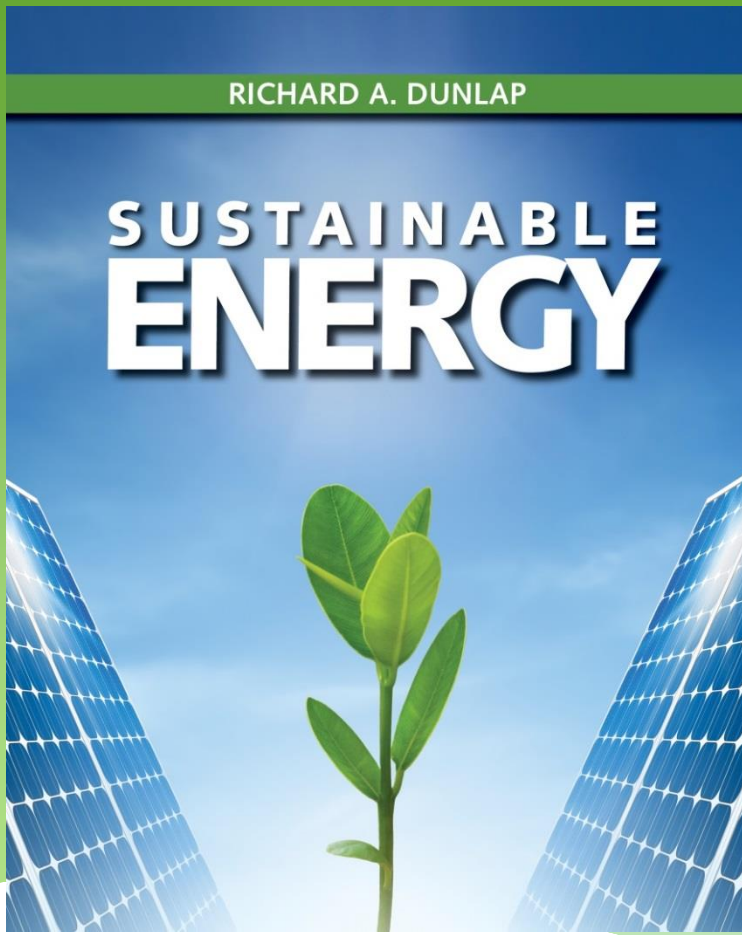
Sustainable Energy



Chapter 1

- Energy Basics

CENGAGE Learning

Learning Objectives

- The relationship between energy and power.
- The forms of energy.
- The laws of thermodynamics.
- Heat engines and their Carnot efficiency.
- Heat pumps and their coefficient of performance.
- How electricity is generated and distributed.

Work and Energy

Energy is defined as the ability to do work.
Work is the product of a force and the distance over which it acts

$$W = Fd \quad (1.1)$$

Force is given by Newton's law as

$$F = ma \quad (1.2)$$

Work done against a gravitational field to lift an object to a height *h* is

$$W = mgh \quad (1.3)$$

and this is equal to the potential energy associated with the object.

Power

Power is the rate at which work is done or energy is the product of power times the time over which it is utilized

$$E = Pt \qquad (1.4)$$

Forms of Energy

Energy can take on many forms:

- Kinetic energy (e.g., of a moving automobile)
- Gravitational potential energy (e.g., of water in a reservoir)
- Thermal energy (e.g., in a pot of boiling water)
- Chemical energy (e.g., stored in a liter of gasoline)
- Nuclear energy (e.g., stored in a gram of uranium)
- Electrical energy (e.g., used by a light bulb)
- Electromagnetic energy (e.g., that associated with a beam of sunlight)

Kinetic energy

Kinetic energy is associated with the movement of an object.

