COGENERATION BASICS – AN OVERVIEW

North Jersey Section AIChE

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ATTRIBUTION

Some information presented on these slides was obtained (with permission) from:

- **Introduction to Cogeneration Operation** – Ben Janvier, President, Enero Solutions, CEP Magazine, November 2017
- *…as well as over 35 years of experience in the chemical process industry!*

What is Cogeneration?

- **…the production of electricity using waste heat (as in steam) from an industrial process or the use of steam from electric power generation as a source of heat** *(Merriam-Webster.com)*
- **…utilization of the normally wasted heat energy produced by a power plant or industrial process, especially to generate electricity** *(Dictionary.com)*
- **Cogeneration or Combined Heat and Power (CHP) is the use of a heat engine or power station to generate electricity and useful heat at the same time** *(Wikipedia)*
- **Cogeneration is more thermally efficient use of fuel than electricity generation alone. In separate production of electricity some energy must be rejected as waste heat, but in cogeneration this thermal energy is put to good use.** *(Wikipedia)*

Cogeneration Types

MicroCHP:

Micro combined heat and power or 'Micro cogeneration" is a so-called *distributed energy resource (DER)*[1]. These are usually less than 5 kW in size and installed in a house or small business.

> [1] *Distributed energy resources (DER) are also sometimes referred to as distributed generation, distributed energy, on-site generation or district/decentralized energy, and may or may not be connected to the grid.*

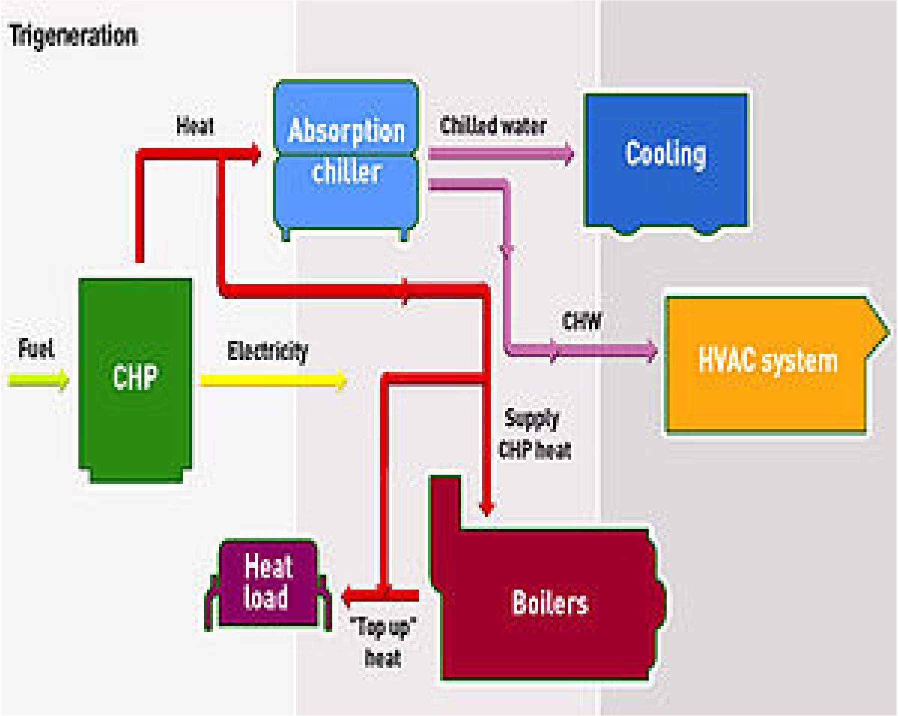
Heat recovery steam generators:

A heat recovery steam generator (HRSG) is a steam boiler that uses hot exhaust gases from gas turbines or reciprocating engines in a CHP plant to heat up water and generate steam. The steam, in turn, drives a steam turbine or is used in industrial processes that require heat.

