GEOS 24705 / ENST 24705 / ENSC 2100
Problem set #10
Due: Tues. Mar 1

Problem 1: Power plants
The power plant is a mechanism for turning heat (usually derived from burning fossil fuels) into electrical energy. We haven't been able to get a trip to a coal-fired power plant this year, but next week we'll go to the Museum of Science and Industry to see their gas-powered generator Read the posted reading from the Hayes book "Infrastructure" on fossil-fueled power plants. Comment on something interesting.

Problem 2: Energy transformation technologies and efficiencies
Part of the 18th century energy impasse was the problem that people could not yet transform heat to work. Now, we have technologies to transform almost every form of energy to every other form. The grid below allows visualizing these. The vertical axis is the form of energy that's being converted FROM. The horizontal axis is the form that's being converted TO. Each box then represents a particular energy transformation. The diagonal boxes represent not conversions but technologies for moving or storing energy without changing form.

To → From ↓	**Electro-magnetic**	**Kinetic**	**Heat**	**Chemical**	**Radiation**	**Nuclear**
Electro-magnetic						
Kinetic						
Heat						
Chemical						
Radiation						
Nuclear						

A. In the first part of this problem you'll try to fill out the grid. We won't grade on how well you fill it out; just use this opportunity to think. Try to focus on human-made technologies, but you can also put in natural transformations. Finish this before looking at the grid that is linked to on the web page, then discuss what you missed and why you might have missed it.

Almost every box can be filled with something. Some examples to get you started: we discussed class that in the absence of electricity, kinetic energy from steam engines had to be transferred to factory equipment by belt drives. So you'd write "belt drive" in the box between kinetic and kinetic. The heat engine itself would go in the box from heat to kinetic.

This problem should also make you think carefully about some everyday technologies. For example, an incandescent light bulb….you put a bulb in a light, plug the light into an electric socket, and the lightbulb produces light. Does that mean that this technology represents a transformation of electrical energy directly to radiation energy? No – what's actually happening is that the filament of the bulb is heating, as we discussed in class, just as a toaster or space heater would, and the hot filament then emits visible light because it is hot. So the full transformation for a standard incandescent bulb is electrical → heat → radiation, and you would properly enter it in both the electrical→heat and the heat→radiation boxes. A fluorescent light bulb is a totally different transformation: electrical energy "excites" the electrons in mercury vapor gas into higher-energy states, those electronics then produce light when they return to their original state. (We'll discuss fluorescents in more detail later.) That intermediate step leaves some ambiguity in how to classify a fluorescent bulb, as we never gave name to the form of energy involved in excited electronic states. A basic light-emitting diode (LED), on the other hand, is a about as direct a transformation of electrical → radiation as is possible, but even LEDs can have complications: for example, the color in many colored LEDs is produced by some substance that fluoresces.

In the rest of the problems, you'll use the grid on the web page to trace out the chain of energy transformations involved in some aspects of your everyday life.

For each transformation, you'll print out a grid and draw the transformations on it. You'll also book-keep the energy losses that occur during that chain. The table on the following page (from Smil) gives conversion efficiencies for many common transformations. It gives nearly all the info you need, but here is some additional info. First, Smil doesn't book-keep the losses in electricity transmission lines. In the U.S., those are on average 7%, i.e. electricity transmission and distribution is about 93% efficient. Smil doesn't list an efficiency for microwaves (e→h); those are typically ~65%, a number consistent with the findings of those students who did the experiment themselves. This chart pre-dates the invention of the commercial LED bulb; good modern LEDs are up to 20% efficient. For solar photovoltaics, the chart lists the best as 20-30% efficient but that's not a reasonable number; commercial PV panels are more like 15%. Smil lists photosynthetic efficiencies for plants as 1-2% max but remember that the efficiency for plant food edible by humans is less, at most 0.5% for fertilized corn. Finally, it's interesting to see that Smil assumes that conversion of food → meat in animals is 30-35% efficient. We saw in prior problem sets that a cow is < 10%, while a modern chicken is 50% efficient. Smil's number looks like an average of the cow and the chicken.

