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
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!*
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?

• Coal is a complex mixture of substances that can be approximated by the chemical formula $\text{C}_{135}\text{H}_{96}\text{O}_{9}\text{NS}$. 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
Future Use of Fossil Fuels

• If society decides to continue to reply 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?

<table>
<thead>
<tr>
<th>Fossil Fuel</th>
<th>GHG Output (pounds CO₂ per kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Sands</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td></td>
</tr>
</tbody>
</table>

http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2report.html
Natural Gas

- Large reserves in Middle East & Russia.

Largest proven natural gas reserves holders (trillion cubic feet)

<table>
<thead>
<tr>
<th>Country</th>
<th>Reserves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russia</td>
<td>1,600</td>
</tr>
<tr>
<td>Iran</td>
<td>1,200</td>
</tr>
<tr>
<td>Qatar</td>
<td>800</td>
</tr>
<tr>
<td>United States*</td>
<td>200</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>100</td>
</tr>
<tr>
<td>Turkmenistan</td>
<td>200</td>
</tr>
<tr>
<td>United Arab Emirates</td>
<td>100</td>
</tr>
<tr>
<td>Venezuela</td>
<td>50</td>
</tr>
<tr>
<td>Nigeria</td>
<td>50</td>
</tr>
<tr>
<td>Algeria</td>
<td>30</td>
</tr>
</tbody>
</table>

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
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

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

http://akrondave.files.wordpress.com/2011/01/marcellus-shale.jpg
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?
Fossil Fuel Emissions

Global Carbon Emission Increase 1958-2012

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
Global Fossil Fuel Emissions

Raupach et al., PNAS, 2007

Most Fossil Fuel Intensive Scenario, IPCC (2007)
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-prolificate economy, and it has made by far the largest historical contribution to the stock of atmospheric CO₂. 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 CO₂ 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 1990-2006 emissions (from the NEAA, IEA and World Resources Institute) both exclude cement production. CO₂ intensity figures (from the IEA) are calculated on a purchasing power parity basis using 2000 prices. *Figures from 2004; 1Europe 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
Tribett et al., in prep, 2015
Per-Capita Carbon Emission Projections
Obama / Xi Deal (Attain & Hold; BAU)

Carbon Projections

Cumulative Carbon 2015 – 2060: 972 GtC

Tribett et al., in prep, 2015
Tribett et al., in prep, 2015
Per-Capita Carbon Emission Projections

Obama / Xi Deal (Attain; Contract & Converge)

Carbon Projections

Cumulative Carbon 2015 – 2060: 714 GtC

Tribbett et al., in prep, 2015
Per-Capita Carbon Emission Projections
Obama / Xi Deal (Attain; Contract & Converge)

Carbon Projections

Cumulative Carbon 2015 – 2060: 601 GtC

Tribett et al., in prep, 2015
IPCC (2013) Links Rise in GMST to Total Cumulative C Emissions
IPCC (2013) Links Rise in GMST to Total Cumulative C Emissions

Our projections
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>
<thead>
<tr>
<th>Country</th>
<th>Target (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU-15**, Bulgaria, Czech Republic, Estonia, Latvia, Lithuania, Romania, Slovakia, Slovenia, Switzerland</td>
<td>−8</td>
</tr>
<tr>
<td>USA***</td>
<td>−7</td>
</tr>
<tr>
<td>Canada, Hungary, Japan, Poland</td>
<td>−6</td>
</tr>
<tr>
<td>Croatia</td>
<td>−5</td>
</tr>
<tr>
<td>New Zealand, Russian Federation, Ukraine</td>
<td>0</td>
</tr>
<tr>
<td>Norway</td>
<td>+1</td>
</tr>
<tr>
<td>Australia</td>
<td>+8</td>
</tr>
<tr>
<td>Iceland</td>
<td>+10</td>
</tr>
</tbody>
</table>

* 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.

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
  – cannot sell emission credits
KYOTO PROTOCOL TO THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE

UNITED NATIONS

1998

Kyoto Protocol

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 Targets

Kyoto target (2008 to 2012) for emissions of CO$_2$, relative to 1990 emissions
selected locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Target</th>
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<tbody>
<tr>
<td>Australia</td>
<td>108%</td>
</tr>
<tr>
<td>EU15</td>
<td>92%</td>
</tr>
<tr>
<td>Iceland</td>
<td>110%</td>
</tr>
<tr>
<td>Japan</td>
<td>94%</td>
</tr>
<tr>
<td>New Zealand</td>
<td>100%</td>
</tr>
<tr>
<td>Norway</td>
<td>101%</td>
</tr>
<tr>
<td>Russia</td>
<td>100%</td>
</tr>
<tr>
<td>US</td>
<td>93%</td>
</tr>
</tbody>
</table>

