GEOS 24705 / ENST 24705
Problem set #2
Due: Tuesday April 7

1. Energy use in the modern industrial world

Background:

In class we estimated a metric of how much power per area (W/m^2) is needed to power the world. Everyone saw the demonstration on the blackboard, but because this number is something we'll come back to over and over I want everyone to repeat the derivation themselves. It's fine to come up with a slightly different number, just justify your arguments. Extra credit for exploring high/low scenarios.

Problems:

A. Estimate the current land surface area per person on Earth. Show the calculation.

B. State your final assumed world population (hoping that the population eventually stabilizes). Give the land surface area per person in this future world.

C. State an assumed fraction of that land that you will devote to energy production. Explain your assumption.

D. Now state the land surface area per person in the future world that will be devoted to energy production.

E. State the target average power usage you want the world to achieve (recognizing that power usage corresponds to wealth). Compare to the average power usage of current Americans and to the current world average (look back at Lecture 1 slides).

F. What is the power per area (W/m^2) required to power your future civilization?

G. If the future world is driven by solar power, what efficiency of conversion of solar radiation energy does your metric in F imply?

2: Evaporation and hydropower energy fluxes

Note – There's a wordy summary but the actual problem is a Google look-up, a unit conversion and a single plug-in calculation.

Background:

You used the precipitation map to diagnose some of the Earth's energy fluxes. Many people got pretty close to the correct numbers, guessing:

- average evaporation ~ 1 m / yr of water
- energy flux driving that evaporation ~ 50 W/m^2
- total flux from the sun incident on the Earth's surface ~ 200 W/m^2

(More precise actual values are 1.03 m/yr *(National Climatic Data Center, 1961-1990 average)*, ~78 W/m^2 *(Trenberth, 1997)*, and ~198 W/m2 *(Trenberth, 1997)*.)

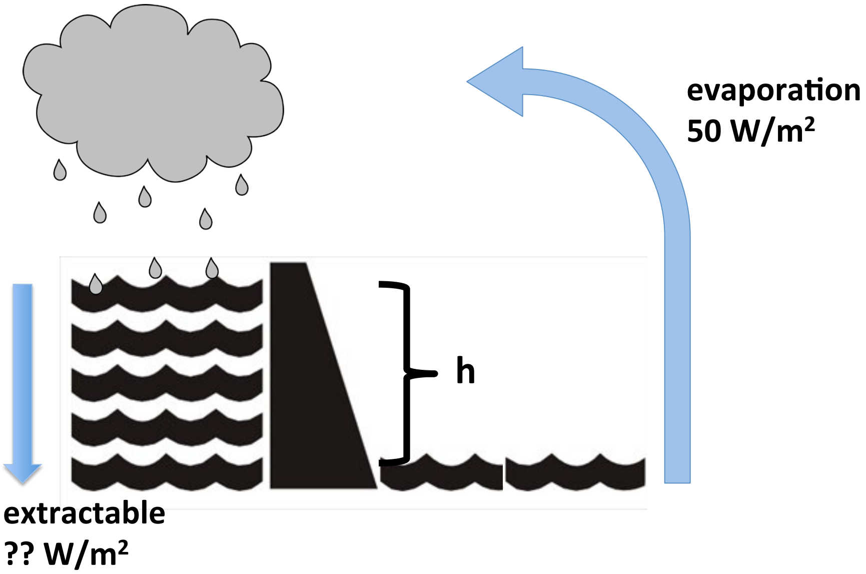
We also talked about how hydropower works, that what we do with dams is a very indirect use of sunlight: we capture the gravitational potential energy of water that was lifted as vapor after evaporating. (Not the latent heat of vaporization, that is dumped out as heat to the atmosphere when the water re-condenses as raindrops).

When water that had been evaporated and lifted falls again as rain we can trap it behind a dam, and then extract energy as we let the water descend the height of the dam. We'll talk later in class about how we manage that extraction (electricity generation). For now, just think about the flux of energy that we could possibly extract from dam water: the *maximum* energy flux that is recoverable in an absolutely unrealistic case. So assume that you could catch *every* raindrop that falls on Earth behind a dam and that you could then extract *all* the potential energy as water descends through the dam. The point of the problem set is to ask, how efficient could hydropower *ever* be at converting energy from the sun into a form of energy we can use?

In class we discussed the definition of energy as force x distance or

Energy = mass * acceleration * distance

To feel a Joule, we used in class the exercise of feeling energy required to lift a bottle of water against the acceleration of gravity (a_g ~ 10 m/s^2). The energy you can extract from falling water is also mass * acceleration * distance.



Problem

A. Pick some reasonable height h for your dam. (You can Google to find information on dams, or just guesstimate). Justify your choice.

B. What is the average flux of water mass that falls on Earth? That is, the mass per area per time, i.e. kg/m^2*s. You're just converting your 1 m/yr of rainfall.

C. Use your answer in B and the energy extractable from falling water

$E = m * a_g * h$

to calculate the maximum flux of energy that you could get via hydropower if you dammed up every raindrop that falls on Earth. Remember that E is in Joules (J), but the units of the flux you're calculating are W/m^2, that is J/(m^2*s).

Compare your answer in C to the total solar flux at the Earth's surface (~ 200 W/m^2). That is, calculate the maximum possible efficiency : extractable flux/solar flux. Give your comparisons in %. ***(Optional):*** Compare the maximum efficiency of hydropower at extracting solar energy to the efficiency of a normal solar photovoltaic cell. (It is OK to Google solar PV efficiency)

D. Many energy-starved countries don't stop at a single dam – they try to capture more energy by building successive dams down the length of a river, i.e. to capture energy over a larger drop than is possible with a single dam. The Yangtze river has been fully terraced with dams. (See cross-section below).

