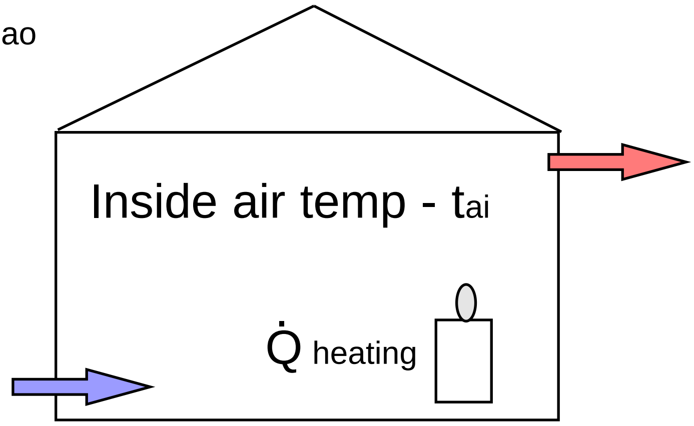
ECONOMIC USE OF ENERGY

HEATING (or COOLING) of BUILDINGS

Outside air temp (OAT) - t_{ao}



Ventilation air flow - $\dot{m}$

Internal Heat production - $\dot{Q}_{total}$

At **steady** conditions $\dot{Q}_{total} = \underbrace{\dot{m}C_p(t_{ai} - t_{ao})}_{\boxed{\text{Ventilation or Infiltration losses}}} + \underbrace{U_oA(t_{ai} - t_{ao})}_{\boxed{\text{Fabric losses}}}$

U_o = Overall heat transfer coefficient for the building

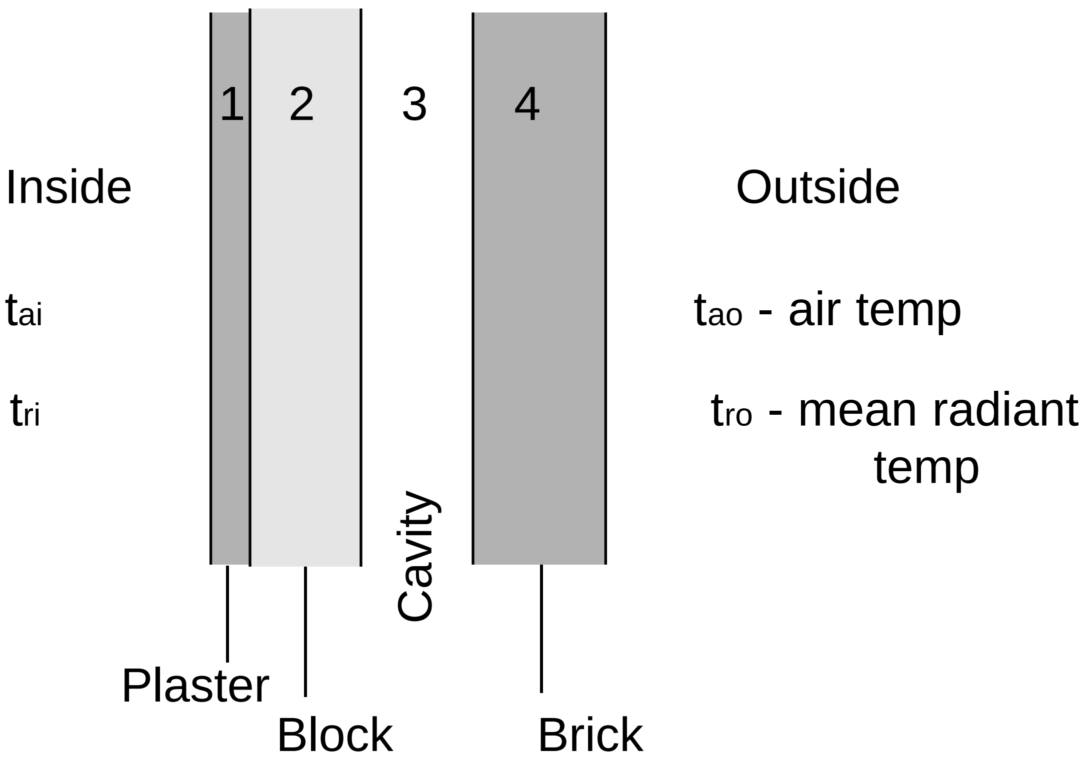
$$\dot{Q}_{total} = \dot{Q}_{heating} + \underbrace{\boxed{\begin{array}{c}\dot{Q}_{occupants} + \dot{Q}_{solar} + \dot{Q}_{lights} + \dot{Q}_{elec.m/s} + \\ \text{(solar gain)}\end{array}}}_{\text{Incidental or Casual gains}}$$

$$U_oA = UA_{roof} + UA_{walls} + UA_{floor} + UA_{windows} + UA_{doors}$$

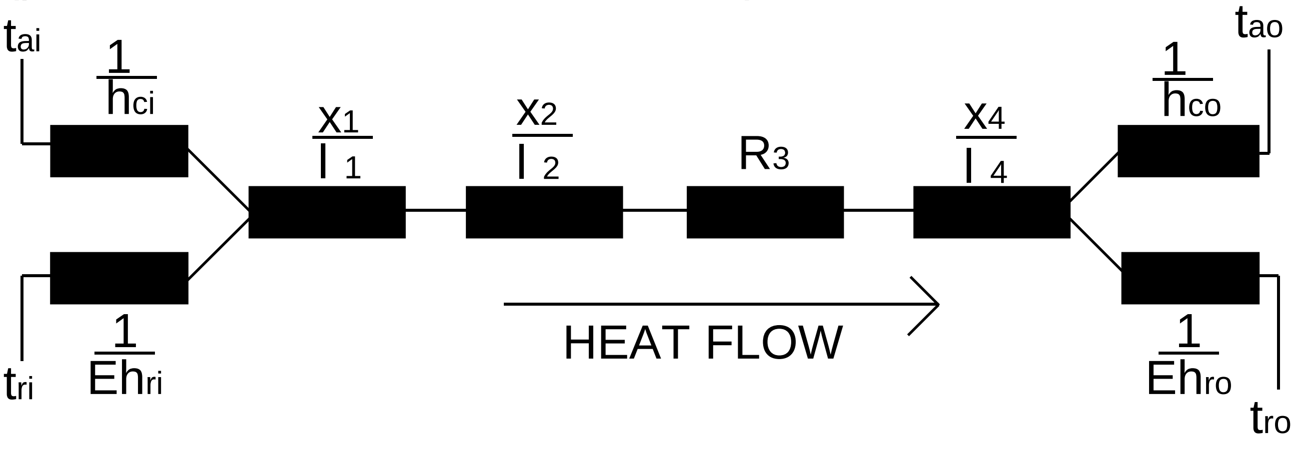
How do we find the thermal transmittance (or U-values) for given structures?

