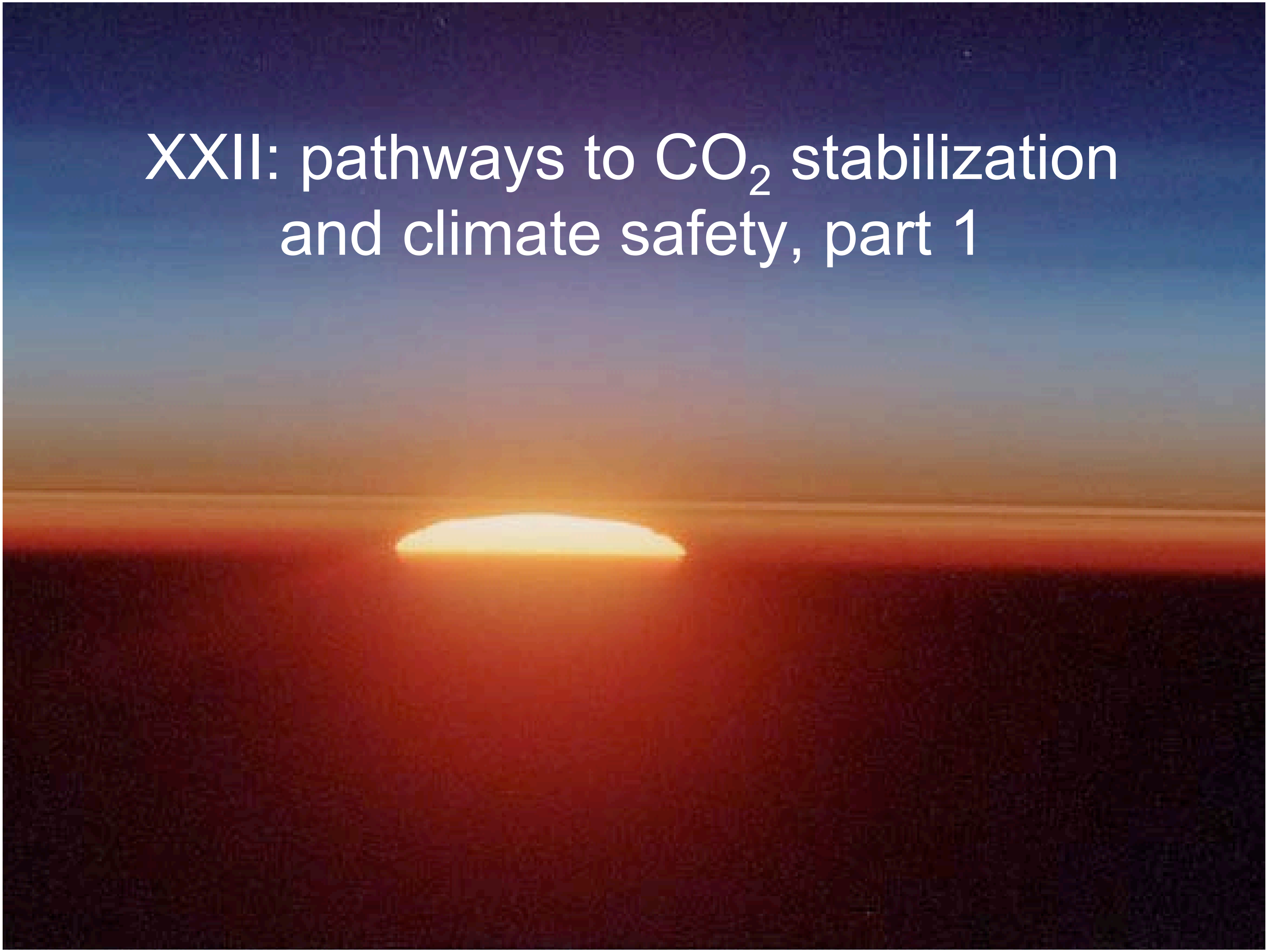

XXII: pathways to CO_2 stabilization
and climate safety, part 1

review

- energy use scales directly to GDP
- as population grows and the rest of the world tries to "catch up" with western living standards (as *per capita* GDP) the global energy demand will increase dramatically- from 15 TW now to *at least* 30 TW by 2050
- in order to meet this demand without unacceptably severe climate consequences, much of it will have to be C-free
- the problem is so big that no single strategy will work

review......

- solar has the biggest potential of the “renewables” but development is needed to become cost competitive with fossil fuels

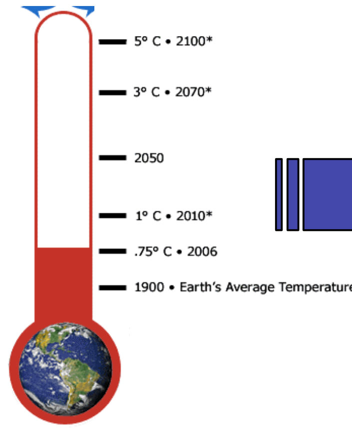
- the temptation to use coal is enormous, thus *carbon capture and sequestration* is essential

- the longer we wait to expand the supply of C-free energy, the bigger the problem because ~half of any C emitted in the interim accumulates in the atmosphere and remains there for hundreds to thousands of years......

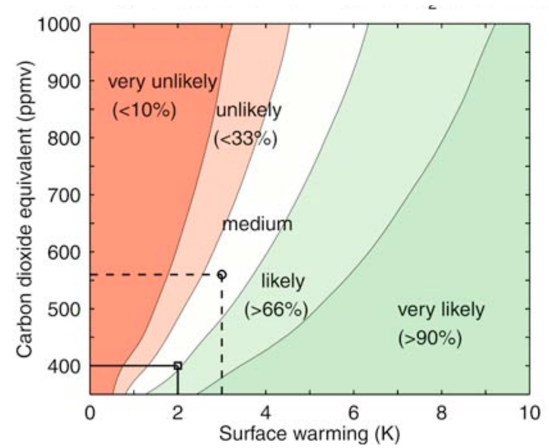
logical flow chart (according to me)

unacceptable impacts

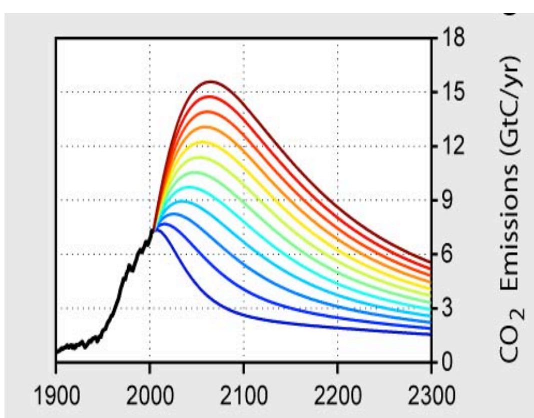
assoc. warming limit



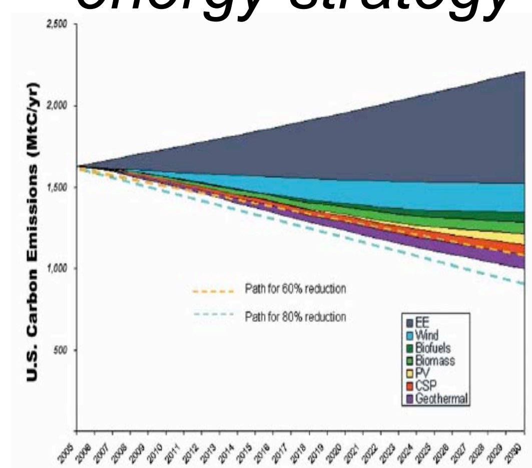
assoc. CO_2 cap



emissions pathway



energy strategy



accommodates population and economic growth

clicker poll results (from last class)

Our group consensus T anomaly (v. pre-industrial T) cap is:

a) <1 °C (0%)
b) 1 °C (15%)
c) 2 °C (21%)
d) 3 °C (61%)
e) 4 °C or more… (3%)

clicker poll results (from last class)

What particular impact was most important in determining the consensus T cap?

a) N/A (we're not worried about impacts*)
b) progressive sea level rise (and flooding)
c) ice sheet instability and sudden sea level rise
d) species loss (incr. extinction rate, incl. corals)
e) other (waiting for more options)

**with possible exception of Venus Syndrome at +10-20 W/m2*

clicker poll results (from last class)

What particular impact was most important in determining the consensus T cap?

a) N/A (we're still not worried about impacts*)
b) widespread drought (and fire)
c) grain shortages, food supply
d) sea-ice loss, albedo flip
e) lecture notes (led by nose, easier than thinking)

**with possible exception of Venus Syndrome at +10-20 W/m2*

clicker poll results (from last class)

What is the CO_2 cap implied by your chosen T cap?

a) < 400 ppm (11%)
b) 400 ppm (23%)
c) 450 ppm (37%)
d) 500 ppm (0%)
e) 550 or more (29%)

clicker poll results (from last class)

How much C-free energy (power for 1yr in TW) will be needed in 2050 to satisfy both global economic growth and CO_2 stabilization cap?

a) 5 TW or less (36%)
b) ~10 TW (22%)
c) ~ 15 TW (39%)
d) ~ 20 TW (3%)
e) 25 TW or more (0%)

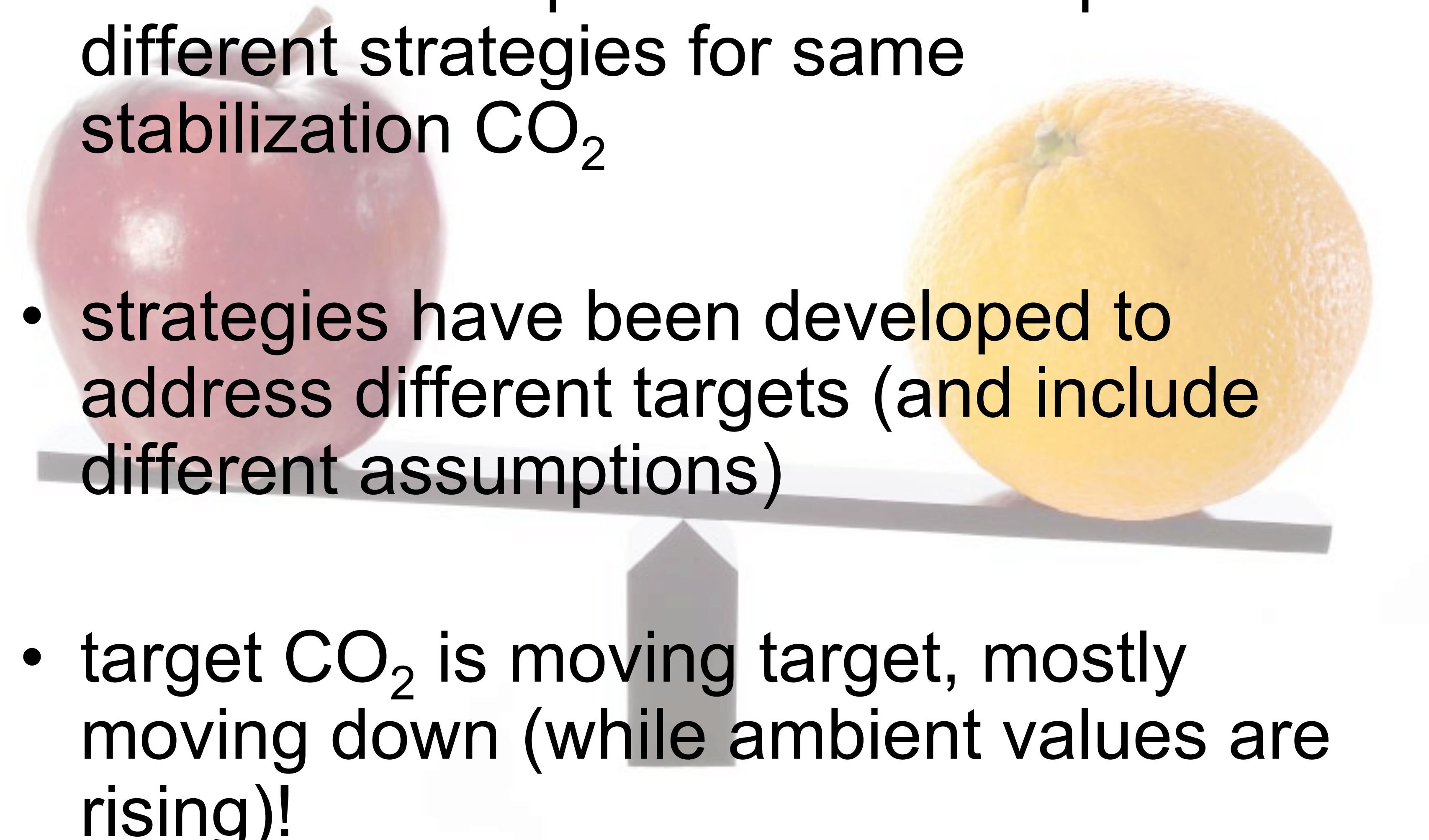
we agreed that large range of answers here results from large range of assumed future energy intensity….