This may be translational motion with kinetic energy

$$E = \frac{1}{2} m v^2 \qquad (1.5)$$

or rotational motion with kinetic energy

$$E = \frac{1}{2} I \omega^2 \qquad (1.6)$$

Potential energy

Potential energy is most commonly associated with the energy of an object in a gravitational field given by

$$E = mgh \quad (1.7)$$

This may be converted into kinetic energy as an object falls through a distance *h*

$$E = \frac{1}{2}mv^2 = mgh \quad (1.8)$$

Thermal energy

Thermal energy is the kinetic energy associated with the microscopic movement of molecules

For a gas this is related to temperature by

$$E = \frac{3}{2}nRT \qquad (1.11)$$

where *n* is the number of moles of gas

Thermal energy of liquids and solids

A quantity of energy *Q* supplied to a material of mass *m* and specific heat *C* will increase the temperature by Δ*T*

$$\Delta T = \frac{Q}{mC} \qquad (1.12)$$

Chemical energy

Chemical energy is the energy associated with chemical bonds.

Chemical energy can be released in exothermic reactions and absorbed in endothermic reactions.

Energy released in combustion reactions (burning) is the heat of combustion.

Important oxidation reactions and heats of combustion

Burning of pure carbon (an approximation of coal)

$$C + O_2 \rightarrow CO_2 + 32.8\ MJ/kg \quad (1.13)$$

Burning of methane (major component of natural gas)

$$C + O_2 \rightarrow CO_2 + 32.8\ MJ/kg \quad (1.13)$$

Burning of ethanol (a common biofuel)

$$C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O + 29.8\ MJ/kg \quad (1.16)$$

Burning of octane (an important component of gasoline)

$$2C_8H_{18} + 25O_2 \rightarrow 16CO_2 + 18H_2O + 46.8\ MJ/kg \quad (1.17)$$

Nuclear energy

Energy associated with the bonds between neutrons and protons in the nucleus

Much greater than chemical energy and may be released during nuclear reactions

Energy release during an exothermic nuclear reaction is related to changes in the total mass of the system by Einstein's relation

$$E_{\text{exo}} = \Delta m c^2 \quad (1.21)$$

Electrical energy

Energy associated with flow of electrons in a conductor

A current I flowing through a conductor with a resistance *R* will experience a voltage drop *V* given by Ohm's law

$$V = IR \quad (1.22)$$

Power dissipated through the resistance is

$$P = VI \quad (1.23)$$

or

$$P = I^2R = \frac{V^2}{R} \quad (1.24)$$

Electromagnetic energy

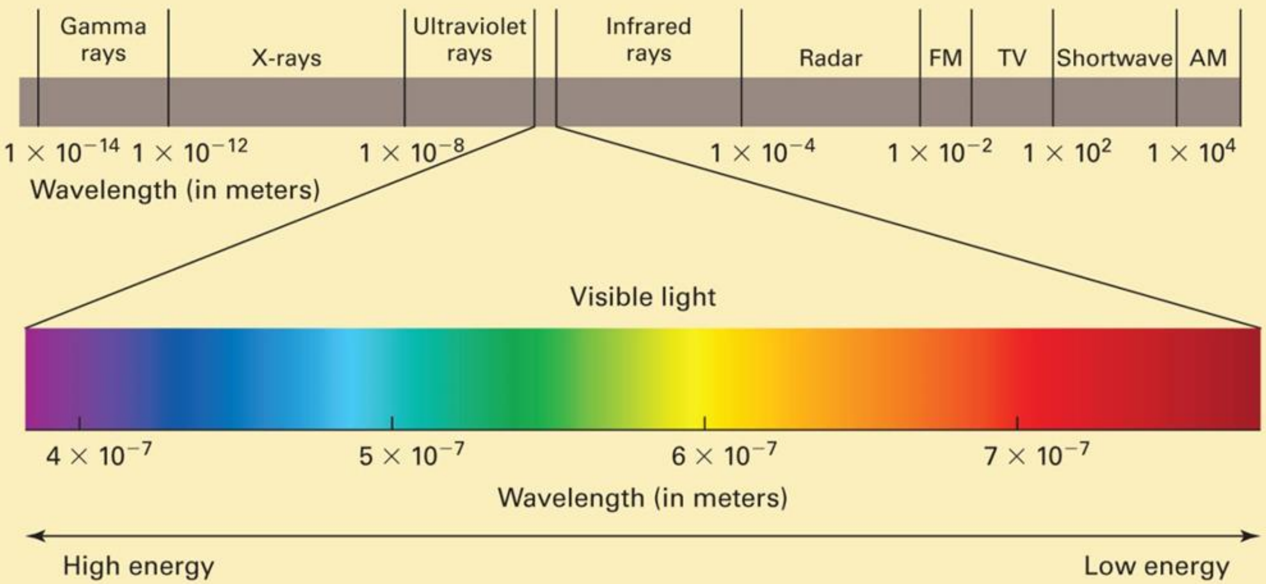
Energy of the electric and magnetic fields associated with electromagnetic waves (such as light)

