GEOS 24705 / ENST 24705
Problem set #3
Due: Thursday April 9

1. Vertical farms

Background:
In class we discussed how vertical farming can't effectively increase the surface area of the Earth, if the plants being farmed rely on sunshine for their energy. If the sun produces an average of 200 W/m^2, that's the amount of power there is.

We didn't discuss the option of powering the growing plants with artificial lights. In this problem you'll explore that option, since that is what is being proposed in this latest New York Times article on a proposed vertical farm to grow kale in New Jersey:
http://www.nytimes.com/2015/04/08/realestate/commercial/in-newark-a-vertical-indoor-farm-helps-anchor-an-areas-revival.html?ref=nyregion
An earlier article is here: http://www.bloomberg.com/bw/articles/2014-10-30/aerofarms-plans-aeroponic-farm-in-newark-to-grow-leafy-greens

Obviously it's more efficient from an energy standpoint to use the sun's energy directly than go through all the transformations required to convert that solar energy into the radiation energy from a lightbulb. Any conversion is less than 100% efficient. Think about our energy system: to power a lightbulb, first you grow plants using solar radiation energy, then after several million years when those plants have become fossil fuels, you burn the fossil fuels to heat an engine which spins a generator which makes electricity which you send through wires and into a lightbulb, where it is converted to radiation energy again. That is, the chain of transformations is:
radiation energy → chemical energy → kinetic energy → electrical energy → radiation energy

We haven't talked about how inefficient each step is, but just looking at that chain, you should think, this can't be good.

In this problem you'll ask yourself – How inefficient is it to grow food under artificial lights? How much will it cost to power the lights in this facility? Can this company possibly make money?

The simplest way to answer those questions is to work in slightly strange unit of cost per energy content (either cost per energy inputs to make the kale, or cost per chemical energy in the kale). And the most reasonable units, to keep the values intuitively understandable, are $/kWh. That is, you'll count energy not in Joules but in kilowatt-hours, i.e. the number of Joules converted if you use 1000 Watts of power for 1 hour.

Problems:
The statement of what you need to answer for each part is highlighted in italics

A. In class we said that the only crop grown commercially under artificial light in the U.S. was marijuana. The high cost of marijuana justified the exorbitant cost of electricity for the lights. The AeroFarms company in the NYT article proposes to grow kale. Let's start the reality check by comparing the price of marijuana to that of kale. You'll work in units of $/gram of dry mass.
Here are some estimates of the price of pot in Colorado, where it is semi-legal:

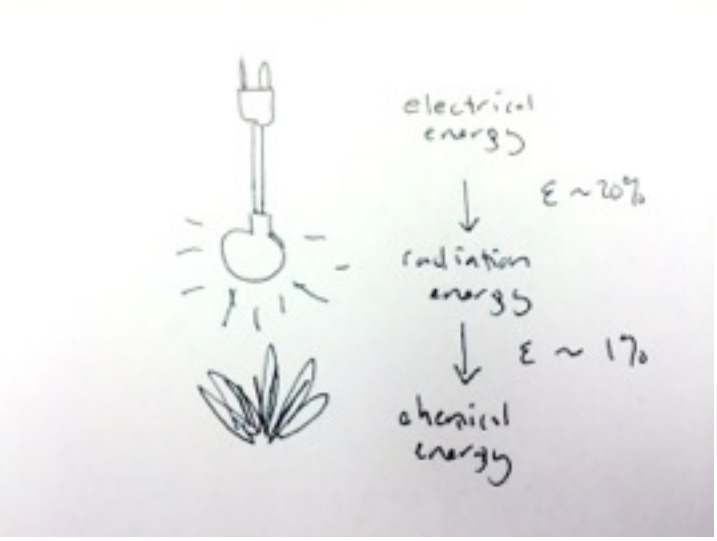
https://www.coloradopotguide.com/colorado-marijuana-blog/2014/november/20/marijuana-prices-in-denver-and-colorado-fall-2014-update/
(and note that semi-legality should have driven the price down). You can assume that the pot being sold is dry, so that the mass quoted is that of the dry carbohydrates only.

Kale is not typically sold dry, so you have to look at the price for moist kale and then try to back out what the mass would be if it were dried. For the cost-conscious, you can buy a nice bag of kale at Walmart: http://www.walmart.com/ip/Nature-s-Greens-Kale-Greens-16-oz/20631705. To estimate what mass that kale would have after it was dried, you can look at nutritional information, which gives the mass of carbohydrates (and protein) per mass of wet kale. http://www.calorieking.com/foods/calories-in-fresh-or-dried-vegetables-kale-raw_f-ZmlkPTcwODcw.html. At this point you don't need to worry about what the calorie content is, just take the ratio of the dry mass to the wet mass.