Cogeneration Types

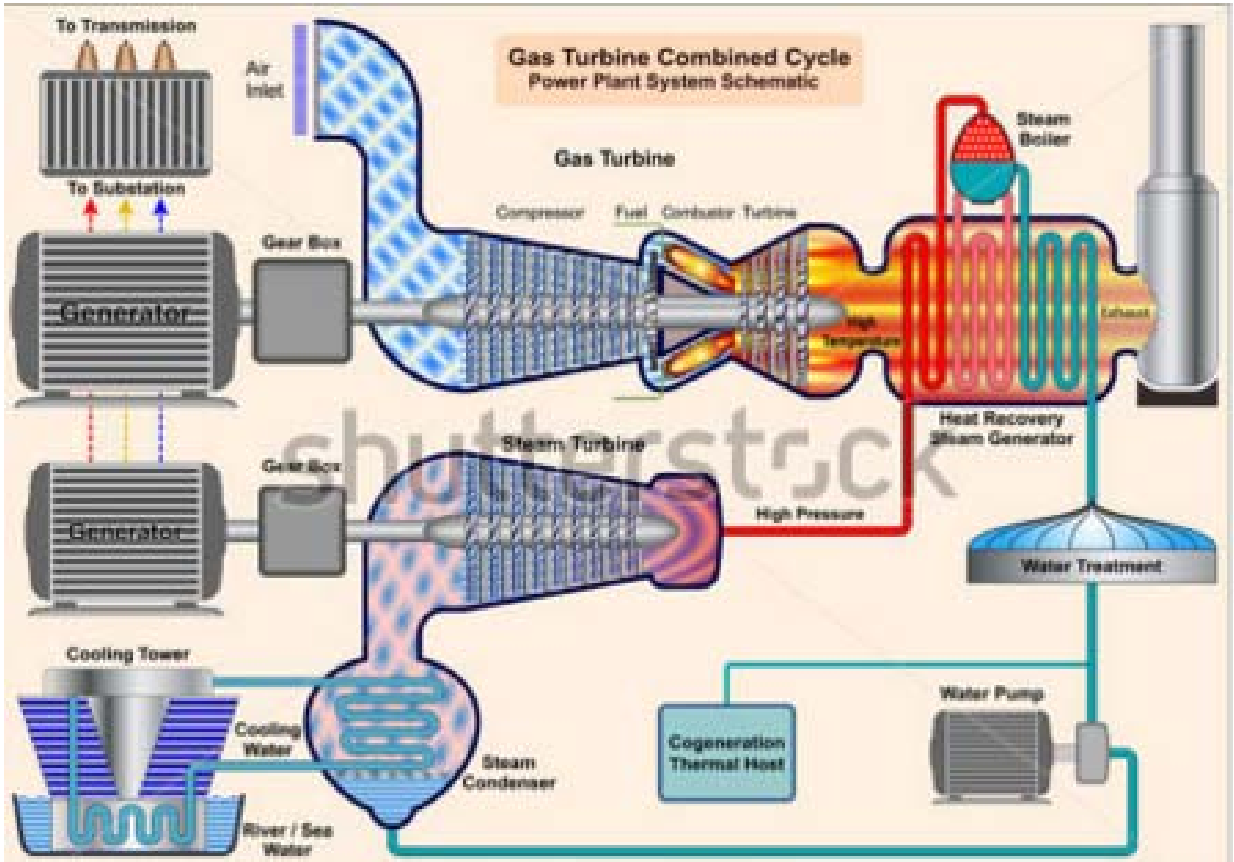
Trigeneration:

A plant producing electricity, heat and cold (*via absorption chillers*), is called a trigeneration or polygeneration plant.



Cogeneration Types

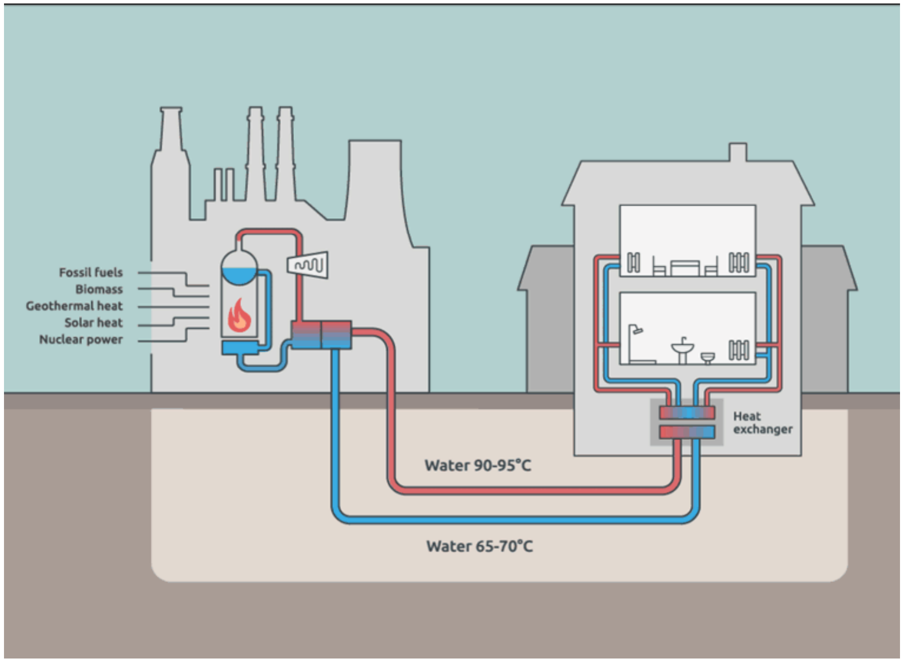
Combined heat and power (CHP):



Cogeneration Types

Combined heat and power district heating:

Perfect example of a CHP district heating network is Manhattan island, where ConEdison distributes 66 billion kilos of 350°F (180°C) steam each year through its seven cogeneration plants, to 100,000 buildings, making it the largest steam district in the United States.



Cogeneration Turbines

(Above) Alston steam turbine

(Left) Assembly of steam turbine rotor at Siemens in Germany

Cogeneration Advantages

- **Typical fossil fuel power plants have an average thermal-to-power efficiency of about 35%-45%**
  - ***Steam turbine can only extract so much electrical energy from high-pressure steam***
  - ***Low pressure steam that exits the turbine cannot be used***

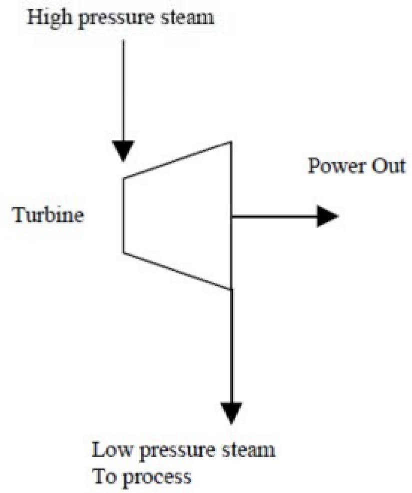
- **Industrial plants have an advantage – usually have several processes that can use the lower pressure outlet steam**
  - ***In cogeneration plants, steam passing through the turbine is maintained at an outlet pressure high enough to be used by process units***
  - ***Since turbine outlet steam energy is re-used, overall cogeneration plant efficiencies can be higher than 85%***
  - ***This allows industrial plants to generate electrical power at lower-than-market costs***