1) By reference to tables eg CIBSE guide A3
2) By calculation from thermal data

U-values by Calculation:- Example



Equivalent Thermal Resistance Network
(per m^2 of area normal to heat flow)



Notes : h_r = radiation heat transfer coefficient assuming black surfaces

E = Emissivity

l may vary with moisture content of the material

$$R_{si} = \frac{1}{(h_{ci} + E\,h_{ri})}$$ the surface thermal resistance etc:

Total thermal resistance = Sum of component resistances

$$q_{total} = S\, q_{components}$$

$$\dot{Q} = U\, A\, DT = \frac{A\, DT}{q_{total}}$$

therefore $$U = \frac{1}{q_{total}}$$

It is usually assumed that $t_{ai} = t_{ri}$ & $t_{ao} = t_{ro}$

ENERGY CONSUMPTION OF BUILDINGS

$$Q_{\ total} = \dot{m}\ Cp(t_{ai} - t_{ao}) + U_o A\ (t_{ai} - t_{ao})$$

Energy = Q x time

TOTAL ENERGY USED $= (\dot{m}\ Cp\ Dt + Uo\ A\ Dt) \times time$

$$= \boxed{(\dot{m}\ Cp + U_o\ A)} \times \boxed{(Dt \times time)}$$

A characteristic of the building: - depends on the heat transfer resistance of the fabric and the degree to which it is ventilated

Climatalogical conditions
- Dt varies hourly, daily, monthly, annually.
How do we measure this?

DEGREE-DAYS

$$\dot{Q}_{total} = \dot{Q}_{heating} + \dot{Q}_{casual}$$

lighting, motors, people etc; all of which offsets $Q_{heating}$

The desired inside temperature depends on 'level of activity' eg:-

Heavy manual work 15 °C

Sendentary office work 20 °C

We'll assume an inside temperature of 19 °C

Below what outside temp do we need to supply heat?

Answer : approx 15.5 °C, ie;

⇧ Cooling required
15.5 °C No heating or cooling
⇩ Heating required

1 degree day is registered when the OAT is 1 degree below 15.5 °C for 1 day ie, degree-days measure the climatological parameter to enable us to do energy consumption predictions or comparisons.

DESIGN HEAT LOAD

The heating requirement or 'load' of a building depends on the outside air temperature, so, for what OAT do we size a heating system?

If we choose 'too low' a temperature - the heating system will be oversized:-

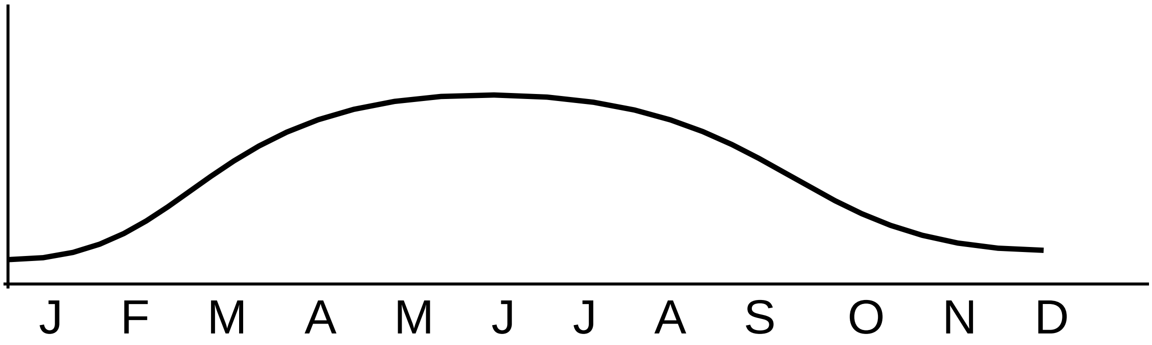
Higher capital cost than necessary

Part load operation for much of its life which often means inefficient operation.

If we choose 'too high' a temperature - the heating system will be undersized :-

Frequent periods of underheating leading to discomfort of occupants etc;

Annual Average Temperature Variation



We choose a design OAT which will enable the heating system to maintain the inside temperature at the desired level for a reasonable proportion of the time.

eg: Hospitals - 99%
Public Buildings- 95%
Houses 90% etc;

The actual decision requires analysis of meteorological data.

For the U.K. a typical design temp. would be -1 °C

ANNUAL HEATING COSTS

If the design heat load is $\dot{Q}$ kW

For one (24h) day at -1 °C (16.5 degree days) the energy required is

$$\dot{Q} \times 24 \qquad \text{kWh}$$

Therefore for one degree-day the energy required is :-

$$\frac{\dot{Q} \times 24}{16.5} \qquad \text{kWh}$$

If there are 'n' degree-days p.a. then the annual energy requirment (heating only) is :-

$$\frac{\dot{Q} \times 24 \times n}{16.5} \qquad \text{kWh p.a.}$$

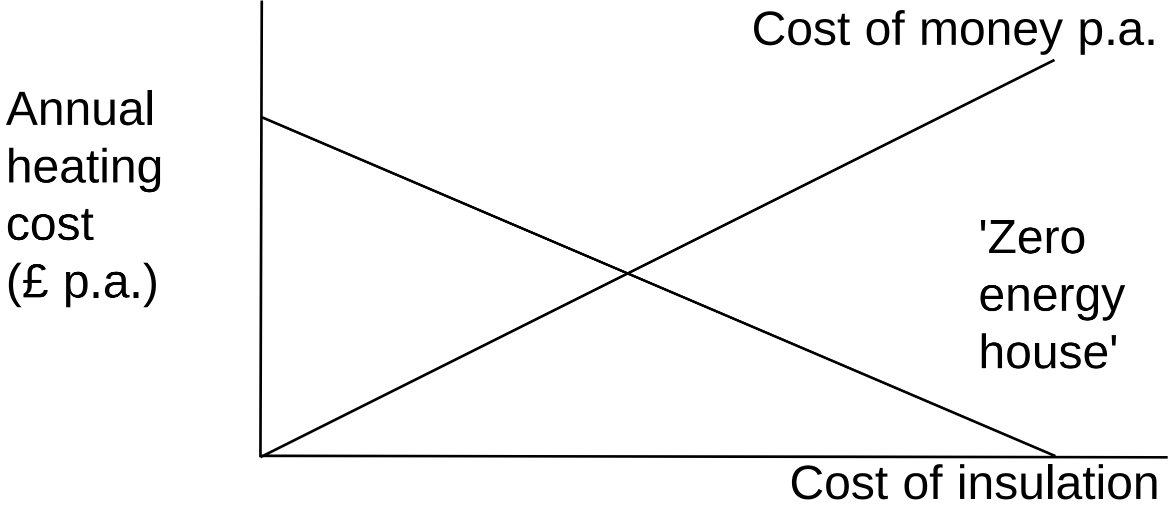
If heating energy cost is 'p' £/kWh and the heating system's average seasonal heating efficiency is h_{heat}
then annual heating cost is :-

$$\frac{\dot{Q} \times 24 \times n \times p}{16.5 \times h_{heat}} \qquad \text{£ p.a.}$$

