The Kyoto Protocol and the Science of CO_2 Stabilization

AOSC 433/633 & CHEM 433

Ross Salawitch

Class Web Site: **http://www.atmos.umd.edu/~rjs/class/spr2015**

Topics for today:

- **Fossil Fuel Sources (continued)**
- **Obama / Xi Accord**
- **Kyoto Protocol**
- **Carbon Sequestration (a few options)**

433 students who are not doing a paper / presentation:
Please have a look at Problem Set 6, which has been posted

Lecture 18
21 April 2015

Atmos Chem & Clim Projects

433:

Dan Eiblum: Climate Change Impact on Air Quality

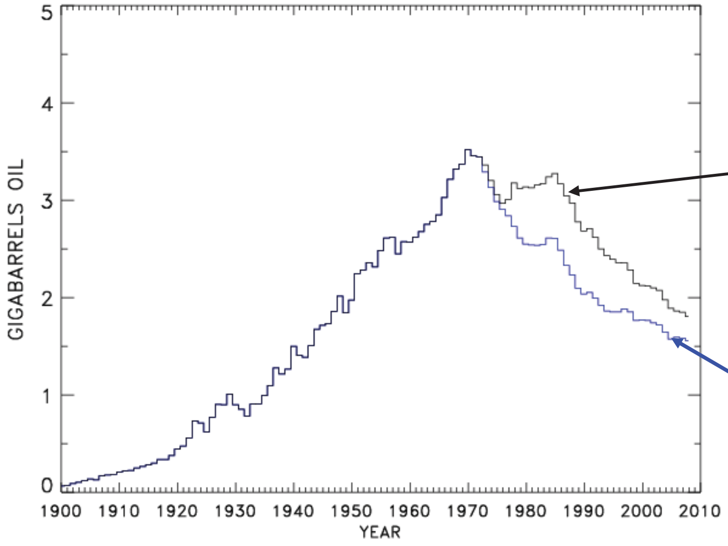
Others ???

633:

Doyeon Ahn: ???
Brian Bennett: ???
Tyler Bodnar: Nuclear Energy
Grace Duke: Impact of SPCZ winds on CO_2 uptake
Colleen Fanelli: ???
Xinzhou Huang: ???
Yunyao Li: Transports of Trace Species by Deep Convection
Maggie Marvin: Formation mechanisms SOA
Gina Mazzuca: ???
Sandra Roberts: ???
Adria Schwarber: Carbon capture and sequestration
Pam Wales: ???

Peak Oil

In the 1950s, Dr. M King Hubbert applied this analysis to the lower 48 United States.   By estimating oil reserves and the maximum production rate, he predicted that US oil would peak in the early 1970's.



The addition of oil from Alaska adds a secondary peak in the mid 1980s. However, oil is still decreasing.

Lower 48 states

United states annual rate of production

http://tonto.eia.doe.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm

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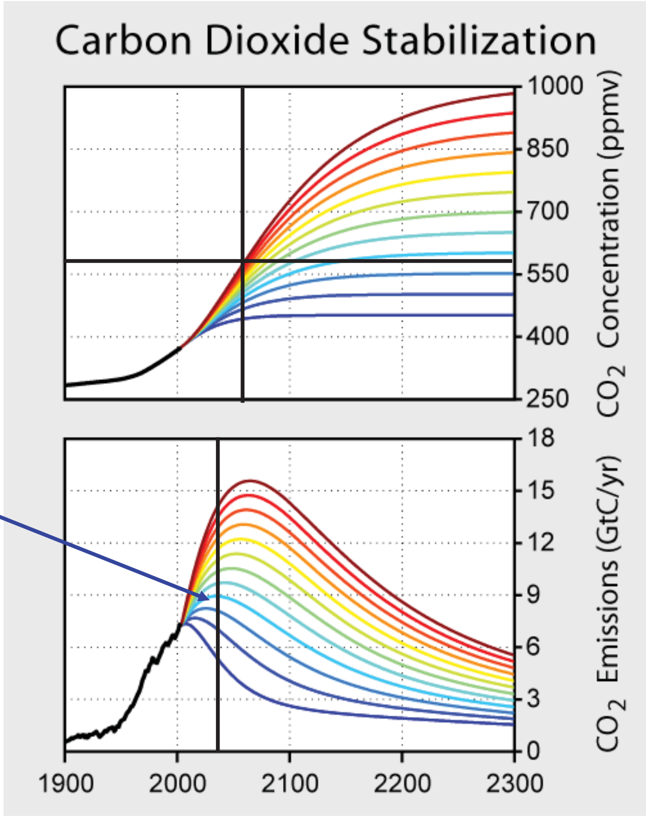
CO_2 is long lived: society must reduce emissions soon or we will be committed to dramatic, future increases!

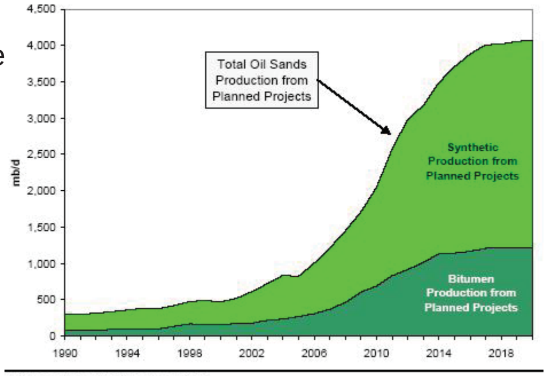


Curve that levels off at ~560 ppm
has emissions peaking ~2030
Less than 20 years from now !

Image: “Global Warming Art” : http://www.globalwarmingart.com/wiki/Image:Carbon_Stabilization_Scenarios_png

Canadian oil sands (tar sands)

- May represent 2/3 of world's total petroleum resource
- Not considered in many estimates of fossil fuel reserve
- Because of oil sands production, **Canada is largest supplier of oil to US**
- "Gold rush" like economic boom in Alberta Canada
- Fossil fuel extraction energy and water intensive: forests flattened and large waste water lakes created



RJ Research estimates and analysis

See http://en.wikipedia.org/wiki/Tar_sands and http://oilsands.alberta.ca/ for more info.

Future Use of Fossil Fuels

- If society decides to continue to reply on fossil fuels, we will become increasingly reliant on (in the short term) and (in the long term)

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- Coal is a complex mixture of substances that can be approximated by the chemical formula $\mathbf{C_{135}H_{96}O_9NS}$. The elements come from prehistoric plant material.
- Coal may also contain, among other elements, copper, arsenic, lead, mercury, and uranium.
- Higher grades of coal, bituminous and anthracite, have been exposed to higher pressure and have less oxygen. Anthracite has less sulfur. **U.S. supply of anthracite is nearly exhausted.**
- The oxymoron “clean coal” means different things to different people

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- The oxymoron “clean coal” means different things to different people
- **Nonetheless, nearly everyone would genuinely consider coal to be “clean” compared to oil sands ☹**

Future Use of Fossil Fuels

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Why else might reliance on coal and oil sands be a concern?

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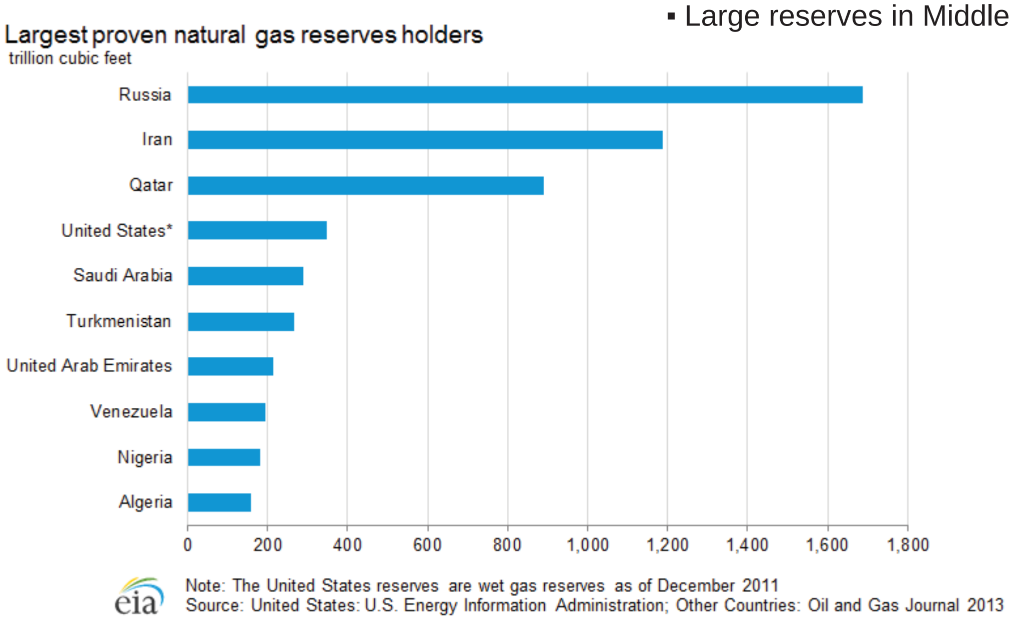
Why else might reliance on coal and oil sands be a concern?

Fossil Fuel	**GHG Output (pounds CO_2 per kWh)**
Oil Sands	**5.6**
Coal	**2.1**
Oil	**1.9**
Gas	**1.3**

http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html
http://www.iop.org/EJ/abstract/1748-9326/4/1/014005

Natural Gas

- Large reserves in Middle East & Russia.



Note: The United States reserves are wet gas reserves as of December 2011
Source: United States: U.S. Energy Information Administration; Other Countries: Oil and Gas Journal 2013

http://www.eia.gov/countries/cab.cfm?fips=rs

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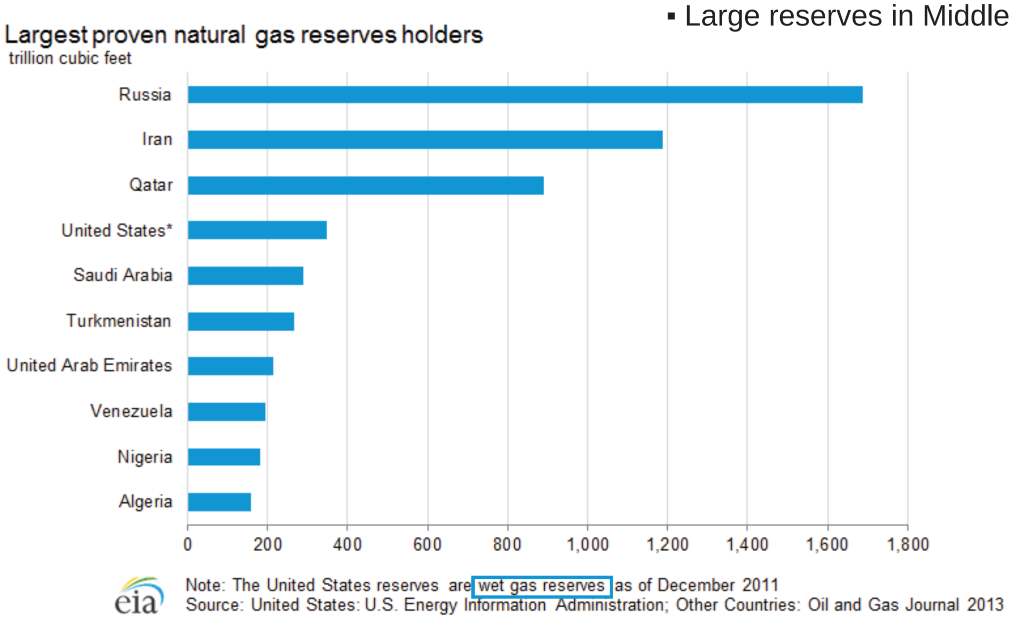
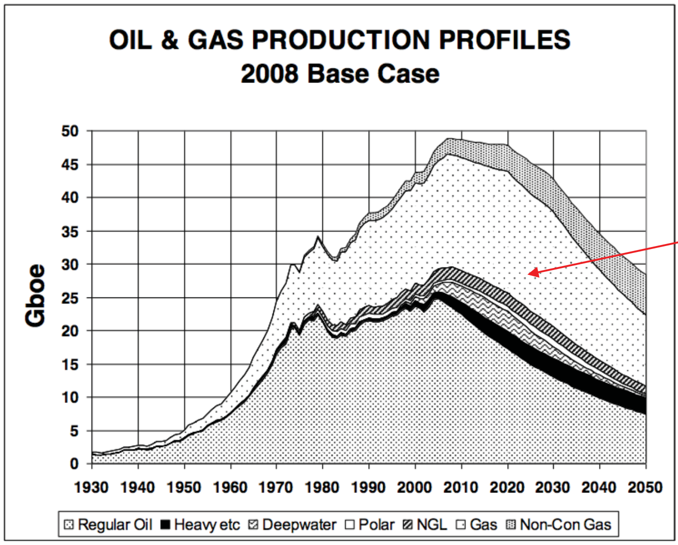


Note: The United States reserves are wet gas reserves as of December 2011
Source: United States: U.S. Energy Information Administration; Other Countries: Oil and Gas Journal 2013

Wet reserves: CH_4, ethane (C_2H_6), and butane (C_4H_{10})
Dry reserves: nearly all CH_4

http://www.eia.gov/countries/cab.cfm?fips=rs

Natural Gas



- Most reserves in Middle East & Russia.
- Hubbert analysis indicates peak of gas production around 2020

http://gailtheactuary.files.wordpress.com/2010/11/colin-campbell-april-2009-forecast.png

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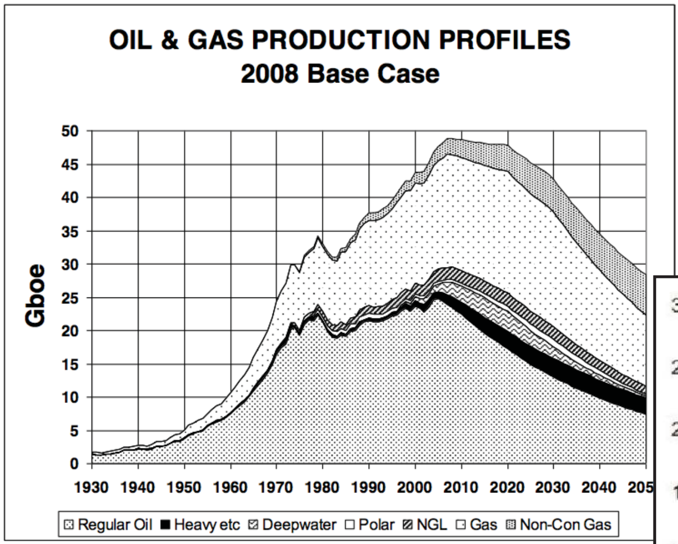
Natural Gas



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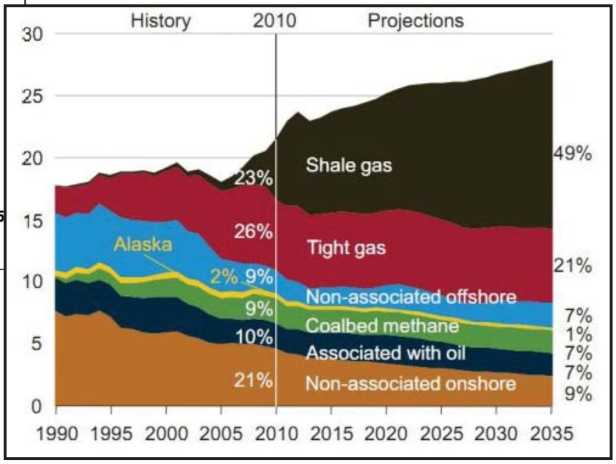
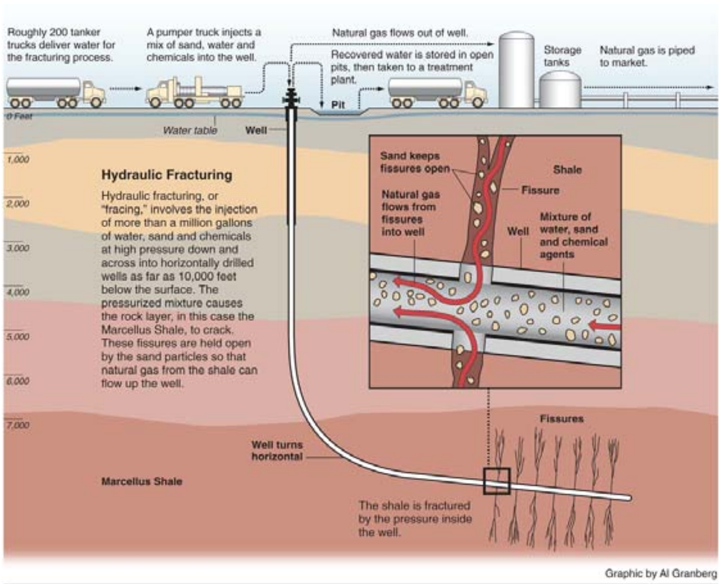
Recent EIA Projection, US



http://www.lngworldnews.com/usa-eia-expects-huge-rise-in-natural-gas-production
http://oilprice.com/Energy/Natural-Gas/The-Differences-In-Fracking-Tight-Sand-And-Shales.html

