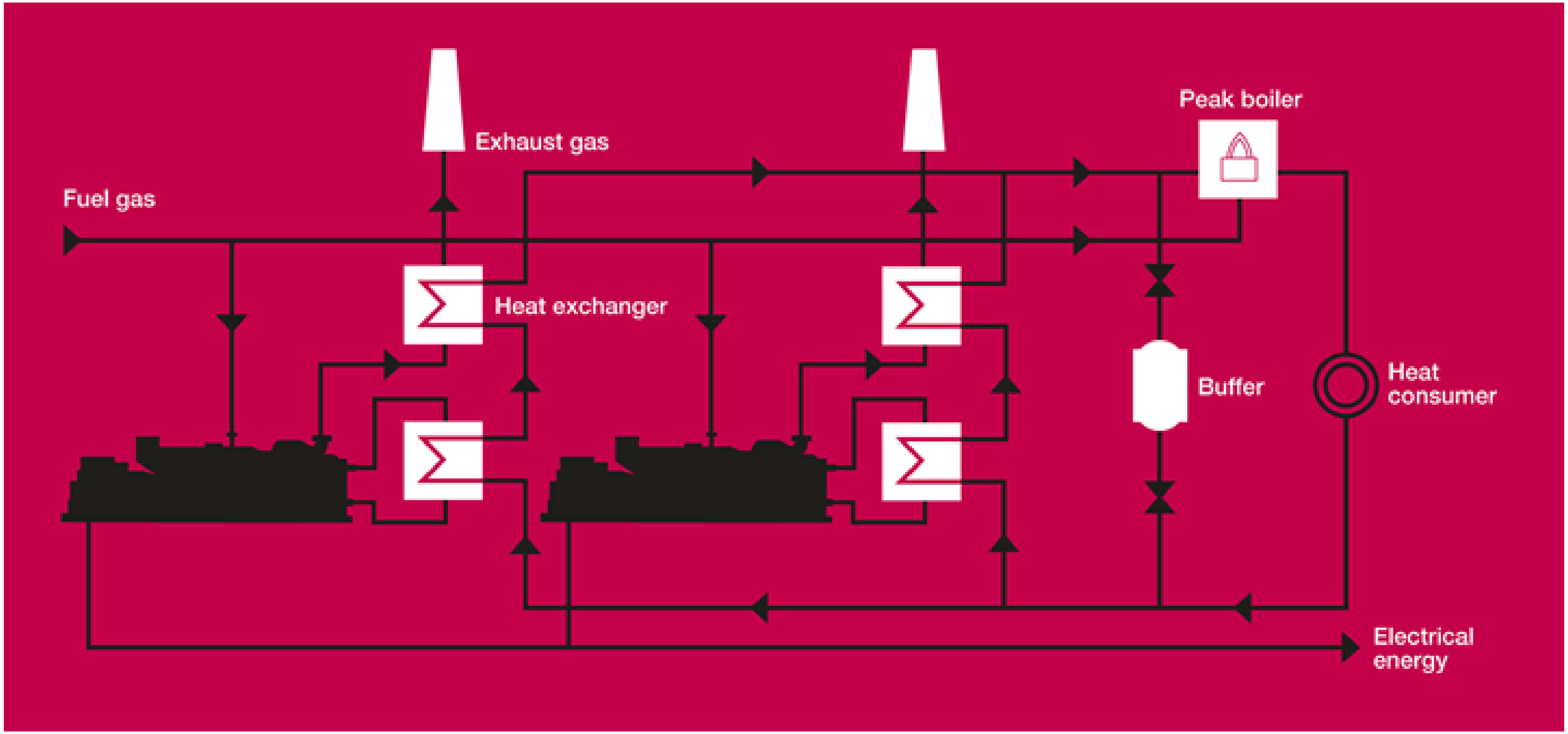
Cogeneration / Combined heat and Power (CHP)

Cogeneration (*cogen*) through **combined heat and power** (*CHP*) is the simultaneous production of electricity with the recovery and utilisation heat. Cogeneration is a highly efficient form of energy conversion and it can achieve primary energy savings of approximately 40% by compared to the separate purchase of electricity from the national electricity grid and a gas boiler for onsite heating.

