Hubbert’s Peak, The Question of Coal, and Climate Change

Dave Rutledge
Chair, Division of Engineering and Applied Science
Caltech

“There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact.”

Mark Twain

Life on the Mississippi

slides (.ppt) and spreadsheets (.xls) at http://rutledge.caltech.edu/
The UN Panel on Climate Change

• The UN Intergovernmental Panel on Climate Change publishes assessment reports that reflect the consensus on climate change

• The 4th report is being released this year
  – Over one thousand authors
  – Over one thousand reviewers

• Updated measurements show that the temperature is rising 0.013°C per year (1956-2005)
IPCC Climate-Change Predictions

• Report discusses climate simulations for fossil-fuel carbon-emission scenarios
• There are 40 scenarios, each considered to be equally valid, with story lines and different government policies, population projections, and economic models
The 40 UN IPCC Scenarios

- Data from the EIA (open symbols, 1980 to 2004)
- Emissions have increased 18% since the Kyoto Agreement was negotiated in 1997
- Large differences in emissions among scenarios
- Oil production in 17 of the scenarios is greater in 2100 than in 2005
World crude-oil production fell in 2006 by roughly the amount of this drop.
Outline

• The 4th UN IPCC Assessment Report
• Hubbert’s peak
  – The history of US oil production
  – How much oil do the Saudis have?
  – The future of world hydrocarbons
  – The Canadian oil sands
• The coal question
  – British coal, a nearly complete history
  – Chinese coal
  – American coal
  – The future of world coal, by regions
• Climate change
  – Simulation of future CO2 levels
  – Simulation of future temperature
  – Carbon capture
  – Wind and sun
• Concluding thoughts
King Hubbert

• Geophysicist at the Shell lab in Houston
• In 1956, he presented a paper “Nuclear Energy and Fossil Fuels” at a meeting of the American Petroleum Institute in San Antonio
• He made predictions of the peak year of US oil production based on two estimates of the ultimate production
Hubbert’s Peak

- From his 1956 paper
- Hubbert drew these by hand, and integrated by counting squares
- For the larger estimate, Hubbert predicted a peak in 1970
What Actually Happened?

- Gb = billions of barrels
- Data from the DOE’s Energy Information Administration (EIA)
- Production has dropped 15 years in a row
US Crude-Oil Production

- EIA data from 1859
- Cumulative normal least mean square fit using Solver in Excel
- Hubbert’s larger ultimate was 200 billion barrels (the Alaska trend is 20 billion barrels)

Ultimate 225Gb

Cumulative Production, Gb

<table>
<thead>
<tr>
<th>Year</th>
<th>Cumulative Production</th>
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<tbody>
<tr>
<td>1900</td>
<td>0</td>
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<tr>
<td>1950</td>
<td>50</td>
</tr>
<tr>
<td>2000</td>
<td>150</td>
</tr>
<tr>
<td>2050</td>
<td>225</td>
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</table>

31Gb remaining
The Largest US Oil Field
Prudhoe Bay, Alaska
Discovered 1968
Prudhoe Bay Oil Production

Cumulative Production, Gb

<table>
<thead>
<tr>
<th>Annual Production, Mb</th>
<th>Trend for ultimate is 12 billion barrels</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>10% per year</td>
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<tr>
<td>0 - 5</td>
<td>10% per year</td>
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<tr>
<td>5</td>
<td>10% per year</td>
</tr>
<tr>
<td>10</td>
<td>10% per year</td>
</tr>
</tbody>
</table>

- Mb = Millions of barrels
- FY1977-2006 data from the Alaska Department of Revenue, Tax Division
- Initially considered as 8 billion barrels of reserves
Estimating Remaining Production from Reserves is Challenging

- *Reserves* refer to fossil fuels that are appropriate to produce, taking the price into account
- Reserves may be listed conservatively, as for Prudhoe Bay
- Coal reserves have been too high, and they are often not properly distinguished from *resources*, which are volume estimates for coal seams of a minimum thickness and a maximum depth
- The German Energy Watch Group was the first to point out that there is a problem with coal reserves worldwide
- Often reserves are not adjusted for production
- New discoveries are important for oil and natural gas
- In most countries, the details of oil reserves are secret, and this means that the published reserves are political statements
OPEC Reserves Go Up and Up!