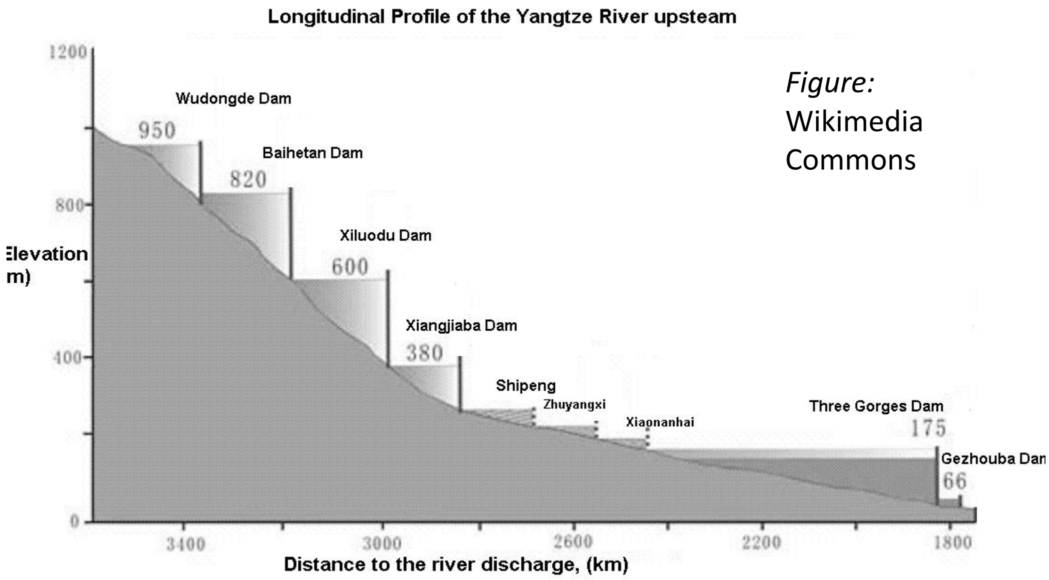


Figure: Wikimedia Commons

If you terraced all the Earth's rivers with dams, what would be a reasonable height h to assume for your estimate of the maximum energy extractable by hydropower? Explain.

E. Given that h, what is the efficiency of hydropower at converting sunlight to electricity?

F. Can hydropower power meet the standards you set in Problem 1 for powering the future world?

3. Biofuel generation by plants over the Earth's lifetime / fossil fuels

Background:

The overwhelming majority of energy captured by plants during photosynthesis (as chemical energy in sugars) is returned as heat when those plants decay. Plants convert solar energy to chemical energy, and decay converts that chemical energy to heat. The Earth's biosphere just serves to delay solar radiation energy a bit on its pathway to becoming heat. But, a little bit of that vegetation doesn't decay immediately if it's buried in anoxic conditions, but instead is preserved as (eventually) fossil fuel.

Some people on the pre-class quiz assumed that ALL the chemical energy converted by photosynthesis would stay as organic matter and would not decay - in other words that ALL plant growth would become fossil fuel. In this problem you'll first assume this is the case, and think about how large a pile of detritus would have built up on land over the Earth's history. Then you'll estimate what fraction of solar energy flux is ACTUALLY preserved as fossil fuel.

For your estimate use following inputs / assumptions, and don't be nervous about big numbers:

- Most of the fossil fuel reserves are believed to come from land plants (which make coal and natural gas), so you can ignore the oceans in this problem.
- Land plants first evolved ~ 450 million years ago.
- The slides in class gave the average land plant photosynthetic efficiency at converting sunlight to chemical energy on land as ~0.2%. (Most of the Earth isn't nice fertile land).
- The energy density of sugars (which most plants are composed of) is ~ 4 Calories / gram. (The capital "C" implies these are nutritionists' calories, not physicists' calories). Fats are more energy dense than sugars, ~ 9 Calories/gram. It's reasonable to assume the energy density of fossil fuels is somewhere between a sugar and a fat.
- We know that oil floats on water, so you can assume the mass density of fossil fuel (mass/volume) is a bit less than that of water (1 gram/cc). (Coal is actually similar to oil).
- You can assume that the mass of fossil fuel reserves in the Earth is around 6000 Gt (1 "Gt" = 1 billion tons, and 1 ton = 1000 kg).

Problems:

A. If plants never decayed, what energy content of organic material would have accumulated per area over the history of the Earth? Give your answer in units of J/m^2, or maybe GJ/m^2 , where the "G" means a billion. Use whatever makes sense.
B. What is the mass of the resulting pile of organic matter? (again in whatever units make sense – maybe $tons/m^2$).
C. What is the height of that pile? (in cm, or m, or km). Is this a plausible scenario?
D. In the real world, what fraction of land plant matter grown over the lifetime of the Earth has been stored as fossil fuel instead of decaying?
E. Assuming that the production of fossil fuel is constant over time, what fraction of incoming solar energy over land is currently being stored as fossil fuels?

4. The human engine

Background:

Some of the greatest power outputs of any humans are put out by professional cyclists. Many top cyclists are capable of doing 400 W of mechanical work steadily for the course of a long (5 hour) bike race (even without doping, it seems). 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: people can't 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.

Problems:

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 your rider – we'll call him 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 Cal/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?