Topic4: Renewable Energy

The University of Manchester

Further Reading

Chapter 18

Renewable Energy

Summary

- Introduction.
- Solar energy.
- Wind energy.
- Hydropower.
- Geothermal energy.
- Biomass energy.

Objectives

- Understand the importance of renewable energy in relation to other energy sources.
- Learn various solar energy applications including solar collectors, solar power systems, photovoltaic systems, and passive solar applications.
- Evaluate the performance of solar energy applications.
- Analyze wind turbines and discuss various factors affecting wind turbine applications.
- Learn various hydraulic turbine types and evaluate performance of hydraulic turbines.
- Introduce geothermal heating, cooling, and power production applications.
- Evaluate the performance of various type geothermal power plants.
- Review biomass resources, conversion to biofuels, biomass products, and solid municipality waste.

18–1 Introduction [4]

Figure 18–1
Percentages of total world energy consumptions by fuel.

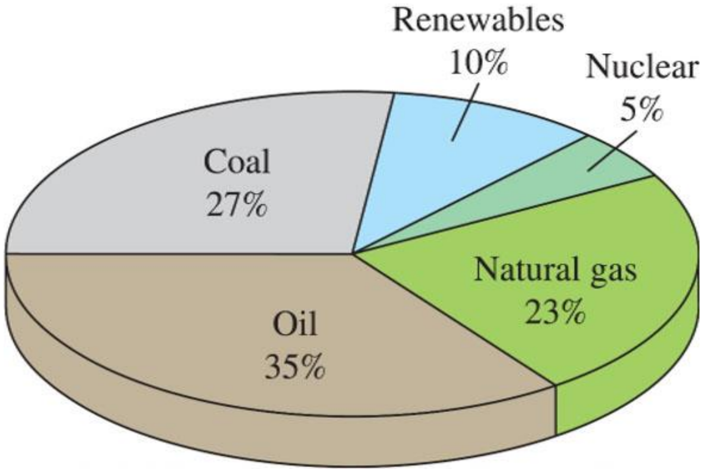

Figure 18–2
World marketed energy use by fuel type, 1990–2035 (quadrillion Btu).

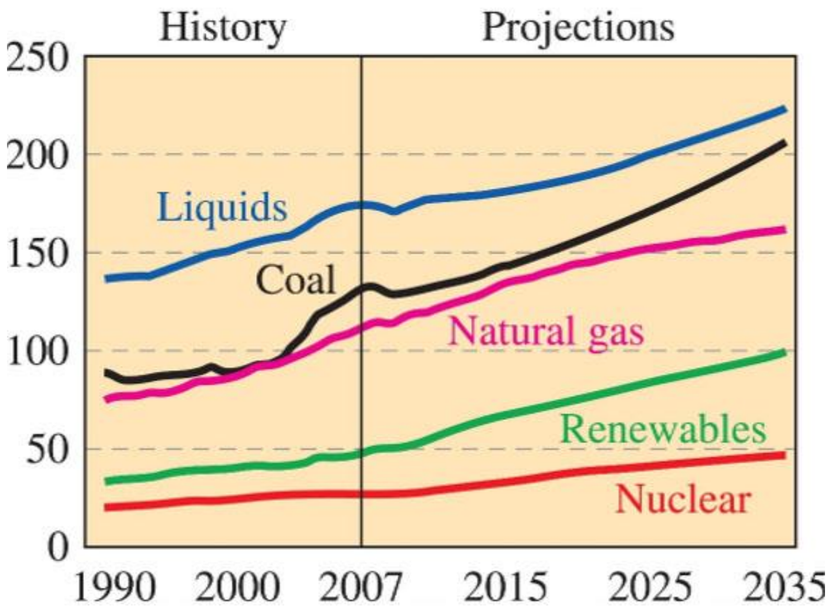

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Figure 18–3

World net electricity generation by fuel, 2007 to 2035 (trillion kilowatthours).

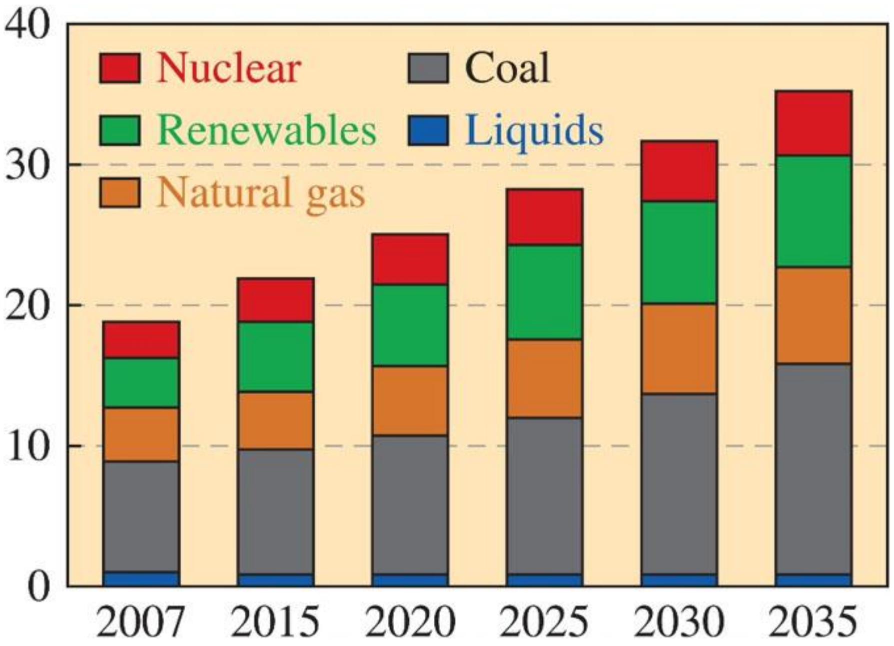
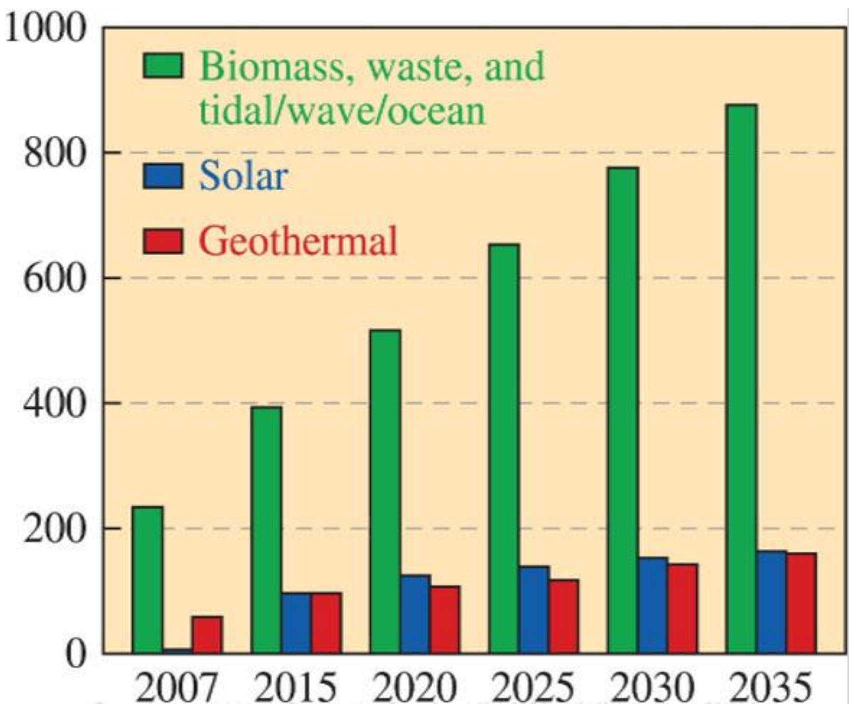


Figure 18–4

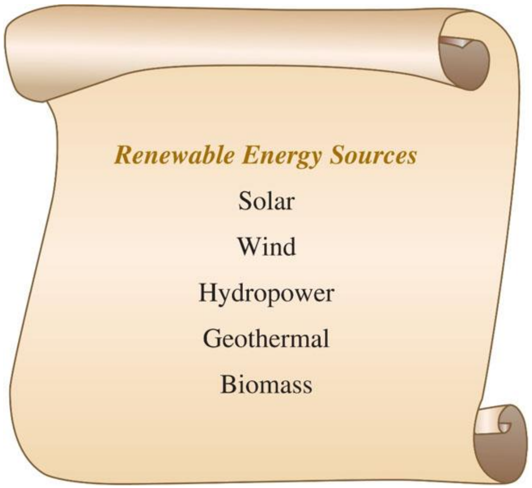
World renewable electricity generation by energy source, excluding wind and hydropower, 2007to 2035 (billion kilowatt-hours)



18–1 Introduction

Figure 18–5

The switch from fossil fuels to renewable energy sources is inevitable.



Renewable: An energy source is called renewable if it can be renewed and sustained without any depletion and any significant effect on the environment.

It is also called alternative, sustainable, or a green energy source.

Fossil fuels such as coal, oil, and natural gas, on the other hand, are not renewable, and they are depleted by use.

They also emit harmful pollutants and greenhouse gases.

Solar: The best-known renewable source is solar energy. Although solar energy is sufficient to meet the entire energy needs of the world, currently it is not economical to do so because of the low concentration of solar energy on earth and the high capital cost of harnessing it.

