Fossil Fuels

Our fantastic flash in the pan

A brief history of fossil fuels

• Here today, gone tomorrow
• What will our future hold?
  – Will it be back to a simple life?
  – Or will we find new ways to produce all the energy we want?
  – Or will it be somewhere in the middle

Finding Oil

Anticlinal Trap

• Oil is trapped in special (rare) geological structures
• Most of the oil in the world comes from a few large wells
• About one in ten exploratory drillings strike oil
  – and this in places known to be oil-rich: get nothing in most of world

The Oil Window

• Organic material must be deposited without decomposing
  – oxygen-poor environment: usually underwater with poor flow
• Material must spend time buried below 7,500 feet of rock
  – so that molecules are “cracked” into smaller sizes
• But must not go below 15,000 feet
  – else “cracked” into methane: gas, but no oil
• So there is a window from 7,500 to 15,000 feet
• Additional circumstances must be met
  – existence of “caprock” to keep oil from escaping: even a drop per second depletes 20 million barrels per million years
  – source rock must be porous and permeable to allow oil flow
• Oil is not in underground lakes—more like soaked sponges
The hydrocarbons

- All fossil fuels are essentially hydrocarbons, except coal, which is mostly just carbon
- Natural Gas is composed of the lighter hydrocarbons (methane through pentane)
- Gasoline is hexane \((C_6)\) through \(C_{12}\)
- Lubricants are \(C_{16}\) and up

<table>
<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
<th>Molecular Mass</th>
<th>Energy (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>(\text{CH}_4)</td>
<td>16</td>
<td>48</td>
</tr>
<tr>
<td>Ethane</td>
<td>(\text{C}_2\text{H}_6)</td>
<td>30</td>
<td>48</td>
</tr>
<tr>
<td>Propane</td>
<td>(\text{C}_3\text{H}_8)</td>
<td>44</td>
<td>48</td>
</tr>
<tr>
<td>Butane</td>
<td>(\text{C}<em>4\text{H}</em>{10})</td>
<td>58</td>
<td>48</td>
</tr>
<tr>
<td>Pentane</td>
<td>(\text{C}<em>5\text{H}</em>{12})</td>
<td>72</td>
<td>48</td>
</tr>
</tbody>
</table>

Hydrocarbon Reactions

- **Methane reaction:**
  \[\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + \text{energy}\]
  \[1 \text{ g} \quad 4 \text{ g} \quad 2.75 \text{ g} \quad 2.25 \text{ g} \quad 55 \text{ kJ}\]

- **Octane reaction:**
  \[2\text{C}_8\text{H}_{18} + 25\text{O}_2 \rightarrow 16\text{CO}_2 + 18\text{H}_2\text{O} + \text{energy}\]
  \[1 \text{ g} \quad 3.51 \text{ g} \quad 3.09 \text{ g} \quad 1.42 \text{ g} \quad 48 \text{ kJ}\]

  - For every pound of fuel you burn, you get about three times that in \(\text{CO}_2\)
  - One gallon of gasoline \(-\text{20 pounds of CO}_2\)
  - Occupies about 5 cubic meters (1300 gallons) of space

Aside: Carbohydrate Reactions

- Typical carbohydrate (sugar) has molecular structure like: \([\text{CH}_2\text{O}]_n\), where \(N\) is some integer
  - Refer to this as “unit block”: \(\text{C}_2\text{H}_4\text{O}_2\) has \(N=6\)
- **Carbohydrate reaction:**
  \[\text{[CH}_2\text{O}]_n + \text{NO}_2 \rightarrow \text{NCO}_2 + \text{NH}_2\text{O} + \text{energy}\]
  \[1 \text{ g} \quad 1.07 \text{ g} \quad 1.47 \text{ g} \quad 0.6 \text{ g} \quad 17 \text{ kJ}\]

  - Less energy than hydrocarbons because one oxygen already on board (half-reacted already)
  - For every pound of food you eat, exhale 1.5 lbs \(\text{CO}_2\)
    - Actually lose weight this way: 0.5 to 1.0 lbs per day in carbon
    - Must account for “borrowed” oxygen mass and not count it

So where does our petroleum go?

- Each barrel of crude oil goes into a wide variety of products
- Most goes into combustibles
- Some goes to lubricants
- Some goes to pitch and tar
- Some makes our plastics
- 35–40% of our energy comes from petroleum
Who’s got the crude oil resources?

