RENEWABLE ENERGY THERMODYNAMICS & HEAT ENGINES

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LECTURE OUTLINE

- ❑ ***Laws of thermodynamics***
- ❑ ***Fuels & combustion***
- ❑ ***Heat engines***
- ❑ ***Heat pumps***

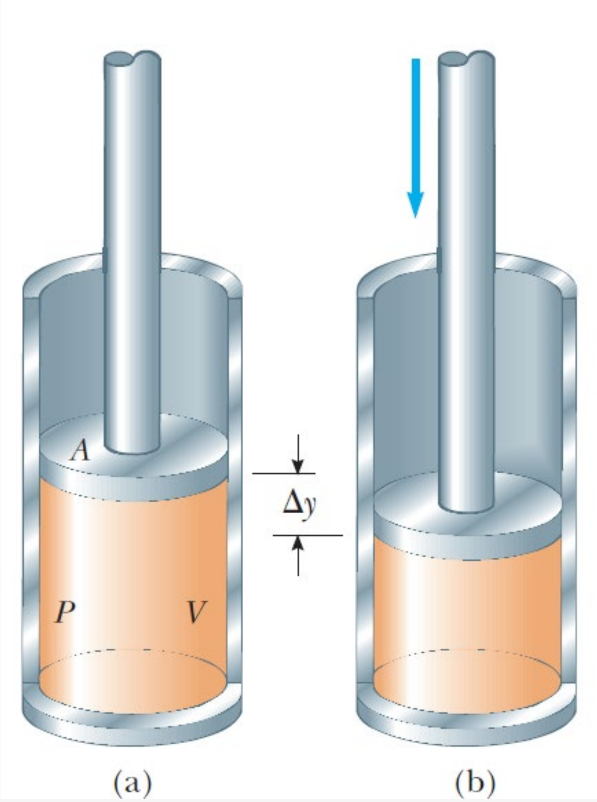
Laws of Thermodynamics

Definition of "Work"

$$W = -F\,\Delta y = -PA\,\Delta y$$

The **work W done on a gas** at constant pressure is given by

$$W = -P\,\Delta V$$



Problem In a system similar to that shown in Active Figure 12.1, the gas in the cylinder is at a pressure of 1.01×10^5 Pa and the piston has an area of $0.100\ \text{m}^2$. As energy is slowly added to the gas by heat, the piston is pushed up a distance of 4.00 cm. Calculate the work done by the expanding gas on the surroundings, W_{env}, assuming the pressure remains constant.

Strategy The work done on the environment is the negative of the work done on the gas given in Equation 12.1. Compute the change in volume and multiply by the pressure.

Solution

Find the change in volume of the gas, ΔV, which is the cross-sectional area times the displacement:

$$\Delta V = A\,\Delta y = (0.100\ \text{m}^2)(4.00 \times 10^{-2}\ \text{m})$$
$$= 4.00 \times 10^{-3}\ \text{m}^3$$

Multiply this result by the pressure, getting the work the gas does on the environment, W_{env}:

$$W_{\text{env}} = P\,\Delta V = (1.01 \times 10^5\ \text{Pa})(4.00 \times 10^{-3}\ \text{m}^3)$$
$$= \boxed{404\ \text{J}}$$

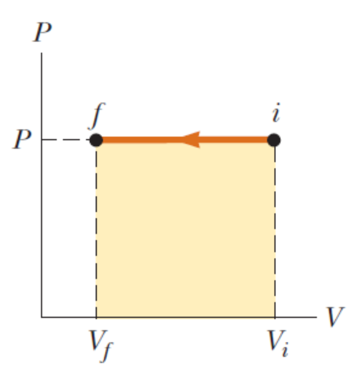


Figure 12.2 The *PV* diagram for a gas being compressed at constant pressure. The shaded area represents the work done on the gas.

First Law of Thermodynamics

If a system undergoes a change from an initial state to a final state, where Q is the energy transferred to the system by heat and W is the work done on the system, the change in the internal energy of the system, ΔU, is given by

$$\Delta U = U_f - U_i = Q + W \qquad \textbf{[12.2]}$$

Problem An ideal gas absorbs 5.00×10^3 J of energy while doing 2.00×10^3 J of work on the environment during a constant pressure process. **(a)** Compute the change in the internal energy of the gas. **(b)** If the internal energy now drops by 4.50×10^3 J and 2.00×10^3 J is expelled from the system, find the change in volume, assuming a constant pressure process at 1.01×10^5 Pa.

Solution

(a) Compute the change in internal energy.

Substitute values into the first law, noting that the work done on the gas is negative:

$$\Delta U = Q + W = 5.00 \times 10^3 \text{ J} - 2.00 \times 10^3 \text{ J}$$
$$= \boxed{3.00 \times 10^3 \text{ J}}$$

(b) Find the change in volume, noting that ΔU and Q are both negative in this case.

Substitute the equation for work done at constant pressure into the first law:

$$\Delta U = Q + W = Q - P\Delta V$$
$$-4.50 \times 10^3 \text{ J} = -2.00 \times 10^3 \text{ J} - (1.01 \times 10^5 \text{ J})\Delta V$$

Solve for the change in volume, ΔV:

$$\Delta V = \boxed{2.48 \times 10^{-2} \text{ m}^3}$$

Second Law of Thermodynamics

The Kelvin–Planck formulation of the **second law of thermodynamics** can be stated as follows:

No heat engine operating in a cycle can absorb energy from a reservoir and use it entirely for the performance of an equal amount of work.

J-L. Charmet/SPL/Photo Researchers, Inc.

LORD KELVIN, British Physicist and Mathematician (1824–1907)

Fuels & Combustion

Fuels and combustion

- Fuels are materials from which useful energy can be extracted.
- The release of energy usually involves combustion.
- Essential features of combustion are:
  - it needs air – or to be more precise, oxygen
  - the fuel undergoes a major change of chemical composition
  - heat is produced, i.e. energy is released.