outline

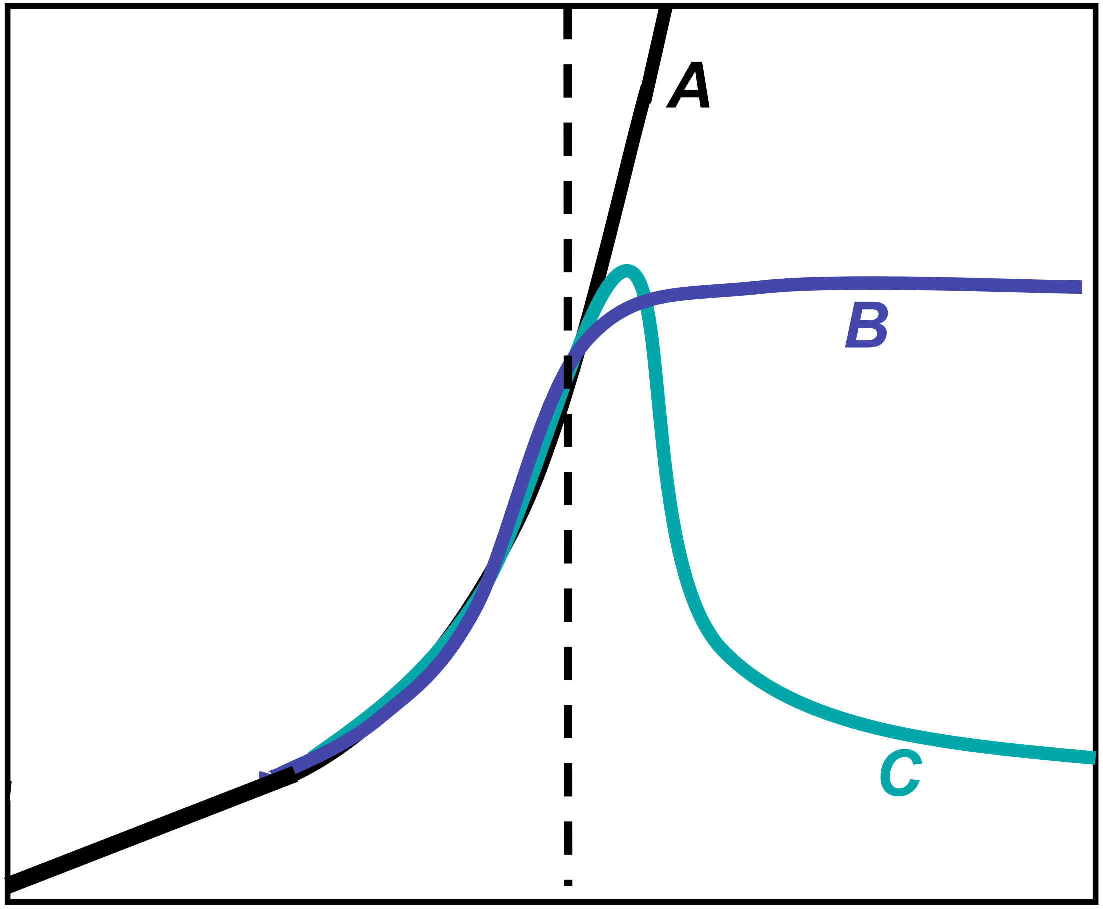
- emissions pathways to CO_2 stabilization
  - emissions schedule can vary, but every molecule counts
  - i.e., mixing ratio depends on cumulative emissions
- carbon pie
  - simple constraint on allowable emissions
  - (replacement E not specified)
- Hansen target CO_2
  - coal phase out by 2030 to avert planetary disaster
  - (replacement E not specified)
- stabilization wedges (*optimists view?*)
  - existing scalable solutions
- M. Hoffert (NYU) interview

up-front apology

- not feasible to present and compare different strategies for same stabilization CO_2
- strategies have been developed to address different targets (and include different assumptions)
- target CO_2 is moving target, mostly moving down (while ambient values are rising)!

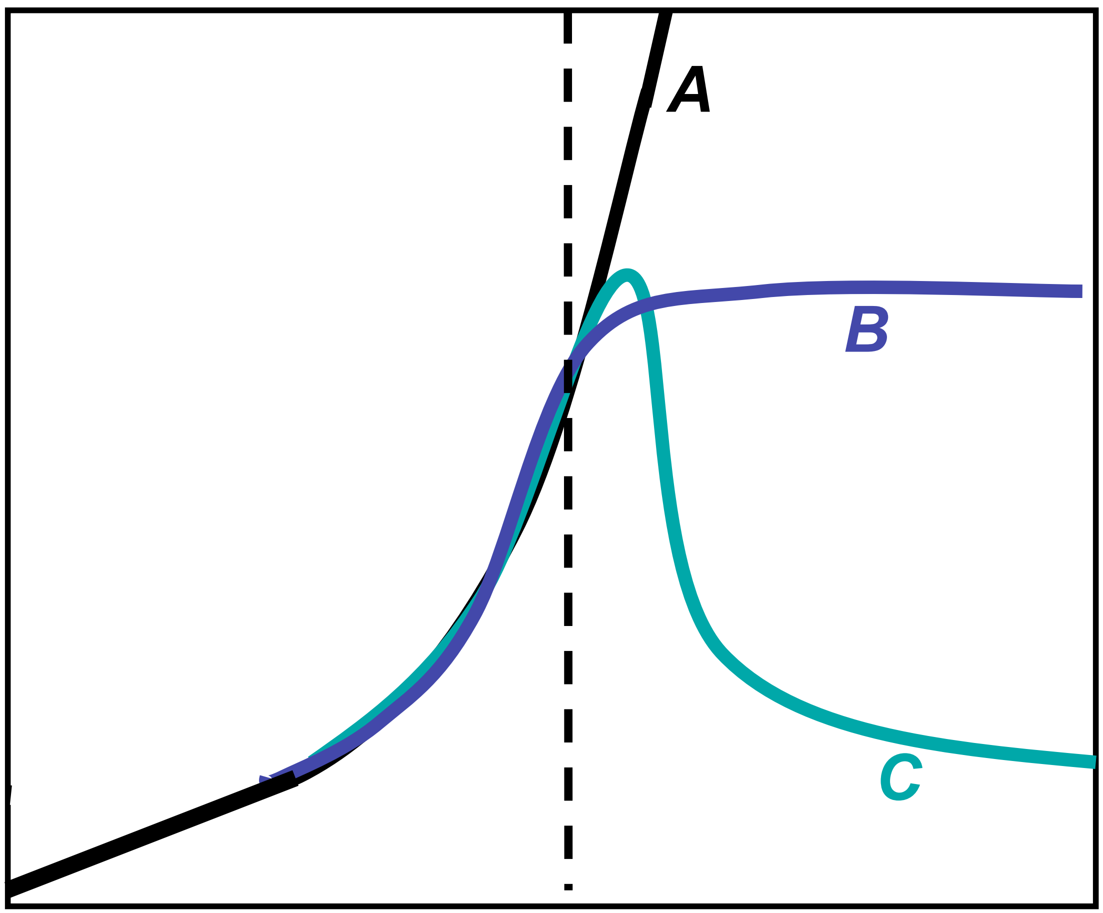


clicker question



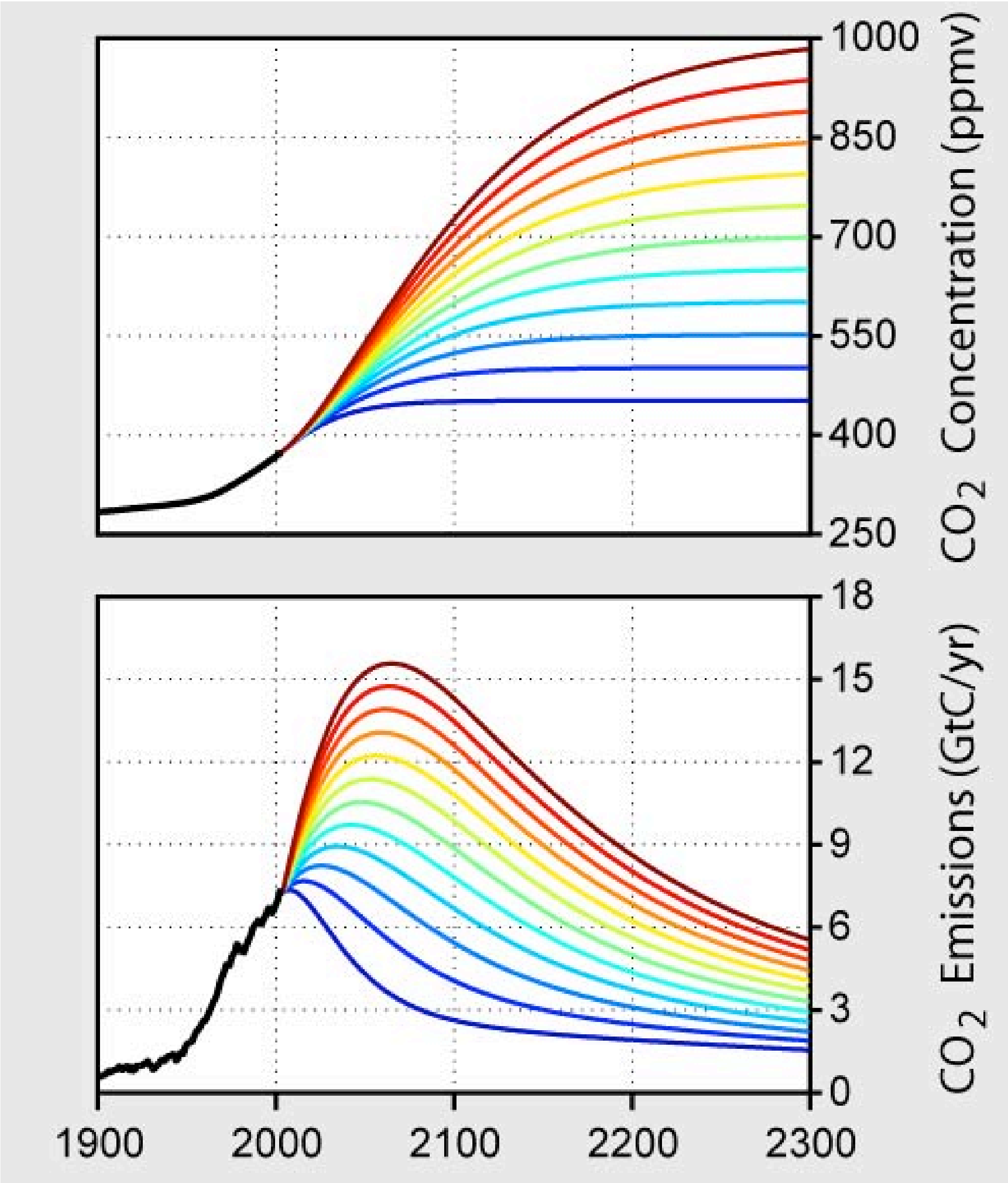
Emissions pathways to CO_2 stabilization must approximate curve A), B), C), D) any of the above, or E) can't tell without a complicated model

clicker question



For CO_2 stabilization, the emissions at the end of curve C ……..
a.) must equal steady state sinks, b.) must stabilize, c.) must fall to zero, d.) *both* a. and b., e.) can't tell without a complicated model

emissions pathways to CO_2 stabilization



- stabilization of the CO_2 concentration at any level *requires* the reduction and eventual stabilization of emissions
- this is because CO_2 has a long (10^2-10^3 yr) lifetime in the atmosphere and because emissions must eventually be balanced by sinks
- the emissions *pathway* to stabilization need not have a specific schedule, but it must add up to the same "cumulative" emissions
- thus any delay in reduction will demand steeper cuts later