- China
- Norway
- Venezuela
- Mexico
- U.S.
- Russia
- Iran
- Nigeria
- Iraq
- Saudi Arabia

Let’s get our barrels straight

- An oil barrel (bbl) is 42 gallons, or 159 liters
- In the U.S., we use about 22 bbl per year per person
  - average person goes through a barrel in 16 days
  - recall: ~60 bbl/yr oil equivalent in all forms of energy:
  - oil is ~35% of our total energy portfolio
- That’s 6.9 billion bbl/yr for the U.S.
  - 19 million bbl/day
    - 10 domestic, 9 imported, in 2011
- For the world, it’s about 30 billion bbl/year
  - 85 million bbl/day

Oil in the World (older data)

<table>
<thead>
<tr>
<th>Country</th>
<th>Production (10^9 bbl/M)</th>
<th>Proved Reserves (10^9 bbl)</th>
<th>No. Producing Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saudi Arabia</td>
<td>8.23</td>
<td>257.704</td>
<td>859</td>
</tr>
<tr>
<td>Former USSR</td>
<td>6.50</td>
<td>57.090</td>
<td>145,000</td>
</tr>
<tr>
<td>United States</td>
<td>6.55</td>
<td>20.177</td>
<td>603,000</td>
</tr>
<tr>
<td>Iran</td>
<td>3.775</td>
<td>92.656</td>
<td>561</td>
</tr>
<tr>
<td>China</td>
<td>3.015</td>
<td>24.000</td>
<td>45,790</td>
</tr>
<tr>
<td>Venezuela</td>
<td>2.940</td>
<td>94.600</td>
<td>12,752</td>
</tr>
<tr>
<td>Mexico</td>
<td>2.618</td>
<td>51.983</td>
<td>4,740</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>2.689</td>
<td>3.823</td>
<td>762</td>
</tr>
<tr>
<td>Nigeria</td>
<td>2.100</td>
<td>17.190</td>
<td>1,452</td>
</tr>
<tr>
<td>Iraq</td>
<td>100,000</td>
<td></td>
<td>829</td>
</tr>
</tbody>
</table>

Excerpts from current Table 2.2 in book

<table>
<thead>
<tr>
<th>Country</th>
<th>Prod (Mbbl/ day)</th>
<th>Reserves (Gbb)</th>
<th>No. Prod. Wells</th>
<th>years left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saudi Arabia</td>
<td>9.03</td>
<td>262.7</td>
<td>1,560</td>
<td>80</td>
</tr>
<tr>
<td>Russia</td>
<td>7.98</td>
<td>69.1</td>
<td>41,192</td>
<td>24</td>
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<tr>
<td>U.S.</td>
<td>5.73</td>
<td>29.4</td>
<td>521,070</td>
<td>14</td>
</tr>
<tr>
<td>Iran</td>
<td>3.74</td>
<td>130.7</td>
<td>1,120</td>
<td>96</td>
</tr>
<tr>
<td>China</td>
<td>3.41</td>
<td>23.7</td>
<td>72,255</td>
<td>19</td>
</tr>
<tr>
<td>Mexico</td>
<td>3.34</td>
<td>16.0</td>
<td>833</td>
<td>13</td>
</tr>
<tr>
<td>Norway</td>
<td>2.86</td>
<td>10.1</td>
<td>833</td>
<td>10</td>
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<tr>
<td>U.A.E.</td>
<td>2.35</td>
<td>97.8</td>
<td>114</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>2.24</td>
<td>16.9</td>
<td>54,061</td>
<td>21</td>
</tr>
<tr>
<td>Kuwait</td>
<td>2.18</td>
<td>96.5</td>
<td>790</td>
<td>121</td>
</tr>
</tbody>
</table>

*1 The Oil and Gas Journal, February 1991.
Notes on Table 2.2

- Not a single country matching U.S. demand of 19 Mbblday
- Reserves:
  - Non-OPEC proved reserves: 173 Gbbl
  - OPEC reserves: 882 Gbbl
  - Total: 1055 Gbbl
- To maintain current production of 85 Mbblday...
  - this will last 34 years
  - means entries in previous table with longer timescales than this would have to step up production, if they can
  - may not be possible to extract oil fast enough for demand
  - Saudi Arabia used to produce at less than 100% capacity, now running full-out

How long will the world oil supply last?

- Not as long as you might think/hope
- We’ll be spent before the century is done, but we’ll have to scale down oil usage before then (in the next few decades)

How about the U.S. Supply?