Combined heat and power plants are typically embedded close to the end user and therefore help reduce transportation and distribution losses, improving the overall performance of the electricity transmission and distribution network

For power users where security of supply is an important factor for their selection of power production equipment and gas is abundant, gas-based cogeneration systems are ideally suited as captive power plants (i.e. power plants located at site of use).


Exhaust gas
Peak boiler
Fuel gas
Heat exchanger
Buffer
Heat
consumer
Electrical
energy

Benefits of Gas Engine CHP

The high efficiency of a CHP plant compared with conventional bought in electricity and site-produced heat provides a number of benefits including

- On site production of power
- Reduced energy costs
- Reduction in emissions compared to conventional electrical generators and onsite boilers

Heat Sources from a Gas Engine

The heat from the generator is available in from 5 key areas:

1. Engine jacket cooling water
2. Engine lubrication oil cooling
3. First stage air intake intercooler
4. Engine exhaust gases
5. Engine generator radiated heat, second stage intercooler

1, 2 and 3 are recoverable in the form of hot water, typically on a 70/90˚C flow return basis and can be interfaced with the site at a plate heat exchanger.

The engine exhaust gases typically leave the engine at between 400 and 500˚C. This can be used directly for drying, in a waste heat boiler to generate steam, or via an exhaust gas heat exchanger combining with the heat from the cooling circuits.

The heat from the second stage intercooler is also available for recovery as a lower grade heat. Alternatively new technologies are available for the conversion of heat to further electricity, such as the Organic Rankine Cycle Engine.

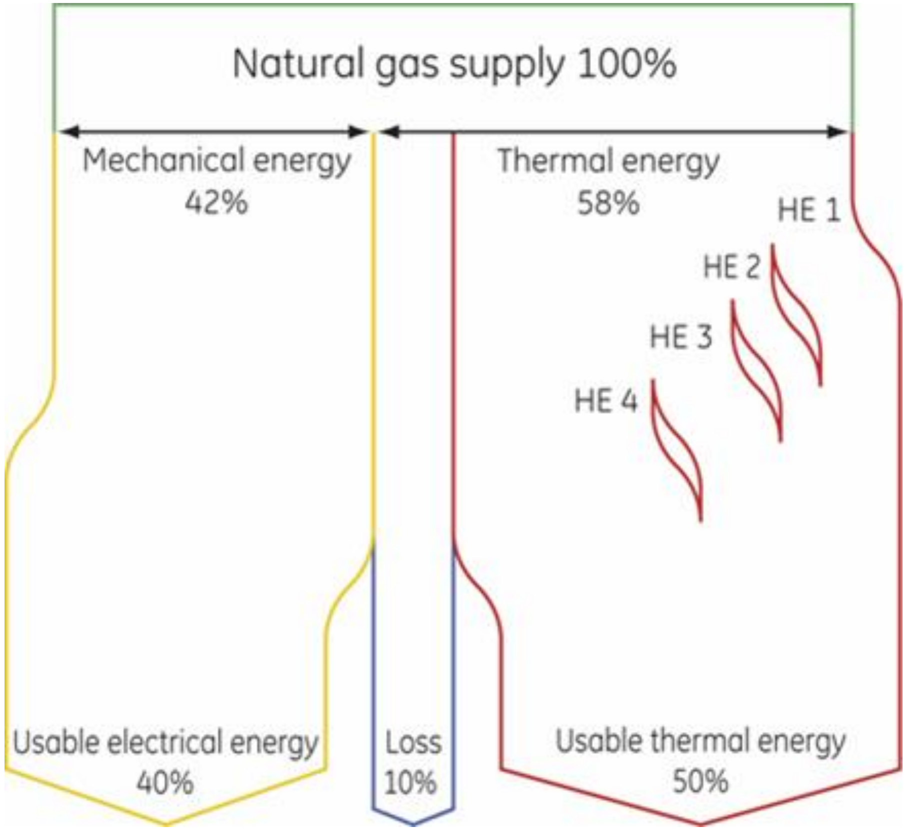
CHP applications

A variety of different fuels can be used to facilitate cogeneration. In gas engine applications CHP equipment is typically applied to natural gas (commercial, residential and industrial applications), biogas and coal gas applications.

CHP System Efficiency

Gas engine combined heat and power systems are measured based upon the efficiency of conversion of the fuel gas to useful outputs. The diagram below illustrates this concept.