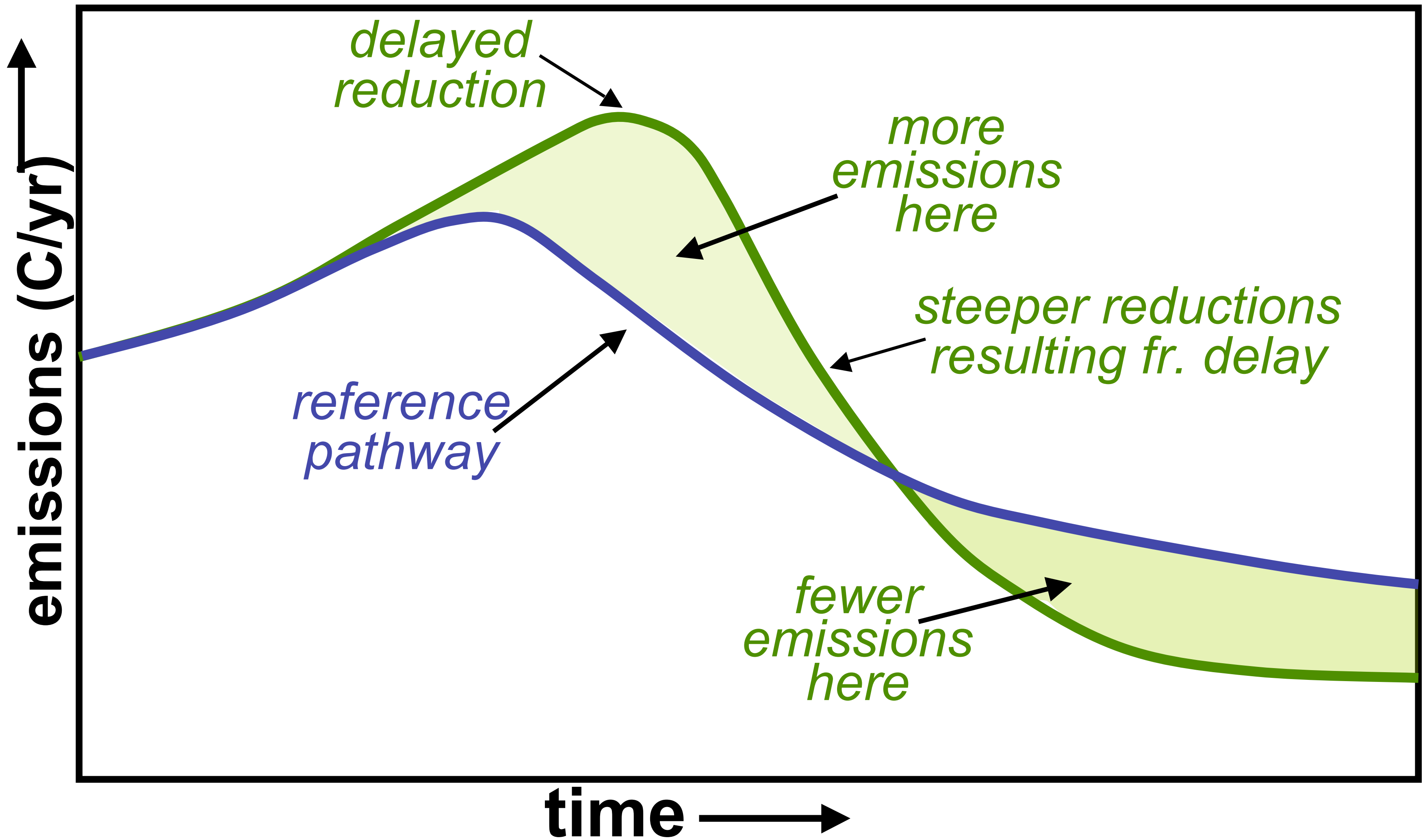
Java climate model

you can experiment with the relationship between C emissions, CO2 and climate using the simple on line model at the Url below (JCM-2004 is suggested)

in class we used the model to look at C emissions vs. C sinks for various CO_2 stabilization targets…

http://www.chooseclimate.org/jcm/index.html

2 different paths to same stabilization CO_2 concentration, same total emissions



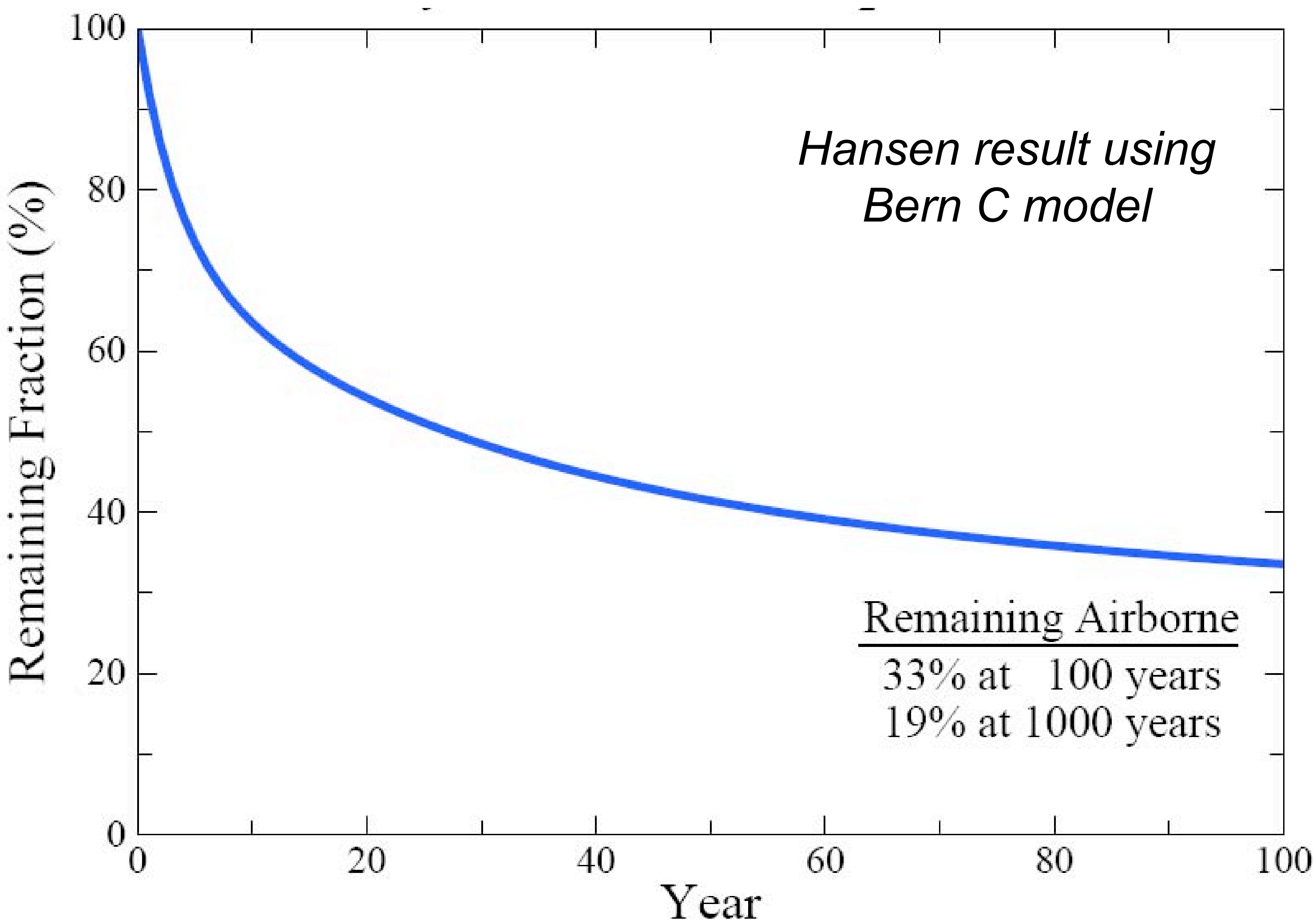
the area under the two curves (cumulative emissions) must be the same, but delayed onset of reduction means steeper & deeper reduction required later

how much emissions allowed for given CO_2 stabilization cap?

Some simple (and simplistic) CO_2 arithmetic:

What is fraction of released CO_2 remaining in atmosphere on short timescales (i.e. years to decades)?

airborne fraction of emitted pulse of CO_2



airborne fraction quickly falls to 50% (consistent with our earlier budget analysis), then decays slowly…

how much emissions allowed for given CO_2 stabilization cap?

Some simple (and simplistic) CO_2 arithmetic:

What is fraction of released CO_2 remaining in atmosphere on short timescales (i.e. years to decades)?: ~50%

Knowing this, how would we compute the influence of released CO_2 (GTC/yr) on the atmospheric increase (in ppm/yr)?

recall calculation of atmospheric conc. Δ

- mass of atmosphere in moles:

$$\frac{5.27 \times 10^{21} g}{28.97 \text{ g/moles}} = 1.819 \times 10^{20} \text{ moles atm}$$

- mass of C in moles:

$$1 \text{ GTC} = \frac{1 \times 10^{15} \text{ gC}}{12 \text{ g/mole}} = 8.33 \times 10^{13} \text{ moles } CO_2 \text{ per GTC}$$

- change in mixing ratio:

$$\frac{8.33 \times 10^{13} \text{ moles } CO_2 \text{ per GTC}}{1.819 \times 10^{20} \text{ moles atm}} = 0.46 \text{ ppm } CO_2 \text{ per GTC}$$

recall calculation of atmospheric conc. Δ

- So for every 1 GTC released, if the airborne fraction is 50% (i.e. no change in carbon cycle feedbacks), the change in CO_2 mixing ratio is 0.23 ppm

- Or, ~1 ppm per 4 GTC emitted

allowable emissions

- for 560 ppm (2x, no overshoot):

  560 ppm-385 ppm = 175ppm x 4 GTC/ppm
  = 700 GTC (global cap)

- for 450 ppm (and no overshoot):

  450 ppm-385 ppm = 65ppm x 4 GTC/ppm
  = 260 GTC (global cap)

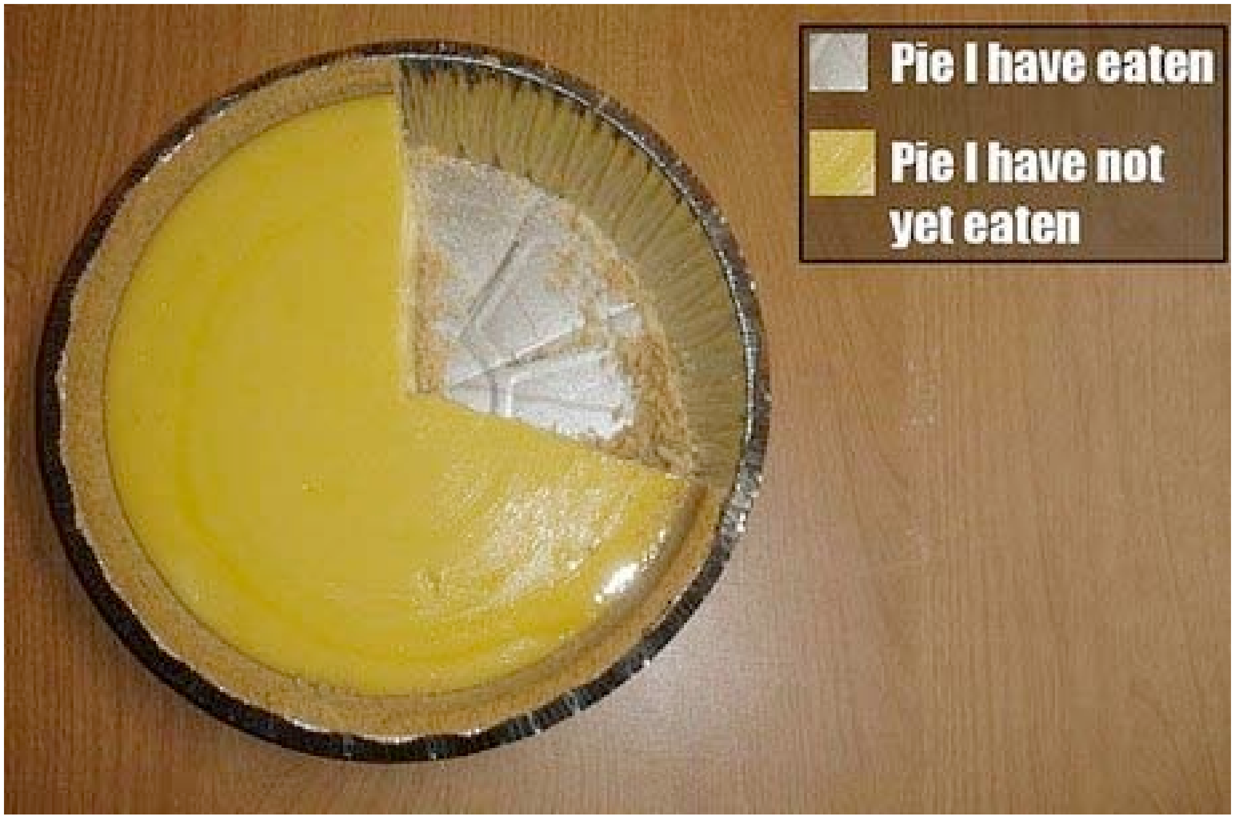
- for 400 ppm (and no overshoot):

