GEOS 24705 / ENST 24705
Problem set #2
Due: Tues. April 3

Problem 1: Energy density

Energy density is a concept that is deeply important to many applications, especially those involving transportation.

Consider a few possible substances from which we typically extract energy, and determine their "mass energy density" (in J/kg, i.e. energy per mass). *(For optional extra credit, repeat for the volume energy density in J/m^3).*

The lower the mass energy density, the heavier the fuel you have to carry. The lower your volume density, the bigger your fuel tank (or battery pack) needs to be.

For these problems, don't Google unless instructed to do so – it's not educational. State the source of your information in your answers.

A. A **carbohydrate diluted** in water: **orange (or other fruit) juice**. You can get the calories off a nutrition label. Remember that American food labels write "calories" for what physicists would term "Calories" or "kilo-calories".

B. **Gasoline** (a hydrocarbon). OK to get info from web, and convert units as necessary.

C. Now answer the question we asked in class - what volume of gasoline would it take to boil away a liter of hot water? Remember that latent heat of evaporation was 2.3 MJ/kg and a liter of water weighs 1 kg.

D. A **pure fat**: an easy option is **cooking oil** of some kind. From the food label.

E. How does your answer for D compare to that in part B? Is it consistent with your knowledge that cars can be run on biodiesel made from waste cooking oil?

F. A **pure carbohydrate**: one easy option would be **flour**. You can get the calories / mass from the nutrition label.

G. What is the relative energy density of fats vs. carbohydrates? Check if this matches the everyday 9/4 rule of thumb (9 kCal/g for fats vs. 4 kCal/g for carbohydrates).

H. *(Optional):* assuming all carbohydrates have the same energy density, how dilute is your orange juice? (i.e. what fraction is water?)

I. Electrochemical energy storage in **batteries**.

The power put out by a battery is

$$P = I \cdot V$$

where P is power, I is electrical current, and V is the battery voltage (which stays constant over the lifetime of the battery. If current is expressed in the standard unit of Amperes (or "Amps") and V in volts then the units of power become the standard Watts (J/s). To provide information on the total energy stored in the battery, manufacturers typically state the integrated current the battery can produce over its lifetime, usually stated in "Amp · hours".

Unfortunately there seems to be no consumer-protection requirement that household battery vendors actually list their Amp · hours. (Imagine going to the grocery store to buy cereal and seeing rows of identically sized boxes, none of which stated how much cereal was actually inside! We'd never tolerate that, but we accept buying batteries without knowing their energy content).

Laptop batteries, however, do typically list Amp-hours, so if you can access a laptop battery the information you need should be written on the label. (Plus you'll need to weigh the battery, of course). If you can't find an actual battery that states its A · hr, a last-resort solution is to Google to see if you can find some manufacturers who list that information. Whichever option you take, state your information source and the type of battery (NiCads, lead-acids, Li-ion batteries all have different energy densities).

J. You frequently hear people discussing electric cars. Why do you never read of any proposals for electric airplanes?

Problem 2: The person-engine

Some of the greatest power outputs of any humans are put out by professional cyclists. Lance Armstrong was capable of doing 400 W of mechanical work steadily for the course of a long (5 hour) bike race. Interestingly, it's not wear and tear on the body that limits the practical length of bike races. The length of bike races is limited not by the legs' tolerance for the exercise but by the stomach's ability to take in fuel: it's hard for people to digest more than 10,000 Calories / day. In this problem you'll be a race director and design a bike race like the Tour de France around that constraint.

A. A Tour de France race averages around 5 hours (note that this is 5 hours hurtling along at 40 km/hour – you would take far, far longer). Assume that Lance puts out 400 W that whole time, and that as a person-engine his mechanical efficiency is 20% (i.e. the power he puts out as work is only 20% of the total power he needs to be taking in). What are his energy requirements for a race day (in J, or Calories)?

Don't forget to add the amount a sedentary person would eat/day – he needs to keep his basal metabolism going too. And be precise with this calculation – don't do an order-of-magnitude estimate.

(Note: the fact that you need to be precise to get the "right" answer means that I fiddled with the inputs a bit to make your answer match reality – in this problem you'll be calculating a small difference of two large numbers, and that's a hard estimation to make).