- Data from the *BP Statistical Review*
- 360Gb rise in reserves, no adjustment for 150Gb produced since 1980
Estimating Remaining Production from a Graph

• In plots of annual production vs cumulative production
  – We can estimate the remaining production from a trend line
  – Advantage is that we can identify points on the trend line
  – Disadvantage is that we cannot make an estimate until the production drops

• Alternative is to plot the growth rate of the cumulative production (annual production over cumulative production) instead of the annual production
  – First applied to *Daphnia* populations in biology in 1963
  – King Hubbert introduced this approach for estimating remaining oil production in 1982
  – Advantage is that we can make an estimate before the peak
  – Disadvantage is that we need to know the cumulative production
Growth-Rate Plot for US Crude Oil

- EIA data (cumulative from 1859, symbols 1900-2006)
How Much Oil do the Saudis Have?

- Official Saudi reserves are 264 billion barrels
- Saudis claim production levels 75% above current level are possible for 50 years
- Matt Simmons was the first to call attention to this discrepancy in his book, *Twilight in the Desert*
Growth-Rate Plot for World Hydrocarbons

- Oil + natural gas + natural gas liquids like propane and butane
- Tboe = trillion barrels of oil equivalent
- The German resources agency BGR gives hydrocarbon reserves as 2.7Tboe
  - Expectation of future discoveries and future OPEC oil reserve reductions
  - Includes 500Gboe for non-conventional sources like Canadian oil sands
World Hydrocarbon Production

- IPCC scenarios assume that 11 to 15Tboe is available
- 3.2Tboe remaining
- 90% in 2071
Fort McMurray, Alberta
Oil Sands
Canadian Oil Sands

- 1.0 Mb per day in 2005, increasing 8% per year
- 35Gb reserves for mining (comparable to one year of world oil production)
- 140Gb reserves for wells
  - Production with a steam process
  - Production and upgrading to synthetic crude oil use 25% of the oil energy equivalent in natural gas
  - Canadian gas reserves are 10Gboe (end of 2005)
  - Annual gas production is 12% of reserves per year
  - Challenges in meeting obligations under the Kyoto agreement
- Kjell Aleklett’s Uppsala Hydrocarbon Depletion Group was the first to call attention to these limitations
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British Coal
British Coal Production

- Data from the US National Bureau of Economic Research (1854-1876), the Durham Coal Mining Museum (1877-1956), and the British Department of Trade and Industry (1957-2006).
- In the peak production year, 1913, there were 3,024 mines.
Growth-Rate Plot for British Coal

- 1854-2006, 1853 cumulative from William Jevons, *The Coal Question*
Remaining Production for British Coal

- Data from the UK Department of Trade and Industry (1993-2006)
- 6 producing underground mines — several with less than ten years of coal
- 35 strip mines are producing, but there are difficulties in getting permits for new mines
Cumulative British Coal Production

- Pre-war fit (1854-1945, ultimate 25.6Gt)
- Post-war fit (1946-2006, ultimate 27.2Gt)
Growth-Rate Plot with Two Trends

Cumulative Production, Gt

Growth Rate for Cumulative

Pre-war

Post-war
Reserves vs Remaining Production

- 1864 reserves from Edward Hull of the Geological Survey
- Other data from the World Energy Council Surveys of Energy Resources
- Resources include seams of 2ft or more at depths of 4000ft or less
Reserves-to-Production Ratio for UK Coal

- 1864 reserves from Edward Hull of the Geological Survey
- Other data from the World Energy Council Surveys
- Current R/P ratio is 7 years
Anthracite in Pennsylvania

- Data from the USGS (Robert Milici)
- Anthracite is a grade of coal used for home heating that burns with little smoke
- Peak production was 90Mt in 1918, current production is 2Mt
Growth-Rate Plot for PA Anthracite

- Data from Robert Milici and the EIA, cumulative from 1800, 1875-2005
- 16% of the 1913 reserves have been produced

Trend curve is for 5.0Gt
Cumulative PA Anthracite Production

- Normal Ims fit for ultimate 5.0Gt, 50% 1916, 90% 1951
Bituminous Coal in Virginia

- Data from Robert Milici and the EIA
- Virginia has coal with high energy content, and much of it is used for metallurgy
Growth-Rate Plot for VA Bituminous

- Data from Robert Milici and the EIA, cumulative from 1800, closed 1900-1935, open 1936-1955, closed 1956-2005, reserves from the EIA
- Trend is for 16% of the 1924 reserves to eventually be produced

Trend is for 800Mt remaining
Reserves are 2.8Gt

Pre-war
Post-war
Cumulative VA Bituminous Production

- Pre-war normal (ultimate 0.40Gt, lms fit for 50% 1926 90% 1946)
- Post-war normal (ultimate 3.03Gt, lms fit for 50% 1981 90% 2020)
Issues in Determining Reserves

• Here are some technical restrictions from the USGS 2000 National Coal Assessment for the Illinois basin
Are American Reserves Still Too High?