  400 ppm-385 ppm = 15ppm x 4 GTC/ppm
  = 60 GTC (global cap)

after Broecker 2007

emissions equity

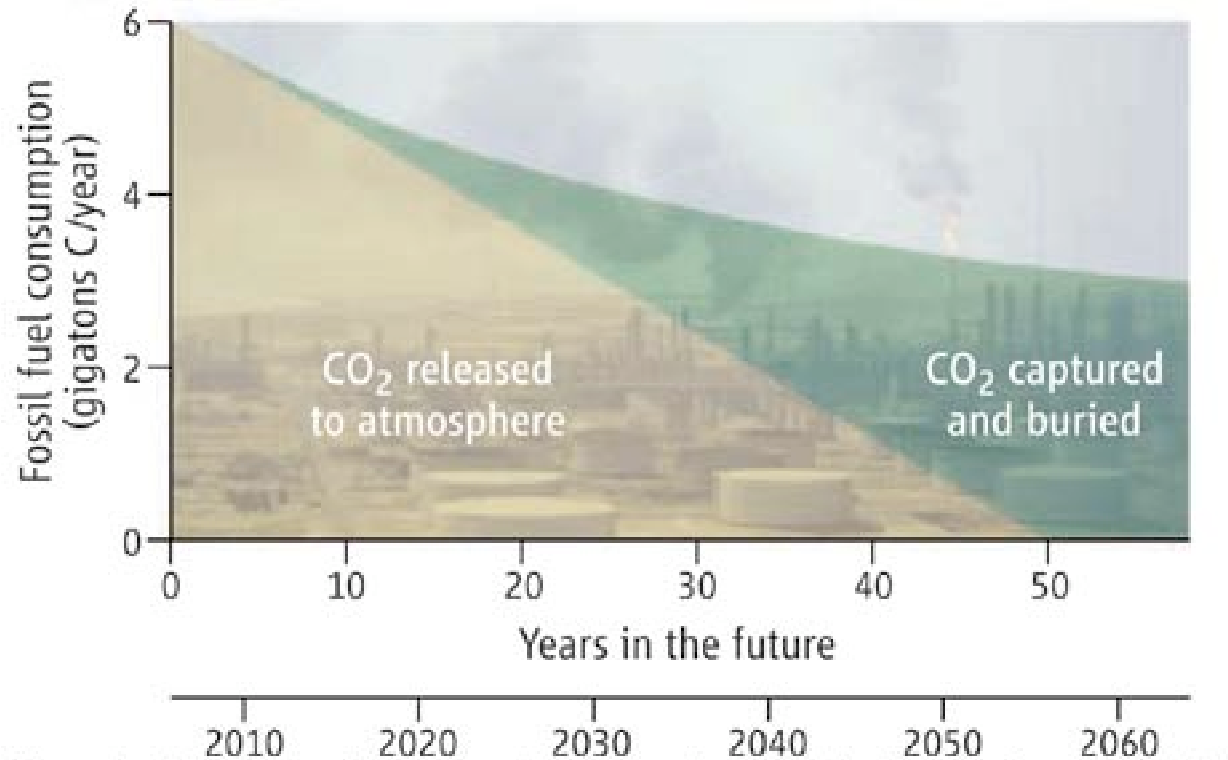
- richest countries = 20% global population



- they get 20% slice of the emissions pie?

after Broecker 2007

our slice (for *560 ppm)



*i.e. CO_2 doubling

Hypothetical scenario for use by rich countries of their 150 GTC (?) slice if the carbon pie. "The excess of fossil fuel burning over the diminishing fossil fuel use limit will likely grow, requiring an increase in the amount of C to be captured and buried"

Broecker 2007

carbon pie

Hypothetical scenario for use by rich countries of their 150 GTC (?) slice if the carbon pie. “The excess of fossil fuel burning over the diminishing fossil fuel use limit will likely grow, requiring an increase in the amount of C to be captured and buried.”

Broecker 2007

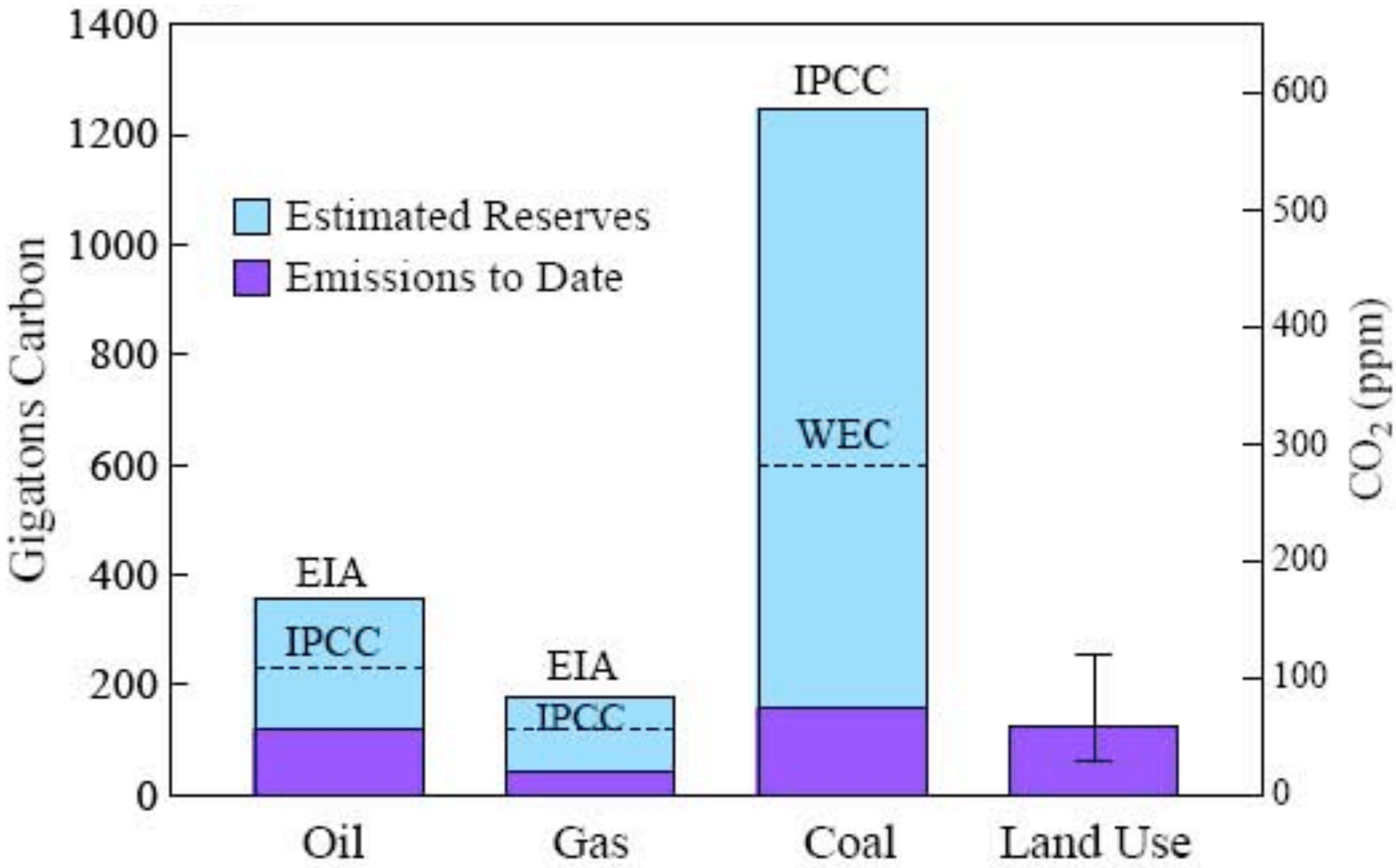
Hansen target

- Jim Hansen's target CO_2 is 350 ppm

- Why? (a more complete answer is subject of extra credit homework)

- How?
  - leave most coal in the ground (phase out existing coal plants by 2030, any new plants must incl. carbon capture & sequestration)
  - re-forestation and bio-fuel w/ sequ. & biochar (*needs to be studied*)
  - (*oil and gas take care of themselves*)

fossil fuel and net land use emissions

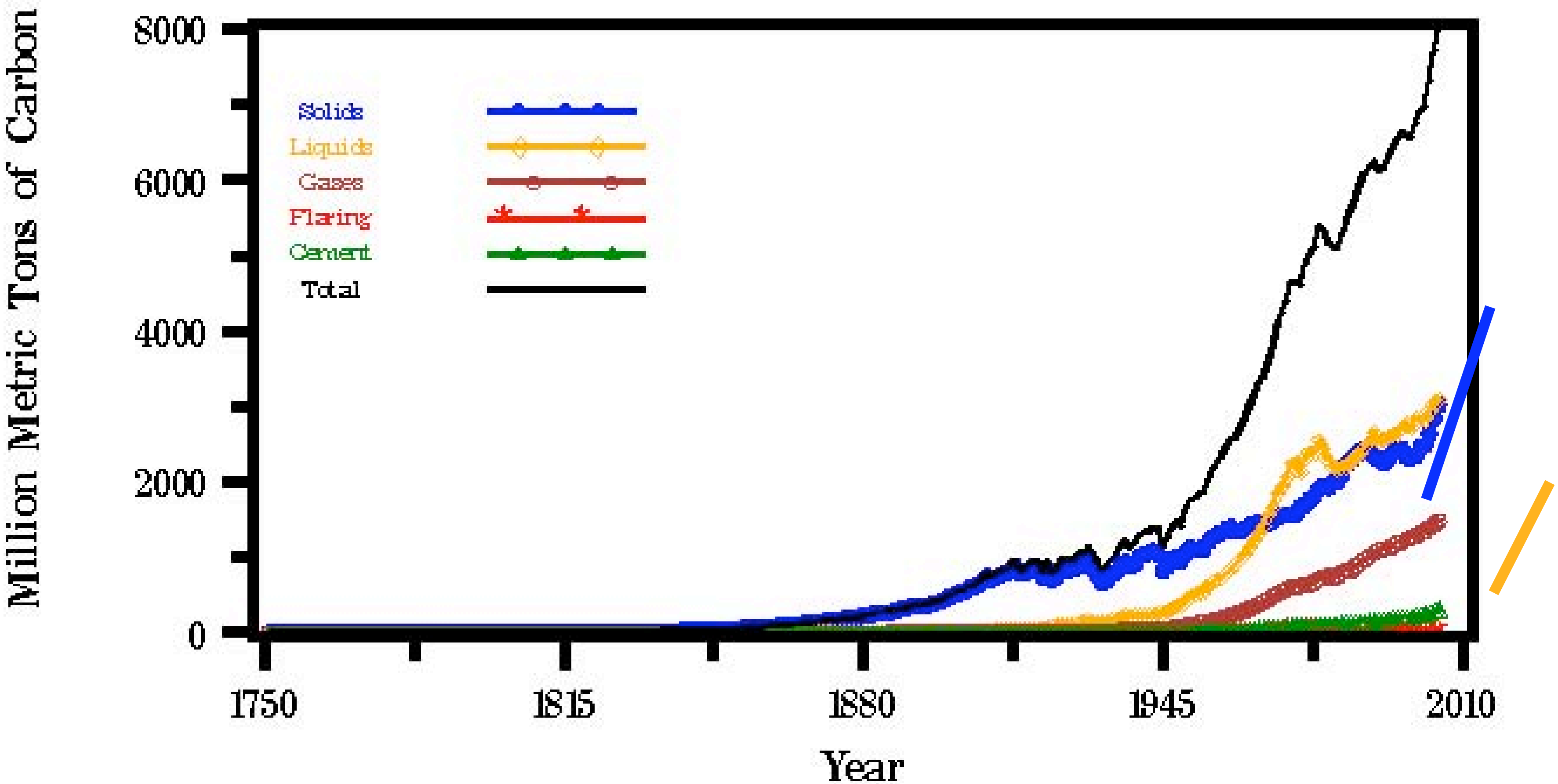


Coal is by far largest potential source of fossil fuel energy- enough for several centuries. Liquids and gas reserves are finite on scale of decades.

