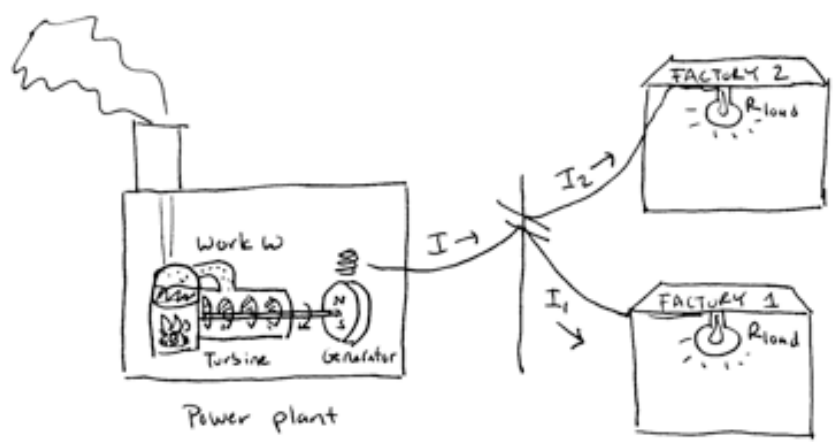
GEOS 24705 / ENST 24705
Problem set #12
Due: Tuesday May 12

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 coal-fired steam turbine and a single 2-pole synchronous generator, as in the pictures below. That means your turbo-generator is supposed to be running at 60 Hz, i.e. 3600 revolutions per minute (rpm). It's properly designed so that at this rotation rate it generates alternating voltage at 120 V for its customers.

(You can either assume you're producing at 120V, or assume that you're implicitly including a couple of transformers in your system without needing to bother to bookkeep them.)



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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 from resistive heating if you try to generate more than 50 MW of power, because the currents get too large. You haven't bothered to install any automatic shutdown mechanism, so you have to control everything 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. Factory #2 has not plugged in their equipment at this time, so no current is flowing. (In the drawing above, I_2 = 0.)

A. **How much current is the generator is putting out? What is the resistance of the Factory 1's load?** (in Ohms, and check your units).

A short time later, Factory #2 switches on with an identical load. ($R_{load2} = R_{load1}$. From this point on in the problem, the two factories will have the same loads).

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

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

D. What is the effective resistance of the two-factory system?

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. If you could hold your voltage to 120 V, what would your total power output be? What happens? (Describe in words.) (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 that can handle 100 MW of power. But, 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 in D.

F. If you could hold your voltage to 120 V, what would your total power output be? What happens? (Describe in words.)

G. What voltage is the generator running at?

H. What speed is the rotor turning?

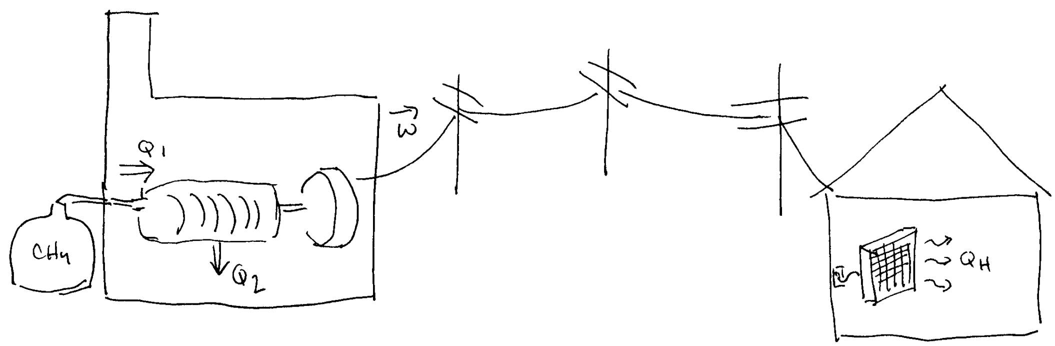
I. What frequency are you putting out?

J. Do you keep your job now?

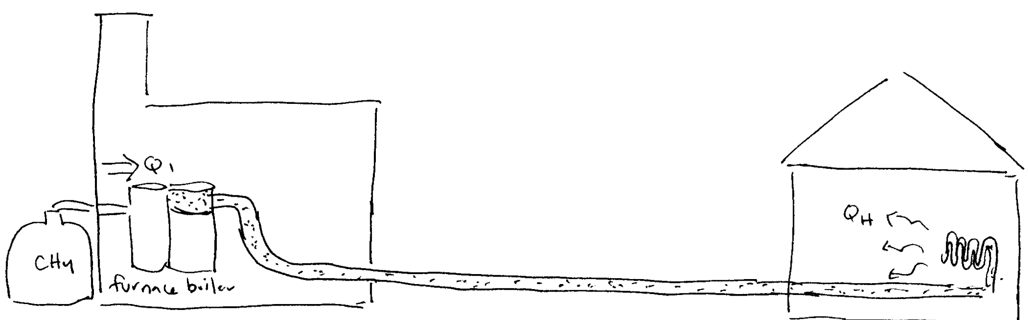
Problem 2. Cogeneration / Design your own power plant

