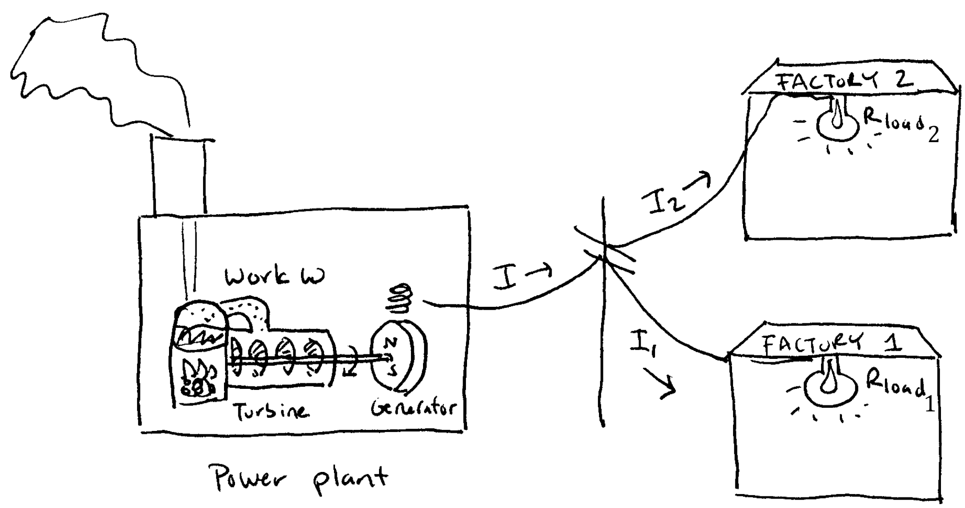
GEOS 24705 / ENST 24705
Problem set #10
Due: Tues. May 3

Problem 1: Stability of power generation.
In this problem you are the facility manager of a power plant that provides power to two factories only. You'll try to maintain the quality of your output power as the demand for electricity changes. You have to maintain your voltage near 120 V and your frequency at 60 Hz or lose your job.

You have a single 2-pole synchronous turbo-generator, as in the pictures below. (That means your turbo-generator is supposed to be running at 3600 rpm). It's properly designed so that at this operation it generates alternating voltage at 120 V. *(In this problem, we'll ignore voltage transformation – assume you're producing at 120V. This means that the currents that are flowing might feel unrealistically high at the generator itself, but that really is how much current is eventually distributed to homes and factories).*



Both components of your system have limits. The turbine can put out a maximum of 60 MW of work (beyond that it just can't go; no matter how fast you dump coal into your firebox – you can't get steam pressures any higher). The generator will obediently source as much current as you ask for, but the manufacturer says that it will overheat dangerously if you try to generate more than 50 MW of power, because of resistive heating if currents get too large. Being lazy, you've installed no protective systems – you assume you can manage all operations by hand.

At time 0, your power plant is running comfortably. Only Factory 1 is "asking" for power, and it is demanding 20 MW, driving a resistive load. In the drawing above, Factory 2 has at this time not plugged in their equipment so no current I_2 is flowing.

A. What is the current the generator is putting out? What must the resistance of the Factory 1's load be? (Check your units to make sure your answer is correct).

A short time later, the second, identical factory starts up with the same power demand. (So $R_{load2} = R_{load1}$. From this point on in the problem, in this problem the two factories will always have identical loads).

B. Just from immediate common sense, how much current will now "want" to flow to the second factory?

C. Again, from immediate common sense, how much total power are you now trying to put out?

D. What must the effective resistance of the two-factory system be? Does more demand mean higher or lower effective resistance?

Due to a rapid growth in the U.S. economy, both factories simultaneously ramp up production and suddenly "ask" for more power. The extra equipment plugged in means that there are effectively more places for the current to flow, so that total resistance becomes 2/3 of its former value.

E. What is the total power they are demanding now? Can your turbine provide it? What happens to your generator? (Hint: rather than calculating numbers out, try to just scale from the previous situation).

Somehow you've managed to hold on to your job, the insurance covers everything, and you've used the insurance settlement to purchase a new generator to cope with the increased demand – this one can handle 100 MW of power. You think you're fine.

The economy continues growing, and one day both factories again simultaneously step up production and drop their effective resistance now to ½ their original values from D.

