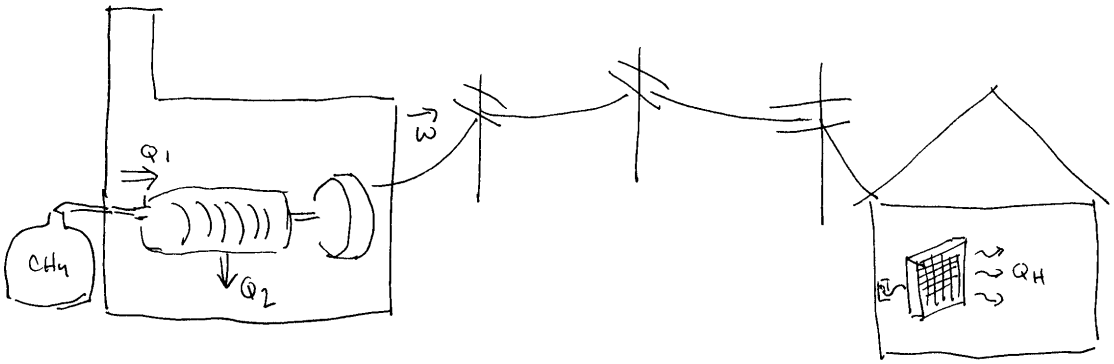
GEOS 24705 / ENST 24705
Problem set #10
Due: Tues. May 4

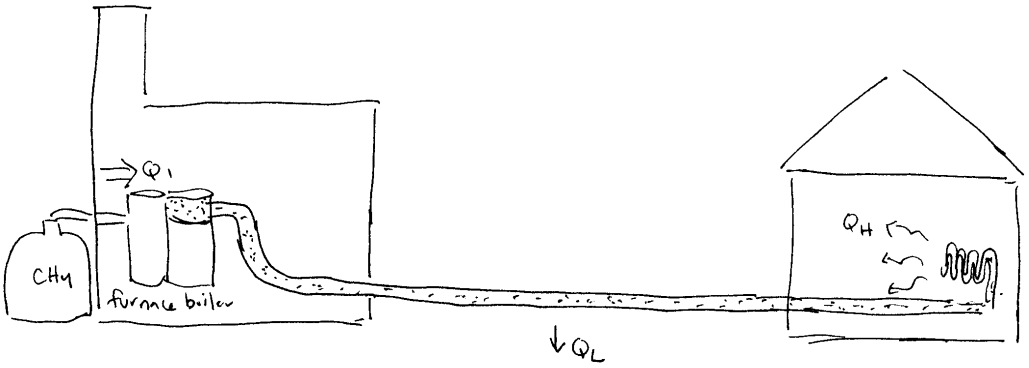
Cogeneration / Design your own power plant

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



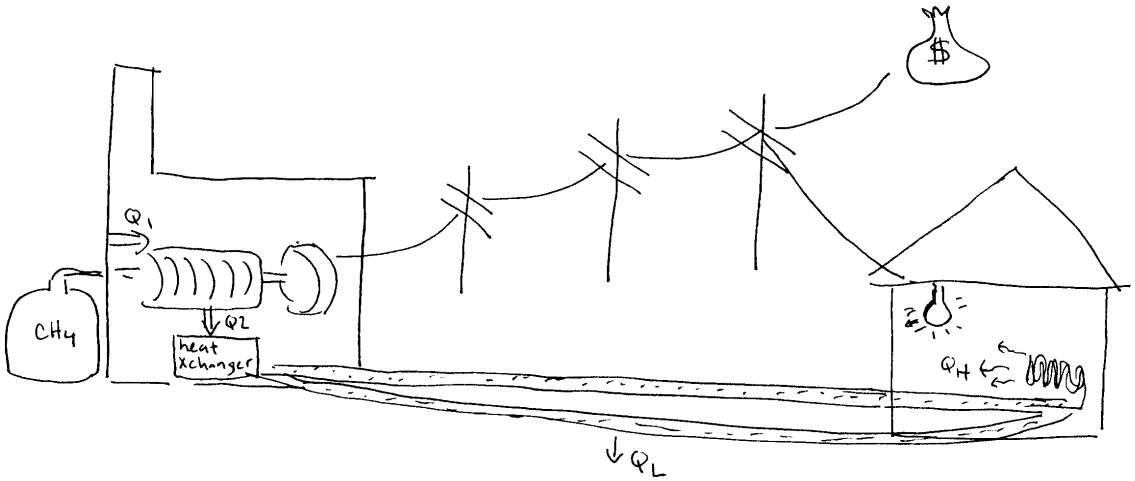
burning stage and use the heat directly (figure below).



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 far enough away 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 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, Energy Manager, U. Chicago, for some of these numbers. He emphasizes that these are estimates only, and not for quotation!

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. In the winter apparently you can trace the location of the steam pipes because heat losses melt the snow above them. If losses were of order of those of heat engine (60%), though, you'd guess the university would be making electricity instead. So transmission losses are likely a few tens of percent at absolute max.