Cogeneration Advantages

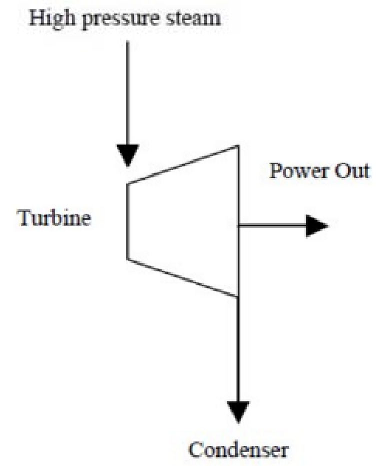
- **Industrial CHP (continued)**
  - ***Cogeneration is common in pulp and paper plants, refineries and chemical plants***
  - ***The heat is typically recovered at higher temperatures (above 100^{o}C) and used for process steam or drying duties***
  - ***This is more valuable and flexible than low-grade waste heat, but there is a slight loss of power generation***
  - ***The increased focus on sustainability has made industrial CHP more attractive, as it substantially reduces carbon foot - print compared to generating steam, or burning fuel on-site and importing electric power from the grid.***

Two Main Steam Turbine Types:

- **Backpressure**



- **Condensing,** *(a.k.a., Extraction)*



Backpressure Steam Turbine

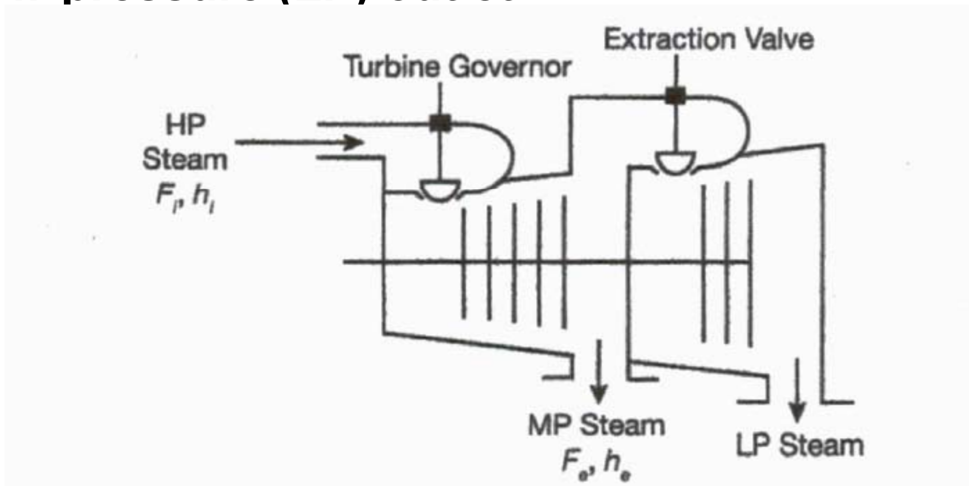
- **The Backpressure steam turbine is the simplest configuration – steam exits the turbine at a higher pressure than atmospheric, making it available for use in other processes**
  - ***Advantages include:***
    - » *The configuration of this steam turbine is very simple making it relatively inexpensive as compared to a condensing steam turbine*
    - » *It requires very little or even no cooling water*
    - » *Its efficiency is higher as it does not reject heat in the condensation process*
  - ***Disadvantages:***
    - » *Highly inflexible, thermal load requirement makes it difficult to change the output value, making it work best under constant load*

Condensing Steam Turbine

- **The Condensing (or Extraction) steam turbine – steam is condensed to less than atmospheric pressure and is returned to the boiler for the regeneration of steam,** *(consequently, it is also known as a "**regenerative steam turbine**")*
  - ***Advantages include:***
    - » *Can be used to generate a high amount of electricity*
    - » *Operation is flexible, output can be regulated to match need*
    - » *Especially useful for driving compressors, pumps and other rotating machinery*
  - ***Disadvantages:***
    - » *Costly turbine with lots of auxiliary components*
    - » *Condensation process reduces the overall efficiency of the system*
    - » *Usually used on an industrial level and requires complex configuration*

Backpressure Turbine w/ Extraction

- **Figure 5 illustrates a single-extraction backpressure turbine with one MP extraction point whose flowrate is controlled by the extraction valve, and a low-pressure (LP) outlet**

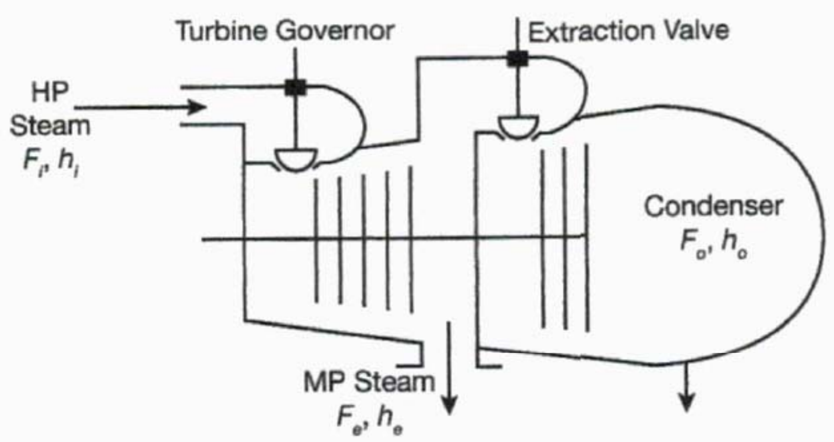


▲ **Figure 5.** This single-extraction backpressure turbine has a medium-pressure (MP) extraction point and a low-pressure (LP) outlet.