Background

In previous problem sets we've explored the tradeoffs between heating with electrical resistance (as in a space heater) vs. by burning fuel in a furnace. Hopefully everyone convinced themselves that it is needlessly inefficient to burn fuel, make electricity, and then convert electricity back to heat rather than just stopping at the burning stage and using the heat directly. You never want to go through a heat engine if you can avoid it, because of the terrible thermodynamic penalty. There's no point in making electricity, which incurs a necessary penalty of over 60% loss of energy, if all you wanted was heat in the first place.



Above: *heating via chemical → heat → electricity → heat*
Below: *heating via chemical → heat*



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.* Your "total system efficiency" can now seem higher than Carnot efficiency, because the waste heat isn't considered waste anymore. You *want* both W and Q_2.

You can build a cogeneration system to meet either of two specifications. Either you 1) make the exact amount of electricity that you need, and then fill any extra heating needs with a furnace, or 2) you generate enough electricity to produce just the amount of waste heat that you need, and then sell any excess electricity. (See figures below).

Above: *Cogeneration type #1: making just enough electricity to meet your electrical needs (and burning extra fuel in a furnace if you need more heat.)*

Below: *Cogeneration type #2: making enough electricity so the waste heat meets your heating needs (and selling extra electricity if you made more than needed.)*

Cogeneration is not always the cheapest alternative, though. Your electricity will be more expensive than that made by big power plants, since you'll always be more inefficient than the big power plants. Also, cogen systems must use natural gas, since your neighbors wouldn't like being next to a coal plant. Those factors could make type 1 cogen too expensive. In type 2 cogeneration, you're an inefficient generator selling power to the electric company for the low wholesale price that is set by the bigger, more efficient plants. Sometimes cogeneration makes financial sense, and sometimes it doesn't.

Universities and even smaller schools do seem to be good candidates for cogen, since they're multi-building facilities that use a lot of both 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 own cogen plants, though it's not clear how many are operating: 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, high schools and even middle schools. Evanston High School has 2.4 MW of electrical power capacity! 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 on whether it's a good investment or not. If you're comfortable with spreadsheets or computer programs, you probably want to use a spreadsheet or program for this problem, but it's not necessary. If you do write a program or use a spreadsheet, attach a printout.

Data (*Energy data from Mike Stopka, 2014 numbers.)*

General

The U. of C. currently has around 4000 undergrads, 8000 grad students, and 15,000 employees (including faculty and hospital staff). (Note that roughly 40% of electricity and 70% of heating at the university goes to the medical center.)

Gas and heating

The U. of C. steam plants heat all buildings on campus, burning natural gas to make steam and circulating that steam throughout campus. The plants burnt 1.95 million mmBTU of natural gas in 2014. (The BTU is a "British thermal unit", a unit of energy; an mmBTU is a million BTUs). Natural gas is sometimes specified in volume (cubic feet), but is often just specific in energy units. The university paid $6.95 per mmBtu in 2014. (Fracking has generated a bounty of cheap natural gas.) Natural gas-fired boilers can be 98% efficient.

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 those 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 352 million kWh of electricity last year. Because the university is a large user, it doesn't just pay a monthly bill to ComEd at normal residential rates, but instead negotiates a long-term set-price contract. At present U. of C. pays 7.52 cents/kWh, close to the average commercial rate. (In 2010 we were stuck paying nearly retail rate because we'd signed a several-year contract at a rate that seemed smart, before the 2008 financial crisis caused rates to fall. Rates have been low ever since because fracking has provided cheap fuel.)

If you are selling electricity back to the grid, the price you will receive is something close to 3.29 cents/kWh averaged over the whole day (peak and non-peak hours). See ComEd ratebook sheets 288-291 (price list on p. 290) at https://www.comed.com/documents/customer-service/rates-pricing/rates-information/current/ratebook.pdf