• From the National Academy of Sciences report on coal, released June 21, 2007

"Present estimates of coal reserves are based upon methods that have not been reviewed or revised since their inception in 1974, and much of the input data were compiled in the early 1970s. Recent programs to assess reserves in limited areas using updated methods indicate that only a small fraction of previously estimated reserves are actually minable reserves."

• For coal, we will take the reserves to be an upper limit on future production
## Production and Reserves

<table>
<thead>
<tr>
<th></th>
<th>Production, Gt</th>
<th>Reserves, Gt</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>2.38</td>
<td>189</td>
</tr>
<tr>
<td>USA</td>
<td>1.05</td>
<td>247</td>
</tr>
<tr>
<td>India</td>
<td>0.45</td>
<td>92</td>
</tr>
<tr>
<td>Australia</td>
<td>0.37</td>
<td>79</td>
</tr>
<tr>
<td>Russia</td>
<td>0.31</td>
<td>157</td>
</tr>
<tr>
<td>South Africa</td>
<td>0.26</td>
<td>29</td>
</tr>
<tr>
<td>World</td>
<td>6.20</td>
<td>963</td>
</tr>
</tbody>
</table>

- 2006 Production numbers from the BP Statistical Review
American Coal
US Coal Production

- Data from Robert Milici and the EIA
- Will consider the East and the West separately
Coal East of the Mississippi

- Does not include Pennsylvania anthracite
- Data from Robert Milici and the EIA, cumulative from 1800, closed 1900-1940, open 1941-1948, closed 1949-2005, reserves from the EIA

Post-war trend is for 35Gt
Remaining reserves are 96Gt
Cumulative Production for the East

- Does not include Pennsylvania anthracite
- Pre-war normal (ultimate 20Gt, lms fit for T50% 1924, T90% 1949)
- Post-war normal (ultimate 81Gt, lms fit for T50% 1994, T90% 2076)
Western Coal
Coal West of the Mississippi

- Data from Robert Milici and the EIA closed 1800-1970, open 1971-1978, closed 1979-2005
- Reserves from the EIA, Montana is the state with the largest reserves, 68Gt, but annual production is only 36Mt

Post-70’s trend is for 35Gt remaining
Reserves are 79Gt without Montana

Pre-70’s trend
Cumulative Production for the West

- Pre-70’s normal (ultimate 1.6Gt, lms fit for 50% 1929, 90% 1958)
- Post-70’s normal (ultimate 48Gt, lms fit for 50% 2022, 90% 2056)
Chinese Coal
Chinese Coal Production

- Problems with data during 1998-2002 because of safety campaign, corrections by Jianjun Tu applied
Growth-Rate Plot for China

- Reserves from the Chinese Ministry of Land and Resources 2001 by way of Sandro Schmidt at the BGR

Trend line for 70Gt remaining
Reserves are 189Gt
Growth-Rate Plot for Australia and New Zealand

- Data (1981-2006) from the BP Statistical Review
- 1990 Australia cumulative from the *History of Coal Mining in Australia*, A.J. Hargraves
- Reserves from the 2004 World Energy Council survey

Trend line for 50Gt remaining
Reserves are 79Gt
Growth-Rate Plot for Europe

- Reserves from the 2004 World Energy Council survey, down from 171Gt in 1990
- 2005 cumulative from the BGR Energy Resources Report
- Does not include the former Soviet Union

Trend line for 21Gt remaining
Reserves are 55Gt
Growth-Rate Plot for Africa

- 2005 cumulative from the 2005 BGR Energy Resources Report
- South African reserves were recently reduced by 20Gt (2006/2007 South Africa Yearbook)

Trend line for 10Gt remaining
Reserves are 30Gt
Former Soviet Union

- Data from BP (closed 1981-1988, open 1989-2006)
- 2005 cumulative from the BGR Energy Resources Report
- Drop that started in 1989 was from the collapse of the Soviet Union
- Reserves from World Energy Council surveys, unchanged since the collapse of the Soviet Union

Trend line for 18Gt remaining
1996 reserves are 157Gt
Growth-Rate Plot for South Asia

- Data (1965-2006) from the BP Statistical Review
- Earlier production from World Energy Council Surveys
- Reserves from the 2004 World Energy Council survey
- Includes Middle East and Turkey

Line is for 5% per year growth
Reserves are 111Gt
Growth-Rate Plot for Central and South America