- ***It is important to note that in a backpressure turbine with extraction, the flowrate of steam into the turbine is equal to the steam user demand – therefore the plant cannot typically control the amount of power generated by the turbine – it will be determined by the overall plant steam demand***

Variations / Permutations

- **Multiple backpressure turbines can be combined in series to form a single turbine with multiple steam outlets**
  - ***Turbines with multiple outlet ports are called "extraction" turbines***
  - ***Frequently used for cogeneration since they allow steam to be extracted at one or more intermediate points in the turbine housing***
- **Condensing turbines with extraction can also be used:**



▲ **Figure 4.** This condensing steam turbine has one medium-pressure (MP) extraction point. Throttling the extraction valve can control the MP extraction steam flow, and with it, the pressure of the MP header.

Condensing Turbine w/ Extraction

- **Condensing turbines with extraction can be advantageous to an industrial user because:**

- *There is virtually no steam production or loss in a turbine, so for **Figure 4**, inlet steam flow (F_i) is equal to the sum of the extraction steam flow (F_e) and the condenser flow (F_o), or:* ***$(F_i) = (F_e) + (F_o)$***

- *Assuming a perfect system with no loss, the power generated by the turbine ($E_{turbine}$) can be calculated by:* ***$(E_{turbine}) = F_e(h_i - h_e) + F_o(h_i – h_o)$***

  - $\mathbf{h_i}$ is the enthalpy at the inlet
  - $\mathbf{h_e}$ is the enthalpy of the extraction steam, and
  - $\mathbf{h_o}$ is the enthalpy of the condenser flow

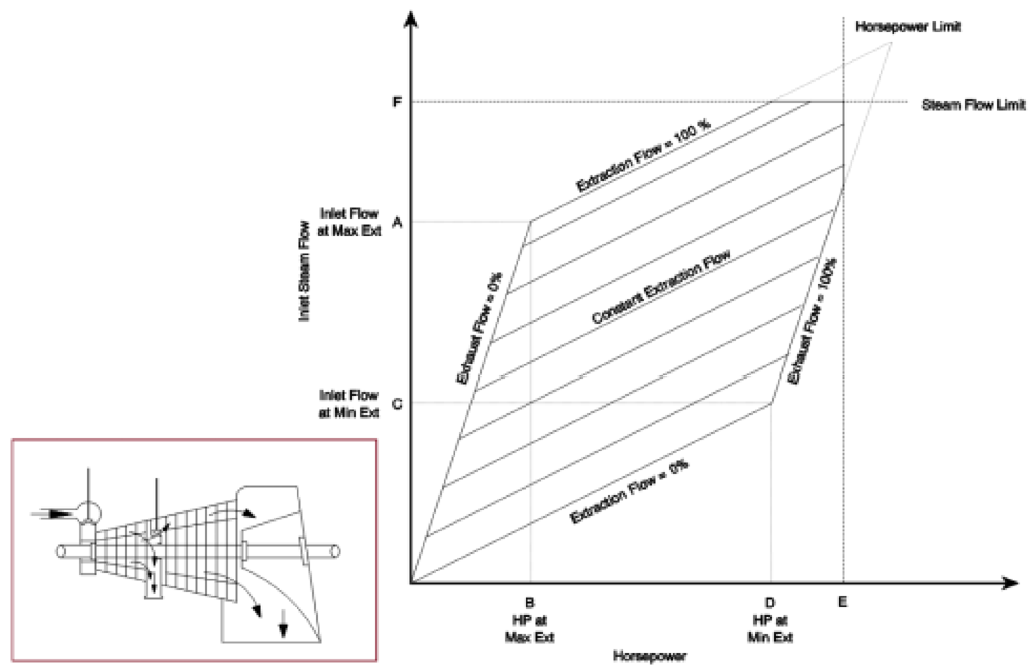
- **This equation demonstrates that a condensing turbine with extraction is capable of generating power independently of the plant's demand for steam, because F_o is an independent variable**

Turbine Map

Similar to a pump curve, the Turbine Map defines the performance characteristics of a (steam) turbine and shows the turbine's flow range per section, (including the condenser turn-down for a condensing turbine).

It is an important design tool since it can be used to calculate the power generating capacity of the turbine and the extraction steam flow constraints for the different steam headers.

