ELEC6221 Power Generation: Technology and Impact on Society

Combined heat and power - CHP

• Combined heat and power technology
• Environmental consideration
• Cost of CHP
Combined Heat and Power

The production of electricity from fossil, biomass or nuclear fuels is an inefficient process.

While some modern plants can achieve nearly 60% energy conversion efficiency, most operate closer to 30% and smaller or older units may reach only 20%. Between 40% and 80% of all the energy burnt in power plants is wasted. The wasted energy emerges as heat which is dumped in one way or another. Sometimes it ends up in cooling water, but most often it is dissipated into the atmosphere. This heat can be considered as a form of pollution.
Between 40% and 80% of all the energy burnt in power plants is wasted.

- This energy cannot be utilised to generate electricity but it can still be employed.
- Low-grade heat can be used to produce hot water or for space heating
- Higher-grade heat will generate steam which can be exploited by some industrial processes. This will improve the overall energy efficiency.

Systems which utilise waste heat are called combined heat and power (CHP) systems (or co-generation). Such systems can operate with an energy utilization factor (often wrongly called efficiency) of up to 90%. This represents a major saving in fuel cost and in environmental degradation.
Combined Heat and Power Technology

Most types of power generation technology are capable of being integrated into a CHP system.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional coal fired</td>
<td>38–47</td>
</tr>
<tr>
<td>Pressurised fluidised bed</td>
<td>45</td>
</tr>
<tr>
<td>Integrated-gasification combined cycle</td>
<td>45</td>
</tr>
<tr>
<td>Heavy gas turbine</td>
<td>30–39</td>
</tr>
<tr>
<td>Aeroderivative gas turbine</td>
<td>38–42</td>
</tr>
<tr>
<td>Gas turbine combined cycle</td>
<td>59</td>
</tr>
<tr>
<td>Fuel cell</td>
<td>36–60</td>
</tr>
<tr>
<td>Lean-burn gas engine</td>
<td>28–42</td>
</tr>
<tr>
<td>Slow-speed diesel</td>
<td>30–50</td>
</tr>
</tbody>
</table>

Whatever energy is not converted into electricity will be available as heat.

Power plant energy conversion efficiencies

Depending on the heat quality different types of technologies will be employed
- High quality steam – high temperature steam – steam turbine or gas turbine based plants
- Low quality steam or hot water – piston engine based plants

- **Base-load CPH plant** – gas turbine and steam turbine plants are best solutions
  - provide base-load electricity generation
- **Follow load CPH plant** – fuel cell or piston engine power plant are better suited
  - follows the load of the user who installs it
Piston engine power plants are available in sizes ranging from a few kW to 65MW. These engines are particularly good at load following; a spark-ignition engine efficiency falls by around 10% at half-load while diesel engine efficiency barely drops over this range. There is no significant penalty in terms of engine wear for variable load operation. Piston engines can also be started quickly, with start-up times as short as 10 sec are typical.
Piston Engine Based CHP

• There are two primary types of piston engine for power generation, the diesel engine and the spark-ignition gas engine.
  – diesel engine is the most efficient, reaching close to 50% energy conversion efficiency.
  – spark-ignition engine burning natural gas can achieve perhaps 42% efficiency but it is much cleaner than the diesel.

• There are four sources of heat in a piston engine: the engine exhaust, the engine jacket cooling system, the oil cooling system and the turbocharger cooling system (if fitted).
  – If all four sources of heat are exploited, roughly 70–80% of the energy in the fuel can be utilised.
  – Most normal CHP application would generate hot water rather than steam.
  – Engine exhaust can provide low- to medium pressure steam and the engine jacket cooling system can provide low pressure steam.

• Applications for piston engine CHP plants include small offices and apartment blocks, hospitals, government installations, colleges and small district heating systems.

• Engines tend to be noisy, so some form of noise insulation is normally required.