Waves have a wavelength λ related to the frequency *f* and the velocity (speed of light)

$$\lambda = \frac{c}{f} \tag{1.25}$$

Electromagnetic spectrum

Electromagnetic radiation includes a wide range of wavelengths, including visible light



Based on http://www.yorku.ca/eye/spectru.htm; http://www.pion.cz/en/article/electromagnetic-spectrum; http://web.princeton.edu/sites/ehs/laserguide/

Figure 1.1: The electromagnetic spectrum. The visible portion of the spectrum is shown in the expanded insert.

Photons

Quantum mechanically electromagnetic radiation can be thought of as quanta of energy called photons

The energy associated with a photon is related to its frequency by Planck's constant

$$E = hf \tag{1.26}$$

The laws of thermodynamics

0. Two systems that are both in thermodynamic equilibrium with a third system are in equilibrium with each other.

1. Energy is conserved.

2. A closed system will move toward equilibrium.

3. It is impossible to attain absolute zero temperature.

Zeroth law of thermodynamics

This law implies that the thermodynamic state of system can be defined by a single parameter, the temperature

For a gas the temperature is defined in terms of the ideal gas law

$$PV = Nk_BT \quad (1.27)$$

Absolute zero

For any temperature scale, the ideal gas law indicates a linear relationship between temperature and pressure where the intercept on the temperature axis give the value of absolute zero.

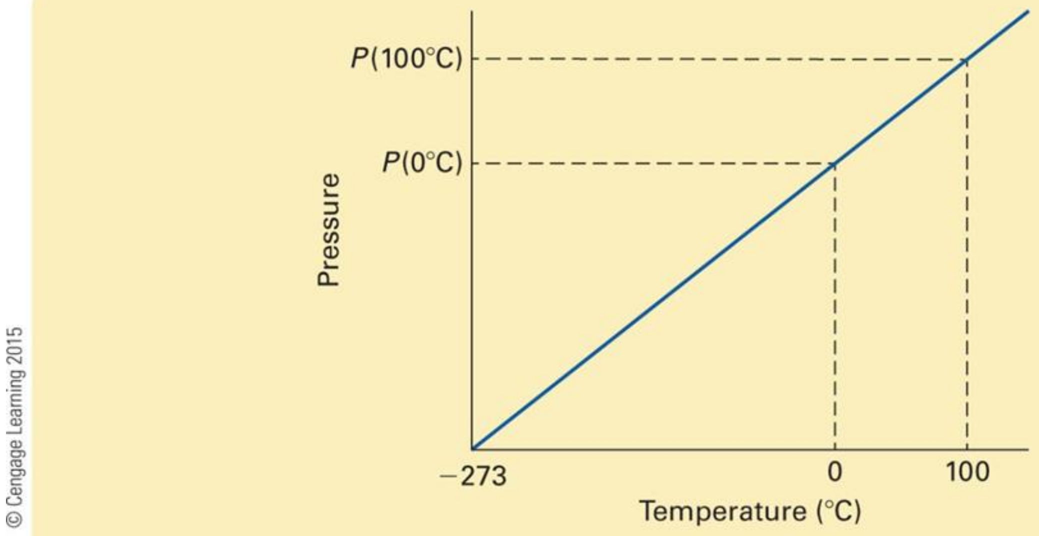


Figure 1.2: Description of an absolute temperature on the basis of the ideal gas law.

