The Kyoto Protocol and the Science of CO₂ Stabilization
AOSC 434/658R & CHEM 434/678A
Ross Salawitch

Class Web Site: http://www.atmos.umd.edu/~rjs/class/spr2011

Topics for today:
• Fossil fuel reserves
• Numerous slides tying to first part of class (climate change)
• Overview of attempts to regulate future atmospheric CO₂ via:
  – Public policy
  – Engineering

Lecture 18
14 April 2011

Fossil Fuel Emissions and Reserves

Figure 1. Fossil fuel-related estimates used in this study. Historical fossil fuel CO₂ emissions from the Carbon Dioxide Information Analysis Center [CDIAC; Marland et al., 2006] and British Petroleum [BP, 2006]. Lower limits for current proven conventional reserve estimates for oil and gas from IPCC [2001a] (dashed lines), upper limits and reserve growth values from US Energy Information Administration [EIA, 2006]. Lower limit for conventional coal reserves from World Energy Council [WEC, 2007; dashed line], upper limit from IPCC [2001a]. Possible amounts of unconventional fossil resources from IPCC [2001a].

Kharecha and Hansen, GBC, 2008.
World Carbon Emissions

20 June 2007

China: 1.70 Gt C per year
US: 1.58 Gt C per year

Historic Carbon Emissions

(c) Cumulative Emissions to 2005

How Much Fossil Fuel Reserve Does The World Really Have?

Hubbert’s Peak

- M. King Hubbert: Shell geophysicist
- 1956: presented a paper “Nuclear Energy and Fossil Fuels” that predicted US oil production would peak in 1970
- Paper was met with skepticism & ridicule
- But: this prediction was remarkably accurate!

Global Oil Production Predicted to Peak Next Decade!

Hubbert-like analysis applied to 47 major oil producing countries leads to conclusion that global production of oil will peak near 2014.

Actual production curve shows effects of economic and geo-political events

Cumulative (cum.) production curve indicates known oil reserves are ~ 2.1 TSTN (trillion stock tank barrels), half of which have been produced

Nashawi et al., Energy Fuels, 2010

http://pubs.acs.org/doi/abs/10.1021/ef901240p
Many countries have experienced peak oil production.


Extensive Literature on This Subject

Copyright © 2011 University of Maryland
This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty
**Fossil Fuel Projections**

**BAU: Business As Usual**

- **CO₂ Emissions (Gt C yr⁻¹)**
  - All Fuels + LU
  - All Fuels
  - Coal
  - Oil
  - Natural Gas

- **Atmospheric CO₂ (ppm)**


---

**Coal Reserves by Country**

<table>
<thead>
<tr>
<th>TOP TEN COUNTRIES</th>
<th>PROVEN COAL RESERVES (MILLION TONNES OIL EQUIVALENT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNITED STATES</td>
<td>121,961.7</td>
</tr>
<tr>
<td>RUSSIA</td>
<td>68,699.3</td>
</tr>
<tr>
<td>CHINA</td>
<td>58,900.0</td>
</tr>
<tr>
<td>INDIA</td>
<td>55,597.3</td>
</tr>
<tr>
<td>AUSTRALIA</td>
<td>41,546.7</td>
</tr>
<tr>
<td>SOUTH AFRICA</td>
<td>33,013.3</td>
</tr>
<tr>
<td>GERMANY</td>
<td>29,666.7</td>
</tr>
<tr>
<td>KAZAKHSTAN</td>
<td>21,666.7</td>
</tr>
<tr>
<td>UKRAINE</td>
<td>16,809.0</td>
</tr>
<tr>
<td>POLAND</td>
<td>14,153.3</td>
</tr>
<tr>
<td>OTHERS</td>
<td>39,157.7</td>
</tr>
</tbody>
</table>


http://www.theglobaleducationproject.org/earth/energy-supply.php
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


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)

Why is this a concern?

Why else might reliance on coal and oil sands be a concern?
Future Use of Fossil Fuels

- If society decides to continue to rely on fossil fuels, we will become increasingly reliant on coal (in the short term) and oil sands (in the long term).