Natural Gas: Fracking



- Pumping of chemical brine to loosen deposits of natural gas from shale
- Marcellus Shale in Penn, NY and NJ is major source region

Image: http://www.propublica.org/images/articles/natural_gas/marcellus_hydraulic_graphic_090514.gif

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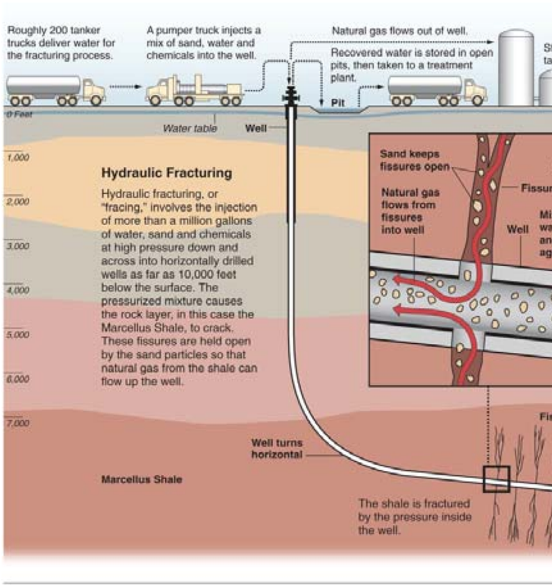
Natural Gas: Fracking



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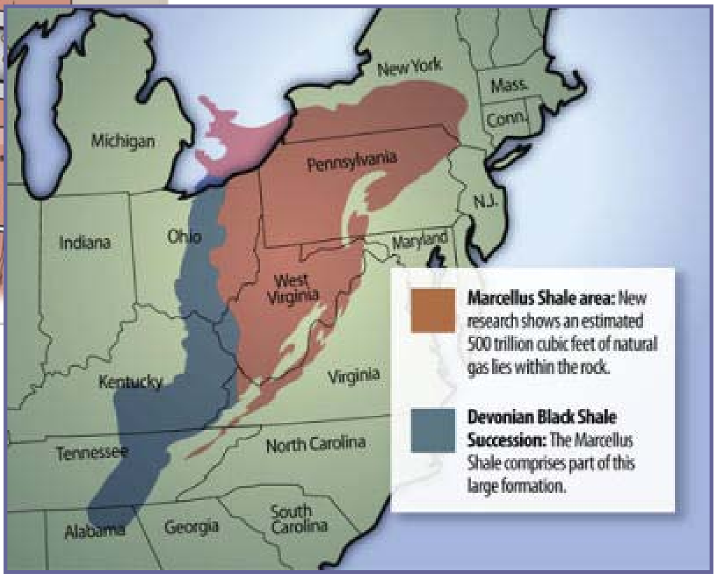
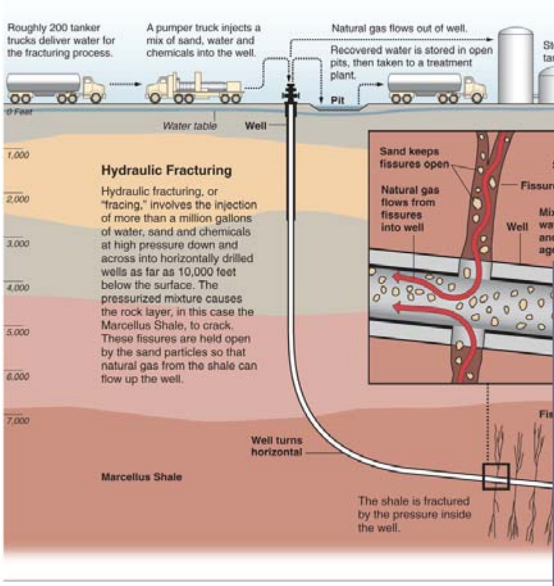


http://akrondave.files.wordpress.com/2011/01/marcellus-shale.jpg

Natural Gas: Fracking



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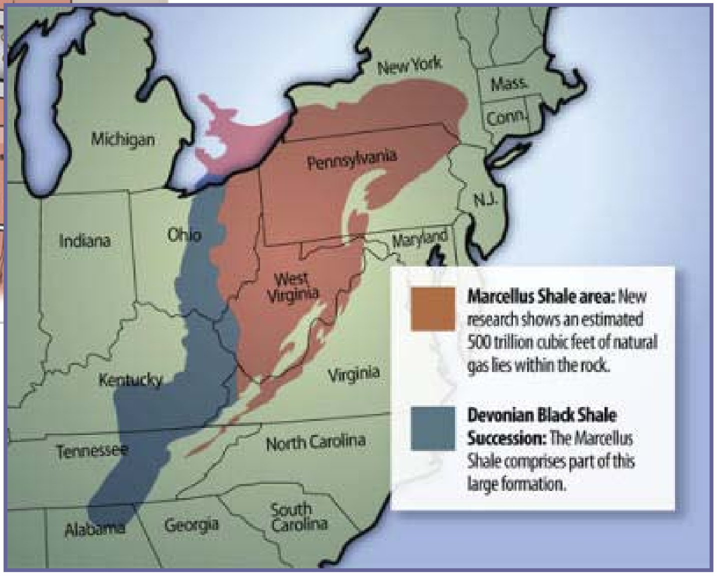

We'll have a lecture devoted to fracking on Thurs, 30 April

http://akrondave.files.wordpress.com/2011/01/marcellus-shale.jpg

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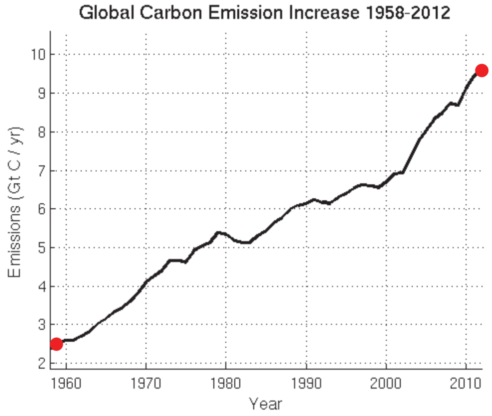
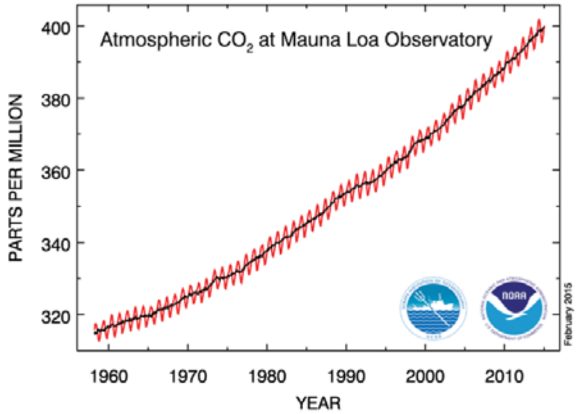
Fossil Fuel Emissions



Fossil fuel emissions, 1959 = **2.5** Gt C
2012 = **9.7** Gt C

What are the primary driving factors for this rise?

How can we quantify standard of living versus population growth contribution to this rise?



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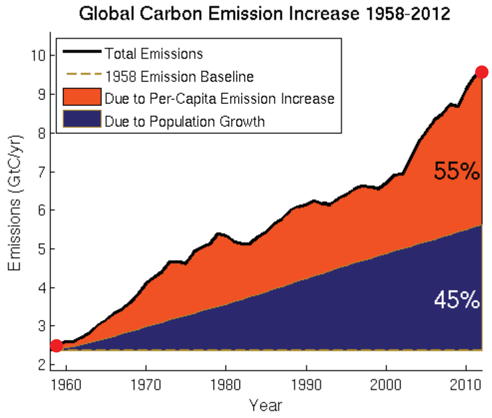

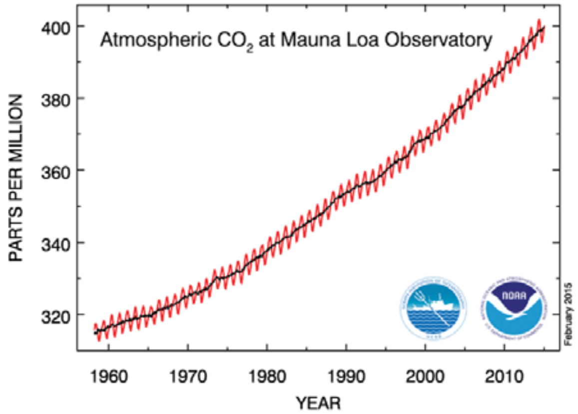

Fossil fuel emissions, 1959 = **2.5** Gt C
2012 = **9.7** Gt C

Population increase & **per-capita rise** both contribute, with per-capita rise being somewhat more important

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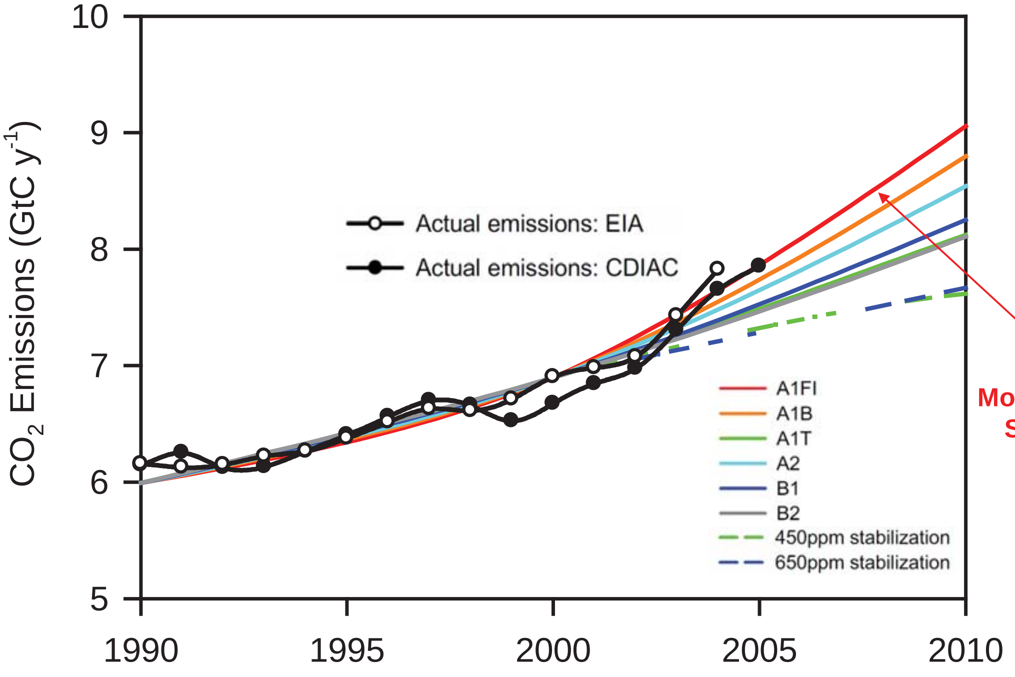
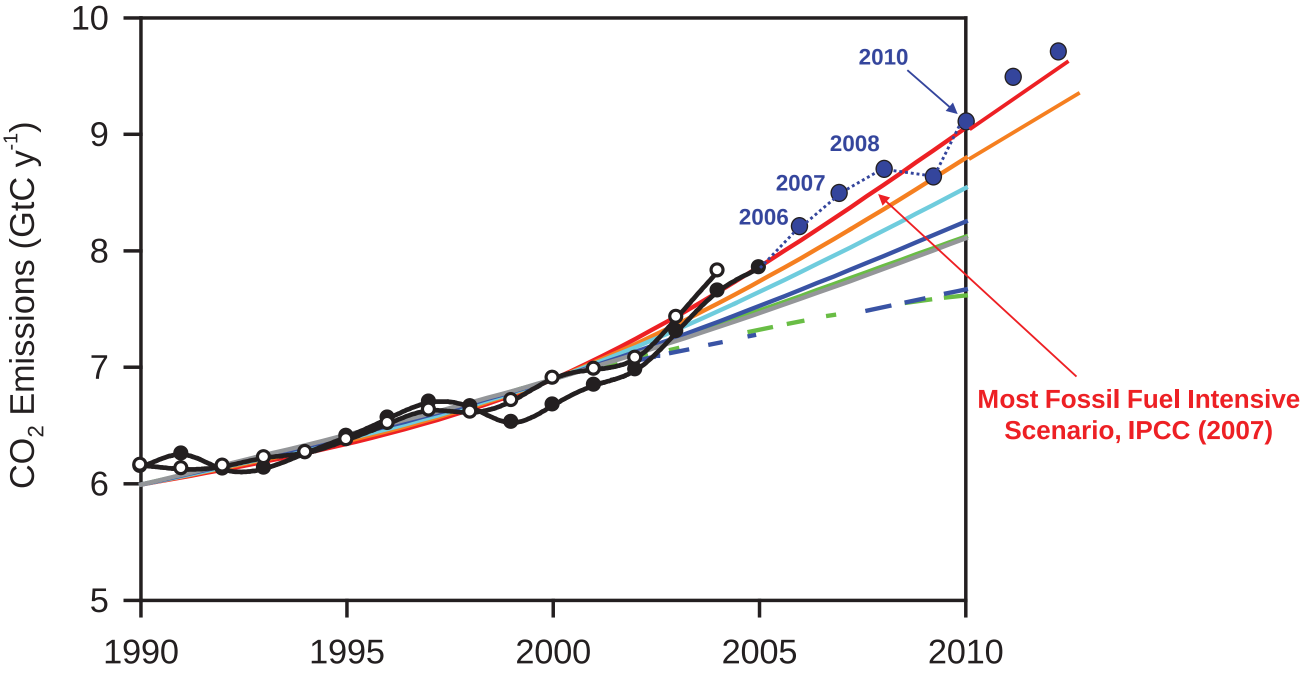
Global Fossil Fuel Emissions



Most Fossil Fuel Intensive Scenario, IPCC (2007)

Raupach *et al.*, *PNAS*, 2007

Global Fossil Fuel Emissions



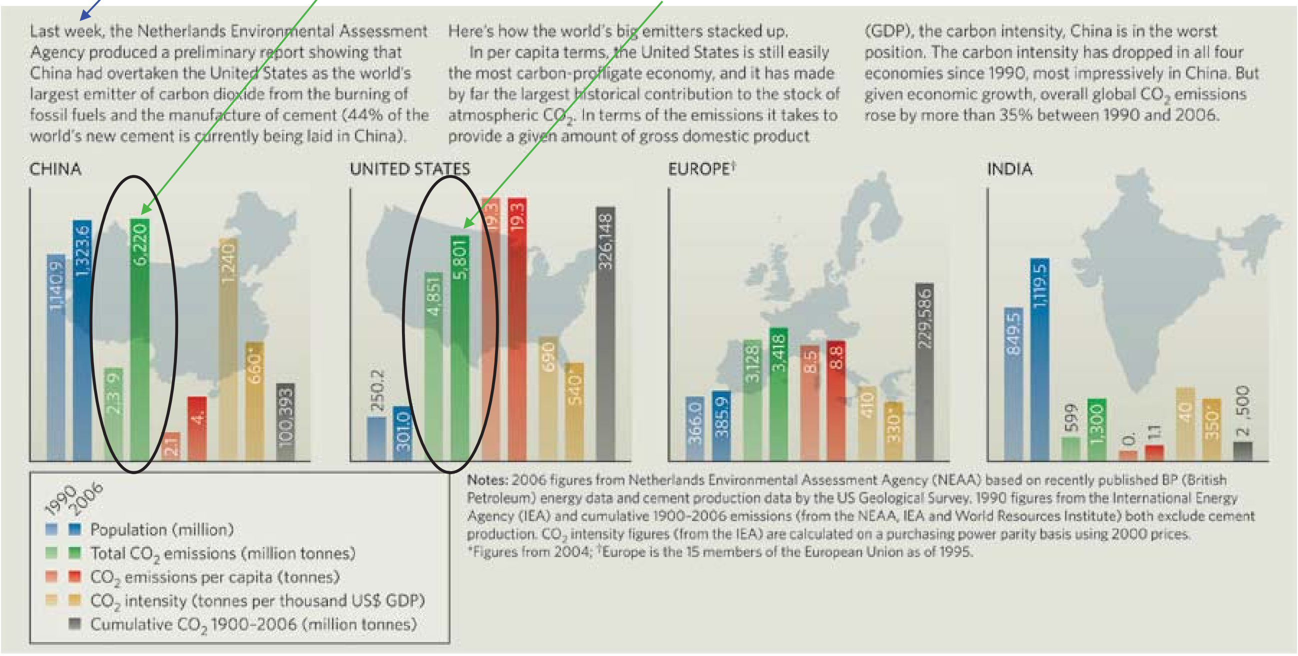
Raupach *et al.*, *PNAS*, 2007
(updated)

World Carbon Emissions

20 June 2007

China: 1.70 Gt C per year

US: 1.58 Gt C per year



Last week, the Netherlands Environmental Assessment Agency produced a preliminary report showing that China had overtaken the United States as the world's largest emitter of carbon dioxide from the burning of fossil fuels and the manufacture of cement (44% of the world's new cement is currently being laid in China).