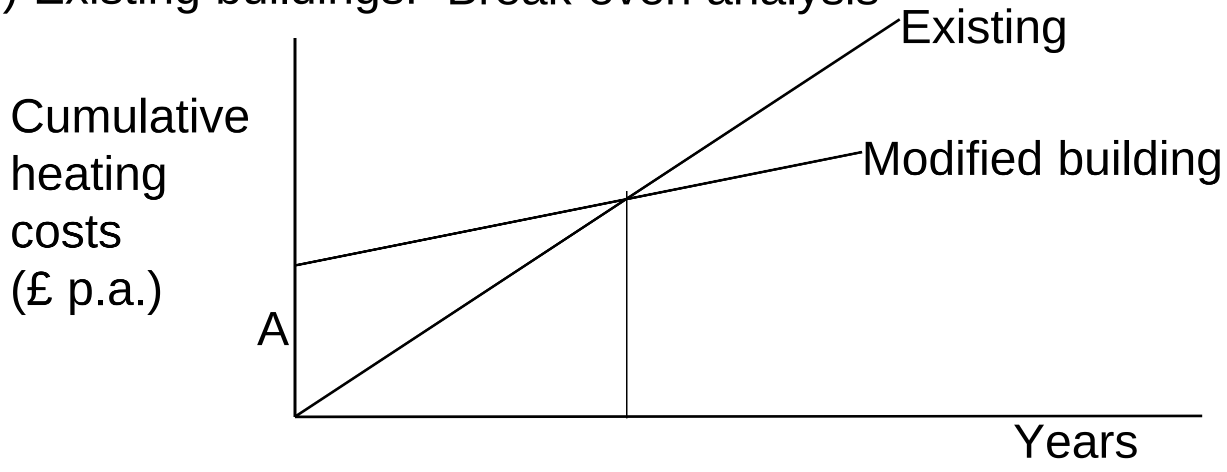
Any energy efficiency measure should be reflected by a change in slope of the heating cost /degree-day graph

ECONOMICS OF INSULATION.

(A) New buildings - the economics are based on a chosen (or available) fuel, it's cost, the capital cost of the building & the heating system:-



(B) Existing buildings: Break-even analysis



Insulation will reduce the slope of the curve but will cost an initial capital sum (A). Break-even time is the point beyond which the total costs of the modified building are less than for the unmodified total cost. ie the point at which 'savings' occur.

This technique (or any similar technique eg discounted cash flow) may be used on any energy conservation measure. The required repayment period would be set by company policy:-

Typically 1 - 3 years may be 'acceptable'.

ECONOMICS OF DOUBLE GLAZING

Single glazed U-value 5 W/m²K

Double glazed U-value 3 W/m²K

Assume double glazed area of 10 m²

Assume gas heating @ 65% efficiency;
energy cost = 1.2 p/kWh

cf. Elec. storage heating energy cost = 2.8 p/kWh
Cost of double glazing approx: £ 1500!
SW degree-days 2200 p.a.

	Single	Double
Q_{des}	21 x 10 x 5 W = 1.010 kW	21 x 10 x 3 W = 0.63 kW
Annual heat reqd	$\frac{1.010 \times 24 \times 2200}{16.5}$ = 3232 kWh	$\frac{0.63 \times 24 \times 2200}{16.5}$ = 2016 kWh
Cost p.a.	£ 38.78 £ 90.50	£ 24.19 (gas) £ 56.45 (elec)

Repayment period:-

$$\frac{1500}{38.78 - 24.19} = 103 \text{ years (gas)}$$

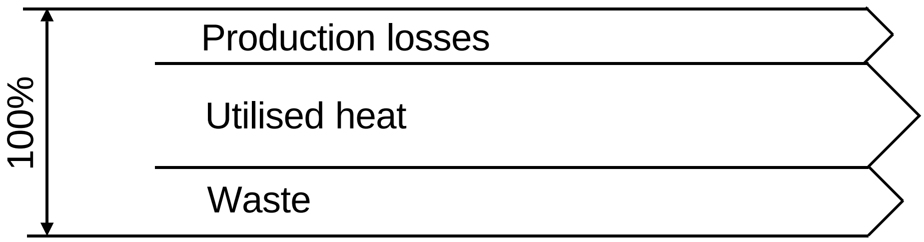
$$\frac{1500}{90.50 - 56.45} = 44 \text{ years (elec)}$$

HEAT RECOVERY

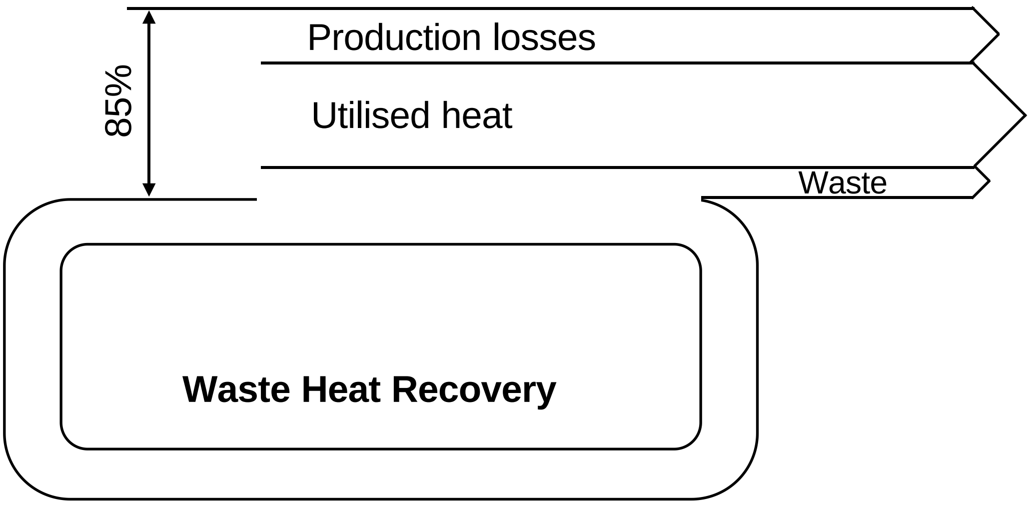
Where a hot gas or liquid stream is produced as the result of combustion or some other heating process, it may be possible to recover a proportion of the energy that would otherwise be rejected to the environment.

The process of recovering heat is known as heat recovery or 'waste' heat recovery.