• Emissions of gas engines can normally be controlled with catalytic-converter systems but diesel engines require more elaborate measures to control their higher nitrogen oxides and particulate emissions.
Steam turbines are available in virtually any size from less than 1 MW to 1300 MW.

Steam turbine will normally be used in a CHP system only where there is a demand for high-quality, high-pressure steam for some industrial process.
Steam Turbine Based CHP

- There are a number of ways in which a boiler/steam turbine system can be used in industrial applications
  - One way is to take heat directly from the boiler to supply the process, with any surplus being used to drive the steam turbine.
  - Alternatively steam can be taken from the boiler to the steam turbine and then from the turbine exhaust to the process.
    - The pressure and temperature of the steam exiting the turbine can be tailored to suit the industrial demand.
  - A third method is to extract steam from the turbine casing at a point before the exhaust.
- Combinations of all these methods are possible, so that the CHP system can be tuned for maximum efficiency.
- The emissions from a steam turbine CHP system will be those of the boiler which generates the steam. Thus the emission-control measure will depend on whether the plant burns coal, wood or gas.
- Noise is unlikely to be a consideration since a steam turbine CHP system will only be used in an industrial environment.
Steam Turbine Based CHP – Energy Flow

\[ Q_{in} = m_3 (h_4 - h_3) \]
\[ Q_{out} = m_7 (h_7 - h_1) \]
\[ Q_{hp} = m_5 h_5 + m_6 h_6 - m_8 h_8 \]
\[ W_{turb} = (m_4 - m_5)(h_4 - h_6) + m_7 (h_6 - h_7) \]

Flexibility to follow electricity and heating demands
Cogeneration Plant - Example

Steam enters the turbine at 7 MPa and 500°C. Some steam is extracted from the turbine at 500 kPa for process heating. The remaining steam continues to expand to 5 kPa. Steam is then condensed at constant pressure and pumped to the boiler pressure of 7 MPa. At times of high demand for process heat, some steam leaving the boiler is throttled to 500 kPa and is routed to the process heater. The extraction fractions are adjusted so that steam leaves the process heater as a saturated liquid at 500 kPa. It is subsequently pumped to 7 MPa. The mass flow rate of steam through the boiler is 15 kg/s. Disregarding any pressure drops and heat losses in the piping and assuming the turbine and the pump to be isentropic, determine (a) the power produced and the utilization factor when no process heat is supplied, and (b) the rate of process heat supply when 10% of the steam is extracted before it enters the turbine and another 70% of the steam is extracted from the turbine at 500 kPa for process heating.
CHP - Example

The work inputs to the pumps and the enthalpies at various states are

\[ w_{\text{pump I,in}} = n_8 (P_9 - P_8) = (0.001005 \text{ m}^3/\text{kg})[ (7000 - 5) \text{kPa}] \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) \]

\[ = 7.03 \text{ kJ/kg} \]

\[ w_{\text{pump II,in}} = n_7 (P_{10} - P_7) = (0.001093 \text{ m}^3/\text{kg})[ (7000 - 500) \text{kPa}] \left( \frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3} \right) \]

\[ = 7.10 \text{ kJ/kg} \]

\[ h_1 = h_2 = h_3 = h_4 = 3411.4 \text{ kJ/kg} \]

\[ h_5 = 2739.3 \text{ kJ/kg} \]

\[ h_6 = 2073.0 \text{ kJ/kg} \]

\[ h_7 = h_f @ 500 \text{kPa} = 640.09 \text{ kJ/kg} \]

\[ h_8 = h_f @ 5 \text{kPa} = 137.75 \text{ kJ/kg} \]

\[ h_9 = h_8 + w_{\text{pump I,in}} = (137.75 + 7.03) \text{ kJ/kg} = 144.78 \text{ kJ/kg} \]

\[ h_{10} = h_7 + w_{\text{pump II,in}} = (640.09 + 7.10) \text{ kJ/kg} = 647.19 \text{ kJ/kg} \]
CHP - Example