Firstly the energy in the fuel gas input is converted into mechanical energy via the combustion of the gas in the engine's cylinders and their resulting action in the turning of the engine's crankshaft. This mechanical energy is in turn used to turn the engine's alternator in order to produce electricity. There is a small amount of inherent loss in this process and in this example the electrical efficiency of the engine is 40% (in reality gas engines are typically between 40-48.7% electrically efficient).



(Diagram key: HE 1 - Mixture intercooler, HE 2 - Oil exchange heater, HE 3 - Engine jacket water heat exchanger, HE 4 - Exhaust gas heat exchanger)

The Five Key Technologies Deployed in Combined Heat Power Systems

Five main technologies are used in typical CHP systems.

These technologies, sometimes referred to as "prime movers," are:

<u>Gas turbines (or combustion turbines).</u>

Such turbines revolutionized airplane propulsion in the 1940s. Since the 1990s they have become a popular choice for power generation systems, including CHP. In this technology, air is taken in, compressed, burned with a fuel (usually natural gas), and then ejected to drive a turbine that generates power. Heat can be recovered from the exhaust and put to use for heating, cooling, or industrial processes.

<u>Steam turbines (or back-pressure steam turbines).</u>

These are used in a majority of power plants across the United States. In these turbines, water is pressurized, heated by a burning fuel, and converted to steam, which is then used to drive a turbine that generates power. The steam turbine was the earliest prime mover used in large-scale power generation, dating back to the late 1800s. In a CHP system, any exhaust steam left after the power-generation step can be put to productive use, as described above.

Reciprocating engines.

Such engines are used in most motor vehicles, and the technology has significantly improved in electrical efficiencies over the past few decades. The engines have a combustion chamber in which fuel is burned. The combustion pushes a piston that drives a crankshaft to generate power. Heat can be recovered from the exhaust and jacket water and put to use.

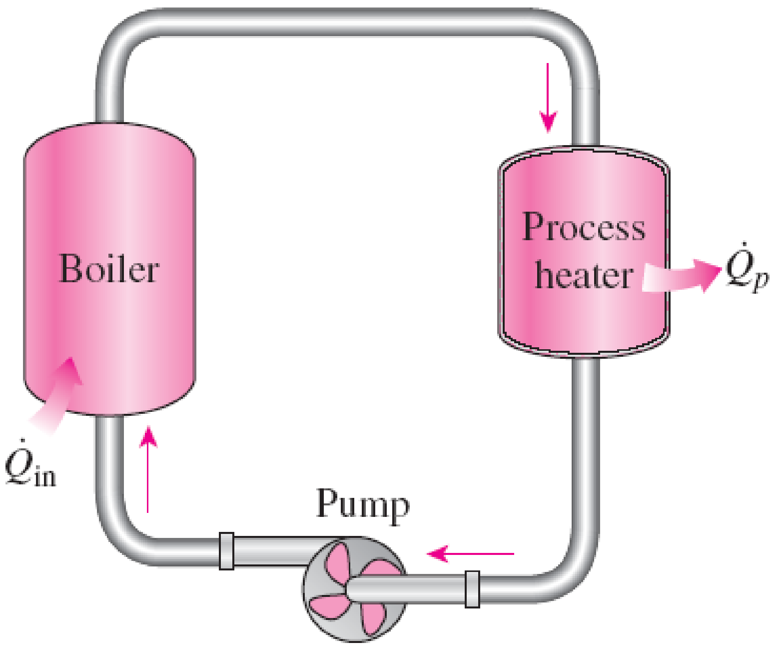
Fuel cells. Fuel cells electrochemically convert fuel to generate electricity. Typically this involves the combining of hydrogen and oxygen. A fossil fuel, such as natural gas, can be chemically reformed to produce hydrogen. Heat generated during the fuel cell's electrochemical reaction can be recovered for certain uses, such as heating water.

Microturbines. These are essentially small gas turbines that employ modified processes and structures to generate power and heat.

CHP system—gas turbine (center), with hot gases heading to heat recovery steam generator (right).

COGENERATION

- Many industries require energy input in the form of heat, called ***process heat***. Process heat in these industries is usually supplied by steam at 5 to 7 atm and 150 to 200°C.
- Energy is usually transferred to the steam by burning coal, oil, natural gas, or another fuel in a furnace.



