GEOS 24705 / ENST 24705
Problem Set #15
Due: Tues. May 22

Problem 1: Wind farms / Kelly Creek

A. Watch the posted wind videos on the website under lecture 14 and comment on something interesting in each one

B. Read the wind section of the Hayes book chapter on power plants (linked to on website under Lecture 10), and discuss something interesting from it. Do note that the Hayes book is from 2005 and wind turbines have changed since then. When Hayes wrote, all wind turbines were the old-style fixed-speed, synchronized turbines I mentioned on PS 14. According to the Kelly Creek FERC filing, their turbines are new-style variable-speed turbines that rotate non-synchronously from the grid and then use power electronics to link their power.

C. Plot the location of Kelly Creek on the map of Illinois wind resources: https://windexchange.energy.gov/maps-data/37 What is the mean wind speed at 80 m hub height? (You can get the lat / lon for Kelly Creek from the site below. Note how precisely lat and lon are specified - location matters for wind!)

D. Read the summary of Kelly Creek here: https://www.thewindpower.net/windfarm_en_24112_kelly-creek.php These are pretty typical wind turbines for new installations, 2 MW with a 100 m rotors. This is the turbine whose brochure is linked on the website under Lecture 14, you can see details about the generators here: http://nozebra.ipapercms.dk/Vestas/Communication/Productbrochure/2MWbrochure/2MWProductBrochure/?page=10. I don't see a good power curve in the brochure, or even the rated wind speed. You can find both if you click on "Vestas 100/2000" on the windpower.net site and scroll to the bottom. Check for rationality: what should the power be at the ***rated*** wind speed? Check on the power curve (hover over it to see values) and confirm: what IS the power at the rated wind speed?

E. ***(Optional)*** You don't know the hub height (something to ask the tour guide), but you can guess it would be above 80 m since that is listed as the absolute minimum for these turbines. So the wind at hub height will probably be a bit higher than your answer above. If you want, you can adjust your wind speed estimate with this Danish Wind Industry Association calculator: http://xn--drmstrre-64ad.dk/wp content/wind/miller/windpower%20web/en/tour/wres/calculat.htm.

F. Then answer: if the wind were blowing at its mean speed at all times, what would the capacity factor of this turbine be on the Kelly Creek site? You may want to ask the tour guide what their capacity factor actually is.

G. ***(Optional)*** The real wind distribution is probably more like a Weibull distribution: http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/weibull.htm. Given this shape, would the true capacity factor be more or less than the value if the wind blew at its mean value all the time, if you didn't need to worry about the cut-out speed? Discuss.

H. ***(Optional)*** There is lots of great information on the Danish Wind Industry Association site, though be warned that it is very old (last updated 2003). Read and discuss something interesting for extra credit.

Problem 2: Can wind power the U.S.?

In PS 14 you estimated the areal energy density of wind, and compared it to our metrics for powering the world. We estimated the requirement for a technology to power the world as a 5% conversion efficiency of that sunlight (10 W/m^2). You probably found that the onshore wind alone likely could not power the world given your assumptions of a rise in wealth and population. The U.S. is already rich and has among the world's highest per capita energy usage. But renewables resources are not equally distributed, and we shouldn't rule out wind without taking a look at the specifics of the situation. In this problem you'll use the wind map from Problem 1 to determine whether the U.S. could operate either just its electric sector, or the whole economy, from wind power alone. Since population growth is fairly small in the U.S., you'll just consider current energy needs rather than planning for the future.

You should imagine yourself appointed the appointed the energy czar of the United States, with absolute powers to appropriate land as needed for the public good. You'll evaluate what land you would have to seize to use wind to fill U.S. current electricity needs, and the what you'd need to meet ALL of U.S. energy needs, eliminating fossil fuels entirely.

A. First, determine the per capita electrical power needs (in W/person), and then multiply by the current U.S. population to get a total in W. The Sankey diagram can give you electricity usage:. The 2017 energy chart is here: https://flowcharts.llnl.gov/content/assets/images/energy/us/Energy_US_2017.png (Note that 1 Quad /year is ~33 GW). Check your numbers by converting to a per capita number and remember that electricity counts for only 1/3 of U.S. primary energy goes to generating electricity and that generation is about 40% efficient).

