GEOS 24705 / ENST 24705
Problem set #14
Due: Tues. May 19th

Water and wind turbines

The energy extractable from natural flows (wind, water) on Earth is best understood with Bernoulli's equation (for incompressible fluids)

$$\text{Energy/mass} = \tfrac{1}{2} v^2 + g \cdot h + p/\rho = \text{ct.}$$

In free flows (wind, free-running rivers) we extract the kinetic energy component only. In dam hydro, we extract the pressure component from water at the dam base, which is equivalent to the potential energy $g \cdot h$ at the top of the dam. For this reason the height or "head" of the dam is a measure of its energy density.

For comparing the energy densities of different fluids, engineers sometimes convert to units of "effective head" – the height of a dam behind which water would have the same *volume* energy density as that in the fluid. If you're considering water, then the effective head is just the energy/mass divided by the acceleration of gravity. If you're considering air, you need to account for the different densities of air and water, so also multiply by $\rho_{air}/\rho_{water} \sim 1/1000$.

Problem 1 – Energy densities of flows

Calculate both the mass energy density (in J/kg) and volume energy density (as effective head, in m) of several fluids from which we might want to extract energy.

A. Water behind the Hoover Dam on the Colorado River, the dam that forms Lake Mead, the second highest in the U.S. at 726.4 feet (221.4 m). When constructed in 1935 this was the largest concrete structure in the world.

B. Water behind Croton Dam on the Muskegon River in Michigan, still a working powerplant, at 12 m height.

Croton Dam, Muskegon River, MI
Photo: Gray Drake Lodge website

Hoover Dam, Colorado River, AZ/NV border
Photo: Wikimedia Commons

C. Water flowing in the Mississippi River, near New Orleans at its end, flowing at a speed of 3 m/s (the fastest rate along the river).

D. Water at the headwaters of the Mississippi at 1.2 m/s

E. Wind at a good normal wind speed for wind turbine operation, 10 m/s. Here remember that the effective head is the dam height for ***water*** that would have the same volume energy density. *(Note: you don't need to worry about the pressure term for wind so the fact that air is a compressible fluid doesn't affect this problem).*

F. What is the ratio of the head of Hoover Dam to the effective wind head in 1E? That ratio tells you how much more power you can get from a big hydro turbine than from a wind turbine of similar size.

   Ponder the implications. We said in class that there's a lot of potential wind energy available. But it's going to take a lot of turbines to collect it, if we want wind to be a significant part of our energy use. (No need to write anything here, just ponder).

G. Compare the energy densities calculated above with the energy densities you calculated in Problem Set 2. How close are hydro and wind energy densities to that of gasoline? Of a battery?

H. *(Optional)* Consider rates of fluid consumption. You car burns gasoline to turn chemical energy into kinetic energy to turn the drivetrain. In highway driving you consume about 2 gallons of gasoline every hour. Now imagine you powered your car via hydro instead. Imagine you have an electric car and charge your battery with energy generated from a hydro turbine.

   In order to drive for an hour, how many gallons of water per hour would you have to let flow through the hydroelectric plant, if you're getting power from Hoover Dam?

Problem 2 – Hydro virtual tour. Watch the following video

A. Watch this video of the differences between the three turbine types (in order, Pelton, Francis, Kaplan). Which turbine is most different (including orientation of its axis)? Comment on the differences that you see.

   http://www.youtube.com/watch?v=HzQPNpP55xQ

B. Watch this video of the Three Gorges Dam hydro project. Comment on at least one interesting thing you observe. Which turbine type is being used?

   http://www.youtube.com/watch?v=tjTh7A4jnbc

   (Optional): There is some interesting footage of Three Gorges while it was being built here: https://www.youtube.com/watch?v=b8cCsUBYSkw

   including shots inside the power houses, & discussion of issues involving building & operating a dam. The narration is a bit pretentious and has a tinge of xenophobia (lots of talking about "The Chinese") but the video is good.

Problem 3: Wind turbine size

A. How big must a wind turbine be if it is to produce 1 MW of power? You can estimate that from the expression for the power carried by the wind that you saw in class. Assume that the wind turbine can extract ~ 50% of the power of the wind, and let the wind be blowing at 8 m/s. What is the diameter of the turbine?

B. Despite their size, wind turbine installation happens very quickly. Watch the following video and comment on something interesting. Then, estimate the length of the turbine blades (note: the diameter is twice the blade length). Describe how you made your estimate – what are you comparing to? Does your estimate match your prediction from A?

   http://www.youtube.com/watch?v=Jf-Q1wyowWc

C. Now, go inside the turbine. First, watch diagrams of the system: https://www.youtube.com/watch?v=LNXTm7aHvWc

   Note that this video from 2010 is already obsolete – turbines have gotten bigger. No one would install a sub-MW turbine these days. And the direct drive system that is described as strange is not strange anymore.

   Second, watch video going the ladder all the way to the nacelle: https://www.youtube.com/watch?v=NG1uGt6qUfM

   Comment on something interesting in each video. Answer: Why is the generator on top of the tower? What is "feathering" and why would anyone do it to a wind turbine?

Problem 4: Rotation rates of wind turbines

You know from problem 1 that wind is a diffuse resource, and from 3 that wind turbines must therefore be big. The size of wind turbines is a bit problematic – it means that wind turbines can't rotate too fast or they'll shake themselves apart. (And efficiency considerations push turbine design to even slower speeds, which we'll discuss in class.) The mismatch between wind turbine rotation rates and our 60 Hz electrical standard then complicates design of wind turbine systems. In steam and gas turbogenerators, the turbine is hooked directly to a synchronous generator whose power is fed directly into the grid. That arrangement is just not possible with wind.

Why? Consider the speed experience by different parts of the blade. The linear velocity of the different parts of the turbine blade will differ, slower near the hub and maximum at the tip of the blade. Remember that in one revolution of the turbine, the tip of the blade travels around a circle of distance $2\pi R$. It is not survivable for the blades if the tip speed breaks the sound barrier (340 m/s).

In this problem you'll answer the question: can you design a modern-size wind turbine to make 60 Hz power directly?

A. First, make reasonable assumptions about the size of your turbine, and state them

B. What rotation rate would the turbine need to have to make 60 Hz power directly with a simple AC generator with one magnet, i.e. 2 poles?

C. What is the tip speed in this case? Could the blades survive this speed?

D. It turns out that wind turbines can only approach their ideal efficiencies if their “tip speed ratio” or tsr - the ratio of the speed of the tip of the blade over the speed of the wind – is near an optimal value of 5-6. For a typical wind speed (say 8 m/s), what is the optimal tip speed of your blades?

E. What is the rotation rate of your turbine, in Hz?

F. How many magnetic poles would be required to make 60 Hz power directly from this turbine? Does that number seem feasible?

Problem 5: Failure modes for wind turbines

A. Failure mode A: describe what has happened

   http://www.youtube.com/watch?v=CqEccgR0q-o&feature=related
   http://www.youtube.com/watch?v=-YJuFvjtM0s&feature=related

B. Failure mode B: describe what has happened

   http://www.youtube.com/watch?v=C_oFPF6Anwo