GEOS 24705 / ENST 24705
Problem set #16
Due: Tues. May 26

Problem 1: Can wind power the world?

In class we discussed our target for finding a power source that could run the whole world in the future and let everyone live like Americans. The criterion we picked was that area energy flux had to be 10 W/m^2 or better.

Can wind get us there? In this problem you'll design a wind farm and calculate the energy flux it can extract from the wind. Remember the power carried as kinetic energy by any moving fluid:

$$P = \frac{1}{2} A \rho v^3$$

where A is the cross-sectional area considered, ρ is the density of the fluid, and v is the velocity. Remember that Betz's law limits the power extracted even by the ideal free-stream wind of hydro turbine to 0.59 of the power carried. In practice even the best wind turbines don't quite reach this limit, but top out at about 0.5. And the wind doesn't blow ideally all the time – the "capacity factor" for wind turbines is usually around 0.3. That means the overall efficiency of extraction of wind kinetic energy is ~ 0.15

We discussed briefly the spacing of windmills. Because each windmill disrupts the velocity field of the wind, they can't be placed right next to each other. The velocity field downstream of a wind turbine also takes a long time to recover. The rule of thumb is to place them at least 3 rotor diameters apart along the direction facing the wind, i.e. to leave room for two other wind turbines in between any two that you build, and to leave 10 rotor diameters behind each turbine.

You need to pick a reasonable wind speed to use as your "v" in computing power. If wind is to be scaled up, we'll run out of the best and windiest sites. A reasonable number for v for wind on a large scale is 8 m/s.

A. How much power/area can you extract from a wind farm? Draw a diagram of a wind farm layout and wind turbine spacing, and derive power/area in W/m^2.

B. Does your answer depend on the size of the turbines? That is, by changing the turbine size, can you extract more power / area?

C. Does windpower meet your criteria of 10 W/m^2?

D. Imagine that you are appointed the energy czar of the United States, with absolute powers, and you have decided to use windpower to fill U.S. electricity needs (~ 1500 W/person – remember that ~1/3 of U.S. primary energy goes to generating electricity and that generation is about 40% efficient). Print out the NREL 80 m wind map at the site below and mark the land you intend to appropriate to install wind farms. (Assume you have unlimited powers to command new transmission to be built as well, so you can simply appropriate the best wind areas if needed. If you choose areas with better wind than 8 m/s, scale your required area at least roughly (remembering that you scale as the cube of wind speed).

E. Now repeat your exercise of C to meet ALL the U.S energy needs (if we electrify cars etc.) You can assume for the time being that these stay at 10,000 W/person, or estimate a lower value for total primary energy use now that you're avoiding wasteful heat engines. NREL map: http://www.nrel.gov/gis/images/80m_wind/awstwspd80onoffbigC3-3dpi600.jpg

For extra credit, repeat assuming bigger turbines at 100 m height: http://www.nrel.gov/gis/wind.html

Problem 2: Can solar power the world?

Background
So far you've been having a lot of trouble finding some natural flow of energy that can power the world renewably. We determined at the very beginning of class that the ultimate source of energy for a renewable world had to be the sun. But the conversion efficiency of plants is low, and growing plants requires taking up the fertile land that we're currently growing food on. The energy densities of wind and hydro are also quite low, because both represent kinetic energy produced by the atmosphere as a heat engine powered by solar radiation – and you know that heat engines are not efficient unless they involve large temperature gradients. It might occur to you at this point that you should give up on all natural conversions of solar energy and try to use solar radiation more efficiently through some human-made technology.

Two potential technologies for conversion of solar radiation energy to usable forms that might meet be able to power the world are ***solar photovoltaics*** and ***solar thermal***.

Solar photovoltaic panels are semiconductors that use the photoelectric effect to convert solar radiation directly to electricity. The average efficiency of conversion for commercial panels sold today is 12-18%. Furthermore, you can put them places where the solar radiation is higher than world (200 W/m2) or U.S. average. The panels do have a nonlinear response to being partially shaded, however – shade from a passing cloud on even a small part of the panel can cut power dramatically. Even if you put your panels in the desert, you probably should apply a capacity factor of ~ 0.8 to account for partial shading reductions in power. But, you get that 20% right back if you install more expensive tracking solar panels that rotate with the sun to maximize the amount of solar energy they catch. These facilities take up a bit more land – the panels have to be spaced a bit further - but are generally considered the most cost-effective.