Hansen et al. 2008

WEC= World Energy Council

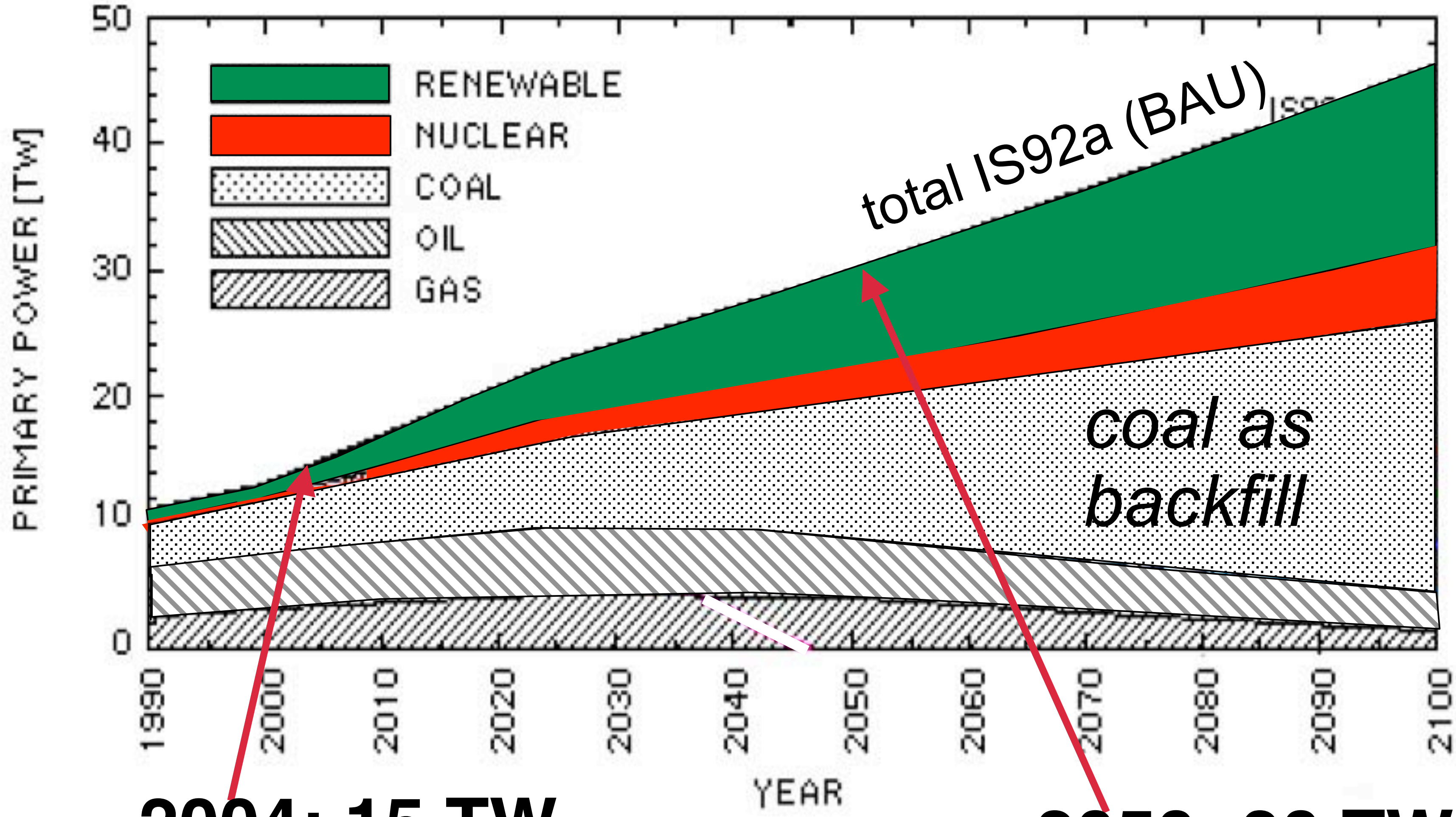
emissions by fuel type



Emissions from coal burning is currently 3 GTC/yr.
Same for oil. Natural gas is 1.5 GTC/yr.

http://cdiac.ornl.gov/trends

recall projected energy by source IPPC BAU



2004: 15 TW

1.05 TW renewable/hydro

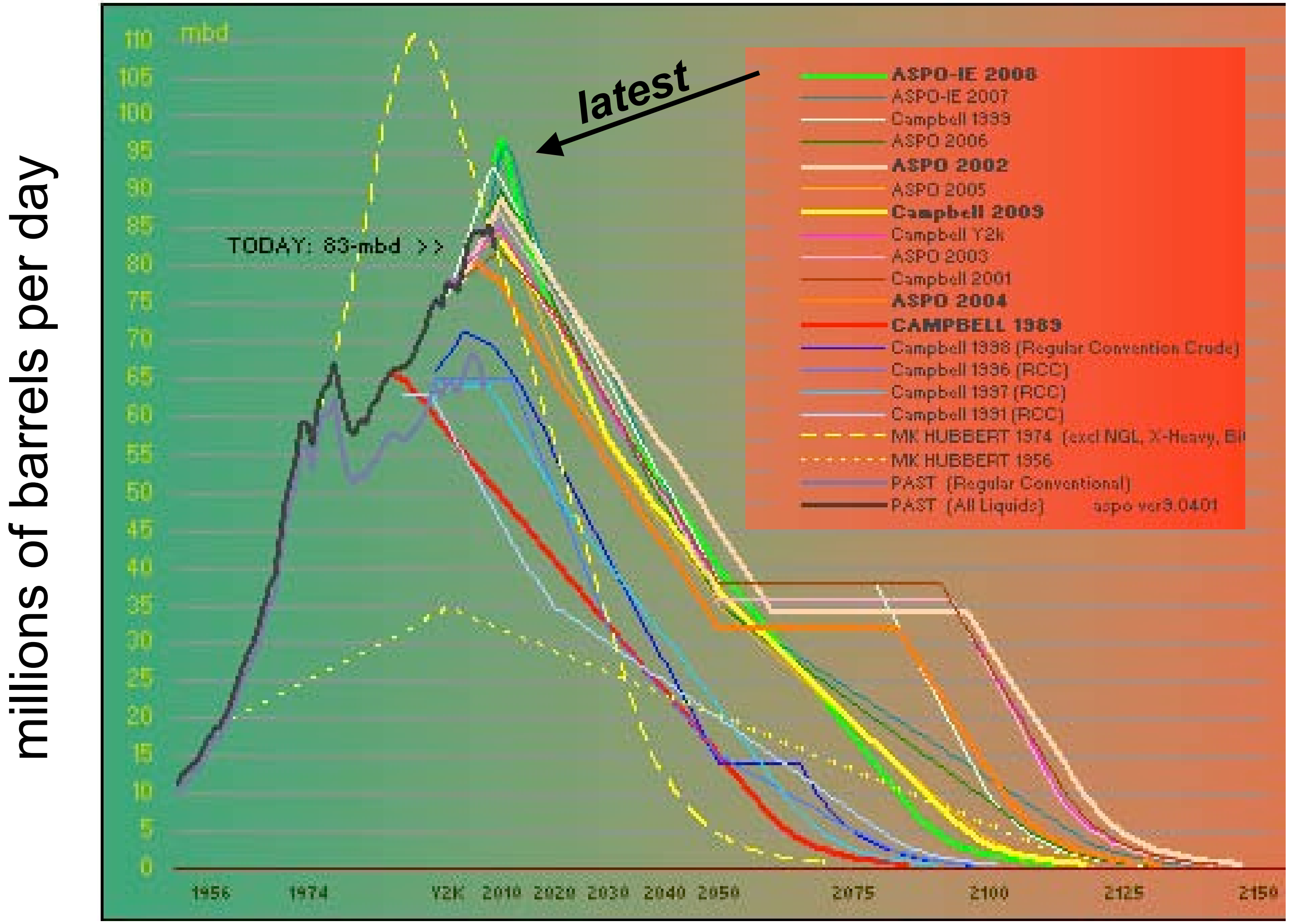
0.92 TW nuclear

2050: 30 TW

~ 8 TW renewable

~ 2 TW nuclear

peak oil



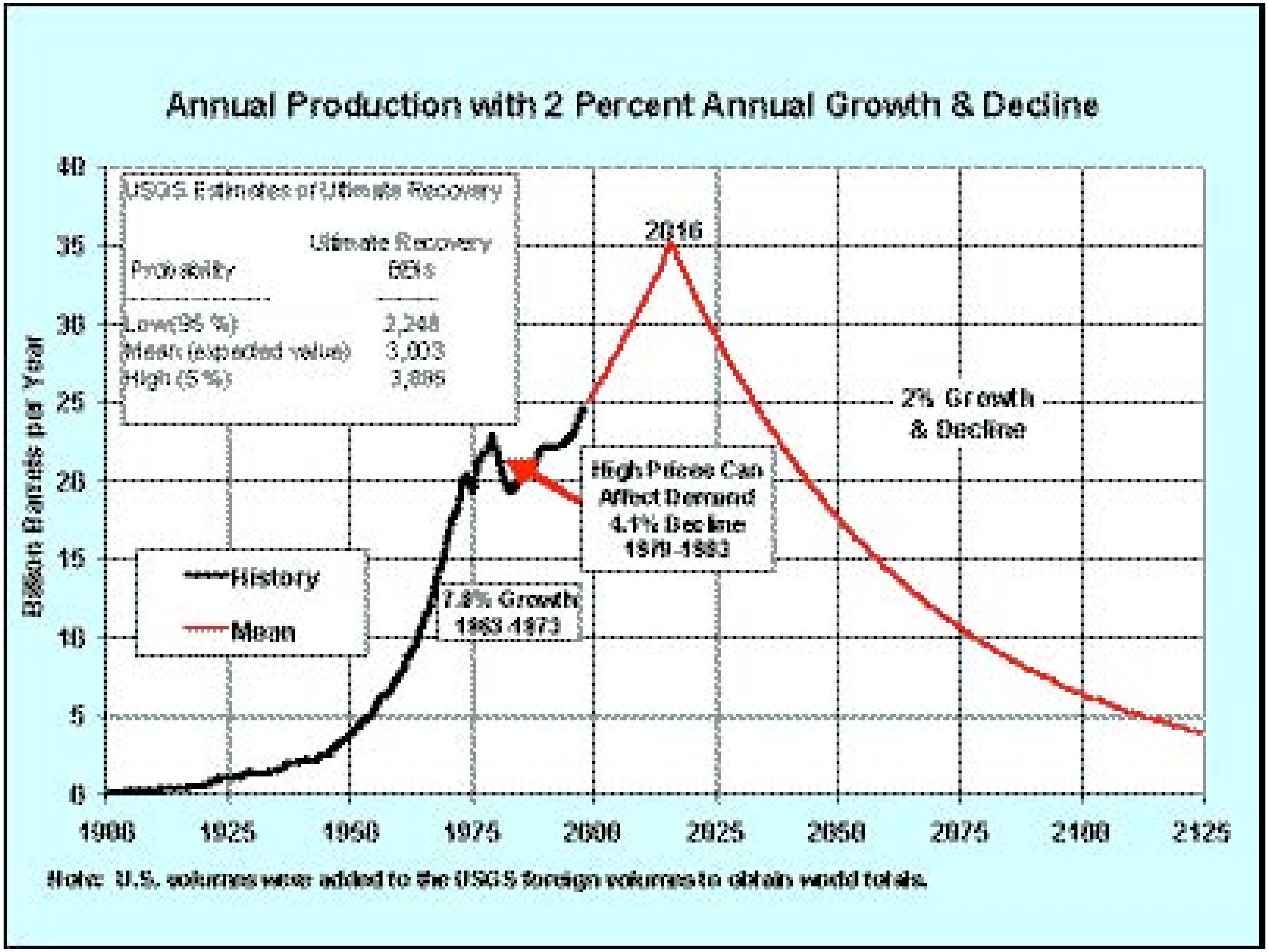
A recent compilation of estimates for rise and fall of oil production…

