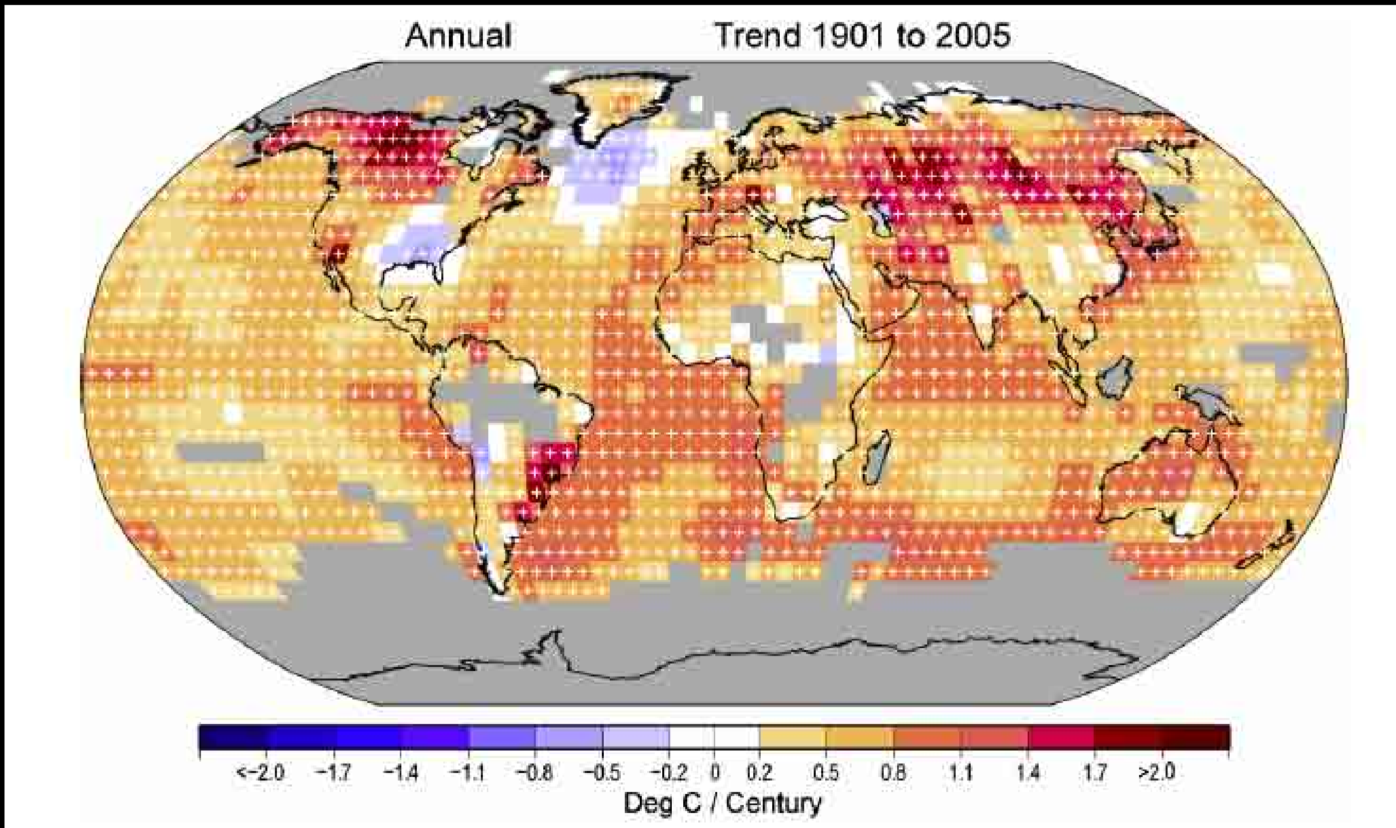
Climate Change Mitigation and Some Links to Adaptation

Susan Solomon

1. Introduction
2. Forcing agents and the stock-flow concept of Sterman
3. Why do we emit so much carbon dioxide and why is mitigation controversial
4. Some options for carbon dioxide emission reduction and the wedge concept of Socolow and Pacala
5. What about emissions of other warming agents?

Image courtesy of NASA.

The World Has Warmed



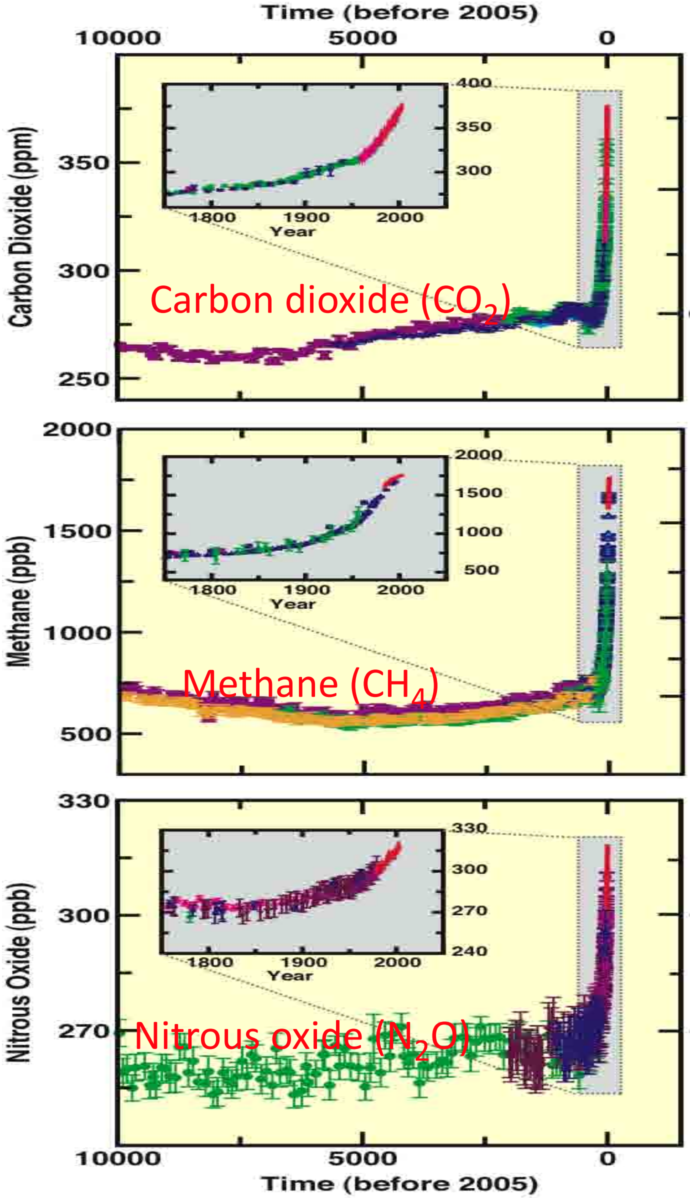
Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 3.9. Cambridge University Press. Used with permission.

Last ten years: warmest decade since at least the late 1800s

Widespread warming has occurred. Globally averaged, the planet is about 0.75°C warmer than it was in 1880, based upon dozens of high-quality long records using thermometers worldwide, including land and ocean.

1	2007
2	2005
3	1998
4	2002
5	2006
6	2008
7	2003
8	2009
9	2001
10	2004
11	1999
12	1995
13	1997
14	1990
15	2000
16	1988
17	1991
18	1981
19	1983
20	1994
21	1987
22	1938
23	1989
24	1944
25	1993

Increases in long-lived greenhouse gases (GHGs)



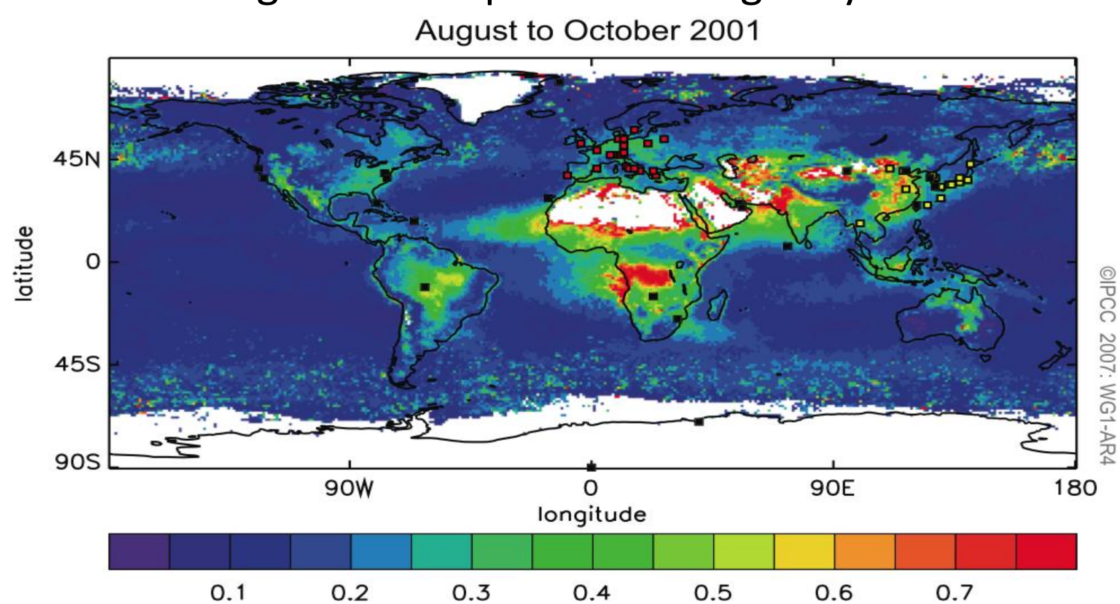
Radiative forcing efficiencies and atmospheric lifetimes differ among different gases.

Methane lives for about 10 years in our atmosphere.

Nitrous oxide lives for about 100 years.

Carbon dioxide is uniquely long-lived. Some of what we emit today (about 20%) will still be here in a thousand years.

Scattering and absorption of sunlight by aerosols



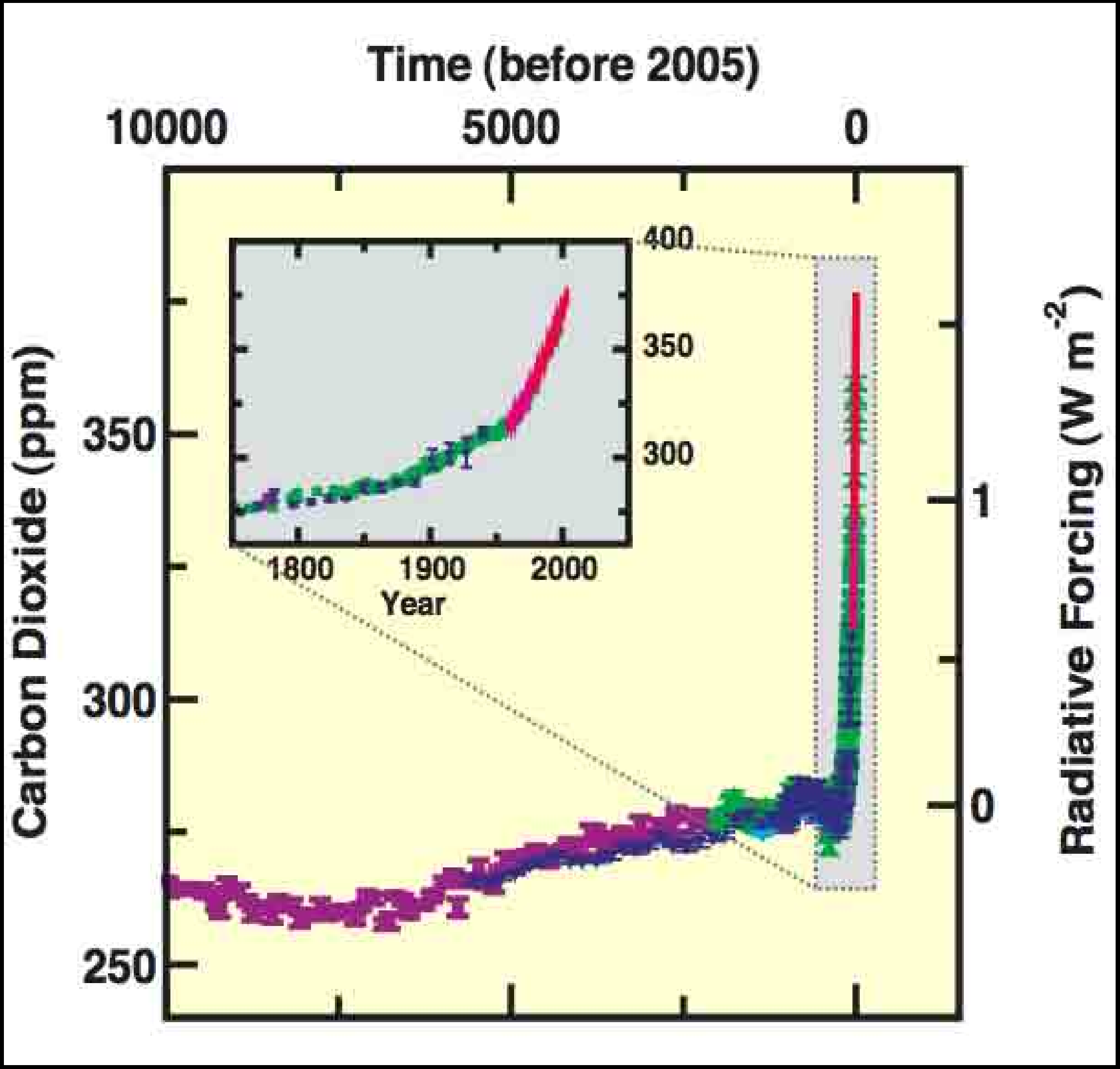
Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.1 and 2.11. Cambridge University Press. Used with permission.

Unprecedented Increases in Carbon Dioxide

- A critical 'greenhouse gas' that absorbs energy and is the largest single driver of current warming

- Increases change the Earth's energy budget, 'forcing' climate to change and acidifying the oceans

IPCC WG1 (2007) ch 2



Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.1. Cambridge University Press. Used with permission.