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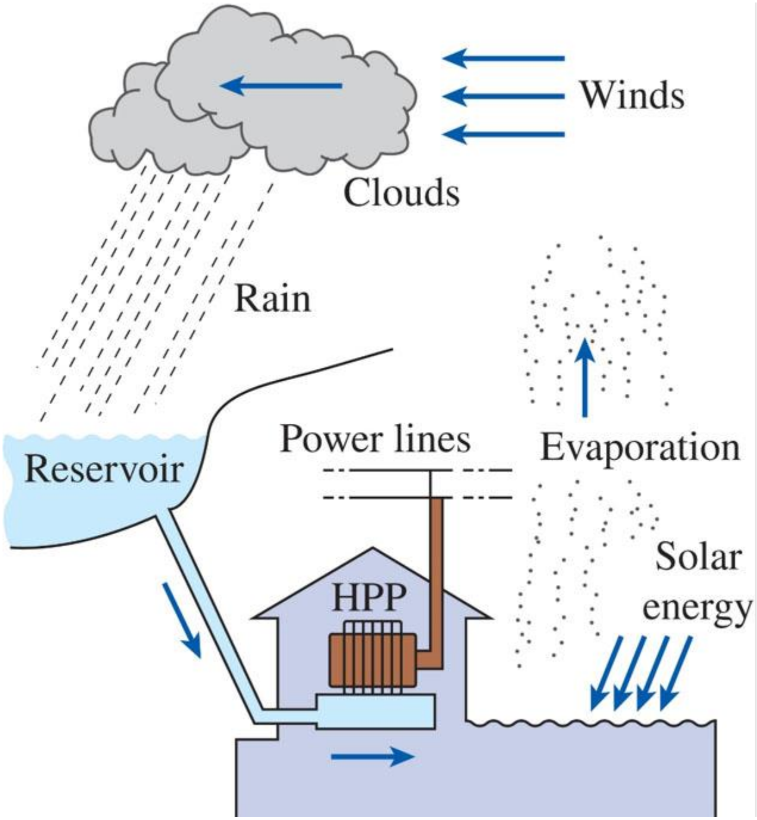
Figure 18–7

The Cycle That Water Undergoes In A Hydroelectric Power Plant.



What we call renewable energy is usually nothing more than the manifestation of solar energy in different forms.

Such energy sources include wind energy, hydroelectric power, ocean thermal energy, ocean wave energy, and wood.

For example, no hydroelectric power plant can generate electricity year after year unless the water evaporates by absorbing solar energy and comes back as a rainfall to replenish the water source

18–2 Solar Energy [1]

The electromagnetic energy emitted by the sun is called solar radiation or solar energy (or solar heat).

Tremendous amounts of energy are created within the sun and only a fraction of this energy reaches earth. This keeps earth at a temperature suitable for life.

The cost of systems that capture solar energy and provide useful energies is high compared to conventional energy sources such as coal, oil, and natural gas.

Other renewable energies such as geothermal, wind, hydro, and biomass appear to be less costly than solar energy but their potentials with the current technologies are much less than solar energy.

18–2 Solar Energy [2]

The conversion of solar energy into other useful forms of energy can be accomplished by three conversion processes:

- Heliochemical process: Basically photosynthesis process, and it is responsible for the production of fossil fuel and biomass.
- Heliothermal process: Solar energy is collected and converted to thermal energy or heat.

Flat-plate collectors, concentrating collectors, and heliostats are common devices that collect solar radiation for conversion to useful heat.

Solar collectors are used for space heating and cooling and for the production of hot water for buildings.

Heliostats are mirrors that reflect solar radiation into a single receiver. The resulting high temperature thermal energy is converted to electricity by a heat engine.

- Helioelectrical process: The production of electricity by photovoltaic or solar cells is accomplished by a helioelectrical process.

This process is different from heliostats in that solar energy is converted to electricity directly in solar cells while it is first converted to thermal energy in heliostats.

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Solar Radiation

- The sun is our primary source of energy.
- The energy coming off the sun, called solar energy, reaches us in the form of electromagnetic waves after experiencing considerable interactions with the atmosphere.
- The solar energy reaching the earth's atmosphere is called the total solar irradiance or solar constant.
- The energy of the sun is due to the continuous fusion reaction during which two hydrogen atoms fuse to form one atom of helium.
- The sun is essentially a nuclear reactor, with temperatures as high as 40,000,000 K in its core region.

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When solar radiation *G* strikes a surface, conservation of energy requires that the sum of the *transmitted*, *reflected*, and *absorbed* solar radiations be equal to the incident solar radiation.

$\alpha + \rho + \tau = 1$ τ is the transmissivity, ρ is the reflectivity, and α is the absorptivity.

All objects at temperatures above absolute zero also emit thermal radiation. The amount of thermal radiation emitted depends on the **emissivity** of the object's surface.

We define the emissivity ε of a surface as a measure of how closely a real surface approximates a blackbody (perfect emitter), for which $\varepsilon = 1$.

Therefore, the emissivity of a surface varies between zero and one, $0 < \varepsilon < 1$.

Figure 18–9

The absorption, reflection, and transmission of solar radiation by a semitransparent material.

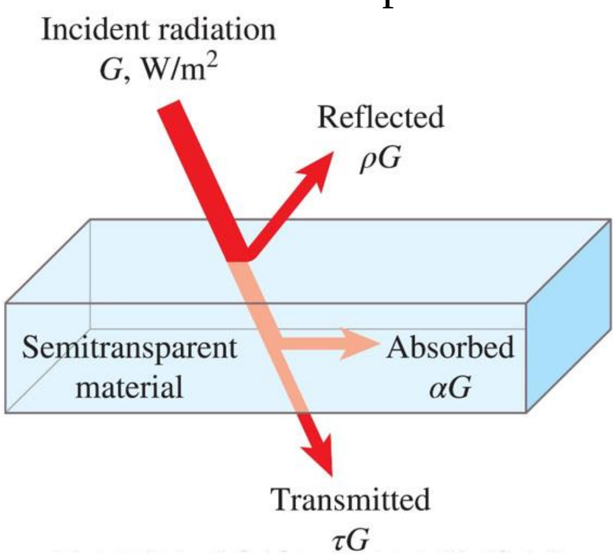

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Table 18–2

Comparison of the solar absorptivity α_s of some surfaces with their emissivity ε at room temperature.

Surface	α_s	ε
Aluminum		
Polished	0.09	0.03
Anodized	0.14	0.84
Foil	0.15	0.05
Copper		
Polished	0.18	0.03
Tarnished	0.65	0.75
Stainless steel		
Polished	0.37	0.6
Dull	0.5	0.21
Plated metals		
Black nickel oxide	0.92	0.08
Black chrome	0.87	0.09
Concrete	0.6	0.88
White marble	0.46	0.95
Red brick	0.63	0.93
Asphalt	0.9	0.9
Black paint	0.97	0.97
White paint	0.14	0.93
Snow	0.28	0.97
Human skin (Caucasian)	0.62	0.97

Data Source: Y. A. Çengel and A. J. Ghajar, Heat and Mass Transfer: Fundamentals and Applications, *4th edition McGraw-Hill Education, 2011.*

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İncident and emitted radiation have different characters:

- Incident radiation is mostly short wavelength
- Emitted radiation is mostly long wavelength (Infrared).

Radiating surfaces are assumed to have two sets of properties: one for solar radiation and another for infrared radiation at room temperature.

The amount of solar radiation incident on a surface depends on

- The latitude, orientation and elevation of the surface.
- The time of the day, clearness of the sky and humidity of air .

Additional reading (Recommended text):

- Table 18–3 gives hourly solar radiation incident on various surfaces at 40° latitude.
- Average daily solar radiation values on a horizontal surface in the United States are given for selected cities in Table 18–4.

Capturing solar energy and producing useful energy from it requires some special equipment.

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Flat-Plate Solar Collector

- Most solar collectors are used to produce hot water.
- Normally used in residential and commercial buildings, but can be used for industrial process heating
- Solar collectors can also be used for space heating in winter.
- Unfortunately, most solar heat is available in summer when space heating is not needed.
- Therefore, most solar collectors are used to produce hot water, and they are very common in southern Europe and Asia where solar energy is available for more than 200 days a year.

Figure 18–10

Solar water collectors on the roof of residential buildings.

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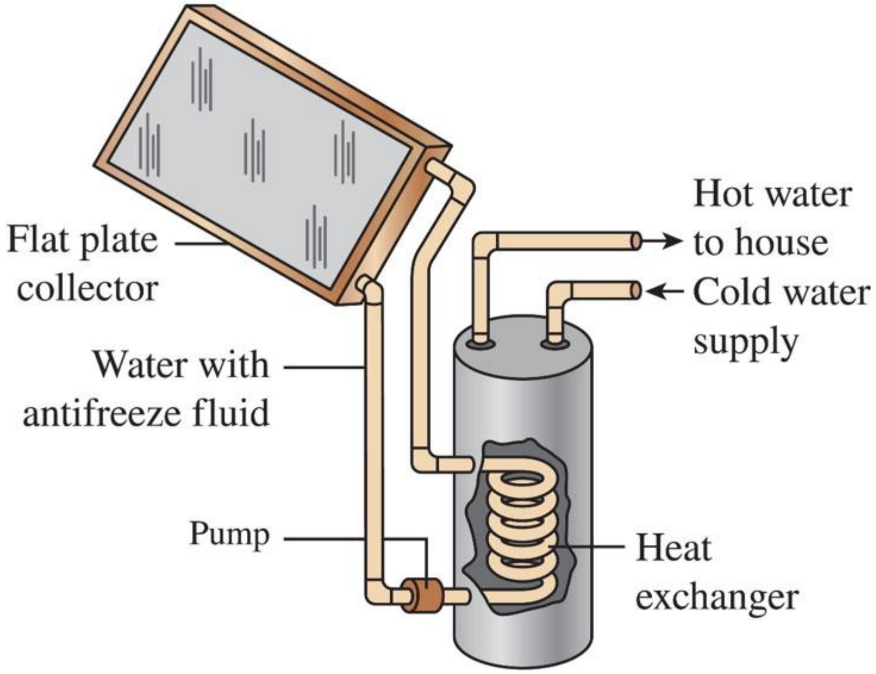
Figure 18–11

An active, closed-loop solar water heater.