B. If Lance can eat only 10,000 Calories per day, how much weight would he lose (kg of fat) each race day? Remember fat is ~ 9 kcal/g. Convert to pounds as well if you don't have a good sense for what a kg is.

C. If there were no rest days during an ~20-day Tour de France, how much mass of fat would Lance lose (in kg or pounds)?

D. If Lance is 165 pounds to begin with, and has 3% body fat, is this a safe amount of fat to lose?

E. As race director you might conclude this is not safe. If so you need to assign some rest days. Assume that on rest days the riders can still eat 10,000 Calories/day and that they sit still or ride gently and recuperate. How many rest days must you schedule to ensure that everyone maintains a safe weight during the Tour?

F. Google – how many rest days are there on the Tour? Did you make the right choice?

Problem 3: Powering the future world - how efficient do renewables need to be?

In class we estimated that

- The average person requires ~100 W power to sustain life
- Each American now uses ~10,000 W of industrial power

That is, that we effectively have about 100 technological servants each. And we probably don't want to give them up.

For much of the rest of the class we'll be investigating the different technologies that might meet these needs. But it may not be easy to meet them with alternative power sources to burning fossil fuels. Extraction of energy from the Earth's natural energy flows is typically inefficient, and we've only got that solar flux of 200 W/m^2 to start with, and the Earth is only so big, and there are a lot of people on it.

In this problem you'll compute compute a target extractable energy flux in W/m2 you need to power the world at our current lifestyle and therefore the target efficiency of conversion that you need for any solar-driven renewables. We'll use those numbers throughout class for evaluating whether any given technology can power the world.

A. First, for simplicity don't think of the whole world, just think of your piece of it. Let the Earth be divided equally among its current population ($\sim 7 \cdot 10^9$ people). How much land does each person get? This will be the land from which you have to derive all your energy. Give your answer both in standard units of m^2 but also for intuition in acres (with 1 acre ~ 4000 m^2).

   As an American you actually have a bigger share of the Earth's land surface area than the average person, but let's play fair in this problem and split it between everyone equally.

   Please don't just Google the land surface area of the Earth. Instead, Google the radius of the Earth if you need to, which is a number you can actually remember, and do simple geometry (remembering that 2/3 of the Earth is oceans). *Or, (optional for extra) you can guess the Earth's size by thinking about distances on the globe that you do know (e.g. the distance across the U.S.) That lets you calculate the Earth's total surface area.*

B. Now plan for the future – the population of the Earth is still growing, so your share is going to shrink in the future. Decide what population level the Earth will eventually stabilize at – what is that?

C. Now shrink your land portion accordingly to accommodate those future people. (Again give it in m^2 and acres).

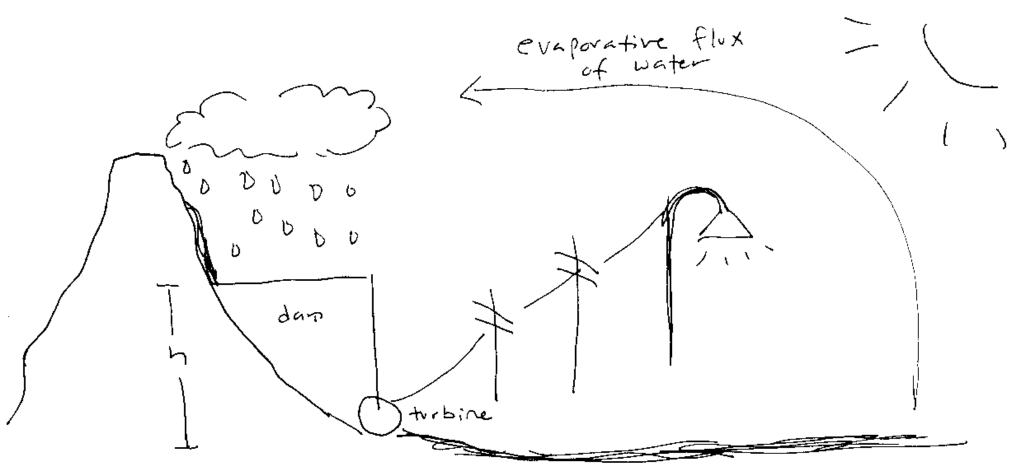
D. Not all of your land is going to be suitable for renewable energy production (only a fraction of your land is suitable for growing crops, or has high wind, and the mountainous or glaciated parts aren't useful for any energy production), and you wouldn't want to plaster your entire parcel with energy-production devices anyway. (You still need to grow your food, and to live somewhere, and to put your factories and industry, and it's nice to actually have a bit of wilderness too). So pick some reasonable fraction of your parcel that you're willing to sacrifice to energy production (and state it here).