F. If you could hold your voltage to 120 V, what would your power output be? Can your turbine supply enough power to meet that demand?

What happens now? Your turbine can only do what it can do. Assume you've desperately increased the steam pressure until the turbine is putting out as much power as it can.

G. What voltage must your generator be running at?

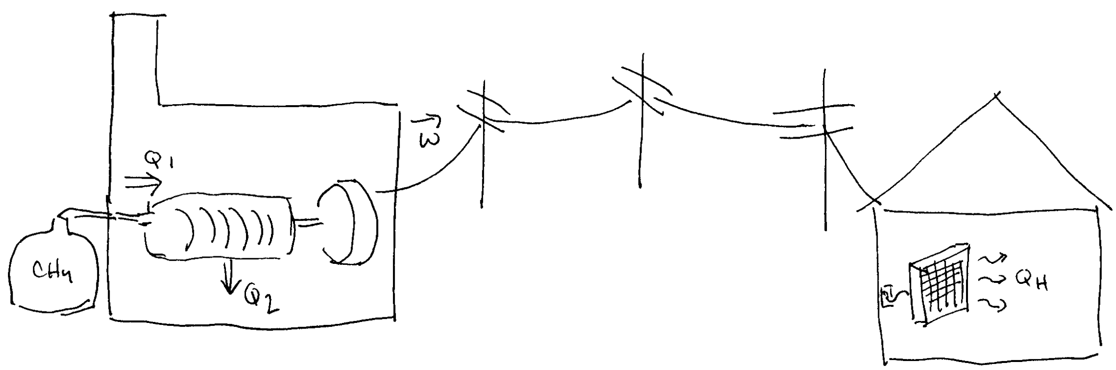
H. What speed is the rotor turning?

I. What frequency are you putting out?

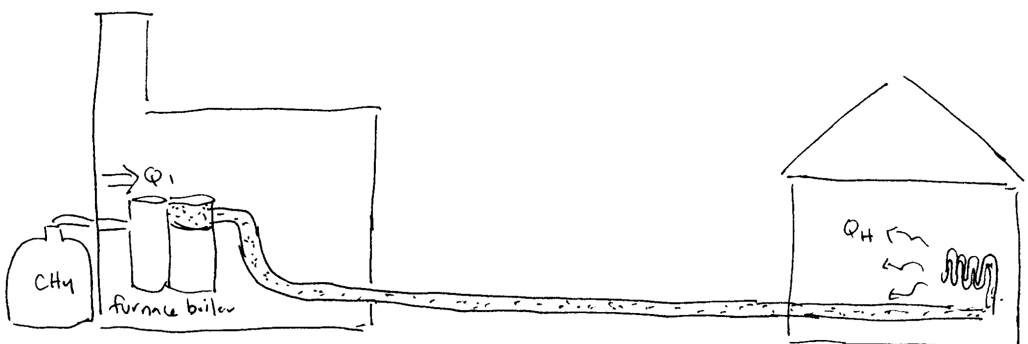
J. Do you keep your job now?

Problem 2. Cogeneration / Design your own power plant
Background

In previous problem sets we've explored the tradeoffs between heating with electrical resistance heating (as in a space heater) vs. heating by burning fuel in a furnace (and transferring that heat to some fluid that circulates around the building you're trying to heat, hot air for natural gas heating or steam for a radiator system). Hopefully everyone convinced themselves that it is needlessly inefficient to burn fuel to make electricity with a wasteful heat engine and then convert electricity back to heat (figure below) than it would have been to just stop at the burning stage and use the heat directly (figure below).



Why bother making electricity, which incurs a necessary penalty of over 60% loss of energy, when all you wanted was heat in the first place?



But what if you wanted both electricity AND heat? Then the question might become, why should you burn fuel in a furnace to make heat, but then buy electricity made with a heat engine that is throwing away exactly the same kind of heat? What counts as waste is a little subjective here. Given a little investment in a turbogenerator, you could make both your heat AND your electricity with no waste at all: *cogeneration* (see figure below). Your "total system efficiency" can now higher than Carnot efficiency, because the waste heat isn't waste anymore: you want both W and Q_2.

