Coal
Energy Markets Are Interconnected

Estimated U.S. Energy Use in 2013: ~97.4 Quads

Source: LLNL. 2014. Data is based on DOE/EIA-0085(2014-01), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (e.g., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 85% for the residential and commercial sectors. 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-Mi-410577

Topics

- Origins
- Coal Reserves
- Coal Consumption
- Mining Issues
- Electricity Production Using Coal
- Coal Ash
- GHG Capture Costs
Topics

- Origins
- Coal Reserves
- Coal Consumption
- Mining Issues
- Coal Ash
- GHG Capture Costs
Coal

- U.S. consumes nearly a billion short tons of coal each year
- About ½ of U.S. electricity derived from coal in 2010
- Understanding the distribution & availability of coal of sufficient quality & quantity to meet the 1990 Clean Air Act Amendments emission standards is important to ensure adequate energy supplies in the future
Coal Formation

- Coal is a derivative of organic material
  - Dense surface vegetation is buried
  - Over time heat & pressure are applied. “Peat” becomes soft brown & ten hard black coal

Coal

- Five major basins in North America
  - Appalachian
  - Illinois
  - Rocky Mountain
  - Gulf Coast
  - Colorado Plateau

http://www.geocraft.com/WVFossils/Energy.html
Coal

- Two great ages of coal formation
  - Cretaceous – 75 million years ago
  - Pennsylvanian (Carboniferous) – 300 million years ago

[Map of the United States showing the geoologic age of coals, with different colors for different age groups.]

Coal Rank

- Anthracite – 95% carbon
- Semi-anthracite
- Bituminous – 50% - 80% carbon
- Sub-bituminous
- Lignite – Less than 50% carbon
- Peat

### ASTM D 388 Classification of Coals by Rank

#### TABLE 1 Classification of Coals by Rank

<table>
<thead>
<tr>
<th>Class/Group</th>
<th>Fixed Carbon Limits (Dry, Mineral-Matter-Free Basis), %</th>
<th>Volatile Matter Limits (Dry, Mineral-Matter-Free Basis), %</th>
<th>Gross Calorific Value Limits (Moist, Mineral-Matter-Free Basis)</th>
<th>Agglomerating Character</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equal or Greater Than</td>
<td>Less Than</td>
<td>Greater Than</td>
<td>Equal or Greater Than</td>
</tr>
<tr>
<td>Anthracite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meta-anthracite</td>
<td>98</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Anthracite</td>
<td>92</td>
<td>98</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Semi-anthracite</td>
<td>86</td>
<td>92</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>Bituminous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low volatile bituminous coal</td>
<td>78</td>
<td>86</td>
<td>14</td>
<td>22</td>
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<tr>
<td>Medium volatile bituminous coal</td>
<td>69</td>
<td>78</td>
<td>22</td>
<td>31</td>
</tr>
<tr>
<td>High volatile A bituminous coal</td>
<td>...</td>
<td>69</td>
<td>31</td>
<td>...</td>
</tr>
<tr>
<td>High volatile B bituminous coal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>High volatile C bituminous coal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Subbituminous</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Subbituminous A coal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Subbituminous B coal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Subbituminous C coal</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Lignitic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lignite A</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Lignite B</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

- This classification does not apply to certain coals, as discussed in Section 1.
- Moist refers to coal containing its natural inherent moisture but not including visible water on the surface of the coal.
- Megajoules per kilogram. To convert British thermal units per pound to megajoules per kilogram, multiply by 0.0023255.
- If agglomerating, classify in low volatile group of the bituminous class.
- It is recognized that there may be nonagglomerating varieties in these groups of the bituminous class, and that there are notable exceptions in the high volatile C bituminous group.
- Coals having 69% or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of gross calorific value.
- Editorially corrected.
Location of coal relative to other fossil fuels

http://geosci.uchicago.edu/~moyer/GEOS24705/Notes/Lecture1517Slides.pdf
Coal Assays

- Proximate & Ultimate analyses

- Composition
  - Mostly carbon & hydrogen (especially on a molar basis)
    - Combustion leads to CO₂ & particulates
  - Other elements
    - Sulfur
      - High sulfur - 1 - 6 wt%
        - Eastern coal – anthracite
      - Low sulfur – less than 1 wt%
        - Western coal
    - Mercury & other heavy metals
Sample Coal Assay