Cogen plants

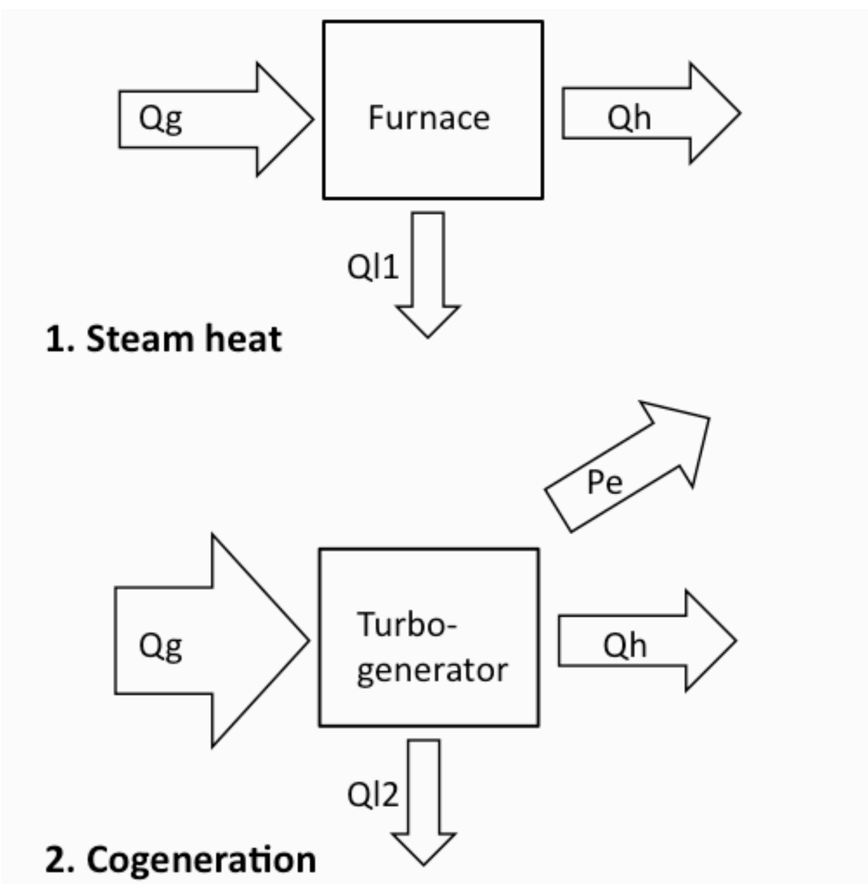
The kind of gas turbogenerator that the university could buy would be about 40% efficient at converting heat to electricity. 60% of input energy becomes waste heat. You have further losses both in making and moving steam, so you should count on getting no more than recovering no more than 50% of input energy as steam heat.

Cogen Design

You can design a type 1 or type 2 system (but students usually find a type 1 system to be easier.) For extra credit, do both.

You should at minimum work through this problem on paper given your baseline assumptions and come up with a yes or no answer to whether the system would save the university money. Alternatively, for extra credit, you can do the calculation with a spreadsheet or program and test the effects of different assumptions (including fuel price) and discuss under what conditions cogen would or wouldn't be financially sensible.

The way to approach this problem is to work backwards from the end-user demand and construct a 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 flow diagrams for current and future systems. For the current system, fill it in from left to right. For the future system, fill it in from right to left. In a type 1 system you would design to meet the university's wintertime heating needs (Qh in diagram below). In a type 2 system, you would design to match the university's electricity needs (Pe). Because energy is conserved, the total of your output power flows should equal the initial power Qg of fuel that you are burning.



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

Once you've charted the energy flows, you'll see if the cogen system 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.

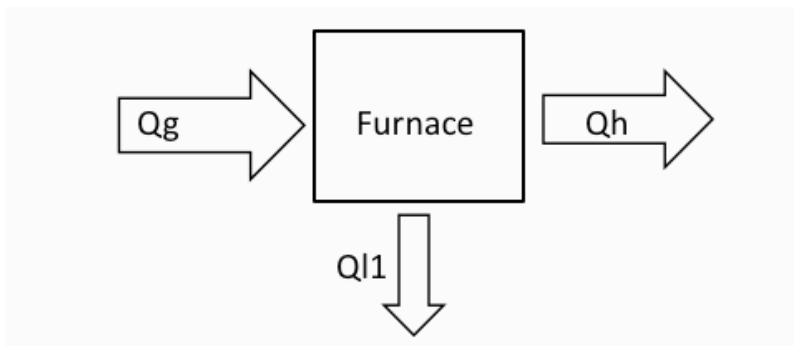
One note: because you won't be as good an electricity generator as a big commercial plant, you should run your cogen plant during the winter only, when you actually need the heat. In the summer, you'd just shut down and buy electricity from ComEd. You can assume that your heating needs are flat over 6 winter months and 0 the rest of the year, and that electricity needs are constant all year. (In reality, there are still some steam needs in the summer, especially for the medical center, about ¼ of the winter load.)

Electrical side, current system

1. What is the electrical power usage per U. of C. student or employee (in W)?
2. What is the annual cost spent on electricity per U. of C. student or employee?
3. What is the total annual cost of electricity spent by the U. of C.?

