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Factors That Influence the CO2 Mitigation Potential of Cogeneration

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Cogeneration as a Policy Tool for CO_2 Control

- Cogeneration is being promoted as a means of improving overall efficiency of fuel utilization to reduce CO_2 emissions.
- Promotion of such systems has lead to misleading statements and information.
- This presentation will review some of the issues associated with cogeneration (or combined heat and power) in order to get a better understanding of the potential for this application.
- Some examples will be presented.

What is Cogeneration

- Cogeneration is the simultaneous generation of electricity and thermal energy for process or thermal use.
- It is not a Combined Cycle. In a combined cycle, at least 2 cycles for generating electricity are combined in order to generate the electricity at greater efficiency.

What is Cogeneration

- Thermodynamics is the science of the movement of heat energy.
- The first law of thermodynamics states that:

  Input = Output at steady state

- The first law governs thermal processes such as heating a room, heating a jacketed vessel, boiling water, freezing ice, etc.

What is Cogeneration

- The second law of thermodynamics governs the performance of heat engines.
- A heat engine converts heat into mechanical work.
  - Examples include steam turbines, gas turbines, gasoline engines, diesel engines, etc.
- The second law has two important features:
  - The first is that heat must flow from the high temperature to the low temperature. Heat can't go uphill without additional work.
  - The second is that heat engines must operate between two reservoirs….a high temperature and a low temperature reservoir are needed.

What is Cogeneration

- In the real world, the low temperature is usually dictated by ambient conditions.
- The high temperature is usually determined by the properties of the working fluid (ie water, steam, hot products of combustion, etc.)
- The maximum theoretical efficiency of a heat engine is determined by the following:

  Max efficiency = (Thot – Tcold)/Thot
- The temperatures are given in absolute temperature (ie R or K).

What is Cogeneration

- It is important not to mix the two efficiencies when comparing various energy processes.
  - For example, boiler efficiency is defined as the amount of energy that ends up in the steam divided by the energy in the fuel that was fired.
  - Typical boiler efficiencies are in the range of 82 – 88%. Most of the loss is stack loss.
  - Electric generating efficiency is defined as the net amount of electricity generated divided by the energy in the fuel that was fired.
  - Typical steam plant efficiencies are in the range of 35 – 42% (HHV).
  - Typical combined cycle efficiencies are in the range of 50 – 54% (HHV).

What is Cogeneration

- You will hear advocates of cogeneration state that cogen plants are about 85% efficient and then compare that figure to the US power grid which averages 33% efficiency in the generation of power.
- These two processes are different and cannot be compared directly.
- The 85% figure is a first law number at full load, steady state operation and more directly comparable to boiler efficiency.
- The power generation efficiency figure is a second law number and is the average over all loads, all types of equipment, and non-steady state operation.

What is Cogeneration

- UConn's state-of-the-art Co-Generation Facility opened in February 2006, replacing several oil-fired utility boilers and enabling the University to meet its own energy needs at the main campus.
- “Co-Generation is defined as the sequential production of both electrical or mechanical energy and useful thermal energy from a single energy source. This allows over 80% of the fuel energy to be harnessed, versus 33% from a conventional electric power plant.”

What is Cogeneration

- Examples of cogeneration
  - A large boiler generates high pressure steam and sends that to a steam turbine. The steam turbine makes some electricity. The steam turbine exhausts steam to run a chemical reactor at a lower pressure.
  - A gas turbine burns gas to make electricity. The exhaust gases are sent to a Heat Recovery Steam Generator (HRSG). The steam is sent to a grain dryer.
  - A boiler generates steam at a modest pressure and sends the steam to a steam turbine. The steam turbine makes some electricity. The steam turbine exhausts steam to a heating system.

Efficiency

- One of the key drivers for cogeneration is improved efficiency. Improvements in efficiency lead directly to reductions in CO_2 emissions.
- It is important to understand the source of this improved efficiency and the relative level of improvement that can be expected.
- It is also important to realize that there may be existing plants that, for one reason or another, have not been optimized for efficiency. While these plants will show marked improvement with the application of cogeneration, it may not be that cogeneration is the cause, by itself, of the improvement.