www.trendlines.ca

ASPO- Assoc. for Study of Peak Oil and Gas

peak oil

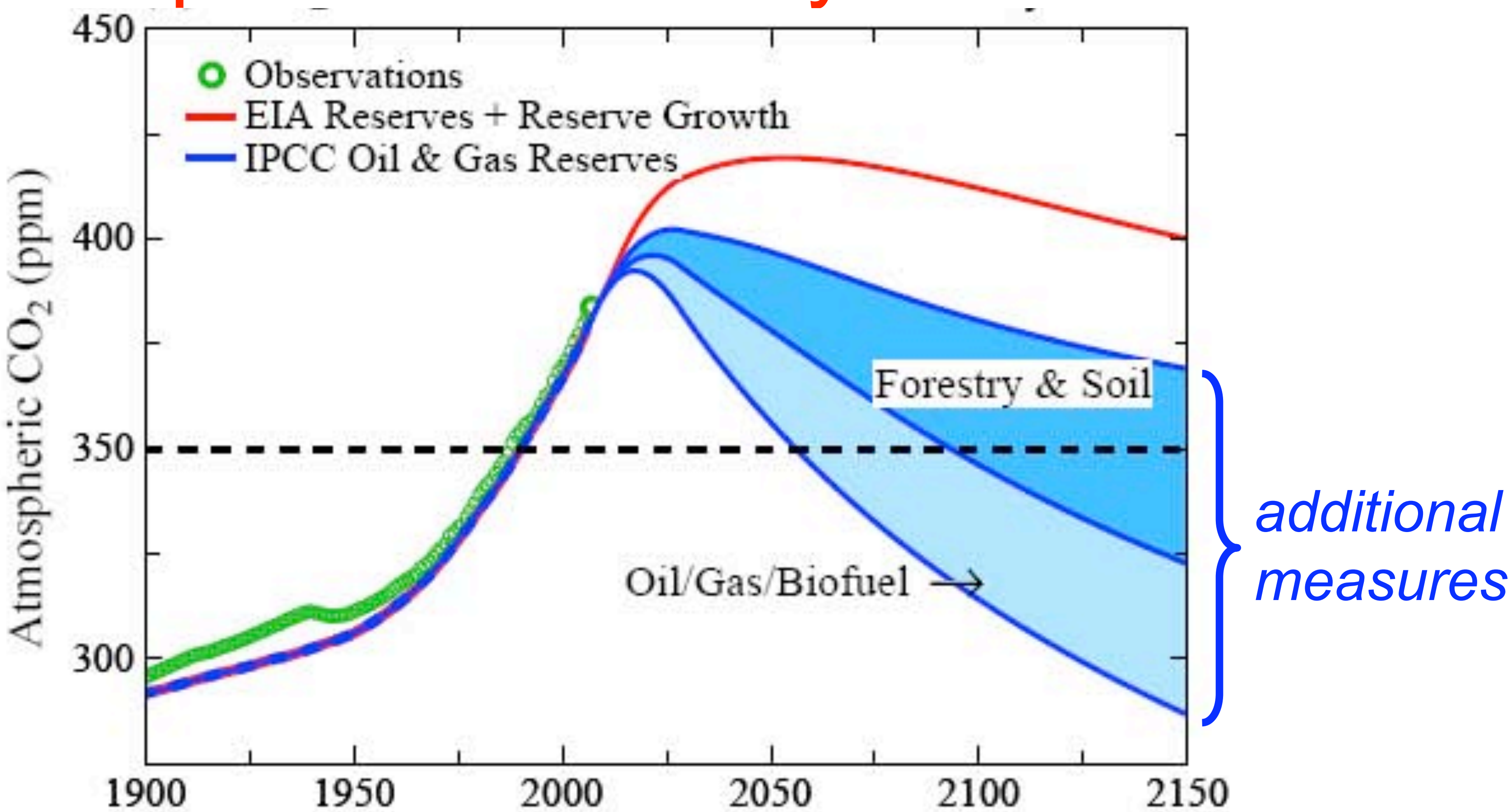
billions of barrels per year



EIA 2000 estimate of peak oil portrays decline of 2%/yr after peak in 2016. If peak is higher, post-peak decline will be steeper (6-10 %/yr).

www.trendlines.ca

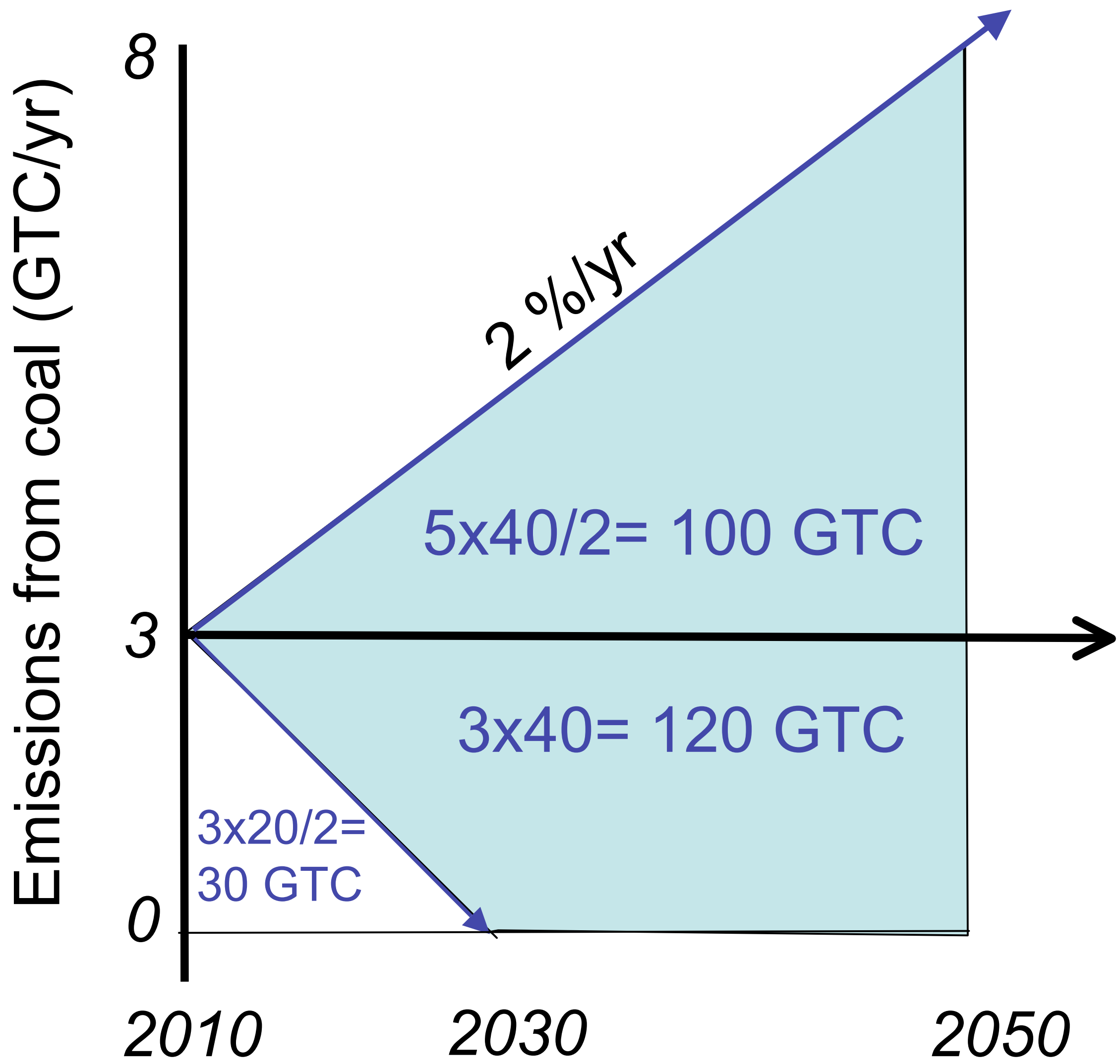
phase out coal by 2030



Hansen's projection of atm. CO_2 assuming coal phase-out by 2030 plus peak and decline of oil (and gas) for two different estimates of oil and gas reserves. If we leave most of the coal in the ground, we have a chance of stabilizing CO_2 below 425 ppm. *If not, we don't…*

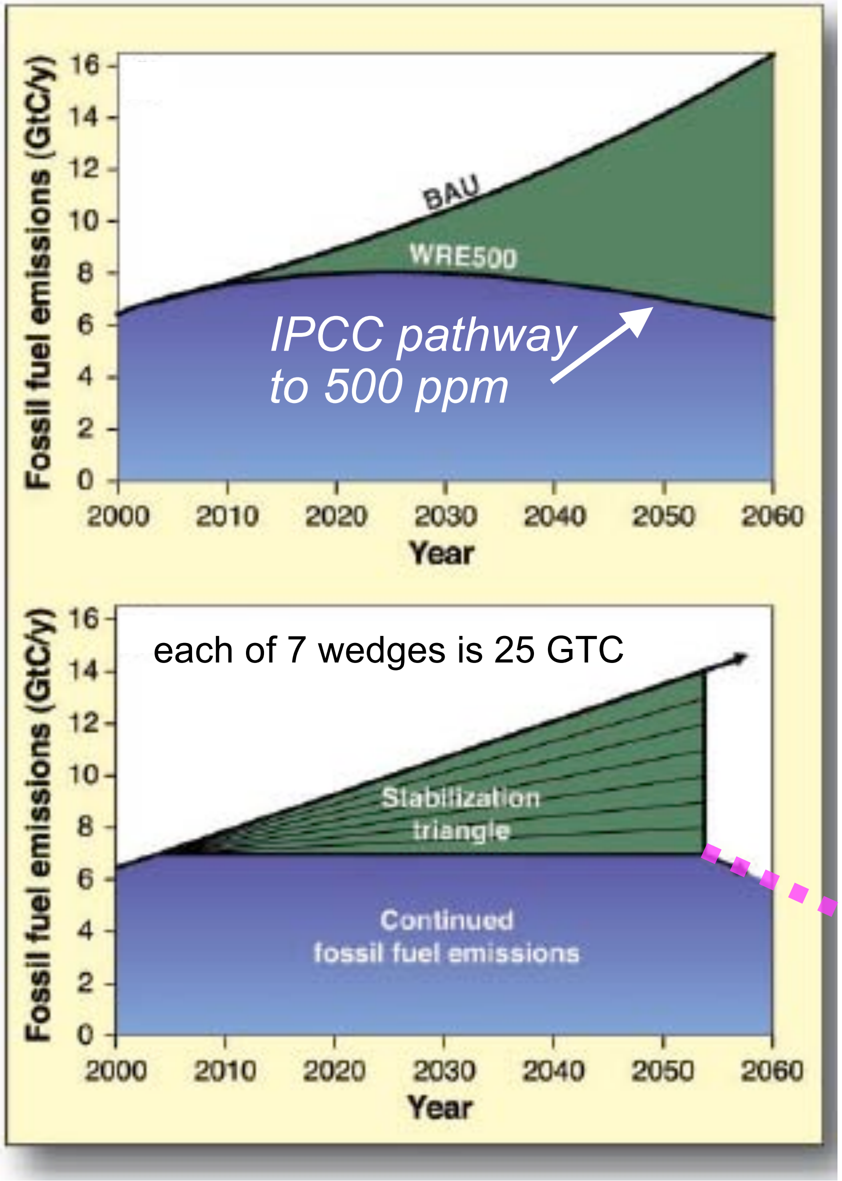
Additional measures needed to lower CO_2 to 350 ppm.

coal emissions….