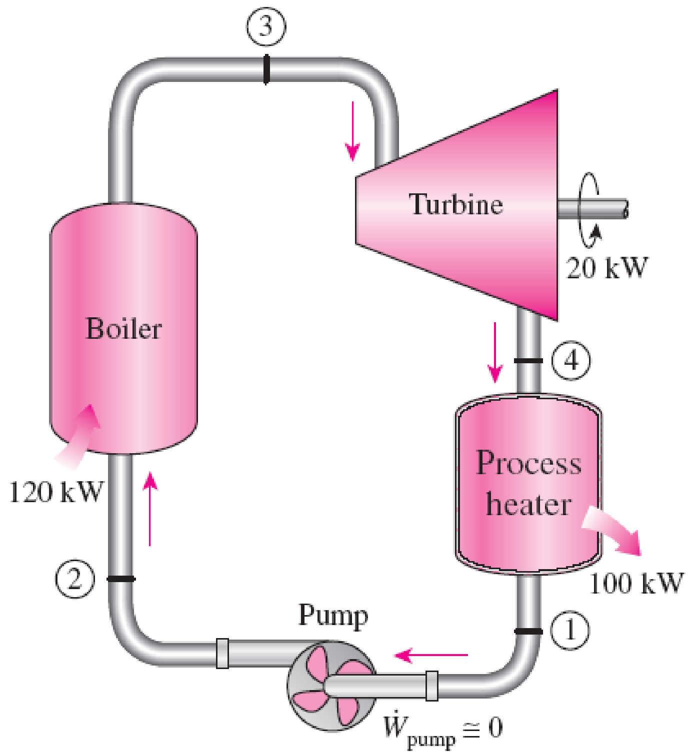
A simple process-heating plant.

Industries that use large amounts of process heat also consume a large amount of electric power.

It makes sense to use the already-existing work potential to produce power instead of letting it go to waste.

The result is a plant that produces electricity while meeting the process-heat requirements of certain industrial processes (cogeneration plant)

Cogeneration: The production of more than one useful form of energy (such as process heat and electric power) from the same energy source



An ideal cogeneration plant.

Utilization factor

$$\epsilon_u = \frac{\text{Net work output} + \text{Process heat delivered}}{\text{Total heat input}} = \frac{\dot{W}_{net} + \dot{Q}_p}{\dot{Q}_{in}}$$

$$\epsilon_u = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}}$$

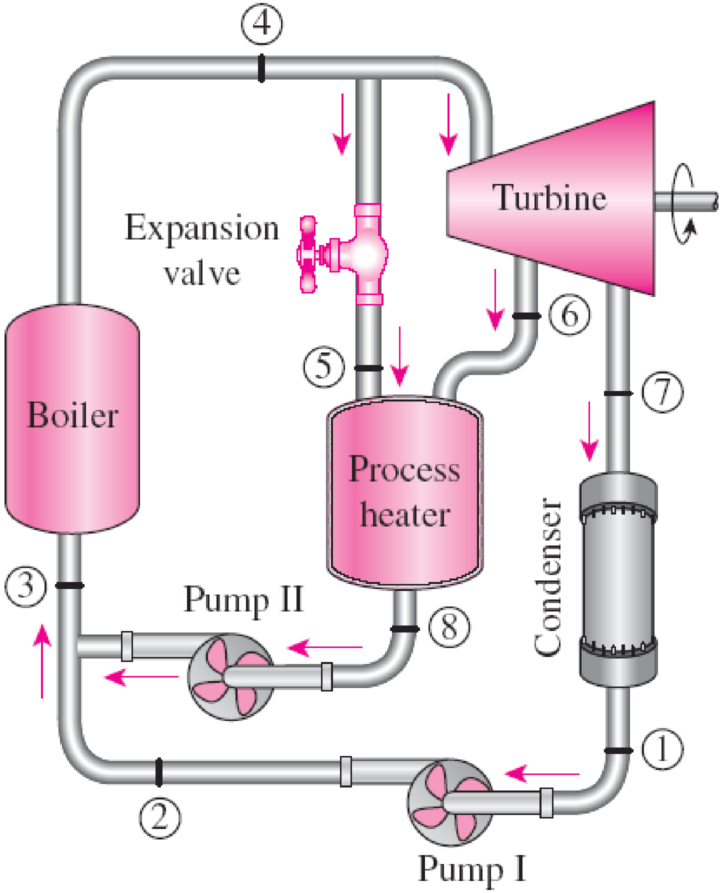
The utilization factor of the ideal steam-turbine cogeneration plant is 100%.