General information

<table>
<thead>
<tr>
<th>Sample Information</th>
<th>Ash composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td>Ash production method</td>
</tr>
<tr>
<td>fossil fuel</td>
<td>815 degC</td>
</tr>
<tr>
<td>subgroup</td>
<td></td>
</tr>
<tr>
<td>coal</td>
<td></td>
</tr>
<tr>
<td>material</td>
<td>Ash composition (wt.% (ash))</td>
</tr>
<tr>
<td>coal, illinois no. 6 bituminous coal</td>
<td>CO₂ · P₂O₅ · SiO₂ · Na₂O · CaO · K₂O</td>
</tr>
<tr>
<td>id number</td>
<td>1274</td>
</tr>
<tr>
<td>1274</td>
<td></td>
</tr>
<tr>
<td>reference</td>
<td></td>
</tr>
<tr>
<td>remarks</td>
<td></td>
</tr>
</tbody>
</table>

Material composition

<table>
<thead>
<tr>
<th>Proximate analysis (wt. %)</th>
<th>Ultimate analysis (wt. %)</th>
<th>Elemental analysis (mg/kg sample (dry))</th>
</tr>
</thead>
<tbody>
<tr>
<td>dry</td>
<td>daf</td>
<td>ar</td>
</tr>
<tr>
<td>Ash</td>
<td>13.2</td>
<td>12.9</td>
</tr>
<tr>
<td>Water</td>
<td>2</td>
<td>H</td>
</tr>
<tr>
<td>Volatiles</td>
<td>33.8</td>
<td>38.9</td>
</tr>
<tr>
<td>N</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Calorific value (kJ/kg)</td>
<td>2.9</td>
<td>3.34</td>
</tr>
<tr>
<td>HHV</td>
<td>26117</td>
<td>30988</td>
</tr>
<tr>
<td>LHV</td>
<td>25200</td>
<td>29032</td>
</tr>
<tr>
<td>HHVₘᵼᵳₑ</td>
<td>25807</td>
<td>29732</td>
</tr>
</tbody>
</table>

From Phyllis database @ http://www.ecn.nl/phyllis/

- Remainder in Proximate Analysis is Non-Volatiles
- “dry” – w/o water
  “daf” – w/o water & ash
  “ar” – as received
- Calorific values have the same heat content but different mass basis.
  Example:
  \[
  (HHV)_{daf} = \left(\frac{25,594}{100} - \frac{100}{100 - (12.9 + 2.0)}\right) = 30,100
  \]
Relationship of the Proximate & Ultimate Analyses

Material composition

<table>
<thead>
<tr>
<th>Proximate analysis (wt. %)</th>
<th>Ultimate analysis (wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>13.2</td>
</tr>
<tr>
<td>Dry</td>
<td>12.9</td>
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<tr>
<td>Daf</td>
<td>64.6</td>
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<tr>
<td>Ar</td>
<td>74.4</td>
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<tr>
<td>Fixed</td>
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<td>Daf</td>
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<tr>
<td>Ash</td>
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<td>Fixed</td>
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<td>N</td>
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<tr>
<td>Volatiles</td>
<td>1.3</td>
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<tr>
<td>Fixed</td>
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</tr>
<tr>
<td>N</td>
<td>1.27</td>
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<tr>
<td>Calorific value (kJ/kg)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>2.9</td>
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<tr>
<td>Daf</td>
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</tr>
<tr>
<td>Ar</td>
<td>2.84</td>
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<td>Cl</td>
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<td>Fixed</td>
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<tr>
<td>Ash</td>
<td>0.119</td>
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<td>HHV</td>
<td>2617</td>
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<tr>
<td>30088</td>
<td></td>
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<tr>
<td>25594</td>
<td></td>
</tr>
<tr>
<td>Fixed</td>
<td>F</td>
</tr>
<tr>
<td>0.121</td>
<td></td>
</tr>
<tr>
<td>0.139</td>
<td></td>
</tr>
<tr>
<td>0.119</td>
<td></td>
</tr>
<tr>
<td>LHV</td>
<td>25200</td>
</tr>
<tr>
<td>29032</td>
<td></td>
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<td>24547</td>
<td></td>
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<tr>
<td>Fixed</td>
<td>Br</td>
</tr>
<tr>
<td>0.121</td>
<td></td>
</tr>
<tr>
<td>0.139</td>
<td></td>
</tr>
<tr>
<td>0.119</td>
<td></td>
</tr>
<tr>
<td>HHV Mine</td>
<td>25807</td>
</tr>
<tr>
<td>29732</td>
<td></td>
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<td>25291</td>
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<tr>
<td>Total:</td>
<td>100</td>
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<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