First law of thermodynamics

Consider an experiment where heat is applied to a cylinder containing gas that is sealed with moveable piston

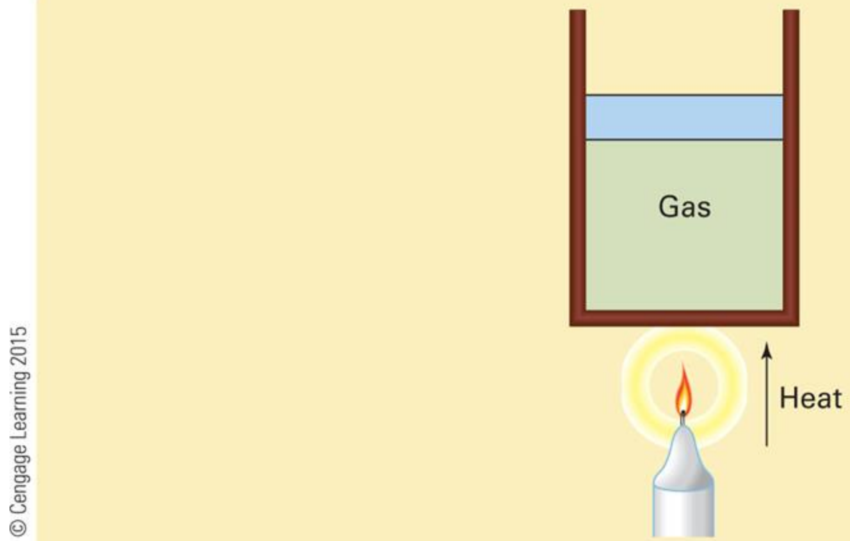


Figure 1.3: Example of the conservation of energy and an illustration of how thermal energy can be used to do mechanical work.

Conservation of energy

If the piston is allowed to move as the gas is heated then the conservation of energy implies that the heat added to the system is given by the sum of the work done on the piston and the change in the internal energy of the gas

$$Q = \Delta U + W \qquad (1.28)$$

Second law of thermodynamics

The implications of the second law are that heat will naturally flow from a hot place to a cold place.

It is the transfer of heat from hot to cold that allows thermal energy to do useful work.

This is analogous to gravitational potential energy - an object in a gravitational field can only do work if it moves from a point of higher gravitational potential to a point of lower gravitational potential.

Heat engines

If heat Q_h is removed from a hot reservoir and a portion of this heat Q_c is added to a cold reservoir then the difference can be used to do work *W.*

Conservation of energy requires that

$$Q_h = Q_c + W \qquad (1.29)$$

Schematic diagram of a heat engine

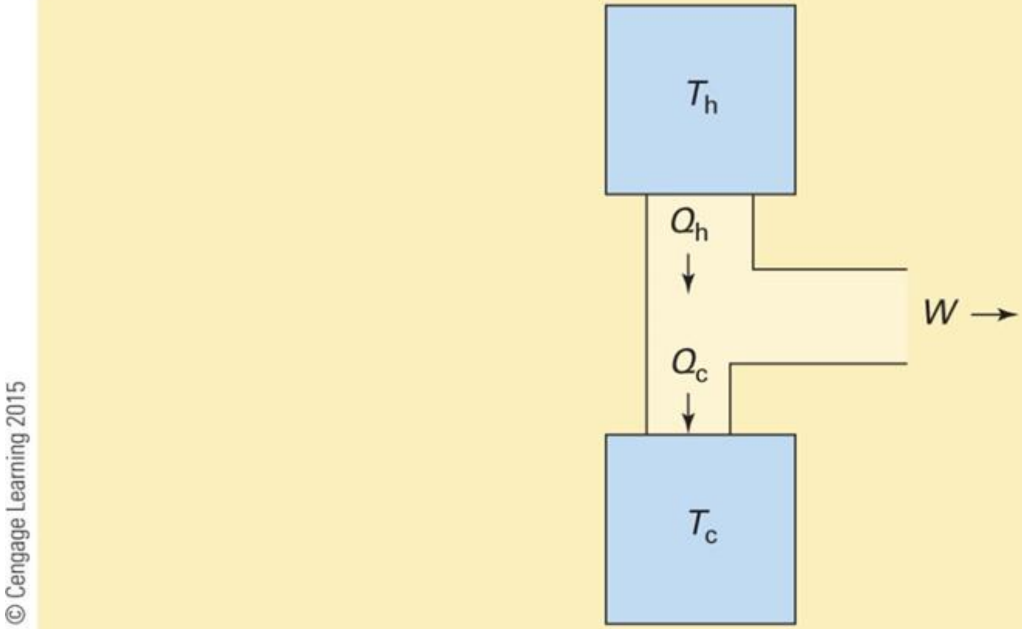


Figure 1.4: Operation of a heat engine to convert thermal energy into mechanical energy.