- Actual cogeneration plants have utilization factors as high as 80%.

- Some recent cogeneration plants have even higher utilization factors.

A cogeneration plant with adjustable loads

At times of high demand for process heat, all the steam is routed to the process-heating units and none to the condenser ($m7= 0$). The waste heat is zero in this mode. If this is not sufficient, some steam leaving the boiler is throttled by an expansion or pressure-reducing valve to the extraction pressure $P6$ and is directed to the process-heating unit. Maximum process heating is realized when all the steam leaving the boiler passes through the PRV ($m5= m4$). No power is produced in this mode. When there is no demand for process heat, all the steam passes through the turbine and the condenser ($m5=m6=0$), and the cogeneration plant operates as an ordinary steam power plant.



$$\dot{Q}_{in} = \dot{m}_3(h_4 - h_3)$$

$$\dot{Q}_{out} = \dot{m}_7(h_7 - h_1)$$

$$\dot{Q}_p = \dot{m}_5 h_5 + \dot{m}_6 h_6 - \dot{m}_8 h_8$$

$$\dot{W}_{turb} = (\dot{m}_4 - \dot{m}_5)(h_4 - h_6) + \dot{m}_7(h_6 - h_7)$$

A cogeneration plant with adjustable loads

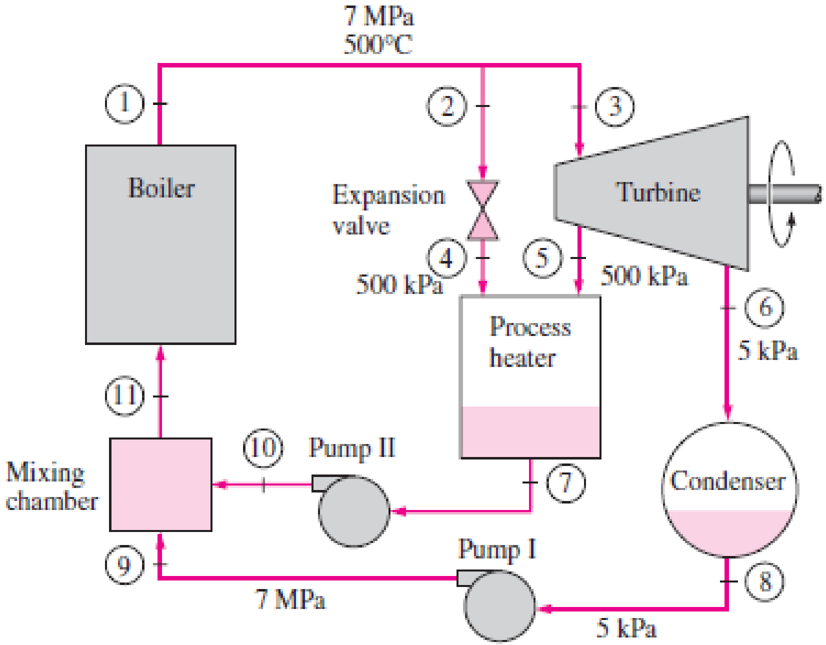
EXAMPLE 10–8 An Ideal Cogeneration Plant

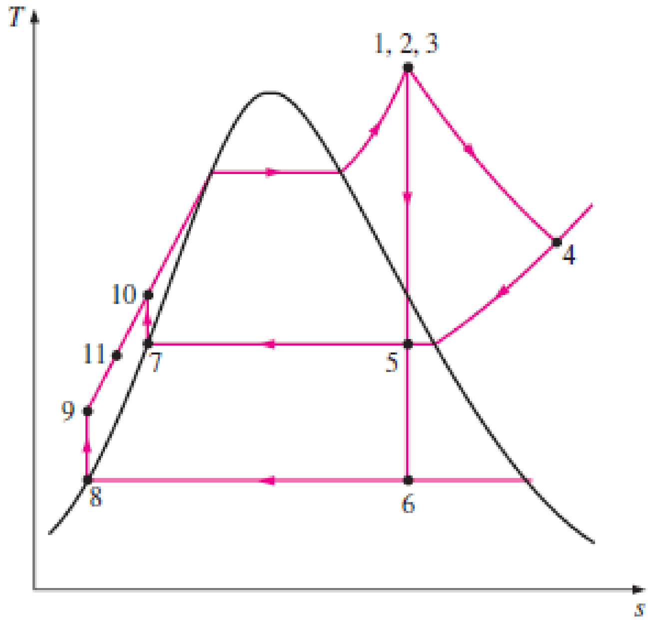
Consider the cogeneration plant shown in Fig. 10–23. Steam enters the turbine at 7 MPa and 500°C. Some steam is extracted from the turbine at 500 kPa for process heating. The remaining steam continues to expand to 5 kPa. Steam is then condensed at constant pressure and pumped to the boiler pressure of 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 maximum rate at which process heat can be supplied, (*b*) the power produced and the utilization factor when no process heat is supplied, and (*c*) the rate of process heat supply when 10 percent of the steam is extracted before it enters the turbine and 70 percent of the steam is extracted from the turbine at 500 kPa for process heating.