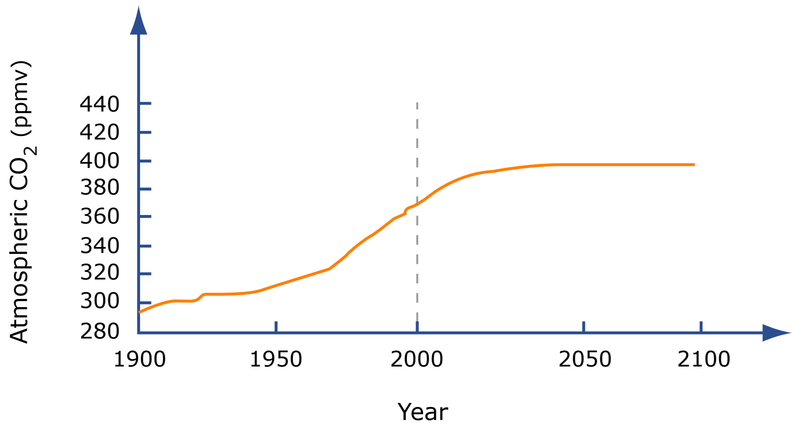
Bathtubs are Key: Sterman (2007)

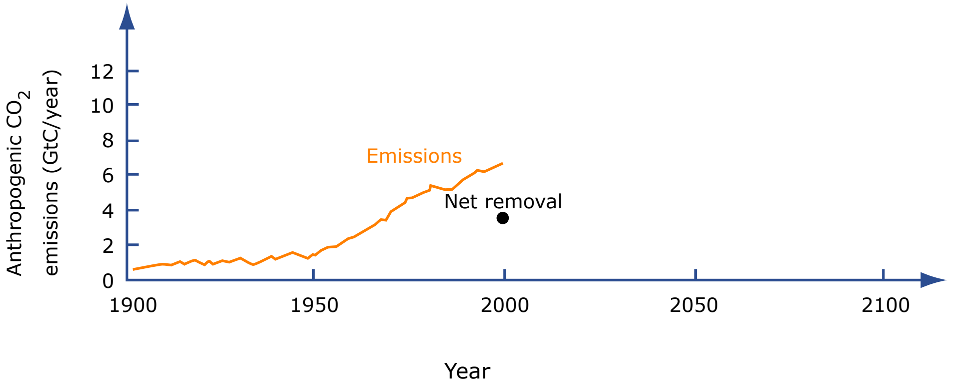
Scenario for atmospheric CO2 concentration versus time

Sketch your estimate of future net CO2 removal and anthropogenic emissions for this 400 ppmv stabilization scenario.

Anthropogenic emissions versus time, and current net removal

Consider a scenario in which the concentration of CO_2 in the atmosphere gradually rises to 400 ppm, about 8% higher than the level in 2000, then stabalizes by the year 2100, as shown here:

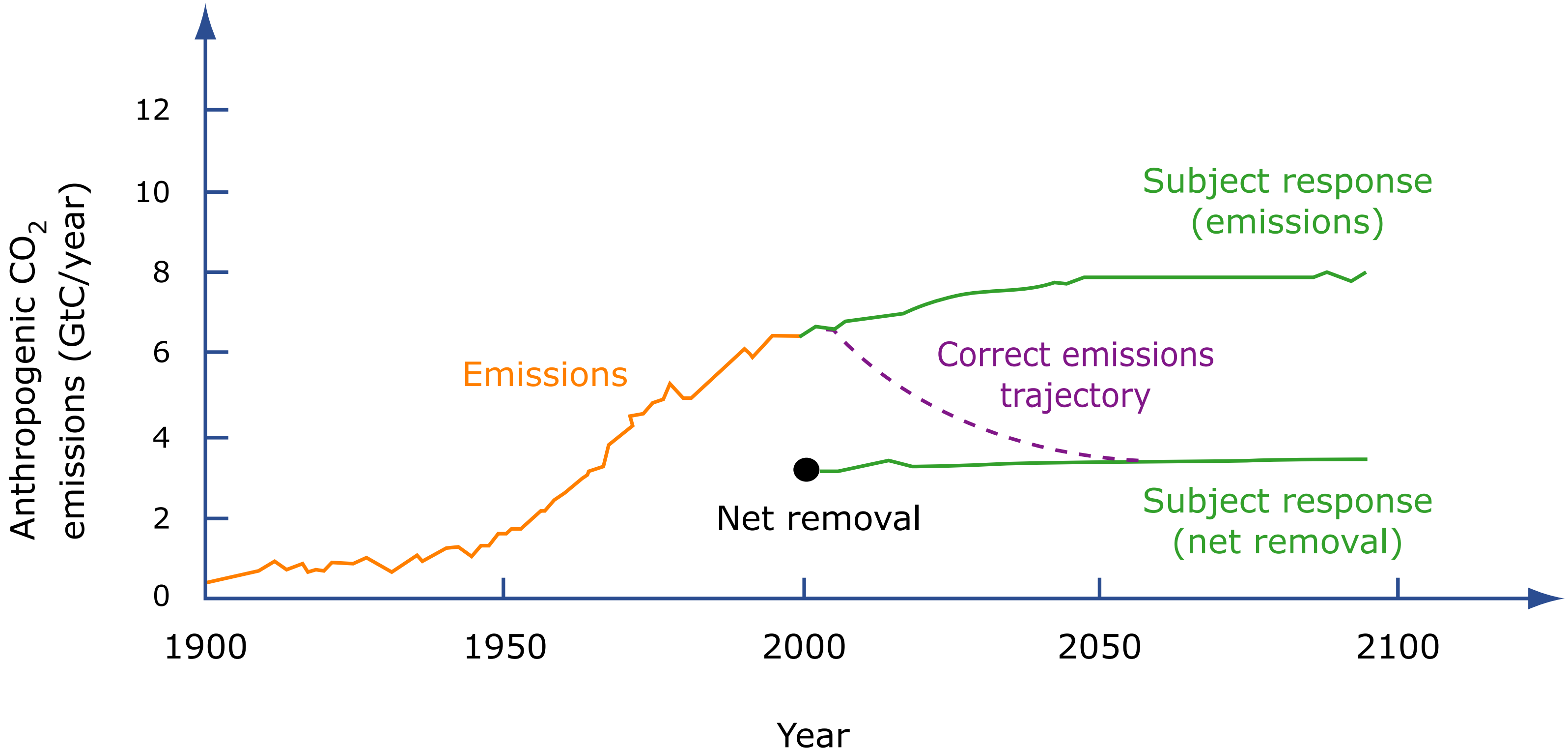




Images by MIT OpenCourseWare.

Sterman, Science, 2007

Bathtubs are Key: Sterman (2007)



A typical reponse to the climate stabilization task.
Future emissions are erroneously correlated with atmospheric CO_2. Purple dashed line indicates the correct emissions path to stabilize CO_2 given the subject's estimate of net removal.

The Amount of Carbon in The Bathtub

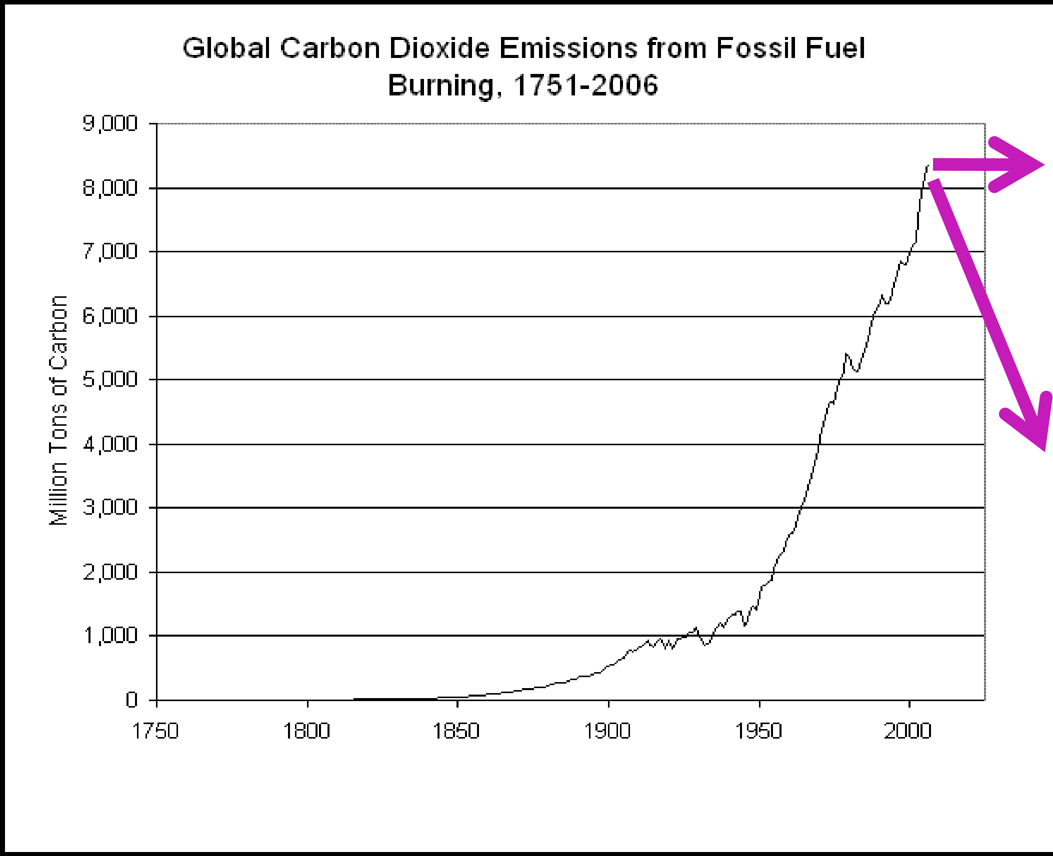


Image courtesy of CD/AC, BP and USGS.

This image has been removed due to copyright restrictions. Please see the image on page http://www.cartoonstock.com/newscartoons/cartoonists/tmc/lowres/tmcn193l.jpg.

Stabilization of CO_2 concentrations globally would require at least 50% emissions reductions

What if the gas was methane?
What if it was HCFC-123?

What drives carbon emissions?

The Kaya identity (8, 9) expresses the global *F* as a product of four driving factors:

$$F = P\left(\frac{G}{P}\right)\left(\frac{E}{G}\right)\left(\frac{F}{E}\right) = Pgef,$$

Where *P* is global population, *G* is world GDP of gross world product, E is global primary energy consumption, $g = G/P$ is the per-capita world GDP, $e = E/G$ is the energy intensity of world GDP, and $f = F/E$ is the carbon intensity of energy. Upper- and lowercase symbols distinguish extensive and intensive variables.

Image by MIT OpenCourseWare.

One way of considering factors involved (not the only way): population, GDP per capita, energy required per unit GDP, emissions per unit energy. --> Population, wealth, efficiency, cleanliness

Carbon emission is integral to all of the world's economies

Learn more by reading Raupach et al., PNAS, 2007

Carbon Dioxide Emission From Fossil Fuel Burning

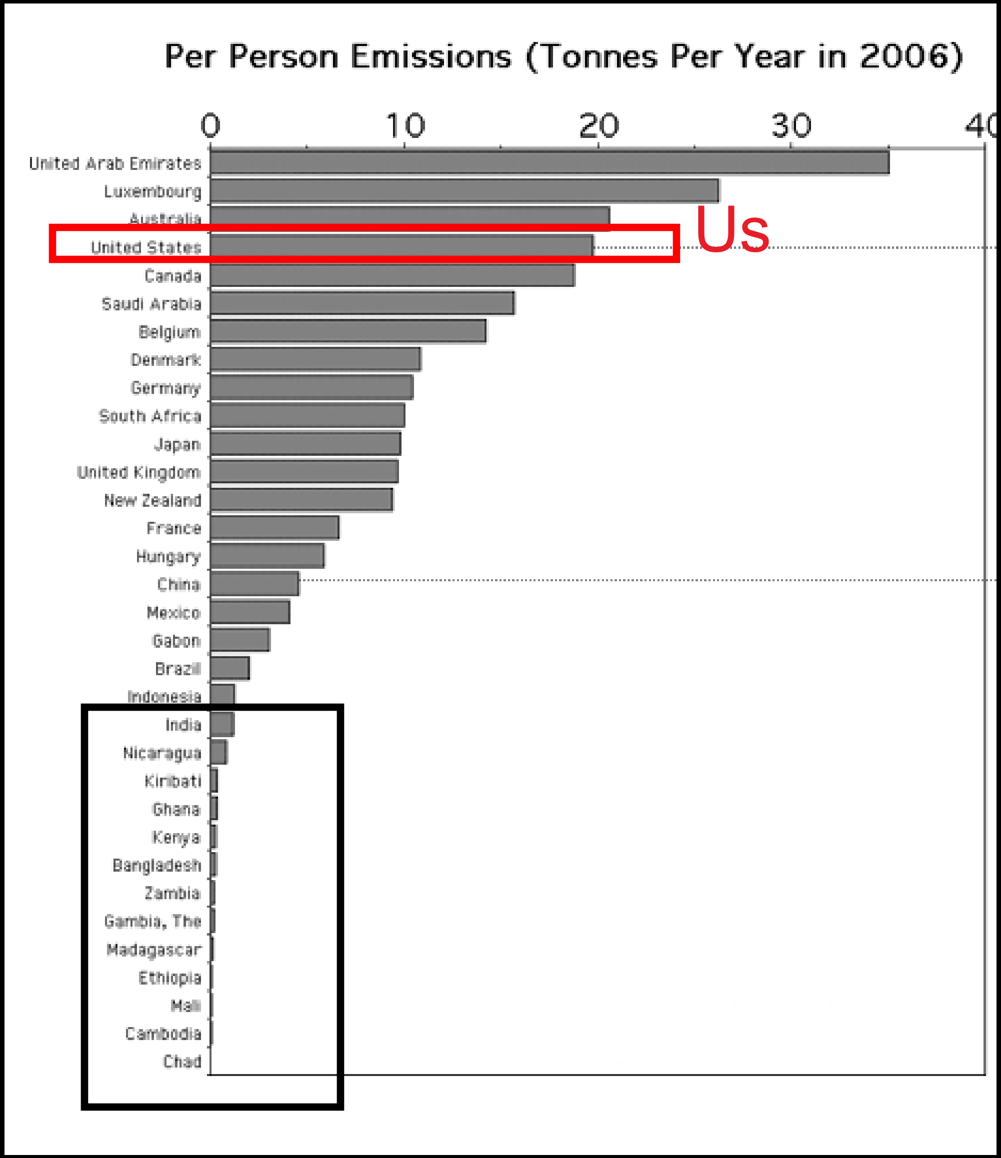


Image courtesy of DOE.