Without Heat Recovery:

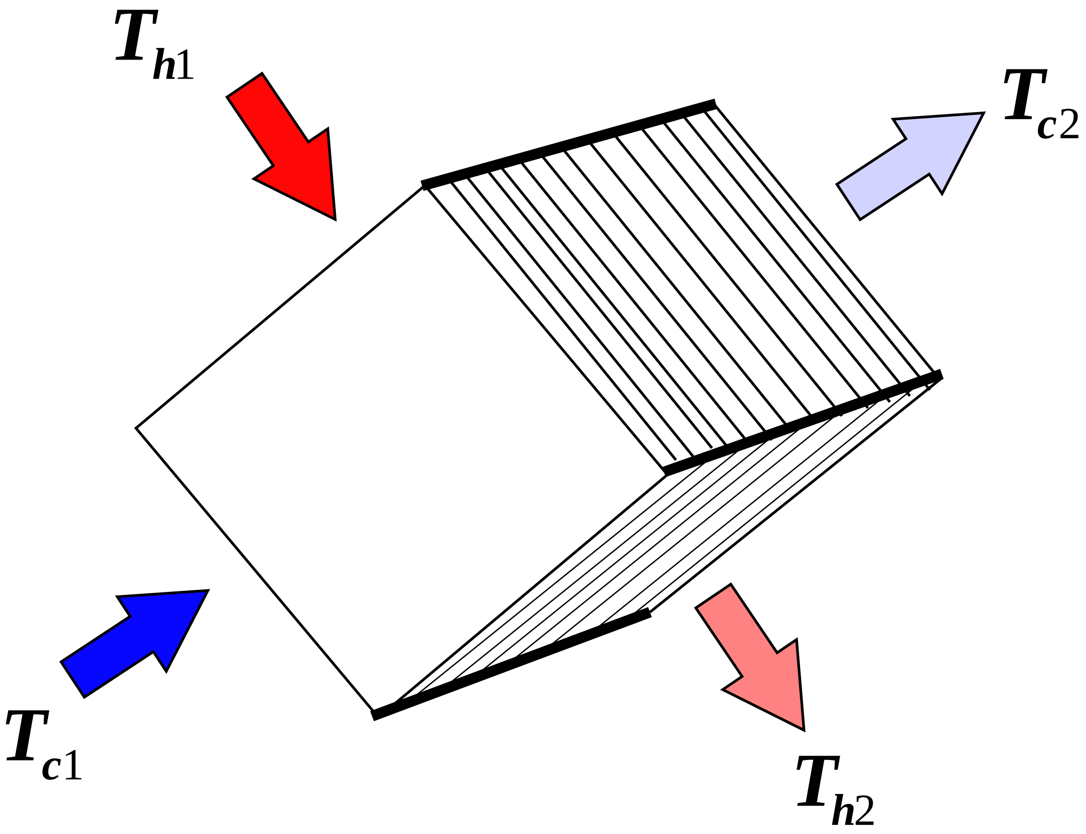


With Heat Recovery:



Heat recovery is usually effected by the use of heat-exchangers (See Heat Transfer notes), where we may use effectiveness-NTU or LMTD methods of analysis/design. We can also define another measure of heat-exchanger performance known simply as its 'thermal ratio'.