Carnot efficiency

The efficiency of a heat engine (in %) is

$$\eta = 100\frac{W}{Q_h} \quad (1.30)$$

Carnot showed that

$$\frac{Q_c}{Q_h} = \frac{T_c}{T_h} \quad (1.33)$$

where temperatures are measured on an absolute temperature scale.

The ideal Carnot efficiency can be expressed in terms of the reservoir temperatures as

$$\eta = 100\left(1 - \frac{T_c}{T_h}\right) \quad (1.34)$$

Heat pump

A heat pump uses mechanical energy (work) to transport heat from a cold reservoir to a hot reservoir

Conservation of energy requires

$$W + Q_c = Q_h \quad (1.35)$$

and the coefficient of performance gives the ratio of heat transported to work input

$$COP = \frac{Q_h}{W} \quad (1.36)$$

or

$$COP = \frac{1}{1 - (T_c/T_h)} \quad (1.38)$$

Schematic diagram of a heat pump

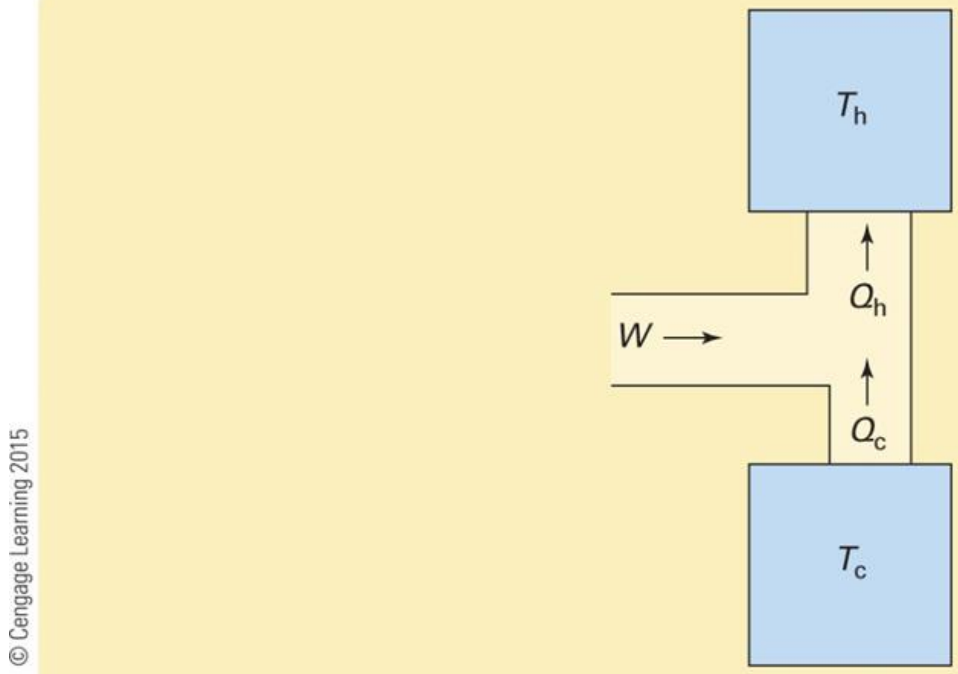


Figure 1.5: Operation of a heat pump that uses mechanical energy to transfer heat.

Applications of heat engines and heat pumps

The concept of a heat engine describes the basic principles of steam turbines or internal combustion engines which convert thermal energy into mechanical energy.

The concept of a heat pump describes the operation of a refrigerator which transports heat from a place we want to keep cold to a warm reservoir (room temperature)

or

A heat pump can be used for heating purposes by transporting heat from the cold outside to the inside of a building.