For the problems below (other than those in italics), you should turn in 1) a printout of the technology grid numbering (or otherwise marking) the progression of transformations, and 2) a calculation of the net efficiency of the entire process. Unless told otherwise, assume that all electricity is produced by burning some fossil fuel and spinning a steam or gas turbine. For transformations that start with some kind of plant matter or fossil fuel, ignore the efficiency of converting sunlight to chemical energy in plants. Just start with the fuel.

B. Cooking with a gas stove

C. Cooking with an electric stove

D. Cooking with a microwave

E. Heating your house with a furnace

F. Heating your house with a space heater

G. Heating your house with a heat pump with COP = 3.5. Here you can assume that the rated COP includes the losses of the electric motor that drives the compressor used in the heat pump (i.e. don't include the small-electric- motor transformation; it's already wrapped into the rated COP).

H. Now you can calculate more exactly: at what COP would a heat pump use the same primary energy as a furnace? You examined this issue PS 8, but you ignored all the inefficiencies other than the heat engine itself. Now you can evaluate the question more carefully.

I. Lighting your house with candles

J. Lighting your house with electricity-powered standard incandescent lightbulbs.

K. Lighting your house with electricity-powered modern LED bulbs

L. Many techno-optimist environmental groups believe that the agriculture of the future involves growing our food indoors under artificial lights (LEDs), in "vertical farms". The argument is that this will save energy, since it allows food to be grown locally, and that it saves on land, since food can be grown in multi-story buildings. Fill out the chart for the chain of transformations in converting chemical energy in fossil fuel into chemical energy in food.

M. Using your answer above, if you were to produce all your 100 W of food in vertical farms, what primary power consumption would that require? How would this compare to your present-day 10,000 W of total power use?

N. Advocates of vertical farms claim that the electricity required for lighting could be produced by renewables. The most efficient of the renewable electricity-generating technologies is solar PV. Fill out the chart for the transformations needed to convert the radiation energy in sunlight into radiation energy from LED lights in your vertical farm. What is the total efficiency? That is, by the time you get done taking sunlight and making electricity and on through the chain til you make light again, what fraction of the original sunlight is this?

O. We presently use a bit over 10% of the Earth's land surface area for growing crops. What fraction of land surface area would be required for solar PV panels to produce electricity to light the lights to grow that food indoors instead? Is this feasible? (Note – try to figure out how to answer this question in a simple elegant way, without multiplying by the surface area of the Earth.) It is OK to report a fraction greater than 1, if you find you would need additional planets to harvest sunlight from.

*P. **(Optional)** How much land would you need if you made your electricity from biofuels instead?*

Table 7 Efficiencies of Common Energy Conversions (percent)

Conversions	Energies	Efficiencies
Large electricity generators	M → e	98–99
Large power-plant boilers	c → t	90–98
Large electric motors	e → m	90–97
Best home natural-gas furnaces	c → t	90–96
Dry-cell batteries	c → e	85–95
Human lactation	c → c	85–95
Overshot waterwheels	m → m	60–85
Small electric motors	e → m	60–75
Large steam turbines	t → m	40–45
Improved wood stoves	c → t	25–45
Large gas turbines	c → m	35–40
Diesel engines	c → m	30–35
Mammalian postnatal growth	c → c	30–35
Best photovoltaic cells	r → e	20–30
Best large steam engines	c → m	20–25
Internal combustion engines	c → m	15–25
High-pressure sodium lamps	e → r	15–20
Mammalian muscles	c → m	15–20
Traditional stoves	c → t	10–15
Fluorescent lights	e → r	10–12
Steam locomotives	c → m	3–6
Peak crop photosynthesis	r → c	4–5
Incandescent light bulbs	e → r	2–5
Paraffin candles	c → r	1–2
Most productive ecosystems	r → c	1–2
Global photosynthetic mean	r → c	0.3

Energy labels: c—chemical, e—electrical, m—mechanical (kinetic), r—radiant (electromagnetic, solar), t—thermal

From V. Smil

Problem 3: "Vertical farming": analysis using costs

Growing food indoors under artificial light is touted by some environmental-minded groups as being "more efficient", and the idea is unfortunately metastasizing across the U.S. See links below:

Aerofarms in New Jersey, growing kale:

- http://www.nytimes.com/2015/04/08/realestate/commercial/in-newark-a-vertical-indoor-farm-helps-anchor-an-areas-revival.html?ref=nyregion
- http://www.bloomberg.com/bw/articles/2014-10-30/aerofarms-plans-aeroponic-farm-in-newark-to-grow-leafy-greens.