Methane is the principal component of the fossil fuel natural gas and of biofuels

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{energy}$$

energy content (or **calorific value** or **heat value**) of the fuel

Example on combustion

BOX 2.1 CO_2 from fuel combustion

As an example, consider the combustion of methane (CH_4). The masses of the atoms of carbon and oxygen are respectively 12 times and 16 times the mass of a hydrogen atom, so we can associate masses with the items in the combustion equation:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$12 + (4 \times 1) + 2 \times (2 \times 16) \rightarrow 12 + (2 \times 16) + 2 \times (2 \times 1 + 16)$$

We can see, therefore, that burning 16 tonnes of CH_4 releases 44 tonnes of CO_2.

So burning one tonne of methane releases 44/16 = 2.75 tonnes (2750 kg) of CO_2.

Values for biomass, industrial waste, coal and oil are normally quoted as the lower heat value (LHV) or net calorific value (NCV) of the fuel. This assumes that any water vapour produced is not condensed

Table 2.1 Heating values and direct CO_2 emissions of some fuels

Fuel	Lower heating value / MJ kg^{-1}	Higher heating value / MJ kg^{-1}	CO_2 emissions LHV / gCO_2 MJ^{-1}
Coal (electricity generation)	24.9	–	90
Road diesel/light heating oil*	42.6 (9.9 kWh litre–1)	45.3	74 (2.7 kg litre–1)
Petrol (gasoline)*	44.8 (9.1 kWh litre–1)	–	70 (2.3 kg litre–1)
Natural gas	47.8	53.1	57
Hydrogen	120	142	zero
Wood (air-dry – 20% moisture)	~15	–	~ zero over life cycle

Source: BEIS, 2016a; BEIS, 2016b; AFDC, 2014

Note:*100% mineral fuel - not blended with biofuels

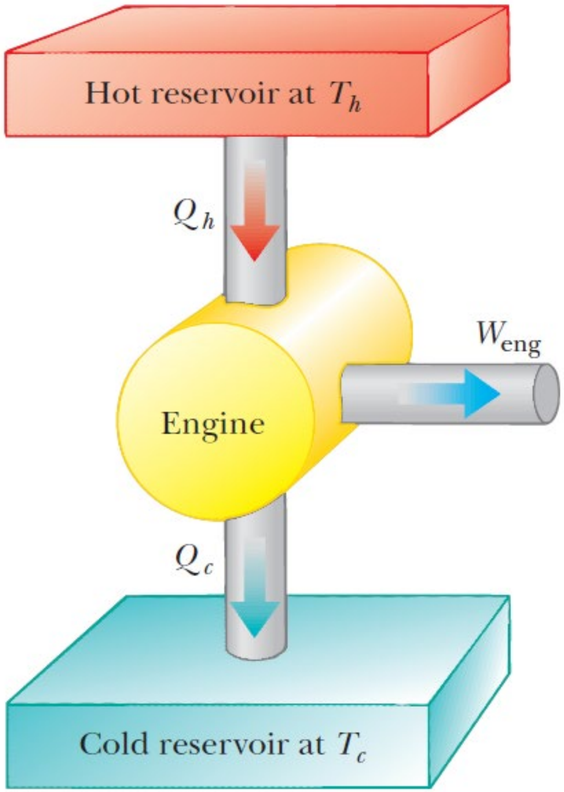
Define emission factor as the amount of CO_2 emitted per kWh of electricity.

Heat Engines

Heat Engines

A **heat engine** takes in energy by heat and partially converts it to other forms, such as electrical and mechanical energy.

In general, a heat engine carries some working substance through a **cyclic process**



ACTIVE FIGURE 12.9
A schematic representation of a heat engine. The engine receives energy Q_h from the hot reservoir, expels energy Q_c to the cold reservoir, and does work W.

$$\Delta U = 0 = Q + W \quad \rightarrow \quad Q_{net} = -W = W_{eng}$$

$$W_{eng} = |Q_h| - |Q_c|$$

The **thermal efficiency** e of a heat engine is defined as the work done by the engine, W_{eng}, divided by the energy absorbed during one cycle:

$$e \equiv \frac{W_{eng}}{|Q_h|} = \frac{|Q_h| - |Q_c|}{|Q_h|} = 1 - \frac{|Q_c|}{|Q_h|}$$

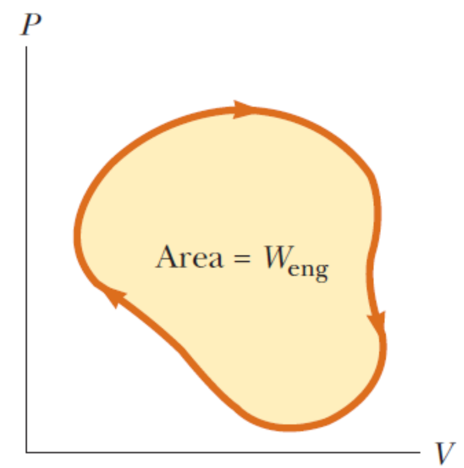


Figure 12.10 The *PV* diagram for an arbitrary cyclic process. The area enclosed by the curve equals the net work done.

We can think of thermal efficiency as the ratio of the benefit received (work) to the cost incurred (energy transfer at the higher temperature)

Problem During one cycle, an engine extracts 2.00×10^3 J of energy from a hot reservoir and transfers 1.50×10^3 J to a cold reservoir. **(a)** Find the thermal efficiency of the engine. **(b)** How much work does this engine do in one cycle? **(c)** How much power does the engine generate if it goes through four cycles in 2.50 s?

(a) Find the engine's thermal efficiency.