Electricity generation

Breakdown of world electricity production

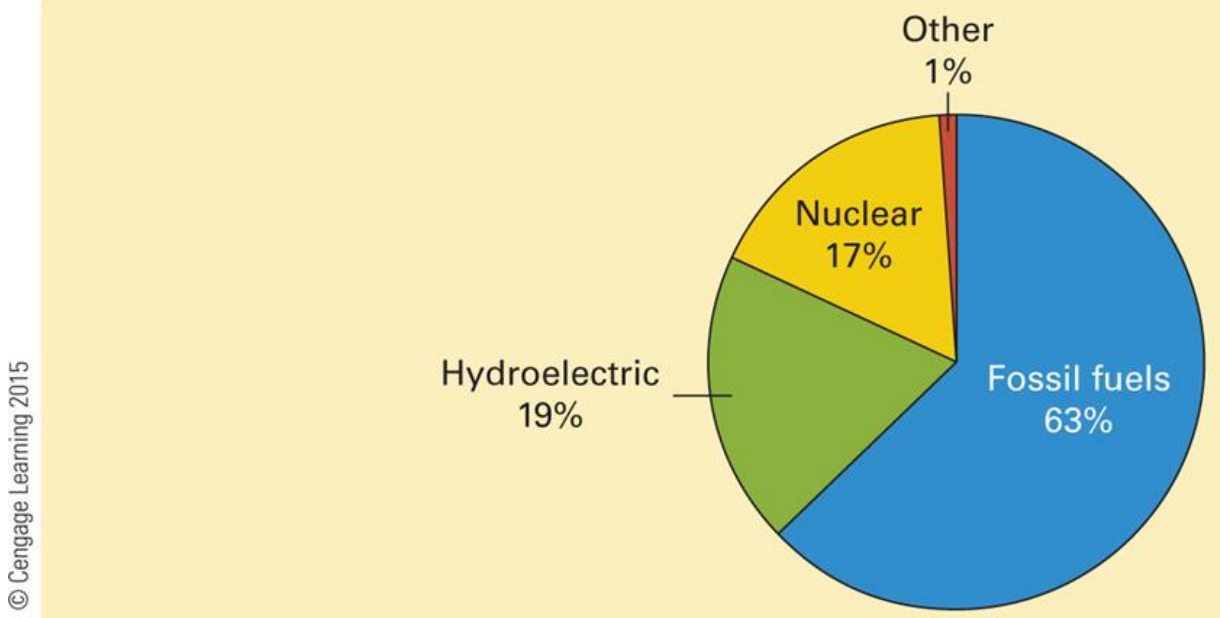


Figure 1.6: Proportions of primary energy sources used for the production of electricity worldwide.

Fossil fuel generating plants

Fossil fuels may be used in

- thermal generating stations
- combustion turbines

Thermal generating stations

Thermal generating stations use the combustion of fossil fuels (commonly coal, but also oil or natural gas) to boil water to make steam which then runs a turbine to turn a generator to produce electricity.