- The estimated total U.S. supply is 230–324 billion bbl
- We’ve used >60% of this, leaving 130 billion barrels
- Production is already down to 60% of peak
- At current rate of production, will be exhausted before 2070
- If we used only U.S. supply, we’d run out in 18 years!!
  - includes bet that we find 105 billion barrels more in U.S.

From EIA AER 2012

- Peak of U.S. oil production in 1970
  - bump when Alaska came online
- Recent uptick in domestic oil & NGPL
  - together with recession-induced reduction in demand makes net imports go below domestic production for first time in ~15 years
we’ve been using oil faster than we find new oil since 1983

Discovery must lead production
- There must be a lag between the finding of oil and delivery to market
- In the U.S., discovery peaked around 1950, production peaked in 1970

Various Estimates of Oil Remaining
- To date, we’ve used about 1000 billion barrels of oil worldwide
- We seem to have about this much left
  - halfway through resource
- There will be some future discovery still, but not likely any new Saudi Arabia
  - ANWR: 5–10 Gbbl → 1 years’ worth at U.S.
    consumption rate
- In any case, global production unlikely to increase appreciably from this point forward
  - despite U.S. production uptick, total world is flatline
  - will soon fail to pump as fast as today’s demand

Worldwide Discovery and Production
- discovery peaked before 1970; production peak soon to follow

The Hubbert Peak Idea
- Hitting new oil field must precede assessment of oil capacity
- Discovery peak (numerical assessment) must follow hits
- Production peak follows discovery (assessment)
- Area under three curves the same (total oil resource)
- Deffeyes estimates that we’ve hit 94%, discovered 82%, and produced 50% as of about 2005
Logistic ("S") curves

Logistic curves result from growth limited by a finite resource: at first exponential, but unable to sustain exponential once resource limits kick in.

- $Q_{\text{max}}$ marks half-way point
- Production rate: $P = a(Q_{\text{max}} - Q)$
- Rate of growth: $\frac{dQ}{dt} = a(P/\text{rate of growth})$

Rate plot for U.S.

- Can plot rate of production ($P$: annual production) divided by resource ($Q$: total produced to date) against total resource, $Q$
  - $P/Q$ is like an interest rate: fractional increase per year
- A "logistic" or S-curve would follow a straight line sloping down
- U.S. oil production does so after 1958
- When you get to zero $P/Q$, you've hit the end of the resource: no more growth

Same fit, in rate history plot

- The best-fit line on the previous plot produces a decent fit to the rate history of oil production in the U.S.
- Supports the peak position well, and implies a total resource of about 225 Gbbl

World Data

- After 1983, world data follows logistic curve
  - shows us halfway along 2,000 Gbbl at 2005 (now-ish)
  - implies the peak is imminent
Fossil Fuels

Discouragement of Oil Usage

- In this country, there is no such thing
- U.S. taxes on gasoline are 6.5 times lower than in most industrialized countries (about 32 cents per gallon in the U.S.)
- The Frito Lay attitude: Burn all you want—we’ll pump more
- Efforts on the part of the U.S. to keep oil prices low have lead to numerous questionable actions on the international scene

Natural Gas

- Conventionally, extracted as oil-drilling byproduct — was once burned off at well head as means of disposal
- Mostly methane, some ethane, and a little propane, butane
- Well-suited to on-the-spot heat generation: water heaters, furnaces, stoves/ovens, clothes dryers — more efficient than using fossil-fuel-generated electricity
- Currently ~4 times cheaper than electricity per energy content, 3× cheaper than gasoline per joule — volatile price history
- Hydraulic Fracturing (“fracking”) changing scene

Fracking Creates Uptick, Lowers Price
Uses of Natural Gas

- Mostly for industrial processes
- Electricity generation climbing fast
- Transportation dragging along at the bottom

Distribution of natural gas

- Impractical to ship: must route by pipe
- 1.3 million miles of pipe (250,000 miles of mains)

How much do we use, and where do we get it?

- In 2011, we used 24.4 tcf (Tera-cubic feet, or $10^{12}$ ft$^3$); about 25 Qhru (26% of total)
- Out of the 24.4 tcf used, 86% was domestic
  - Lion’s share from Canada, dribbles from Algeria, Mexico
- Have used about 1,300 tcf to date

How much do we have left (pre-fracking)?