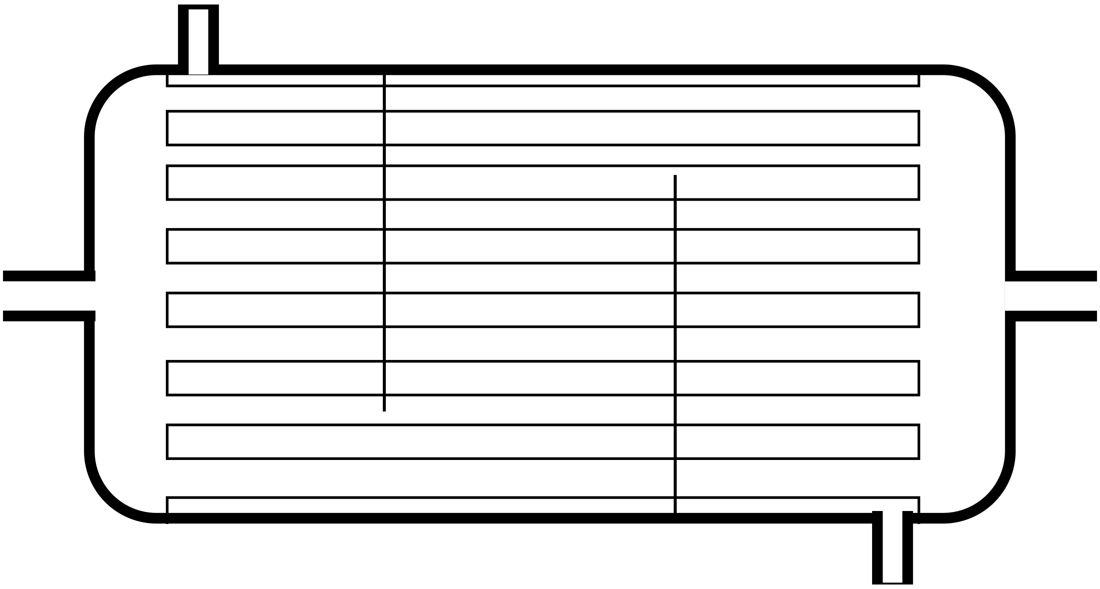
Cross-flow HX



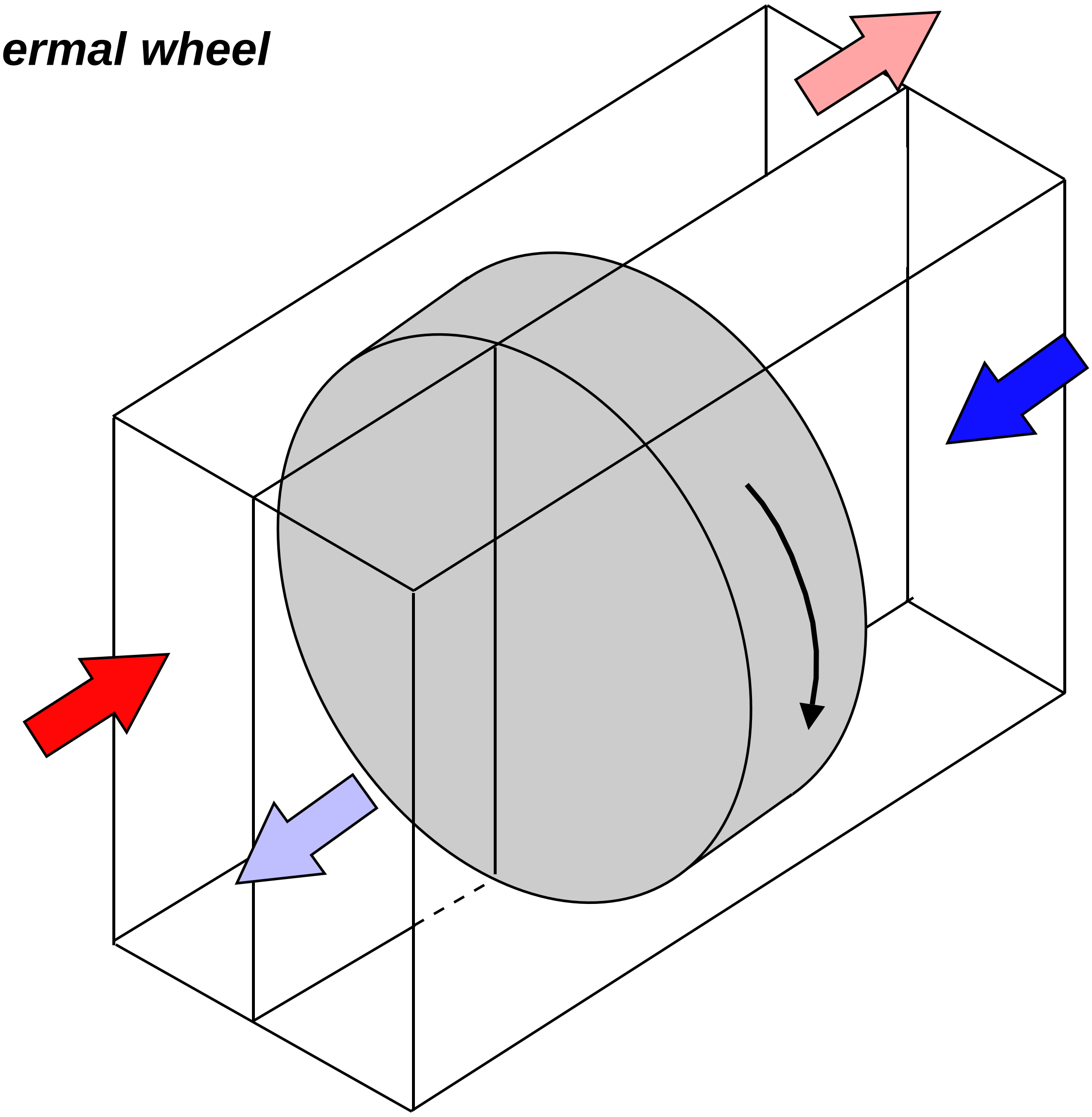
$$\textbf{Thermal ratio} = \frac{T_{c2} - T_{c1}}{T_{h1} - T_{c1}}$$

$$\textbf{Effectiveness} = \frac{\dot{m}_c Cp_c (T_{c2} - T_{c1})}{(\dot{m} Cp)_{\max} (T_{h1} - T_{c1})}$$