And an even larger new effort bankrolled by Jeff Bezos of Amazon, growing salad greens:

- http://www.bbc.com/news/business-40659617l

In the previous problem, you evaluated the efficiency of the chain of transformations involved. For making electricity from solar PV, that chain is

radiation energy → electrical energy → radiation energy

For making it from biofuel, the chain is

radiation energy → chemical energy → kinetic energy → electrical energy → radiation energy

You should have noticed that even in the best of those two options, the total efficiency was not large.

In this problem you'll examine feasibility using another metric, cost. Generally cost and energy scale well together, because energy is not free. If a process requires more energy, it costs more. Cost therefore is a useful metric: it aggregates all the losses and inefficiencies that went into making the electricity, so lets you ignore the upstream part of the energy conversion chain.

There is only one agricultural product in the U.S., besides salad greens, that is routinely grown indoors under artificial lights – marijuana. And marijuana grow houses are often identified by their suspiciously high electricity bills, so much so that there are legal disputes now over whether the DEA can subpoena utility bills without a search warrant. The high cost of growing plants indoors has produced a further trend toward growers actually stealing electricity: https://www.eenews.net/stories/1060036221

In this problem you'll ask: what is the "embedded energy" of food grown indoors? What is the cost of that energy? If you were to grow food indoors in Illinois, what price would you have to charge for it just to cover your electric bill? (Presuming you are not resorting to stealing).

EMBEDDED ENERGY

A. In an earlier project you evaluated the energy density of wood, in MJ/kg. Restate that here, and check its plausibility by also converting the metric of 4 Cal/g for carbohydrates to MJ/kg. This can serve as your energy density of (dry mass of) vegetables grown indoors. (Remember that vegetables are mostly water. What you're calculating here is the energy density if you fully dried out a vegetable in a dehydrator.)

B. Calculate the efficiency of turning electricity into chemical energy in salad greens. As you did in Problem 2L, you multiply through the energy conversion chain, but here it is only electricity → radiation → chemical. We ignore the upstream part of the chain. For the plant's efficiency at converting light to chemical energy, you can assume a photosynthetic efficiency of ~1%. (Remember that you eat all of the salad greens.) *Bonus points:* find an actual report of photosynthetic efficiency for one of these farms.

C. Divide A by B to get the embedded electrical energy per kg of dry mass of salad green (again in MJ/kg). Make sure that you understand what we are doing in this step.

D. Now go another step further and consider the embedded *primary* energy per kg of dry mass of salad greens. That is, divide A by the efficiency for the full chain that you calculated in 2L. (Reality check: this should be about 3 x your value in C.)

E. Compare your embedded primary energy in D to that for other manufactured products, and discuss. (See table below from Smil.) The highest-energy material we use in everyday life is aluminum, which requires not only enormous amounts of energy but of energy in the form of electricity, since it is extracted from ore in an electrochemical process. Ordinary smelting of aluminum is extremely difficult. Before this electrochemical process was discovered, aluminum used to be more precious than gold or platinum.

Table 8 Typical Energy Costs of Common Materials (MJ/kg)

Material	Energy cost	Made or extracted from
Aluminum	227–342	Bauxite
Bricks	2–5	Clay
Cement	5–9	Clay and limestone
Copper	60–125	Sulfide ore
Glass	18–35	Sand, etc.
Iron	20–25	Iron ore
Limestone	0.07–0.1	Sedimentary rock
Nickel	230–70	Ore concentrate
Paper	25–50	Standing timber
Polyethylene	87–115	Crude oil
Polystyrene	62–108	Crude oil
Polyvinylchloride	85–107	Crude oil
Sand	0.08–0.1	Riverbed
Silicon	230–235	Silica
Steel	20–50	Iron
Sulfuric acid	2–3	Sulfur
Titanium	900–940	Ore concentrate
Water	0.001–0.01	Streams, reservoirs
Wood	3–7	Standing timber
Fertilizer	70	Natural gas used to fix N_2