The reason you might buy electricity and still have a furnace is of course, as we discussed before, that electricity is easy to transport but heat isn't. If you want to use a big and efficient power plant, it'll be sited too far from its customers to send them its waste heat as well. And if you want to make electricity on-site and use the waste heat, you'll be stuck with a smaller, less-efficient turbine or engine. (Plus, given the public dislike of coal-burning in urban environments, you'll also be stuck buying expensive natural gas for fuel). This is the cogeneration dilemma. Sometimes cogeneration, with its requirement of being small and local, makes financial sense, and sometimes it doesn't.

Universities and even smaller schools seem to be great candidates for cogen, since they're multi-building facilities that use a lot of both steam heat and electricity. They're big enough energy users that buying a turbogenerator isn't ridiculous, and they usually own enough land to install the system in some quiet corner. Many schools near U. Chicago do in fact operate cogen plants: the Illinois Institute of Technology, the University of Illinois at Urbana-Champaign, Northeastern Illinois University (Chicago), Illinois Central College (Peoria), Northwestern University (Evanston), Lewis University (Romeoville)… as well as a bunch of smaller colleges, including College of DuPage (Glen Ellyn), Triton College (River Grove), Joliet Junior College, Elgin Community College, Sauk Valley Community College (Dixon), Highland Community College (Freeport)… not to mention at least 18 high schools and even middle schools. Evanston High School alone generates 2.4 MW of electrical power! But the University of Chicago makes no electricity.

Is this sensible? In this problem set you'll use actual U. of Chicago energy data to consider the economics of cogeneration. You'll design and price out a system for the university and evaluate its revenue stream vs. cost, and make a recommendation to the university. If you're comfortable with spreadsheets or computer programs, you might want to use a spreadsheet or program for this problem, but it's not necessary. If you do use either, attach a printout.

Data

Thanks to Bill Hines, former Energy Manager, U. Chicago, for some of these numbers. These are 2009 numbers, and are estimates only.

General

The U. of C. currently has around 4000 undergrads, 8000 grad students, and 15,000 employees (including faculty and hospital staff).

Gas and heating

The U. of C. steam plants heat effectively all buildings on campus, burning natural gas to make steam and circulating that steam throughout campus.

The plant burns 2.3 million mmBTU of natural gas per year. (The BTU is a "British thermal unit", a unit of energy).

Natural gas energy content is usually given as ~ 1020 BTU per cubic foot, with the volume of gas given at normal atmospheric pressure and temperature.

Facilities' cost for natural gas prices works out to ~ $9/mmBTU. (mmBTU = million BTUs) when you include the profit from People's Gas and overhead of the university.

Natural gas-fired boilers can be 98% efficient.

Gas turbines are about 40% efficient at converting heat to work. For a cogen system, assume another ~10% is un-retrievable loss to inefficiency in the heat exchanger, friction in bearings etc.. The remainder goes into steam heat.

Steam transmission in pipes involves some losses, especially in the case of U. Chicago since the steam travels in tunnels for blocks through Hyde Park to get to all the buildings on campus. But for this problem, we can ignore the losses, because we're not considering abandoning steam heating – the amount of steam that the university needs is what it is, inclusive of losses.

Electricity

The U of Chicago purchased 325 million kWh of electricity last year.