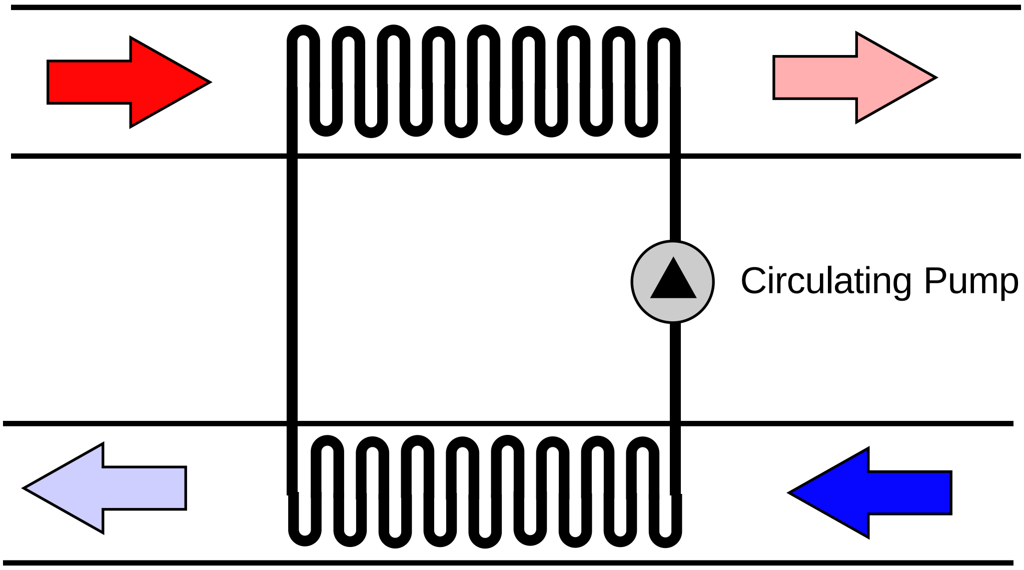
Conventional Shell-and-Tube HX



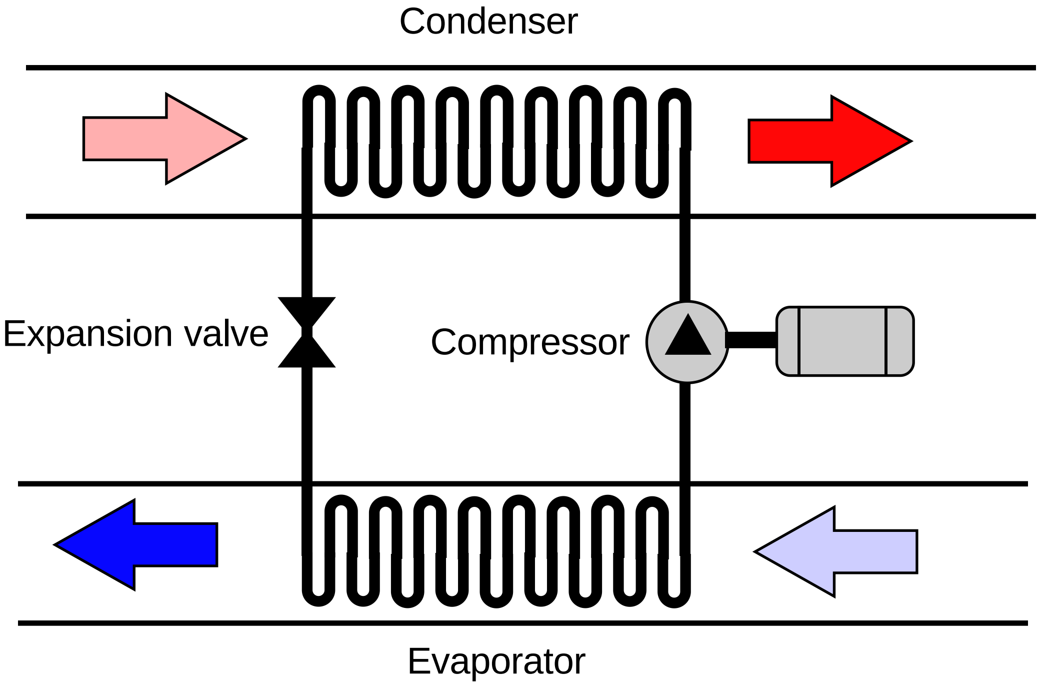
Thermal wheel



'Run-around' coils



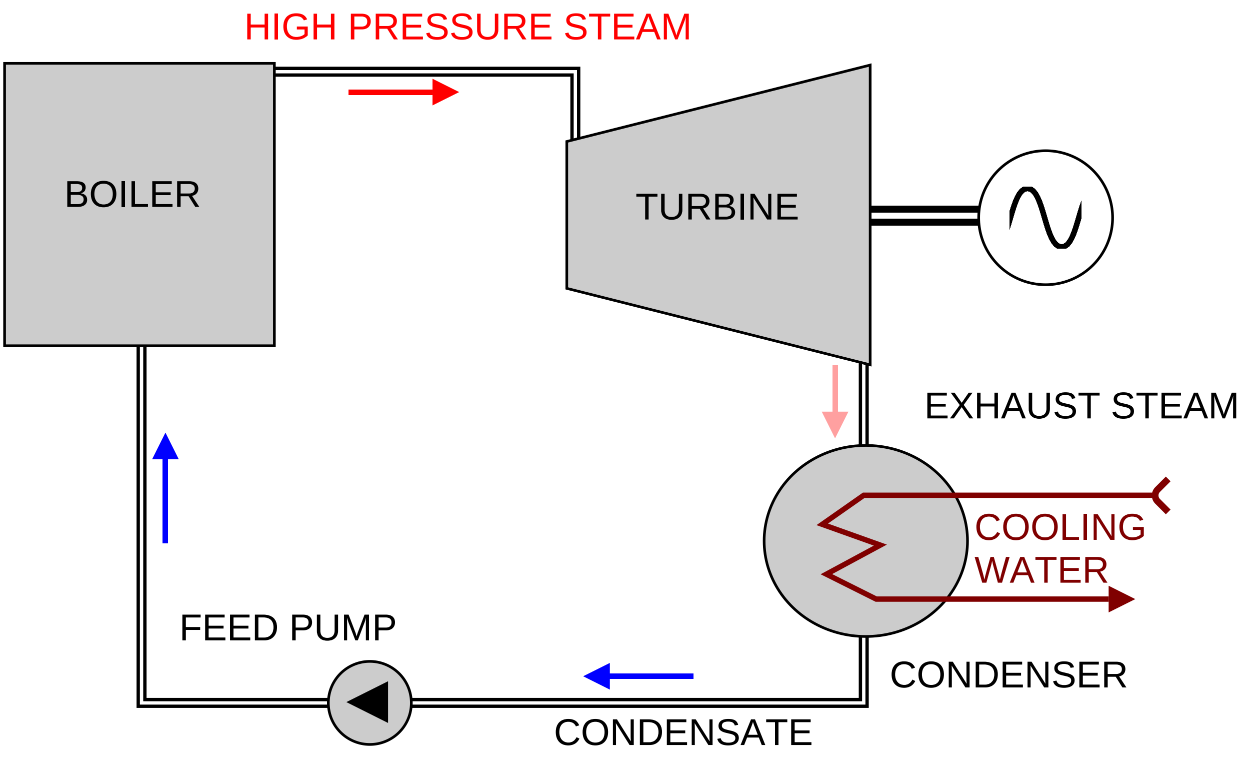
Heat-pump



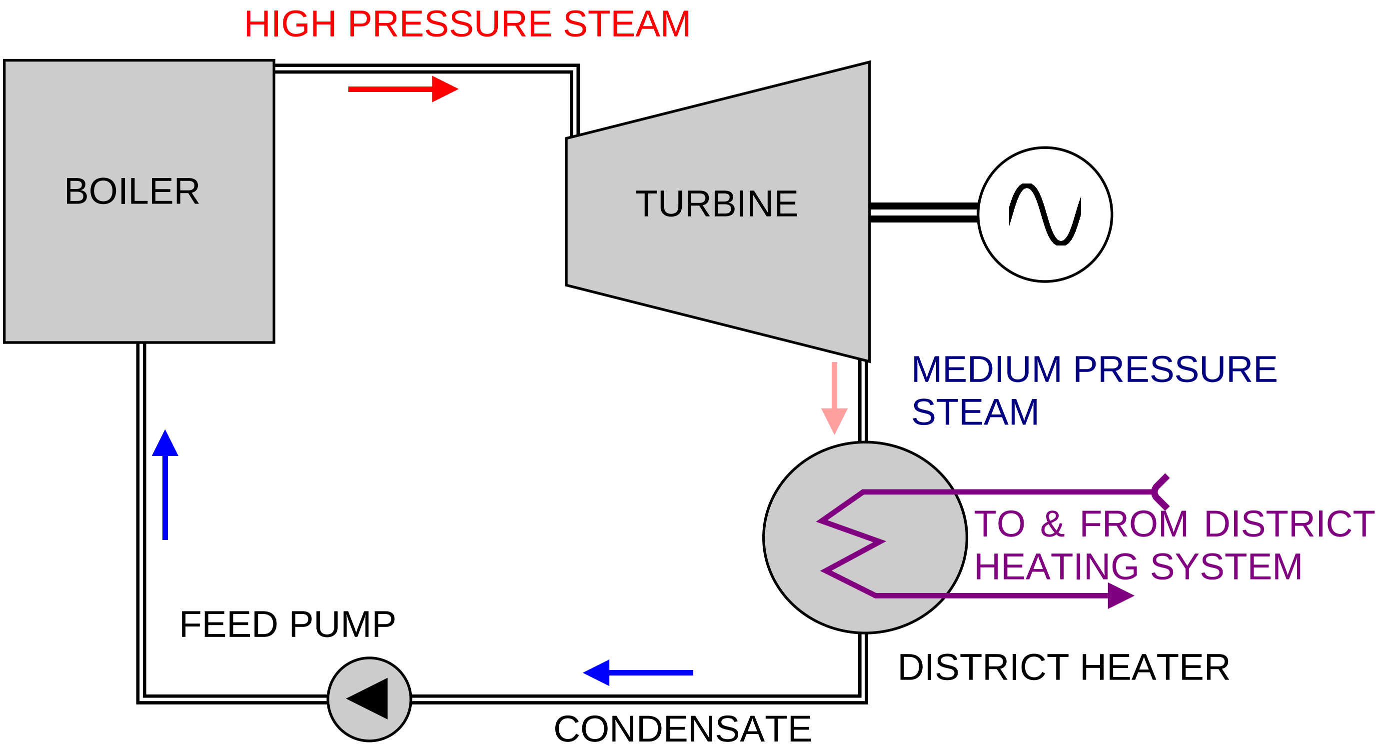
This is the only system capable of upgrading the temperature, it has been called a 'thermal transformer'.