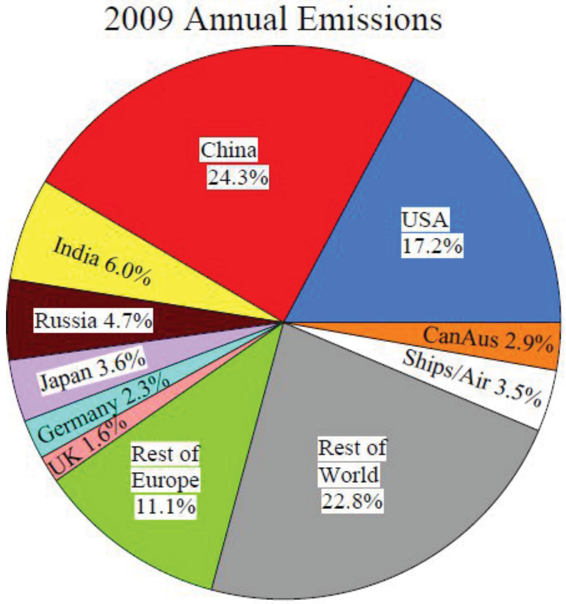
Here's how the world's big emitters stacked up.

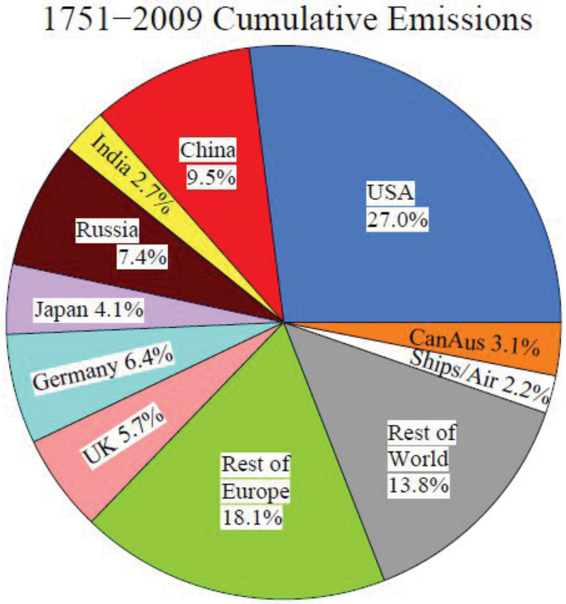
In per capita terms, the United States is still easily the most carbon-profligate economy, and it has made by far the largest historical contribution to the stock of atmospheric CO_2. In terms of the emissions it takes to provide a given amount of gross domestic product (GDP), the carbon intensity, China is in the worst position. The carbon intensity has dropped in all four economies since 1990, most impressively in China. But given economic growth, overall global CO_2 emissions rose by more than 35% between 1990 and 2006.

Notes: 2006 figures from Netherlands Environmental Assessment Agency (NEAA) based on recently published BP (British Petroleum) energy data and cement production data by the US Geological Survey. 1990 figures from the International Energy Agency (IEA) and cumulative 1900–2006 emissions (from the NEAA, IEA and World Resources Institute) both exclude cement production. CO_2 intensity figures (from the IEA) are calculated on a purchasing power parity basis using 2000 prices. *Figures from 2004; †Europe is the 15 members of the European Union as of 1995.

Source: http://www.nature.com/nature/journal/v447/n7148/fig_tab/4471038a_F1.html

Carbon Emissions





http://transitionvoice.com/wp-content/uploads/2010/12/Hansen-12-6-10-figure-1.jpeg

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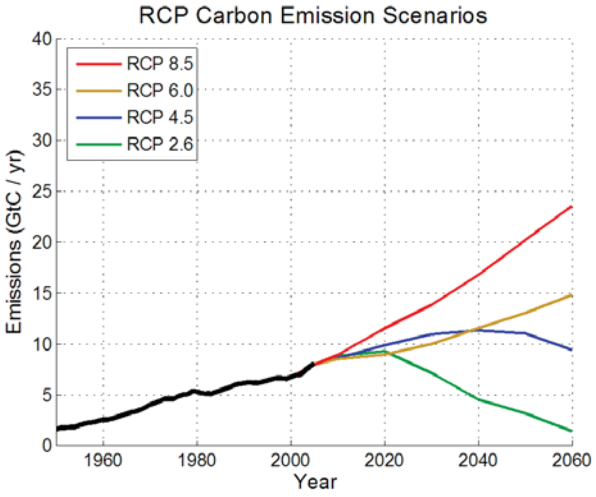
Obama – Xi Accord

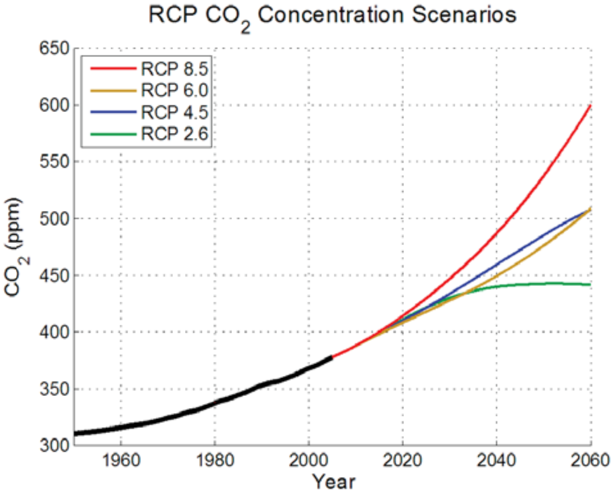
- The Presidents of the United States and China announced their respective post-2020 actions on climate change, recognizing that these actions are part of the longer range effort to transition to low-carbon economies, **mindful of the global temperature goal of 2°C**. The **U.S.** intends to achieve an economy-wide target of **reducing emissions by 26% to 28% below its 2005 level in 2025** ; **China** intends to achieve **peaking of CO_2 emissions around 2030** and make best effort to peak early & intends to increase share of non-fossil fuels in primary energy consumption to ~20% by 2030.

- The United States and China hope that by announcing these targets now, they can inject momentum into the global climate negotiations and inspire other countries to join in coming forward with ambitious actions as soon as possible, preferably by the first quarter of 2015 … to reach a successful global climate agreement in Paris in late 2015.

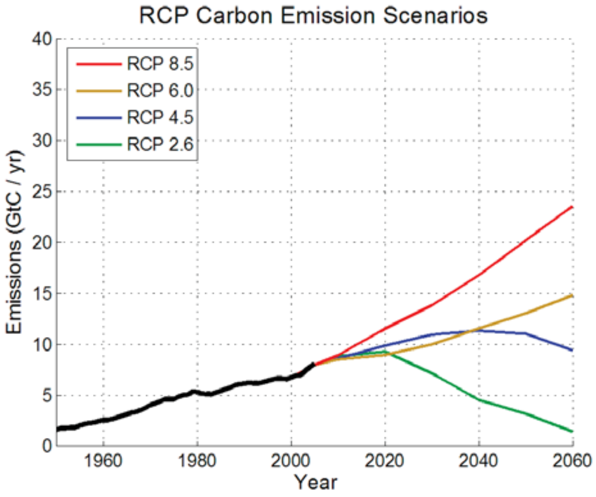
- The two sides have among other things:
  - established the U.S.-China Climate Change Working Group (CCWG), under which they have launched initiatives on vehicles, smart grids, carbon capture, energy efficiency, GHG data management, forests and industrial boilers;
  - agreed to work together towards the global phase down of hydrofluorocarbons (HFCs)
  - created the U.S.-China Clean Energy Research Center, which facilitates collaborative work in carbon capture and storage technologies, energy efficiency in buildings, and clean vehicles; and
  - agreed on a joint peer review of inefficient fossil fuel subsidies under the G-20.

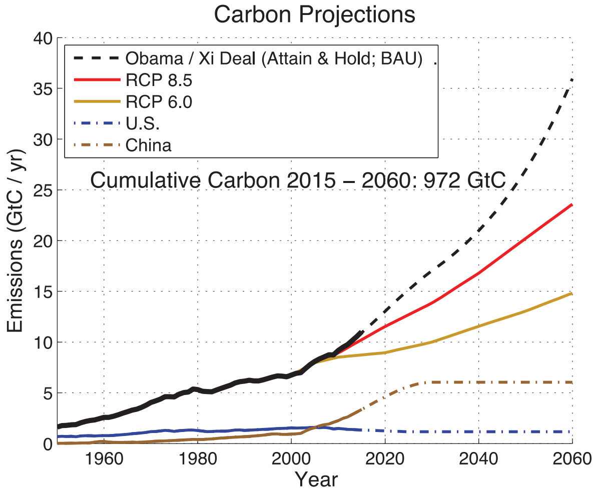
Text: http://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change
Image: http://www.asianews.it/news-en/China-and-the-United-States-agree-to-climate-agreement-by-2030-32676.html





Tribett et al., in prep, 2015





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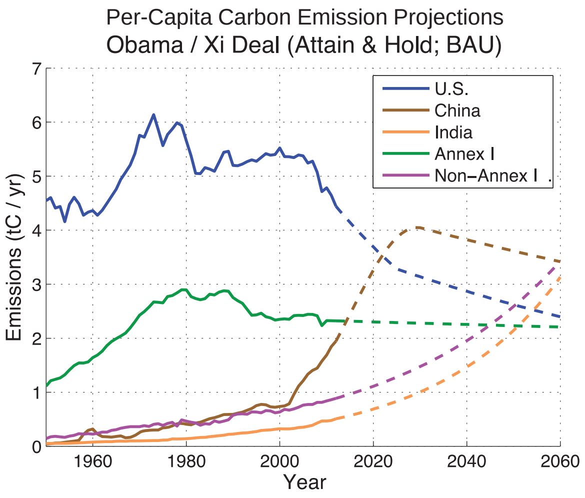

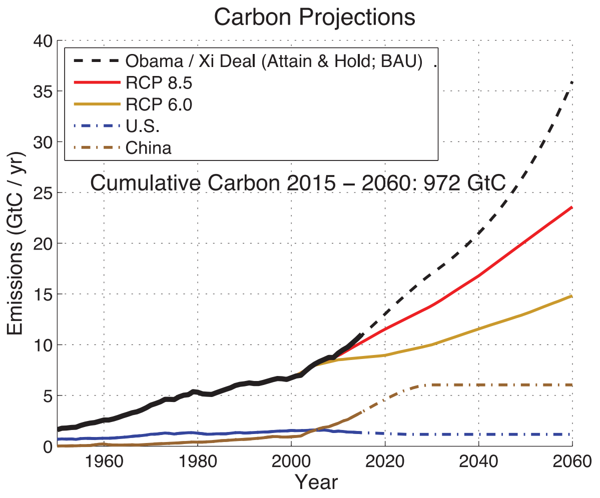

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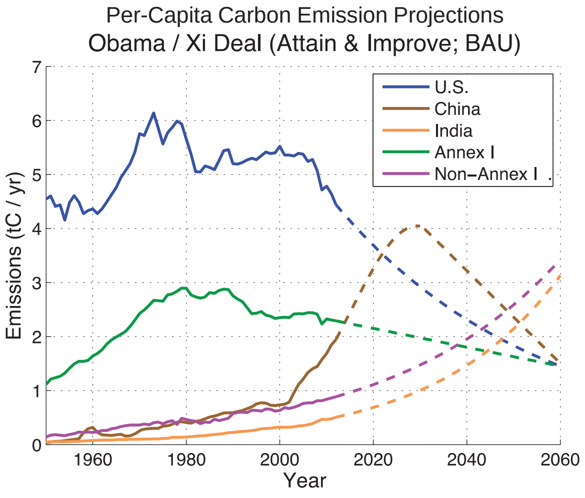

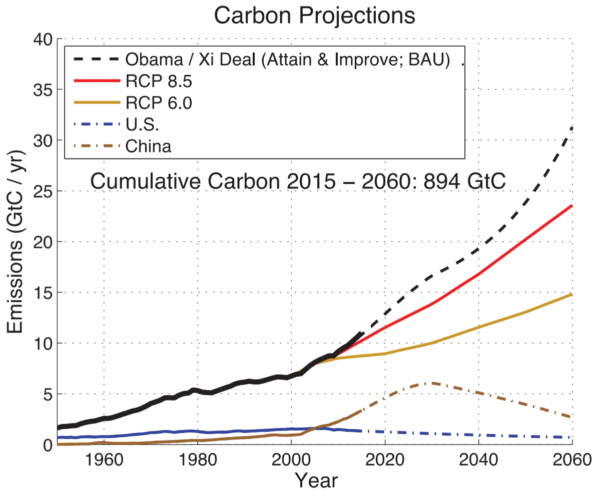

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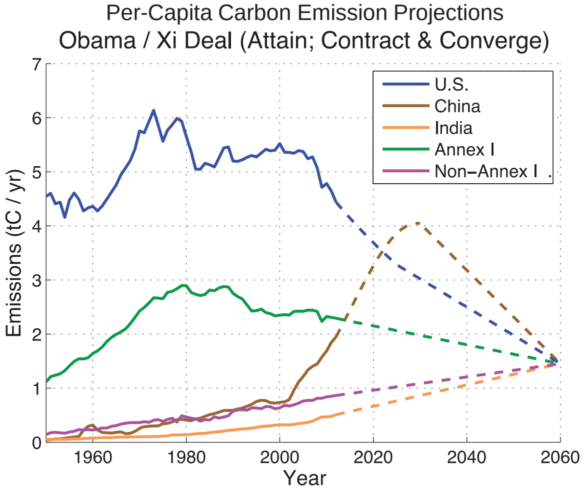