PRICES

F. What is the cost of electricity in Illinois? Here you want the retail price, the price paid by consumers buying electricity. (The wholesale prices is that received by generators selling electricity.) The U.S.Energy Information Agency (EIA) collects data on prices in each state: https://www.eia.gov/electricity/state/. To be most accurate, you would want to choose not the mean price over the whole state but the mean commercial price as a guide to what you'd pay as a big commercial grower. (Big purchasers of electricity get discounts.) To find that price, click on the state, then on "Full data tables" and look at Table 8, which includes "retail price by sector". For now, leave the retail price in units of cents/kWh.

G. Why is electricity not sold in Joules? Answer - how many Joules are there in a kWh? Convert your price to cents per MJ.

H. In part C you estimated the electrical energy in MJ per kilogram of dry carbohydrate. Now multiply by price to get the price in $ per kg of carbohydrate *just for electricity alone*.

I. We want to compare your 'embedded electricity price' to actual store prices for salad greens, but this is complicated by the fact that in grocery stores, greens are sold by the full weight inclusive of water. To do a price comparison, you need to figure out first how much of the salad green mass is not just water. Conveniently Walmart puts nutritional info for their salad products online, see for example https://www.walmart.com/ip/Marketside-Baby-Kale-Spinach-8-oz/33057976 You can just divide the weight of the carbohydrates, proteins, and fats by the serving size to get the fraction of dry weight to total weight. *For extra credit*, reality-check the label accuracy in any of a number of ways: double check the calories per gram, check against other salad products, etc. (https://www.walmart.com/c/kp/salad-mixes).

J. Convert your electricity-related $/kg_dry_mass to a $/kg_wet and then to $/oz. This is the extra that you'd have to boost salad prices by to cover your electricity bills for your indoor farm.

K. Use the article below to estimate an actual price premium for indoor-grown greens, in $/oz: https://medium.com/edenworks/market-trends-affecting-indoor-agriculture-e59266fa3814 (that is, the extra price vs. greens grown outdoors.) Compare to your value in J, and discuss. The factor in your calculation that is likely the most uncertain is the estimate of photosynthetic efficiency. Since salad greens are fast-growing baby plants, picked before they mature, they may have a higher efficiency of converting light to chemical energy than that over the entire lifetime of a mature plant. ***Optional*** – use the true price premium from the linked article to "correct" your estimate of 1% photosynthetic efficiency.

L. ***Optional:*** Salad greens are of course already absurdly expensive per calorie. To evaluate the penalty if we were to grow *all* our food indoors, we should instead evaluate the premium for staple foodstuffs like corn and soybeans. Those premiums would be even greater, both because these crops are cheaper and because the photosynthetic efficiency of crops of which only part is edible is lower than what you assumed for salad greens. **Estimate by what fraction you'd need to increase the price of corn or soybeans to grow them indoors**.

   Prices are forecast here (in $/bushel): http://farmdocdaily.illinois.edu/2017/10/expectations-for-corn-and-soybean-prices.html The weight per bushel depends on the crop and on its moisture content, and are listed on multiple agricultural sites. At a 15.5% moisture content, shelled corn is about 56 pounds/bushel, and soybeans are 60 pounds/bushel. You will need to convert to a price per dry mass.

M. ***Optional:*** Look up the cost of marijuana (you can find it in $/oz or $/gram, including on the map here: http://www.priceofweed.com/. **Is the price of marijuana high enough to allow growing it indoors under lights, without requiring stealing electricity?** (You can assume that the prices here are for dry mass, and that marijuana's energy content per dry mass is just like any other plant.)

MORE ON PRICES

N. The EIA list of state electricity price differences allows an interesting comparison to the state Sankey diagrams you looked at in the last PS: https://flowcharts.llnl.gov/commodities/energy. What features seem to lead to high prices? What features seem to lead to low prices? Discuss and provide examples.