Combined Heat and Power (CHP)

Steam Turbine Plant

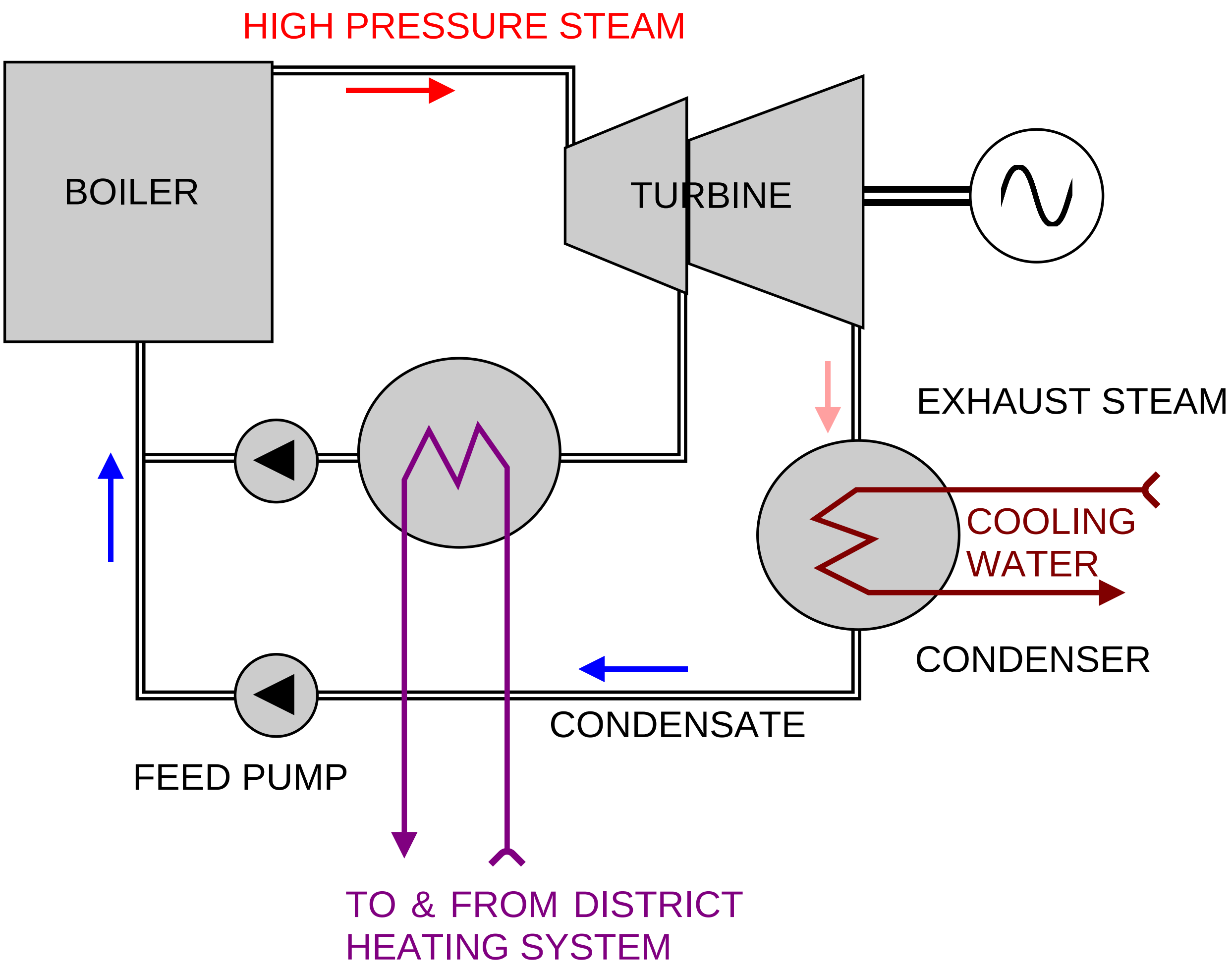


The above shows a simplified steam turbine arrangement for the production of electricity. High pressure steam, raised in a boiler from the heat of combustion of fossil fuel or from nuclear heat, is expanded through a turbine and work is extracted via the alternator in the form of electricity. The low pressure exhaust steam is condensed, rejecting its latent heat to cooling water, and the cycle completed by pumping the condensate back to the boiler. The heat rejected to the condenser cooling water is finally disposed of into the atmosphere via cooling towers or direct to a river or the sea. Typically, a little over half of the heat of combustion of the fuel is rejected to the cooling water, the temperature of which is raised to between 15°C and 35°C. The amount of cooling water used is quite large and there is very little use for such large amounts of tepid water although fish farming and horticulture are possible applications for smaller quantities.



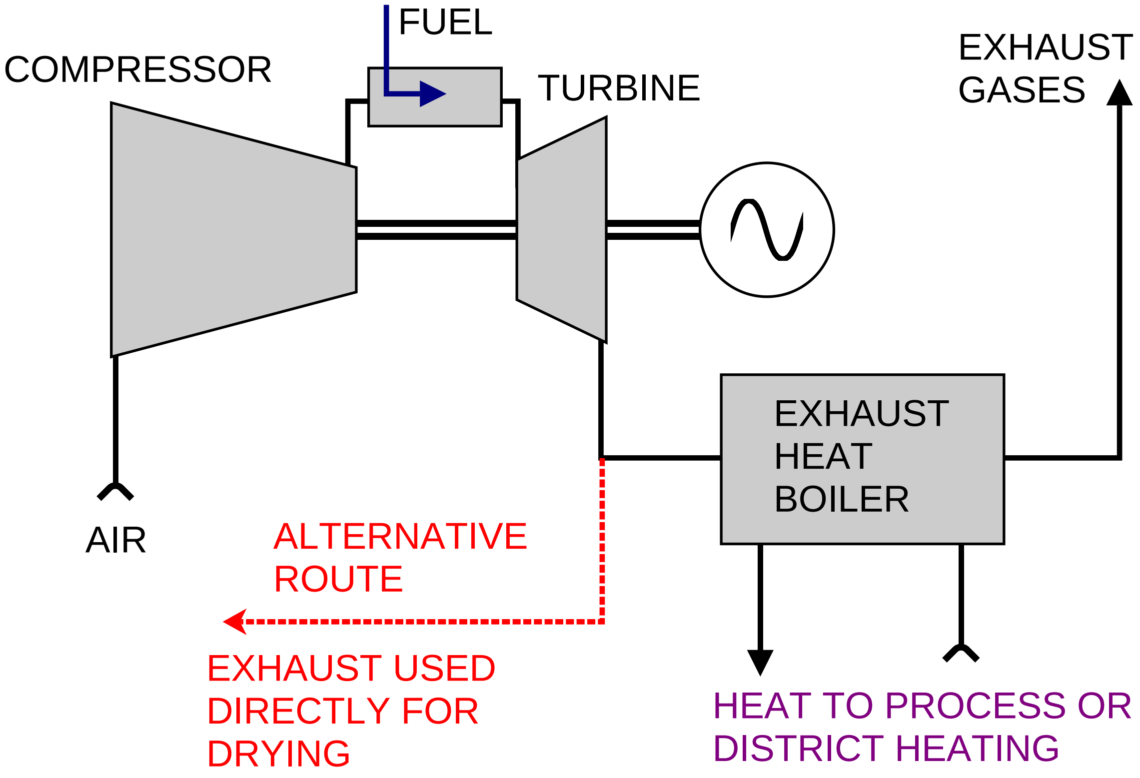
Steam turbine plant can, however, be designed to operate in such a way that the heat of condensation is extracted at a sufficiently high temperature to be useful.
Although upgrading of the condenser temperature results in some reduction in electrical output, the energy utilisation of the plant, {(work + useful heat)/heat supplied} will be greater than that produced in an electricity only plant.