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

Removal of NO\textsubscript{x} from Power Plants

NO\textsubscript{x} Control:
SCR Selective Catalytic Reduction

- 4\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}
- 6\text{NO}_2 + 8\text{NH}_3 \rightarrow 7\text{N}_2 + 12\text{H}_2\text{O}

Slide courtesy John Sherwell, Md Dept of Natural Resources
http://www.dnr.maryland.gov/bay/pprp
SO$_2$ emissions: largely driven by coal combustion

Projection of SO$_2$ emissions made in 1997:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>US</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Canada</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Asia</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
</tr>
</tbody>
</table>


China has implemented flue gas desulphurization at more than 50% of its coal fired power plants as of 2008. SO$_2$ emissions are stable from China and the rest of Asia!

Lu et al., ACP, 2010
Atmospheric CO₂ is long-lived and clearly associated with increased surface radiative forcing & rising temperature

Figures from IPCC (2007)

Copyright © 2011 University of Maryland
This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty
Global Fossil Fuel Emissions

2009 emissions: 8.4 Gt

Most Fossil Fuel Intensive IPCC Emission Scenario

CO$_2$ is long lived: society must reduce emissions soon or we will be committed to dramatic, future increases!

Curve that levels off at ~550 ppm has emissions peaking in 2027 (less than 20 years from now!)

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

Copyright © 2011 University of Maryland
This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty
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)
  – 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

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 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
  – Allows developed countries to implement projects that reduce emissions or increase natural GHG sinks in developing countries; such projects can be counted towards the emission reductions of the investing country
  – Australian Carbon Data Accounting Model
    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 Gases

<table>
<thead>
<tr>
<th>GHG</th>
<th>GWP</th>
<th>Industrial Use</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1</td>
<td>Fossil fuel combustion; Land use changes</td>
<td>Multiple, ~172 yrs</td>
</tr>
<tr>
<td>CH₄</td>
<td>23</td>
<td>Fossil fuel combustion; Rice paddies; Animal waste; Sewage treatment and landfills; Biomass burning</td>
<td>~10 yrs</td>
</tr>
<tr>
<td>N₂O</td>
<td>296</td>
<td>Agriculture &amp; river chemistry associated with pollution Biomass burning &amp; fossil fuel combustion</td>
<td>~115 yrs</td>
</tr>
<tr>
<td>HFCs</td>
<td>12 to 12000</td>
<td>Refrigerant (HFC−134a: CH₂F₂CF₃), foam blowing agent, and by product of HCFC manufacture</td>
<td>Range from 1.5 to 270 yrs; 14 yr for HFC-134a</td>
</tr>
<tr>
<td>PFCs</td>
<td>5000 to 12000</td>
<td>Aluminum smelting (CF₃) Semiconductor manufacturing (CF₄)</td>
<td>1000 to 50,000 yrs</td>
</tr>
<tr>
<td>SF₆</td>
<td>22200</td>
<td>Insulator in high voltage electrical equipment Magnesium casting Shoes and tennis balls (minor source)</td>
<td>3200 yrs</td>
</tr>
</tbody>
</table>
GWP – Global Warming Potential

\[
\text{GWP (SF}_6) = \int_{\text{time initial}}^{\text{time final}} a_{\text{SF}_6} \times [\text{SF}_6(t)] \, dt \\
\int_{\text{time initial}}^{\text{time final}} a_{\text{CO}_2} \times [\text{CO}_2(t)] \, dt
\]

where:

- \(a_{\text{SF}_6}\) = Radiative Efficiency (W m\(^{-2}\) ppb\(^{-1}\)) due to an increase in SF\(_6\)
- \(a_{\text{CO}_2}\) = Radiative Efficiency (W m\(^{-2}\) ppb\(^{-1}\)) due to an increase in CO\(_2\)
- SF\(_6\)(t) = time-dependent response to an instantaneous release of a pulse of SF\(_6\)
- CO\(_2\)(t) = time-dependent response to an instantaneous release of a pulse of CO\(_2\)