Solution A cogeneration plant is considered. The maximum rate of process heat supply, the power produced and the utilization factor when no process heat is supplied, and the rate of process heat supply when steam is extracted from the steam line and turbine at specified ratios are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Pressure drops and heat losses in piping are negligible. **3** Kinetic and potential energy changes are negligible.

Analysis The schematic of the cogeneration plant and the *T-s* diagram of the cycle are shown in Fig. 10–23. The power plant operates on an ideal


7 MPa
500°C
Boiler
Expansion valve
500 kPa
500 kPa
Turbine
Process heater
5 kPa
Condenser
Mixing chamber
Pump II
Pump I
7 MPa
5 kPa


T
s
1, 2, 3
4
5
6
7
8
9
10
11

cycle and thus the pumps and the turbines are isentropic; there are no pressure drops in the boiler, process heater, and condenser; and steam leaves the condenser and the process heater as saturated liquid.

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

$$w_{\text{pump I,in}} = v_8(P_9 - P_8) = (0.001005\ \text{m}^3/\text{kg})[(7000 - 5)\text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= 7.03\ \text{kJ/kg}$$

$$w_{\text{pump II,in}} = v_7(P_{10} - P_7) = (0.001093\ \text{m}^3/\text{kg})[(7000 - 500)\ \text{kPa}]\left(\frac{1\ \text{kJ}}{1\ \text{kPa}\cdot\text{m}^3}\right)$$

$$= 7.10\ \text{kJ/kg}$$

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

$$h_5 = 2739.3\ \text{kJ/kg}$$

$$h_6 = 2073.0\ \text{kJ/kg}$$

$$h_7 = h_{f\,@\,500\ \text{kPa}} = 640.09\ \text{kJ/kg}$$

$$h_8 = h_{f\,@\,5\ \text{kPa}} = 137.75\ \text{kJ/kg}$$

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

$$h_{10} = h_7 + w_{\text{pump II,in}} = (640.09 + 7.10)\ \text{kJ/kg} = 647.19\ \text{kJ/kg}$$

(*a*) The maximum rate of process heat is achieved when all the steam leaving the boiler is throttled and sent to the process heater and none is sent to the turbine (that is, $\dot{m}_4 = \dot{m}_7 = \dot{m}_1 = 15$ kg/s and $\dot{m}_3 = \dot{m}_5 = \dot{m}_6 = 0$). Thus,

$$\dot{Q}_{p,\text{max}} = \dot{m}_1(h_4 - h_7) = (15\ \text{kg/s})[(3411.4 - 640.09)\ \text{kJ/kg}] = \mathbf{41{,}570\ kW}$$

The utilization factor is 100 percent in this case since no heat is rejected in the condenser, heat losses from the piping and other components are assumed to be negligible, and combustion losses are not considered.

(*b*) 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 (that is, $\dot{m}_3 = \dot{m}_6 = \dot{m}_1 = 15$ kg/s and $\dot{m}_2 = \dot{m}_5 = 0$). Maximum power is produced in this mode, which is determined to be

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

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

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

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

Thus,

$$\epsilon_u = \frac{\dot{W}_{\text{net}} + \dot{Q}_p}{\dot{Q}_{\text{in}}} = \frac{(19{,}971 + 0) \text{ kW}}{48{,}999 \text{ kW}} = \mathbf{0.408 \text{ or } 40.8\%}$$

That is, 40.8 percent of the energy is utilized for a useful purpose. Notice that the utilization factor is equivalent to the thermal efficiency in this case.