The human side of climate change.

Who?

Source: Energy Information Agency, DOE

Why: Going, Doing, Making, Being Comfortable…..

In short, just about everything.

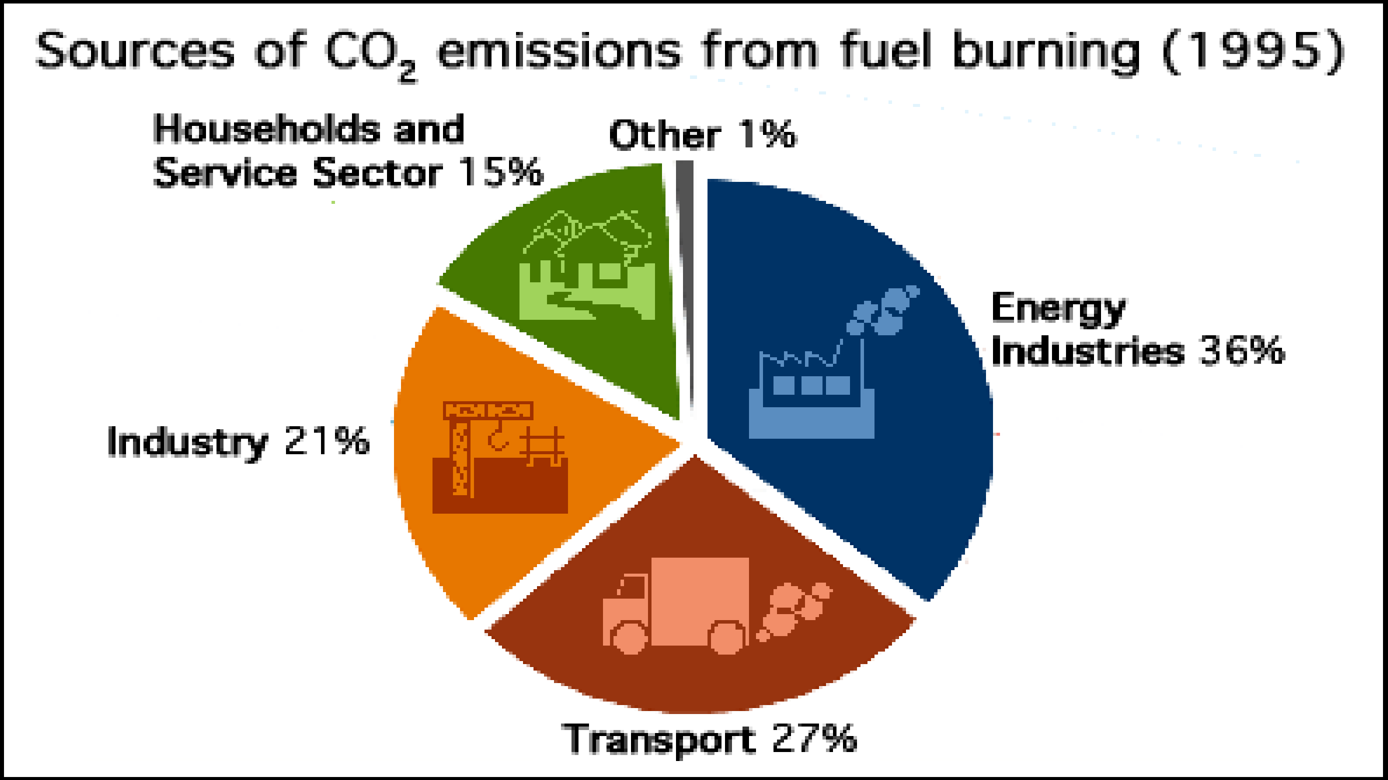


Image courtesy of EPA.

People in the Mirror: Carbon Dioxide Emission From Fossil Fuel Burning

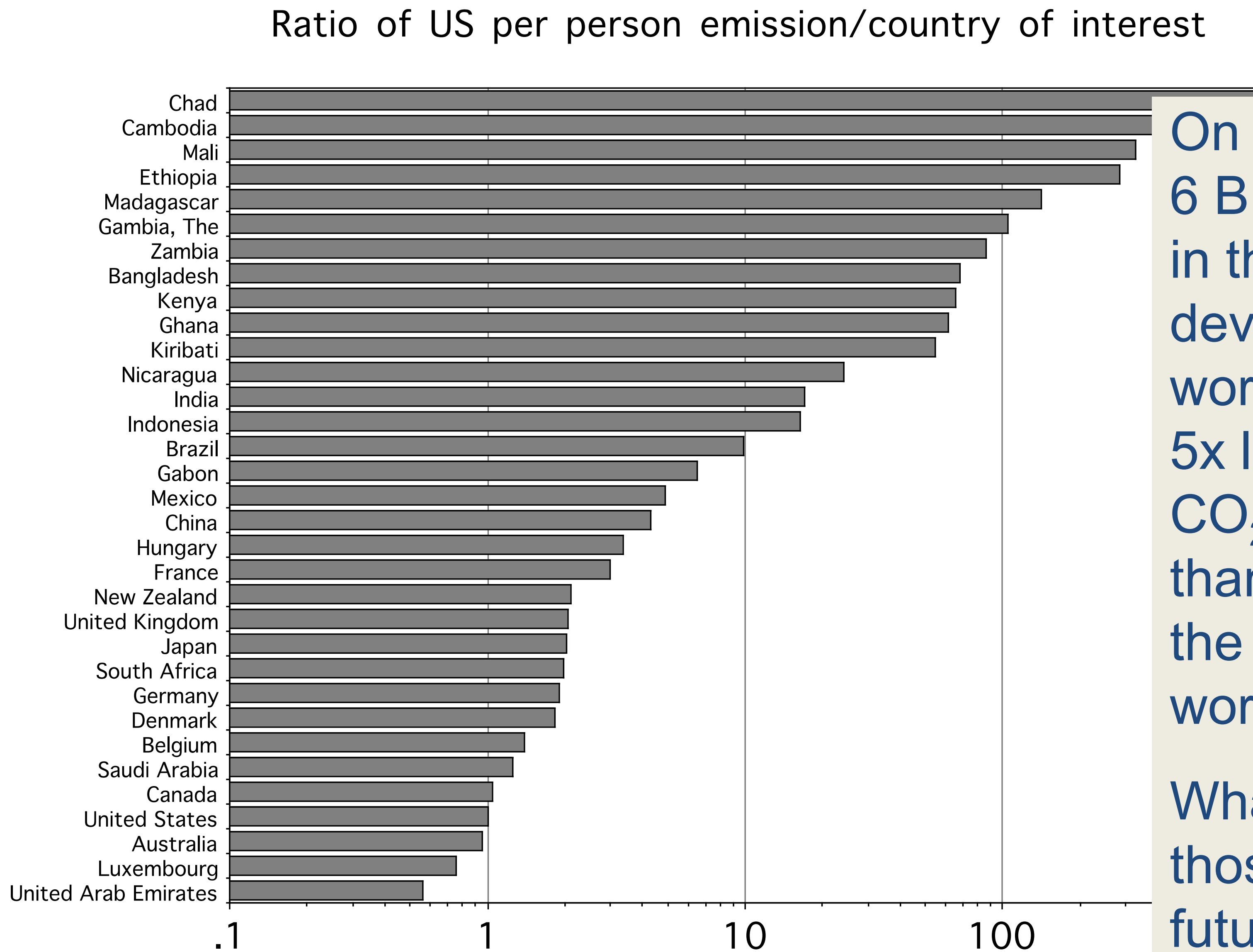


Image courtesy of DOE.

Source: Energy Information Administration, US DOE 2006

On average, the 6 B people now in the developing world emit about 5x less fossil CO_2 per person than the 1B in the developed world.

What about those people's future?

The Amount of Carbon in The Bathtub

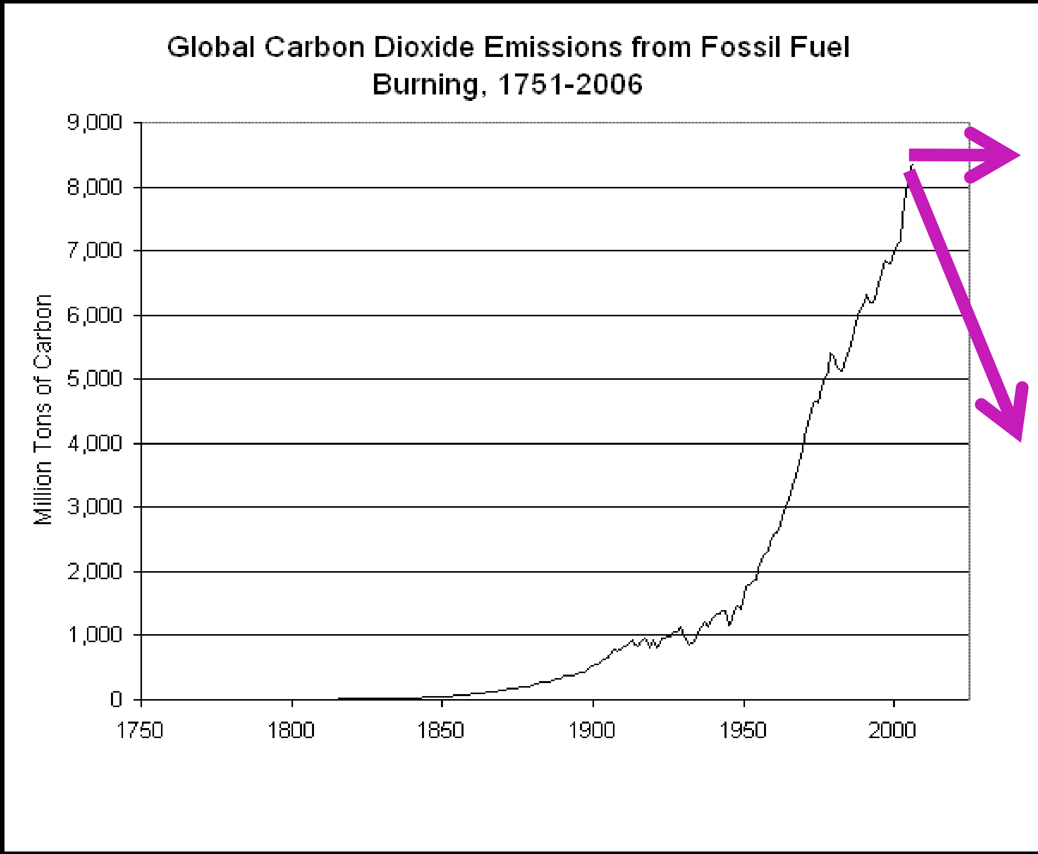


Image courtesy of CD/AC, BP and USGS.

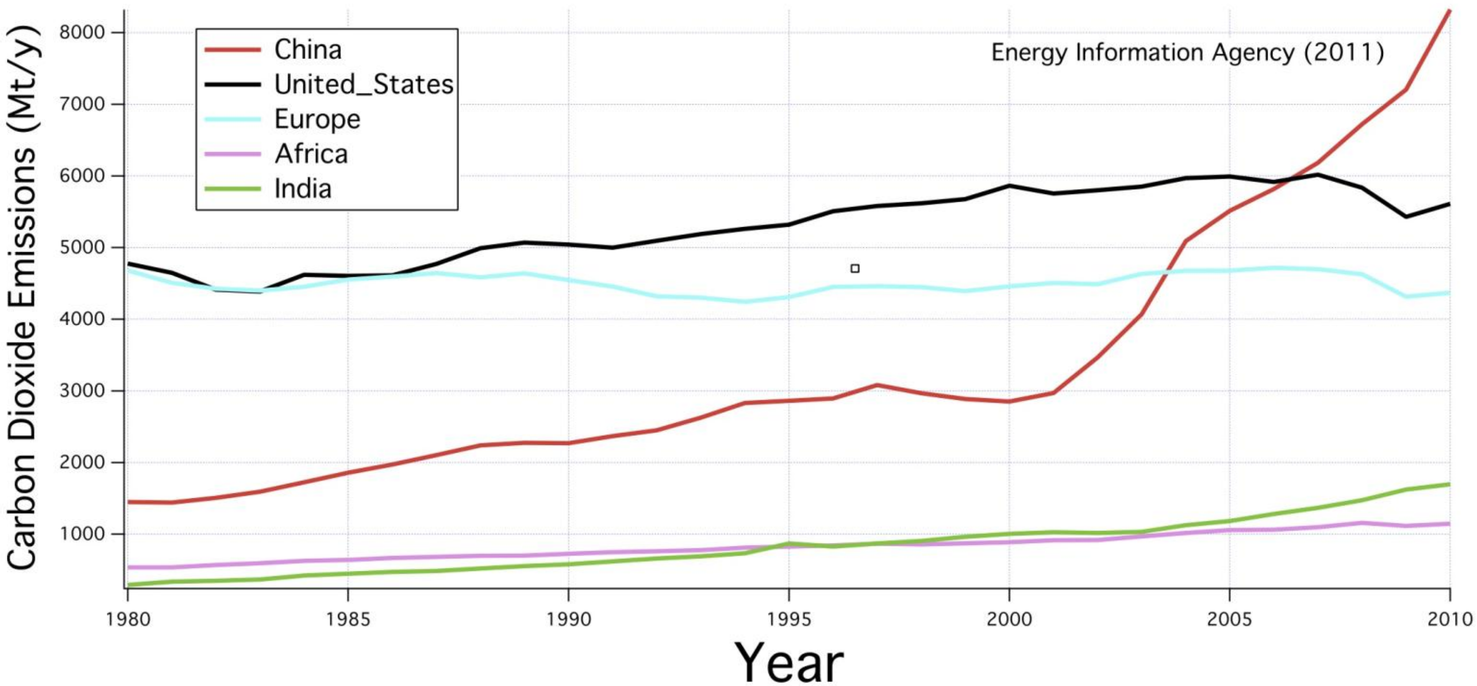
This image has been removed due to copyright restrictions. Please see the image on page http://www.cartoonstock.com/newscartoons/cartoonists/tmc/lowres/tmcn193l.jpg.

Can we mitigate carbon emissions at the same time that the world's poor countries develop and increase their energy needs?

This image has been removed due to copyright restrictions. Please see the image on page http://bushlandsafaris.com/cultural.htm.

- 6/7 of the people emit about 5x less per person than 1/6

What about total emissions, not per capita?
Let's add it up by country…..



