GEOS 24705 / ENST 24705
Problem set #18
Due: Tues. June 2

Problem 1: energy densities of fossil fuels
Background

The energy "content" of a fossil fuel is *the energy that would be released when the fuel is burnt.* By considering the chemical bonds in the reactants before the burning occurs and those in the products afterwards, you can determine the chemical energy released and so back out the energy density (energy/mass) of the fossil fuel. All fossil fuels (coal, oil and its derivatives, natural gas) are nearly pure hydrocarbons (molecules made of only Hs and Cs). For a hydrocarbon fuel reacting with oxygen, the reaction is

Fuel + oxygen -> carbon dioxide + water

The oxygen is called the "oxidant"; the fuel plus oxygen together are the "reactants", and the carbon dioxide and water are the things produced – the "products".

Note that energy density you'd derive is a function of *how* fuel is to be combusted (with oxygen). The energy release is a function of the whole reaction, not just of the bonds in a molecule of the fuel. So what we call a fuel's energy density is dependent on how we assume the reaction will proceed. Luckily on Earth oxygen is such a good and common oxidant that we can assume all combustion involves reaction with oxygen.

Some chemistry background: you can think of a chemical bond between two atoms as being a link between electrons in those atoms. If two atoms each share one of their electrons, they have a shared pair. Different atoms have different numbers of electrons they "want" to share: carbon tends to make four bonds, oxygen two, and hydrogen with its lone electron can only make a single bond. If two atoms make two different bonds with each other that is termed a "double bond" and indicated by a "=").

What we term the "bond energy" of a chemical bond is not energy "contained" by the bond – it is the energy that would be required to *break* that bond. The higher the value, the harder the molecule is to break apart. A reaction will occur spontaneously when molecules that are relatively easy to break apart are converted to others that are harder to tear apart – that is, when the combined bond energies of the reactants are *less* than those of the products. If a reaction would occur spontaneously (and release heat), the difference in energies between reactants and products is negative.

Bond	Energy (kJ/mole)
C-H	410
O=O	494
C=O	799
O-H	460
C-C	347
C=C	519 (if in rings)
C-O	360

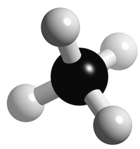
Because bond energies are small, it is common to use units of energy per "mole", where one mole = $6.022 \cdot 10^{23}$ (molecules or atoms or bonds). That number is termed "Avogadro's number", and is chosen so that 1 mole of H atoms has mass ~ 1 gram. (1 mole of C is then ~12 g, O~ 16 g)

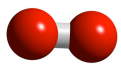
Problem

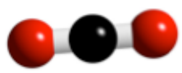
Consider the burning of one of the simplest hydrocarbons, methane (CH_4), the primary constituent of natural gas. You used the energy content of methane already in the cogen problem set; now calculate it from first principles.

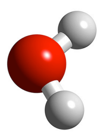
Burning methane, as in burning any hydrocarbon, means combining it with oxygen to form carbon dioxide and water:

$$CH_4 + 2 \cdot O_2 \rightarrow CO_2 + 2 \cdot H_2O$$

Methane: 

Oxygen: 

Carbon dioxide: 

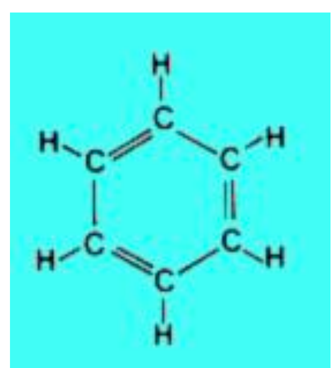
Water: 

A. Compute the net energy released in burning one mole of natural gas

B. Compute the energy density of methane (in MJ/kg)

C. Compare that energy density to the value for gasoline that you've used previously. Does your comparison make sense?

D. *(Optional)* Estimate the energy density of gasoline, and compare to values we've used in previous problem sets. Gasoline is actually a mixture of different molecules. For the purpose of this problem, you can use benzene as your model for gasoline (it's one component and is nice and simple).



Benzene
C_6H_6

Problem 2: Virtual tours of fossil fuel extraction

The modern "pumpjack" looks somewhat like an early Newcomen or Watt engine:

L. Pumpjack, R. Watt's "Old Bess" engine, both used for pumping liquids

Both actually use similar pumps. But, in the steam engines, the cycle time of the engine was the same as that of the pump – the piston connected directly to the rocker beam. The pumpjack is driven by a high-speed diesel engine, so it needs complicated gearing to allow the beam to rock much more slowly than the engine pistons are oscillating.