Split Volatiles + Fixed into the elemental analysis
Coal Model Compounds

Given's Model

Wiser's Model

C_{99}H_{77}O_{10}N_{2}

http://www.coalscience.com/cc.htm

C_{146}H_{133}O_{17}N_{6}S_{9}
Coal Combustion Stoichiometry

- Convert mass amounts in ultimate analysis for non-ash portion to molar amounts to create a “model” molecule.
- First approximation is to assume complete combustion.
  - Actual combustion much more complex.
- Example: use 100 kg basis for model molecule.

<table>
<thead>
<tr>
<th>Ultimate Analysis - daf</th>
<th>kg</th>
<th>kg-mol</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>72.1</td>
<td>6.00</td>
</tr>
<tr>
<td>H</td>
<td>6.1</td>
<td>6.05</td>
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<tr>
<td>O</td>
<td>16.8</td>
<td>1.05</td>
</tr>
<tr>
<td>N</td>
<td>1.15</td>
<td>0.08</td>
</tr>
<tr>
<td>S</td>
<td>3.83</td>
<td>0.12</td>
</tr>
<tr>
<td>Cl</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Br</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Total:</td>
<td>99.98</td>
<td>13.31</td>
</tr>
</tbody>
</table>

- \[ C_{6.00}H_{6.05}O_{1.05}N_{0.08}S_{0.12} + 7.1475 \, O_2 \rightarrow 6.00 \, CO_2 + 3.025 \, H_2O + 0.12 \, SO_2 + 0.08 \, NO \]
Estimating the Calorific Values for Coal

- Procedure 14D1.1 to estimate the gross & net calorific values of coal from their ultimate analyses

\[ Q_v = 146.58C + 568.78H + 29.4S - 6.58A - 51.53(O + N) \]
\[ Q_{gross} = Q_v + 2.6H - 0.33O \]
\[ Q_{net} = Q_v - 92.2H - 0.33O - 10.50M \]
Topics

• Origins
• Coal Reserves
• Coal Consumption
• Mining Issues
• Coal Ash
• GHG Capture Costs
The U.S. Leads in Coal Reserves

- United States
- Former Soviet Union
- China
- India
- Australia
- Germany
- South Africa
- Poland
- Czech Republic
- Other

World Total: 1,088 Billion Short Tons

Source: Energy Information Administration, World Recoverable Coal Reserves; International Energy Annual 2002
Coal reserves

Coal reserves are more substantial than oil and gas

Global reserves should last several hundred years

The US has 25% of global reserves...
Coal Production in United States

Top Coal Producing States (2009)


http://www.eia.doe.gov/energyexplained/index.cfm?page=coal_where
Resource or Reserve?

• Resource
  - Geologic existence of a mineral deposit that could someday be extracted.

• Reserve
  - That part of the resource believed to be economically and legally recoverable with today’s or near future mining technology.
Demonstrated Reserve Base (DRB)
US Energy Information Admin.