Thermal side, current system

At right is the power flow diagram for the current system when it is in use. Qg is chemical energy in natural gas, Q_{L1} is irretrievable losses in the furnace, and Qh is the heat reaches the buildings. It is best to fill in this diagram for winter only.



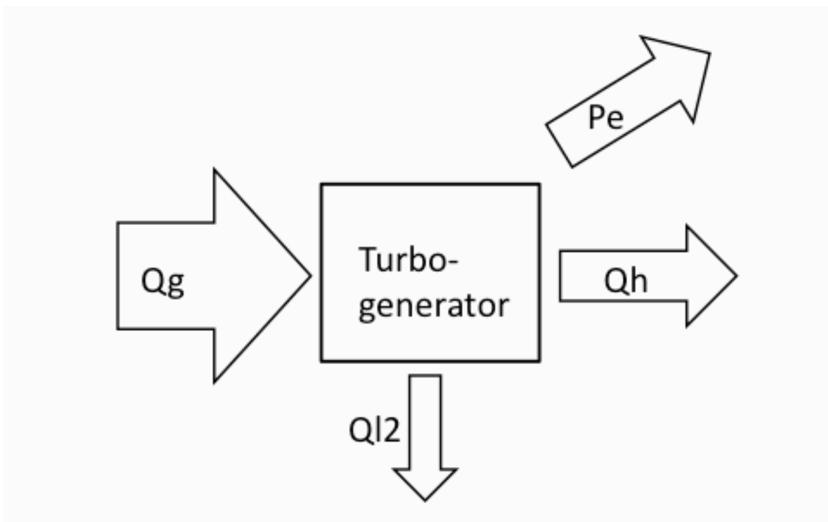
4. For context: what volume of gas does U. Chicago purchase and burn every year? (in cubic feet or other intuitive volume units; look up the conversion). The cubic feet in which natural gas is usually specified is the volume the gas would occupy if it were at room temperature and atmospheric pressure. We get this gas from a pipeline owned by People's Gas; it is distributed at a pressure only slightly over 1 atmosphere.
5. What is the U. of C.'s current power usage for heating, in W, averaged over the whole year?
6. For the winter alone? (Assume we heat only in winter, and let winter be 6 months long.)
7. Fill in the thermal flowchart above.
8. What is this wintertime heating power use per U. of C. student or employee?
9. What is the annual cost of the natural gas the U. of C. buys?
10. What is the total annual cost of running the steam plant, if operations and maintenance add 10% to the fuel cost?

11. What is the total annual 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)

12. 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 vs with electrical resistance heaters (space heaters)?

13. ***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



14. Fill in the chart above. Work backwards through the diagram. First fill in your specified electricity if type 1 (design for current Pe), or you heat needs if type 2 (design for current Qh). Use the information you just estimated, and the efficiencies given in the data section. Note how you got each number.

15. What is the annual fuel cost for the plant that provides your electricity? (Remember, the plant diagrammed above is going to run only half the year).

16. Take your answer above and add 20% to the fuel cost for operations and maintenance to get the total operational cost.

17. In a type 1 system: is the heat output from the cogen plant smaller than your total wintertime heating needs? If so, how much extra heating will you need to fulfill your total wintertime needs?

    In a type 2 system: is your electricity generation bigger or smaller than your usage? How much electricity would you need to purchase or to sell back to the grid?

18. Estimate the additional cost or revenue based on your answer to #17. In a type 1 system, if you buy more fuel for heating, add 10% to fuel cost for operations & maintenance of the plant. In a type 2 system, if you buy electricity, you pay 7.52 cents/kWh. If you sell electricity, you only get ~ 3.29 cents/kWh.

Overall economics

19. Would a cogen system have lower operational costs than our current practices? Compute the savings or cost to the U. of C. of the cogen system over the current system. Show all terms.

20. No matter what your answer in 19 is, think about the cost of actually building the cogen plant. How much will it cost to purchase and install an appropriate turbogenerator or turbogenarators? These are sold as a single unit; shop for one online. Describe your chosen system, justify why it's appropriate for the U. of C., and state its cost (or inferred cost). Provide a reference (e.g. weblink) for your source of information. Some possibly useful sites are listed below but you can shop in whatever way you want.

    http://www.powerplantsonline.com/gasturbinegenerator.htm

    http://www.industrialgeneratorsforsale.com

    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.

    If you absolutely can't find the right size generator, estimate a $/W price as best you can and scale that to your needs, but cite a source in your discussion and explain how you used it to infer a cost for U. Chicago.

21. If cogen is a net cost saver, how many years will it take for the turbogenerator purchase and installation to pay off?

22. Would you recommend that the university build a cogen plant under these assumptions? (Ignoring for now any practical difficulties or our investment in our current system.)

OPTIONAL.

23. 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), how does that alter your cost calculation?

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

25. Explore the implications of different electricity prices.