The difference between 2%/yr growth (BAU) in coal burning vs. coal phase out by 2030 is ~200 GTC by 2050.

stabilization wedges



- difference between BAU and emissions needed to stabilize CO_2 at 500 ppm can be approximated by a flat-bottomed triangle out to ~2050

- area of triangle is:
  (14 GTC/yr-7 GTC/yr) x (50 yr) / 2
  = *175 GTC of avoided emissions*

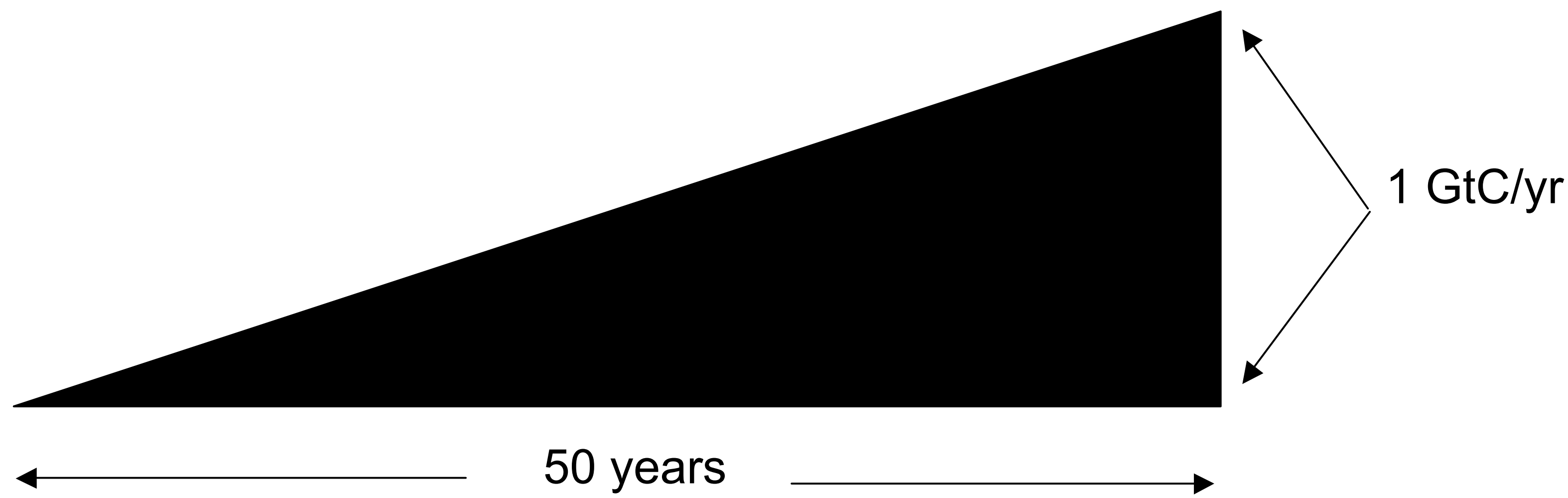
- the stabilization can be achieved now (*maybe*) with present techonology, providing 50 yrs for development and deployment of new energy technologies

- *emissions must then drop by another 2/3 between 2050-2100 to achieve stabilization at 500 ppm*

Pacala and Socolow '04

what is a "wedge"?

A "wedge" is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr. The strategy has already been commercialized at scale somewhere.

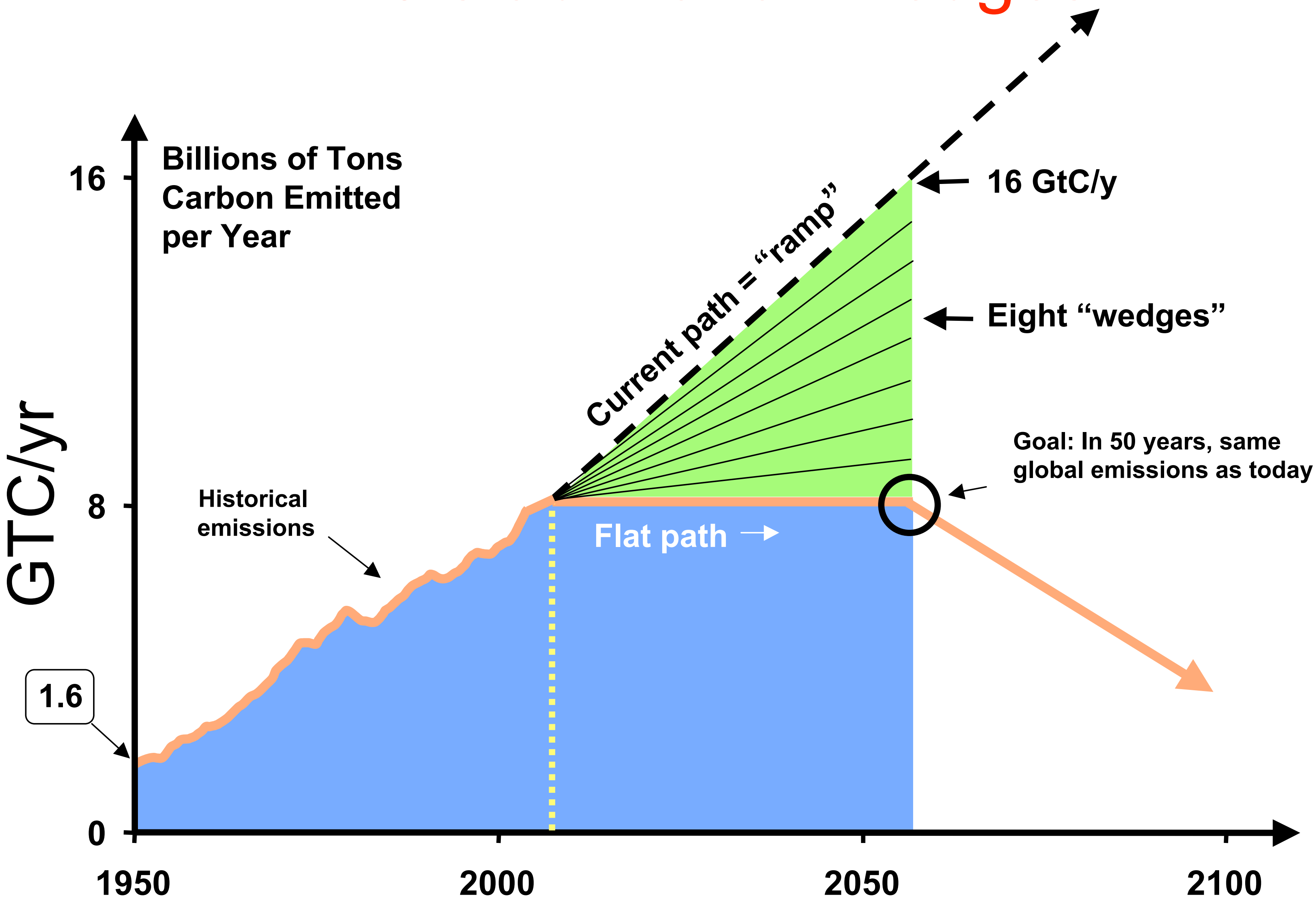


Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years. This is 2.5 trillion dollars at $100/tC.

A "solution" to the CO_2 problem should provide at least one wedge.

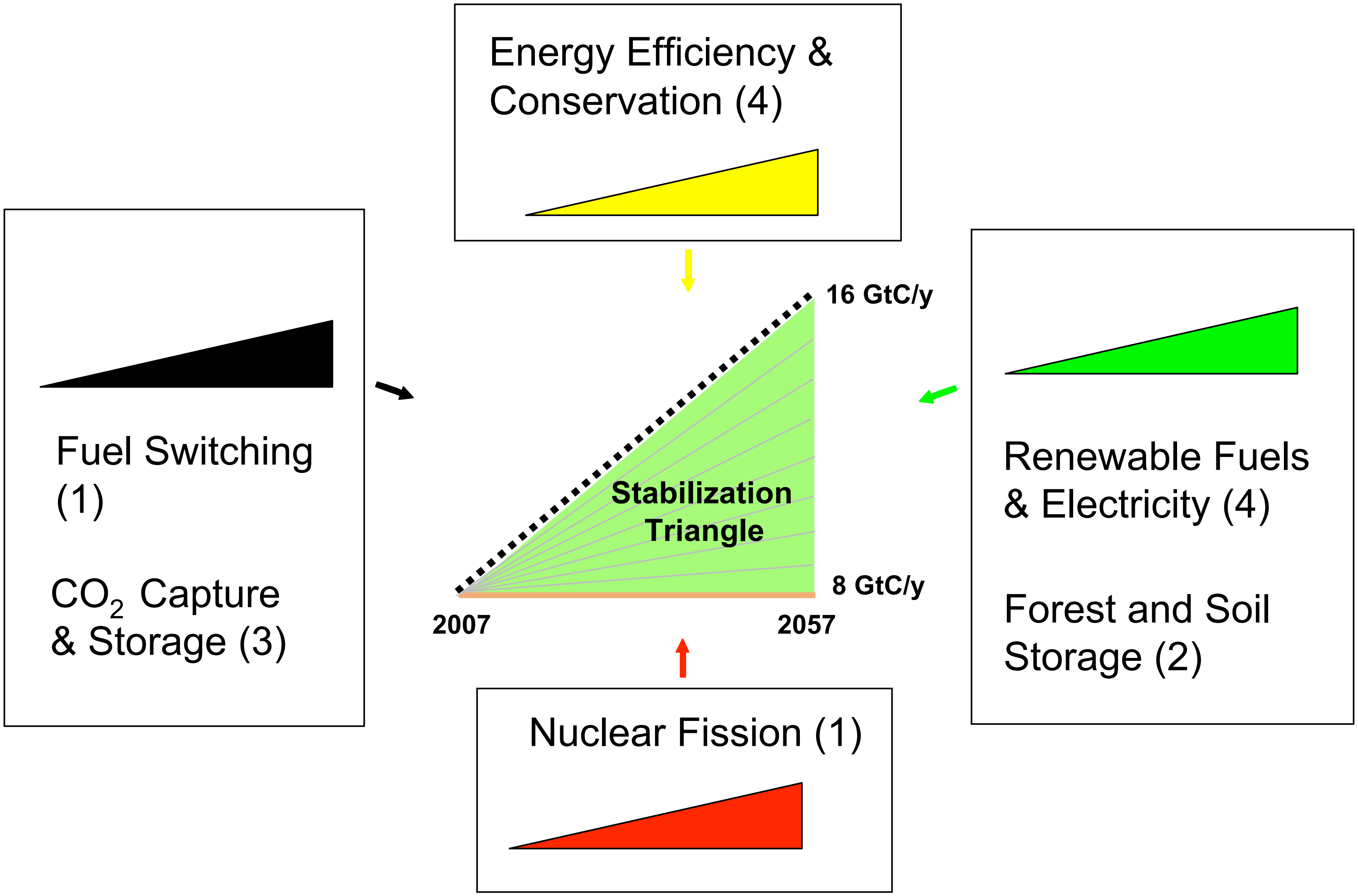
stop press: need another wedge due to emissions since 2004!

8 stabilization wedges



i.e. current path is a doubling in 50 yrs, so 8 GTC/yr now is 16 GTC/yr in 50 yrs

15 wedge strategies in 4 categories



15 wedge strategies in 4 categories

Wedge Summary Table

Category	Technology	Electricity	Fuel	Heat	Sink
Efficiency	Efficient vehicles		X		
	Reduced use of vehicles		X		
	Efficient buildings	X	X	X	
	Efficient baseload coal plants	X			
Decarbonization of power	Gas baseload power for coal baseload power	X			
	Capture CO2 at baseload power plant	X			
	Nuclear power for coal power	X			
	Wind power for coal power	X			
	PV power for coal power	X			
Decarbonization of fuel	Capture CO2 at H2 plant		X		
	Capture CO2 at coal-to-synfuels plant		X		
	Wind H2 in fuel-cell car for gasoline in hybrid car		X		
	Biomass fuel for fossil fuel		X		
Forests and agricultural soils	Reduced deforestation, plus reforestation, afforestation, and new plantations				X
	Conservation tillage				X

details of each strategy at:

http://www.princeton.edu/~cmi/resources/wedgesumtb.htm

(*worth a close look!*)

Photos courtesy of Ford Motor Co., DOE, EPA

Efficiency

Double the fuel efficiency of the world's cars <u>or</u> halve miles traveled

There are about 600 million cars today, with 2 billion projected for 2055

Produce today's electric capacity with double today's efficiency

Average coal plant efficiency is 32% today

Use best efficiency practices in all residential and commercial buildings

Replacing all the world's incandescent bulbs with CFL's would provide 1/4 of one wedge

E, T, H / $

Sector s affected:

E = Electricity, T =Transport, H = Heat

Cost based on scale of $ to $$$

Fuel Switching

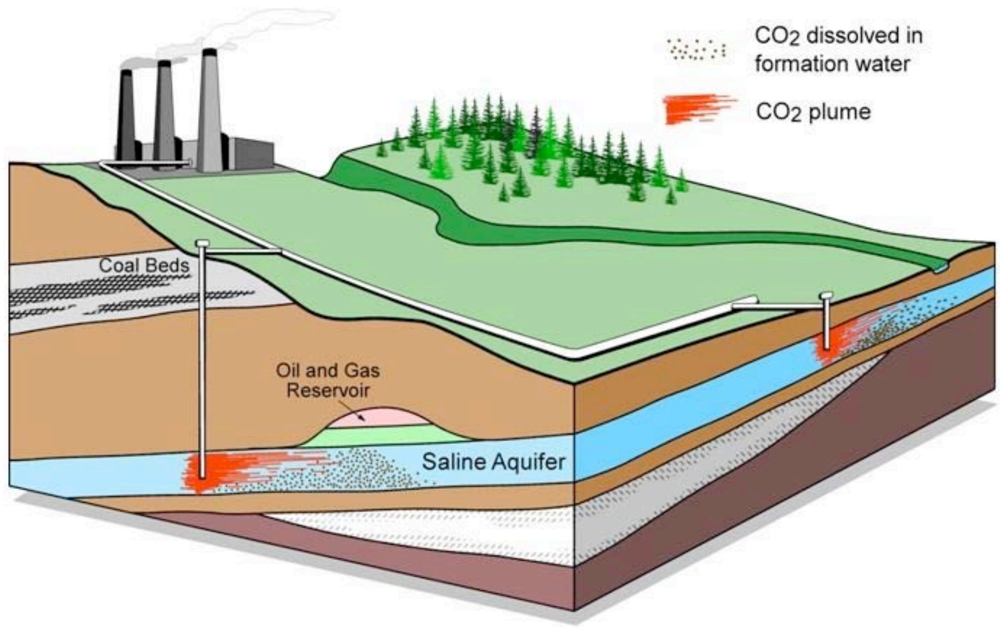
Photo by J.C. Willett (U.S. Geological Survey).