- An estimate of the in-place coal resources in the US (The DRB estimates are not reserves)
- USBM for the first time used uniform definitions and criteria for the entire US in 1974
- Fourth estimate issued by the EIA in 1997 is the only “publicly available, nationwide data file of the quantities of minable coal conforming to a uniform set of criteria”
- Updated 1-1-2006 the DRB = 493 billion stons
- Estimated Recoverable Reserves = 268 bil. stons
National Coal Council

- In 1987 the National Coal Council questioned the widely held numbers reported for coal reserves (EIA 1985 DRB was reported *486 billion tons*)
- They found where state reserve report revisions were undertaken the old numbers were overstated by 70%
- NCC reported a recoverable US coal reserve base of *170 billion tons* (vs. EIA at 275 bt)
- State, federal and local laws, rules, regulations and policies adversely impact the amount coal that can be recovered
Table 1: U.S. Coal Resources and Reserves in 2005\textsuperscript{[1]}

<table>
<thead>
<tr>
<th>Category</th>
<th>Amount (billion short tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recoverable Reserves at Active Mines</td>
<td>19</td>
</tr>
<tr>
<td>Estimated Recoverable Reserves</td>
<td>270</td>
</tr>
<tr>
<td>Demonstrated Reserve Base</td>
<td>490</td>
</tr>
<tr>
<td>Identified Resources</td>
<td>1,700</td>
</tr>
<tr>
<td>Total Resources (above plus undiscovered resources)</td>
<td>4,000</td>
</tr>
</tbody>
</table>
Table 2: World Energy Council estimates of past production and recoverable reserves as of January 1, 2006 (Billion Metric Tons)

<table>
<thead>
<tr>
<th>Region</th>
<th>Production through 2005</th>
<th>Recoverable Reserves</th>
<th>Share of Recoverable Reserves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe (incl. Turkey)</td>
<td>114.7</td>
<td>79.9</td>
<td>9%</td>
</tr>
<tr>
<td>US and Canada</td>
<td>66.5</td>
<td>249.3</td>
<td>29%</td>
</tr>
<tr>
<td>China (incl. Japan &amp; S. Korea)</td>
<td>43.8</td>
<td>115.0</td>
<td>14%</td>
</tr>
<tr>
<td>South Asia (incl. Indonesia &amp; Philippines)</td>
<td>12.0</td>
<td>66.3</td>
<td>8%</td>
</tr>
<tr>
<td>Russia (incl. Kazakhstan, Uzbekistan)</td>
<td>26.3</td>
<td>192.7</td>
<td>23%</td>
</tr>
<tr>
<td>Australia and New Zealand</td>
<td>8.9</td>
<td>77.2</td>
<td>9%</td>
</tr>
<tr>
<td>Africa</td>
<td>7.4</td>
<td>49.6</td>
<td>6%</td>
</tr>
<tr>
<td>Latin America</td>
<td>1.6</td>
<td>17.5</td>
<td>2%</td>
</tr>
<tr>
<td><strong>World Total</strong></td>
<td><strong>281.2</strong></td>
<td><strong>847.5</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
Reassessment of the Gillette field

- The Gillette field in the Powder River Basin, WY is the world's most productive.
- 2006: 431 million tons, or 37% of US.
- 2008: USGS concluded that the recoverable coal is 10.1 billion tons
  - This is about half the 2002 estimate.
- At $60/ton, the estimated reserve would rise to 77 billion short tons.
Are Published Reserve Figures Overstated?

Dave Rutledge: In 2007, CalTech professor Dave Rutledge made an independent analysis of ultimate coal output based technique borrowed from "peak oil" analysis known as Hubbert Linearization.[13][14] Like Energy Watch Group, Rutledge concluded that published coal reserve figures are significantly overstated. As of the end of 2005, Rutledge projected future coal use in metric tons (Gt), compared to a World Energy Council "recoverable reserves" figure of 847.5 Gt.

Table 3: David Rutledge Projection of future production as of January 1, 2006[15] (Billion Metric Tons)

<table>
<thead>
<tr>
<th>Region</th>
<th>Production through 2005</th>
<th>Future Production</th>
<th>Share of Total Projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe (incl. Turkey)</td>
<td>114.7</td>
<td>40</td>
<td>11%</td>
</tr>
<tr>
<td>US and Canada</td>
<td>66.5</td>
<td>75</td>
<td>20%</td>
</tr>
<tr>
<td>China (incl. Japan &amp; S. Korea)</td>
<td>43.8</td>
<td>71</td>
<td>19%</td>
</tr>
<tr>
<td>South Asia (incl. Indonesia &amp; Philippines)</td>
<td>12.0</td>
<td>66</td>
<td>17%</td>
</tr>
<tr>
<td>Russia (incl. Kazakhstan, Uzbekistan)</td>
<td>26.3</td>
<td>48</td>
<td>12%</td>
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<tr>
<td>Australia and New Zealand</td>
<td>8.9</td>
<td>50</td>
<td>13%</td>
</tr>
<tr>
<td>Africa</td>
<td>7.4</td>
<td>15</td>
<td>4%</td>
</tr>
<tr>
<td>Latin America</td>
<td>1.6</td>
<td>17</td>
<td>5%</td>
</tr>
<tr>
<td>World Total</td>
<td>281.2</td>
<td>382</td>
<td>100%</td>
</tr>
</tbody>
</table>
Topics