- Estimated recoverable amount: 871 tcf
- 40 years at current rate
- Estimates like this do account for future discoveries
- Present proven reserves provide only 8 years’ worth
Fossil Fuels

Lecture 7

EIA Projections

- In Energy Outlook 2012 document:
  - expect continued decline in traditional forms
  - shale gas expected to explode
  - prices expected to stay low
    - pay no attention to past volatility!
- My worry: extrapolation based on low-hanging fruit
  - the easiest/best stuff exploited first
  - not enough history to make robust prediction

Coal

- Coal is a nasty fuel that we seem to have a lot of
- Primarily carbon, but some volatiles (CO, CH₄)
- Reaction is essentially \( C + O_2 \rightarrow CO_2 + \text{energy} \)
- Energy content varies depending on quality of coal, ranging from 4–7 Cal/g
- Highly undesirable because of large amounts of ash, sulphur dioxide, arsenic, and other pollutants
- Also ugly to remove from the ground

Coal types and composition

<table>
<thead>
<tr>
<th>Coal type</th>
<th>Percentage</th>
<th>Fixed Carbon</th>
<th>Volatile Matter</th>
<th>Moisture Content</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Graphite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anthracite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bituminous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bituminous sub-bituminous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lignite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td></td>
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</tr>
</tbody>
</table>

Use of Coal

- 93% of the coal used in the U.S. makes steam for electricity generation
- 7% is used for industry (largely steel production)
- 0.1% used on Halloween for trick-or-treaters
- Usage profile has changed a lot in last ~60 years

Use of Coal Sector Shares, 1948 and 2011

- Elementary
- Industrial
- Commercial
- Residential
- Electric Power
Estimated Worldwide Coal Reserves

<table>
<thead>
<tr>
<th>Country</th>
<th>Amount (10^9 tonnes)</th>
<th>Percentage of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>250</td>
<td>25</td>
</tr>
<tr>
<td>Russia</td>
<td>230</td>
<td>23</td>
</tr>
<tr>
<td>Europe</td>
<td>138</td>
<td>14</td>
</tr>
<tr>
<td>China</td>
<td>115</td>
<td>12</td>
</tr>
<tr>
<td>Australia</td>
<td>82</td>
<td>8.3</td>
</tr>
<tr>
<td>Africa</td>
<td>55</td>
<td>5.6</td>
</tr>
<tr>
<td>South America</td>
<td>22</td>
<td>2.2</td>
</tr>
<tr>
<td>North America</td>
<td>7.7</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>984</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

*1st edition of book had U.S. at 1500 billion tons. What happened to all that coal?†
†1st edition of book had Russian coal at 4300 billion tons. Gross overestimates?

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U.S. Coal Production History

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When will coal run out?

- We use 10^9 tonnes of coal per year, so the U.S. supply alone could last as long as 250 years at current rate
- Using variable rate model, more like 75–100 years
  - especially relevant if oil, gas are gone
- This assumes global warming doesn’t end up banning the use of coal
- Environmental concerns over extraction also relevant

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Shale Oil

- Possibly 600–2000 billion barrels of oil in U.S. shale deposits
  - compare to total U.S. oil supply of 230 billion bbl
- Economically viable portion may only be 80 billion bbl
- 8 times less energy density than coal
  - lots of waste rock: large-scale disposal problem
- Maximum rate of extraction may be only 5% of our current rate of oil consumption
  - limited by water availability: requires 3x as much water as oil
  - contaminated process water is an issue
Tar Sands

- Sand impregnated with viscous tar-like sludge
- Huge deposit in Alberta, Canada
  - 300 billion bbl possibly economically recoverable
  - update: 2007 estimate from Alberta Energy at 133 Gbbl
- It takes two tons of sands to create one barrel of oil
  - energy density similar to that of shale oil
- In 2003, 1 million bbl/day produced
  - grand hopes for 3 Mbbl/day; or 4% of world oil production
  - current rate is up to 1.3 Mbbl/day
- Production cost is about $30 per barrel, so economically competitive

References and Assignments

- *Hubbert’s Peak: The Impending World Oil Shortage*, by Kenneth Deffeyes
- *Beyond Oil*, by same author
- *Out of Gas: The end of the Age of Oil*, by David Goodstein
- *The Party’s Over*, by Richard Heinberg
- Read Chapter 2 in book
- Read Chapter 3 for next week/lecture
- HW3 available on website, due Friday 4/26
- Quiz 2 due by Friday, 4/19 at 11:59 PM on TED