- The solar collector shown in Figure 18–10 is a thermosyphon solar water heater system, which operates on a natural circulation.
- An active, closed loop solar water heater uses a pump for the circulation of water containing antifreeze fluid (Figure 18–11).
- The use of antifreeze fluid ensures that there is no freezing during subfreezing ambient temperatures.
- Water containing antifreeze is heated in the collector and gives up its heat to water in a heat exchanger.
- The resulting hot water is used in the residence.
- This system may be equipped with an electric resistance heater to provide hot water when solar energy is not available.

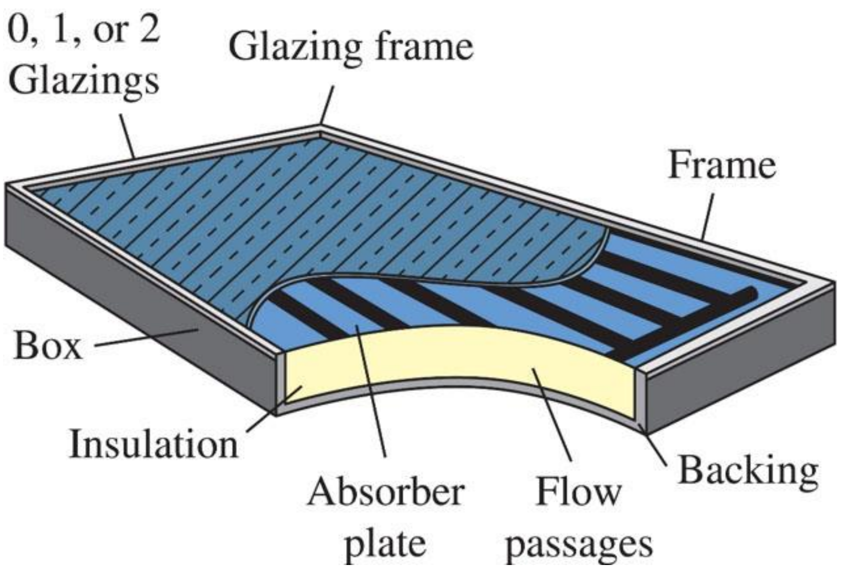
18–2 Solar Energy [19]

- A flat-plate collector consists of a glazing, an absorber plate, flow tubes, insulation, glazing frame, and a box enclosure .
- The absorber plate absorbs solar energy transmitted through the glazing, which is a type of glass.
- Flow tubes are attached to the absorber plate and water is heated as it flows in the tubes by absorbing heat from the absorber plate.
- Sides and back are insulated to minimize heat losses.
- The rate of solar heat absorbed by the absorber plate is:

$$\dot{Q}_{abs} = \tau \alpha A G$$

Figure 18–12

The cutaway view of a flat-plate solar collector.



τ the transmissivity of the glazing

α the absorptivity of the absorber plate

A the area of the collector surface, in m^2

G the solar insolation or irradiation (solar radiation incident per unit surface area), in W/m^2

18–2 Solar Energy [20]

$$\dot{Q}_{\text{abs}} = \tau\alpha AG$$

The rate of solar heat absorbed by the absorber plate

$$\dot{Q}_{loss} = UA(T_c - T_a)$$

Heat is lost from the collector by convection to the surrounding air and by radiation to the surrounding surfaces and sky

$$\begin{aligned}\dot{Q}_{useful} &= \dot{Q}_{abs} - \dot{Q}_{loss} \\ &= \tau\alpha AG - UA(T_c - T_a) \\ &= A\left[\tau\alpha G - U(T_c - T_a)\right]\end{aligned}$$

The useful heat transferred to the water is the difference between the heat absorbed and the heat lost:

$$\dot{Q}_{useful} = \dot{m}c_p(T_{w.out} - T_{w,in})$$

If the mass flow rate of water flowing through the collector *is known*

U heat loss coefficient, W/m²·°C.
c_p specific heat of water, J/kg·°C.
T_c average collector temperature, °C
T_a air temperature, °C
$T_{w,in}$, $T_{w,out}$ inlet and outlet water temperatures, °C

The efficiency of a solar collector may be defined as the ratio of the useful heat delivered to water to the radiation incident on the collector:

$$\eta_c = \frac{\dot{Q}_{useful}}{\dot{Q}_{incident}} = \frac{\tau\alpha AG - UA(T_c - T_a)}{AG} = \tau\alpha - U\frac{T_c - T_a}{G}$$

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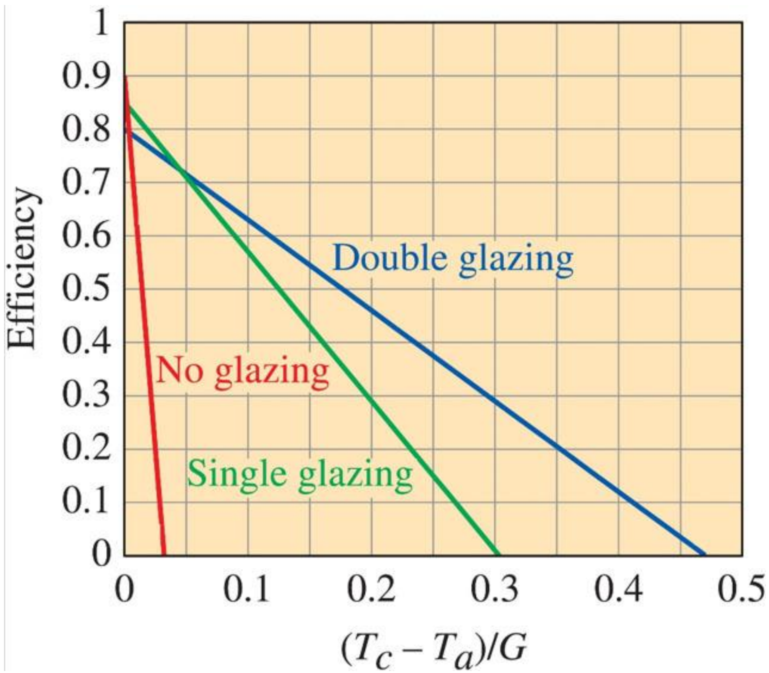
This equation gives the collector efficiency as a function of average temperature of the collector.

$$\eta_c = \frac{\dot{Q}_{useful}}{\dot{Q}_{incident}} = \frac{\tau\alpha AG - UA(T_c - T_a)}{AG} = \tau\alpha - U\frac{T_c - T_a}{G}$$

Figure 18–13

Collector efficiency for three different collectors. The data in Table 18–5 are used.



Typical values of transmissivity-absorptivity product $\tau\alpha$ and the overall heat transfer coefficient U are given in Table 18–5.

An unglazed collector allows more solar radiation input to the collector due to higher $\tau\alpha$ values but also involves higher heat transfer coefficients.

Even though the $\tau\alpha$ values go down slightly from no glazing to single and double glazing cases, the U value decreases much more significantly, as shown in Table 18–5.

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Table 18–5: Typical flat-plate solar collector properties

	$\tau\alpha$	**U,** $W/m^2.^oC$	**U,** $Btu/h.ft^2.^oF$
No glazing	0.90	28	5
Single glazing	0.85	2.8	0.5
Double glazing	0.80	1.7	0.3

Source: J. W. Mitchell, Energy Engineering. New York: Wiley, 1983.

$$\eta_c = F_R \tau\alpha - F_R U \frac{T_{w,in} - T_a}{G}$$

Note how the collector temperature (difficult to obtain) has been replaced with the water inlet temperature

- F_R is the **collector heat removal factor**.
- This relation is known as the **Hottel-Whillier-Bliss equation**.
- Also a linear equation, with slope $-F_R U$.
- maximum collector efficiency when $\left(T_{w,in} - T_a\right) = 0$
- The maximum efficiency in this case is equal to the intercept in the figure, which is equal to $F_R \tau\alpha$.

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The solar collector is normally fixed in position. As the angle of solar incident radiation changes throughout the day, the product $\tau\alpha$ also changes. This change can be accounted for by including an *incident angle modifier* $K_{\tau\alpha}$ in Equation 18–7 as

$$\eta_C = F_R K_{\tau\alpha}\tau\alpha - F_R U \frac{T_{w,\text{in}} - T_a}{G}$$

The value of $K_{\tau\alpha}$ is a function of the incident angle, and its value changes between 0 and 1. The standard collector test data are normally based on a value of 1 for $K_{\tau\alpha}$.