Efficiency

- What do we mean by efficiency?
- There are many different efficiency concepts to consider.
  - Combustion efficiency
  - Boiler efficiency
  - Cycle efficiency
  - Gross plant heat rate
  - Net plant heat rate
  - Marginal heat rate

Efficiency

- In order to calculate these efficiencies, we need to know something about the composition and heat content of the fuel.
- Natural gas is a common fuel. Its primary constituent is methane, whose molecular formula is CH_4.
- The combustion of methane can be described as follows:

  $CH_4 + 2O_2 = CO_2 + 2H_2O$

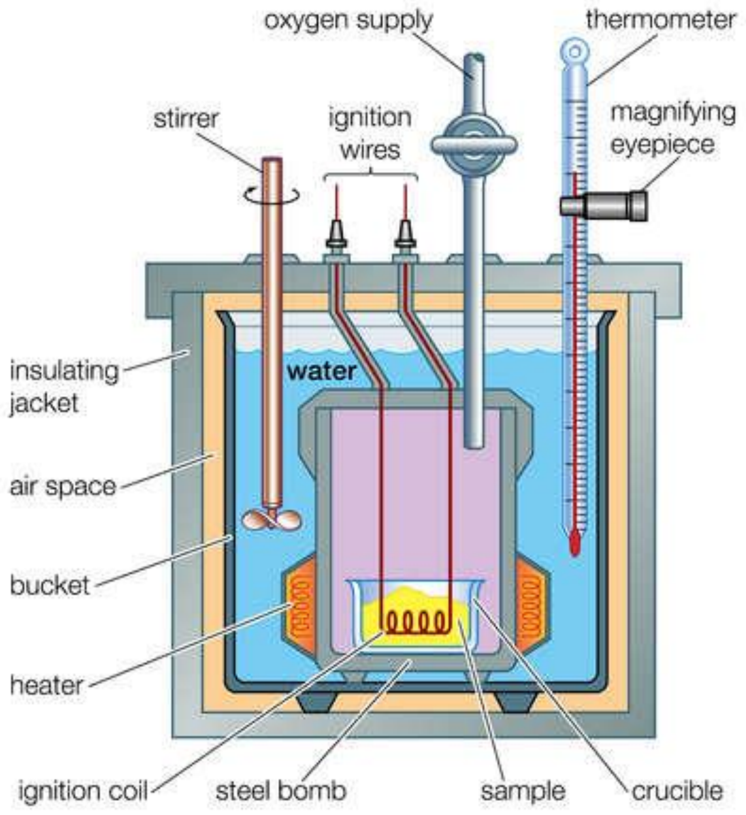
- Note that there is water in the products of combustion.

Efficiency

- In order to measure the heat that will be liberated during the combustion process, we need to measure the "heating value" of the fuel.
- This is done in a bomb calorimeter.
- The heating value of the fuel is given in BTU/lb.
- A BTU (British Thermal Unit) is the amount of energy needed to raise 1 lb of water 1 F.
- If we know the heating value of the fuel and the lbs. of fuel burned, then we know the heat input.

Efficiency

- In order to measure the BTU content of the fuel, representative samples of the fuel must be collected. These samples are sent to a fuel laboratory for analysis. The heating value of the fuel (BTU content) is measured in a bomb calorimeter and reported as BTU/lb of fuel.



Efficiency

- Since the calorimeter is run in a lab at room temperature, the water produced from the combustion of the fuel is present as liquid water.
- That means that the water has given up its latent heat of vaporization.
- As a result, the bomb calorimeter measures the higher heating value (HHV) of the fuel.
- If the water were to remain as a vapor, less energy would be liberated. In this case, the lower heating value (LHV) would be measured.

Efficiency

- When firing natural gas, the fuel is 25% by weight hydrogen, which produces a significant amount of water vapor. The difference between LHV and HHV can be 10% or more.
- This difference is significant. If the efficiency of a plant is calculated on an LHV basis and the fuel is purchased on an HHV basis, the plant will be short of fuel.
- The gas turbine industry and the EU use LHV for their calculations.