Recent increases in wealth in China

What's fair?

Should China pay more to develop than we did? Should Africa?

Carbon Intensity of the Global Economy

This image has been removed due to copyright restrictions.
Please see the image on page http://www.globalcarbonproject.org/global/images/general/ThumbCoal_dredge.jpg.

- ≈ -50% globally since 1970 but flattening out recently (can you guess why?)

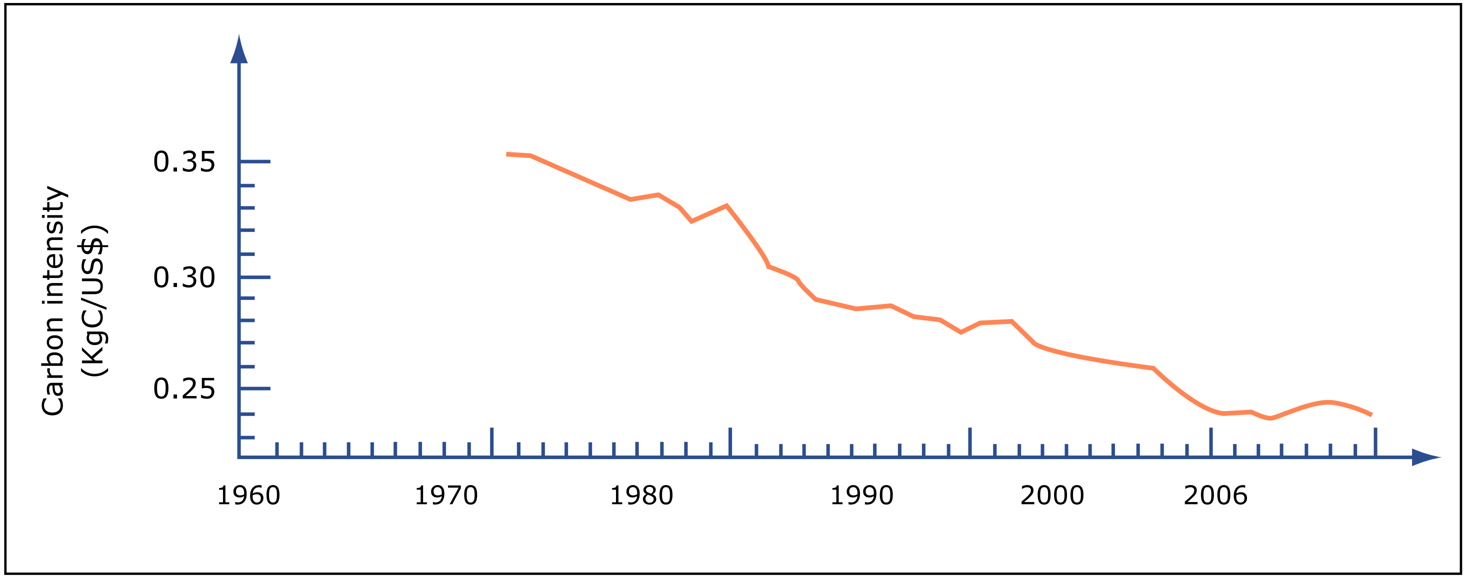


Image by MIT OpenCourseWare.

Infrastructure Commitments

Power plants,
homes
~50 years

This image has been removed due to copyright restrictions. Please see the image on page http://www.behance.net/gallery/Fossil-Fuels-are-Burning/5161371.

This image has been removed due to copyright restrictions. Please see the image on page http://suppateam.files.wordpress.com/2008/11/traffic-jam1.jpg.

Cars ~10 years

This image has been removed due to copyright restrictions. Please see the image on page http://www.lmco.net/content.cfm?n=projects.

The next few decades…it's up to us.

This image has been removed due to copyright restrictions.
Please see the image on page http://www.behance.net/gallery/Fossil-Fuels-are-Burning/5161371.

What will be built: power plants, cars, planes, trains, appliances, homes, etc…..
(leads to about 3-7° C warming by 2100).

This image has been removed due to copyright restrictions.
Please see the image on page http://www.amazon.ca/Blade-Runner-Final-Cut-Blu-ray/dp/B004GDB7OA.

This image has been removed due to copyright restrictions.
Please see the image on page http://www.nydailynews.com/entertainment/tv-movies/voice-star-trek-majel-barrett-roddenberry-dead-76-article-1.357407.

Our joint choices on what 'stuff' to build matter a great deal.

Past and future emissions from 'stuff' we already have
(leads to about 1-1.4° C warming)

See Davis et al., Science, 2010

Blade runner or star trek?

Emissions past and future

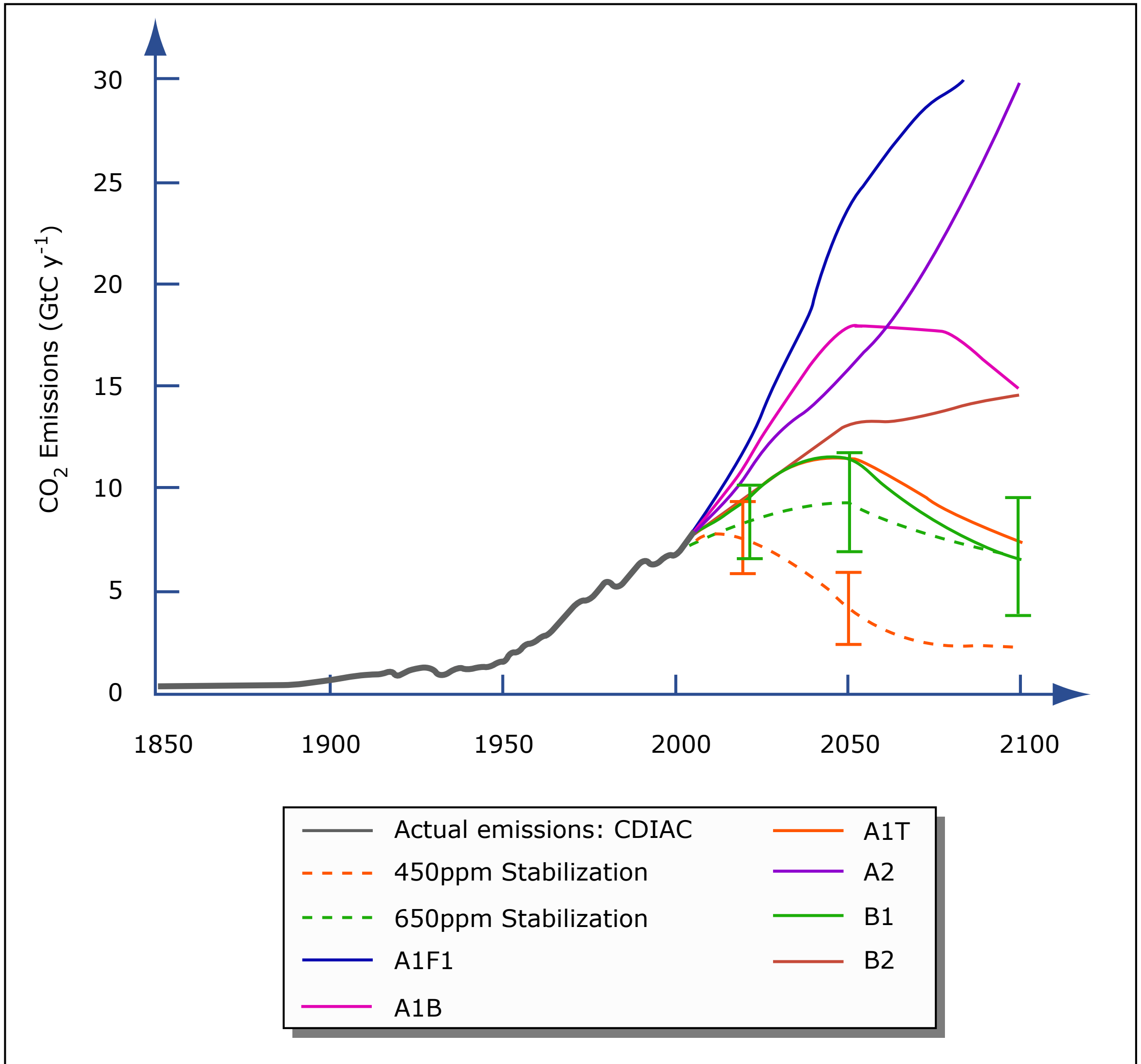


Image by MIT OpenCourseWare.

- Typical scenarios
- A1FI, A1B, etc show plausible futures with no additional climate policy; note uncertainties even with no policy.
- Stabilization at 450 would require large emissions reductions within the next several decades; 650 would imply reduced rate of growth soon, and bigger reductions by 2050.

This image has been removed due to copyright restrictions.
Please see Figure 4 in Bolin, and Kheshgi. *Science* (2000).

From Bolin and Kheshgi, Science, 2000.

Information and implications:

- units here are tC not tCO_2
- ≈75% of the total accumulated CO_2 in the atmosphere came from developed countries during 1860-1990.
- The integrated per capita contribution of developed countries to today's fossil fuel CO_2 burden is about 20x larger than that of developing countries. The current annual contribution is about 5x.
- Stabilization at e.g., 550 suggests future DC share less than 1tC per person/yr, many times lower throughout the 21st century than what it took for the developed world to develop.
- Gridlock at UN level: developed and developing....
- Role of science and tech?

Political Matters:
numbers; north-south issues, connections

(1) the times are difficult

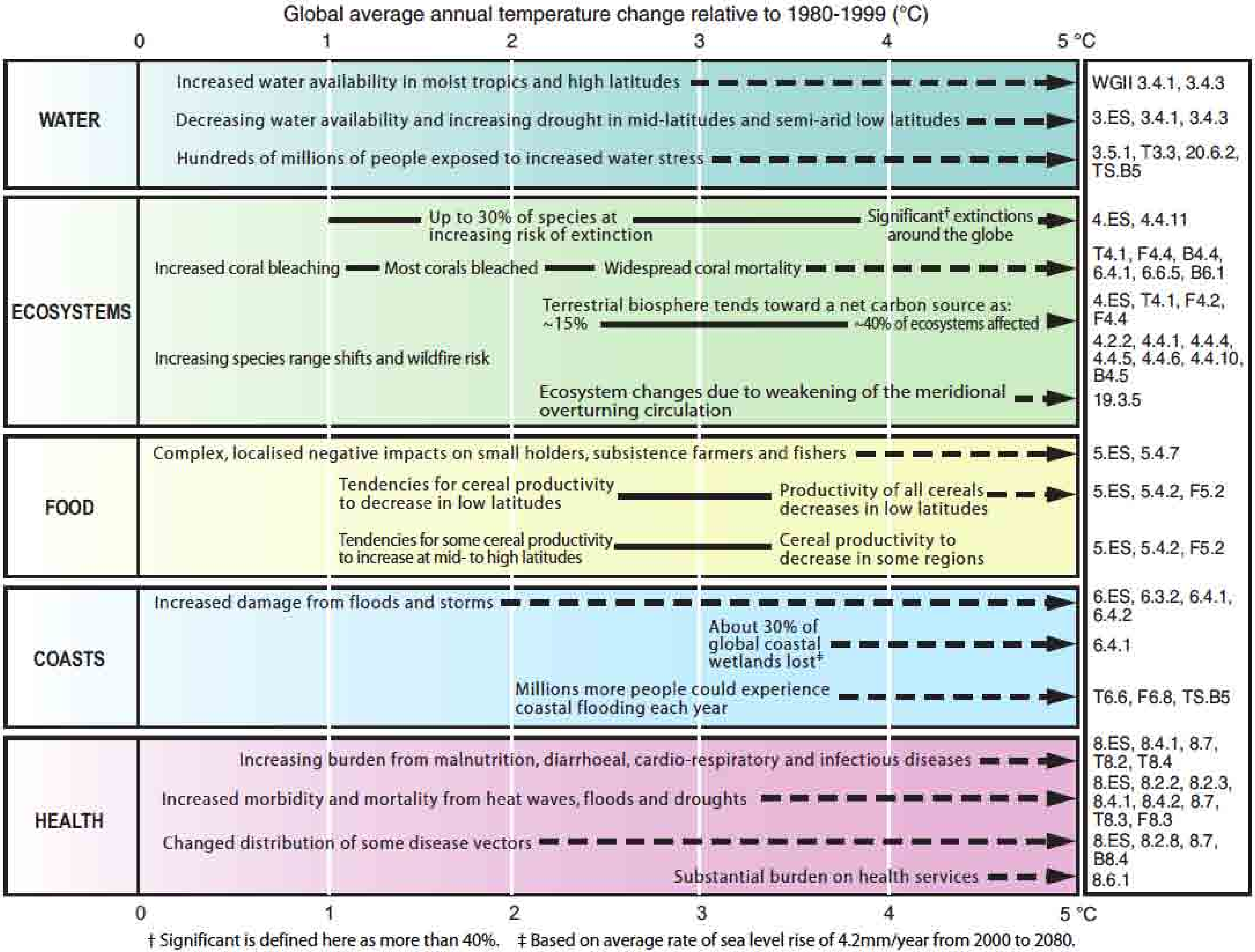
(2) The numbers at the table are large

(3) Equity issues?

These images have been removed due to copyright restrictions. Please see the images on page http://www.iisd.ca/climate/cop10/fri1012.html

Never before has there been a greater need for a joint and well-informed societal choice, or a more difficult one.

A Very Few Words About Impacts and Adaptation



Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland. Used with permission.