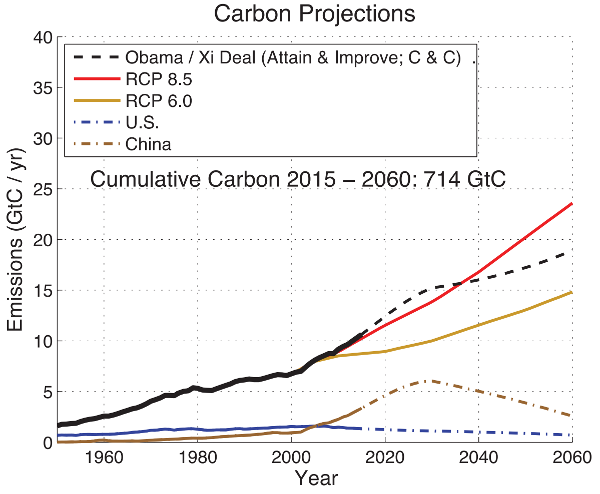

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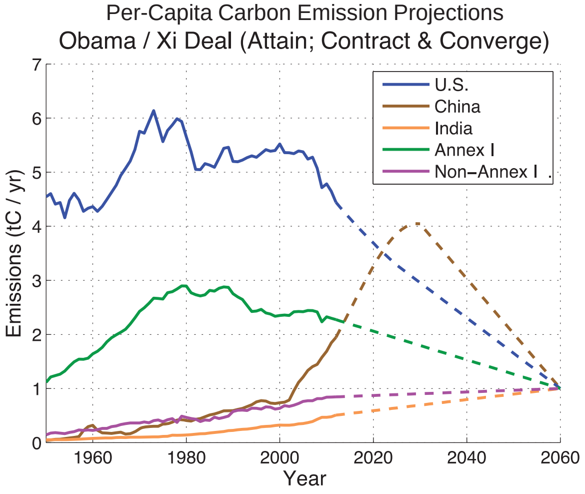
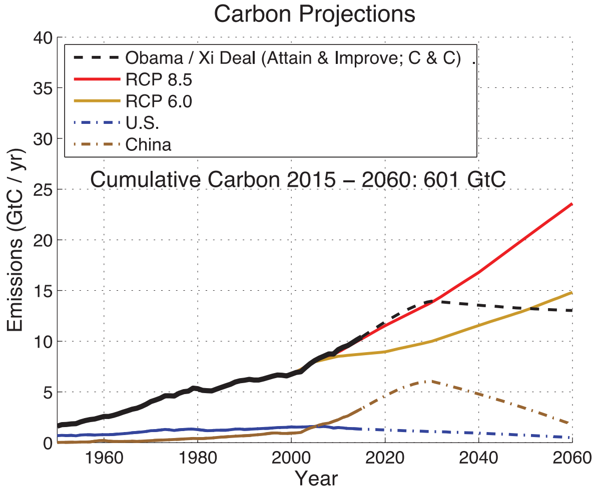
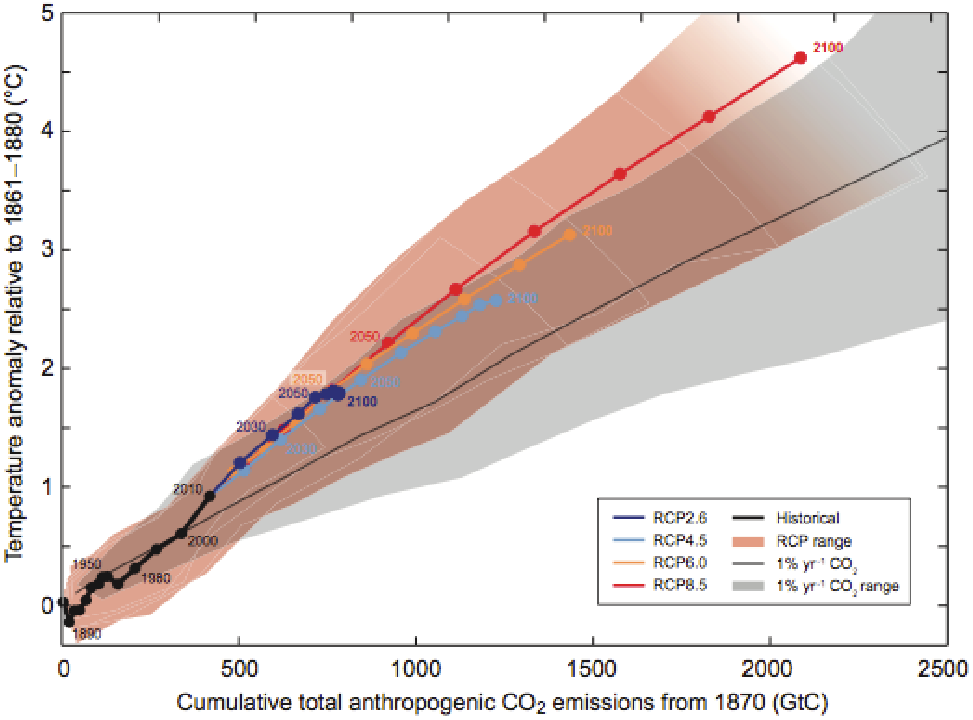




Tribett et al., in prep, 2015

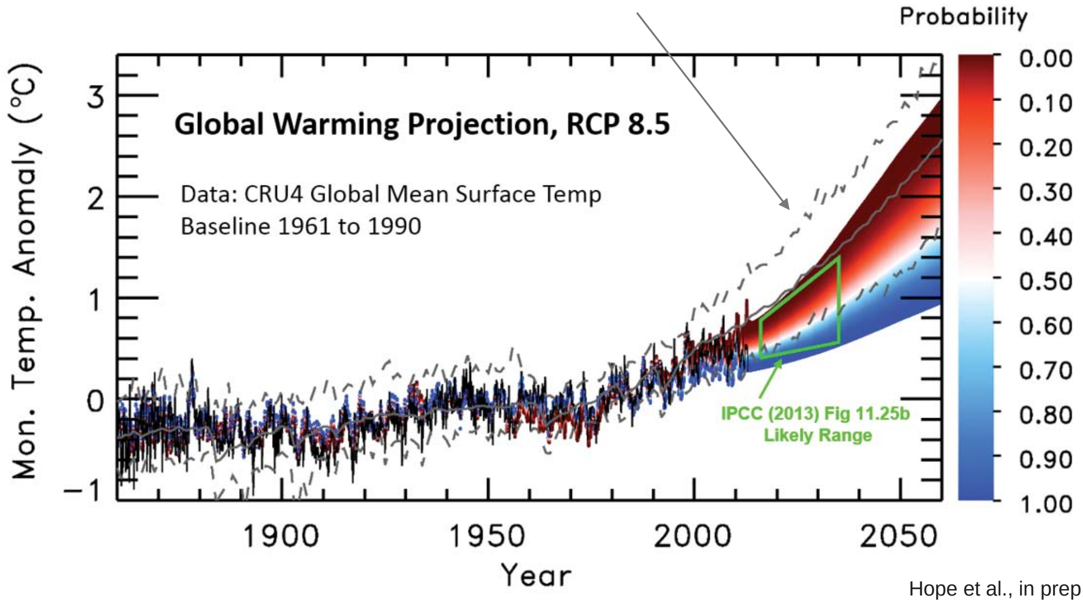
IPCC (2013) Links Rise in GMST to Total Cumulative C Emissions



IPCC AR5 SPM.10

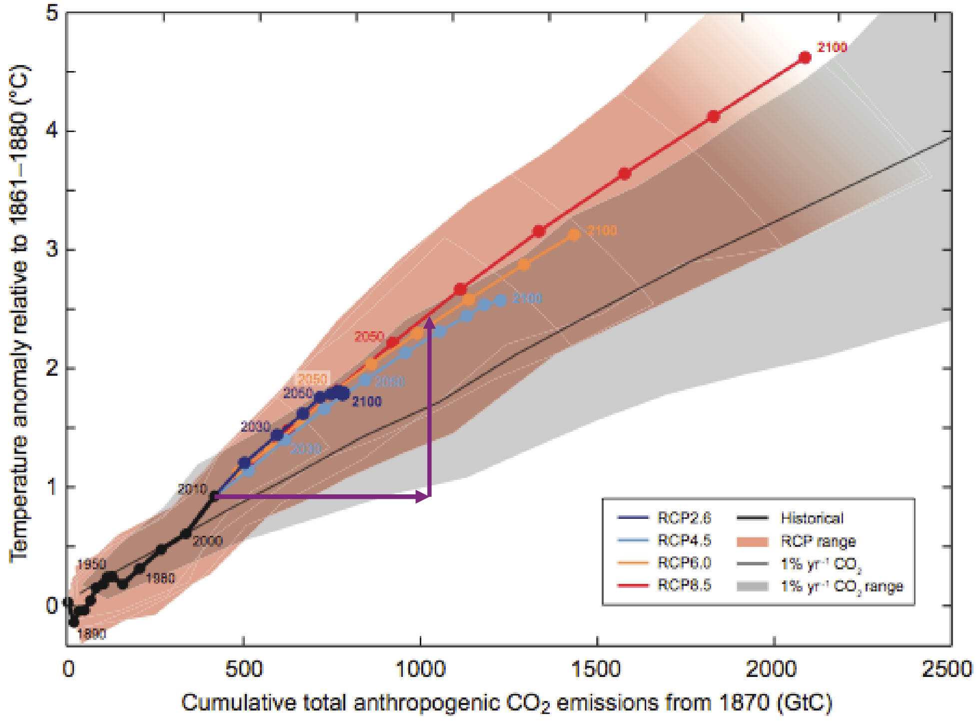
IPCC (2013) Links Rise in GMST to Total Cumulative C Emissions using models that likely warm too fast

Gray lines: CMIP5 Upper Limit, Multi-model Mean, and Lower Limit



Hope et al., in prep, 2015

IPCC (2013) Links Rise in GMST to Total Cumulative C Emissions



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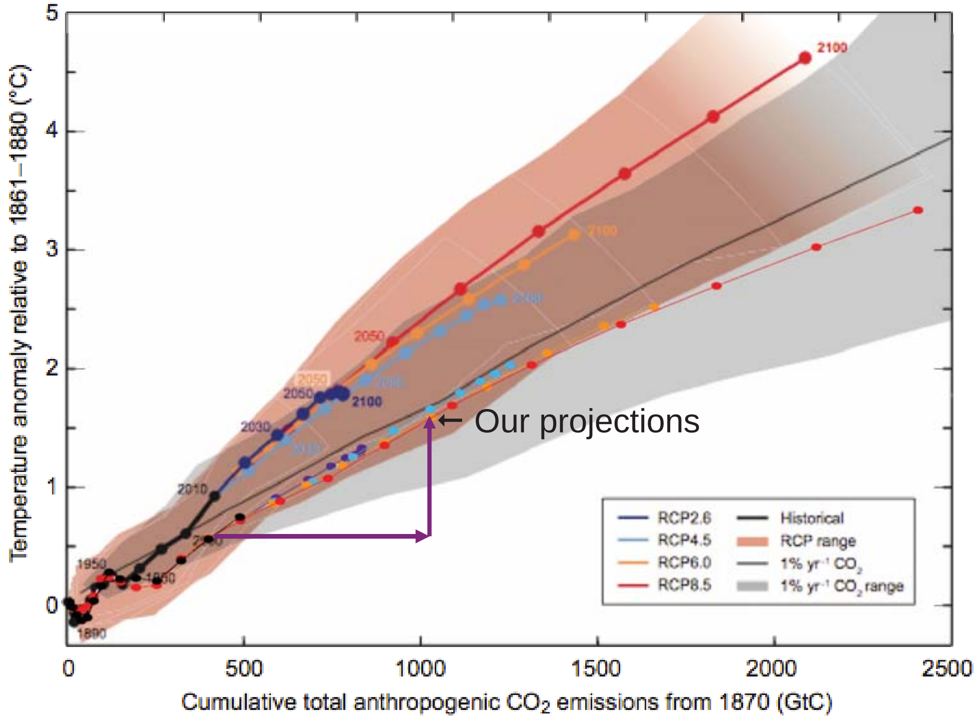

← Our projections

IPCC AR5 SPM.10

Kyoto Protocol

- Negotiated in Kyoto, Japan in November 1997
  - – Annex I countries: Developed countries (Table 10.1 of Houghton) with varying emission targets, 2008-2012 relative to 1990, ranging from +10% (Iceland) to –8% (EU-15)

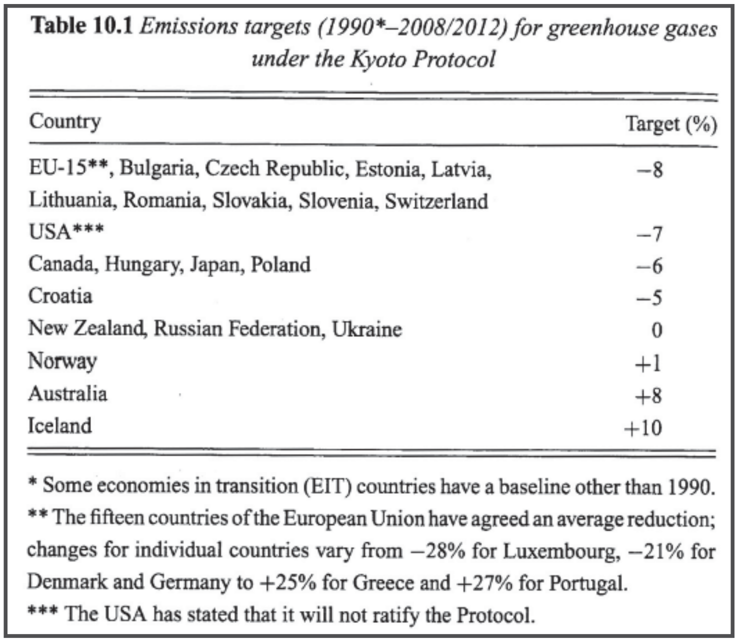

Table 10.1 *Emissions targets (1990*–2008/2012) for greenhouse gases under the Kyoto Protocol*

Country	Target (%)
EU-15**, Bulgaria, Czech Republic, Estonia, Latvia, Lithuania, Romania, Slovakia, Slovenia, Switzerland	−8
USA***	−7
Canada, Hungary, Japan, Poland	−6
Croatia	−5
New Zealand, Russian Federation, Ukraine	0
Norway	+1
Australia	+8
Iceland	+10

* Some economies in transition (EIT) countries have a baseline other than 1990.
** The fifteen countries of the European Union have agreed an average reduction; changes for individual countries vary from −28% for Luxembourg, −21% for Denmark and Germany to +25% for Greece and +27% for Portugal.
*** The USA has stated that it will not ratify the Protocol.