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Concentrating Solar Collector

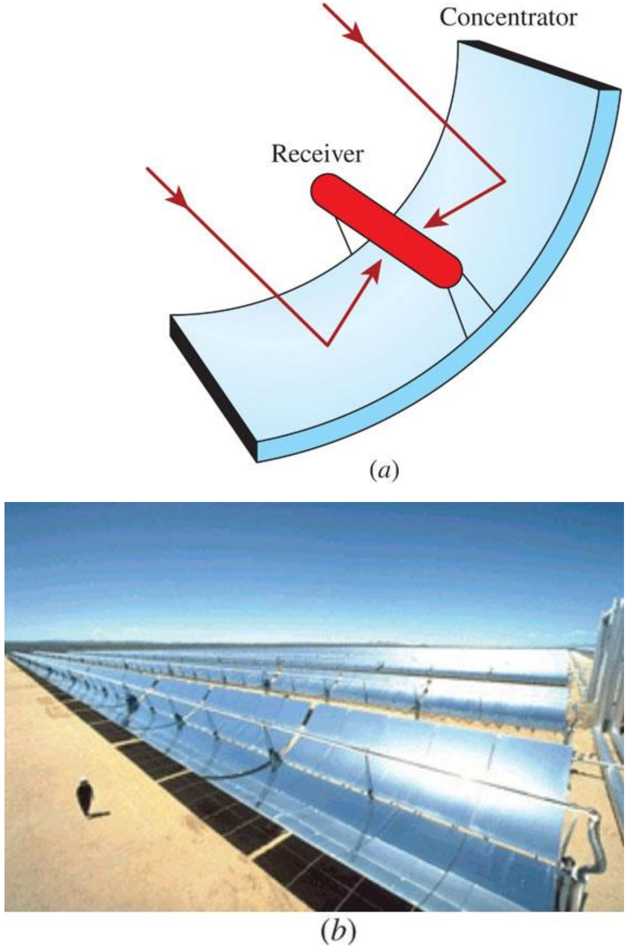
- Hot fluid (i.e. water, steam, air) at much higher temperatures can be produced using *concentrating collectors*.

- The most common type of concentrating solar collector is a parabolic trough collector.

- In a concentrating collector, solar radiation strikes the collector surface with aperture area A_a and this radiation is reflected or redirected into a smaller receiver area A_r.
- The *concentration*
- *factor* $CR = \frac{A_a}{A_r} > 1$

Figure 18–15

Parabolic trough collector. (*a*) Schematic diagram. (*b*) Photo.



18–2 Solar Energy [25]

- The effectiveness of the aperture-to-receiver process is a function of surface orientation and their radiative properties such as absorptivity and reflectivity.
- This effectiveness is expressed by an optical efficiency term η_{ar}.Then, the net rate of solar radiation supplied to the receiver is $\dot{Q}_r = \eta_{ar} A_a G$
- The rate of heat loss from the collector is expressed as $\dot{Q}_{loss} = UA_r(T_c - T_a)$:
- The useful heat transferred to the fluid is $\dot{Q}_{useful} = \dot{Q}_r - \dot{Q}_{loss} = \eta_{ar} A_a G - UA_r(T_c - T_a)$
- The efficiency of this solar collector is defined as the ratio of the useful heat delivered to the fluid to the radiation incident on the collector:

$$\eta_c = \frac{\dot{Q}_{useful}}{\dot{Q}_{incident}} = \frac{\eta_{ar} A_a G - UA_r(T_c - T_a)}{A_a G}$$

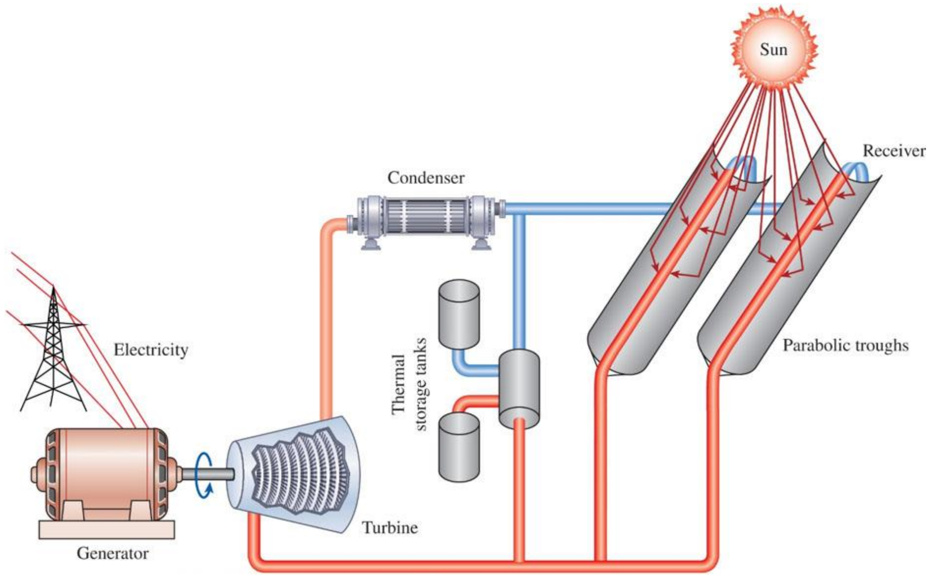
$$= \eta_{ar} - \frac{UA_r(T_c - T_a)}{A_a G} = \eta_{ar} - \frac{U(T_c - T_a)}{CR \times G}$$

18–2 Solar Energy [26]

- If the collector efficiency is plotted against the term $(T_c - T_a)/(\text{CR} \times G)$, we obtain a straight line, similar to that for a flat-plate collector. The slope of this line is equal to $-U$.
- Temperatures in the receiver of a concentrating collector can reach 400°C.
- Linear concentrating solar power (CSP) collectors are parabolic collectors arranged around a linear receiver tube.
- The heated fluid is usually water and it can be used for space heating, process heating and cooling, or even for electricity production.

Figure 18–15

A solar concentrator power plant using parabolic trough collectors.



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- A common application of CSP collectors is generating steam in the receiver tubes, and running this steam through a turbine to generate electricity.
    - Water coming out of condenser is heated, boiled, and superheated by absorbing solar heat, and it is routed to the power turbine.
    - Some existing parabolic trough systems produce 80 MW of electricity.
- If the parabolic trough collectors are oversized, excess heat can be stored and this heat can be used during nighttime or cloudy days to produce electricity.
- These solar plants can be integrated with conventional power plants using natural gas or coal.
    - The system may be designed such that electricity is supplied by solar as much as possible and the conventional system is used as backup when solar heat is not available.

- The efficiency of a solar system used to produce electricity may be defined as the power produced divided by the total solar irradiation.
- A_c is the collector surface area receiving solar irradiation and G is the solar irradiation.

$$\eta_{th,solar} = \frac{\dot{W}_{out}}{\dot{Q}_{incident}} = \frac{\dot{W}_{out}}{A_c G}$$

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Solar- Power-Tower Plant

- A *solar-power-tower* plant (i.e. Solar 1 in California) uses a large array of mirrors called ***heliostats*** that track the sun and reflects solar radiation into a tower mounted receiver. Temperatures as high as 900°C are obtained at the receiver.
    - Molten salt tanks are heated by concentrated solar heat reaching a temperature of above 500°C.
    - Water runs through the molten salt tanks in which it is boiled and superheated.
    - The resulting steam is directed to turbines to produce power.
    - Steam leaving the turbine is condensed and pumped back to the molten salt tanks to repeat the heat engine cycle.
    - An oil-sand storage unit that can help supply electricity after sunset.
    - The plant can store solar heat and use it for a period of 15 hours in the absence of daylight.
    - The plant has an installed capacity of 19.9 MW and can produce 110 GWh of electricity per year.
    - The plant has an installed capacity of 19.9 MW and can produce 110 GWh of electricity per year.

- In 1991 dollars, the total cost of electricity produced by Solar 1 plant was $14,000/kW,
    - 5 to 10 times greater than the cost of electric power stations that run on fossil fuels and other renewables.

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Figure 18–17

A solar-power-tower plant uses large array of mirrors called *heliostats* that track the sun and reflect solar radiation into a receiver mounted on top of a tower.

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Solar Pond

- A promising method of power generation involves collecting and storing solar energy in large artificial lakes a few meters deep, called solar ponds .
- Solar energy is absorbed by all parts of the pond, and the water temperature rises everywhere.
- The top part of the pond, however, loses to the atmosphere much of the heat it absorbs, and as a result, its temperature drops.
- This cool water serves as insulation for the bottom part of the pond and helps trap the energy there.
- Usually, salt is planted at the bottom of the pond to prevent the rise of this hot water to the top.
- A power plant that uses an organic fluid, such as alcohol, as the working fluid can be operated between the top and the bottom portions of the pond.
- The main disadvantage of a solar pond power plant is the low thermal efficiency.
- For example, If the water temperature is 35°C near the surface and 80°C near the bottom of the pond, the maximum thermal efficiency can be determined from Carnot relation to be

$$\eta_{th,\max} = 1 - \frac{T_L}{T_H} = 1 - \frac{(35+273)K}{(80+273)K} = 0.127 \ or \ 12.7 \ percent$$

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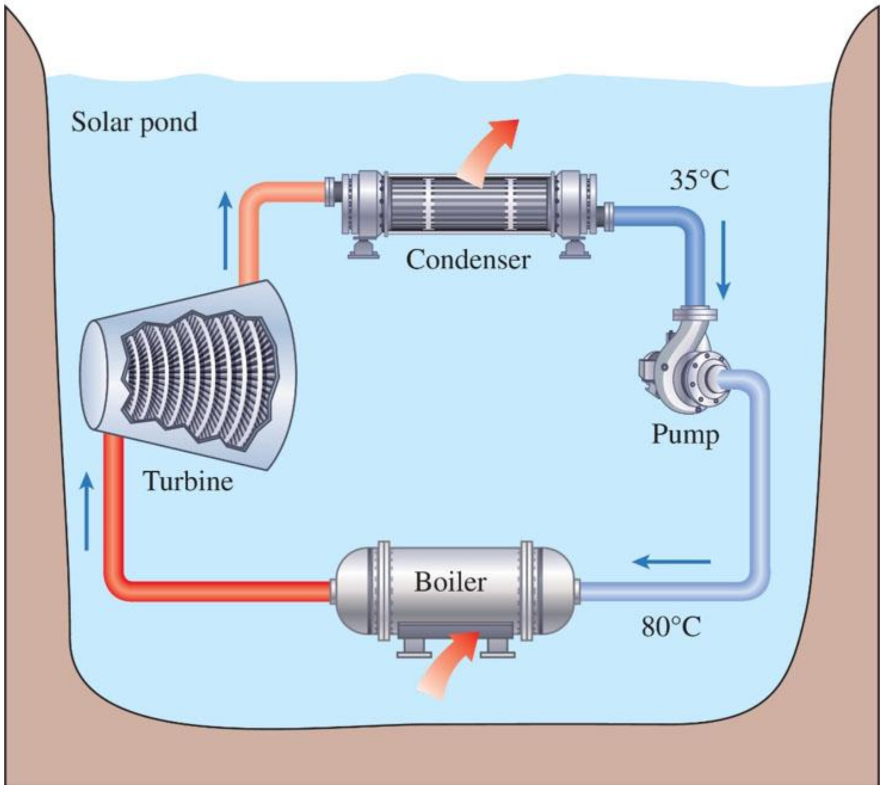
Figure 18–18
Operation of a solar pond power plant.