B. Next determine the total power needed if you electrified the economy and powered it by wind. Here you can't just plug in 10,000 W/person, since if you use windpower you'd avoid the energy losses of heat engines as waste heat. (Your wind areal energy density already accounted for the energy losses of wind turbines as uncaptured kinetic energy.) So your electricity sector needs are now just the output electricity. For transportation you can use the efficiency of electric motors (see the Smil table from a previous problem set) rather than the 20-25% efficiency of internal combustion engines used for transportion. Replacing gas heating of residential and commercial buildings with electrically powered heat pumps would also require a bit less energy, since as you saw in prior problem sets the COP of heat pumps is > 1. (That is, they pump more heat than the electricity required to drive them.) State your assumptions clearly. Then, as in B, state your resulting energy needs as both W/person and W for the entire U.S.A.

C. Now seize the land you'll need to generate the power in the case of A. Print out the NREL 100 m wind map (https://www.nrel.gov/gis/wind.html) and mark the land you intend to appropriate to install wind farms. You are only allowed onshore sites, since as discussed in the slides, there are few good offshore wind sites that have both strong winds and shallow waters. You can however assume you have unlimited powers to command new transmission to be built as well, so go ahead and appropriate the best wind areas. As you saw at Kelly Creek, wind and agriculture can co-exist, so you need not worry about loss of farmland. If your chosen areas have significantly better wind than you assumed in PS 14 above, scale your assumed areal energy density at least roughly, remembering that output power scales as the cube of wind speed. Explain your assumptions clearly, and discuss the results.

D. Now repeat your land-seizure plans only now to meet ALL the U.S energy needs as you calculated in B. Can wind power the U.S. economy? Discuss.

E. *(Optional).* Draw the additional transmission lines you'd need on your maps of appropriate land, and estimate how much power has to be moved by new transmission lines, and of what length. This lets you estimate the cost of new transmission. The rule of thumb for transmission costs is $500-700/(MW*km).

Problem 3: Can solar power the U.S.?

Background

You might find in Problem 2 that using windpower involves appropriating an uncomfortable fraction of the U.S. land surface, but was do-able with that sacrifice. Earlier, we found that using hydro alone was simply not feasible. But note that both these technologies necessarily have low areal energy density: hydro and wind both capture kinetic energy produced by atmospheric heating, i.e. by the atmosphere operating as a heat engine. And you know that heat engines are not efficient unless they involve large temperature gradients. So those natural conversions of solar energy were always going to be fairly inefficient. Plant, for biological reasons, also seemed fairly inefficient (and then they'd produce fuel that had to be burnt in a heat engine, incurring still further losses). We can however convert sunlight to electricity more efficiently with human-made technology.

Two potential technologies for conversion of solar radiation energy that could power the world are ***solar photovoltaics*** and ***solar thermal*** (also called "concentrating solar power" or CSP).

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 the world or U.S. average. The panels have typically had a nonlinear response to being partially shaded – shade from a passing cloud on even a small part of the panel can cut power dramatically – but if you site them in the desert that is not a problem. (And recent changes in how they are wired reduces the partial-shading problem). You can boost your capacity factor by an extra 20% or so (multiply it by 1.2) 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 for utility-scale solar.

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. They involve concentrating sunlight to power a heat engine. Mirrors 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 to very high temperatures (usually ~ 600 C). The hot fluid is circulated to make steam and run a perfectly ordinary steam turbine (or in some cases to power a Stirling cycle engine); the turbine or engine then spins a generator just as in any other fossil-fuel-powered power plant. The high temperature means that you get the normal efficiency of industrial heat engines (~30%), rather than the low efficiency of the atmospheric heat engine: concentrating mirrors overcome the low areal energy density of renewables. The chief advantage of CSP that it is easy to store heat, unlike electricity, so a CSP plant can generate power at all times, whether or not the sun is shining.