When no process heat is supplied, all the steam leaving the boiler passes through the turbine and expands to the condenser pressure of 5 kPa \((m_3=m_6=m_1=15 \text{ kg/s and } m_2=m_5=0)\). Maximum power is produced in this mode.

\[
\dot{W}_{turb,\text{out}} = \dot{m}(h_3 - h_6) = (15 \text{ kg/s})[(3411.4 - 2073.0) \text{ kJ/kg}] = 20,076 \text{ kW}
\]

\[
\dot{W}_{\text{pump,in}} = (15 \text{ kg/s})(7.03 \text{ kJ/kg}) = 105 \text{ kW}
\]

\[
\dot{W}_{\text{net,\text{out}}} = \dot{W}_{turb,\text{out}} - \dot{W}_{\text{pump,in}} = (20,076 - 105) \text{ kW} = 19,971 \text{ kW} \approx 20.0 \text{ MW}
\]

\[
\dot{Q}_{\text{in}} = \dot{m}_1(h_1 - h_{11}) = (15 \text{ kg/s})[(3411.4 - 144.78) \text{ kJ/kg}] = 48,999 \text{ kW}
\]

Thus,

\[
\epsilon_u = \frac{\dot{W}_{\text{net}} + \dot{Q}_p}{\dot{Q}_{\text{in}}} = \frac{(19,971 + 0) \text{ kW}}{48,999 \text{ kW}} = 0.408
\]

- 40.8\% of the energy is utilized for a useful purpose
- Utilization factor is equivalent to the thermal efficiency in this case
$\dot{E}_{in} = \dot{E}_{out}$

$\dot{m}_4 h_4 + \dot{m}_5 h_5 = \dot{Q}_{p,\text{out}} + \dot{m}_7 h_7$

$\dot{Q}_{p,\text{out}} = \dot{m}_4 h_4 + \dot{m}_5 h_5 - \dot{m}_7 h_7$

$\dot{m}_4 = (0.1)(15 \text{ kg/s}) = 1.5 \text{ kg/s}$

$\dot{m}_5 = (0.7)(15 \text{ kg/s}) = 10.5 \text{ kg/s}$

$\dot{m}_7 = \dot{m}_4 + \dot{m}_5 = 1.5 + 10.5 = 12 \text{ kg/s}$

$\dot{Q}_{p,\text{out}} = (1.5 \text{ kg/s})(3411.4 \text{ kJ/kg}) + (10.5 \text{ kg/s})(2739.3 \text{ kJ/kg})$

$- (12 \text{ kg/s})(640.09 \text{ kJ/kg})$

$= 26.2 \text{ MW}$

Heat input in the boiler is 43.0 MW
11MW of electric power is produced (25.6% of input)
BUT Utilization factor is 86.5%
Gas turbine generating capacities range from 3 MW up to over 250MW. Units of any size can be used in CHP systems and gas turbines are probably the cheapest prime movers available today. However they are best suited for continuous base-load operation. Regular output change can increase wear and maintenance significantly.
Gas Turbine Based CHP

• The heat output from a gas turbine is all found in its exhaust. This is a high-temperature source and it can be used to generate high temperature, high-pressure steam.

• Hence a gas turbine will normally only be used in a CHP application where there is a need for high-quality steam. This steam will be generated in a waste-heat boiler attached directly to the turbine exhaust.

• Two features provide the gas turbine with additional flexibility in CHP applications
  - Turbine is capable of generating steam of sufficient quality to power a steam turbine. This means that steam demand can be balanced with electricity output by exploiting unwanted steam in a steam turbine to generate additional power.
  - Exhaust from a gas turbine contains a considerable quantity of oxygen because the gas turbine combustion system employs an excess of air. This means that if necessary a waste-heat boiler can be fitted with a supplementary firing system to generate additional steam.