Efficiency

- The water vapor that is present in the products of combustion is theoretically available to be condensed, thus liberating the heat of vaporization.
- As a result, the ASME Power Test Codes all use HHV for their performance calculations.
- We will use HHV unless otherwise noted.
- The gas turbine industry also uses ISO conditions.
  - Sea level, one atmosphere, 59F, 60% relative humidity
  - Values quoted are at full load, gross output, clean and new

Efficiency

- Cycle efficiency
  - When we talk about power generation, there is generally some kind of power cycle used to make the power. Examples include:
    - Steam cycles (Rankine cycles)
    - Brayton cycles (open cycle gas turbines)
    - Combined cycles
  - For these cycles, efficiency is defined by how much electricity is generated divided by the energy in the fuel that was fired.
  - These cycles are governed by the second law of thermodynamics.

Efficiency

- In a typical power plant, there are internal needs for electricity including pumps, fans, valves, motors, controls, etc.
- For the power plant owner, the amount of electricity that is available for sale is what is important in determining the plant revenue. This amount is what is available after the internal demand for power is satisfied and is referred to as the net power available.
- The amount of generation before the internal demand is the gross power.
- The internal demand is referred to as auxiliary power consumption.

Efficiency

- The heat rate is the amount of energy (BTU) needed to generate a Kwhr of electricity.
- The gross plant heat rate is the heat rate before subtracting the aux power.
- The net plant heat rate is the heat rate after subtracting the aux power and represents the energy needed to produce power for sale.
- 100% efficiency corresponds to 3413 BTU/Kwhr.
- The actual efficiency can be calculated by dividing 3413 by the plant heat rate.

Efficiency

- Typical Power Plant Efficiencies
  - Coal Fired Steam Plant Sub Critical 36%
  - Coal Fired Steam Plant Super Critical 39%
  - Coal Fired Steam Plant SOA 41%
  - Coal Fired Steam Plant Advanced USC 45%
  - Combined Cycle Plant, Clean and New 52%
  - Combined Cycle Plant, Clean and New SOA 54%
  - Combined Cycle Plant, Hot Humid Day 49%
- All of these figures are based on full load and HHV fuel values.