The above shows a CHP system for district heating incorporating 'back-pressure' turbine operation in which all the steam is condensed in a heat exchanger at a pressure and temperature (85-110°C) higher than for a normal condensing turbine.



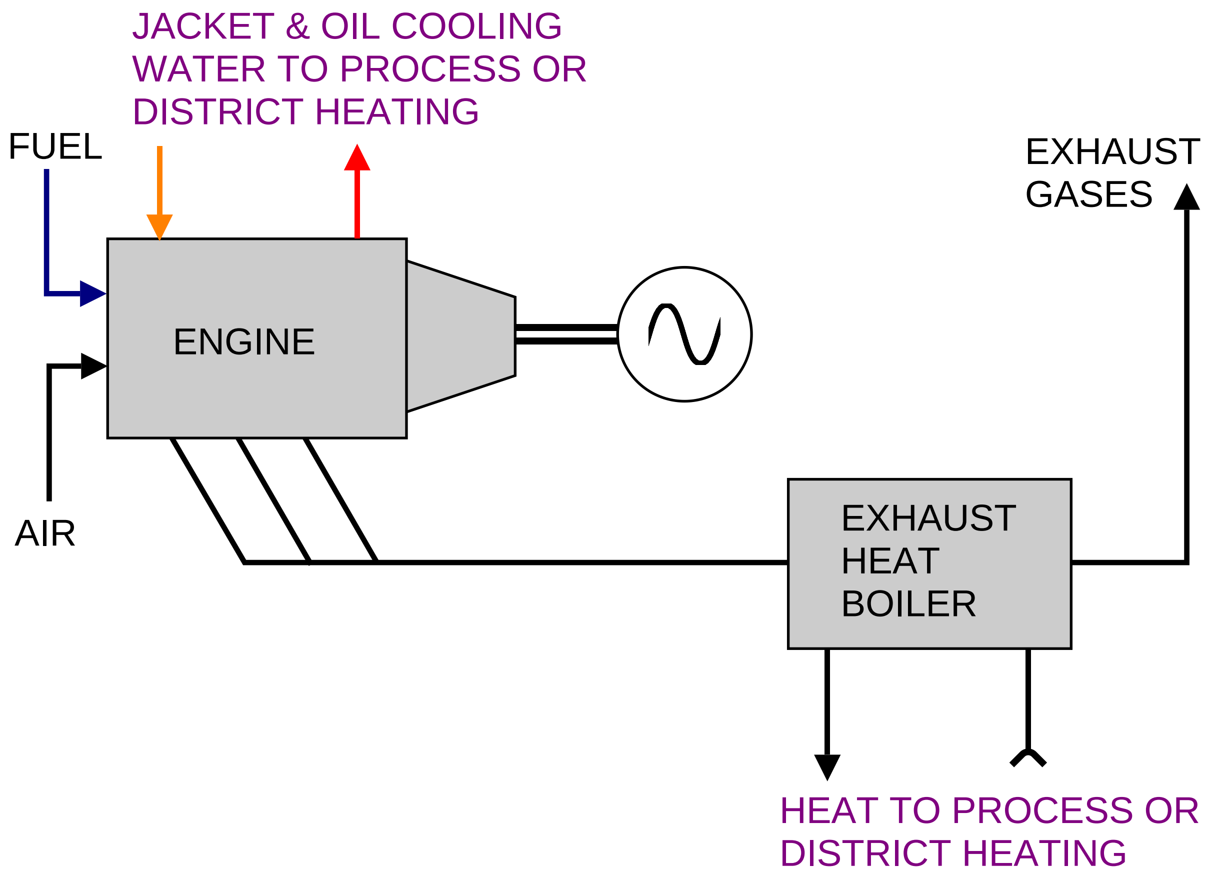
The above shows a CHP 'pass-out' turbine for district heating. In this case some of the steam is extracted at an intermediate temperature to provide heat for district heating, while the rest, after full expansion through the turbine, is condensed in the 'conventional' manner. In industrial applications the intermediate temperature steam, in back-pressure or pass-out operation, may go directly to the industrial process. The choice of equipment for 'in-house' factory CHIP generation (i.e. whether back-pressure or pass-out turbines, or a combination of these) will depend largely on the heat/electricity ratio required to be met. The size of steam turbine unit can vary from only a few megawatts for industrial applications to some hundreds of megawatts.

Gas Turbine plant



The above shows a gas turbine CHP system. The high temperature gaseous products of combustion which would normally be rejected in an electricity only scheme, are passed through a heat exchanger producing heat in the form of steam for an industrial process or in the form of hot water for district heating. Gas turbine exhaust gas can also be used directly for drying. This type of plant is less capital intensive than steam turbine plant but its overall efficiency for electricity production is lower and because of this and the need to use expensive fuels such as gas and distillate fuel oil, the gas turbine has higher operating costs than a steam turbine. Gas turbine sizes can range from under 1 MW(e) to large machines in the order of 50 to 100 MW(e). The high temperature exhaust from a gas turbine can also be used to raise steam for steam turbines.
In the longer term, fluidised bed combustors using coal or any low grade fuels may be used in association with gas turbines, as can coal derived synthetic fuels.

Internal combustion engines



This group includes gas engines, diesel engines, dual-fuel engines and petrol engines. Sizes range up to some tens of MW(e) for low speed, heavy fuel oil diesel engines.
The above shows how heat can be extracted from the exhaust of a reciprocating engine in much the same way as from a gas turbine. The heat in the jacket and oil cooling water can also be utilised in certain applications.