18 MW tracking solar PV installation at Five Points, CA. *Image: Blue Oak Energy*

Solar thermal plants are less high-tech and consist of no elements that would be unfamiliar to a 19th century engineer (and nothing incomprehensible to an 18th century engineer). The basically involve using sunlight to power a heat engine, but a more efficient heat engine than the atmosphere is. Mirrors are used to capture incoming solar radiation (very efficiently, perhaps 90%) and direct it onto a tube of some substance (usually oil, sometimes molten salt) to heat it. The hot fluid is circulated in turn to heat water and make steam, which then runs a perfectly ordinary steam turbine that spins a generator just as in any other fossil-fuel-powered power plant. Think of a nuclear plant, only instead of a reactor core providing the heat, your reactor is the sun and you are concentrating sunlight from mirrors to produce heat. Again, these plants can be placed in sunny locations. Unlike solar PV there is no nonlinear partial shading response.

Parabolic trench collectors, solar thermal installation near Barstow, CA, built in 1984. Operated by NextEra Energy. *Image copyright unknown.*

Most solar thermal plants no longer use the trough system (above) Instead, they use a "power tower" system where multiple mirrors focus solar radiation on the top of a tower and heat a boiler there. By concentrating more solar power on one small location they obtain higher temperatures and so higher efficiencies. The towers and tracking systems are obviously more expensive than troughs, though, so there's a financial tradeoff – the extra power generated has to be worth it.

PS20 power tower, Seveille, Spain, 1255 mirrors, power up to 20 MW. Operational 2013. *Image: SWNS.com.*

Problems

A. To start the problem off, restate your target energy conversion efficiency to power the world, that you've derived at the beginning of class. **State your target both as a fractional conversion of average sunlight.** Does solar PV seem plausible?

B. Rescale the solar PV efficiency to account for the fact that panels have to have some physical spacing – you need extra land from which you can't generate power. **What fraction of the sunlight *falling on the whole PV facility* is turned to electricity?** You can look at the image for a PV facility here in the "Background" section. Try to visualize the panels rotated flat to the ground, and then estimate how much extra space the facility needs beyond the areas of the panels.

C. Now, decide you are the Energy Czar of the U.S. with unlimited powers of eminent domain to seize land for energy production. Pick a general region for installing large-scale solar plants based on the NREL U.S. map of annual mean solar insolation: http://www.nrel.gov/gis/images/map_pv_us_annual10km_dec2008.jpg. You want to pick locations that are sunny, cloud-free, flat, and cheap. The map uses irritating areal energy density units of kWh/m2/day rather than W/m2 so you have to convert units. **State the (estimated) average W/m2 of solar insolation in the region you are considering appropriating.**

D. Given the effective efficiency of your PV facility, **what is the W/m^2 you can generate from your choice of solar technology in that location?** (You can pick solar thermal if you do the optional problem I)**.**

E. Does a solar PV facility in this region meet your target energy goal of A?

F. Now, appropriate as much land as you need to set up your energy system of choice. **Print out the NREL map and block out on it the land you would have to seize to fill all current U.S. electricity needs with your favorite solar technology.** (You can use solar thermal if you estimate its efficiency in the optional problems below).

G. As above, get ambitious and assume that you will get rid of fossil fuels entirely – you'll electrify cars etc. **Appropriate enough land to meet all of US *energy* needs, and mark your appropriation on a new printout of the map.** For the purpose of this problem, you can assume 10,000 W/m2 or reduce that number (explain your reasoning) to account for the fact that you would be avoiding inefficient heat engines for some uses. Whatever you do, it's best to make the same assumptions you did in the wind version of this problem so you can compare the maps.

Problem 3: Are internal combustion engines really the optimal choice?

Read the posted readings about steam-based alternatives to the internal combustion engine, and improvements in the internal combustion engine. Right now is a time of booming innovation in engines, reconsidering century-old designs. Comment on

- What are the advantages of steam for automobiles?
- How are modern developments mitigating the disadvantages of steam?
- What are some of the proposed modifications of the ICE to increase efficiency?

Problem 4: Automobile history virtual tour

Take a virtual tour through the early history of the automobile in the U.S. here:

http://earlyamericanautomobiles.com/1900.htm

(Be warned, the site is buggy and has lots of broken links, but the later chapters generally describe later automobiles).

Pick two different time periods and read the relevant pages, and describe some features of the auto's evolution. Consider factors such as: how do you steer, where is the engine, how are the wheels suspended, etc. Note the different technologies represented in different periods (not only internal combustion engines but external-combustion steam and electric).

Note also the larger diversity in the early years (both of technologies and also of companies). The early years are full of relatively short-lived companies you've never heard of.

1900 Haynes-Apperon advertisement
(said to be wildy overstated)