- An ocean thermal energy converter (OTEC) system uses the same principle, but in this case the water at the sea or ocean surface is warmer as a result of solar energy absorption.
- The water at a deeper location is cooler.
- Then, a heat engine can be operated that utilizes the surface warm water as heat source and deep cold water as the heat sink.
- Experiments have been performed using the OTEC principle but the results have not been promising due to large installation cost and low thermal efficiency.

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Photovoltaic Cell

- Electricity can be produced from solar energy by using solar collectors to collect solar heat into a fluid and routing this fluid into a turbine.
- This may be viewed as indirect conversion of solar energy into electricity.
- Direct conversion of solar radiation into electricity is possible by the use of photovoltaic cell systems.
- A photovoltaic system consists of an array of solar cells.
- An understanding of the operation of solar cells requires physics of atomic theory and semiconductor theory.
- The cell involves a *p*-type semiconductor and an *n*-type semiconductor.

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- Silicon is commonly used as a semiconductor material in solar cells.
- The silicon is doped with phosphorus to produce the n -type semiconductor while it is doped with boron to produce the p -type semiconductor.
- There is a current density flow at the *p*-*n* junction of a solar cell.

Figure 18–19
Operation of a solar cell.

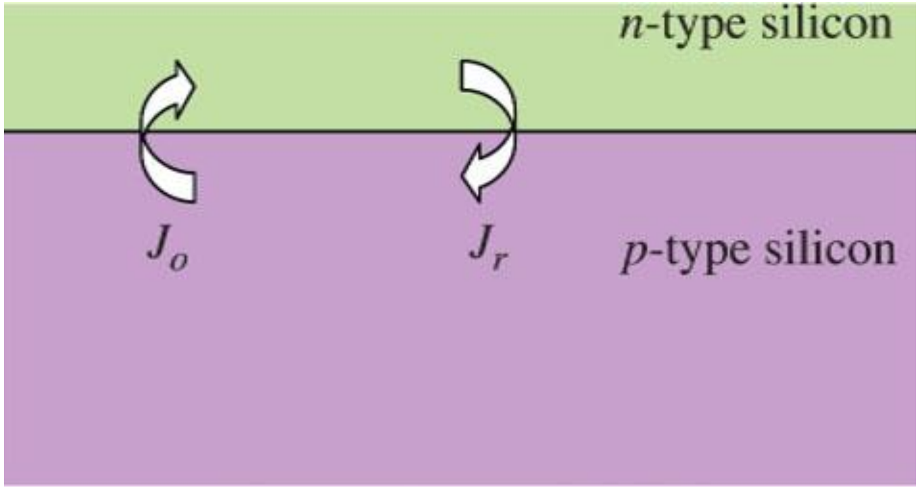

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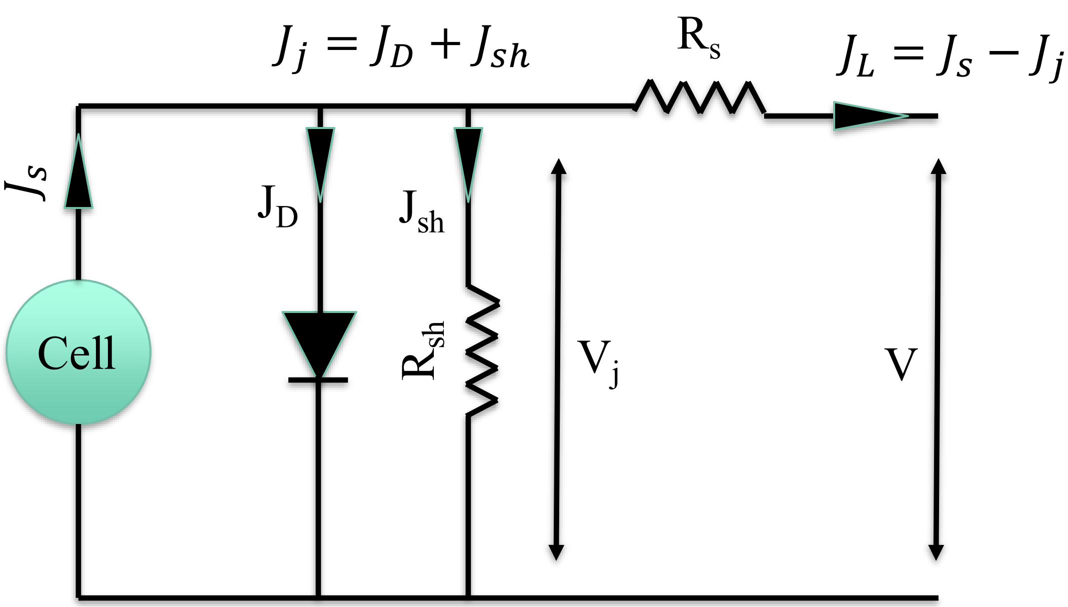
Figure 18–20

Equivalent circuit for solar cell.



Eliminating *resistive* losses

$R_s = 0$

$R_{sh} \to \infty$

$V_j = V$

$$J_L = J_s - J_0\left\{\exp\left(\frac{V}{V_T}\right) - 1\right\}$$

Shockley diode equation

$$J_D = J_0\left\{\exp\left(\frac{V_j}{V_T}\right) - 1\right\}$$

reverse or *scale* current

$V_T = kT/q$

V_T is the *thermal voltage*

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- An expression for the ratio of the load current density J_L to J_s may be obtained by dividing the equation for J_L by J_s:

$$\frac{J_L}{J_s} = 1 - \frac{J_o}{J_s}\left[\exp\left(\frac{e_0 V}{kT}\right) - 1\right]$$

- The voltage is zero $V = 0$ when the cell is short-circuited and thus $J_s = J_L$.
- The cell output passes solely through the junction (diode) when the circuit is open and $J_L = 0$. The voltage in this case is called the open circuit voltage. The above equation can then be solved for V_{oc} to yield:

$$V_{oc} = \frac{kT}{e_o}\ln\left(\frac{J_s}{J_o} + 1\right)$$

- The power output delivered to the load is:

$$\dot{W} = J_L V A$$

- Differentiate with respect to V and To obtain V_{max} for the maximum power output:

$$\exp\left(\frac{e_0 V_{max}}{kT}\right) = \frac{1 + J_s / J_o}{1 + \dfrac{e_o V_{max}}{kT}}$$

Note that the maximum voltage V_{max} is implicit in this equation. A trial-error approach or an equation solver is needed to solve for V_{max}.

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The maximum power output of the cell is

$$\dot{W}_{\max} = \frac{AV_{\max}\left(J_s + J_o\right)}{1 + \dfrac{kT}{e_0 V_{\max}}}$$

The maximum conversion efficiency of a solar cell can be written as

$$\eta_{cell} = \frac{\dot{W}}{AG}$$

The conversion efficiency of a solar cell can be expressed as

$$\eta_{cell,\max} = \frac{\dot{W}_{\max}}{AG} = \frac{AV_{\max} J_s + J_o}{AG\left(1 + \dfrac{kT}{e_0 V_{\max}}\right)} = \frac{V_{\max}\left(J_s + J_o\right)}{G\left(1 + \dfrac{kT}{e_o V_{\max}}\right)}$$

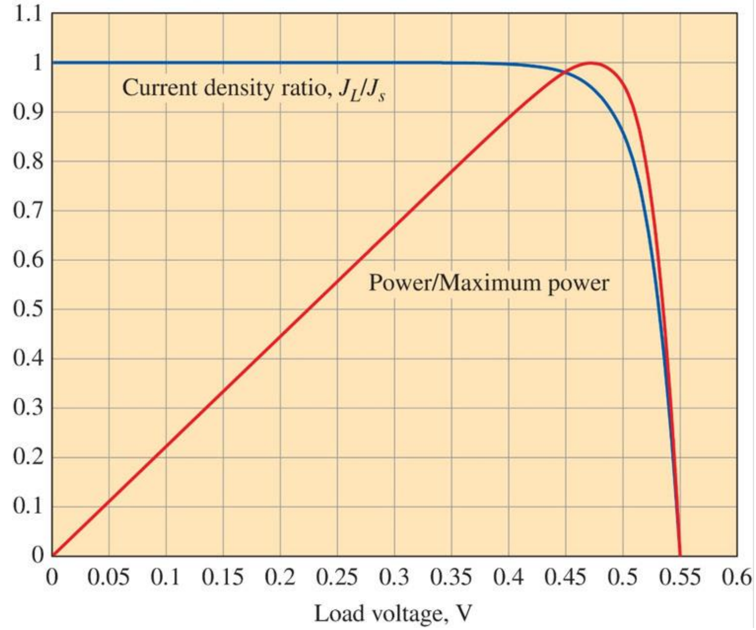
18–2 Solar Energy [39]

- Plot the current density ratio J_L / J_s as a function of load voltage for a specified value of open circuit voltage V_{oc}.
- Also can be plot power output normalized with respect to maximum power against load voltage.
- The plots in Fig. 18–21 are obtained with V_{oc} = 0.55 V and T = 300 K. Note that a high-quality silicon solar cell can produce an open circuit voltage of about 0.6 V.
- For short circuit case ($J_L = J_s$ or $J_L / J_s = 1$), the voltage is zero, and the power output is zero.
- For open circuit voltage case ($J_L = 0$), the voltage is 0.55 V, and the power output is also zero.