Answer: *what is the cost of marijuana, in $/$g_{dry}$? What is the cost of kale in those units? By what fraction does the cost of marijuana exceed that of kale?*

B. Let's consider the efficiency of the system required to grow food under artificial lights (diagram below). In this question you'll answer, how much energy would you need to use if you grew ALL your food indoors?

The diagram starts the system with electricity, because we haven't talked yet about the upstream part of the energy conversion chain (the electricity generation part). Remember that the upstream part of the chain contributes even more inefficiency. What you'll calculate here is the amount of electricity you need to grow food, which is a lower limit to the total primary energy you'd need to grow food. Your true total energy needs would be even higher.



Efficiencies: The article says that AeroFarm will use LEDs (light-emitting diodes), which are indeed the most efficient type of bulb at converting electrical energy to the visible radiation that we see (and that plants use to grow). The efficiency of commercial LEDs can now reach ~ 20%. We discussed in class that the efficiency of farming for conversion of radiation to chemical energy, on good farmland, is ~ 1%. Although you might have a nagging sense that kale is probably not the ideal plant to grow if you're just trying to produce calories, this is a good enough number to use in this problem set.

Answer: *What is the ratio of electrical energy input to chemical energy in the kale? How much electrical energy would it take to meet all your food needs with plants grown under LED lights? By what factor would that increase your total energy use?*

Now, you'll figure out how much the energy will cost for AeroFarm to grow kale, and compare that to the price of kale. The relevant input information you'll need here is the price of electricity. If the farm is paying normal retail rate, their electricity costs them something like 10 cents/kWh. You should also remember from class that the energy content of carbohydrates (or proteins) is something like 4 kcal/g_{dry}.

C. ***Answer****: What is the retail price of kale and marijuana in units of $/kWh chemical energy content?* (Just convert your $/$g_{dry}$ from part A.)

D. ***Answer:*** *What is the cost of the electricity used to grow any plant under LEDs, in the same units of $/kWh of chemical energy content of the plant?* (You know the $/kWh of electricity, and in part B you figured out how much of electricity was needed to produce a given amount of chemical energy.)

E. ***Answer:*** *Can AeroFarm make money if they sell their kale at Walmart? How much more would they have to charge for their kale than Walmart does, in order to recover their electricity costs? If you were a venture capitalist, would you invest in this company? Based on your answer of part B, is this company "green"?*

Extra credit problems

There are in fact several similar companies growing kale indoors in Chicago: Green Sense Farms (http://gizmodo.com/chicagos-huge-vertical-farm-farm-glows-under-countless-1575275486 and http://greensensefarms.com), and FarmedHere (http://farmedhere.com)

F. Green Sense Farms claims that their process is "sustainable": "Because we aren't dependent on the sun or rain, we can grow consistently near our customers. Our proximity means we can deliver faster and fresher, using less fuel and creating fewer emissions." Discuss in the context of the answers above. ***Answer:*** *What is the comparison you'd have to make to decide if this mode of farming produced more or fewer CO_2 emissions than conventional farming outside city limits?*

G. Neither farm's website lists prices, but FarmedHere baby kale is sold at Whole Foods. Take a field trip to Whole Foods and find the price of their baby kale. ***Answer:*** *What is that price, in $/$g_{dry}$? Can FarmedHere be turning a profit without some kind of subsidy?*

H. Double check the rule-of-thumb of 4 kcal/gram by looking at the nutritional information for kale. Here you have to ignore the indigestible dietary fiber – just consider the mass of those parts of the kale that you can digest when comparing to its caloric content. ***Answer:*** *What is the kcal/g of this kale? Was 4 kcal/g a good approximation?*

I. Use estimates of the yield of kale (mass wet / area) and the growing time of kale before harvest, to estimate the photosynthetic efficiency of kale plants. That is, *what fraction of the sun's input power is converted to chemical energy in kale?* (You'll need to use

information from your part A answer to convert to dry mass). Kale yields and growing times are given here: http://www.johnnyseeds.com/assets/information/vegetablecharts.pdf.

For the input solar power, you could assume that kale is grown with the global mean solar flux, or you could decide to take into account that kale is grown only in the summer and at midlatitudes or higher (no tropical kale farms!), and use the slides of Lecture 2 to estimate a different solar input power in W/m^2.