Extraction Turbine Map

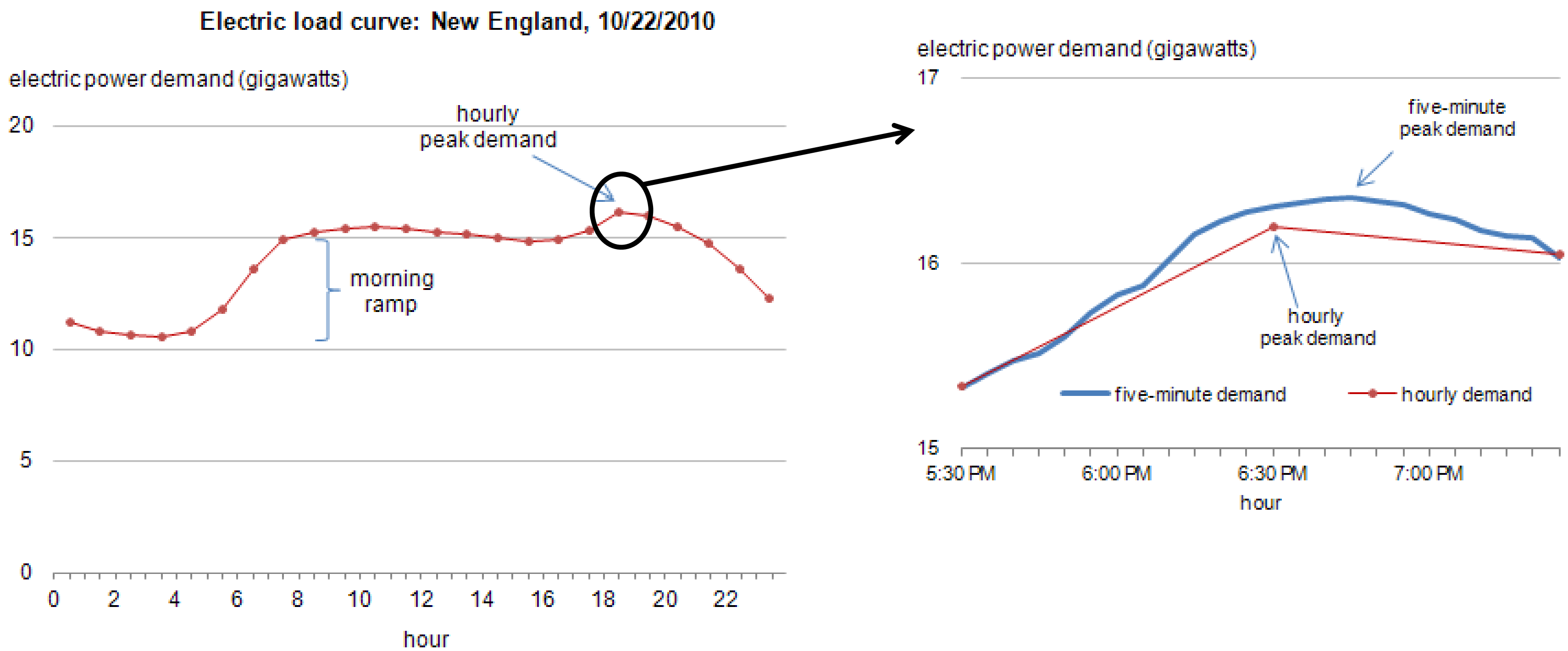


Cogeneration Economics

- The profitability of cogeneration is determined by many factors, but most importantly, the cost of buying versus generating power
- At times, it may be cheaper to buy power versus generate it
  - *Since power demand is time-dependent, its real-time costs will fluctuate*
  - *Power is usually cheaper during low-demand hours, (i.e.; 2 am), and more expensive during peak hours, (i.e.; 6 pm)*
  - *You may need to vary power generation to follow utility price fluctuations*

Electricity Demand Variations

Demand for electricity changes through the day



Source: U.S. Energy Information Administration based on data from Independent System Operator New England

What is your cost of steam?

- **To determine the profitability of making additional steam for power generation, you need to know your cost of steam**
  - ***Very Basically*, *this is based upon your fuel type, fuel cost, boiler efficiency, feed-water temperature and steam pressure***
  - **However, to determine the true cost of steam, we need to know more details about the steam in question:**
    - » *Are we discussing steam at the point of use?*
    - » *Steam at the point of generation?*
    - » *From which boiler?*
    - » *At what header pressure or at what quality?*
    - » *Average costs or marginal costs?*
      - *If average costs, do they include both fixed and variable costs, or only the latter?*
  - **Furthermore, we must distinguish between the cost of generation and the cost of consumption. *(This can become tricky for multiple boilers and multiple fuel sources)***

https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/tech_brief_true_cost.pdf

What is your cost of steam?

- **Calculating the cost of generating steam is relatively easy. The total variable cost of raising steam, C_G, is the sum of all these individual contributions, typically expressed as dollars per thousand pounds ($/1,000 lbs) of steam generated:**

$$C_G = C_F + C_W + C_{BFW} + C_P + C_A + C_B + C_D + C_E + C_M$$

- **Where:**
  - C_F = *cost of fuel*
  - C_W = *cost of raw water required for boiler*
  - C_{BFW} = *Boiler feed water treatment, (clarification, softening, demineralization)*
  - C_P = *Feed-water pumping power*
  - C_A = *Combustion air fan power*
  - C_B = *Sewer charges for boiler blow-down*
  - C_D = *Ash disposal*
  - C_E = *Environmental emissions control*
  - C_M = *Maintenance materials and labor*

https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/tech_brief_true_cost.pdf

What is your cost of steam?

- **Cost of fuel, or C_F, is usually the dominant component, accounting for up to 90% of the total cost of steam. It is calculated as follows:**

$$C_F = a_F \times (H_S - h_W) / 1{,}000 / \eta_B$$

- **Where:**
  - a_F = *fuel cost, ($/MMBtu)*
  - H_S = *enthalpy of steam, (Btu/lb)*
  - h_W= *enthalpy of boiler feed-water, (Btu/lb)*
  - η_B= *overall boiler efficiency, (expressed as a fraction)*

- **In principle, one should calculate the individual cost components rigorously for the site-specific conditions. In practice, it is usually sufficient to use an approximation:** $C_G = C_F\ (1 + 0.30)$
  - *The number* ***0.30*** *represents a typical value for the sum of all of the other cost components of the equation on the previous slide (in oil- and gas-fired facilities)*

https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/tech_brief_true_cost.pdf

What is your cost of steam?