   A side note here on government actions to promote renewables: these have differing effects on consumer prices depending on how they are implemented. Federal subsidies for windpower and solar are paid to the producers, and allow them to sell power more cheaply than they otherwise would. These subsidies therefore reduce consumer prices (though note that the cost does come out of your taxes in the end.) State preferences for renewables are often expressed as mandates for utilities, and therefore serve to raise consumer prices. Residential solar power (which in these diagrams bypasses the "electricity generation" box) receive a large implicit subsidy because of "net metering". The simplest way to think of the effects of net metering is that homeowners with solar panels can effectively sell power at the retail rather than the wholesale price

O. We might as well consider wholesale prices as well. We will need to think about wholesale prices when evaluating the cost-effiectiveness of any renewable energy technology. The EIA lists wholesale prices too, but these are not organized by state, since wholesale electricity markets confusingly cross state boundaries. Chicago is actually in the "PJM" market, which started with Pennsylvania New Jersey and Maryland: https://www.eia.gov/electricity/wholesale/ What is a representative wholesale electricity price in this market? Compare to the retail price.

P. Compare the wholesale prices for electricity and natural gas. You can get both from the EIA site. You need to convert units to compare them. What is the price of natural gas in cents/kWh? What is the ratio of the price of electricity to that of natural gas? Discuss in the context of the efficiency of producing electricity from natural gas.

DEBUNKING ARGUMENTS

One of the arguments routinely made in favor of vertical farms is that they "reduce the energy required for transportation". This is a classic case of the fallacy of the visible. Because people can see trucks, they fixate on them. The electricity system is invisible to them, and so they don't even think about the lighting. The purpose of this class is to get people to understand the scale of that part of the energy system that you don't see.

You should already realize that the energy cost of transporting food must be much less than the cost of growing food under lights. Transportation of food is a minor component of total energy use now. (Go back and look at the Sankey – it'd be some small fraction of that green "oil" bar). But your calculations in problem 2 suggested that switching to indoor farming instead to save that oil would result in increasing total energy use by a factor of several! There's an English saying (from the time when their currency unit was the "pound"): "penny saved, pound foolish." That is, some people, in the effort to try to save a little, end up wasting a lot more without noticing it. In Part Q below you'll estimate the "penny" that's being saved.

Q. Estimate the energy cost of transporting food. The best units for this are again in MJ/kg. We'll be the most generous here and do the calculation for salad greens, which are mostly water (as you saw in Part I) and so more expensive to transport. We should consider only truck transport and not air freight here.

   The first step is to get the embedded primary energy per kg for indoor-farmed salad greens. You calculated the embedded energy per mass of dry food of Part D, but you now need to multiply by the ratio (dry weight/total weight) of Part I to get the energy/total mass.

The next step is to estimate the primary energy used in transporting a given mass of food. You can assume that trucks run always full; they certainly try to since running empty doesn't make them any money. You can Google for any values that you want, or use the hints below. The American Transportation Institute reports an average fuel economy for heavy-duty trucks of 6.2 miles per gallon, or, more sensibly, 1/6.2 = 0.16 gallons per mile. You know the energy density of gasoline from your past problem set in MJ/kg; diesel is just a bit less. You do need to be aware that the mass density of gasoline or diesel is less than that of water, about 80% (remember oil floats on water). A generous estimate for the "load" of a heavy-duty semi truck used to haul food is 40,000 pounds of cargo. You have to make some reasonable estimate of how far food is transported from fields to cities.

Finally, **compare the primary energy cost of driving food around (MJ/kg) to the embedded primary energy (MJ/kg) of growing it indoors and eliminating the need to drive.** Discuss.

R. ***(Optional)*** Use the ATI report, which estimates driving cost per mile, to estimate the cost of transporting food. http://atri-online.org/wp-content/uploads/2016/10/ATRI-Operational-Costs-of-Trucking-2016-09-2016.pdf Compare to the cost of electricity used to grow food indoors.

S. ***(Optional)*** Repeat the calculation for air freight. Air transport is energetically more expensive for heavy cargo than is truck transport. Figure 7 of this paper https://pdfs.semanticscholar.org/8d4f/1fb5a1bfe0369ce820936c8cae4cfb785a9a.pdf has estimates of mass of fuel burnt per ton of cargo as a function of distance. The middle of the range looks like about 0.35 kg fuel per ton cargo per mile. Compare the primary energy cost of truck vs. air transport.