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

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

Early solar thermal plants used the trough system (top), but most recent ones use a “power tower” system (bottom) 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, so there’s a financial tradeoff, but the extra power generated seems to be worth it.

Problems

A. 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.

B. Now, in your role as Energy Czar of the U.S. with unlimited powers of eminent domain, seize the necessary land for energy production. Pick a general region for installing large-scale solar plants based on the NREL map of annual mean solar insolation. The NREL site is buggy and I don't like their latest maps, but this older one is OK: https://commons.wikimedia.org/wiki/File:NREL_USA_PV_map_lo-res_2008.jpg You want to pick locations that are sunny, cloud-free, flat, and cheap. The map uses irritating areal energy density units of kWh/m^2/day rather than W/m^2 so you have to convert units. **State the (estimated) average W/m^2 of solar insolation in the region you are considering appropriating.**

C. Given the effective efficiency of your PV facility, **what is the W_{elect}/m^2 you can generate from your choice of solar technology in that location?** Discuss.

D. *(Optional)* Repeat C for solar thermal. Estimate the effective efficiency of solar thermal at producing electricity from the information above and from the photographs shown, and then compute the resulting areal energy density (i.e. W_{elect}/m^2),How does it compare to solar PV?

E. Appropriate as much land as you need to set up an energy system capable of meeting current U.S. electricity needs. **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.**

F. Repeat the above but now, as you did for windpower, for the case where you get rid of fossil fuels entirely and use solar to meet all U.S. energy needs. **Mark your appropriation on a new printout of the map.**

G. Compare to your wind maps and discuss.

Problem 4 – Hydro virtual tour

We won't spend a lot of time talking about hydro, and you've seen that it cannot power a wealthy, energy-hungry world. But hydro is still important to understand for several reasons. First, for developing countries, it is often the first electricity generation that they have, and for the very poor it may be the dominant electricity generation. A dam hydro project is a big engineering task, but once built (often with foreign engineers) it lasts for a very long time, produces cheap power, and takes very little maintenance. Hydro requires no elaborate infrastructure or supply chains to support it – the fuel arrives naturally, and the turbines and generators are extremely simple and durable. The second reason to care about hydro is that it can be an excellent resource for smoothing out demand spikes: for a dam, letting more water out through the turbines is effectively instant. In some cases "pumped hydro" can be used to smooth out both supply and demand: at night, when demand is low (in places other than CA or HI) and electricity is cheap, water is pumped uphill, and during the day, when demand peaks and electricity prices are high, water is let out of the reservoir to produce electricity.

A. Watch this video of the differences between the three turbine types (in order, Pelton, Francis, Kaplan). Comment on their differences and discuss.
   http://www.youtube.com/watch?v=HzQPNpP55xQ

B. Watch this video of the Three Gorges Dam hydro project. Comment on something interesting you observe. Which turbine type is being used? Is that a reasonable choice? http://www.youtube.com/watch?v=tjTh7A4jnbc

C. ***(Optional)*** Watch footage of Three Gorges while it was being built here: https://www.youtube.com/watch?v=b8cCsUBYSkw . The video includes shots inside the power houses, & discussion of issues involving building & operating a dam. The narration is a bit pretentious and the repetition of "the Chinese" is a bit unsettling but the video is good. Watch continuously to about 5:30 and then skip around. At 8:30-9:30 they blow up the cofferdams. 11:00-12:00 is grouting the river bed,~14:00 dealing with floodwater, ~14:45 ship locks, ~ 20:00 silt. Discuss what 's most interesting or surprising to you.

D. ***(Optional)*** A dam is only as strong as its foundation. If you need to grout your dam and don't, calamity happens. Read the recent NY article describing the danger of the Mosul dam in Iraq since maintenance stopped after capture by ISIS. Discuss for extra credit. http://www.nytimes.com/2016/01/11/world/middleeast/neglect-may-do-what-isis-didnt-breach-iraqi-dam.html