A. Watch the video here on the "sucker rod pump" used in oil wells. What reminds you of the older lift pump?

   http://www.youtube.com/watch?v=SFJFiyXTOa0

B. Watch the video here on the pumpjack's gearing system and explain how the 1200 rpm rotation of the engine is downconverted to the speed of the pump. (What is that speed?)

   http://www.youtube.com/watch?v=FU0dYV3LvAk&feature=related

C. Watch these fracking videos, first on drilling the wells…

   http://www.youtube.com/watch?v=fBQCQ6HL2Yw

D. ..and then on the fracking process itself, and comment on something interesting. Both videos are by a drilling company so obviously are positive on safety issues.

   http://www.youtube.com/watch?v=7ned5L04o8w

Problem 3: Getting away from fossil fuels / cost of renewables generation

Background
In this problem you'll estimate the cost of producing electricity from windpower and solar PV. (The "levelized cost of electricity" or LCOE). You'll compare that number to the U.S. wholesale electricity price and estimate the subsidy that is needed to make either of these

choices compete with fossil fuels. (Note that wind is the cheapest non-hydro renewable at present.)

To construct a policy that incentivizes generation companies to build renewables, you first need to figure out how much renewable generation would cost. The LCOE is simply

LCOE = (present value of total costs) / (liftetime energy production)

Wind costs: The cost of wind turbines and total installed cost (in $/kW) is discussed in the Wind Technologies Market Report (the 2013 report is linked to from the class website; see figures 38-42 and discussion p. 49-50). Remember that these are costs for *capacity* and the turbine won't always make this much power. The operational and maintenance cost for windpower is shown in Figure 43-44 (in $/MWh); for discussion of what goes into O&M see http://www.windustry.org/community_wind_toolbox_8_costs. Lifetime: a conservative lifetime assumption is 20 years.

***Solar costs*:** The installation cost for new utility-scaled solar PV is given in the 2014 "Tracking the Sun" report from Lawrence Berkeley linked to from the website. See the executive summary on p. 1, also Figures 30-31 and discussion on p. 41-42. Note that rated capacity assumes that you're getting 1000 W/m^2 incoming insolation, far above the world average. If you put your solar panel somewhere with average insolation of 250 W/m^2, then your "capacity factor" would be something like 25%. Operations & maintenance: in the absence of other information, you can just scale up the final solar PV cost by 10% as an estimate. Lifetime: a conservative assumption is 20 years.

Problems: Fill in the table below, and answer the questions below. The letters for the table rows refer to the individual sub-problems.

		Wind	**Solar**
A	**Capital cost** ($\$/W_{cap}$)		
B	**Capital cost w/ financing** ($\$/W_{cap}$)		
C	**Capital cost now correcting for capacity factor** ($\$/W_{true}$)		
D	**Total power produced over lifetime** (kWh/W_{true})		
E	**Capital cost per energy** (cents/kWh)		
F	**O&M costs** (cents/kWh)		
G	**Total LCOE** (cents/kWh)		
H	**Nec. subsidy** (cents/kWh)		

A. Provide a value for the cost to put up the wind turbine or PV panels in the first place. Costs are given in terms of "rated" power under optimal (wind) or impossible (solar) conditions. They're not the power you're actually going to produce. You should assume utility-scale installations here, which are a lot cheaper than smaller installations. Discuss your number, where you got it from, what you assumed. State what % smaller it is than for a residential-scale installation. State whether (for solar) you're installing with or without a tracking system.

B. Adjust your cost of A to account for the fact that you needed to borrow money to build your facility. You can do a real estimation based on an assumed interest rate or, for those without economics training, do the quick-and-dirty hack of assuming that financing costs roughly double your capital cost (multiply A by 2). Explain your assumptions.

C. Estimate the "capacity factor" for each installation, and scale your power by it to get the cost per actual power you expect.

For wind, you can use the helpful (if sometimes deceptive) metrics in the industry, where the quality of wind locations is given by a "capacity factor" that describes how much electricity the turbine actually produces relative to its the theoretical maximum capacity. Read the LBL wind report and justify the capacity factor you pick. Explain what you're estimating: wind in the best interior "wind belt" sites? In the average U.S.?

For solar, state the average insolation at the location where you'll put your solar facility. The capacity factor that is the actual insolation you see divided by 1000 W/m^2, times whatever % boost you get from tracking. It's OK to assume the facility requires no downtime and produces ~100% of the time.

In actual fact the efficiency of solar panels degrades over the years, and wind turbines require more maintenance and downtime as they age, but for this problem it's OK to ignore those complications.

D. Figure out how much electricity will be produced over the lifetime of the installation, in units of kWh, for each 1 W of capacity.