Houghton, Global Warming: The Complete Briefing, 3d Edition, 2004

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  - –Annex II countries: sub-group of Annex I countries that agree to pay cost of technology for emission reductions in developing countries
    - Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States of America
  - –Developing countries: all countries besides those in Table 10.1 of Houghton
- Went into effect in 16 February 2005 after signed by __________
- Annex I countries:
  - –agree to reduce GHG emissions to target tied to 1990 emissions. If they cannot do so, they must buy emission credits or invest in conservation
- Developing countries:
  - – no restrictions on GHG emissions
  - – encouraged to use new technology, funded by Annex II countries, to reduce emissions
  - – can not sell emission credits

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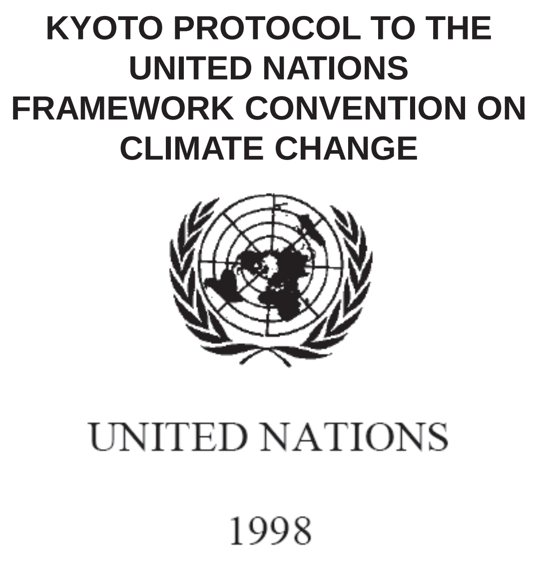
  - Annex I countries: Developed countries (Table 10.1 of Houghton) with varying emission targets, 2008-2012 relative to 1990, ranging from +10% (Iceland) to –8% (EU-15)
  - Annex II countries: sub-group of Annex I countries that agree to pay cost of technology for emission reductions in developing countries
    - Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States of America
  - Developing countries: all countries besides those in Table 10.1 of Houghton
- Went into effect in 16 February 2005 after signed by Russia
- Annex I countries:
  - agree to reduce GHG emissions to target tied to 1990 emissions. If they cannot do so, they must buy emission credits or invest in conservation
- Developing countries:
  - no restrictions on GHG emissions
  - encouraged to use new technology, funded by Annex II countries, to reduce emissions
  - can not sell emission credits

Kyoto Protocol



KYOTO PROTOCOL TO THE
UNITED NATIONS
FRAMEWORK CONVENTION ON
CLIMATE CHANGE

UNITED NATIONS

1998

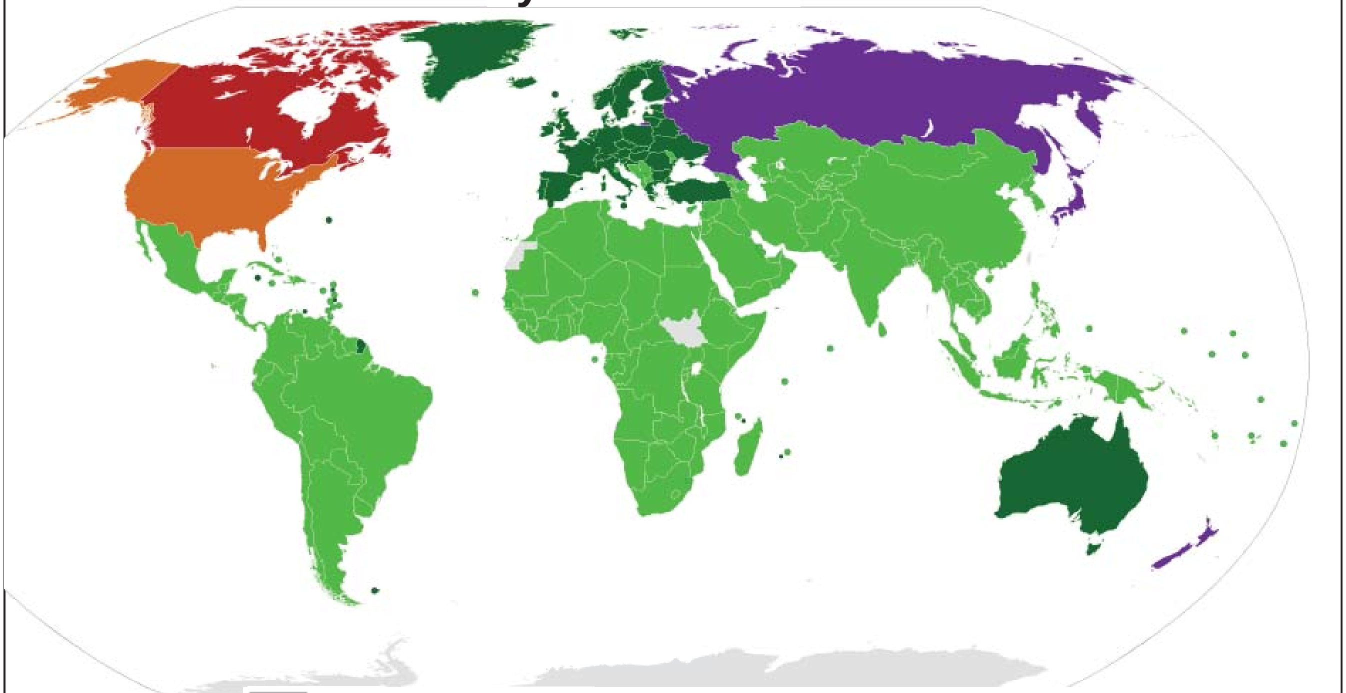
Article 3

1. The Parties included in Annex I shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases listed in Annex A do not exceed their assigned amounts, calculated pursuant to their quantified emission limitation and reduction commitments inscribed in Annex B and in accordance with the provisions of this Article, **with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012**.

2. Each Party included in Annex I shall, by 2005, have made demonstrable progress in achieving its commitments under this Protocol.

3. The **net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990**, measured as verifiable changes in carbon stocks in each commitment period, **shall be used to meet the commitments** under this Article of each Party included in Annex I. **The greenhouse gas emissions by sources and removals by sinks associated with those activities shall be reported in a transparent and verifiable manner** and reviewed in accordance with Articles 7 and 8.

Kyoto Protocol

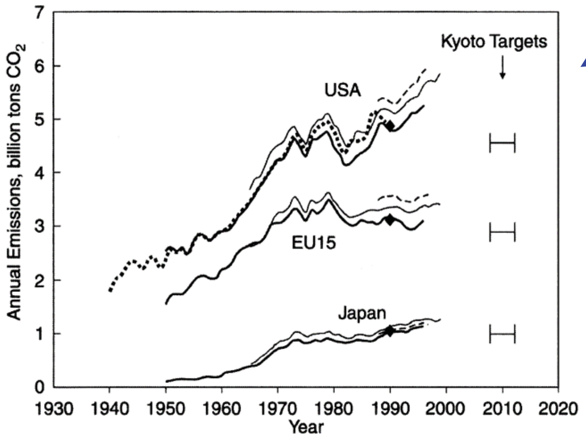


- 🟩 Parties; Annex I & II countries with binding targets
- 🟩 Parties; Developing countries without binding targets
- ⬜ States not Party to the Protocol
- 🟧 Signatory country with no intention to ratify the treaty, with no binding targets
- 🟥 Countries that have denounced the Protocol, with no binding targets
- 🟪 Parties with no binding targets in the second period, which previously had targets

http://schools-wikipedia.org/wp/k/Kyoto_Protocol.htm

Kyoto Protocol Targets

CO_2 emissions



Does not include:
- **LULUCF (land use, land-use change and forestry)**
- **GHGs other than CO_2**

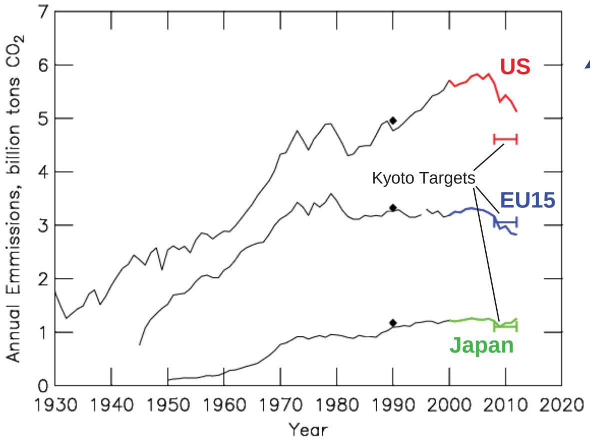
Kyoto target (2008 to 2012) for emissions of CO_2, relative to 1990 emissions
selected locations

Australia	108%
EU15	92%
Iceland	110%
Japan	94%
New Zealand	100%
Norway	101%
Russia	100%
US	93%

The Collapse of the Kyoto Protocol and the Struggle to Slow Global Warming
David G. Victor, Princeton University Press, 2001.

Kyoto Protocol Targets

CO_2 emissions



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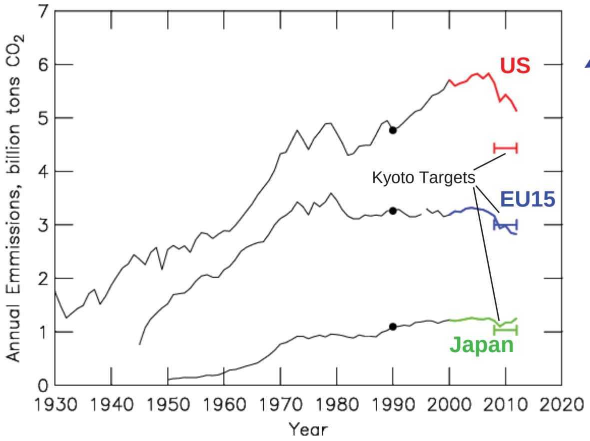

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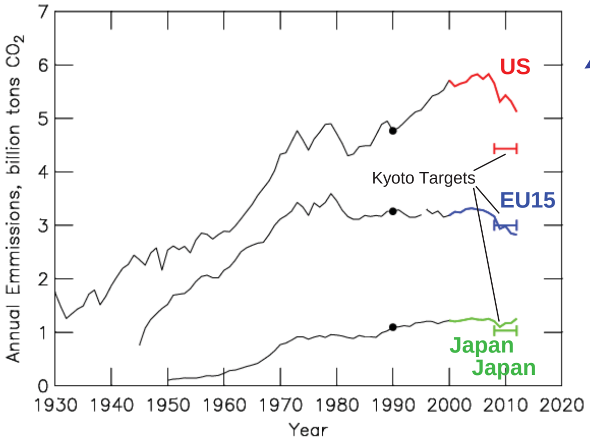

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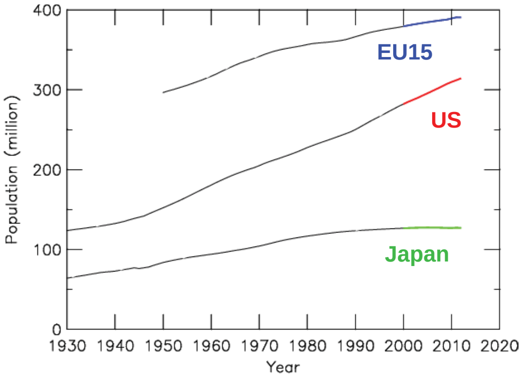

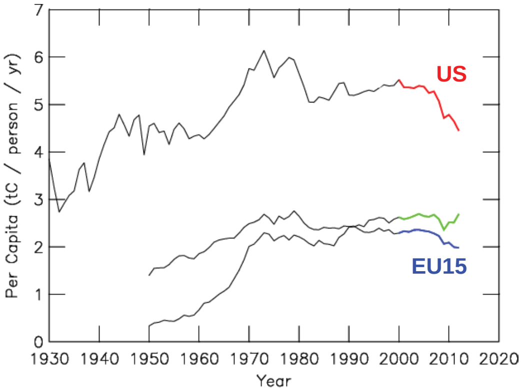

Kyoto Mechanisms

- Joint Implementation
  - Allows developed countries to implement projects that reduce emissions or increase natural GHG sinks in other *developed countries*; such projects can be counted towards the emission reductions of the investing country
- Clean Development Mechanism
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  - Australian Carbon Data Accounting Model http://www.climatechange.gov.au/en/government/initiatives/ncat.aspx being discussed as pilot for international metric for quantifying effects of reforestation on the carbon fluxes
- Emissions Trading
  - Annex I countries can purchase emission units from other *Annex I countries* that find it easier to reduce their own emissions

Kyoto Emission Penalties

What happens if a country fails to reach its Kyoto emissions target?

The Kyoto Protocol contains measures to assess performance and progress.
It also contains some penalties. Countries that fail to meet their emissions targets by the end of the first commitment period (2012) must make up the difference plus a penalty of 30 per cent in the second commitment period

Their ability to sell credits under emissions trading will also be suspended

http://www.cbc.ca/news/background/kyoto/

Kyoto Gases

GHG	GWP, 100-yr	Industrial Use	Lifetime
CO_2	1	Fossil fuel combustion; Land use changes	Multiple, ~172 yrs
CH_4	25	Fossil fuel combustion; Rice paddies; Animal waste; Sewage treatment and landfills; Biomass burning	~10 yrs
N_2O	298	Agriculture & river chemistry associated with pollution Biomass burning & fossil fuel combustion	~115 yrs
HFCs	124 to 15000	Refrigerant (HFC–134a: CH_2FCF_3), foam blowing agent, and by product of HCFC manufacture	Range from 1.5 to 270 yrs
PFCs	7400 to 12200	Aluminum smelting (CF_4) Semiconductor manufacturing (CF_4)	1000 to 50,000 yrs
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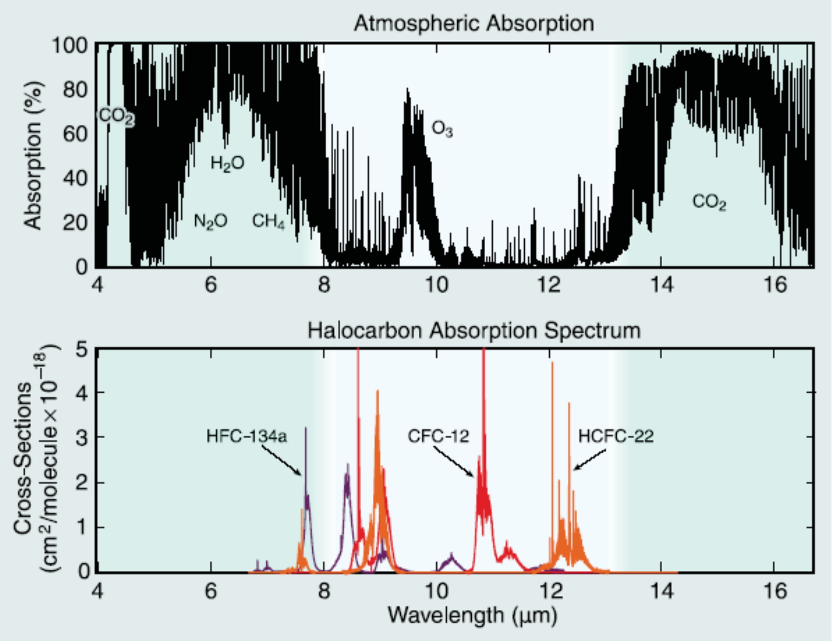
HFCs Spectra



IPCC "SROC": Special Report on Safeguarding the Ozone Layer and the Global Climate System

http://www.ipcc.ch/pdf/special-reports/sroc/sroc_full.pdf

GWP – Global Warming Potential

$$\text{GWP (HFC}-\text{134a)} = \frac{\int_{\text{time initial}}^{\text{time final}} a_{\text{HFC}-\text{134a}} \times [\text{HFC}-\text{134a(t)}]\ \text{dt}}{\int_{\text{time initial}}^{\text{time final}} a_{\text{CO2}} \times [\text{CO}_2\text{(t) dt}]}$$

where:

$a_{\text{HFC-134a}}$ = Radiative Efficiency (W m^{-2} ppb^{-1}) due to an increase in HFC-134a

a_{CO2} = Radiative Efficiency (W m^{-2} ppb^{-1}) due to an increase in CO_2

HFC-134a (t) = time-dependent response to an instantaneous release of a pulse of HFC-134a