The Collapse of the Kyoto Protocol and the Struggle to Slow Global Warming

CO$_2$ emissions

Does not include:
- LULUCF (land use, land-use change and forestry)
- GHGs other than CO$_2$
Kyoto Protocol Targets

Kyoto target (2008 to 2012) for emissions of CO$_2$, relative to 1990 emissions

<table>
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<tr>
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Does not include:
- LULUCF (land use, land-use change and forestry)
- GHGs other than CO$_2$

The Collapse of the Kyoto Protocol and the Struggle to Slow Global Warming
Kyoto Protocol Targets

Kyoto target (2008 to 2012) for emissions of CO₂, 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

Does not include:
- LULUCF (land use, land-use change and forestry)
- GHGs other than CO₂
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 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

<table>
<thead>
<tr>
<th>GHG</th>
<th>GWP, 100-yr</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>25</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>298</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>124 to 15000</td>
<td>Refrigerant (HFC–134a: CH₂FCF₃), foam blowing agent, and by product of HCFC manufacture</td>
<td>Range from 1.5 to 270 yrs</td>
</tr>
<tr>
<td>PFCs</td>
<td>7400 to 12200</td>
<td>Aluminum smelting (CF₄) Semiconductor manufacturing (CF₄)</td>
<td>1000 to 50,000 yrs</td>
</tr>
<tr>
<td>SF₆</td>
<td>22800</td>
<td>Insulator in high voltage electrical equipment Magnesium casting Shoes and tennis balls (minor source)</td>
<td>3200 yrs</td>
</tr>
</tbody>
</table>
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**

\[
GWP (HFC-134a) = \frac{\int_{time\ initial}^{time\ final} a_{HFC-134a} \times [HFC-134a(t)] \ dt}{\int_{time\ initial}^{time\ final} a_{CO2} \times [CO_2(t)] \ dt}
\]

where:

- \(a_{HFC-134a}\) = 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\(_2\)FCF\(_3\)

HCFC-22 is CH\(_3\)CClF\(_2\)

<table>
<thead>
<tr>
<th>Time Horizon</th>
<th>20-yr</th>
<th>100-yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau) (yr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HFC-134a</td>
<td>13.4</td>
<td>3710</td>
</tr>
<tr>
<td>HCFC-22</td>
<td>11.9</td>
<td>1300</td>
</tr>
</tbody>
</table>

Table 8.A.1, IPCC (2013)
Not all HFCs are equal wrt Global Warming

WMO/UNEO 2011 “Twenty Questions”
http://esrl.noaa.gov/csd/assessments/ozone/2010/twentyquestions
Radiative Forcing due to HFCs

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

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


http://en.wikipedia.org/wiki/Special_Report_on_Emissions_Scenarios#SRES_scenarios_and_climate_change_initiatives

Velders et al., PNAS, 2009
Radiative Forcing due to PFCs

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

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

Figure 4  Radiative forcing of C$_2$F$_6$, CF$_4$, and SF$_6$ from 2010 to 2100.

• **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

<table>
<thead>
<tr>
<th>Ref Year</th>
<th>GHG reductions 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>US*</td>
<td></td>
</tr>
<tr>
<td>EU-15</td>
<td>1990 20 to 30%</td>
</tr>
<tr>
<td>Japan**</td>
<td></td>
</tr>
<tr>
<td>Norway</td>
<td>1990 30 to 40%</td>
</tr>
</tbody>
</table>

* 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
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: CO₂ Stabilization Wedges

<table>
<thead>
<tr>
<th>Action</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Energy efficiency and conservation</em></td>
<td>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)</td>
</tr>
<tr>
<td>Economy-wide carbon-intensity reduction (emissions/$GDP)</td>
<td>Increase fuel economy for 2 billion cars from 30 to 60 mpg</td>
</tr>
<tr>
<td>1. Efficient vehicles</td>
<td>Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5000 miles per year</td>
</tr>
<tr>
<td>2. Reduced use of vehicles</td>
<td>Cut carbon emissions by one-fourth in buildings and appliances projected for 2054</td>
</tr>
<tr>
<td>3. Efficient buildings</td>
<td>Produce twice today’s coal power output at 60% instead of 40% efficiency (compared with 32% today)</td>
</tr>
<tr>
<td>4. Efficient baseload coal plants</td>
<td>Replace 1400 GW 50%-efficient coal plants with gas plants (four times the current production of gas-based power)</td>
</tr>
<tr>
<td><em>Fuel shift</em></td>
<td>Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)</td>
</tr>
<tr>
<td>6. Capture CO₂ at baseload power plant</td>
<td>Introduce CCS at plants producing 250 MtoH₂/year from coal or 500 MtoH₂/year from natural gas (compared with 40 MtoH₂/year today from all sources)</td>
</tr>
<tr>
<td>7. Capture CO₂ at H₂ plant</td>
<td>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</td>
</tr>
<tr>
<td>8. Capture CO₂ at coal-to-synfuels plant</td>
<td>Create 3500 Sleipners</td>
</tr>
<tr>
<td>Geological storage</td>
<td></td>
</tr>
</tbody>
</table>