- Origins
- Coal Reserves
- Coal Consumption
- Mining Issues
- Coal Ash
- GHG Capture Costs
Coal plants targeted by all bills

Sources of U.S. Energy Related CO\textsubscript{2} Emissions: 2004

- Electricity Generation from Coal: 33.8%
- Transportation: 33.1%
- Other Electricity Generation: 7.0%
- Commercial: 4.0%
- Residential: 6.6%
- Industrial: 15.4%

Source: EPA 2006
Overview – World Coal Trends

- China - Continues to add about one new coal power plant per week
  - 70 GW coal capacity added in 2007
  - 2007 addition equivalent to entire UK electric grid
  - 29 new gasification plants in service since 2004
    - All are chemical/fuels production
- India - Also planning for large capacity additions
  - 30 GW under construction (mostly coal)
  - Current electricity consumption per capita < 5% of US
- Europe – 50 new coal plants?
  - April, 2008 New York Times report indicates Europe plans 50 new coal plants by 2013
Overview – World Coal Use is Expected to Grow

Source: CATF from IEA WEO 2006
High natural gas prices driving new coal rush and higher carbon emissions

Coal’s Resurgence in Electric Power Generation

- 159 new plants proposed
- No plans to capture and store CO₂
- Locks us in for decades to highest-carbon energy, with huge environmental AND financial risk
- Ratepayers shouldn’t bear the risk of these imprudently incurred costs
Costs have increased for all technologies.
Prices from Puget Sound Energy RFPs

Overview –
US Market Trends

• The past and present:
  • About ½ of all coal projects proposed since 2001 have been cancelled
    – Capital cost increases have rendered new coal projects uneconomic
    – Uncertainty over CO2 regulation has favored cancellations

• The uncertain future (5-10 years):
  • Scenario 1
    – Capital costs don’t change enough relative to alternatives
  • Scenario 2
    – Recession cuts material and labor costs
    – Reserve margins fall prompting PSC action
    – Congress resolves CO2 regulatory uncertainty
Topics

- Origins
- Coal Reserves
- Coal Consumption
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- Coal Ash
- GHG Capture Costs
Extraction & Transportation

• Two different mining techniques – surface & underground
  ▪ Surface mining is cheaper
    • Coal seam must be no deeper than 60 m (200 ft)
    • Accounts for 2/3 of U.S. production but only 40% of world production
  ▪ Transportation can represent up to 70% of delivered cost
  ▪ Transportation by barge cheaper, but 60% in U.S. delivered by rail

• Coal typically must go to a preparation plant to increase its heating value
Coal Mining

• One of the most hazardous professions

• Strip mining has become more prevalent
  ▪ Higher worker safety
  ▪ Produces more significant footprint – reclamation needed

[Bar graph showing coal miner deaths from 1870 to 1990]

[Images ofStrip mining areas and construction equipment]
Topics

- Origins
- Coal Reserves
- Coal Consumption
- Mining Issues
- Electricity Production Using Coal
- Coal Ash
- GHG Capture Costs
Coal for Electricity Production

- Coal burned in boiler (furnace) to heat steam. Steam makes electricity in a Rankine cycle.
  - Flue gas clean-up may be required for sulfur, mercury, ...
  - If allowed, river water might be used for once-through cooling. Warm water returned to river.