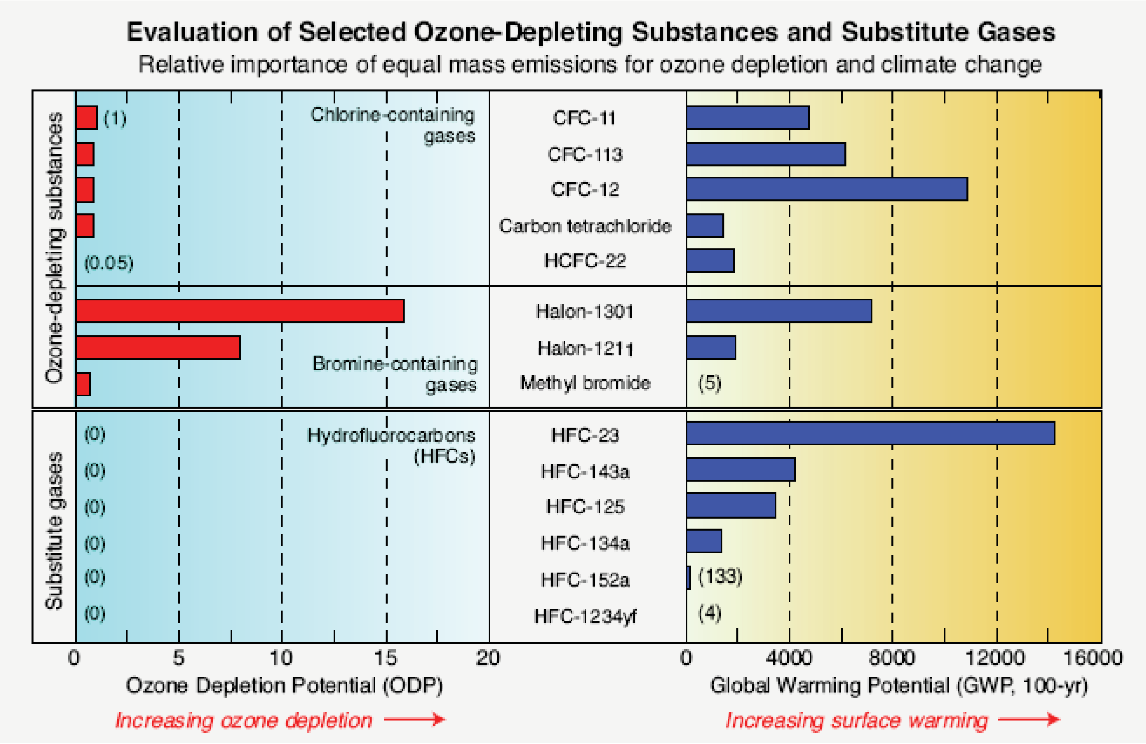
CO_2 (t) = time-dependent response to an instantaneous release of a pulse of CO_2

Note: HFC-134a is CH_2FCF
HCFC-22 is CH_3CClF_2

		GWP Time Horizon	
	τ (yr)	20-yr	100-yr
HFC-134a	13.4	3710	1300
HCFC-22	11.9	5280	1760

Table 8.A.1, IPCC (2013)

Not all HFCs are equal wrt Global Warming



Evaluation of Selected Ozone-Depleting Substances and Substitute Gases

Relative importance of equal mass emissions for ozone depletion and climate change

WMO/UNEO 2011 “Twenty Questions”
http://esrl.noaa.gov/csd/assessments/ozone/2010/twentyquestions

Radiative Forcing due to HFCs

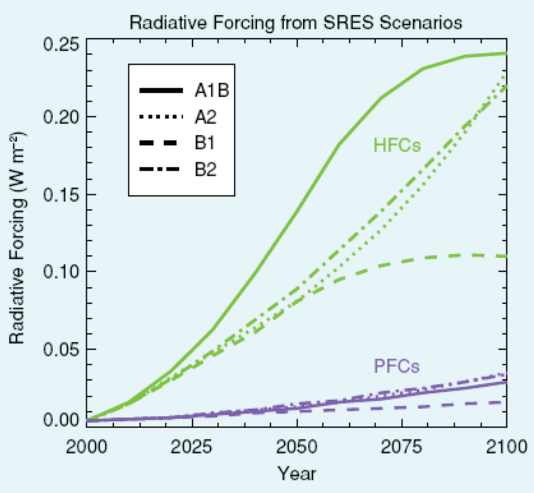
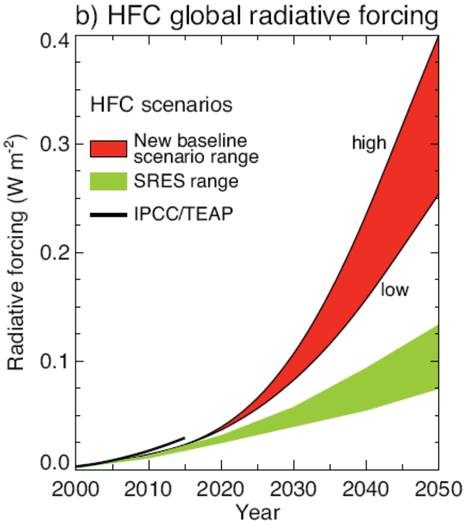


Fig 2.9

IPCC “SROC”: Special Report on Safeguarding the Ozone Layer & Global Climate System, 2005

http://www.ipcc.ch/pdf/special-reports/sroc/sroc_full.pdf



Velders et al., PNAS, 2009

SRES: Special Report on Emission Scenarios: used in past IPCC reports including IPCC (2007)
http://en.wikipedia.org/wiki/Special_Report_on_Emissions_Scenarios#SRES_scenarios_and_climate_change_initiatives

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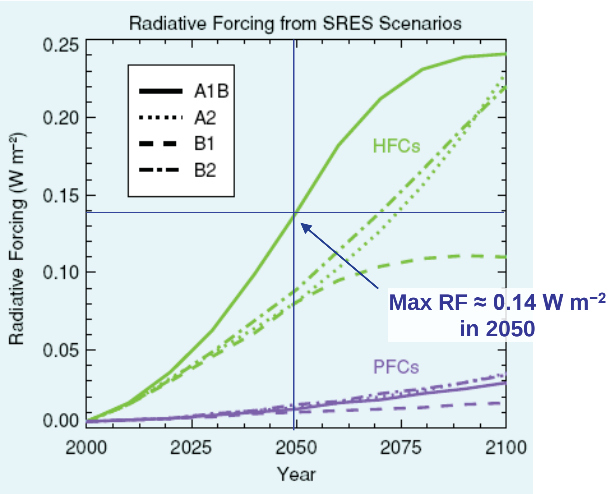
Radiative Forcing due to HFCs



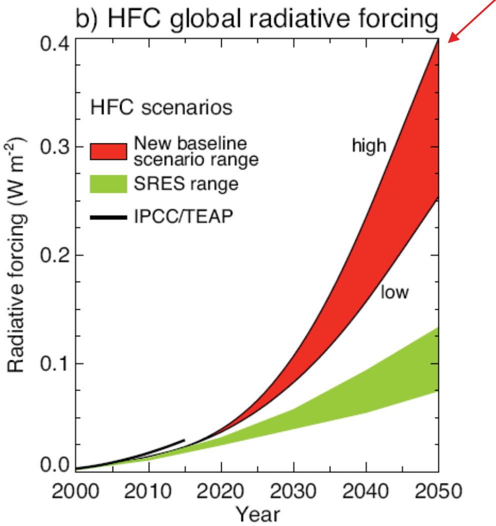
Max RF ≈ 0.14 W m^{-2}
in 2050

Fig 2.9

IPCC “SROC”: Special Report on Safeguarding the Ozone Layer & Global Climate System, 2005

http://www.ipcc.ch/pdf/special-reports/sroc/sroc_full.pdf

Max RF ≈ 0.40 W m^{-2}
in 2050



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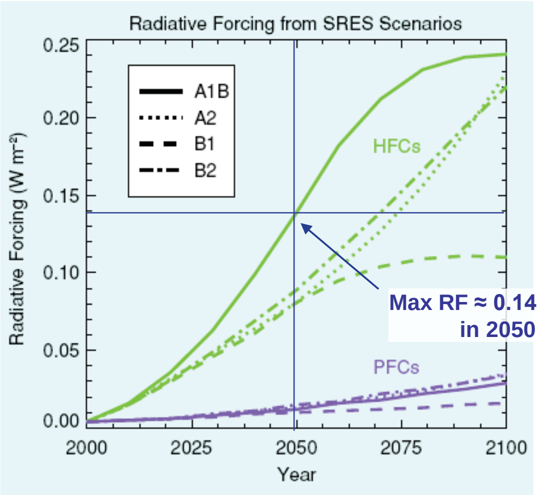

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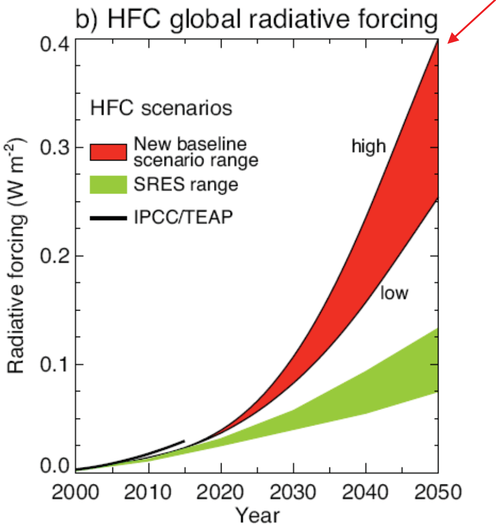
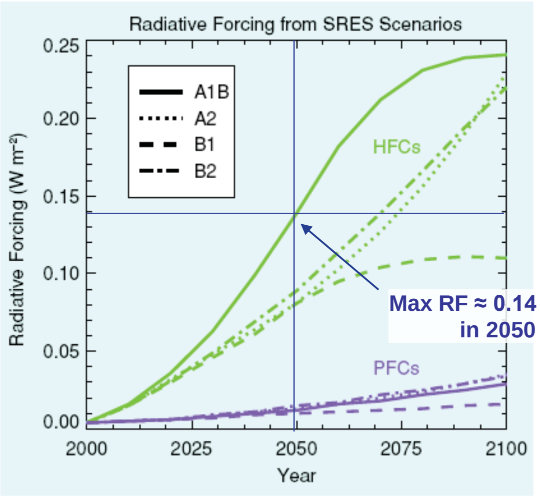


CO_2 will double in 2053 according to RCP 8.5 scenario developed for next IPCC

What is RF associated with 2 × CO_2 ?!?

Radiative Forcing due to HFCs



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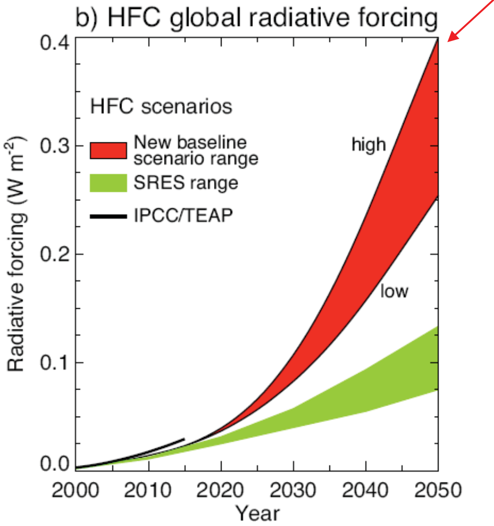

CO_2 will double in 2053 according to RCP 8.5 scenario developed for next IPCC

What is RF associated with 2 × CO_2 ?!?

$$
\begin{aligned}
\Delta RF_{2\times CO2} &= 5.35\ \mathrm{W\ m^{-2}}\ \ln\left(CO_{2\ \mathrm{FINAL}} / CO_{2\ \mathrm{INITIAL}}\right) \\
&= 5.35\ \ln(2)\ \mathrm{W\ m^{-2}} = 3.7\ \mathrm{W\ m^{-2}}
\end{aligned}
$$

Radiative Forcing due to PFCs

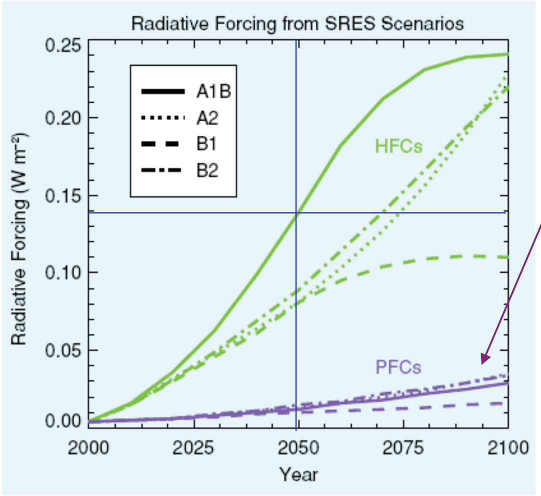

Fig 2.9

IPCC “SROC”: Special Report on Safeguarding
the Ozone Layer & Global Climate System, 2005

http://www.ipcc.ch/pdf/special-reports/sroc/sroc_full.pdf

PFC: Perfluorocarbons

- Contain only C & F
- Strong bonds: chemically stable

  τ_{CF4} = 50,000 yr !
- Applications: medical, electrical, cosmetics

http://www.davidofford.com/perfluorocarbons/perfluorocarbons-and-its-uses

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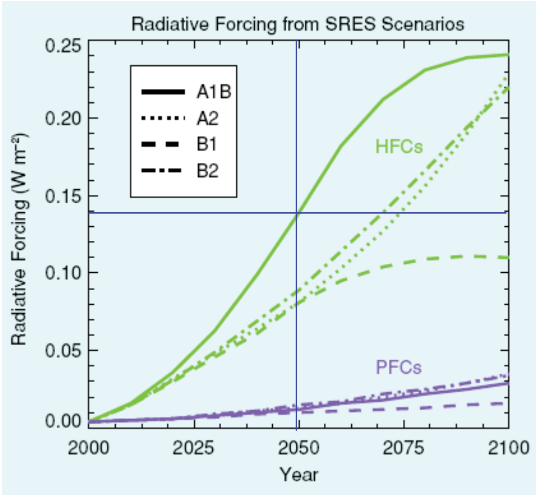
Radiative Forcing due to PFCs



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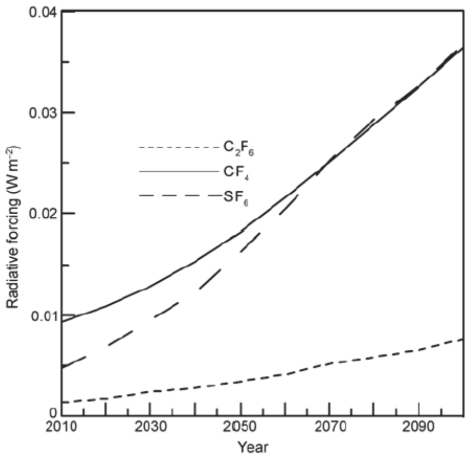
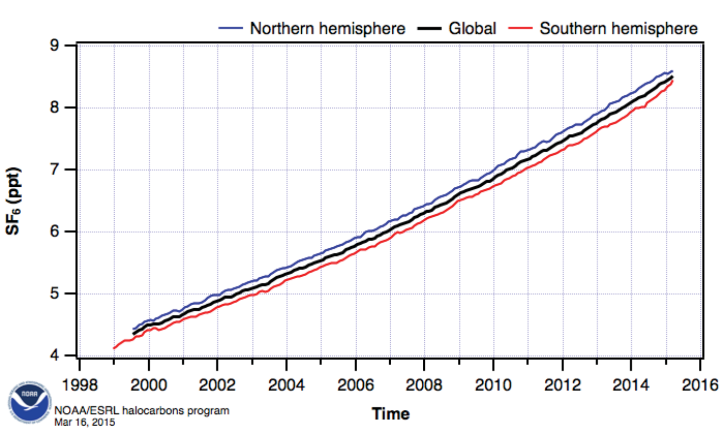


Figure 4 Radiative forcing of C_2F_6, CF_4, and SF_6 from 2010 to 2100.

Zhang et al., Sci China
Earth Sci, 2011

Radiative Forcing due to SF_6



http://www.esrl.noaa.gov/gmd/hats/insitu/cats/conc/mlosf6.html

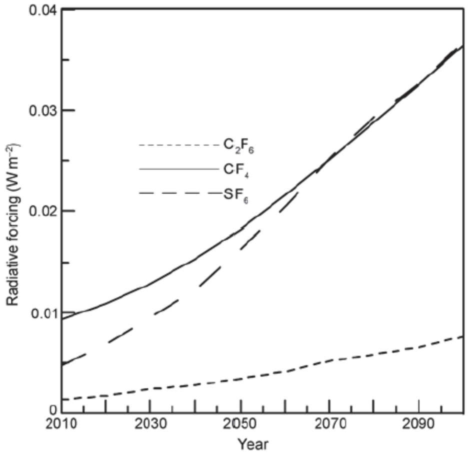


Figure 4 Radiative forcing of C_2F_6, CF_4, and SF_6 from 2010 to 2100.