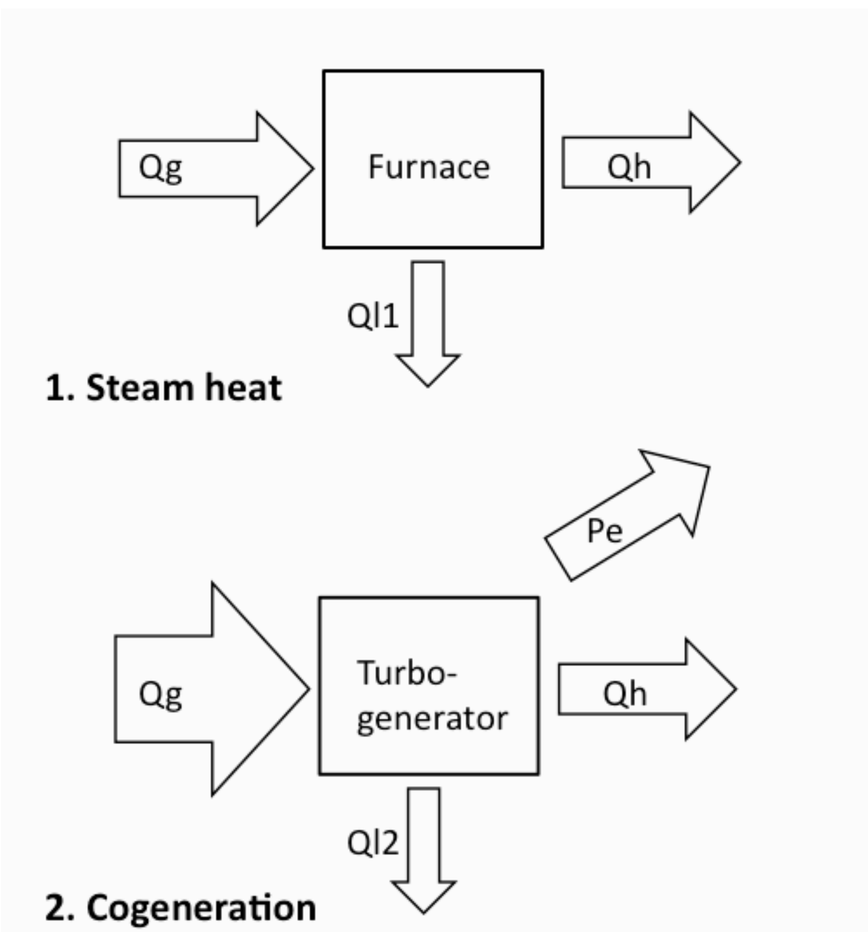
The U. of C. purchases power from ComEd as a large user, in long-term contracts at negotiated prices. Currently we are locked into a contract for 9 cents/kWh (fully "loaded" with overhead for the university, ComEd, and PJM, the grid operator). That's higher than the 2010 average commercial customer rate (7.5 cents/kWh in Jan 2010) and only a hair below 2010 average retail rates (9.85 cents/kWh), because the contract was signed before the financial crisis caused rates to fall, but rates have been rising in 2011 (to 10.41 cents/kWh average retail rate) and so our deal is looking wiser now. *(Source for price comparison: U.S. Energy Information Administration)*

Cogen Design

In this problem you'll figure out whether investing in cogen is a good choice for the University of Chicago. As of last year, the university hadn't done a real study of the economics of cogen, so you can't be sure they are making wise decisions now.

You can (at minimum) work through this problem on paper given your baseline assmptions and come up with a yes (good decision) or no (bad decision) answer. Alternatively, or extra credit, you can do the calculation with a spreadsheet or program and then later test the effects of different assumptions (including fuel price) and discuss under what conditions cogen would or wouldn't be sensible.

The way to approach this problem is to work backwards from the end-user demand to the generation system that can meet that demand. The ordering of the questions walks you through this process, but it is also very helpful to make a flow diagram as you work backwards, tracing the energy flows back to the generation system and including an arrow for the wasting of some fraction of that flow every time you hit an inefficient conversion. Part of the problems below is to fill out these diagrams. You can use the templates given here or make your own.



Energy flows *(in W, or J over some time period)*

Qg = gas heat /time used

Qh = heat flow to university

Ql1 = losses in furnace

Ql2 = irrecoverable losses in turbogenerator

Pe = electricity produced

Before you can design a new system, you need to figure out how much heating power you need to deliver to campus buildings (Qh). You'll let that heating need drive your design of a new system (at least, the first try at a design). Certainly you shouldn't make more waste heat than this ….there's no point in generating expensive electrical power whose waste heat you'd throw away.

Then, you can start on cogen design, making sure that steam power Qh delivered to the buildings is the same in the new system. Start on the use side, the right hand side, and work your way upstream to the generator. When you're done, you should have made a map of energy flows throughout the system. Because energy is conserved, the total of your output power flows should equal the initial power Qg of fuel burning.