The maximum power occurs at a voltage close to open circuit voltage, which is 0.47 V in this case. The current density ratio remains close to unity until the open circuit voltage is approached. Then, it decreases rapidly before it becomes zero at the open circuit case. The trends and characteristics shown in Figure 18–21 are typical of most solar cells.

Figure 18–21

Current density ratio J_L/J_s and power output ratio $\dot{W}/\dot{W}_{max}$ in a solar cell as a function of load voltage.



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- Solar radiation incident on a solar cell is originated from the sun.
- The upper limit for the efficiency of a fuel cell may be determined from the Carnot efficiency relation by using effective surface temperature of the sun (5780 K) and an ambient temperature of 298 K:

$$\eta_{cell,\max} = 1 - \frac{T_L}{T_H} = 1 - \frac{298K}{5780K} = 0.948 \text{ or } 94.8 \text{ percent}$$

Silicon has been commonly used in solar cells but the commercial silicon solar cells have a low efficiency (between 15 and 20 percent).

Other materials have been tested extensively in order to increase solar cell efficiencies.

They include cadmium telluride, cadmium sulfide, copper indium diselenide, gallium arsenide, gallium phosphide, and indium phosphide.

Copper indium diselenide and gallium arsenide are among the most promising materials.

An efficiency of 40 percent has been approached for gallium arsenide solar cells in laboratory environment.

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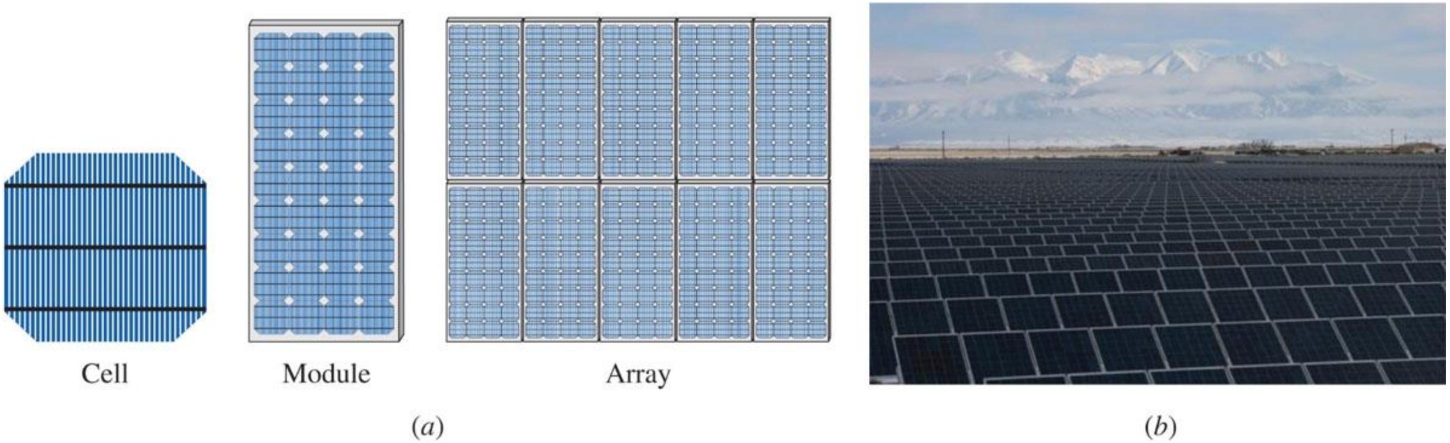
- Using multiple junction design with high solar irradiation has resulted in a research efficiency of 43 percent. Note however that, the cost of high-efficient solar cells appears to be much greater than silicon solar cells.
- A single solar cell produces only 1 to 2 W of power.
- Multiple cells should be connected to form modules and modules should be connected into arrays so that reasonable amounts of power can be generated.
- This way, both small and large photovoltaic systems can be installed depending on the demand.

Figure 18–22

(*a*) A photovoltaic system typically consists of arrays, which are obtained by connecting modules, and modules consist of individual cells. (*b*) Solar arrays.



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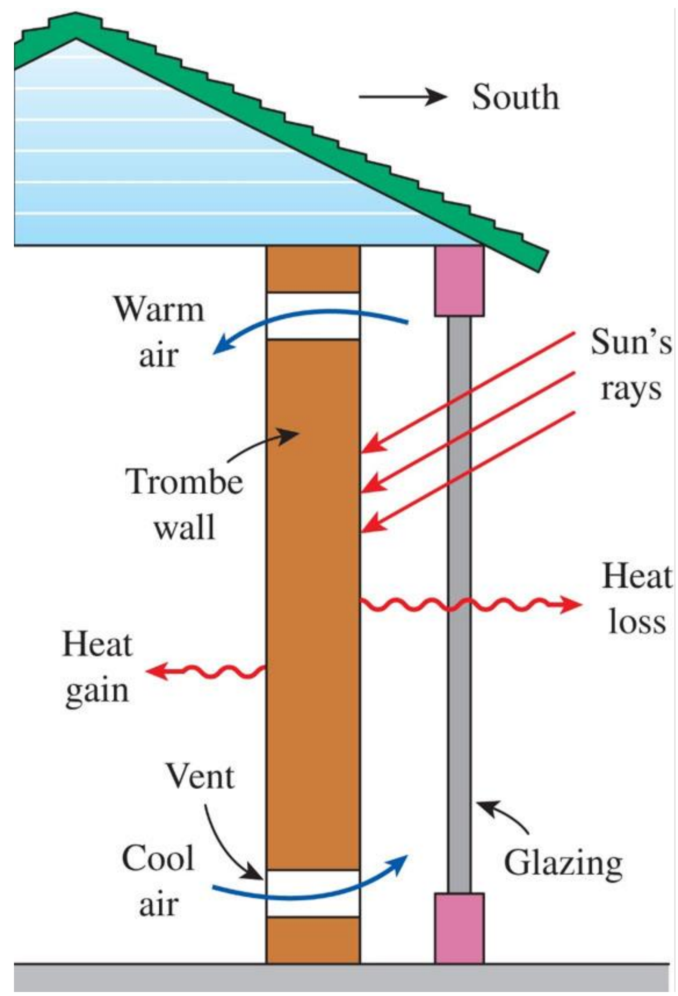
The University of Manchester

Passive Solar Applications

- Passive use of solar energy = no involvement of mechanical equipment
- Significant energy savings can be accomplished if a house is designed and built to receive maximum solar heat in winter (to reduce heating energy consumption) and minimum solar heat gain in summer (to reduce cooling energy consumption).
- This may include correct selection of orientation of walls and windows, size and type of windows, wall materials, and surface color and finishing of wall surfaces.
- Dark painted thick masonry walls called trombe walls are commonly used on south sides of passive solar homes to absorb solar energy, store it during the day, and release it to the house during the night.
- Also, air vents are commonly installed at the bottom and top of the trombe walls so that the room air enters the parallel flow channel between the trombe wall and the glazing, rises as it is heated, and enters the room through the top vent.

Figure 18–23

Schematic of a trombe wall.



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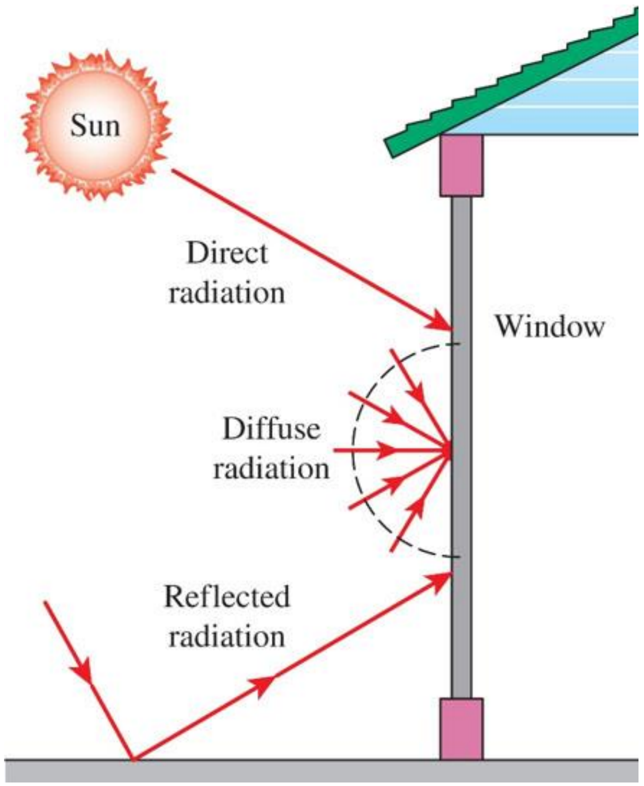
Solar Heat Gain Through Windows

- The part of solar radiation that reaches the earth's surface without being scattered or absorbed is the direct radiation.
- Solar radiation that is scattered or reemitted by the constituents of the atmosphere is the diffuse radiation.
- Direct radiation comes directly from the sun following a straight path, whereas diffuse radiation comes from all directions in the sky.
- The entire radiation reaching the ground on an overcast day is diffuse radiation.
- The radiation reaching a surface, in general, consists of three components: direct radiation, diffuse radiation, and radiation reflected onto the surface from surrounding surfaces.
- When solar radiation strikes a glass surface, part of it (about 8 percent for uncoated clear glass) is reflected back to outdoors, part of it (5 to 50 percent, depending on composition and thickness) is absorbed within the glass, and the remainder is transmitted indoors.
- The Standard 3-mm (1/8-in)-thick single-pane double-strength clear window glass transmits 86 percent, reflects 8 percent, and absorbs 6 percent of the solar energy incident on it.