A Very Few Words About Impacts and Adaptation

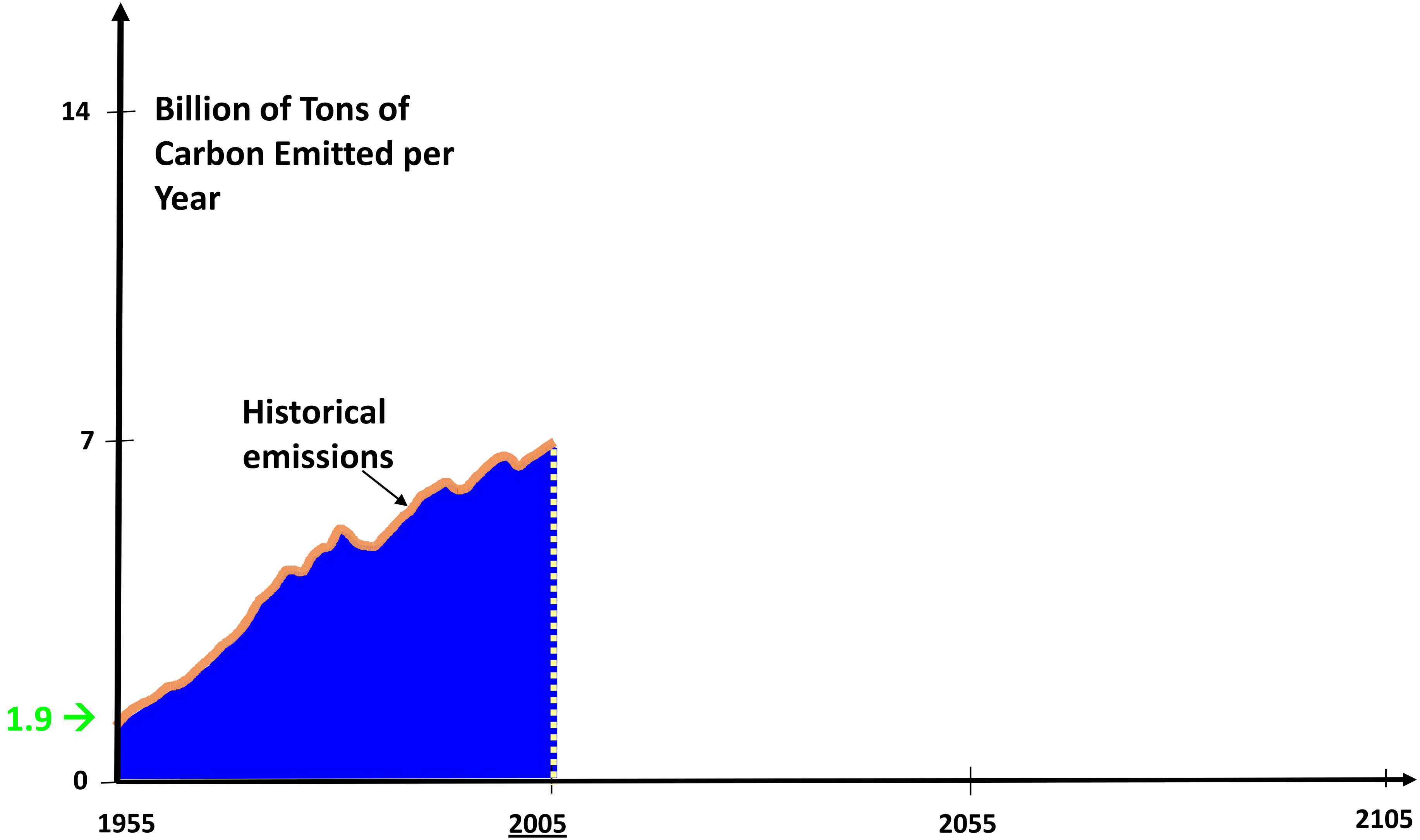
Table 4.1. Selected examples of planned adaptation by sector.

Sector	Adaptation option/strategy	Underlying policy framework	Key constraints and opportunities to implementation (Normal font = constraints; *italics = opportunities*)
Water {WGII, 5.5, 16.4; Tables 3.5, 11.6,17.1}	Expanded rainwater harvesting; water storage and conservation techniques; water reuse; desalination; water-use and irrigation efficiency	National water policies and integrated water resources management; water-related hazards management	Financial, human resources and physical barriers; *integrated water resources management; synergies with other sectors*
Agriculture {WGII 10.5, 13.5; Table 10.8}	Adjustment of planting dates and crop variety; crop relocation; improved land management, e.g. erosion control and soil protection through tree planting	R&D policies; institutional reform; land tenure and land reform; training; capacity building; crop insurance; financial incentives, e.g. subsidies and tax credits	Technological and financial constraints; access to new varieties; markets; *longer growing season in higher latitudes; revenues from 'new' products*
Infrastructure/ settlement (including coastal zones) {WGII 3.6, 11.4; Tables 6.11, 17.1}	Relocation; seawalls and storm surge barriers; dune reinforcement; land acquisition and creation of marshlands/wetlands as buffer against sea level rise and flooding; protection of existing natural barriers	Standards and regulations that integrate climate change considerations into design; land-use policies; building codes; insurance	Financial and technological barriers; availability of relocation space; *integrated policies and management; synergies with sustainable development goals*
Human health {WGII 14.5, Table 10.8}	Heat-health action plans; emergency medical services; improved climate-sensitive disease surveillance and control; safe water and improved sanitation	Public health policies that recognise climate risk; strengthen health services; regional and international cooperation	Limits to human tolerance (vulnerable groups); knowledge limitations; financial capacity; *upgraded health services; improved quality of life*
Tourism {WGII 12.5, 15.5, 17.5; Table 17.1}	Diversification of tourism attractions and revenues; shifting ski slopes to higher altitudes and glaciers; artificial snow-making	Integrated planning (e.g. carrying capacity; linkages with other sectors); financial incentives, e.g. subsidies and tax credits	Appeal/marketing of new attractions; financial and logistical challenges; potential adverse impact on other sectors (e.g. artificial snow-making may increase energy use); *revenues from 'new' attractions; involvement of wider group of stakeholders*
Transport {WGII 7.6, 17.2}	Realignment/relocation; design standards and planning for roads, rail and other infrastructure to cope with warming and drainage	Integrating climate change considerations into national transport policy; investment in R&D for special situations, e.g. permafrost areas	Financial and technological barriers; availability of less vulnerable routes; *improved technologies and integration with key sectors (e.g. energy)*
Energy {WGII 7.4, 16.2}	Strengthening of overhead transmission and distribution infrastructure; underground cabling for utilities; energy efficiency; use of renewable sources; reduced dependence on single sources of energy	National energy policies, regulations, and fiscal and financial incentives to encourage use of alternative sources; incorporating climate change in design standards	Access to viable alternatives; financial and technological barriers; acceptance of new technologies; *stimulation of new technologies; use of local resources*

Note:
Other examples from many sectors would include early warning systems.

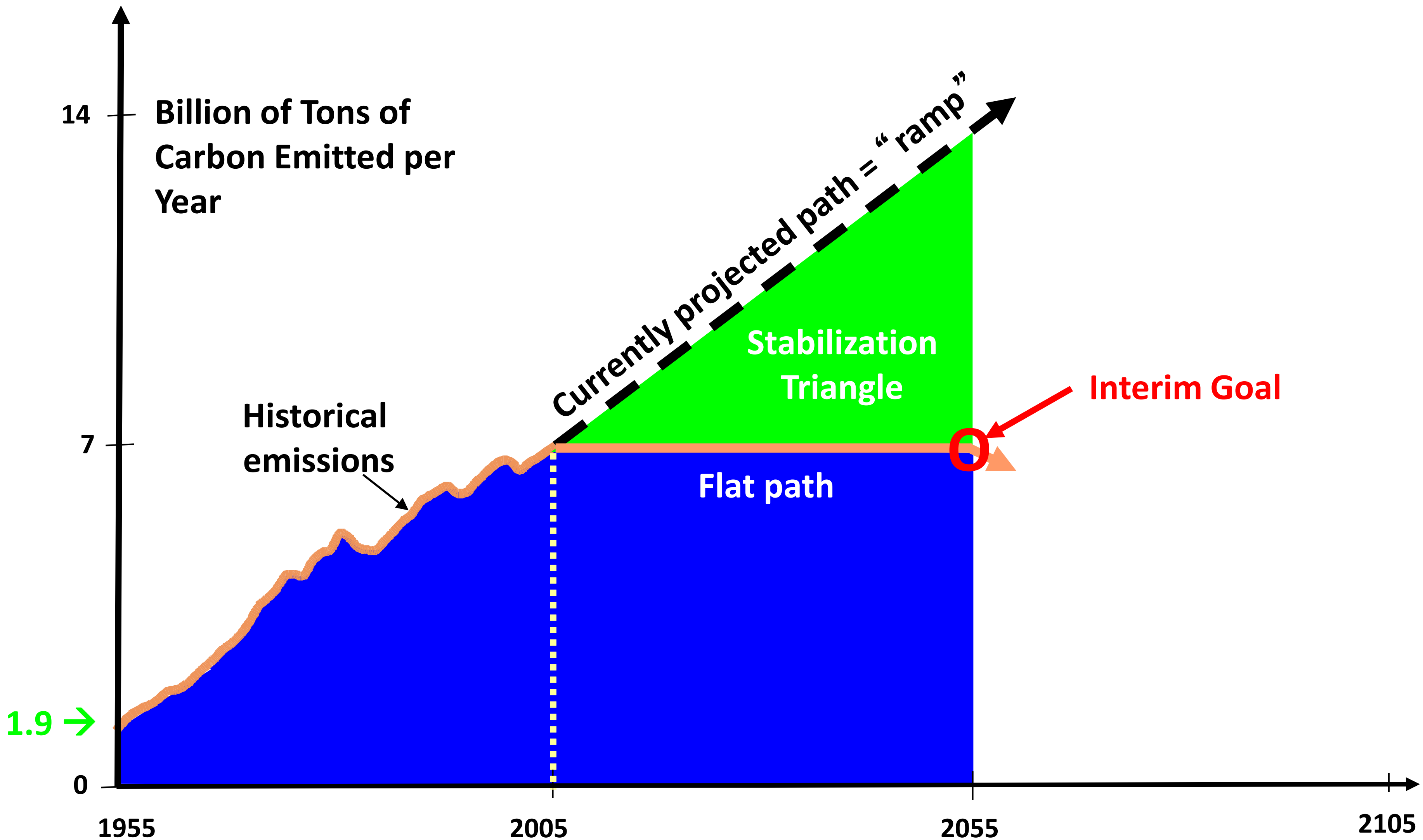
IPCC Synthesis Report, 2008.

Past Emissions



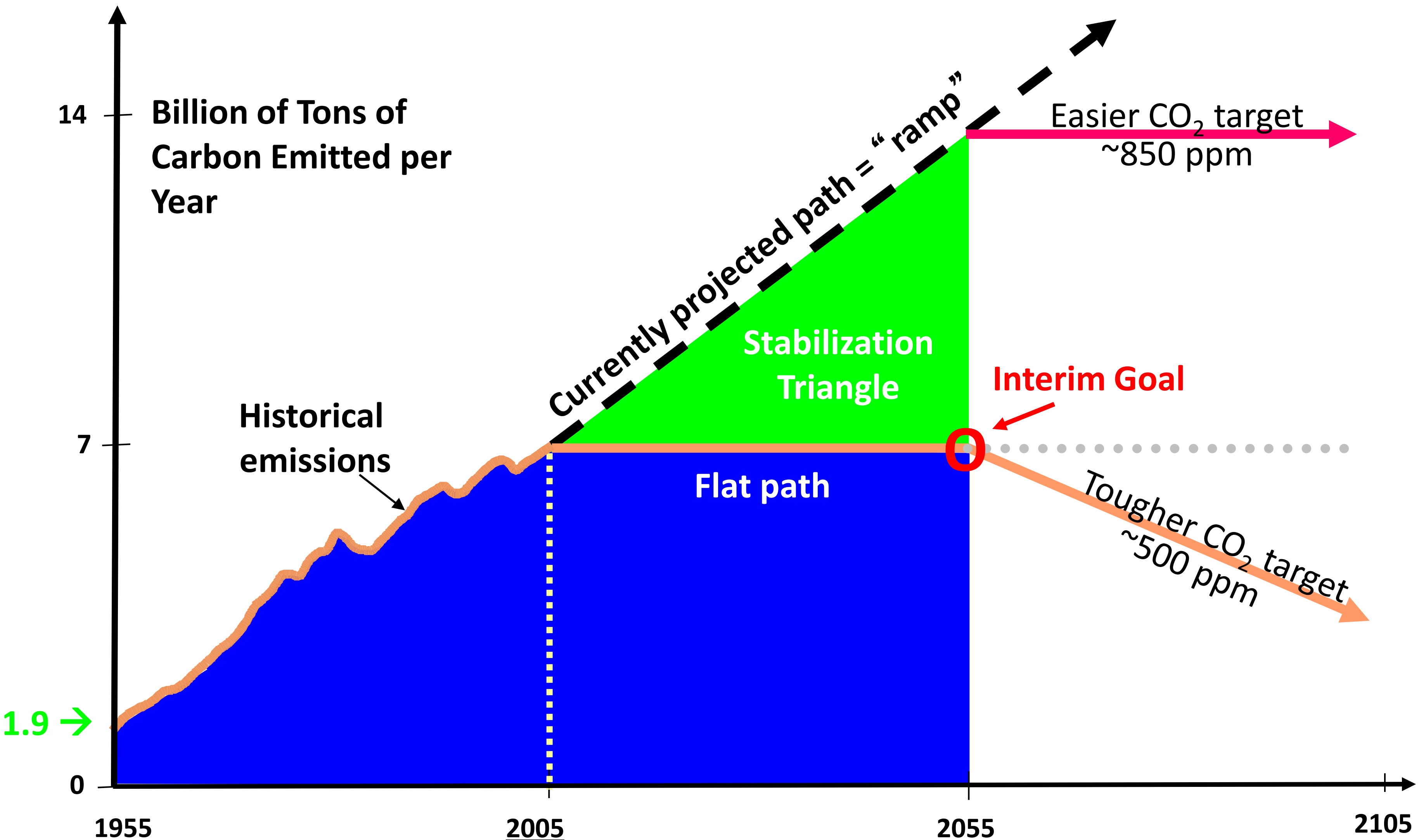
After Socolow and Pacala

The Stabilization Triangle



After Socolow and Pacala

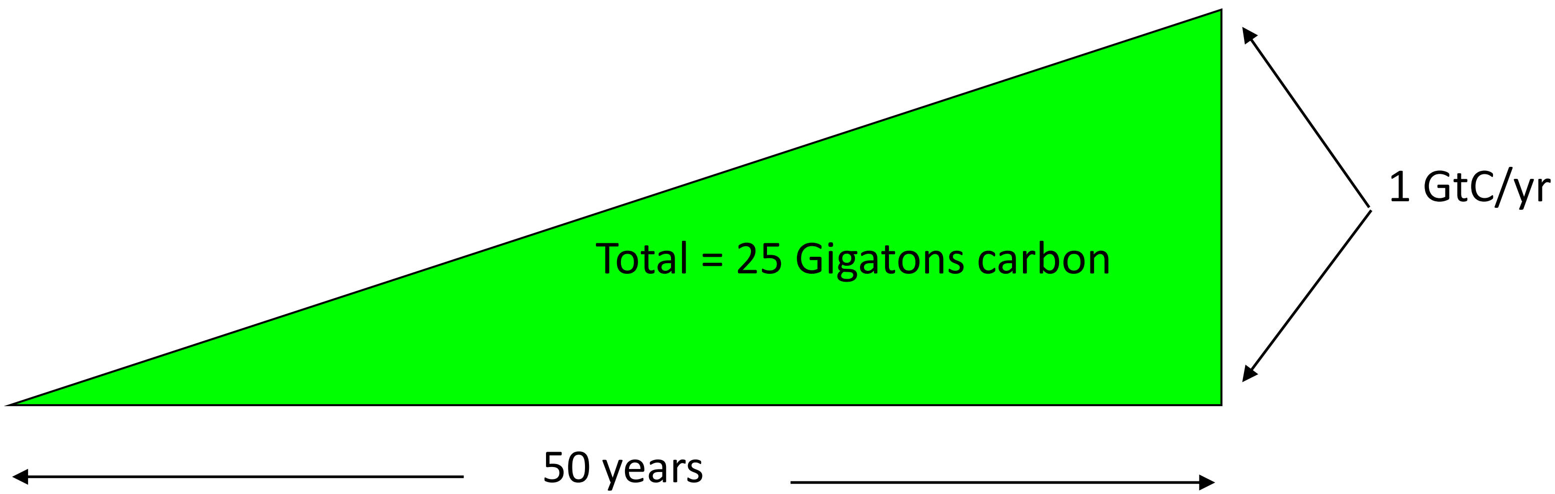
Beat doubling or accept tripling



What is a wedge and does it help us think about this problem?