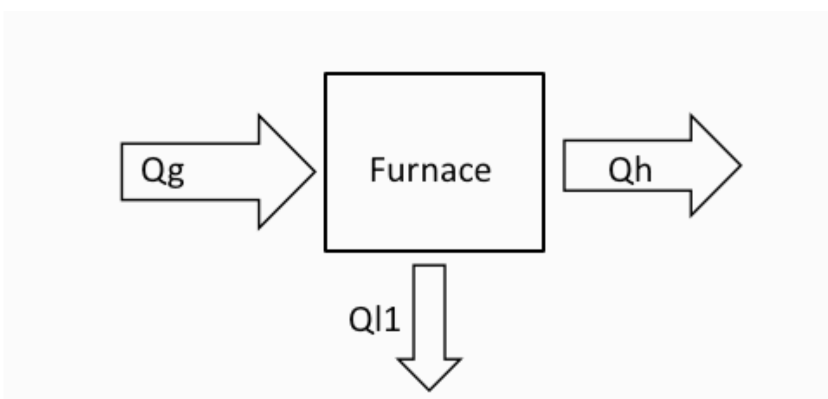
Finally, you'll see if that design saves you money or costs you more.

Some of the questions below are for context or for fun, but the overall order is designed to lead you through the design problem.

In the problem here, you can assume that you run your cogen plant during the winter only, and in the summer when you don't need heat, you shut down and just buy electricity from ComEd instead of making your own. In reality, there are still some steam needs in the summer, especially for the medical center, about ¼ of the winter load. Optional points people should feel free to play with more realistic assumptions.

Thermal side, current system

The power flow diagram for the current system when it is in use. As you go through the problems below, write down all the powers). Q_{L1} is irretrievable losses in the natural gas furnace and Q_{L2} is transmission losses as steam is moved to campus. (See also data section).



1. For context: what volume of gas does U. Chicago purchase and burn every year? (in cubic feet, cubic meters, any other intuitive volume units). We get this gas from a pipeline owned by People's Gas.

2. What is the U. of C.'s current power usage for heating, in W, averaged over the whole year?

3. During the winter alone? (since we don't heat in summer)

4. What is this wintertime heating power use per U. of C. student or employee?

5. What is the annual cost of the natural gas the U. of C. buys?

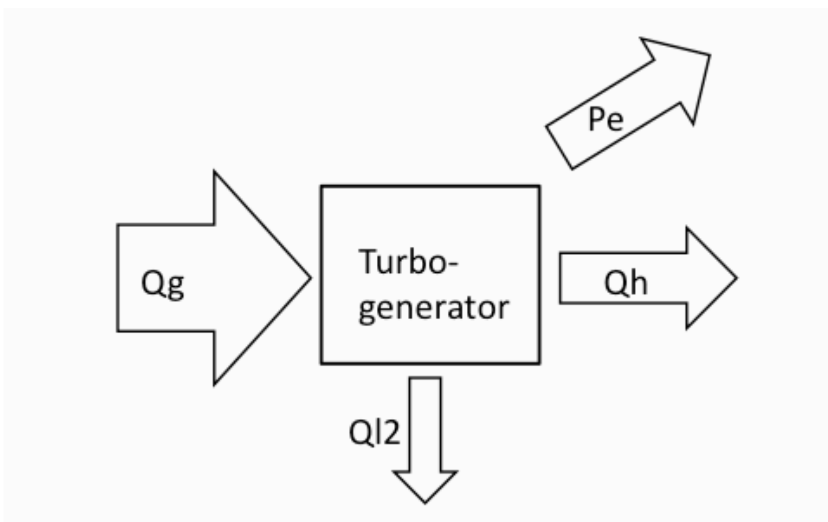
6. What is the total annual cost of running the steam plant, if operations and maintenance add 10% to the fuel cost?

7. What is the total cost of heating per U. of C. student or employee? As a reality check, compare to your own heating bill, if you get one. (Divide by the number of people in your household to get a per capita number)

8. Convert units: what is the heating cost in units of cents/kWh, for comparison with electricity prices? Is it financially smarter for the university to heat with steam or with electrical resistance heaters (space heaters)?

9. *Optional:* How big would the transmission losses in the steam pipes have to be before it made $ sense for the university to heat with space heaters, given their current electricity prices?

Thermal side, cogen system



10. Work backwards through the diagram above, filling in all numbers from the information you have or have just estimated.

11. What is the annual fuel cost for this plant? (Remember, the plant diagrammed above is going to run only half the year).

12. Take your answer above and add 20% to the fuel cost for operations and maintenance to get the total operational cost. What is that?