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## Pacala and Socolow: CO₂ Stabilization Wedges

<table>
<thead>
<tr>
<th>Action</th>
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</tr>
</thead>
<tbody>
<tr>
<td>9. Nuclear power for coal power</td>
<td>Add 700 GW (twice the current capacity)</td>
</tr>
<tr>
<td>10. Wind power for coal power</td>
<td>Add 2 million 1-MW-peak windmills (50 times the current capacity)</td>
</tr>
<tr>
<td></td>
<td>&quot;occupying&quot; $30 \times 10^6$ ha, on land or offshore</td>
</tr>
<tr>
<td>11. PV power for coal power</td>
<td>Add 2000 GW-peak PV (700 times the current capacity) on $2 \times 10^6$ ha</td>
</tr>
<tr>
<td>12. Wind H₂ in fuel-cell car for gasoline in hybrid car</td>
<td>Add 4 million 1-MW-peak windmills (100 times the current capacity)</td>
</tr>
<tr>
<td>13. Biomass fuel for fossil fuel</td>
<td>Add 100 times the current Brazil or U.S. ethanol production, with the use of $250 \times 10^6$ ha (one-sixth of world cropland)</td>
</tr>
<tr>
<td>14. Reduced deforestation, plus reforestation, afforestation, and new plantations.</td>
<td>Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)</td>
</tr>
<tr>
<td>15. Conservation tillage</td>
<td>Apply to all cropland (10 times the current usage)</td>
</tr>
</tbody>
</table>

*Forests and agricultural soils*

*Nuclear fission*

*Renewable electricity and fuels*
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.)

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

\[ 2\text{RNH}_2 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow (\text{RNH}_3)_2\text{CO}_2 \]

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

Where to Place the Sequestered Carbon?

STORING CARBON DIOXIDE UNDERGROUND AND IN THE OCEAN

STORAGE UNDERGROUND

<table>
<thead>
<tr>
<th>STORAGE UNDERGROUND</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Beds</td>
<td>Potentially low costs</td>
<td>Immature technology</td>
</tr>
<tr>
<td>Mined Salt Domes</td>
<td>Custom designs</td>
<td>High costs</td>
</tr>
<tr>
<td>Deep Salina Aquifers</td>
<td>Large capacity</td>
<td>Unknown storage integrity</td>
</tr>
<tr>
<td>Depleted Oil or Gas Reservoirs</td>
<td>Proven storage integrity</td>
<td>Limited capacity</td>
</tr>
</tbody>
</table>

STORAGE IN OCEAN

<table>
<thead>
<tr>
<th>STORAGE IN OCEAN</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droplet Plume</td>
<td>Minimal environmental effects</td>
<td>Some leakage</td>
</tr>
<tr>
<td>Towed Pipe</td>
<td>Minimal environmental effects</td>
<td>Some leakage</td>
</tr>
<tr>
<td>Dry Ice</td>
<td>Simple technology</td>
<td>High costs</td>
</tr>
<tr>
<td>Carbon Dioxide Lake</td>
<td>Carbon will remain in ocean for thousands of years</td>
<td>Immature technology</td>
</tr>
</tbody>
</table>

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

- 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!

*National Geographic, June 2008*
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>

Cost of capture: \(~$54 / \text{ton} \text{ CO}_2 \times 10 \times 10^9 \text{ tons C / yr} = $ 540 \text{ billion}\)

Present cost of fossil fuel: $ 56 / barrel \(\approx $ 484 / \text{ton}\)

World GDP, 2010: \(\$ 75.6 \text{ trillion}\) CO₂ capture = 0.7 % of world GDP = 11 % of cost, barrel of oil

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC)

Carbon Dioxide Capture and Storage

Afforestation

• If 100,000 km² (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

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• Land available ✓ Cost ✓

Sequestration of CO\textsubscript{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
Cap and Trade vs Carbon Tax

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

<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 “threshold” problem, but Con: tightening limits could force the economy to bear high costs Con: Identification and agreement on a dangerous threshold are not imminent</td>
<td>Pro: 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 “liberal” 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 “stock” problem; risks of climate change are mainly a function of the slowly growing “stock” of CO2 in the atmosphere</td>
<td>Pro: Easier to allocate commitments because not distributing semi-permanent assets</td>
<td>Con: Very difficult to monitor real impact of taxes that are applied to economies in tandem with other tax and investment policies</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
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.

http://tonto.eia.doe.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm
Mathematics of Peak Oil

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

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

\[ P_m = \text{maximum production rate} \]
\[ t_m = \text{time when max. production occurs} \]
\[ \sigma = \text{standard deviation} \]

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

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

units=barrels, tons, etc.

All three of these curves have the same area!!