- TVA’s Kingston Fossil Plant near Knoxville, TN
  - High pressure steam 1000°F & 1800 psig (540°C & 124 bar-g)
  - 10 billion kW-hr annually
  - Requires 14,000 ton/day coal (about 140 rail cars per day)

http://www.tva.com/power/coalart.htm
Flue Gas Clean Up

- Sulfur emissions as SO₂
  - Wet scrubbing – absorb SO₂ in a alkaline solution.
  - Limestone or lime scrubbing to make calcium sulfite (CaSO₃)
    - Limestone: \( \text{CaCO}_3 (s) + \text{SO}_2 (g) \rightarrow \text{CaSO}_3 (s) + \text{CO}_2 (g) \)
    - Lime: \( \text{Ca(OH)}_2 (s) + \text{SO}_2 (g) \rightarrow \text{CaSO}_3 (s) + \text{H}_2\text{O} (l) \)
  - Forced oxidation (controlled oxidation) used primarily with limestone & wet lime to produce gypsum (CaSO₄·2H₂O)
    - \( \text{CaSO}_3 (\text{sol}) + \frac{1}{2}\text{O}_2 (g) \rightarrow \text{CaSO}_4 (\text{sol}) \)
    - May be sold if local market for it
Flue Gas Clean Up

• Mercury removal
  ▪ Hg\(^{2+}\) can come out in wet scrubbers
  ▪ Halogen addition to react with & remove elemental mercury
  ▪ Activated carbon injection with particulate collector

• NO\(_x\)
  ▪ Low NOx burners & overfire air systems to reduce formation during combustion
  ▪ SCR (Selective Catalytic Reduction) units – convert NO\(_x\) to N\(_2\)
  ▪ Main reactions involve reduction with ammonia (mostly aqueous or anhydrous, may be derived from urea)
    ▪ \(4\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}\)
    ▪ \(2\text{NO}_2 + 4\text{NH}_3 + \text{O}_2 \rightarrow 3\text{N}_2 + 6\text{H}_2\text{O}\)
    ▪ \(\text{NO} + \text{NO}_2 + 2\text{NH}_3 \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O}\)
Topics

- Origins
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Coal Ash vs. CCPs

- Coal combustion products are residuals from the combustion of coal and emission control systems:
  - Fly ash
  - FGD (synthetic) gypsum
  - Bottom ash and boiler slag
  - Air emission control system residues (other FGD co-products)

- “Coal Ash” and “CCPs” have been terms used interchangeably; CCPs now apply to both ash and FGD byproducts
Fly Ash

- Fine particles like flour or talc
- Exhibits “pozzolanic” characteristics
  - Siliceous or siliceous and aluminous materials, when in the presence of water, react with calcium hydroxide to produce cementitious properties
- Besides natural ash, there are two types
  - Class F from bituminous coal (lignite?)
  - Class C from sub-bituminous coal (lignite?)
What Makes Fly Ash Useful?

- Non-hazardous nature
- Mineralogical and pozzolanic characteristics allow it to be used in lieu of other natural materials
- Spherical shape
- Easily transportable
- Can be conveyed dry or in moistened form
Fly Ash Benefits

- Additive to concrete as a replacement for portland cement
  - Enhances durability
  - Reduces permeability
  - Improves workability
- Makes good concrete better
- Potential economic savings at time of placement and through life cycle
Bottom Ash

- Heavier than fly ash and granular in nature. Can be used:
  - as raw feed for cement production
  - in soil applications to improve drainage and blended with other materials for composting
  - in masonry blocks and concrete products
  - in road base and mineral fillers in asphalt
  - as a component of artificial aggregates
Structural Applications

- Highway overpasses, embankments, railroad realignments and new track work; also in mining
- Serves as low-cost material that be blended with available borrow materials
- Standards & guidelines established by ASTM International & others
- Large volumes of CCPs can be used
Soil Stabilization

- Fly ash alone (Class C) or with portland cement, CKD or lime can be used to modify soils
  - To dry wet working areas
  - To increase stiffness
  - Reduce permeability
  - Reduce plasticity and swelling
  - Control compressibility and moisture
- Typically more economical than just portland cement
Environmental Benefits of CCPs

- Reduces greenhouse gas emissions
- Conserves natural resources
- Reduces energy impacts of extraction and processing
- Cuts down on need for landfill space
December 22, 2008, a coal ash dam failed at a Tennessee Valley Authority coal-fired generating station, releasing 1.2 billion gallons of ash/water slurry and contaminating hundreds of acres. TVA is spending over $1M per day to clean up the spill.
KINGSTON, Tenn., Feb. 2 (UPI) -- The Tennessee Valley Authority is responsible for the fallout from an accidental 2008 coal ash dispersal around Kingston, Tenn., lawsuits allege.