Substitute Q_c and Q_h into Equation 12.12:

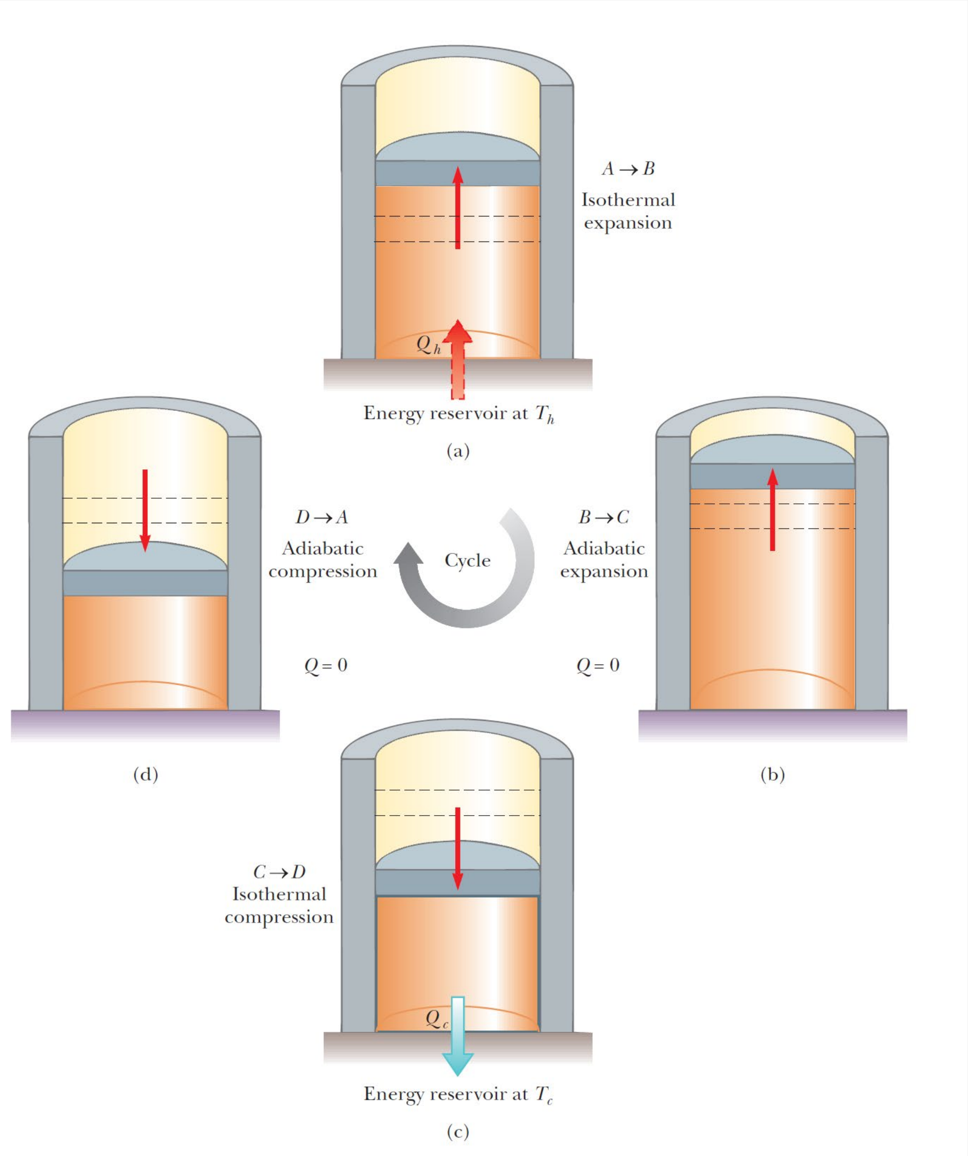
$$e = 1 - \frac{|Q_c|}{|Q_h|} = 1 - \frac{1.50 \times 10^3\ \text{J}}{2.00 \times 10^3\ \text{J}} = \boxed{0.250, \text{ or } 25.0\%}$$

$$W_{\text{eng}} = |Q_h| - |Q_c| = 2.00 \times 10^3\ \text{J} - 1.50 \times 10^3\ \text{J}$$
$$= \boxed{5.00 \times 10^2\ \text{J}}$$

$$\mathcal{P} = \frac{W}{\Delta t} = \frac{4.00 \times (5.00 \times 10^2\ \text{J})}{2.50\ \text{s}} = \boxed{8.00 \times 10^2\ \text{W}}$$

The Carnot Engine

No real engine operating between two energy reservoirs can be more efficient than a Carnot engine operating between the same two reservoirs.



SADI CARNOT, French Engineer (1796 – 1832)

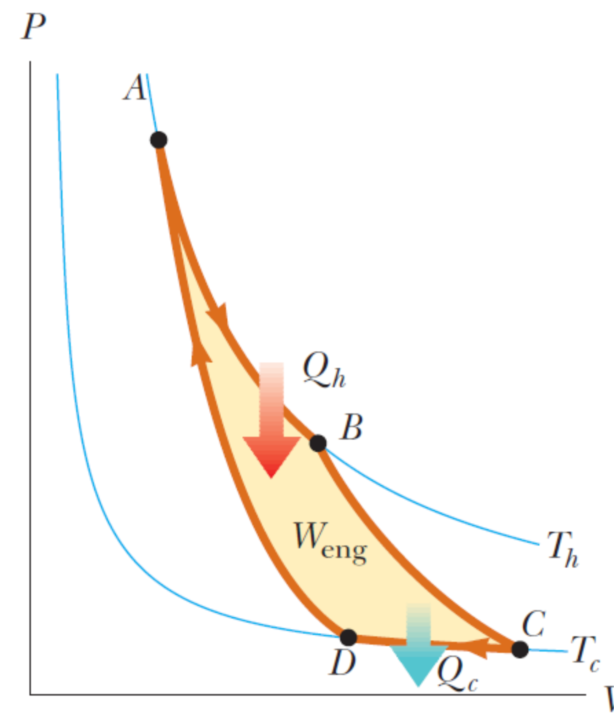
Carnot Engine Efficiency

For a Carnot engine, the following relationship between the thermal energy transfers and the absolute temperatures can be derived:

$$\frac{|Q_c|}{|Q_h|} = \frac{T_c}{T_h}$$

Engine Efficiency

$$e_C = 1 - \frac{T_c}{T_h}$$



ACTIVE FIGURE 12.16
The *PV* diagram for the Carnot cycle. The net work done, W_{eng}, equals the net energy received by heat in one cycle, $|Q_h| - |Q_c|$.