(*c*) Neglecting any kinetic and potential energy changes, an energy balance on the process heater yields

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_4h_4 + \dot{m}_5h_5 = \dot{Q}_{p,out} + \dot{m}_7h_7$$

or

$$\dot{Q}_{p,out} = \dot{m}_4h_4 + \dot{m}_5h_5 - \dot{m}_7h_7$$

where

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

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

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

Thus

$$\begin{aligned}\dot{Q}_{p,out} &= (1.5 \text{ kg/s})(3411.4 \text{ kJ/kg}) + (10.5 \text{ kg/s})(2739.3 \text{ kJ/kg}) \\ &\quad - (12 \text{ kg/s})(640.09 \text{ kJ/kg}) \\ &= \mathbf{26.2\ MW}\end{aligned}$$

Discussion Note that 26.2 MW of the heat transferred will be utilized in the process heater. We could also show that 11.0 MW of power is produced in this case, and the rate of heat input in the boiler is 43.0 MW. Thus the utilization factor is 86.5 percent.

ORC Based CHP systems

Combined heat and power (CHP) generation system is a flexible technology that allows the simultaneous production of heat and power in the same process offering high reliability with the possibility of being driven by alternative and clean renewable energy resources including biomass combustion heat, solar thermal energy and low-grade waste heat.

Using CHP systems for electricity and heat production for both industrial and residential applications is very cost-effective and can save up to 35% of the primary energy generated compared with conventional heat and power systems .

A framework for the development of highly efficient CHP generation systems was provided in the European Directive 2004/8/EC in order to attain primary savings in the internal energy market . The total CHP systems capacity installed in the EU has exceeded 100 GW where Germany is leading with 22% of the EU overall capacity followed

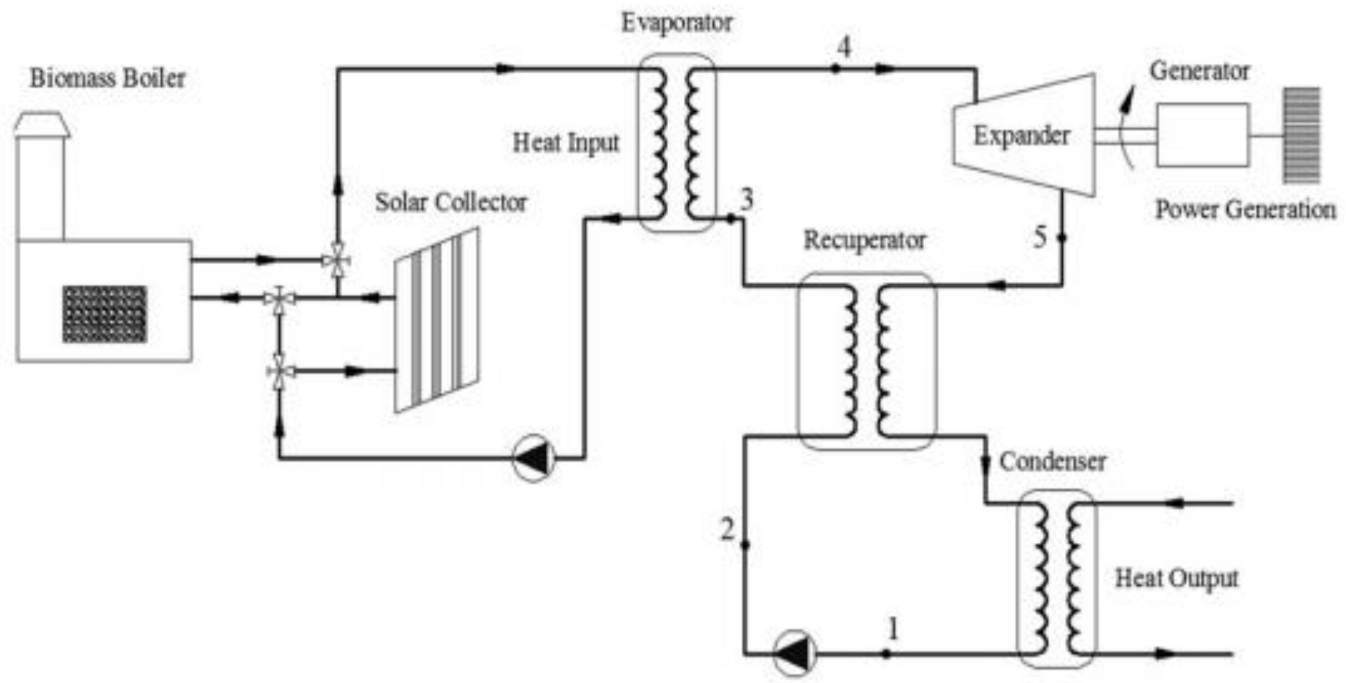
Some of the technologies are commercially available such as **reciprocating and micro-turbine engines**, whereas others are still in the research and development phase including **organic Rankine cycle (ORC) units and fuel cell-based systems.**

