GEOS 24705 / ENST 24705
Problem set #17
Due: Th. May. 27

Problem 1: Fossil fuel reserves

In class we showed figures proven world reserves of coal, oil, and natural gas. These numbers are repeated below, with the Canadian oil sands included in the total for oil. The table below also shows current rates of production of each fossil fuel. I’ve converted all energies into standardized energy units of bboe (billion barrels of oil equivalent) for easy comparison - usually oil, gas, and coal reserves are all given in different units, which is extremely aggravating. You can readily convert barrels of oil equivalent to Joules (1 boe = 6.1 GJ) and bboe/year to Watts. You an also convert the production units to bboe/year. For dealing with coal, it’s OK to assume coal is \(~30\) MJ/kg in energy density.

If you have a careful eye you’ll note that I adjusted the natural gas reserve estimate upwards from 700 in the slides to 1100 (corrected now in slides). Estimates of reserves can differ widely, but the current consensus is more like 1100. See http://www.eia.doe.gov/emeu/international/reserves.html for a table of oil and gas reserves estimates from several reputable sources (which still vary by \(\sim10\%\)). The coal estimate is from the World Coal Institute, by mass, converted by assuming an energy content of \(~30\) MJ/kg. Production estimates are from the EIA.

<table>
<thead>
<tr>
<th>Source</th>
<th>Proven reserves (in (10^9) boe or bboe)</th>
<th>Current annual production</th>
</tr>
</thead>
<tbody>
<tr>
<td>World oil + tar sands</td>
<td>1200</td>
<td>33 bboe /yr (80 M barrels/day)</td>
</tr>
<tr>
<td>World coal</td>
<td>4500</td>
<td>30 bboe / yr (6700 M tons/yr)</td>
</tr>
<tr>
<td>World gas</td>
<td>1100</td>
<td>19 bboe / yr (3 (\cdot) 10^{12} m³ / yr)</td>
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</tbody>
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For this problem, it’s safe to assume that no fuel is being stockpiled, so the rate of production = the rate of consumption.

A. Are the relative sizes of production (and consumption) of oil, coal, and natural gas here consistent with the “spaghetti diagram” that’s been shown in class?

B. Fossil fuels should represent over 80% of world primary energy consumption. From this and the table above, what is the global average per capita power usage, in W? (You’ll need to assume a population size). Is the number you derive reasonable, compared to what you know already?

C. Energy use is increasing. We made a scenario in class in which the world population doubles, and everyone gets as rich (and energy-using) as Americans. If that happens, by what fraction will world per capita usage change by? World total power usage?
D. If fossil fuel extraction rates stayed constant (forget population growth, forget people getting richer), and no new reserves are found, what is the lifetime for each fossil fuel type before it runs out?

E. World energy use in the last decades has been growing at ~2% / year. If this acceleration continues, how long will it take before you have the power usage in the scenario of C? Either solve analytically or plug some test numbers into 
\[ Q_n = Q_o \cdot (1+r)^n \] (r is the rate of growth and n is number of years) and iterate til you get a good-enough answer.

F. (Optional: check that this timescale is also roughly consistent with population doubling. Population growth is ~ 1%/yr at present).

G. From your answers in C and D: can we accomplish the scenario, where we keep growing steadily in energy use til everyone is as rich as Americans, letting population double, while using the same energy mix as present, if all we’ve got is the proven reserves?

Of course, proven reserves may be a small fraction of total fossil carbon available. More readily recoverable sources may be found. And as prices rise, we will likely go after more and more difficult-to-extract sources. Though oil and gas may well run out, coal may be an order of magnitude or more larger than what we now call proven reserves. We don’t know yet how much fossil carbon we’ll really go after

Problem 2: Carbon dioxide emissions

Consider the effect that burning fossil fuels has on atmospheric carbon dioxide concentration.

The current concentration of CO₂ in the atmosphere is 385 parts per million. (That is, 385 out of every million air molecules are CO₂ rather than the more common N₂, O₂, Ar, or H₂O). This amount of CO₂ corresponds to about 800 Gt (billion tons) of carbon in the atmosphere.

Note: the mass of carbon is not the same as that of carbon dioxide – here we’re counting only the carbon atoms, not the entire molecular weight. Confusingly, you’ll find both units in the literature (mass of C or mass of CO₂); the most important thing is to state your units clearly and to be consistent.

Ignore for now all the oil and gas that aren’t burnt directly but are turned into e.g. asphalt or plastics, that stick around. Assume that all of the fossil fuel production is combusted so that hydrocarbons CₙHₘ -> CO₂ and H₂O. For back-of-the-envelope purposes, since hydrogen atomic mass is small in comparison (1 g as compared to carbon’s 12), you can assume that the mass of all hydrocarbons is due only to carbon. (Optional, if you want to be more careful: the C:H ratio is 1.3:1 for coal, 1:1 for crude oil, and 1:4 for natural gas).

A. Write down the annual mass of carbon currently emitted as CO₂ for each of the fossil fuels (oil, gas, coal), and add those to get a total. (Give the mass of carbon emitted, not the full mass of the carbon dioxide).
B. Assume that ~50% of the fossil-fuel derived C emissions are remaining in the atmosphere. (The remainder is taken up by the ocean and by plant growth on land). By what fraction is our fuel use increasing atmospheric CO$_2$ concentrations each year at present?

C. Assume you burn all the fossil fuel in the proven reserves above. Assume for this problem (it's not quite true) that the proportion of CO$_2$ emissions taken up by ocean and land plants will still be 50%. What will the concentration of atmospheric CO$_2$ be when you are done burning all the fossil fuel reserves? Give your answer in Gt C and also in ppm. (*Hint*: to get the ppm, just scale to current conditions, i.e. X% increase in GtC is an X% increase in ppm).

D. The IPCC thinks we’ll burn much more carbon than proven reserves, as much as 5000 Gt of fossil carbon. (This probably means e.g. digging up much of Utah to extract oil shale – it’d be ugly). If we do this, what is the atmospheric CO$_2$ concentration when we’re done burning it all?

E. In the Eocene, 30 M years ago, CO$_2$ concentrations were estimated at around 1000 ppm, and there were crocodiles and palm trees in Britain - climate must have been warmer. Given this evidence, does your answer in D worry you?

F. (no grade, just think): Which is worse, to have the energy system the world depends on come to a halt within decades, or to experience global warming at nearly unprecedented rates? Comment if you feel like it.

**Problem 3: (Optional) Deepwater Horizon**

Some scientists have estimated the Deepwater Horizon spill as up to 100,000 barrels per day. What does that really mean? Get a sense of its scale.

A. Convert this to Watts (or kW or MW or GW)

B. Compare to U.S. rate of oil consumption.

C. Compare to something visceral (e.g. gasoline from that oil would power how many big-rig trucks driving across the U.S., or whatever else gives you physical intuition).