---

**HFCs Spectra**

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


Copyright © 2011 University of Maryland
This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Canty
**HFCs and PFCs**

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


---

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


Cap and Trade vs Carbon Tax

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

Cap and trade regulates ___________
Carbon tax regulates ___________

Comparison of Architectures for Greenhouse Gas Regulation

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Economic wisdom</th>
<th>Allocation</th>
<th>Monitoring</th>
<th>Enforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap and Trade (Kyoto)</td>
<td>Pro: Best way to empower market forces to control a &quot;threshold&quot; problem, but Con: Tight quantity limits could force the economy to bear high costs</td>
<td>Con: Perhaps impossible to negotiate an allocation that would not cause some major emitting nations to withdraw</td>
<td>Pro: Easy to monitor permit trades; easy to monitor emissions if trading is restricted to fossil fuel CO2 only Con: Kyoto Protocol includes six greenhouse gases—impossible to monitor all fluxes reliably if trading</td>
<td>Pro: Can rely on national legal systems in &quot;liberal&quot; nations if buyer liability is the rule Con: If sellers are liable for non-compliance then system will require international enforcement institutions of unprecedented strength</td>
</tr>
<tr>
<td>Coordinated taxes</td>
<td>Pro: Most efficient instrument when managing a &quot;stock&quot; problem; risks of climate change are mainly a function of the slowly growing &quot;stock&quot; of CO2 in the atmosphere</td>
<td>Pro: Easier to allocate commitments because not distributing semi-permanent assets Con: Very difficult to monitor real impact of taxes that are applied to economies in tandem with other tax and investment policies</td>
<td></td>
<td>Con: Requires strong and intrusive international institutions</td>
</tr>
</tbody>
</table>

The Collapse of the Kyoto Protocol and the Struggle to Slow Global Warming
David G. Victor, Princeton University Press, 2001
The EU-15 should meet its collective target of cutting greenhouse gas emissions by 8% for the period 2008–2012.

Based on recent EEA estimates ... EU-15 average emissions for 2008 and 2009 (the two first years of the commitment period) were lower than target by 94 Mt CO2-equivalent per year (2.2 % of base-year emissions). This over-achievement ... increases to more than 253 Mt CO2-equivalent per year when two factors are taken into account:

- governments' planned net annual acquisition of emissions units through the Kyoto Protocol's flexible mechanisms to comply with their targets (2.7 % of base year emissions)
- expected annual carbon sequestration from LULUCF activities (1.0 % of base-year emissions)

LULUCF: land use, land-use change and forestry

Info in 2.0 Mb file that is available at hot text “Tracking progress towards Kyoto and 2020 targets in Europe”
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/

Climate News

• Cancun (December 2010)
  − Consensus on measures to protect tropical rain forests, promote clean technologies, and help poorer nations adopt to rising sea level
  − No meaningful action on CO₂ emissions

• Bangkok (April 2011 … last week)
  − Key divisions between developed and developing countries … negotiations brought to a standstill over this division
  − EU: pushing for second Kyoto commitment period, beyond 2012
  − U.S., Japan, Russia, Canada: opposed to second Kyoto commitment period


• Washington DC (April 2011 … last week … related to Continuing Resolution)
  − “U.S. EPA efforts to protect public health by enforcing clean air and water rules will be undermined by a planned 16 percent budget reduction, environmental groups said”
  − “Republicans argued for a larger cut plus provisions that would bar the EPA from enforcing rules on reducing carbon dioxide from power plants and factories”


• Next round of talks: Bonn, Germany, June 2011
Regional Greenhouse Gas Initiative “RGGI”
http://www.rggi.org/home

- RGGI caps CO₂ emissions from region’s fossil fuel power plants (> 25 Mega Watt)
  - Regional CO₂ emissions held constant from 2009 through 2014
  - Beginning 2014 regional CO₂ emissions decrease for a total reduction of 10% by 2018
  - All fossil fuel fired facilities must own allowances equal to their annual CO₂ emissions