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- **Calculating C_F is done as follows:**

Example

A boiler fired with natural gas costing $8.00/MMBtu produces 450-pounds-per-square-inch-gauge (psig) saturated steam and is supplied with 230°F feedwater. Using values from the tables, calculate the fuel cost of producing steam.

$$\text{Steam Cost} = (\$8.00/\text{MMBtu}/10^6\ \text{Btu/MMBtu})^{1} \times 1{,}000\ \text{lb} \times 1{,}006\ (\text{Btu/lb})/0.857$$
$$= \$9.39/1{,}000\ \text{lb}$$

C_G therefore = 9.39 (1 + 0.30), or **$12.21 / 1,000 lbs**

This table gives the (H_s-h_w) term

Table 1. Energy Required to Produce One Pound of Saturated Steam, Btu*

Operating Pressure, psig	Feedwater Temperature, °F				
	50	100	150	200	250
150	1,178	1,128	1,078	1,028	977
450	1,187	1,137	1,087	1,037	986
600	1,184	1,134	1,084	1,034	984

* Calculated from steam tables based on the difference between the enthalpies of saturated steam and feedwater.

Table 2. Energy Content and Combustion Efficiency of Fuels

Fuel Type, sales unit	Energy Content, Btu/sales unit	Combustion Efficiency, %
Natural Gas, MMBtu	1,000,000	85.7
Natural Gas, thousand cubic feet	1,030,000	85.7
Distillate/No. 2 Oil, gallon	138,700	88.7
Residual/No. 6 Oil, gallon	149,700	89.6
Coal, ton	27,000,000	90.3

[1] Conversion factor - MMBtu to Btu

https://energy.gov/sites/prod/files/2014/05/f16/steam15_benchmark.pdf

What is your cost of power?

- **Use your cost of steam, along with turbine efficiency, to determine your cost of producing electricity, i.e.; $/kWh**
- **The back-pressure turbine is the most efficient form of electricity generation, *(since the process steam is "used twice", once to generate power and a second time to satisfy process loads),* we will use that for the cost calculation example:**

$$\frac{Cost}{kWh} = \frac{\$}{MMBTU} x \frac{3413BTU}{kWh} x \frac{1}{gen.eff} \Rightarrow \frac{Cost}{kWh} = \left(\frac{\$}{MMBTU} \Big/ 278 \right)$$

*All that must be known is the cost of steam, in **$ / MMBTU of steam**, and generator efficiency, typically 95%, (which was used for the above example). Assuming a generator efficiency of 95%, just divide your steam cost by 278. The calculated figure will be accurate, regardless of turbine type or turbine efficiency.*

Note:** Since 1 lb of steam ~ 1,000 BTU - **$ /1,000 lbs steam ~ $ / MMBtu steam

http://www.maintenanceworld.com/the-cost-of-producing-electricity/

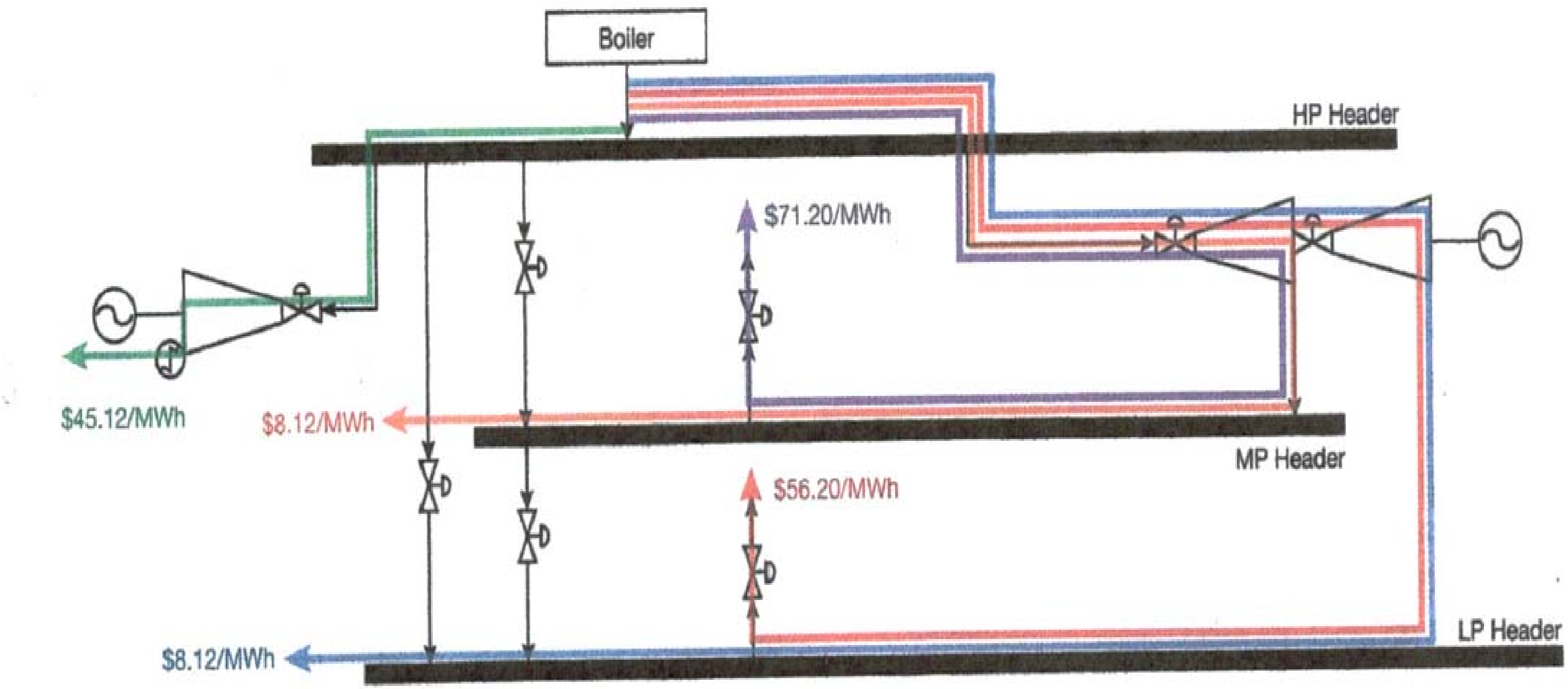
Is Cogeneration the best use of your steam?