• This allows a gas turbine CHP system to be matched accurately to heat and electricity demand, allowing efficiencies of up to 90%.
Other CHP

• Micro turbines based CHP
  ▪ Low efficiency 20-30% as a stand-alone unit
  ▪ But exhaust heat can be used to generate low-pressure steam or hot water

• Fuel cells base CHP
  ▪ Efficiencies range from 36% in operating units available today
  ▪ Extremely good at load following, where their part-load loss of efficiency is minimal
  ▪ In CHP applications they can deliver up to 85% utilization

• Nuclear power
  ▪ Normally seen as best suited to base-load power generation
  ▪ In principle nuclear power can be used for CHP in exactly the same way as any other source of heat
    − In Russia and Eastern Europe some nuclear plants supply district heat
    − Environmental concerns attached to nuclear generation have limited this type of use
Environmental consideration of CHP - Noise

It is considered because many CHP installations are designed for installation in commercial or urban domestic situations where any noise output is likely to be intrusive.

Fuel cells – most silent
However there is likely to be some noise associated with pumps and perhaps cooling systems. Designs intended for use close to homes or workplaces should be able to minimise noise to such an extent that it is no longer a consideration.

Micro turbines – modern units are quiet
These are designed to be operated in close proximity to human activity.

Piston engine - always noisy
Small piston-engine-based CHP systems are often intended for use in offices or for small district heating systems. However the engines are always noisy. They will normally require sound insulation and specially designed exhaust silencers for using in proximity with homes or offices. Underground or rooftop sites have often been employed to keep the units as isolated as possible.
Large piston engine plants, gas turbines and steam turbines are all relatively noisy and none is suitable for use close to housing or commercial units. These can all be used in large distributed generation applications but considerable attention to physical isolation of the site will be necessary.
Environmental consideration of CHP

Heat Waste – is it a problem?

The heat that is released into the environment by power stations can be classified as a form of pollution. This source of pollution is often ignored. **Global Warming!** However there are situations – such as using river water for power station cooling – where heat output can change the local environmental conditions significantly.

Energy Utilization

The most significant impact of CHP is to increase the energy efficiency of power generation. When a CHP plant is installed, the heat it captures and utilises will replace one of the other sources of heat energy. So the fuel or electricity previously needed to produce this heat will be saved.

Manufacturers claim that a CHP plant is perhaps 80% or 90% efficient while the underlying power generating unit is only 30% efficient. Such figures are slightly misleading since they do not mean that 80% of the energy is being turned into electricity. **Utilization factor** is the most accurate term to use.

A more useful measure would be the amount of fuel saved by the use of CHP. For example if a power plant has a fuel to electricity conversion efficiency of 33%, and in a CHP installation 83% of the energy is captured, then 50% of the fuel energy is being captured as heat. Thus half the CHP plant fuel is replacing fuel otherwise needed to generate heat.
Summary - CHP

• The most significant impact of CHP is to increase, often dramatically, the efficiency of power generation.
  – Power plants at best can only convert 60% of the energy in the fuel they burn into electricity. Generally efficiency is much lower.
  – On average probably 60–70% of all the fuel burned to generate electricity is dissipated as waste heat.
  – At the same time offices, homes, small commercial and large industrial plants use electricity or fossil fuel to produce heat for space heating, for hot water and to provide the energy for chemical reactions.

• When a CHP plant is installed, the heat it captures and utilises will replace one of these other sources of heat energy. So the fuel or electricity previously needed to produce this heat will be saved. This clearly represents a dramatic improvement in the use of energy and it is for this reason that CHP is considered by many to be a key element in future global energy strategies.
  – The reduced use of fuel as a consequence of CHP will also reduce atmospheric emissions. Here again the effect is dramatic.

• Finally one might also consider the economics of CHP. But how is one to quantify the savings made from the use of CHP?
  – How much heat do we need? (Most heat waste are from large power plants)
  – If a homeowner with a domestic boiler for central heating and hot water, and with a grid connection for electricity, installs a CHP unit which produces both, it will take a simple calculation to determine how much that homeowner has saved. Similar calculations apply to industrial installations.
  – Normally such calculations show that the saving is significant