Stirling and Rankine units are the two most favourable and feasible technologies for micro-CHP systems in buildings driven by renewable energy resources due to their flexibility, low emissions and acceptable efficiencies.

However, Stirling engines need high-quality heat, which is accompanied by high investment costs. Thus, Rankine-based micro-CHP units provide an effective technology to supply heat and electricity for residential applications with an acceptable efficiency.

Utilizing the same technology as the ordinary steam-based Rankine units, ORC-based micro-CHP systems employ organic working fluids as the main driver instead of water. They have received an increasing attention in the recent years in the field of micro-scale power generation and heating in residential and building applications with various advantages compared to the ordinary steam cycle

Thermodynamic analysis of an a solar-biomass driven Organic Rankine Cycle



Schematic of an ORC based micro CHP plant

Thermodynamic analysis of ORC

$$W_P = \dot{m} \times (h_2 - h_1) \quad (1)$$

The ideal work output provided by the expander is given by:

$$W_{Ex} = \dot{m} \times (h_4 - h_5) \quad (2)$$

where h is the enthalpy of the working fluid (J/kg), and $\dot{m}$ is the working fluid mass flow rate (kg/s). The ORC net work can be expressed as follows:

$$W_{net} = \dot{m} \times [(h_4 - h_5) - (h_2 - h_1)] \quad (3)$$

On the other side, the external heat input at the evaporator can be given by:

$$Q_{in} = \dot{m} \times (h_4 - h_3) \quad (4)$$

The overall ORC thermal efficiency is the ratio of the net work over the total input external heat and can be given by:

$$\eta_{\mathrm{ORC}} = \frac{W_{\mathrm{net}}}{Q_{\mathrm{in}}} \tag{5}$$

The mechanical efficiency of the expander is defined as the electric power output W_{Ele} divided by the expander actual work output:

$$\eta_{\mathrm{mech}} = \frac{W_{\mathrm{Ele}}}{\dot{m} \times (h_4 - h_5)} \tag{6}$$

The expander isentropic efficiency is defined as the ratio of the actual work produced by the expander over the ideal work and can be given by the following equation:

$$\eta_{\mathrm{is}} = \frac{(h_4 - h_5)}{(h_4 - h_{5'})} \tag{7}$$

where $h_{5'}$ is the isentropic enthalpy of the working fluid at the expander outlet.

The useful heat absorbed by the condenser water can be given by

$$Q_{\mathrm{cond}} = \dot{m}_{\mathrm{cond}} \times (h_{\mathrm{cond\_out}} - h_{\mathrm{cond\_in}}) \tag{8}$$

where $\dot{m}_{\mathrm{cond}}$ is the mass flow rate (kg/s) of the condenser cooling water. The total amount of solar energy available at the solar collector is expressed as follows:

$$Q_{\mathrm{Sol}} = I_{\mathrm{Sol}} \times A_{\mathrm{col}} \tag{9}$$

where I_{Sol} is the total solar radiation flux (W/m^2) available at the collector and A_{col} is collector aperture area (m^2). The heat of combustion provided by the biomass boiler is given in terms of the rate of consumption of the biomass pellets $\dot{m}_{Bio}$ and lower heating value (LHV) of the wood pellets:

$$Q_{Bio} = \dot{m}_{Bio} \times \mathrm{LHV} \tag{10}$$

Thus, the ORC-based micro-CHP system electrical and thermal efficiencies are given by the following equations, respectively:

$$\eta_{Ele} = \frac{W_{out}}{Q_{Sol} + Q_{Bio}} \tag{11}$$

$$\eta_{Th} = \frac{Q_{cond}}{Q_{Sol} + Q_{Bio}} \tag{12}$$