13. How much will it cost to purchase and install an appropriate turbine and generator? (or multiple units). Shop for a turbo-generator online (more tips below), describe your chosen system, justify why it's appropriate for the U. of C., and state its cost (or inferred cost – if you can't find a turbo-generator of exactly the right size, use ones to you find to infer a price for the size you want. Provide a reference (e.g. weblink) for your source of information. Some useful sites are listed below but you can shop widely.

http://www.powerplantsonline.com/steamturbinegenerator.cfm

http://www.cogeneration.net/Cogeneration.htm

http://www.generatorsforsale.ca

http://www.ch-non-food.com/powerpl1.html

Make sure you are buying a 60 Hz AC generator and a gas turbine: no steam (we can't burn coal in Hyde Park) and no reciprocating engines (inefficient). Don't buy something that is broken or flunked its emissions tests. If your system is already designed for cogen, add 10% to the cost for installation. If it's not designed for cogen, add 20% for installation and modification.

Electrical side

14. What is the electrical power usage per U. of C. student or employee (in W)?

15. What is the annual cost spent on electricity per U. of C. student or employee?

16. What is the total annual cost of electricity spent by the U. of C. in the current system?

17. If you built the cogen system, would you need to buy any power from ComEd during the winter?

18. When you decided on the specifications for your generator, did you make an error in not considering the different electrical power usage during nighttime and daytime? (Daytime is probably higher than nighttime)?

19. Compute how much power the university must purchase or can sell back to ComEd during winter.

20. Compute the price you'd get (or have to pay) for that wintertime power.

    The ComEd rate book is available for download at https://www.comed.com/sites/customerservice/Pages/rateinformation.aspx Click on "ComEd's Entire Schedule of Rates for Electric Service". Bill Hines says *"For the cogeneration questions, I…draw your attention to Rider POG ["Original sheet #288"]. As you will see with the options provided, one can sell all the power to the grid and then have ComEd charge you the retail rate or you can sell the net off to the grid. See [3rd page of rider] for the rates that ComEd will compensate you for sales."*

    The point of using this rather than my giving you a number is so you'll see firsthand how complicated the deregulated electricity system is.

21. Now add in your summertime power purchases and compute the annual revenue brought in by (-$) or cost for (+$) electricity with your cogen plant.

    For the purposes of this problem, you can decide that you're a POG in the winter but that in summer you have to buy power at the rate you already contracted with ComEd. (I believe we actually agreed to buy a big chunk of energy at the rate, so we have to keep buying Joules at 9 cents/kWh til we've worked our way through the contract and are free again).

Economics

22. Compute the annual savings or cost to the U. of C. of the cogen system over the current system. That's (electricity cost before + fuel cost before) – (electricity cost now + fuel costs now).

23. If the cogen system is profitable, how many years will it take for the purchase of the cogen plant to pay off? If you're not an econ or business student, you can underestimate and just consider how many years of savings add up to the purchase cost, or fudge it and assume that the interest you pay on your loan would roughly double the effective cost. Econ and business school students make more realistic assumptions about the cost of capital and state them.

24. Would you recommend that the university build a cogen plant under these assumptions? (Ignoring for now the practical difficulties, and the fact that the university just built a ~$100M steam plant that is not set up for cogen).

OPTIONAL. But recommended

25. It's possible to use waste heat steam to drive chilled water production via centrifugal machines, giving you a reason to be running a cogen plant all year round. If the university did this (assume for the moment that chilled water costs at present are about the same as heating costs), now how much is the annual savings from or cost of using cogen? And if there are savings, how long for you to recoup the investment?

26. You designed the cogen system to meet heating demand, not electricity demand. What would the economics look like if you met electricity demand instead? (So you make only enough electrical power for your own needs, and buy extra natural gas for heating if that doesn't provide enough heat).

OPTIONAL. Explore parameter space, including any of the questions below

27. What price would natural gas have to be to change your judgment on cogen?

28. Explore the implications of different electricity prices.

29. What if you could sell at hour-by-hour prices rather than a fixed rate, and run your turbine more during peak energy use hours? Do some Googling and estimate what the cost implications might be. There are many proposals to allow hourly pricing on the retail purchase side, and that presumably would be extended to small generators too.