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.

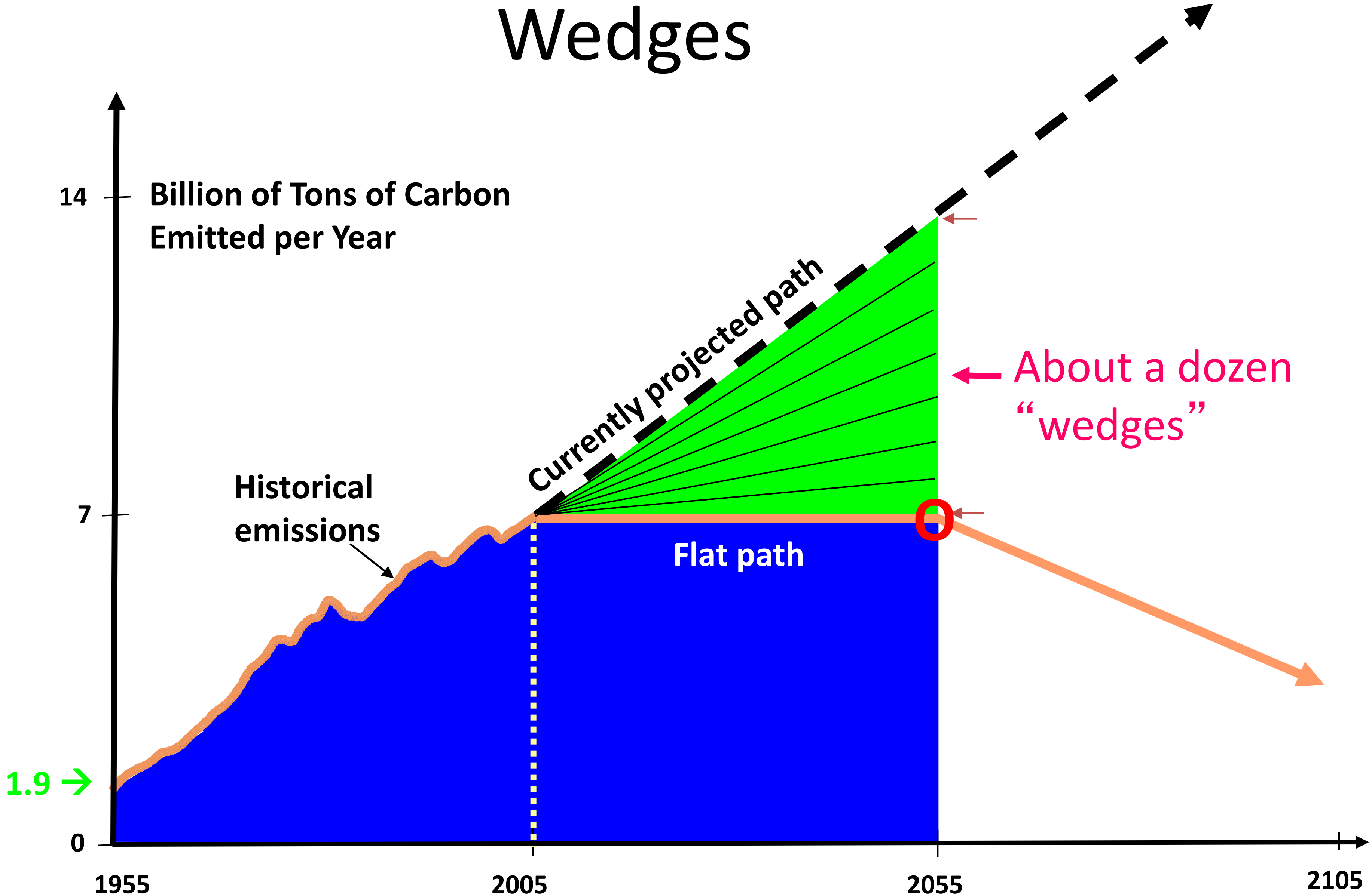


Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years.

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

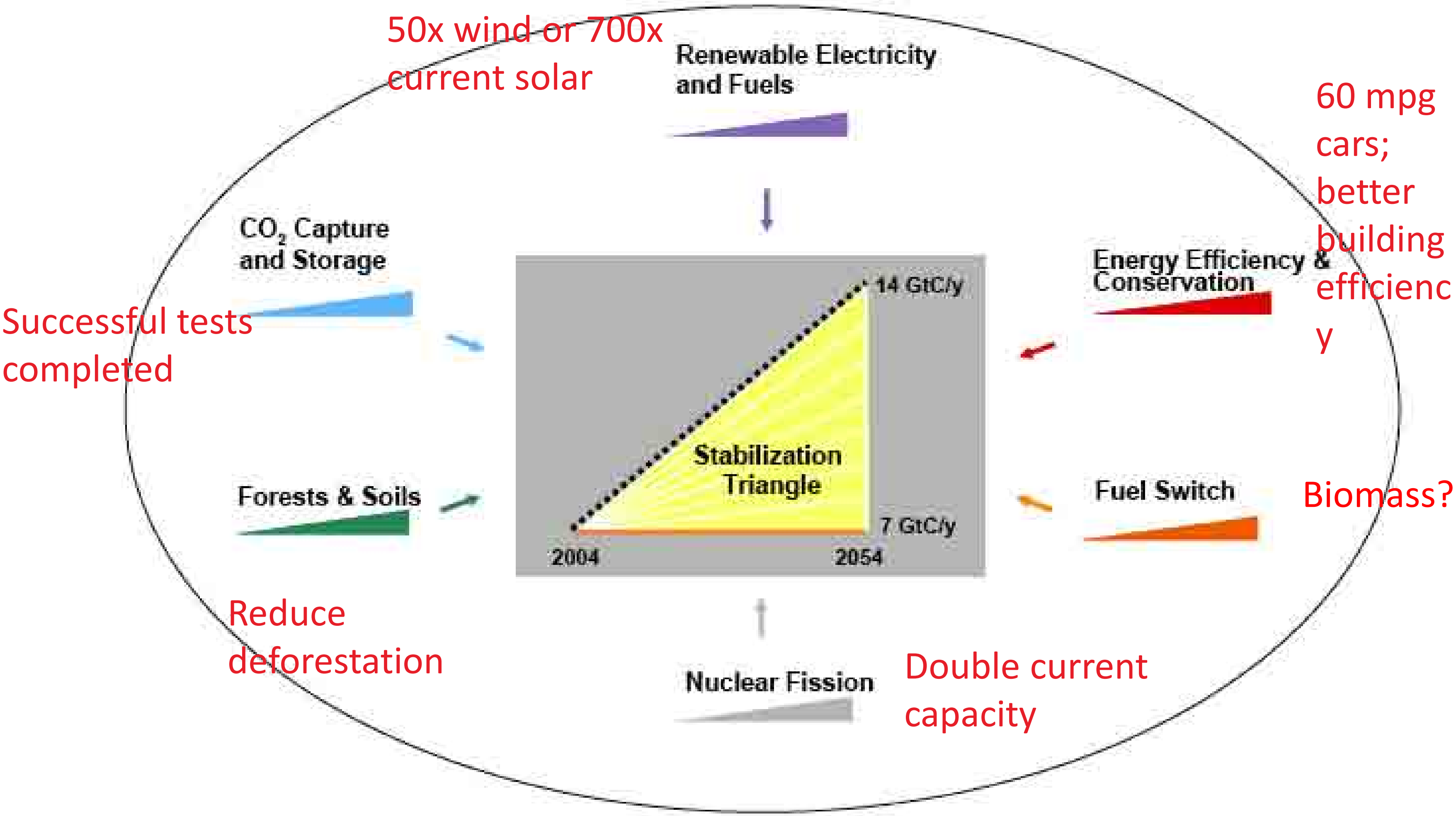
After Socolow and Pacala

Wedges



After Socolow and Pacala

A Range of Future Choices



There are no silver bullets but there is much silver buckshot. Why do some economists object to the wedge concept? What will it take to realize a few wedges?

After Socolow and Pacala

Table 4.2 *Selected examples of key sectoral mitigation technologies, policies and measures, constraints and opportunities. {WGIII Tables SPM.3, SPM.7}*

Sector	Key mitigation technologies and practices currently commercially available. *Key mitigation technologies and practices projected to be commercialised before 2030 shown in italics.*	Policies, measures and instruments shown to be environmentally effective	Key constraints or opportunities (Normal font = constraints; *italics = opportunities*)
Energy Supply {WGIII 4.3, 4.4}	Improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; renewable heat and power (hydropower, solar, wind, geothermal and bioenergy); combined heat and power; early applications of carbon dioxide capture and storage (CCS) (e.g. storage of removed CO_2 from natural gas); *CCS for gas, biomass and coal-fired electricity generating facilities; advanced nuclear power; advanced renewable energy, including tidal and wave energy, concentrating solar, and solar photovoltaics*	Reduction of fossil fuel subsidies; taxes or carbon charges on fossil fuels	Resistance by vested interests may make them difficult to implement
		Feed-in tariffs for renewable energy technologies; renewable energy obligations; producer subsidies	*May be appropriate to create markets for low-emissions technologies*
Transport {WGIII 5.4}	More fuel-efficient vehicles; hybrid vehicles; cleaner diesel vehicles; biofuels; modal shifts from road transport to rail and public transport systems; non-motorised transport (cycling, walking); land-use and transport planning; *second generation biofuels; higher efficiency aircraft; advanced electric and hybrid vehicles with more powerful and reliable batteries*	Mandatory fuel economy; biofuel blending and CO_2 standards for road transport	Partial coverage of vehicle fleet may limit effectiveness
		Taxes on vehicle purchase, registration, use and motor fuels; road and parking pricing	Effectiveness may drop with higher incomes
		Influence mobility needs through land-use regulations and infrastructure planning; investment in attractive public transport facilities and non-motorised forms of transport	*Particularly appropriate for countries that are building up their transportation systems*
Buildings {WGIII 6.5}	Efficient lighting and daylighting; more efficient electrical appliances and heating and cooling devices; improved cook stoves, improved insulation; passive and active solar design for heating and cooling; alternative refrigeration fluids, recovery and recycling of fluorinated gases; *integrated design of commercial buildings including technologies, such as intelligent meters that provide feedback and control; solar photovoltaics integrated in buildings*	Appliance standards and labelling	Periodic revision of standards needed
		Building codes and certification	*Attractive for new buildings.* Enforcement can be difficult
		Demand-side management programmes	Need for regulations so that utilities may profit
		Public sector leadership programmes, including procurement	*Government purchasing can expand demand for energy-efficient products*
		Incentives for energy service companies (ESCOs)	*Success factor: Access to third party financing*
Industry {WGIII 7.5}	More efficient end-use electrical equipment; heat and power recovery; material recycling and substitution; control of non-CO_2 gas emissions; and a wide array of process-specific technologies; *advanced energy efficiency; CCS for cement, ammonia, and iron manufacture; inert electrodes for aluminium manufacture*	Provision of benchmark information; performance standards; subsidies; tax credits	*May be appropriate to stimulate technology uptake.* Stability of national policy important in view of international competitiveness
		Tradable permits	Predictable allocation mechanisms and stable price signals important for investments
		Voluntary agreements	Success factors include: clear targets, a baseline scenario, third-party involvement in design and review and formal provisions of monitoring, close cooperation between government and industry
Agriculture {WGIII 8.4}	Improved crop and grazing land management to increase soil carbon storage; restoration of cultivated peaty soils and degraded lands; improved rice cultivation techniques and livestock and manure management to reduce CH_4 emissions; improved nitrogen fertiliser application techniques to reduce N_2O emissions; dedicated energy crops to replace fossil fuel use; improved energy efficiency; *improvements of crop yields*	Financial incentives and regulations for improved land management; maintaining soil carbon content; efficient use of fertilisers and irrigation	*May encourage synergy with sustainable development and with reducing vulnerability to climate change, thereby overcoming barriers to implementation*
Forestry/forests {WGIII 9.4}	Afforestation; reforestation; forest management; reduced deforestation; harvested wood product management; use of forestry products for bioenergy to replace fossil fuel use; *tree species improvement to increase biomass productivity and carbon sequestration; improved remote sensing technologies for analysis of vegetation/soil carbon sequestration potential and mapping land-use change*	Financial incentives (national and international) to increase forest area, to reduce deforestation and to maintain and manage forests; land-use regulation and enforcement	Constraints include lack of investment capital and land tenure issues. *Can help poverty alleviation.*
Waste {WGIII 10.4}	Landfill CH_4 recovery; waste incineration with energy recovery; composting of organic waste; controlled wastewater treatment; recycling and waste minimisation; *biocovers and biofilters to optimise CH_4 oxidation*	Financial incentives for improved waste and wastewater management	*May stimulate technology diffusion*
		Renewable energy incentives or obligations	Local availability of low-cost fuel
		Waste management regulations	Most effectively applied at national level with enforcement strategies

IPCC Synthesis Report, 2008.