- **There are usually several "steam paths" in a plant. Each path starts at a boiler, and ends at some type of heat sink, (*e.g.; vent valve, condenser, process unit*)**
- **Consequently, each steam path in a plant will have its own thermal-to-power conversion ratio:**

$$(MWh_{electrical} / MWh_{thermal})$$

- **The cost of steam generation (\$ / $MWh_{thermal}$), divided by the thermal-to-power conversion ratio for that use, determines the *specific cost of generating power* with that steam**
- ***…let's look at an example***

Specific Cost of Generating Power



▲ **Figure 6.** This plant has five possible steam paths with different internal costs for power generation. Steam must be sent through the most profitable path to ensure that the cogeneration does not operate at a loss.

Specific Cost of Generating Power

- **Power generation through cogeneration using back-pressure turbine(s), where steam is sent to process units will have an internal specific cost of $8.12 / MWh *(orange and blue lines)***
- **Power generated by condensing steam in the condensing turbine will have an internal specific cost of $45.12 / MWh *(green line)***
- **Power generated by pushing steam onto the MP header and venting it will have an internal specific cost of $71.20 / MWh *(purple line)***
- **Power generated by pushing steam onto the LP header and venting it will have an internal specific cost of $56.20 / MWh *(red line)***
- **Obviously, generating power is not free if the thermal cost is not zero. So, generating power at a higher cost than that at which it can be purchased, is not a profitable decision**