The steam turbine power station: The Rankine Cycle

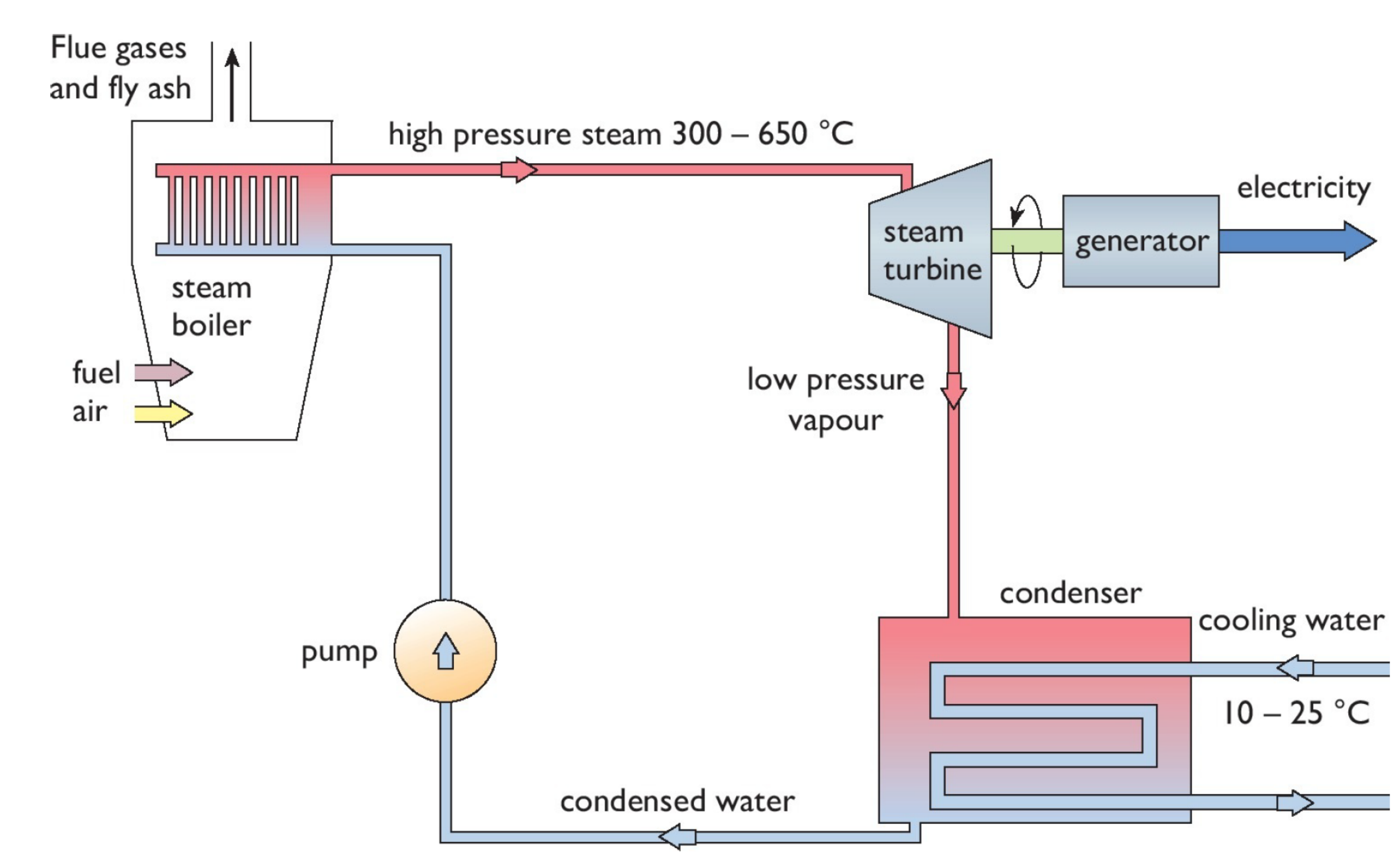


Figure 2.1 Basic power station system with turbine and generator

Boiler Types

Pulverized Fuel

- The combustion temperature must be high enough to produce steam, but not high enough to oxidize the nitrogen in the combustion air to NO_x.
- The flue gases will contain a large quantity of fine ash (fly ash) and some sulfur dioxide.
- The fly ash can be separated out using techniques such as cyclones and electrostatic precipitators.
- The SO_2 can be separated by reacting the flue gases with wet limestone ($CaCO_3$), turning it into gypsum ($CaSO_4$).

