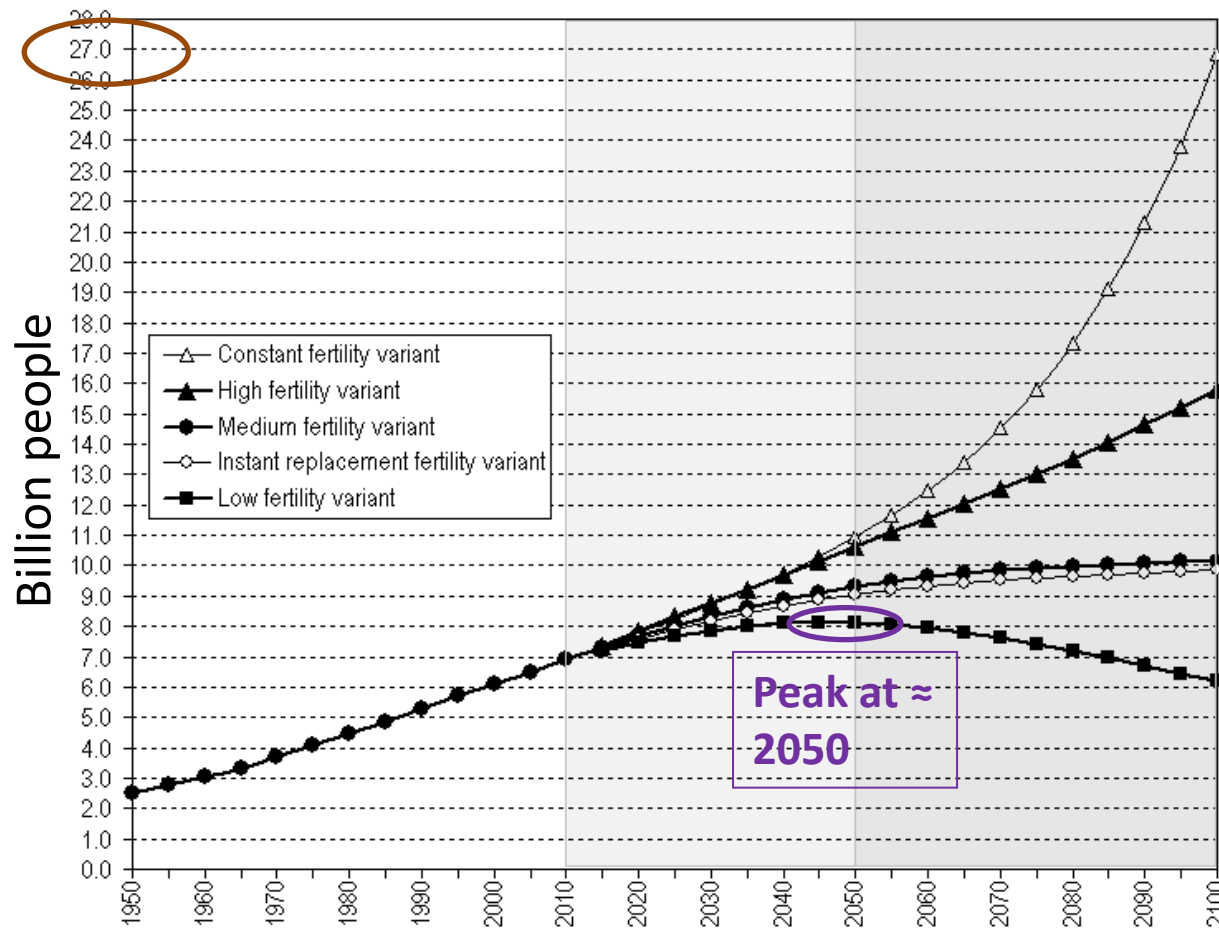


A vented stove



What IE investigations would address abject poverty?

Demography: Undervalued



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

High: 15.8, 2.6 kids/Mom

Medium: 10.1, 2.1 kids/Mom

Low: 6.2, 1.6 kids/Mom

$dPop/dt$: -0.8%/yr in 2100. If sustained, there would be 2.8 billion in 2200 and 250 million in 2500.

Pace of change: Minimally explored

How quickly change can occur?

History is useful: How quickly did automobiles displace horses, and why neither faster nor slower?

Looking ahead:

How quickly will science provide key insights (how the earth works, what is toxic)?

How quickly can a technology gain market share?

How will human values change (diet, consumerism)?

What goes wrong when change is attempted too quickly?

Entropy: A concept worth promoting

We are not running out of what is indestructible. Rather, we are rearranging the planet and undoing the gift of inhomogeneity.

Entropy measures specialness. Low entropy means special, unusual, remarkable, wonderful. Depletion increases entropy: homogenizes, produces a convergence to the mean, destroys the remarkable.

There is no zoo, there are no easements, there are not even Low Entropy Protection Master Plans to protect 1% veins of copper and 100-foot thick seams of coal from going extinct.

Waste management lowers entropy. Landfills can become remarkable mines.

Destiny Studies

It is the task of the next decades to discipline our understanding of *our collective future*. Traditional religions dwell on what happens to us as *individuals* long-term – in heaven or hell, for example. They have had less to say about what happens to humankind collectively, here on earth long-term. Imagine a new academic discipline whose domain is the art and science of looking ahead. It may be called Destiny Studies.

Yale will have a Program in Destiny Studies. IE courses will be taught in this Program.

April 2065

Imagine a day of review of industrial ecology happening in this room in April 2065.

What will the speakers highlight as key achievements of the previous 50 years? What will they acknowledge as unfinished business, requiring the attention of their successors?

I hope they will have broadened this field. If they have not tackled sustainability in its entirety, may they have made conscious choices about their field's boundaries.

Above all, I hope their successes will have provided them with a sense of fulfillment comparable to what Tom must feel right now, after a day of such moving and well deserved recognition.