Figure 18–24

Direct, diffuse, and reflected components of solar radiation incident on a window.



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- The solar energy transmitted inside a building represents a heat gain for the building.
- The solar radiation absorbed by the glass is subsequently transferred to the indoors and outdoors by convection and radiation.
- The sum of the transmitted solar radiation and the portion of the absorbed radiation that flows indoors constitutes the solar heat gain of the building.
- The solar heat gain coefficient (SHGC) measures the fraction of incident solar radiation that enters through the glazing

$$SHGC = \frac{\dot{Q}_{solar,gain}}{G} = \tau_s + f_i \alpha_s$$

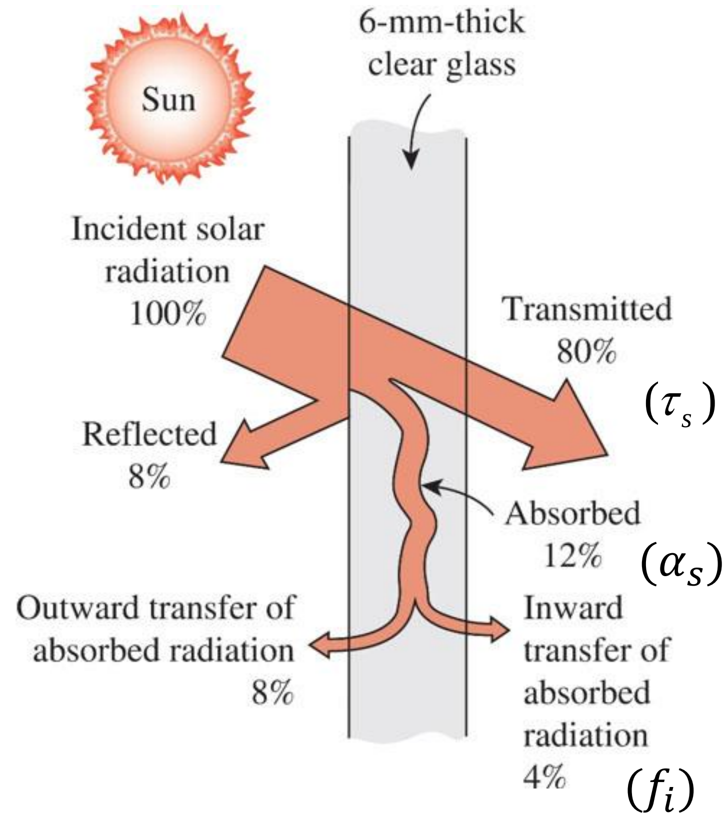
- The value of *SHGC* ranges from 0 to 1, with 1 corresponding to an opening in the wall (or the ceiling) with no glazing. When the *SHGC* of a window is known, the total solar heat gain through that window is determined from

$$\dot{Q}_{Solar,gain} = SHGC \times A_{glazing} \times G$$

- $A_{glazing}$ is the glazing area of the window G is the solar heat flux incident on the outer surface of the window, in W/m^2

Figure 18–25

Distribution of solar radiation incident on a clear glass.



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- Another way of characterizing the solar transmission characteristics of different kinds of glazing and shading devices is to compare them to a well-known glazing material that can serve as a base case.
- This is done by taking the standard 3-mm (1/8-in) thick double-strength clear window glass sheet whose SHGC is 0.87 as the reference glazing and defining a shading coefficient SC as

$$SC = \frac{SHGC}{SHGC_{ref}} = \frac{SHGC}{0.87} = 1.15 \times SHGC$$

- Therefore, the shading coefficient of a single-pane clear glass window is SC = 1.0.
- The values for winter design conditions may be slightly lower because of the higher heat transfer coefficients on the outer surface due to high winds and thus higher rate of outward flow of solar heat absorbed by the glazing, but the difference is small.
- Note that the larger the shading coefficient, the smaller the shading effect, and thus the larger the amount of solar heat gain.
- A glazing material with a large shading coefficient allows a large fraction of solar radiation to come in.

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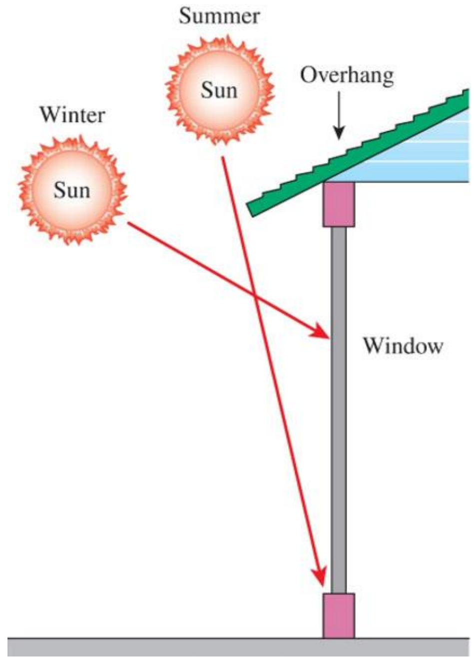
Solar heat entering a house through windows is preferable in winter since it reduces heating energy consumption but it should be avoided as much as possible in summer since it increases cooling energy consumption.

- Shading devices are used to control solar heat gain through windows.
- Shading devices are classified as internal shading and external shading, depending on whether the shading device is placed inside or outside .
- External shading devices are more effective in reducing the solar heat gain since they intercept the sun's rays before they reach the glazing.
- The sun is high in the horizon in summer and low in winter.
- A properly sized roof overhang or a horizontal projection blocks off the sun's rays completely in summer while letting in most of them in winter, as shown in Fig. 18–26.
- A window can also be shaded from outside by vertical or horizontal or architectural projections, insect or shading screens, and sun screens.
- To be effective, air must be able to move freely around the exterior device to carry away the heat absorbed by the shading and the glazing materials.

Figure 18–26

A properly sized overhang blocks off the sun's rays completely in summer while letting them through in winter.



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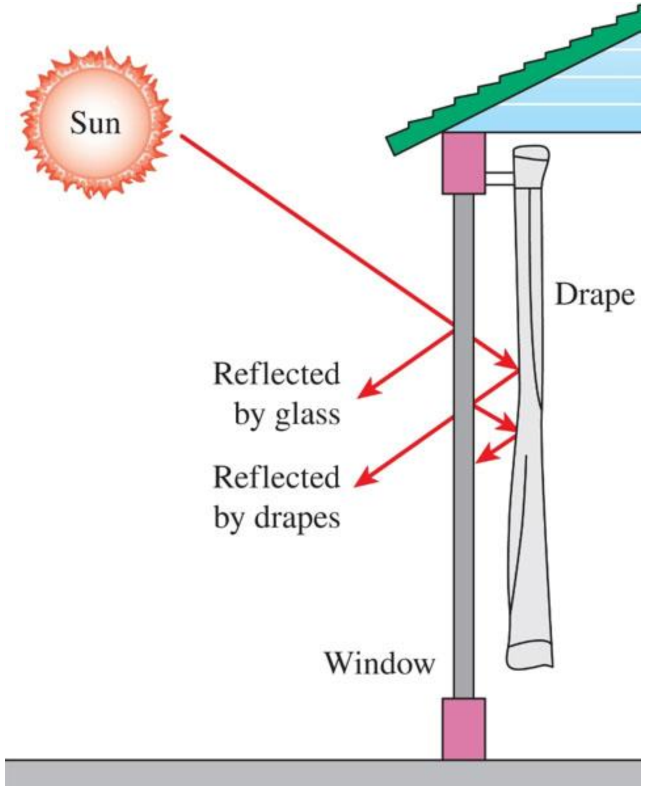
- Some type of internal shading is used in most windows to provide privacy and aesthetic effects as well as some control over solar heat gain.
- Internal shading devices reduce solar heat gain by reflecting transmitted solar radiation back through the glazing before it can be absorbed and converted into heat in the building.
- Draperies reduce the annual heating and cooling loads of a building by 5 to 20 percent, depending on the type and the user habits.
- In summer, they reduce heat gain primarily by reflecting back direct solar radiation.
- The shading coefficient of draperies depends on the openness factor, which is the ratio of the open area between the fibers that permits the sun's rays to pass freely, to the total area of the fabric.
- Tightly woven fabrics allow little direct radiation to pass through, and thus they have a small openness factor.
- The reflectance of the surface of the drapery facing the glazing has a major effect on the amount of solar heat gain.
- Light-colored draperies made of closed or tightly woven fabrics maximize the back reflection and thus minimize the solar gain.

Figure 18–27

Draperies reduce heat gain in summer by reflecting back solar radiation, and reduce heat loss in winter by forming an air space before the window.