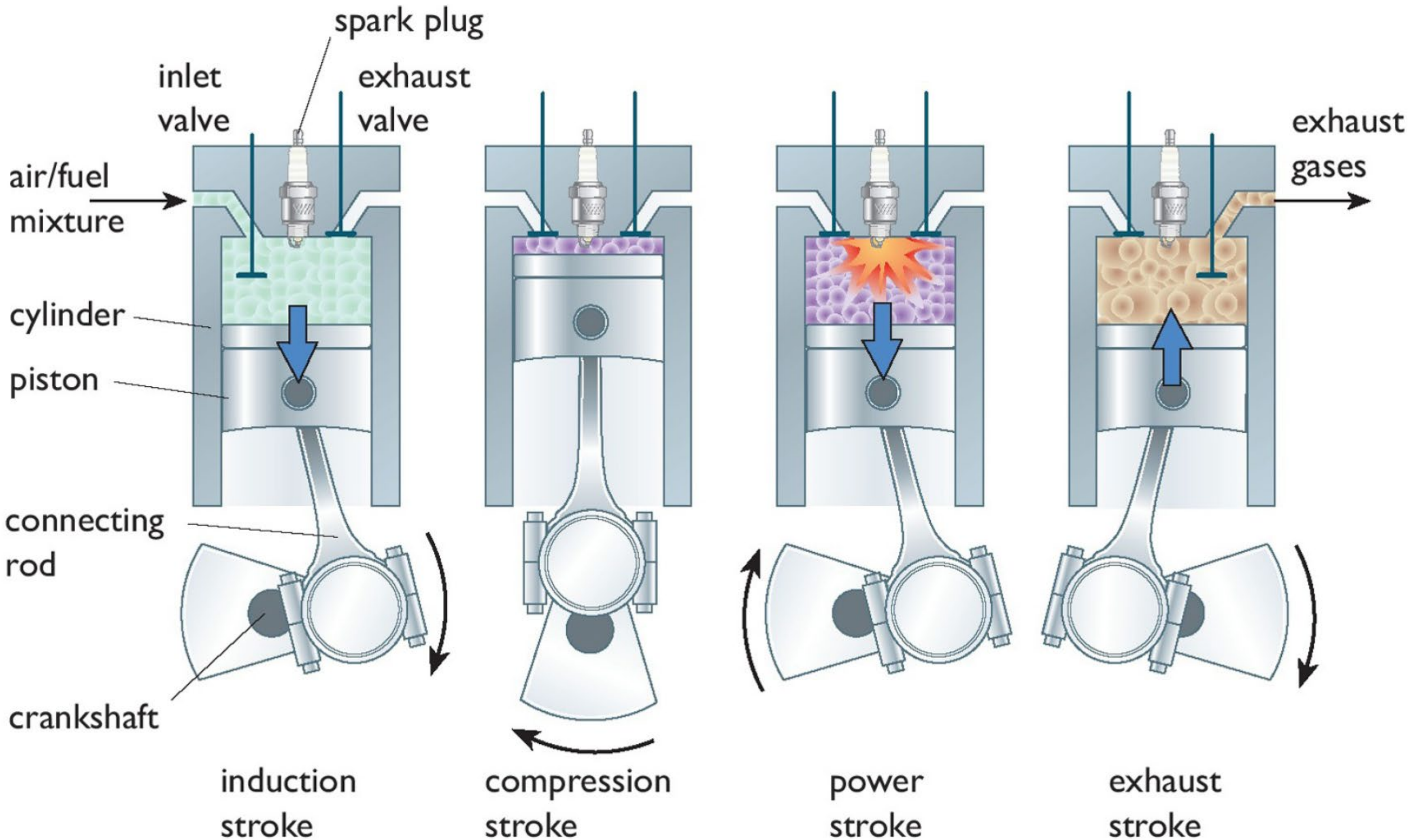
Fluidized Bed

- The fuel is ground down into small and fed into the moving bed.
- Limestone can be added to the fuel to absorb any sulfur content.
- The ash is continually extracted from the bed, rather than from the flue gases as in the pulverized fuel boiler

Organic Rankine Cycle (ORC) engines

- The **Organic Rankine Cycle** (ORC) uses a working fluid with a lower boiling point.
- This can be a common hydrocarbon (e.g. butane - inflammable), which boils at only 0 °C at atmospheric pressure.
- Alternatively an ORC may use one of a range of hydrofluorocarbons (HFCs) used as refrigerants in refrigerators and heat pumps.
- The **Kalina cycle** is an ORC variant that uses a mixture of ammonia and water as a working fluid.
- An ORC power plant uses low temperature heat to boil the working fluid and drive a turbine with the high pressure vapor in exactly the same manner as a steam turbine power plant.
- It can be used in an Ocean Thermal Energy Conversion (OTEC) system making use of the (small) temperature difference between the surface and bottom of deep sea water or in a ‘binary cycle’ geothermal plant

Internal combustion engines



Environmental Impact of Internal combustion engines

- The compression ratio (ratio of maximum-to-minimum volume) is typically 10:1 in gasoline car engines.
- The diesel engine is similar, except that the compression ratio is higher, around 20:1, and the diesel fuel spontaneously ignites (without spark plugs) at the high temperature and pressure produced by the compression.
- Diesel engines are more efficient than gasoline engines. However they produce more pollution in the form of NOx and particulates.

The combined cycle gas turbine (CCGT)