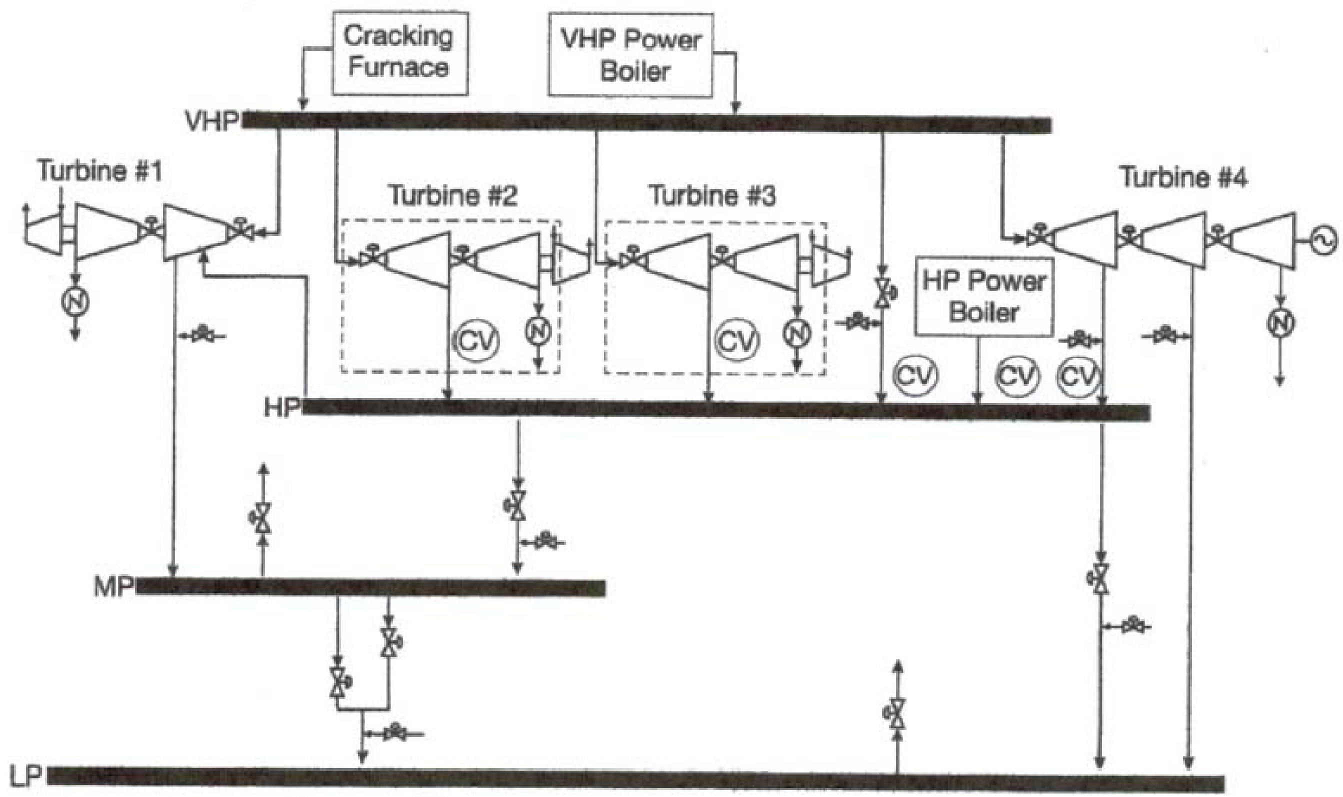
Process Control Challenges

- **It is important to remember, the addition of a steam turbine often causes larger steam pressure variability and more operational issues. Remember these important considerations during the commissioning phase of the installation:**
  - ***Stabilize the existing steam system and boilers***
  - ***Tune and optimize the performance of the turbine extraction pressure controllers***
  - ***Ensure that turbine governor logic and control limits are properly integrated with the plant's steam controls in the DSC system***
  - ***Verify that proper trip logic is configured for the turbine by-pass system***
  - ***Ensure proper controls are in place to handle a steam turbine failure***

Process Control Challenges

- **Adding a steam turbine to an existing plant makes process control more complicated and will exacerbate any existing control problems in the plant. Before commissioning the turbine, ensure that the proper tuning methodology has been used to optimize the performance of:**
  - ***Drum level controllers***
  - ***Header pressure controllers (PRV's will now be part of the by-pass system and may need to be modified to improve controller response)***
  - ***Steam header pressure controllers***
  - ***HP steam header pressure control (HP header pressure stability will be much more important with a steam turbine in the mix)***
  - ***Combustion controllers within the boiler, (e.g.; air, fuel, oxygen)***

Process Control Challenges - Example



▲ **Figure 9.** A complex steam header system for an olefin plant may involve several boilers, turbines, as well as pressure-reducing valves and vents.

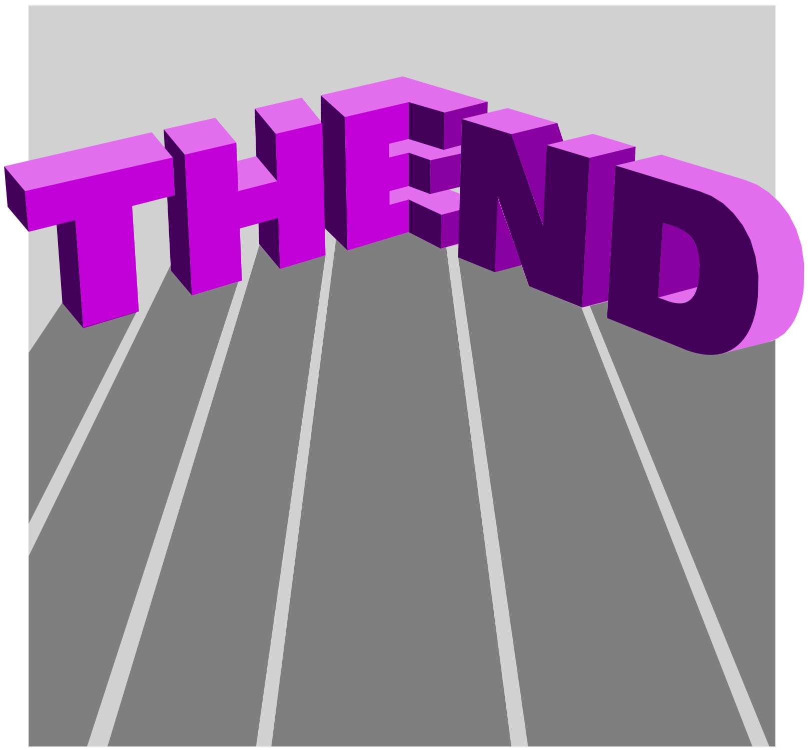
An Olefin steam plant might include:

- **Four steam headers**: *(VHP, HP, MP, LP)*
- **Three boilers:** *(cracking furnace heat recovery boiler, VHP boiler and HP boiler)*
- **Turbine(s) driving compressors:** ***Turbine 1*** *(condensing, with single MP extraction),* ***Turbines 2 & 3*** *(condensing with single HP extraction)*
- **Turbine(s) generating power:** (*Turbine 4, condensing, dual extraction)*
- **PRV's and steam vents:** *(to balance the steam load)*

In summary:

- **Begin any cogeneration project by asking these questions:**

  1. ***If power cost is low and fuel expensive, why bother generating power internally?***
  2. ***Is there a maximum amount of power than can be exported to the grid?***
  3. ***Is there a minimum amount of power than needs to be purchased?***
  4. ***Is the price of power constant, or variable, i.e.; a function of the grid load?***
  5. ***Is grid stability fragile, increasing the potential for having to run in the plant in "island mode"?***
  6. ***Are power rates too low and fuel costs too high to justify a condensing unit?***
  7. ***Are there seasonal or hourly variations in steam demand that need to be considered?***
  8. ***What is the current and future maximum thermal output of the existing boilers? (Generating power will increase the thermal power demand of the plant.)***
  9. ***How many steam headers are available if extraction turbines are being considered?***
  10. ***What is the current and future process steam demand? (Will determine future turbine size and power capability)***


THE END

"There is no expedient to which a man will not resort to avoid the real labor of thinking."

Sir Joshua Reynolds

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