Zhang et al., Sci China
Earth Sci, 2011

SF_6: Sulfur hexafluoride

- τ_{SF6} = 3,200 yr
- Applications: gaseous dielectric in electrical transformers; insulator for windows; retina surgery
- Also had been used in sneakers but Nike has phased out this use:

http://americancarbonregistry.org/carbon-registry/projects/nike-sf6-substitution-project

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Kyoto Gases

GHG	GWP, 100-yr	Industrial Use	Lifetime
CO_2	1	Fossil fuel combustion; Land use changes	Multiple, ~172 yrs
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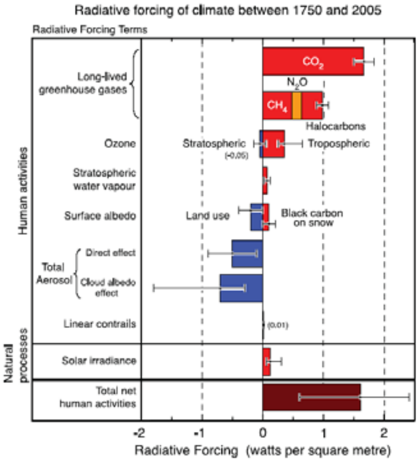

Why doesn't tropospheric ozone appear as a Kyoto gas?

Kyoto Gases

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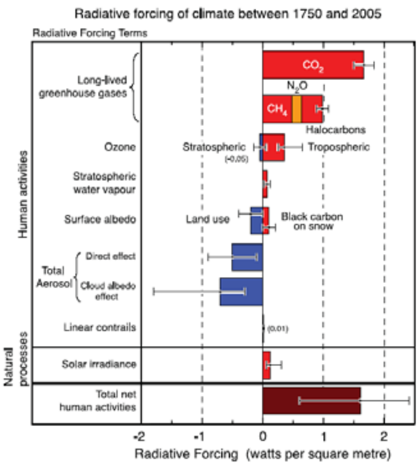

Why doesn't tropospheric ozone appear as a Kyoto gas?

Why not CFCs and HCFCs ?

Climate News

- **Durban, South Africa (Dec 2011)**
  - Renewed the Kyoto Protocol in principle and a new process called the Durban Platform for Enhanced Cooperation (DPEC) was put in place
  - DPEC: countries will negotiate a new "outcome with legal force" by 2015 that would replace the Kyoto Protocol
- **Rio De Janeiro, Brazil (June 2012)**
  - 192 governments renewed their commitment to sustainable development, including a 49 page document, but commitment was non-binding
- **Doha, Qatar (Dec 2012)**
  - Amendment to Kyoto Protocol framed, for 2nd commitment period 1 Jan 2013 to 31 Dec 2020

	Ref Year	GHG reductions 2020
US*		
EU-15	1990	20 to 30%
Japan**		
Norway	1990	30 to 40%

* US did not participate

** Japan indicated that it does not intend to be under obligation of the second commitment period of the Kyoto Protocol

- **Paris (30 Nov to 11 Dec 2015)**
  - 11th session of the Conference of the Parties to the Kyoto Protocol

Pacala and Socolow: CO_2 Stabilization Wedges

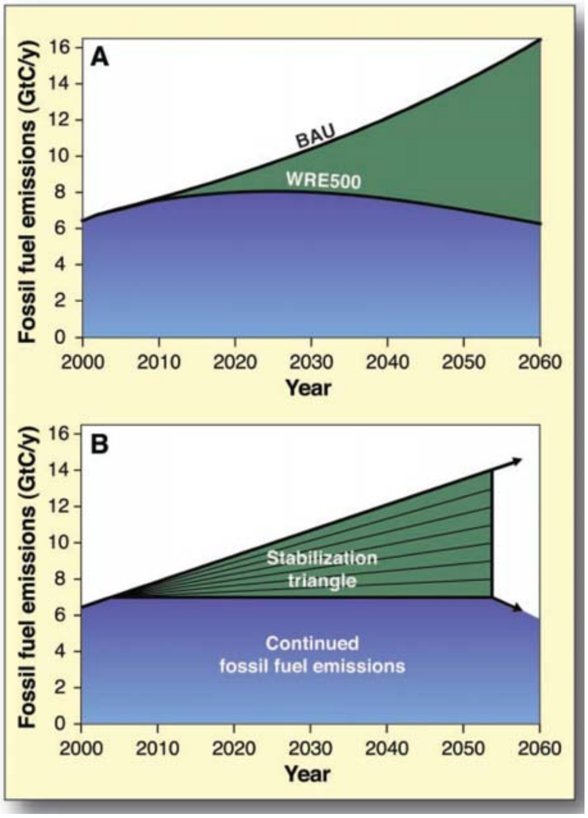

Fig. 1. (**A**) The top curve is a representative BAU emissions path for global carbon emissions as CO_2 from fossil fuel combustion and cement manufacture: 1.5% per year growth starting from 7.0 GtC/year in 2004. The bottom curve is a CO_2 emissions path consistent with atmospheric CO_2 stabilization at 500 ppm by 2125 akin to the Wigley, Richels, and Edmonds (WRE) family of stabilization curves described in (*11*), modified as described in Section 1 of the SOM text. The bottom curve assumes an ocean uptake calculated with the High-Latitude Exchange Interior Diffusion Advection (HILDA) ocean model (*12*) and a constant net land uptake of 0.5 GtC/year (Section 1 of the SOM text). The area between the two curves represents the avoided carbon emissions required for stabilization. (**B**) Idealization of (A): A stabilization triangle of avoided emissions (green) and allowed emissions (blue). The allowed emissions are fixed at 7 GtC/year beginning in 2004. The stabilization triangle is divided into seven wedges, each of which reaches 1 GtC/year in 2054. With linear growth, the total avoided emissions per wedge is 25 GtC, and the total area of the stabilization triangle is 175 GtC. The arrow at the bottom right of the stabilization triangle points downward to emphasize that fossil fuel emissions must decline substantially below 7 GtC/year after 2054 to achieve stabilization at 500 ppm.

Pacala and Socolow, Science, 2004

http://www.princeton.edu/mae/people/faculty/socolow/Science-2004-SW-1100103-PAPER-AND-SOM.pdf

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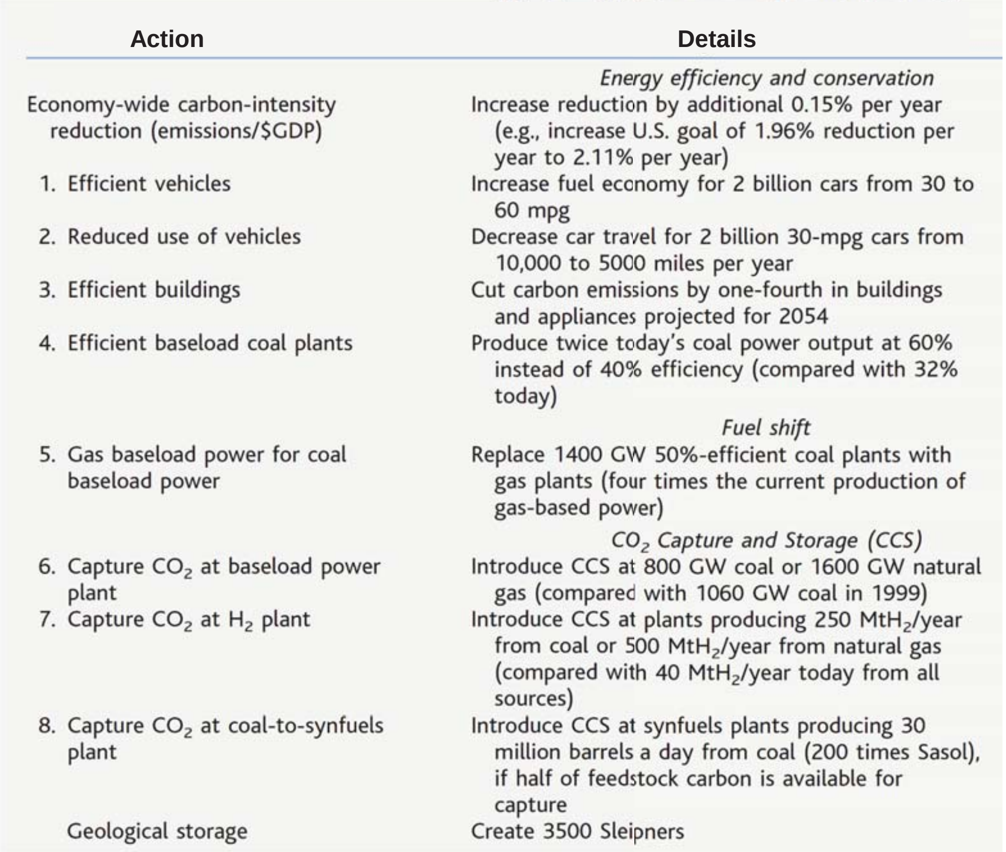
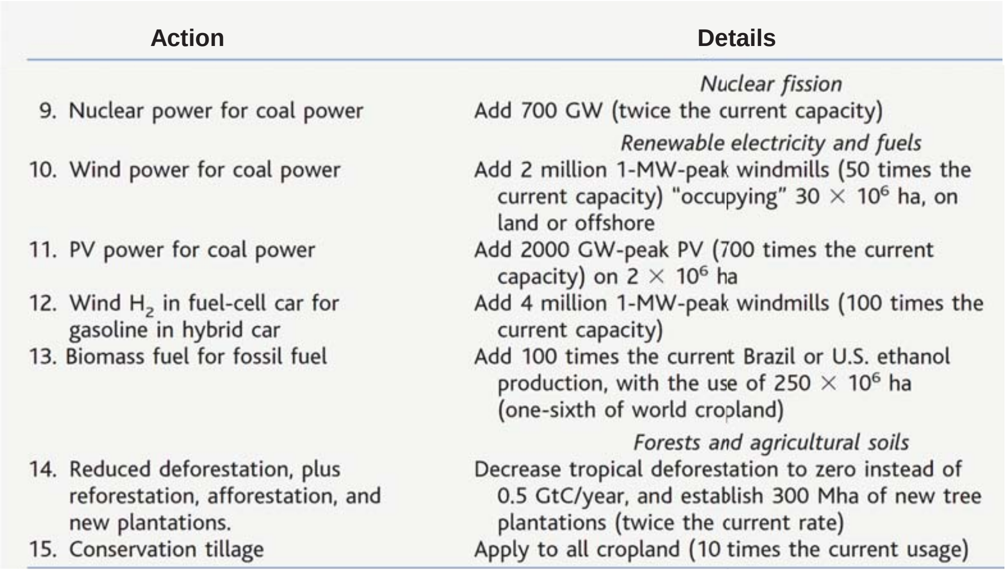
Pacala and Socolow: CO_2 Stabilization Wedges



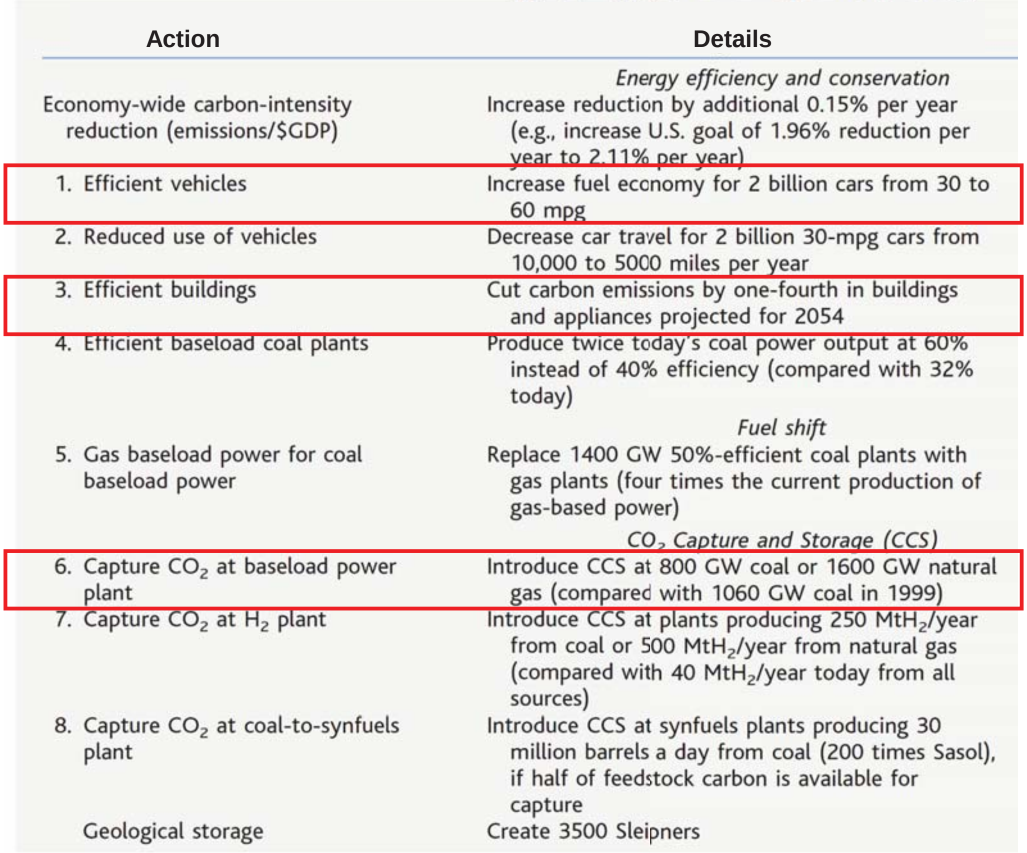
Action	Details
	Energy efficiency and conservation
Economy-wide carbon-intensity reduction (emissions/$GDP)	Increase reduction by additional 0.15% per year (e.g., increase U.S. goal of 1.96% reduction per year to 2.11% per year)
1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg
2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5000 miles per year
3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054
4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)
	Fuel shift
5. Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (four times the current production of gas-based power)
	CO_2 Capture and Storage (CCS)
6. Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)
7. Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources)
8. Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels plants producing 30 million barrels a day from coal (200 times Sasol), if half of feedstock carbon is available for capture
Geological storage	Create 3500 Sleipners

Pacala and Socolow: CO_2 Stabilization Wedges



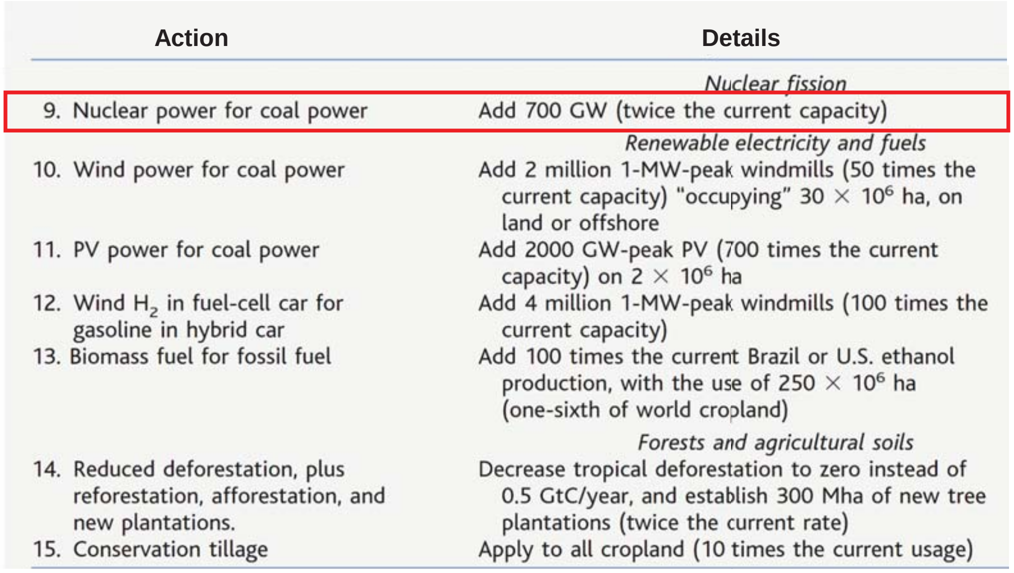
Action	Details
	Nuclear fission
9. Nuclear power for coal power	Add 700 GW (twice the current capacity)
	Renewable electricity and fuels
10. Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times the current capacity) "occupying" 30 × 10^6 ha, on land or offshore
11. PV power for coal power	Add 2000 GW-peak PV (700 times the current capacity) on 2 × 10^6 ha
12. Wind H_2 in fuel-cell car for gasoline in hybrid car	Add 4 million 1-MW-peak windmills (100 times the current capacity)
13. Biomass fuel for fossil fuel	Add 100 times the current Brazil or U.S. ethanol production, with the use of 250 × 10^6 ha (one-sixth of world cropland)
	Forests and agricultural soils
14. Reduced deforestation, plus reforestation, afforestation, and new plantations.	Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)
15. Conservation tillage	Apply to all cropland (10 times the current usage)