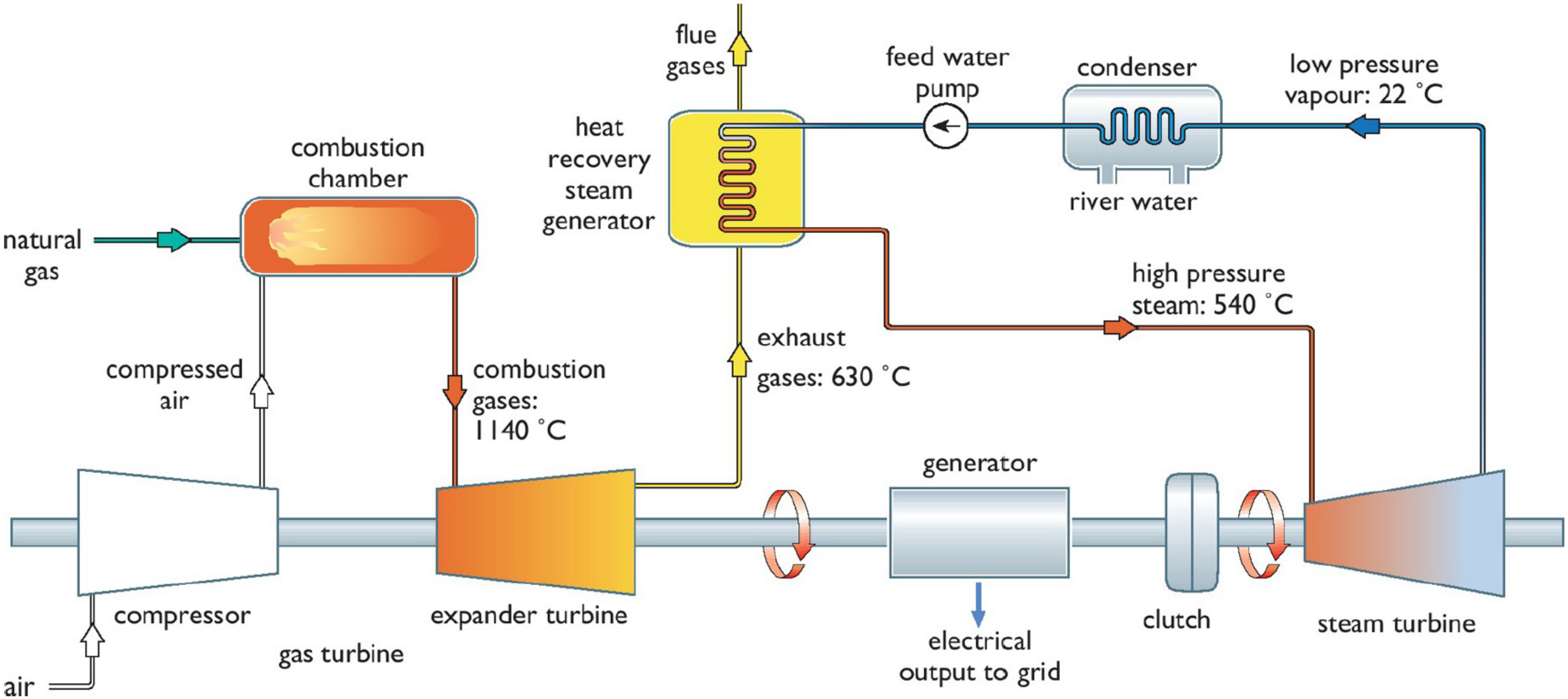


Figure 2.4 Combined cycle gas turbine generation plant

CCGT Features

- The power plant has an electrical generator mounted on a single drive shaft, which spins at 3000 rpm.
- This is connected both to an industrial gas turbine and, through a clutch, to a steam turbine.
- The exhaust gases from the gas turbine, which leave at about 630 °C are fed to a steam boiler, more formally known as a **heat recovery steam generator (HRSG)**, and used to raise steam at 540 °C.
- This is then fed to a conventional steam turbine connected to the opposite end of the generator via a clutch, producing a further electricity.
- The station draws cooling water from a river estuary giving an average working temperature in the condenser of 22 °C.
- Efficiency of 60% can be achieved with combustion temperatures of 1600 ^{O}C.

Refrigerators & Heat Pumps

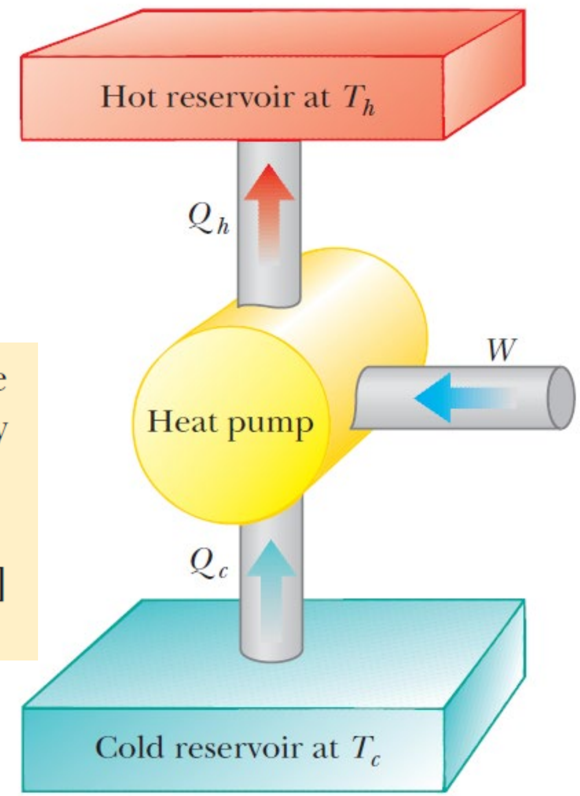
Refrigerators and Heat Pumps

The work is done in the compressor unit of the refrigerator, compressing a refrigerant, such as freon, causing its temperature to increase.

The coefficient of performance for a refrigerator or an air conditioner is the magnitude of the energy extracted from the cold reservoir, $|Q_c|$, divided by the work W performed by the device:

$$\text{COP(cooling mode)} = \frac{|Q_c|}{W} \qquad [12.13]$$

COP= $T_c/(T_h-T_c)$



ACTIVE FIGURE 12.12
Schematic diagram of a heat pump, which takes in energy $Q_c > 0$ from a cold reservoir and expels energy $Q_h < 0$ to a hot reservoir. Work W is done *on* the heat pump. A refrigerator works the same way.