Climate Change 2008: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Table 4.2, IPCC, Geneva, Switzerland. Used with permission.

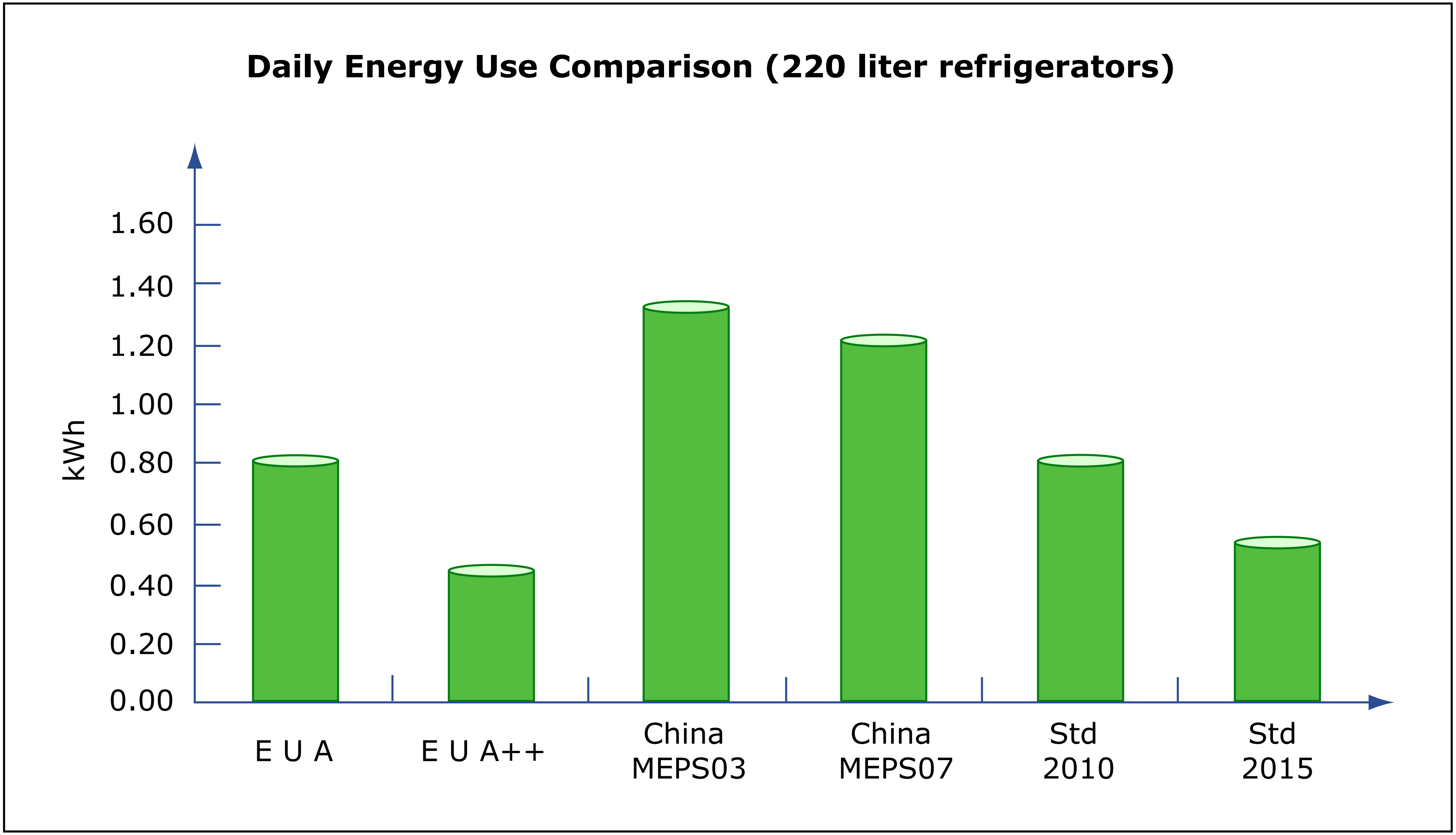
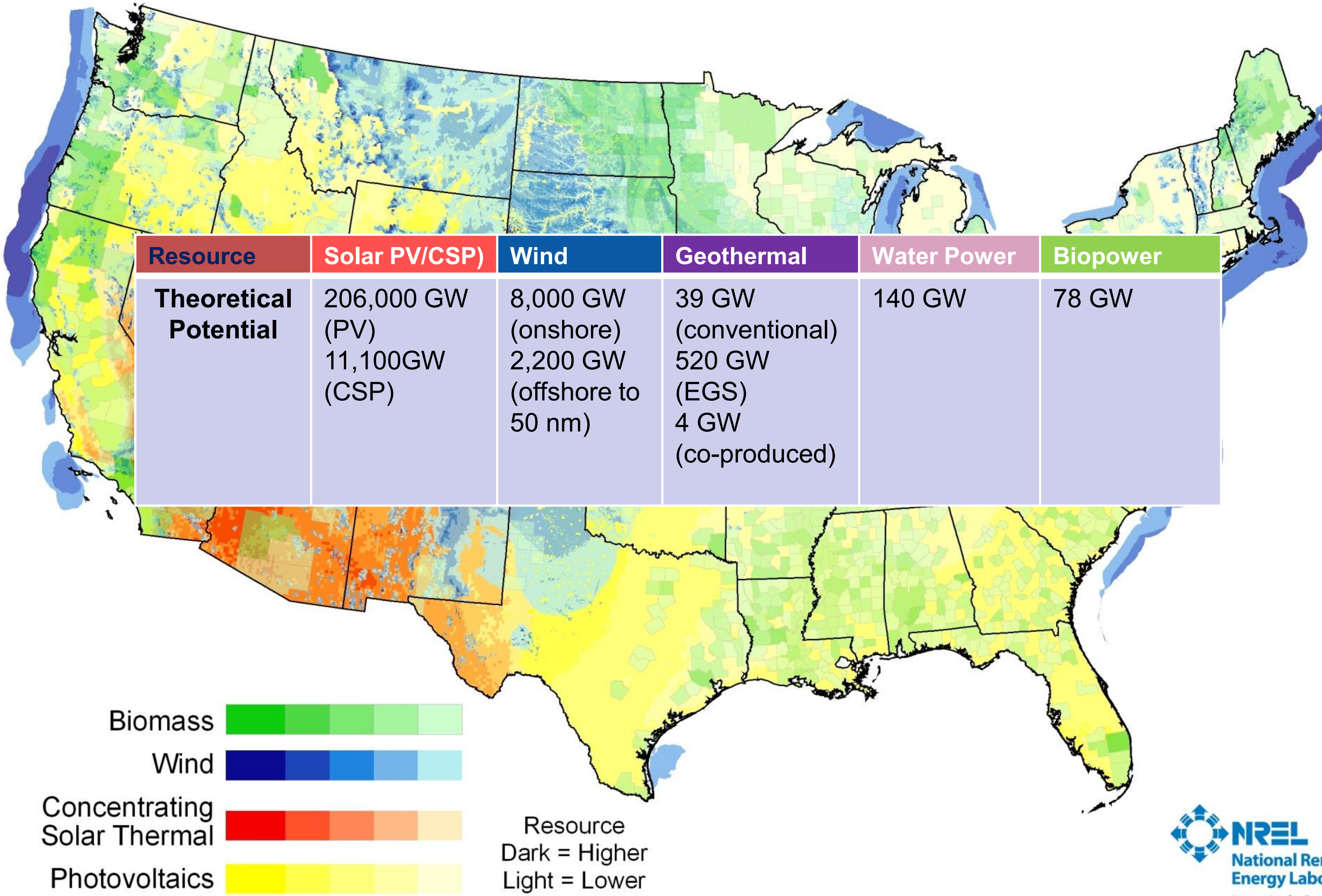


Image by MIT OpenCourseWare.

U.S. Renewable Resources

Current ≈ 3000 GW

Resource	Solar PV/CSP)	Wind	Geothermal	Water Power	Biopower
Theoretical Potential	206,000 GW (PV) 11,100GW (CSP)	8,000 GW (onshore) 2,200 GW (offshore to 50 nm)	39 GW (conventional) 520 GW (EGS) 4 GW (co-produced)	140 GW	78 GW



NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Image courtesy of DOE.

Variable Renewable Resources

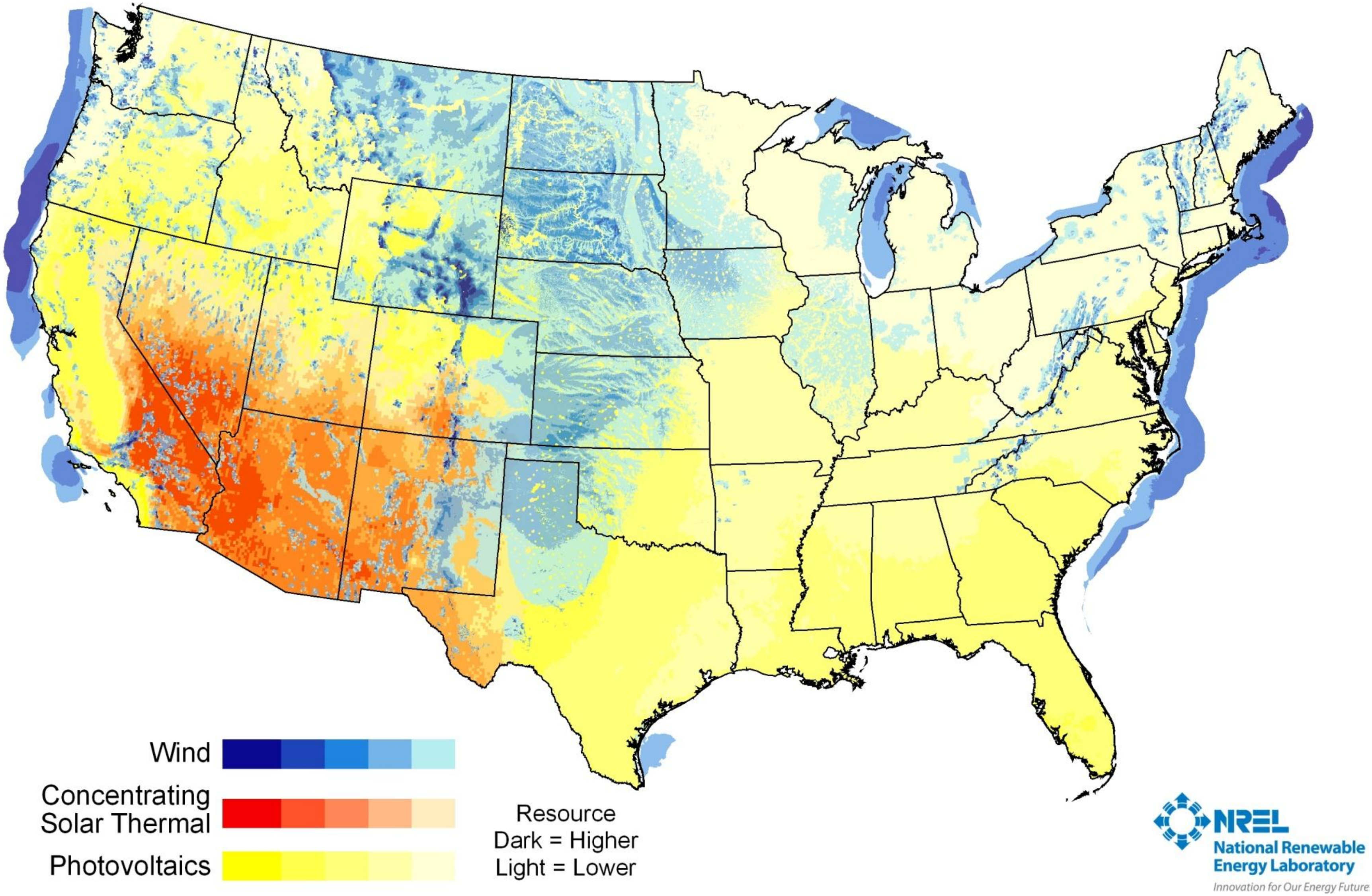


Image courtesy of DOE.

Solar Resource

Meeting all of U.S. demand with current PV technologies would require about 100-200 m2 per person (average).

Variable source

Storage?

SmartGrid?