E. With your assumptions above, what W/m2 of energy extraction do you need to support your American lifestyle?

F. What efficiency of extraction of incoming solar flux are you requiring?

(Optional) **Problem 4**

Consider the energy system below: when the sun shines, water is evaporated from streams and lakes (a transformation which requires energy) and becomes water vapor. That water vapor rises, and eventually cools, condenses into liquid again, and falls as rain. If people build a dam, trapping the water at altitude, they can recover some of that energy by letting the water spin a turbine and generate electricity. The maximum energy that could be recovered per mass of water that flows through the turbine is the same energy that would be required to lift that water against gravity, g·h. (Note that recovering that much would require a hypothetical perfectly efficient turbine).



Remember that the energy required to lift a mass up against the force of gravity is $E = m \cdot g \cdot h$, where m is the mass, g is the acceleration of gravity ($\sim 10\ m/s^2$), and h is the distance lifted. The energy per unit mass of this lifting is therefore $= g \cdot h$ (in units of J/kg).

In class we talked about the energy required to evaporate water, and made an estimation of the "latent heat of evporation" L_v, the energy per unit mass of water evaporated (units J/kg or J/m^3).

A. Assuming a perfectly efficient turbine (the best possible case) and a reasonable height for the dam (pick something logical), what power (in W/m2 of the Earths' surface) can be derived from hydropower?

B. Compare the energy per mass of water you can extract hydropower to the energy per mass that went into evaporating that water in the first place. Given you answer as an efficienc. Efficiency means

   Power extracted in desirable form / input power driving system

C. Now give the efficiency relative to the input flux of solar energy incident on the Earth. In other words, how efficient is hydropower at extracting solar energy for man's use?

D. Compare your answer in C to your target efficiency from problem 3. Can you meet humankind's power needs with hydropower alone?

(Optional) **Problem 5: The person-engine vs. the automobile**

Which uses less energy, bicycling or driving?

A. Estimate how many Joules you need to bike a given distance: that is, guess your Joules/km (or some other distance). You can just assume some reasonable speed and some reasonable number of extra calories/hour burnt while biking at that speed. Or you can guess your power output as mechanical work (not as much as Lance!) and divide by an assumed efficiency to get your total power consumption and again guess a reasonable biking speed.

B. Estimate how many Joules a car needs to drive that same distance (and you might as well use one of the better mileage cars – consider the Prius). You should know typical mpg for a Prius at reasonable driving speeds, and from the above you should know the Joules/gallon of gasoline (or at least, you know it if you did the volume energy density calculation. If not, remember that gasoline is somewhat less dense than water).

C. What's the ratio of energy used in biking vs driving over the same distance?

D. Convert units – what is your "effective mpg" while biking?

E. The energy savings of bicycling led a bunch of university students a few years ago to decide to carry materials for their university by cargo bikes rather than by truck. They said "it's slower but it's the green choice!" Check whether this was truly a green choice.

   A person-engine plus bicycle looks like a pretty good option compared to a car for just moving one person. But a bike is very light, while a car has to move some 4000 pounds of metal around. You'd expect the energy consumed to scale roughly with the mass being carried, and when hauling freight, the mass of the bike or even truck starts to be negligible in comparison to the freight mass – it's the cargo that counts.

   To fairly compare a car and a bike for the purpose of freight hauling, then, you might instead scale your comparison of part C above by the mass of each vehicle. (That is, give energy/distance*mass) How does the person-engine compare to the internal combustion engine now? Is it "greener" to use rickshaw drivers or Priuses to move freight around?