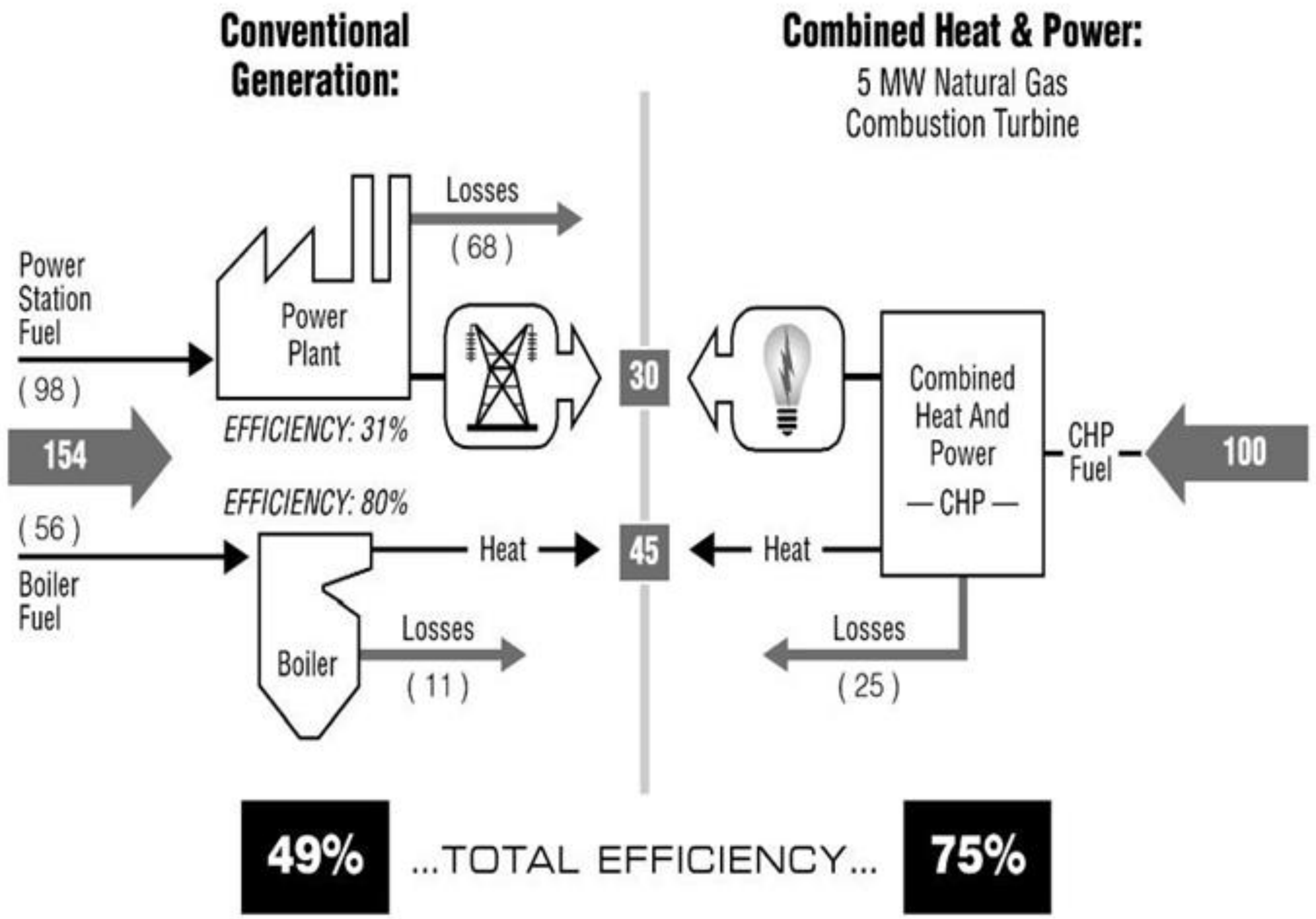
Efficiency

- You will see reports and ads stating the combined cycle efficiency is 60%.
- This figure is based on the LHV of the fuel and ISO conditions, clean and new, at full load, gross.
  - The use of LHV increases the efficiency by about 10%.
  - The use of ISO conditions adds another few percent.
  - Gas turbine performance degrades on Day 1.
- When this figure is compared to the average grid based power of 33% (HHV), we are mixing systems again.

Efficiency

- In cogeneration, we have two processes.
  - The power process governed by the second law
  - The thermal process governed by the first law.
- We can’t compare these two efficiencies directly with a power plant efficiency.
- In order to make a valid comparison, we need to calculate the marginal heat rate for the generation of electricity in the cogeneration plant. The thermal energy is assumed to be the same for the cogeneration plant and the stand alone plant making thermal energy.