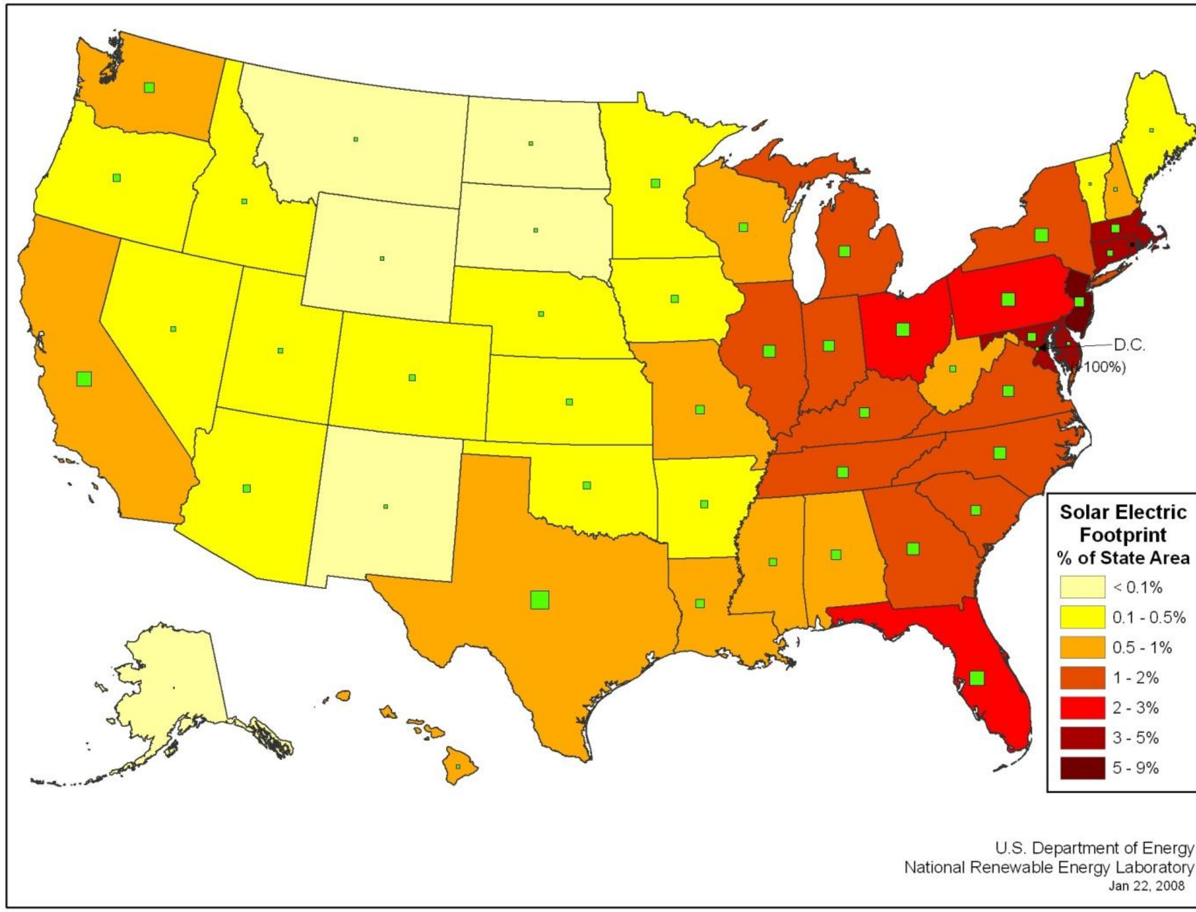
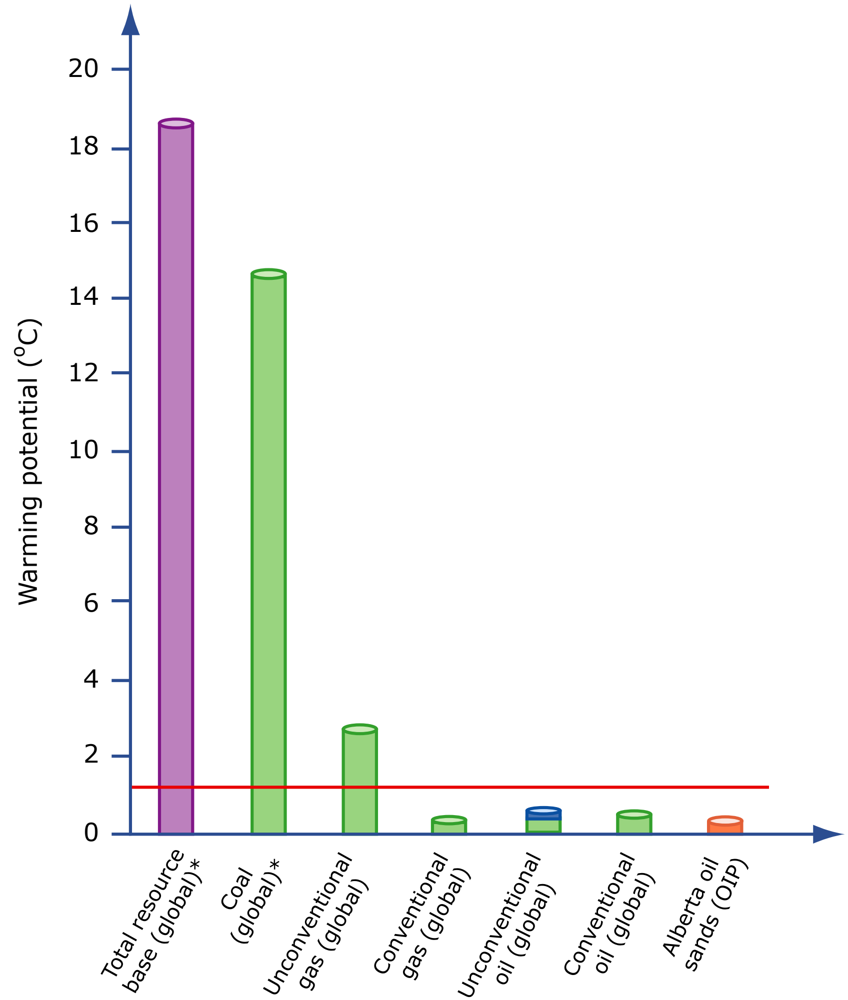


Image courtesy of DOE.

(With biomass, it requires 7000-9000 m2/person, or about 50% of the state area). What other factors make biomass controversial?



Central estimate of the potential for warming of the different fossil-fuel resources
The red line indicates the limit of 2.0 ^{o}C warming from pre-industrial times agreed to under the Copenhagen Accord. Note, that here we only consider the effects of anthropogenic carbon dioxide. The potential for warming associated with proven Alberta oil-sand reserves is indicated as a barely visible sub-component (shown in blue) of unconventional oil (global). The potential warming of the total Alberta oil-sands oil-in-place (OIP) is shown in orange. *The carbon-climate response method is not valid for emissions above about 20×10^{17} g C, so these figures are not valid climate change estimates, but are included for comparison.

Image by MIT OpenCourseWare.

Need for carbon capture and storage?

This image has been removed due to copyright restrictions. Please see the image on page http://www.nationalgrid.com/corporate/About+Us/climate/CCS2/.

Snake Oil or Solution?

$$\underset{\text{Mg-olivine}}{Mg_2SiO_4} + 2CO_2 = \underset{\text{magnesite}}{2MgCO_3} + \underset{\text{quartz}}{SiO_2} \quad [2a]$$

$$\underset{\text{Mg-olivine}}{Mg_2SiO_4} + \underset{\text{CaMg-pyroxene}}{CaMgSi_2O_6} + 2CO_2 + 2H_2O$$
$$= \underset{\text{serpentine}}{Mg_3Si_2O_5(OH)_4} + \underset{\text{calcite}}{CaCO_3} + \underset{\text{magnesite}}{MgCO_3} \quad [2b]$$

This image has been removed due to copyright restrictions. Please see the image on page http://www.travelforboomers.com/wp-content/upl oads/2012/05/Green-sand-beach1.png.

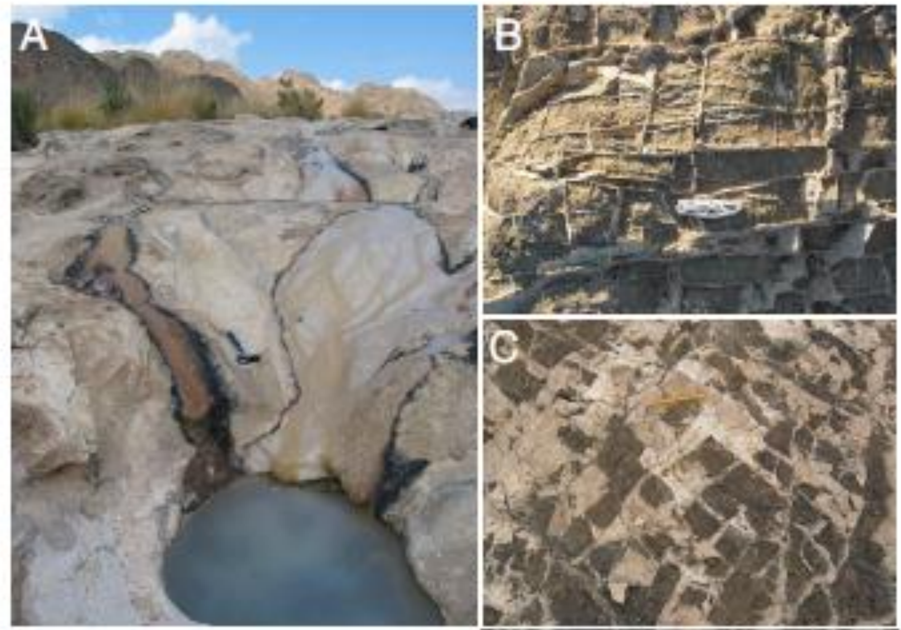


Fig. 1. Photographs of travertine and carbonate veins in Oman. (*A*) Actively depositing travertine near the village of Falaij (22.846°N, 58.056°E) with rock hammer for scale, altered peridotite in the background. (*B*) White carbonate veins weathering out in positive relief in altered peridotite at "Duck" (22.815°N, 58.838°E) with pocket knife for scale. (*C*) White carbonate veins in altered peridotite north of the village of Batin (22.925°N, 58.671°E) with pencil for scale.

Olivine beaches everywhere?

Global anthropogenic GHG emissions

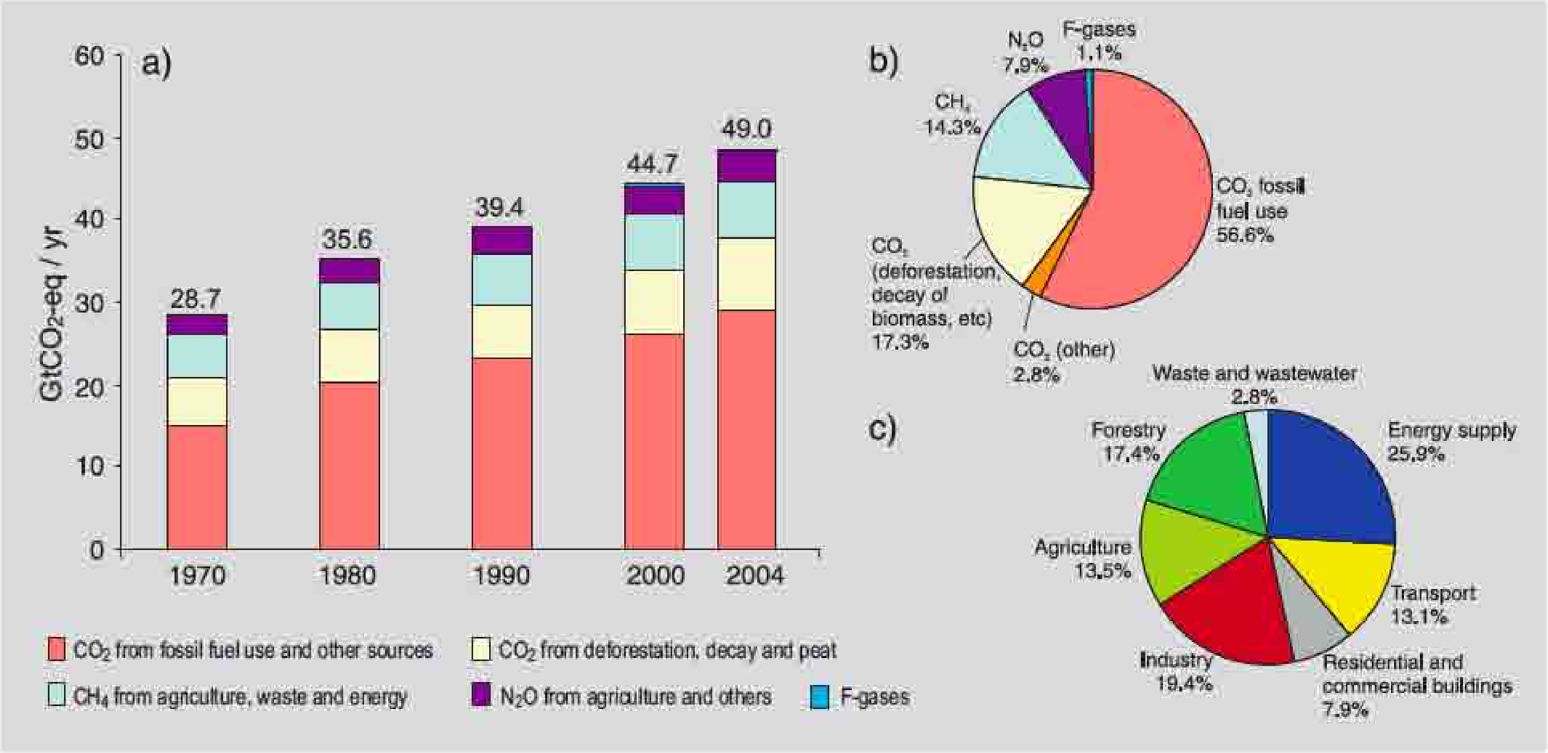


Figure 2.1. *(a) Global annual emissions of anthropogenic GHGs from 1970 to 2004.[5] (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq. (Forestry includes deforestation.) {WGIII Figures TS.1a, TS.1b, TS.2b}*

IPCC Synthesis Report, 2008.

This image has been removed due to copyright restrictions. Please see Figure 1 of the paper Shindell et al. "Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security". *Science* (2012).

Clean-burning stoves: benefits for health and air quality as well as climate

This image has been removed due to copyright restrictions.
Please see the image on page http://www.zomppa.com/wp-content/uploads/2012/02/Global-Alliance-for-Clean-Cookstoves-Poster-2.jpg

This image has been removed due to copyright restrictions.
Please see the image on page http://www.rockflower.org/v/vspfiles/assets/images/dfstove3.jpg

‘Methane Only’: Technical measures for methane emissions

1. Extended recovery of **coal mine** gas
2. Extended recovery and flaring (instead of venting) of associated gas from **production of crude oil and natural gas**
3. Reduced **gas leakage** at compressor stations in long-distance gas transmission pipelines
4. Separation and treatment of biodegradable **municipal waste** through recycling, composting and anaerobic digestion
5. Upgrading primary **wastewater treatment** to secondary/tertiary treatment with gas recovery and overflow control
6. Control of methane emissions from **livestock**, mainly through farm-scale **anaerobic digestion** of manure from cattle and pigs with liquid manure management
7. Intermittent aeration of continuously flooded **rice paddies**

UNEP: Shindell et al, 2011

‘BC Tech’: Technical measures for black carbon

1. Replacing **traditional coke ovens** with modern recovery ovens, including the improvement of end-of-pipe abatement measures (in developing countries)
2. Replacing **traditional brick kilns** with vertical shaft kilns and Hoffman kilns where considered feasible (in developing countries)
3. **Diesel particle filters** for road vehicles and off-road mobile sources (excluding shipping)
4. Particle control at **stationary engines**
5. **Improved stoves** in developing countries in residential sector

UNEP: Shindell et al, 2011

Let's discuss…

This image has been removed due to copyright restrictions.
Please see the image on page http://www.thebreakthrough.org/blog/wedges.JPG