Heat Pumps

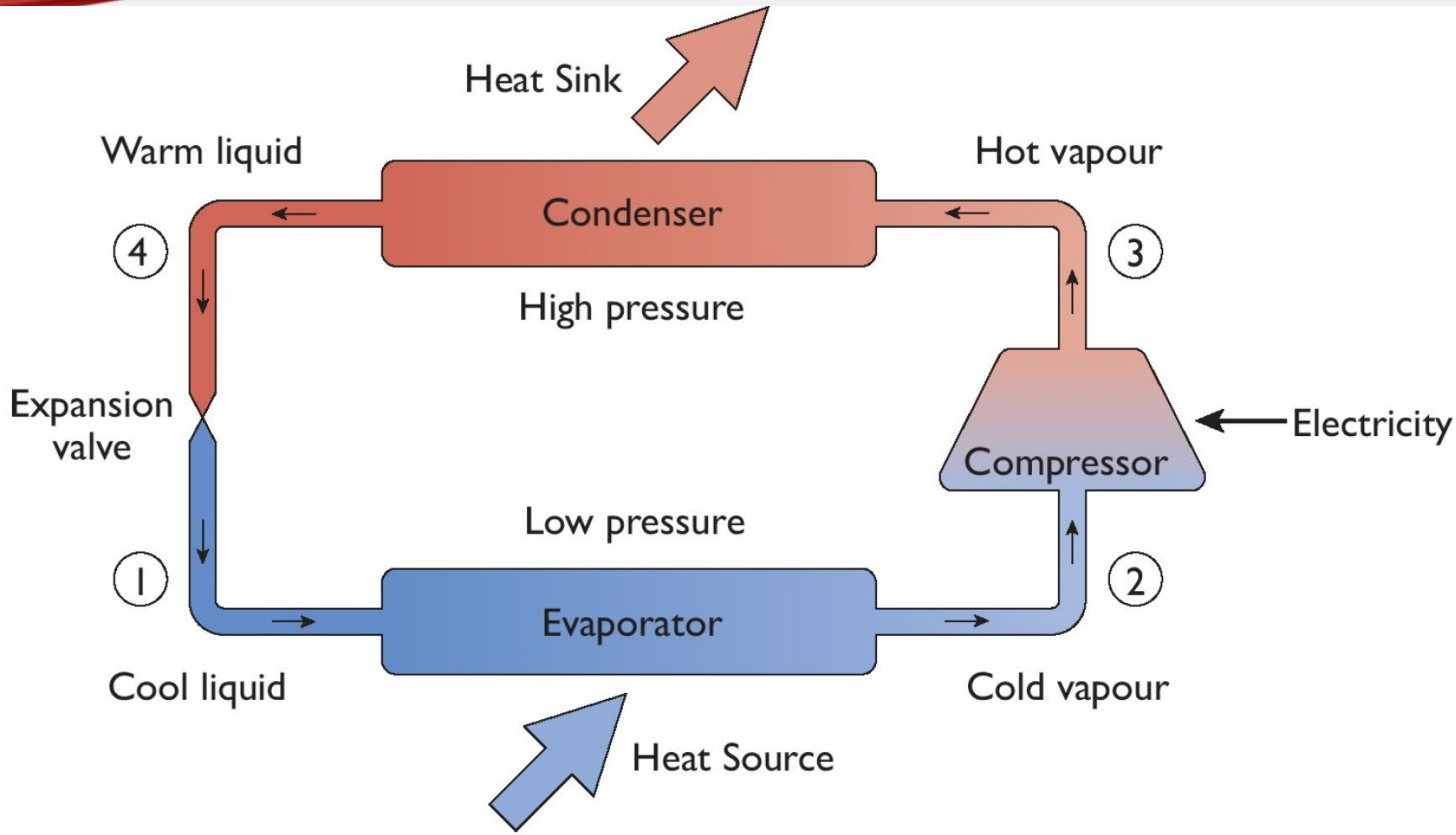


Figure 2.5 Schematic diagram of a heat pump

Environmental Effects of Heat Pumps

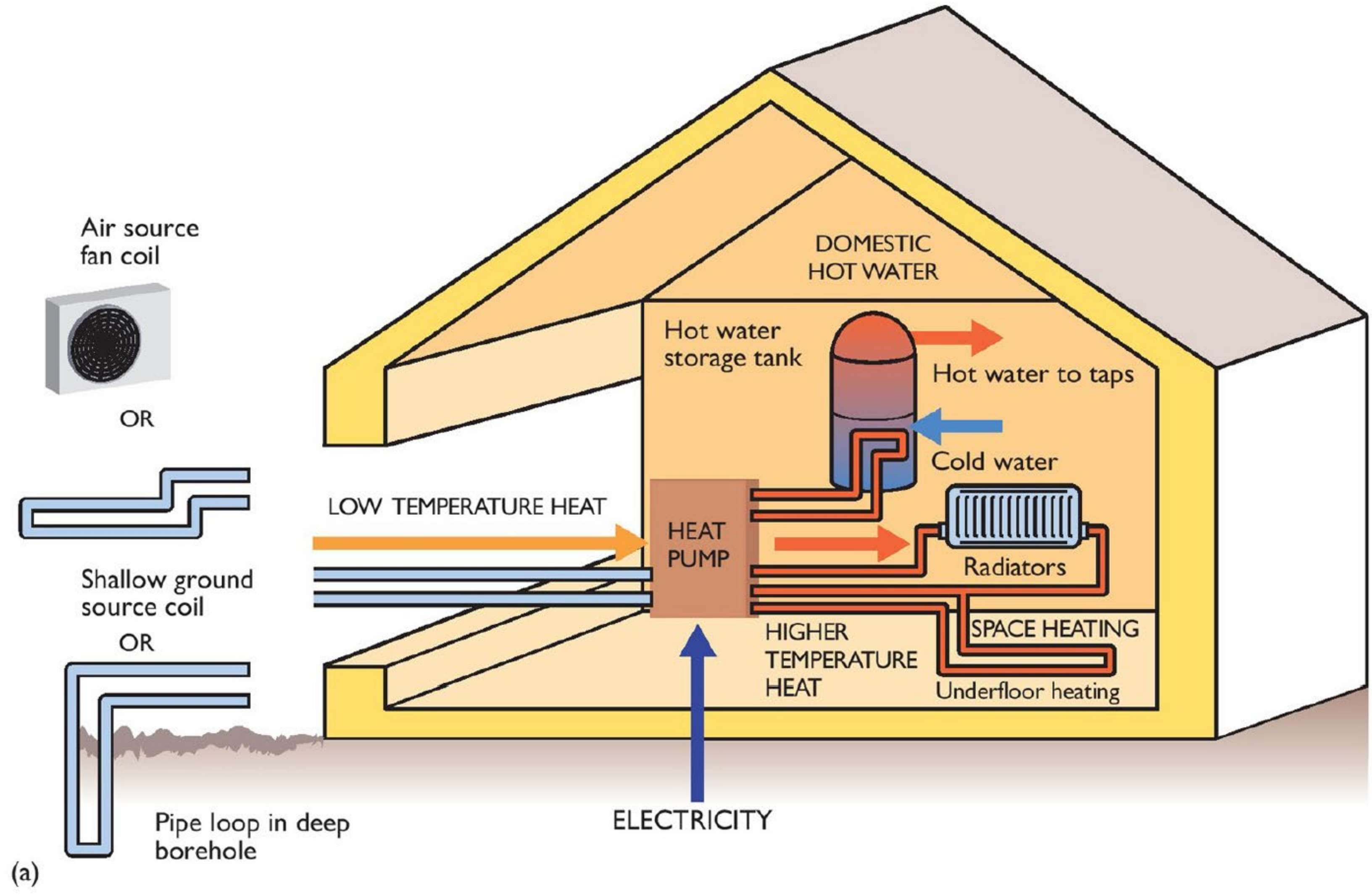
- Freon-12, a chlorofluorocarbon (CFC), a hydrocarbon where some of the hydrogen atoms have been substituted by atoms of chlorine and fluorine leaks from and breaks down the ozone layer which shields the Earth's surface from ultra-violet radiation from the Sun.