Schematic of a thermal generating station

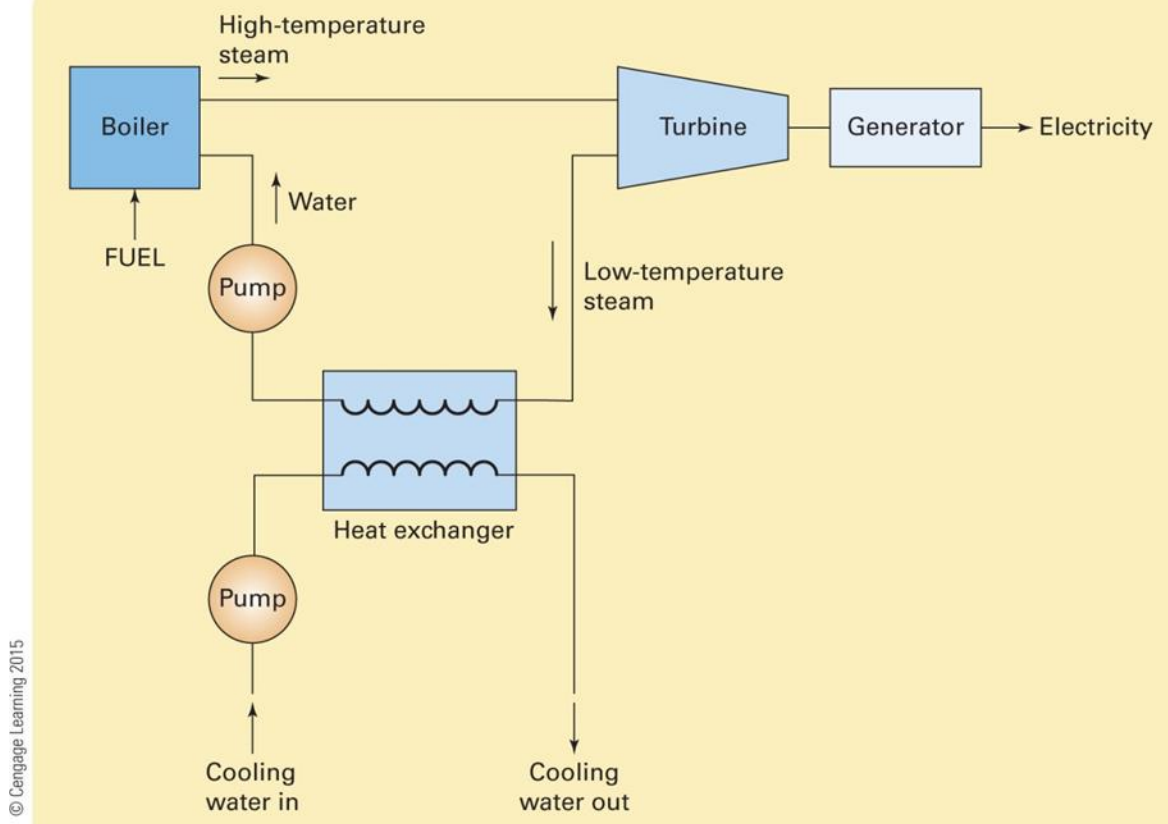


Figure 1.7: Schematic diagram of a typical fossil fuel or nuclear power generating station.

Rotor assembly of a steam turbine

Figure 1.9: Rotor assembly of a turbine showing multiple stages of turbine blades.

Heat transfer to the environment

We need to remove heat from the cold reservoir in order to improve the Carnot efficiency

Two common ways of doing this are

- Once through water cooling using the ocean, river, lake, etc.
- Atmospheric cooling towers

Cooling towers to transfer heat to the atmosphere

Figure 1.10: Cooling towers typically used for thermal generating stations.

Combustion turbine

Similar to a jet engine

Uses liquid or gaseous fuels (e.g. gasoline or natural gas)

More expensive to operate than a coal fired thermal station but can be brought on-line quickly during times of high demand

Combustion turbines

Figure 1.11: Natural gas-fired combustion turbines at the Pyramid Generating Station operated by Tri-State G&T Inc. near Lordsburg, New Mexico.

Distribution of electricity

Power loss due to resistance in transmission cables is minimized by using high voltage.

Losses are inversely proportional to the voltage squared

$$P_{\text{loss}} = \frac{P_{\text{trans}}{}^2 R}{V^2} \quad (1.42)$$

Power distribution transformers

Transformers are used to step up voltage for distribution and to step down voltage for end users.

Figure 1.12: Small power distribution transformer on a utility pole in a residential area.

Summary

- Energy is the ability to do work.
- Power is energy produced or expended per unit time.
- Energy can be categorized as: kinetic, potential, thermal, chemical, nuclear, electrical or electromagnetic energy.
- The zeroth law of thermodynamics allows for the definition of a temperature scale
- The first law of thermodynamics describes the conservation of energy.
- The second law of thermodynamics describes the operation of heat engines and heat pumps.
- Heat engines use the flow of heat to produce mechanical energy
- Heat pumps use mechanical energy to transport heat from a cold place to a hot place.
- Fossil fuels can be used to generate electricity in thermal generating stations or in combustion turbines.
- Electricity is most efficiently distributed using high voltages.