Four lawsuits filed against the utility group allege that the impact is still being felt from the dispersal of 1 billion gallons of sludge on Dec. 22, 2008, The (Nashville) Tennessean said Monday.

The wet coal ash was spread across nearly 300 acres of land after an earthen wall containing the sludge at a power plant in Kingston, Tenn., collapsed.

The ash is said to contain heavy metals such as arsenic, mercury and lead.

Peggy Blanchard, one of the Kingston area residents involved in the lawsuits, alleges the incident prompted her to suffer "losses," while also devastating the area environment, the newspaper reported.

"My main concern is not to make money but to redeem my losses," she said in reference to her lawsuit involvement. "I grieve as much for the environment here as for the losses the people have suffered."

Vanderbilt University law professor Richard Nagareda told the Tennessean that the Tennessee Valley Authority could lose up to hundreds of millions of dollars over the lawsuits, three of which were filed in federal courts, and similar claims.
Energy Situation in China

Share of Total Primary Energy Supply* in 2004

People's Republic of China

- Coal: 61.7%
- Oil: 19.3%
- Gas: 2.6%
- Hydro: 1.9%
- Nuclear: 0.8%
- Comb. renew. & waste: 13.7%

1609 348 ktoe
# Coal Production

## Top Five Coal Producers 2006 [Mt]

<table>
<thead>
<tr>
<th>Country</th>
<th>Production</th>
<th>Share of world</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>2,380</td>
<td>38.4%</td>
</tr>
<tr>
<td>USA</td>
<td>1,054</td>
<td>17.0%</td>
</tr>
<tr>
<td>India</td>
<td>447</td>
<td>7.2%</td>
</tr>
<tr>
<td>Australia</td>
<td>374</td>
<td>6.0%</td>
</tr>
<tr>
<td>Russia</td>
<td>309</td>
<td>4.9%</td>
</tr>
</tbody>
</table>
# Coal Reserves

## Top Five Coal Reserves 2006 [Mt]

<table>
<thead>
<tr>
<th>Country</th>
<th>Reserve</th>
<th>Share of world</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>246 643</td>
<td>27.1 %</td>
</tr>
<tr>
<td>Russia</td>
<td>157 010</td>
<td>17.3 %</td>
</tr>
<tr>
<td>China</td>
<td>114 500</td>
<td>12.6 %</td>
</tr>
<tr>
<td>India</td>
<td>92 445</td>
<td>10.2 %</td>
</tr>
<tr>
<td>Australia</td>
<td>78 500</td>
<td>8.6 %</td>
</tr>
</tbody>
</table>
Simple model
Coal production forecast
CO₂ costs make pulverized coal plants uneconomic

Levelized Cost of Electricity (2010) vs. CO₂ Price

Source: Preliminary information developed by Black & Veatch for AWEA, except Coal PC w/CCS, which adds IPCC estimates for the cost of CCS to Black & Veatch’s Coal PC costs.
CO₂ prices make wind cheaper than new coal

Source: Preliminary information developed by Black & Veatch for AWEA, 2006.
Topics

• Origins
• Coal Reserves
• Coal Consumption
• Mining Issues
• Coal Ash
• GHG Capture Costs
CO₂ prices make other renewables cheaper than new coal

Levelized Cost of Electricity (2015) vs. CO₂ Price

Wind becomes even more competitive than new coal by 2015

Levelized Cost of Electricity (2015) vs. CO2 Price

- Coal PC
- Coal IGCC w/ CCS
- Offshore Wind
- Wind Class 3
- Wind Class 4
- Wind Class 6

No PTC, wind integration or transmission costs included

Source: Preliminary information developed by Black & Veatch for AWEA, 2006.
Overview — US Gasification Trends

• IGCC
  • Many IGCC plants cancelled recently due to capital cost increases
  • Several proposed IGCC have converted to SNG production
  • Proposed IGCC air permit applications reflect trend toward lower emissions
    – Selexol for deeper SO2 reductions
    – SCR for deeper NOx reductions
  • Partial capture under consideration at several proposed plants
  • Strong interest in enhanced oil recovery ("EOR") for CO2