Pacala and Socolow: CO_2 Stabilization Wedges



Action	Details
	Energy efficiency and conservation
Economy-wide carbon-intensity reduction (emissions/$GDP)	Increase reduction by additional 0.15% per year (e.g., increase U.S. goal of 1.96% reduction per year to 2.11% per year)
1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg
2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5000 miles per year
3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054
4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)
	Fuel shift
5. Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (four times the current production of gas-based power)
	CO_2 Capture and Storage (CCS)
6. Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)
7. Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources)
8. Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels plants producing 30 million barrels a day from coal (200 times Sasol), if half of feedstock carbon is available for capture
Geological storage	Create 3500 Sleipners

Pacala and Socolow: CO_2 Stabilization Wedges



Action	Details
	Nuclear fission
9. Nuclear power for coal power	Add 700 GW (twice the current capacity)
	Renewable electricity and fuels
10. Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times the current capacity) "occupying" 30 × 10^6 ha, on land or offshore
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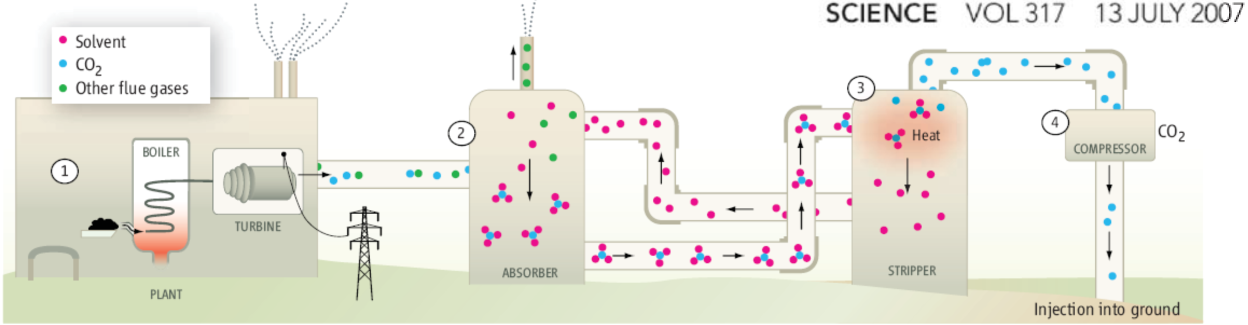
Carbon Capture & Sequestration

CATCHING THE FLUE (GAS)



SCIENCE VOL 317 13 JULY 2007

How a retrofit works. (1) Most coal plants burn coal to create steam, running a turbine that produces electricity. After treatment for pollutants, the flue gas, a mixture of CO_2 (blue) and other emissions (green), goes out a smokestack. To collect CO_2 for storage, however, the mixture of gases is directed to an absorber (2), where a solvent like MEA (pink) bonds with the CO_2 molecules. The bonded CO_2–solvent complexes are separated in the stripper (3), which requires heat. More energy is needed for the next step (4), which produces a purified CO_2 stream for ground storage as well as solvent molecules that can be reused. (Schematic not to scale.)

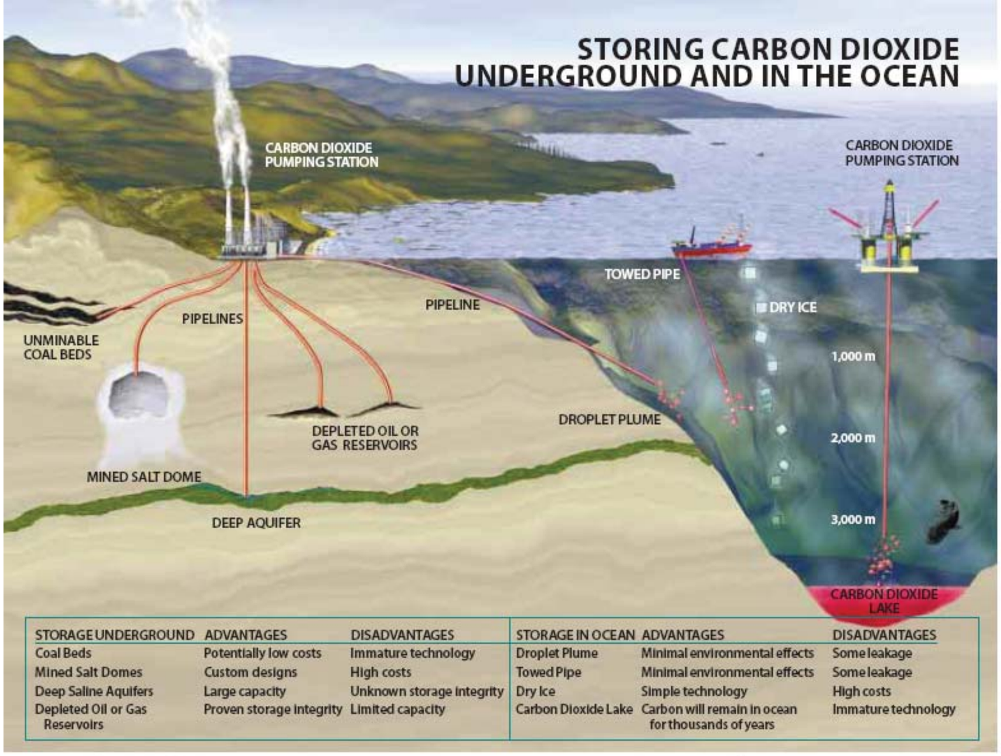
MEA-monoethanolamine $(CH_2CH_2OH)NH_2$ in an aqueous solution will absorb CO_2 to form ethanolammonium carbamate.

$$2RNH_2 + CO_2 + H_2O \rightarrow (RNH_3)_2CO_2$$

MEA is a weak base so it will re-release the CO_2 when heated

Kintisch, *Science*, 2007

Where to Place the Sequestered Carbon?



STORAGE UNDERGROUND	ADVANTAGES	DISADVANTAGES	STORAGE IN OCEAN	ADVANTAGES	DISADVANTAGES
Coal Beds	Potentially low costs	Immature technology	Droplet Plume	Minimal environmental effects	Some leakage
Mined Salt Domes	Custom designs	High costs	Towed Pipe	Minimal environmental effects	Some leakage
Deep Saline Aquifers	Large capacity	Unknown storage integrity	Dry Ice	Simple technology	High costs
Depleted Oil or Gas Reservoirs	Proven storage integrity	Limited capacity	Carbon Dioxide Lake	Carbon will remain in ocean for thousands of years	Immature technology

STORAGE SITES for carbon dioxide in the ground and deep sea should help keep the greenhouse gas out of the atmosphere where it now contributes to climate change. The various options must be scrutinized for cost, safety and potential environmental effects.

Herzog *et al*., *Scientific American*, 2000

Carbon Sequestration in Action:

Sleipner, Norway

National Geographic, June 2008

- North Sea natural gas field: enormous capacity
- Captures ~90% of CO_2 that is generated
- CO_2 pumped into 200 m thick sandstone layer 720 m below sea floor
- Project initiated in response to $50 ton tax on CO_2 emissions instituted by Norwegian Government in 1996
- Investment in capital cost paid off in about one and a half years !

CO_2 Capture and Storage (CCS) Costs:

CCS component	Cost range	
Capture from a power plant	15–75 US$/t$CO_2$ net captured	~$45/ ton
Capture from gas processing or ammonia production	5–55 US$/t$CO_2$ net captured	
Capture from other industrial sources	25–115 US$/t$CO_2$ net captured	
Transportation	1–8 US$/t$CO_2$ transported per 250km	~$4.5/ ton
Geological storage	0.5–8 US$/t$CO_2$ injected	~$4.5/ ton
Ocean storage	5–30 US$/t$CO_2$ injected	
Mineral carbonation	50–100 US$/t$CO_2$ net mineralized	

⇧

Cost of capture: **~$54 / ton** CO_2 × 10 × 10^9 tons C / yr = **$ 540 billion**

Present cost of fossil fuel: $ 56 / barrel ≈ **$ 484 / ton**

World GDP, 2010: **$ 75.6 trillion** CO_2 capture = 0.7 % of world GDP
= 11 % of cost, barrel of oil

⇦ Back of the envelope analysis

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC)

WMO UNEP

Carbon Dioxide Capture and Storage

http://www.ipcc.ch/pdf/presentations/briefing-montreal-2005-11/presentation-special-report-co2.ppt

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Afforestation

- If 100,000 km^2 (size of Ireland) was re-planted every year, for 40 years (size of Australia) would sequester between 20 and 50 Gt of C from the atmosphere
- ⇨ between **5** and **10** % of emissions, 2015 to 2055

http://www.worldlandtrust.org/images/places/brazil/wetland-before-after-joy-and-mick-braker-vl.jpg

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- But Houghton cautions:
  - forests are dark … as albedo declines, T rises, particularly in winter
  - once trees are fully grown, sequestration stops (yikes)
  - offset is small fraction of total projected C emission and we have used an area the size of Australia (yikes yikes)

http://www.worldlandtrust.org/images/places/brazil/wetland-before-after-joy-and-mick-braker-vl.jpg

Sequestration of CO_2 from the Atmosphere: Carbon Burial

- Prof Ning Zeng (UMCP) advocates planting, harvesting, and burial of rapidly growing trees (proposal is to collect dead trees on forest floor and selectively log live trees)

- Meetings have been held to discuss this idea:

  Ecological carbon sequestration via wood burial and storage: A strategy for climate mitigation and adaptation
  September 9-10, 2010, the Heinz Center, Washington, DC

- A UMd Gemstone Project has addressed this issue

  http://teams.gemstone.umd.edu/classof2010/carbonsinks

- Statements from Zeng, Carbon Sequestration Via Wood Burial, *Carbon Balance and Management*, 2008 http://www.cbmjournal.com/content/3/1/1 :
  - Here I suggest an approach in which wood from old or dead trees in the world's forests is harvested & buried in trenches under a layer of soil, where the anaerobic condition slows the decomposition of the buried wood.
  - Because of low oxygen below the soil surface, decomposition of buried wood is expected to be slow

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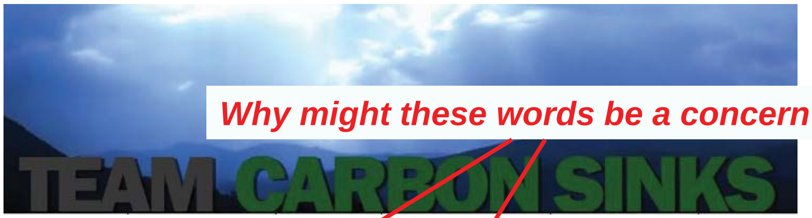

Why might these words be a concern ?!?

- Statements from Zeng, Carbon Sequestration Via Wood Burial, *Carbon Balance and Management*, 2008 http://www.cbmjournal.com/content/3/1/1 :
  - Here I suggest an approach in which wood from old or dead trees in the world's forests is harvested & buried in trenches under a layer of soil, where the anaerobic condition slows the decomposition of the buried wood.
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Cap and Trade vs Carbon Tax

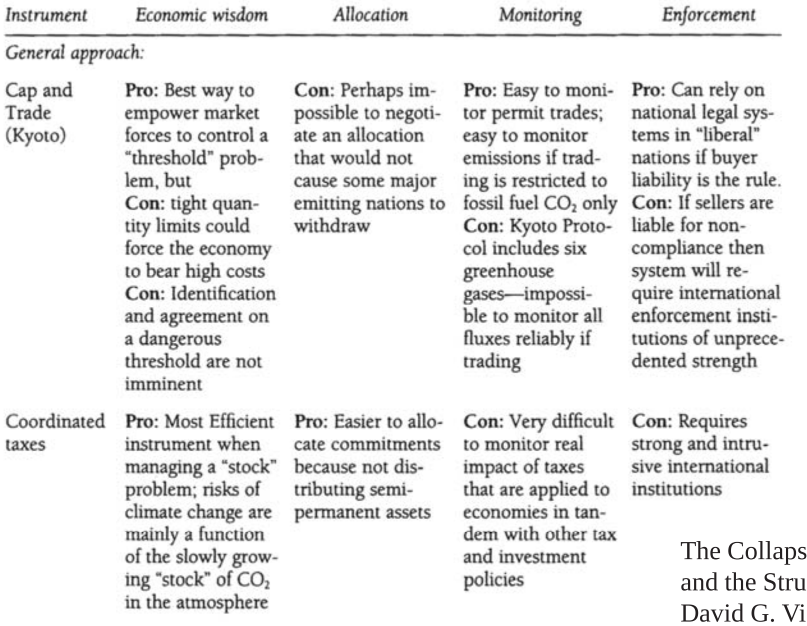
Extra Slide

From an economic point of view, these two policies are vastly different

Cap and trade regulates amount emitted

Carbon tax regulates price of emission

Comparison of Architectures for Greenhouse Gas Regulation



Instrument	Economic wisdom	Allocation	Monitoring	Enforcement
General approach:				
Cap and Trade (Kyoto)	**Pro**: Best way to empower market forces to control a "threshold" problem, but **Con**: tight quantity limits could force the economy to bear high costs **Con**: Identification and agreement on a dangerous threshold are not imminent	**Con**: Perhaps impossible to negotiate an allocation that would not cause some major emitting nations to withdraw	**Pro**: Easy to monitor permit trades; easy to monitor emissions if trading is restricted to fossil fuel CO_2 only **Con**: Kyoto Protocol includes six greenhouse gases—impossible to monitor all fluxes reliably if trading	**Pro**: Can rely on national legal systems in "liberal" nations if buyer liability is the rule. **Con**: If sellers are liable for noncompliance then system will require international enforcement institutions of unprecedented strength
Coordinated taxes	**Pro**: Most Efficient instrument when managing a "stock" problem; risks of climate change are mainly a function of the slowly growing "stock" of CO_2 in the atmosphere	**Pro**: Easier to allocate commitments because not distributing semipermanent assets	**Con**: Very difficult to monitor real impact of taxes that are applied to economies in tandem with other tax and investment policies	**Con**: Requires strong and intrusive international institutions

The Collapse of the Kyoto Protocol
and the Struggle to Slow Global Warming
David G. Victor, Princeton University Press, 2001

Mathematics of Peak Oil

Extra Slide

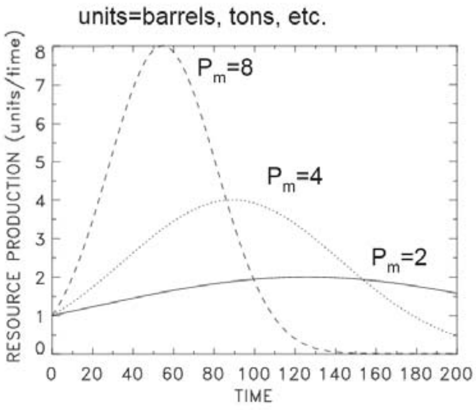
We'll use a symmetric, bell shaped curve to represent production rates over time. In this case, production corresponds to

$$P = P_m \exp\left[-\frac{1}{2}\left(\frac{t - t_m}{\sigma}\right)^2 \right]$$

P_m = maximum production rate
t_m = time when max. production occurs
σ = standard deviation

As before, we'll solve for Q, the total amount of resource produced,

$$Q_\infty = \int_{-\infty}^{\infty} P_m \exp\left[-\frac{1}{2}\left(\frac{t - t_m}{\sigma}\right)^2 \right] dt = \sigma P_m \sqrt{2\pi}$$



All three of these curves have the same area!!