- Other refrigerants have been developed to solve this problem (HFC 134a).

Table 2.3 Refrigerants and their environmental properties

Refrigerant	DGWP	Environmental problems
Freon-12	10 900	A chlorofluorocarbon (CFC). Damaging to the ozone layer and a strong greenhouse gas. Now banned.
HFC 134a	1430	A hydrofluorocarbon (HFC). Developed as a replacement for Freon-12. Commonly used in heat pumps. Now being phased out because of its high DGWP
HFO-1234yf	<1	Hydrofluoroolefins (HFO). Developed as a
HFO-	<1	replacement for HFC 134a

Domestic heat pumps



The **system performance factor** (SPF):

SPF = Heat output from condenser / Electrical work input

From consideration of the conservation of energy $W = Q_1 - Q_2$.

The coefficient of performance (COP) =

$Q_1 / W = Q_1 / (Q_1 - Q_2)$

Carnot's theorem says that this ratio will be the same as that of the associated temperatures (in the Kelvin scale, of course):

COP = $T_1 / (T_1 - T_2)$

This can obviously be greater than 1.

For example, if the evaporator was at 0 °C and heat was required at 60 °C, the maximum theoretical COP would be

COP = (60 + 273) / (60 – 0) = 5.55

A practical value for these temperatures might be less than 4.

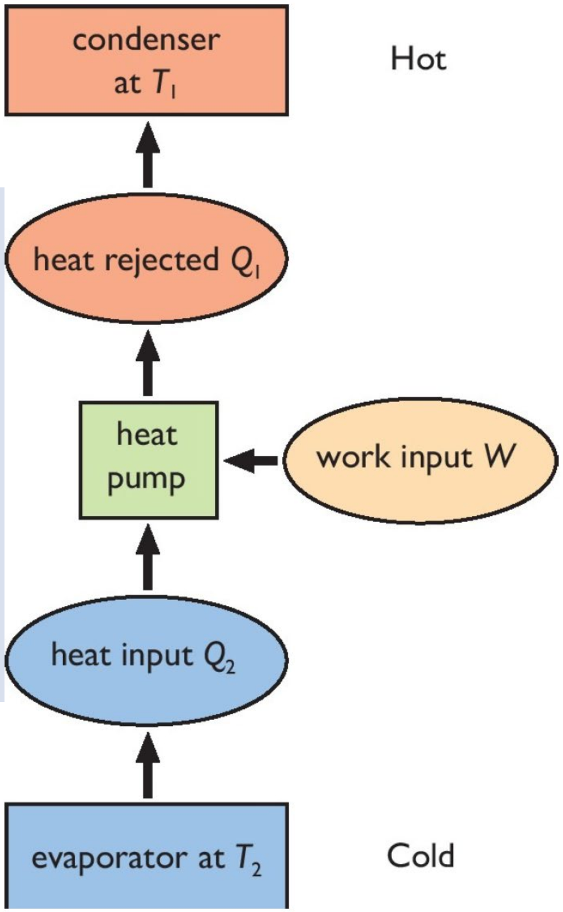


Figure 2.7 Carnot diagram for a heat pump

Replace COP with SPF

Evaporator Options

air source heat pump

ground source heat pump

(b) A fan-coil evaporator unit for an air source heat pump (c) Evaporator ground source heat exchanger. Slinky coils in a trench about to be buried.

Table 2.4 Heat extraction rates for shallow ground source evaporators - operation period 2400 hours per year

Ground quality	**Specific heat extraction flow rate / W m^{-2}**
Dry, non – cohesive soil	8
Moist cohesive soil	16 to 24
Water saturated sand or gravel	32

System Performance Factor (SPF)

- A more accurate measure of the overall performance than the COP is thus the **system performance factor (SPF)**.
- This is the ratio of the heat produced by the heating system to the electricity consumed.
- Measured SPF values are in the range from 2.2 to 4.0, with ground source heat pumps performing better than air source ones

Useful heating energy produced = electricity consumed × SPF

Environmental benefits of Heat Pumps

Table 2.6 Direct CO_2 emissions for different fuels and heating methods

Heating fuel and method	**CO_2 emissions /kg per kWh of heat**
Natural gas, 90% efficient condensing boiler	0.20
Light heating oil, 90% efficient condensing boiler	0.28
Direct resistance heating, 100% efficiency – 2015 UK generation mix	0.33
Electric heat pump, SPF = 3.0 – 2015 UK generation mix	0.11

In 2014 a typical UK household required about 13 000 kWh of heating energy per year (BEIS, 2016d). For such a household using light heating oil the annual heating emissions would be 13 000 × 0.28 = 3640 kg CO_2.

If a heat pump with an SPF of 3.0 was installed then the annual emissions would be 13 000 × 0.11 = 1430 kg.

The annual emissions saving =

3640 – 1430 = 2210 kg or 2.21 tonnes of CO_2 per year.

Why do Heat Pumps Provide Renewable Energy?

- The *heat gains* from heat pumps, i.e. the difference between the heat output and the electricity input, have been classified as *renewable energy* but only if the SPF is greater than 2.5.

- Gains from air source heat pumps are termed *aerothermal*; those from rivers or lakes are *hydrothermal* and those from energy stored in the form of heat beneath the surface of solid earth’ are classified as *geothermal* energy.

- This differs from the ‘deep geothermal energy’.