Substitute 1400 natural gas electric plants for an equal number of coal-fired facilities

E, H / $

A wedge requires an amount of natural gas equal to that used for all purposes today

Carbon Capture & Storage



Graphic courtesy of Alberta Geological Survey

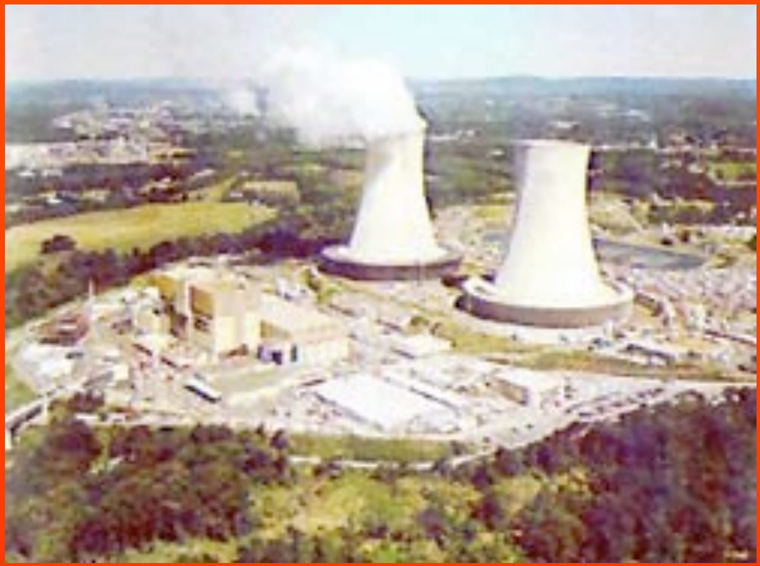
Implement CCS at

- **800 GW coal electric plants or**
- **1600 GW natural gas electric plants or**
- **180 coal synfuels plants or**
- **10 times today's capacity of hydrogen plants**

There are currently three storage projects that each inject 1 million tons of CO_2 per year – by 2055 need 3500.

E, T, H / $$

Nuclear Electricity



Graphic courtesy of NRC

Triple the world's nuclear electricity capacity by 2055

The rate of installation required for a wedge from electricity is equal to the global rate of nuclear expansion from 1975-1990.

E/ $$

Wind Electricity

Photo courtesy of DOE

Install 1 million 2 MW windmills to replace coal-based electricity,

OR

Use 2 million windmills to produce hydrogen fuel

E, T, H / $-$$

A wedge worth of wind electricity will require increasing current capacity by a factor of 30

Solar Electricity

Photos courtesy of DOE Photovoltaics Program

Install 20,000 square kilometers for dedicated use by 2054

A wedge of solar electricity would mean increasing current capacity 700 times

E / $$$

Biofuels

Photo courtesy of NREL

Scale up current global ethanol production by 30 times

Using current practices, one wedge requires planting an area the size of India with biofuels crops

T, H / $$

Natural Sinks

Eliminate tropical deforestation

OR

Plant new forests over an area the size of the continental U.S.

OR

Use conservation tillage on *all* cropland (1600 Mha)

Conservation tillage is currently practiced on less than 10% of global cropland

B / $

Photos courtesy of NREL, SUNY Stonybrook, United Nations FAO

wedge issues

•emissions and GDP growth related, but ~1.5%/yr emissions growth already includes improving energy intensity (i.e. 1.5%/yr per capita GDP growth + 0.9%/yr population growth - 0.8%/yr energy intensity in W/$)

•thus BAU already includes some of efficiency gains implied by wedge strategies (*recall following slide*)

•the difference of 1% above equates to ~330 GTC or ~2 wedges

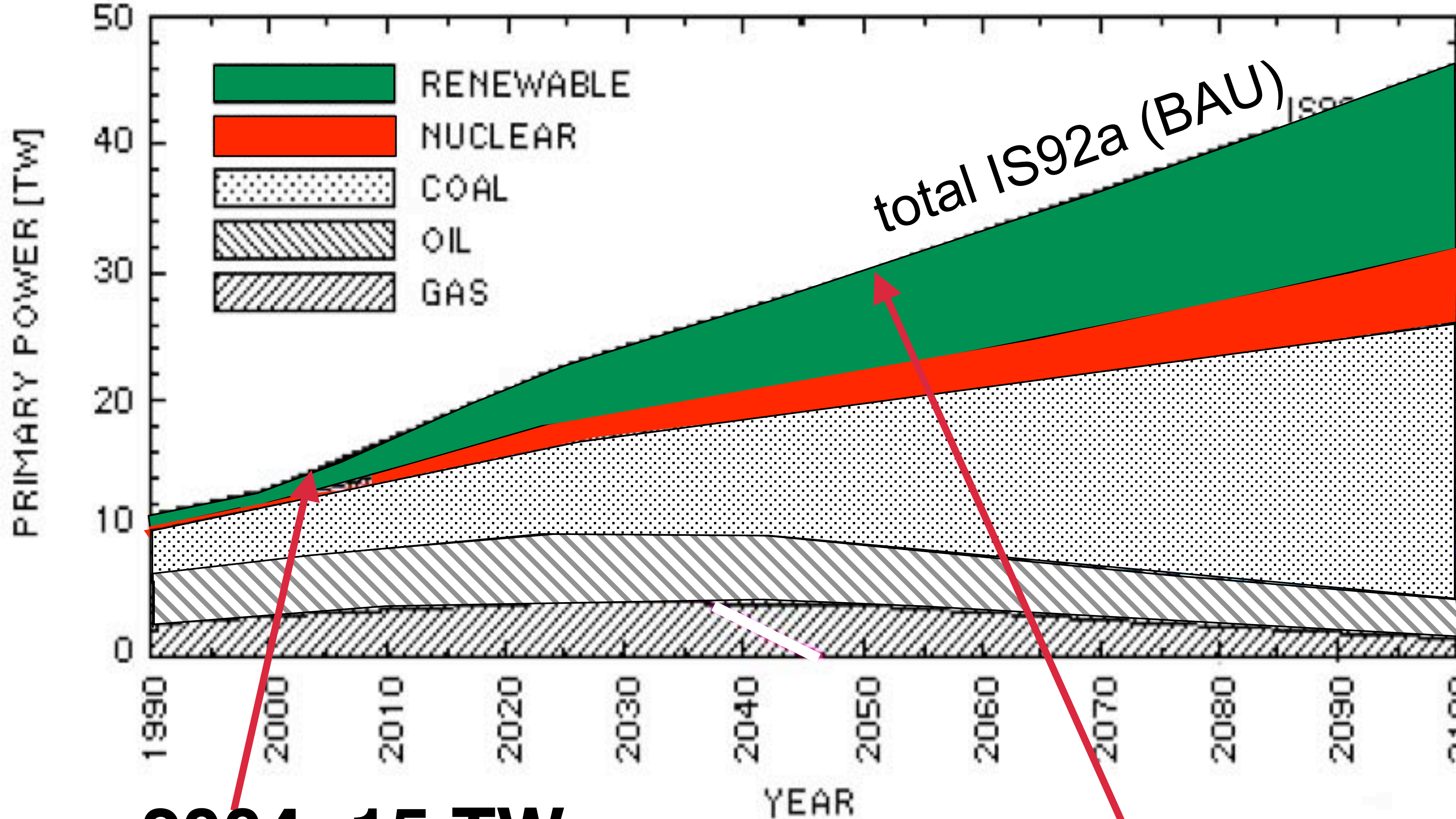
•*any wedge must add to what is already assumed for BAU, and wedges must be additive and not overlapping*

•any delay means more wedges in next 50 years

•number of wedges needed after that sky rockets

•but, wedges could buy us 50 years for development and deployment of new energy technologies

recall projected energy by source IPPC BAU



2004: 15 TW

1.05 TW renewable/hydro

0.92 TW nuclear

2050: 30 TW

~ 8 TW renewable

~ 2 TW nuclear

stop press!

•*shortly after class I heard John Holdren lay out the argument for 9 wedges (+1 GTC/yr by 20XX), as needed "for 50:50 chance of avoiding climate catastrophe"*

•*written transcript and audio are available at:*

http://www.loe.org/shows/segments.htm?programID=09-P13-00016&segmentID=2

(living on earth)

and "rocket scientist" (literally)

NYU PHYSICS

DEPARTMENT
PEOPLE
RESEARCH
EVENTS
COURSES
RESOURCES

ALUMNI
GSAS
CAS

Martin Hoffert

PHYSICS

Faculty | Emeritus Faculty | Research Scientists | Staff | Graduate Students | Retired | Visitors

Emeritus Faculty

Professor of Physics
Ph.D. 1967 (astronautics), M.S. 1964 (astronautics), Polytechnic Institute of Brooklyn; M.A. 1969 (liberal studies, sociology, economics), New School for Social Research; B.S. 1960 (aeronautical engineering), Michigan

Global environmental change, geophysical fluid dynamics,oceanography, biogeochemical cycles and alternate energy technology

Hoffert video at :

http://www.scientificblogging.com/david_houle/urgency_and_global_warming_an_interview_with_martin_i_hoffert

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Web links

- BEYOND FOSSIL FUELS
  an interview with Professor Martin Hoffert on PBS.
- *Beam It Down: How the New Satellites Can Power the World*
  By Martin I. Hoffert and Seth D. Potter
  (www.techreview.com/articles/oct97/hoffert.html)

Research My research interests are global environmental change, geophysical fluid dynamics, oceanography, biogeochemical cycles and alternate energy technology.

key points

- stabilization of the atmospheric CO_2 concentration at any level utlimately requires reduction and then stabilization of C emissions at a level that balances net sinks
- any delay in reducing emissions requires steeper & deeper cuts later in order to achieve the same stabilization CO_2 conc. (because every molecule counts)
- it is possible to derive a simple estimate of the total allowable new emissions for a given stabilization CO_2 target (but this assumes that C-cycle feedbacks do not change, and such estimates are therefore likely to be too permissive)
- coal phase out by 2030 (w/ any new plants fitted with CCS technology) is one good way to limit emissions, but will require substantial replacement energy
- the stabilization wedge approach can buy us time, but the number of wedges needed is likely substantially larger than originally suggested
- a major engineering and technology effort is needed now in order to avert unacceptable climate change impacts
- rapid development and deployment of carbon capture and sequestration is essential!

learning goals

- be able to describe the relationship between stabilization CO_2 conc. and the assoc. C emissions pathway(s)
- be able to describe how delayed implementation of any emissions reduction scheme influences later reduction requirements
- be able to describe a “business as usual” energy demand forecast
- be able to describe the concept of the “stabilization triangle”, the “stabilization wedge” and “avoided emissions”
- become familiar with some of the ways we might fill out a portfolio of “stabilization wedges”