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 current average commercial customer rate (7.5 cents/kWh in Jan 2010) and only a hair below average retail rates (9.85 cents/kWh) because the contract was signed before the financial crisis and rates have been falling since. *(Source for price comparison: U.S. Energy Information Administration)*

Problem Set – 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.

Before you can design a new system, you need to figure out how much heating power you need to deliver to campus buildings. 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 to produce waste heat you'll throw away anyway. You don't know that; you only know how much natural gas we buy, but some of that is wasted. So you'll have to first you'll go forwards through the current heating system to determine the heating power delivered to U. Chicago buildings.

Then you can start on cogen design, making sure that steam power delivered to the buildings is the same in the new system. Now start on the use side, the right hand side, and work your way upstream to the generator. When you're done and sit back and look at the diagram, 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 of fuel burning.

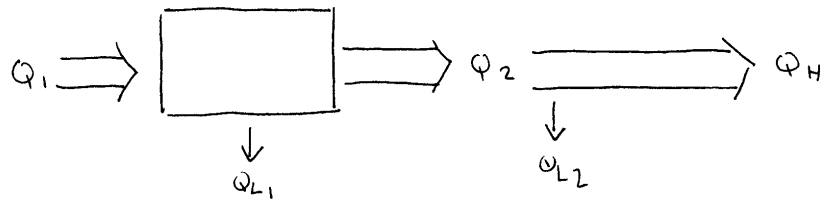
Finally, you'll see if that design saves you money or costs you more.

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 first iteration of the design (i.e., the required problem; people wanting option problems can play with the numbers more), you can assume that you run your cogen plant during the winter and in the summer when you don't need heat, shut down and just buy electricity from ComEd instead of making your own.

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

3. Assume a loss through the pipes under Hyde Park. What is that heat loss, in W? What is the wintertime power actually required for the steam to heat U. Chicago buildings, inclusive of these transportation losses?

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?

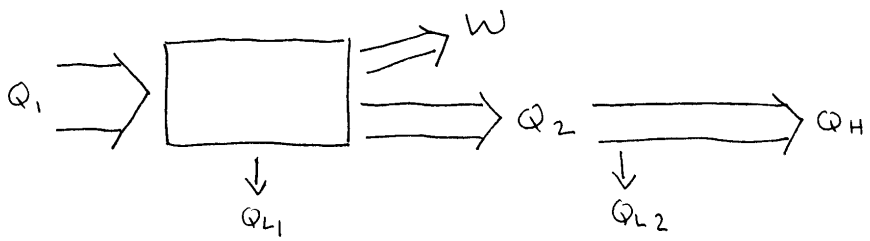
7. What is the total cost of heating per U. of C. student or employee? As a reality check, compare to your own heating bill, if you get one. (Divide by the number of people in your household to get a per capita number)

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?

10. You calculated an annual average heating power. But since you'll only run during winter, you should figure out instead what your wintertime power usage is. You can assume for simplicity that we heat for 6 months, always at the same rate of power use, then turn off for 6. What is the power consumption (in W) for heat *during the heating season*?

Thermal side, cogen system



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

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

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

14. How much will it cost to purchase and install an appropriate turbine and generator? (or multiple units). Shop for a turbongenerator online (more tips below), describe your chosen system, state its cost, justify why it's appropriate for the U. of C., and provide a reference (e.g. weblink). (Photos are fun too). 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. You don't have to call for prices (though you can!); it's OK to make an educated guess as to the price of your system based on other prices you see. (You can even scale prices to the size of generator you really want, but justify your cost estimate, regardless of what you do). 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

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

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

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

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

19. 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)?

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

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

    Bill Hines says *"For the cogeneration questions, I have attached ComEd's tariff book and draw your attention to Rider POG (go to p. 314 [of the pdf document]). 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 p. 316 for the rates that ComEd will compensate you for sales."*

    The tariff book is on the website. I'm making you suffer through this so you'll see firsthand how complicated the deregulated electricity system is.

22. 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

23. 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).

24. If the cogen system is profitable, how many years will it take for the purchase of the cogen plant to pay off? For most students, just consider how many years of savings add up to the purchase cost. Econ and business school students can also include the cost of the loan you took out to buy the equipment.

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, you long to recoup the investment?

26. Would you recommend that the university build a cogen plant? With or without year-round operation?

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

27. Natural gas prices are volatile. What price would natural gas have to be to change your judgment on cogen? How likely is that?

28. Electricity prices seem volatile too, given that the ComEd book seems to claim they dropped by a factor of 2 from 2009 to 2010. Explore the implications of different electricity prices.

29. In problem 21, you had to pick an option for selling power back to ComEd. What cost difference would it make to choose a different option?

30. You designed the cogen system to meet heating demand, not electricity demand. Was that a reasonable assumption? What would the economics look like if you met electricity demand instead?

31. 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.