Efficiency



EPA's statement on cogeneration

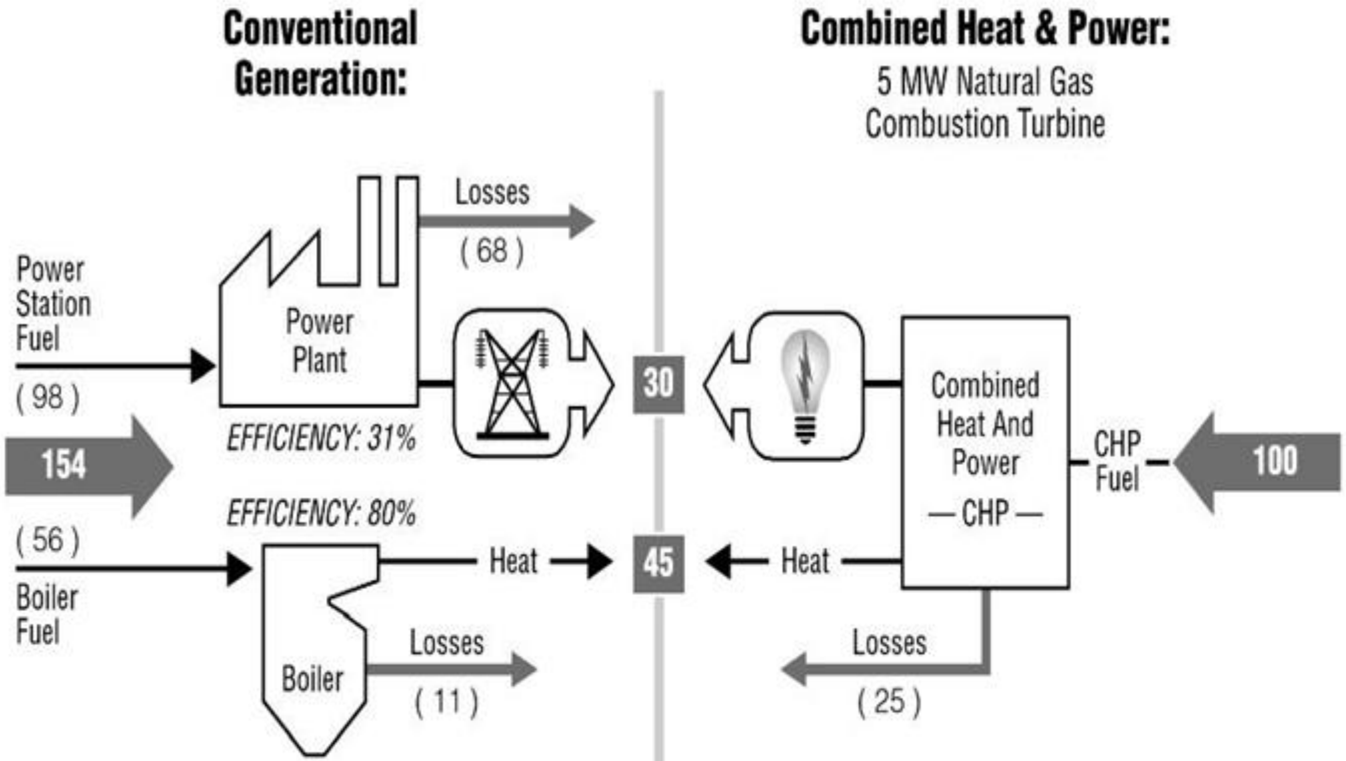
Efficiency

Combined Cycle @ 54%

56

109

53



Boiler Eff @ 85%

69%

49% ...TOTAL EFFICIENCY... 75%

Cogen compared to an SOA combined cycle

Implications for CO2 Reductions

- Looking at the figures on the last slide, the actual fuel savings for a typical new industrial cogeneration plant vs a new, state of the art combined cycle plant at a utility and a new industrial boiler, the fuel savings are more like 8.3% rather than the 35% originally depicted.
- That translates into CO2 savings of only 8.3% rather than 35%.
- Similarly, when the 85% and 31% are compared, the expected fuel savings would be 64%, as opposed to the more realistic 8.3%.
- These figures have policy implications as Congress looks to reward companies for efficiency improvements and needs to have a means to properly evaluate the incentives to be provided.

Appendix

Efficiency

- Combustion Efficiency
  - Combustion efficiency is defined as the fraction of the fuel that is burned, or combusted.
    - More specifically it is the heat liberated by combustion divided by the heat content of the fuel introduced to the combustion process.
    - A good burner system has better than 99.8% combustion efficiency.
    - That means that the majority of the fuel has been burned.
    - It does not address what happens to the energy that has been liberated by the combustion process.

Efficiency

- Boiler efficiency
  - Boiler efficiency is defined as the amount of energy that ends up in the boiled water (ie the steam) divided by the energy content of the fuel fired.
  - Losses that impact boiler efficiency are primarily stack losses (ie the hot flue gases that go up the stack). Stack losses include moisture losses from moisture in the fuel plus moisture losses from the water formed by the products of combustion.
  - Combustion efficiency and boiler efficiency are governed by the first law of thermodynamics.

Efficiency

- As an example, suppose that we have a boiler that is designed to generate steam at 1200 psi and 900 F. We have a thermal load requirement for steam at 500 psi and 500 F.
- We can design the boiler capacity for the thermal load requirement. That is, the pounds of steam that we need will be the design load for the boiler.
- We can use a “back pressure” steam turbine to exhaust the steam at 500 F and a little above 500 psi.