- Data (1981-2005) from the 2006 BP Statistical Review
- 2005 Cumulative from the BGR Resources Report
- Reserves from the 2004 World Energy Council survey

Line is for 6% per year growth
Reserves are 20Gt

Cumulative Production, Gt

Growth Rate for Cumulative
Reserves vs Trends for Remaining Production

<table>
<thead>
<tr>
<th>Region</th>
<th>Reserves Gt</th>
<th>Trends Gt</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>255</td>
<td>140</td>
</tr>
<tr>
<td>East Asia</td>
<td>190</td>
<td>70</td>
</tr>
<tr>
<td>Australia and New Zealand</td>
<td>79</td>
<td>50</td>
</tr>
<tr>
<td>Europe</td>
<td>55</td>
<td>21</td>
</tr>
<tr>
<td>Africa</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>Former Soviet Union</td>
<td>223</td>
<td>18</td>
</tr>
<tr>
<td>South Asia</td>
<td>111</td>
<td></td>
</tr>
<tr>
<td>Central and South America</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>World (at 3.6boe/t)</td>
<td>963 (3.5Tboe)</td>
<td>440 (1.6Tboe)</td>
</tr>
</tbody>
</table>

- North America includes trends for the East (35Gt), the West (35Gt), reserves for Montana (68Gt), and trends for Canada and Mexico (total of 2Gt)
- IPCC scenarios assume 18Tboe is available for production
Future Fossil-Fuels Production

- Cumulative Production, Tboe

- 3.2Tboe hydrocarbons remaining
- 1.6Tboe coal remaining

- 90% in 2071
- 90% in 2088
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Comparing with the IPCC Scenarios

- Carbon coefficients from the EIA: oil (110kg/boe), gas (79kg/boe), coal (141kg/boe), and future hydrocarbons weighted by BGR reserves (98kg/boe)
- Our Producer-Limited profile has lower emissions than any of the 40 IPCC scenarios
- Jean Laherrere was the first to point out this anomalous situation
Simulated CO$_2$ Levels

- Predictions using the program MAGICC from Tom Wigley at the National Center for Atmospheric Research in Boulder with a modified WRE profile
- The Producer-Limited Profile gives a peak CO$_2$ concentration of 460ppm in 2070
- The Super-Kyoto Profile gives a 440ppm peak
- The Producer-Limited total temperature rise is a maximum of 1.8°C in 2150.
- The Super-Kyoto Profile (dashed lines) does not decrease the peak.
- Only 0.8°C rise is associated with future fossil-fuel production.
Wind and Sun

• The time constants of around 50 years for fossil-fuel exhaustion imply that a transition to renewable sources of energy is likely
• Wind is the fastest growing renewable
  – Current world capacity is 74GW, increasing at 25% per year
  – 19% of new US capacity last year
  – Advantage is a production learning curve
• Solar photovoltaics for the home and business
  – World production in 2006 was 2.2GW, up 33% from 2005
  – Advantage is that there is no need for new transmission lines
  – Caltech is installing a 230-kW plant on top of a parking structure
• Concentrating solar
  – Current capacity is 350MW, built in the 80s in the Mojave Desert
  – New Nevada Solar One with 64MW near Las Vegas
  – Advantages are that it uses the direct sunlight available in the Southwest, and the possibility of thermal storage
  – The major California utilities, Southern California Edison, San Diego Gas and Electric, and Pacific Gas and Electric, are each planning to spend a billion dollars on concentrating solar plants
Suitability for solar thermal power plants:

- Excellent
- Good
- Suitable
- Unsuitable

- From Schott Glass
- Area in red circle in California could supply sufficient energy to replace the entire US grid
Nevada Solar One
June 2, 2007
Concluding Thoughts

• Results
  – Projection for future hydrocarbon production (3.2Tboe) is 20% larger than reserves
  – Projection for future coal production (1.6Tboe) is 50% of reserves
  – The 10%-90% production period for fossil fuel is around 100 years
  – Stretching out production does not reduce the temperature maximum

• Implications
  – Since the projection for future fossil-fuel production is less than all 40 UN IPCC scenarios, producer limitations could provide useful constraints in climate modeling
  – To lessen the effects of climate change associated with future fossil-fuel use, we must reduce ultimate production rather than slow it down

• Opportunities
  – One-third of US fossil-fuel reserves are on federal lands, so ultimate production could be reduced substantially by limits on new leases for mining and drilling
  – The US has an outstanding resource in its direct sunlight
Thanks for Advice, Criticism, Discussion, and Slides

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