• Substitute Natural Gas ("SNG")
  • Natural prices are rising
  • 10+ US SNG projects planned/permitted
  • Many plans feature EOR
Overview – Emerging Gasification Technologies

- New technologies could advance gasification deployment in next 5-10 years, ahead of current projections
  - Advanced modular gasification systems
  - Underground coal gasification
  - Prefabricated gasification systems
  - Advances in key technology areas
    - Air and CO2 compression
    - Oxygen plants
    - Warm syngas cleanup
    - Geomonitoring (for UCG)
- Today’s visible innovation is by
  - Small companies
  - Sometimes in China, with lower construction costs and faster schedules
IGCC – What is it?

• It’s not coal combustion
• It is chemical conversion of coal to gaseous fuel
  • Generally by adding oxygen at high temperature and pressure
  • Efficient, proven process (most coal energy is retained in syngas)
• …with syngas cleanup
  • Efficient PM, sulfur, mercury, CO2 removal due to small gas volume
  • Proven chemical industry processes
• …and syngas combustion in combined cycle turbine
  – Very efficient (towards 60%)
  – Low NOx emissions
  – Sulfur, mercury, CO2 emissions depend on extent of syngas cleanup
Tampa Electric Polk Power Station

250 MW – Operating Since 1996
IGCC Schematic

**Feeds**
- Oxygen
- Coal

**Gasification**
- Water Shift Reaction
- Syngas Removal

**Gas Refining**
- Mercury Removal
- Sulfur/CO₂ Removal
- Sulfur Recovery

**End-products**
- Combustion Turbine
- Electricity
- Steam
- CO₂ Compression
- Sulfur
- Methanol
- Ammonia
- Hydrogen
- Chemicals

**Additional Elements**
- Solids
- Mercury
- CO₂ Sequestration Option

**Clean Air Task Force**
Three “Flavors” of IGCC Proposed

• “Standard”
  • Amine and diluent (steam, N2) injection for SO2 and NOx control
  • Examples: Polk, Florida and Wabash, Indiana (since 1990s)

• “More Like Natural Gas”
  • Selexol and SCR for SO2 and NOx control
  • Emissions for criteria pollutants approach natural gas combined cycle (NGCC) levels
  • Examples: Taylorville, IL, and Edwardsport, IN

• “Near-Zero Emission”
  • Also captures most CO2
  • Example: Hydrogen Energy, Carson, CA
Efficiency Comparison
Impact of CO₂ Capture on IGCC COE & CO₂ Avoided Cost (without Transportation & Storage) (June 2006 $ Basis, Bituminous coal)
Topics

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Will Coal Last Forever?

- Proven reserves – 250 billion tons.
- Current usage rate – 1 billion ton/yr.
  - Remember the 35 yr doubling time for electricity demand.
  - CO2 capture has ~30% parasitic loads – to export 100 MW need to generate 130 MW
  - Plus plans are underway for coal-to-liquids plants, synthetic natural gas plants, ammonia plants, etc.
- **Economically** recoverable reserves are closer to 125 billion tons.
- So... we don’t have unlimited reserves but we do have a whole lot. Maybe 50-75 years given current projections.
Can Coal be Clean?

- Dilute emissions: SO₂, NOx, mercury, particulates (PM10 & PM2.5).
  - Can be cleaned.
- Carbon capture expensive for a conventional plant because of large gas flow rates.
- Alternate technologies
  - IGCC (integrated gasification, combined cycle)
    - Gasification: create a mixture of CO, CO₂, H₂, steam. Sulfur can be removed. Carbon capture much easier than a conventional plant.
    - Coal gas goes to a gas turbine – jet engine bolted to the floor.
    - Exhaust of the turbine boils water for a steam turbine.
    - Very high overall efficiencies – but much higher capital cost and risk.
  - Oxycombustion
    - Burn coal in pure oxygen, resulting in a flue gas that is almost entirely CO₂
    - Dilute pollutants (SO₂, NOx, etc.) cleaned using conventional technologies
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