- 10 States are part of RGGI
  - Each state has an emissions cap
  - Regional market for CO₂ emission allowances

- Maryland joined on 20 April 2007
  - Bill passed in Annapolis
  - Participation governed by Md Dept of the Environment (MDE)

- Eleven auctions have been held; 3 more scheduled this year
  - Auction info: http://www.rggi.org/market/co2_ auctions/results
  - $162.5 million has been generated for Md

Maryland RGGI Revenue and Allocation

<table>
<thead>
<tr>
<th>Revenues as of March 2011</th>
<th>% (Original %)</th>
<th>Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millions of $</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38.2</td>
<td>46 (17.5)</td>
<td>Energy efficiency projects</td>
</tr>
<tr>
<td>84.2</td>
<td>50 (17)</td>
<td>Low income electricity assistance</td>
</tr>
<tr>
<td>43.5</td>
<td>23 (23)</td>
<td>General Rebates</td>
</tr>
<tr>
<td>13.9</td>
<td>6.5 (10.5)</td>
<td>Clean energy, education, &amp; climate programs</td>
</tr>
<tr>
<td>6.0</td>
<td>3.0 (3.5)</td>
<td>Administration</td>
</tr>
<tr>
<td><strong>162.5</strong></td>
<td><strong>100.0</strong></td>
<td><strong>Maryland Total: $ 162.5 million</strong></td>
</tr>
</tbody>
</table>


Copyright © 2011 University of Maryland
This material may not be reproduced or redistributed, in whole or in part, without written permission from Ross Salawitch or Tim Cauty
Carbon Capture & Sequestration

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 CO₂ (blue) and other emissions (green), goes out a smokestack. To collect CO₂ for storage, however, the mixture of gases is directed to an absorber (2), where a solvent like MEA (pink) bonds with the CO₂ molecules. The bonded CO₂-solvent complexes are separated in the stripper (3), which requires heat. More energy is needed for the next step (4), which produces a purified CO₂ stream for ground storage as well as solvent molecules that can be reused. (Schematic not to scale.)

**Carbon Capture & Sequestration**

**CATCHING THE FLUE (GAS)**

**SCIENCE** VOL 317 13 JULY 2007

MEA-monoethanolamine (CH₂CH₂OH)NH₂ in an aqueous solution will absorb CO₂ to form ethanolammonium carbamate.

\[ 2RNH₂ + CO₂ + H₂O \rightarrow (RNH₃)₂CO₂ \]

MEA is a weak base so it will re-release the CO₂ when heated.

Kintisch, Science, 2007

Where to Place the Sequestered Carbon?

**STORING CARBON DIOXIDE UNDERGROUND AND IN THE OCEAN**

**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

- Captures ~90% of CO₂ that is generated
- CO₂ pumped into 200 m thick sandstone layer 720 m below sea floor
- Project initiated in response to $50 ton tax on CO₂ emissions instituted by Norwegian Government in 1996
- Investment in capital cost paid off in about one and a half years!

CO₂ Capture and Storage (CCS) Costs:

<table>
<thead>
<tr>
<th>CCS component</th>
<th>Cost range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture from a power plant</td>
<td>15–75 US$/tCO₂ net captured</td>
</tr>
<tr>
<td>Capture from gas processing or ammonia production</td>
<td>5–55 US$/tCO₂ net captured</td>
</tr>
<tr>
<td>Capture from other industrial sources</td>
<td>25–115 US$/tCO₂ net captured</td>
</tr>
<tr>
<td>Transportation</td>
<td>1–8 US$/tCO₂ transported per 250km</td>
</tr>
<tr>
<td>Geological storage</td>
<td>0.5–8 US$/tCO₂ injected</td>
</tr>
<tr>
<td>Ocean storage</td>
<td>5–30 US$/tCO₂ injected</td>
</tr>
<tr>
<td>Mineral carbonation</td>
<td>50–100 US$/tCO₂ net mineralized</td>
</tr>
</tbody>
</table>