Efficiency

- This back pressure steam turbine will generate some electricity.
- We can calculate the energy flow needed to generate the steam at 1200 psi and 900 F from the steam tables and the boiler efficiency.
- We can do the same thing for the steam at 500 psi and 500 F.
- We can calculate the steam turbine generation of electricity by knowing the isentropic efficiency of the steam turbine (actual divided by theoretical).

Efficiency

- Once we know these 3 figures, we can calculate the marginal heat rate. We take the total energy flow and subtract that needed to make the thermal energy. The difference is divided by the electric generation to give the marginal heat rate.
- The actual energy savings will be the difference between the marginal heat rate for the cogeneration plant and the heat rate for a conventional power plant times the power generated for the cogeneration plant.

Efficiency

- The heat content of the steam is referred to as the enthalpy of the steam.
- Steam tables have been prepared so that these values can be looked up given the steam conditions. Thus,
    - Steam at 1200 psi and 900 F has an enthalpy of 1441 BTU/lb.
    - Steam at 500 psi and 500 F has an enthalpy of 1234 BTU/lb.
- Assume the steam requirement for thermal energy is 500,000 lb/hr, or 617 MMBTU/hr.

Efficiency

- The steam turbine has an 88% isentropic efficiency and the generator has a 97% efficiency.
- The power output (gross) will be
  - 207 BTU/lb x 500,000 lb/hr x 0.88 x 0.97/3413 BTU/kwhr, or
    - 25.9 Mw
- The difference between the energy to produce the high pressure steam and the lower pressure steam is 127 MMBTU/hr. (879 – 752)
- The marginal heat rate is
  - 127 MMBTU/25, 900 Kwhr = 4903 BTU/Kwhr

Efficiency

- This is the gross heat rate. The net heat rate will subtract the aux power for the generating plant. Assume 2% for this calculation.
- The net heat rate will be
  - 4903/.98 = 5003 BTU/Kwhr
- This figure compares favorably with a good, subcritical steam plant with a net plant heat rate of 9500 BTU/Kwhr.
- The savings in energy will be about 4500 BTU/Kwhr x 25,900 Kw or 116 MMBTU/hr

Efficiency

- Now let's compare this analysis with the typical claim for cogeneration which is:
  - Cogeneration is 85% efficient while the average grid efficiency is only 33%.
- This statement is actually meaningless. The 85% figure is a first law calculation (ie 85% of the fuel energy is actually used). The 33% figure is the average of all fuels at all loads over an entire year, including startups and shutdowns and is governed by the second law.

Efficiency

- The energy needed in the boiler to generate 500,000 lb/hr of steam at 1200 psi and 900 F is:
  - (500,000 lb/hr x 1441 BTU/lb)/0.82 or 879 MMBTU
  - 0.82 is the boiler efficiency for a gas fired boiler.
- The energy that would have been needed to generate steam at 500 psi and 500 F is:
  - (500,000 lb/hr x 1234 BTU/lb)/0.82 or 752 MMBTU
- The difference in enthalpy across the steam turbine is (1441 – 1234) or 207 BTU/lb.

Efficiency

- In our example plant, we fired 879 MMBTU/hr.
- Using 85%, we would claim that we made use of 747 MMBTU/hr.
- Using 33%, we would claim that the grid would have only made use of 290 MMBTU/hr.
- If this were true, the savings would be 457 MMBTU/hr.
- The actual savings was 116 MMBTU/hr.

Efficiency

- What we have seen is the marginal heat rate is around 5000 BTU/Kwhr, which would imply a 68% marginal efficiency to produce the next Kwhr.
- That figure assumes full load at all times and is not an average. Still, if the facility does run at full load, we can only compare the two power figure numbers. The thermal energy portion remains the same (ie there is no savings on the thermal portion of the facility).
- The 68% figure compares favorably with the 33% average, or even the 36% figure for full load for a conventional steam plant.

Efficiency

- Note that we actually fired 879 MMBTU/hr.
- If we accepted the typical 85% efficiency for cogen and 33% efficiency for power generation, we would calculate the savings as 457 MMBTU/hr, as opposed to the 116 MMBTU/hr when estimated correctly. Then we would be disappointed when the engineering studies did not show the savings that we anticipated.
- This plant had an actual first law efficiency of 80%. (617 + 88)/879 = 0.80