E. Get the cost per energy by dividing C ($/W capacity) by D (lifetime energy/W capacity).

F. Now, add the recurring costs. Since renewables don't use fuel, you only have to add in operation and maintenance costs. See "background" for sources of info.

G. Add your capital costs from E to your O&M costs in F to get the full levelized cost of electricity generation in cents/kWh.

H. Given the difference between your LCOE and the wholesale electricity price (see figure 57 in the Wind technologies report). You should be a bit higher because of assumed subsidies. Those subsidies are what allow wind "power purchase agreements" to fall in line with actual wholesale prices. Estimate the subsidy required to support each technology. Discuss reasons for and against providing additional subsidy for solar in particular.

I. ***(Optional)*** The federal production tax credit (PTC) lowered input capital costs by 30%. By your calculations, was the PTC alone enough to make windpower feasible? Solar PV?

(Optional but strongly recommended) Problem 4: Carbon taxes

In this problem you'll do a quick calculation of the price per CO_2 emissions of different fuels, choose a tax that would substantially alter the electric sector, and you'll see how that tax would affect transportation.

Data

Gasoline: The average cost of gasoline in the United States is given in $/gallon here: http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm. (1 gal -> 3.8 liters). Gasoline is lighter than water, ~75% less dense. The density of water you should know.

Coal: The cost of coal in the U.S. depends on the type of coal – you saw this in PS6 problem 3. A reasonable cost for the kind of coal used in electricity generation seems to be around $60/short ton. A short ton is 0.9 metric tons.

Masses and composition: The C:H:O ratios for coal and gasoline are given in the slides for Lecture 18. The atomic masses of C, H, and O are about 12, 1, and 16 grams per mole, respectively. (For the purposes of this problem you don't need to ever think about how many atoms are in a mole).

Electricity: Assume capacity factors for electricity generation for coal-fired and natural-gas plants based on past class materials.

Problems

A. In preparation for later problems, calculate: what mass of CO_2 would result from burning 1 kg of C with oxygen?

B-F Fill in the values in the following table. Notes are below. Extra extra-credit points for doing natural gas as well as coal

		Gasoline	**Coal**	**Elec. fr. coal**	**Nat. gas**	**Elec. from gas**
B	**Carbon fraction** (kg C / kg fuel)			X		X
C	**Fuel cost per mass** ($ or c / kg)			X		X
D	**Fuel cost per C** ($ or c / kgC)			X		X
E	**Fuel cost per CO_2** ($/tCO2 or cents/kg$CO_2$)			X		X
F	**Fuel cost per energy** ($ or c /MJ and c/kWh)					
G	**CO_2 per energy** (kgCO2/kWh; tCO2/MWh)					

In the last two rows, in the "Elec." Columns you're just rescaling by the plant efficiency to get values in terms of the electrical energy produced rather than the total chemical energy in the fuel).

H. How much more does chemical energy cost as gasoline than as coal?

I. Double-check that your fuel costs for producing electricity is reasonable – **is the fuel cost for producing electricity less than the wholesale electricity price?**

J. Calculate the size of the carbon tax you would have to apply for windpower to be cheaper than coal-fired electricity, based on your required subsidy from problem 3. That is, **how much do you need to value the avoided CO_2 emissions? Give your value in \$/ton CO_2.**

(If you solved for natural gas too, also state the required carbon tax to privilege wind over natural gas.)

K. Repeat for solar PV – **what is the \$/tonCO2 you'd need to incentivize it?**

L. By what fraction would the carbon tax in J alter the current price of coal? That is, what is the (price of coal + carbon tax)/price of coal

M. By what fraction would the carbon tax in J alter the current price of gasoline? As in L, give the (price of gasoline + carbon tax)/price of gasoline.

N. Look at the history of gasoline prices in the website given above, and discuss: **would the additional tax you added substantially affect gasoline usage?**

O. In light of this, what are the arguments for and against fuel economy standards?

P. What are your individual CO_2 emissions (tCO_2/year)? You can just assume that your 10,000 W consist of 1/3 coal, 1/3 gas, and 1/3 oil. If you didn't do the natural gas column above, natural gas has about ½ the CO2 emissions per unit of fuel energy as does coal.)

Q. How much would the carbon tax you just applied cost you, if your usage didn't change? (\$/year cost) *(Of course, the whole point is to change usage, and also most proposals for carbon taxes involve returning revenue to consumers through reduction in other taxes, so you wouldn't lose this much necessarily)*

R. Multiply your answer above by the U.S. population to get the total annual cost for the whole U.S. What fraction of GDP would this carbon tax represent?