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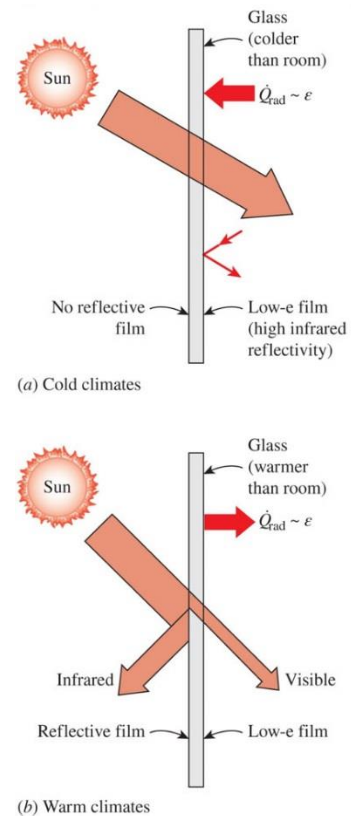
- The shading coefficients of drapes also depend on the way they are hung.
- Usually, the width of drapery used is twice the width of the draped area to allow folding of the drapes and to give them their characteristic “full” or “wavy” appearance.
- A flat drape behaves like an ordinary window shade.
- A flat drape has a higher reflectance and thus a lower shading coefficient than a full drape.
- The effectiveness of manually operated shading devices, on the other hand, varies greatly depending on the user habits, and this variation should be considered when evaluating performance.
- The primary function of an indoor shading device is to provide thermal comfort for the occupants.
- An unshaded window glass allows most of the incident solar radiation in, and also dissipates part of the solar energy it absorbs by emitting infrared radiation to the room.
- The emitted radiation and the transmitted direct sunlight may bother the occupants near the window.
- Glare from draperies can be minimized by using off-white colors. Indoor shading devices, especially draperies made of a closed-weave fabric, are effective in reducing sounds that originate in the room, but they are not as effective against the sounds coming from outside.
- The type of climate in an area usually dictates the type of windows to be used in buildings.

18–2 Solar Energy 50

- In cold climates where the heating load is much larger than the cooling load, the windows should have the highest transmissivity for the entire solar spectrum, and a high reflectivity (or low emissivity) for the far infrared radiation emitted by the walls and furnishings of the room.
- In warm climates where the cooling load is much larger than the heating load, the windows should allow the visible solar radiation (light) in, but should block off the infrared solar radiation.
- Such windows can reduce the solar heat gain by 60 percent with no appreciable loss in daylighting.
- This behavior is approximated by window glazings that are coated with a heat-absorbing film outside and a low-e film inside (Fig. 18–28).
- Properly selected windows can reduce the cooling load by 15 to 30 percent compared to windows with clear glass.
- Tinted glass and glass coated with reflective films reduce solar heat gain in summer and heat loss in winter.

Figure 18–28

Radiation heat transfer between a room and its window is proportional to the emissivity of the glass surface, and low-e coatings on the inner surface of the windows reduce heat loss in winter and heat gain in summer.



18–3 Wind Energy 3

Wind Turbine Types and Power Performance Curve

- Numerous innovative wind turbine designs have been proposed and tested over the centuries.
- We generally categorize wind turbines by the orientation of their axis of rotation

  horizontal axis wind turbines (HAWTs)

  vertical axis wind turbines (VAWTs)

- An alternative way to categorize them is by the mechanism that provides torque to the rotating shaft: lift or drag. So far, none of the VAWT designs or drag-type designs has achieved the efficiency or success of the lift-type HAWT.
- This is why the vast majority of wind turbines being built around the world are of this type, often in clusters affectionately called wind farms.

18–3 Wind Energy [2]

Figure 18–29

(*a*) Wind farms are popping up all over the world to help reduce the global demand for fossil fuels. (*b*) Some wind turbines are even being installed on buildings! (These three turbines are on a building at the Bahrain World Trade Center.)

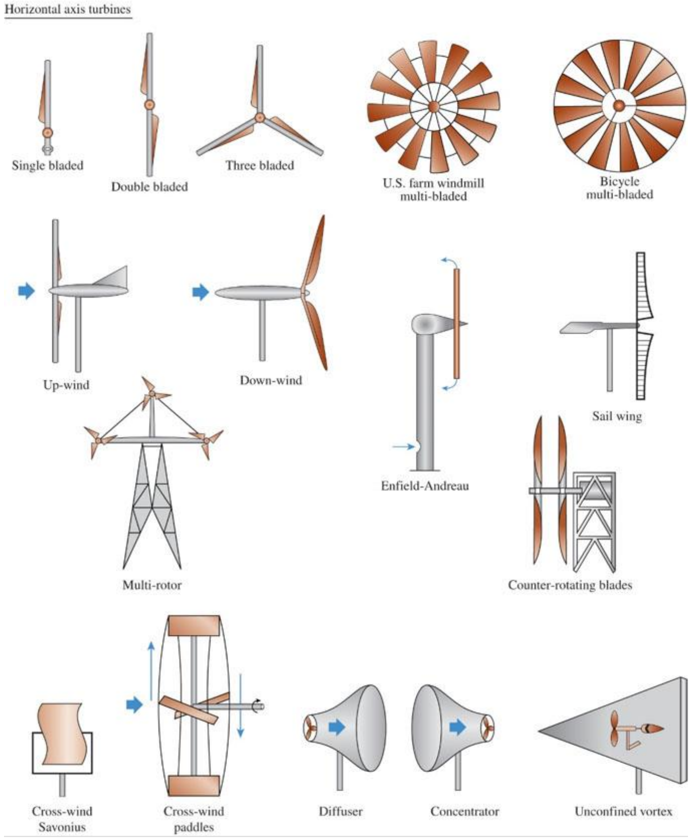
- Wind turbines produce power only when the wind is blowing, and the power output of a wind turbine is unsteady.
- Wind turbines need to be located where the wind blows, which is often far from traditional power grids, requiring construction of new high-voltage power lines.
- Wind turbines are expected to play an ever increasing role in the global supply of energy for the foreseeable future.

18–3 Wind Energy [4]

Horizontal Axis Turbines

Figure 18–30

Various wind turbine designs and their categorization.



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18–3 Wind Energy 5

Vertical Axis Turbines

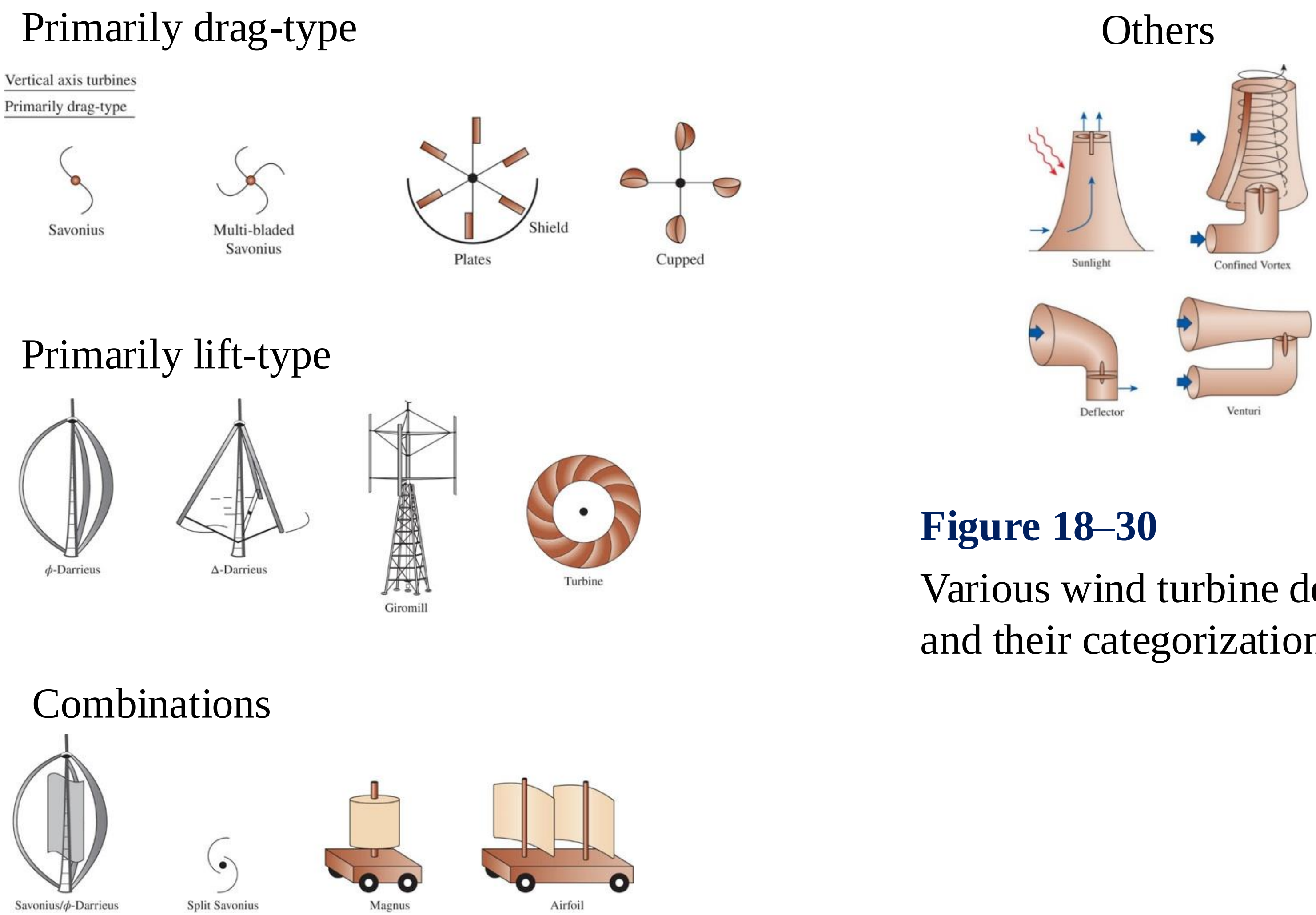


Figure 18–30

Various wind turbine designs and their categorization.

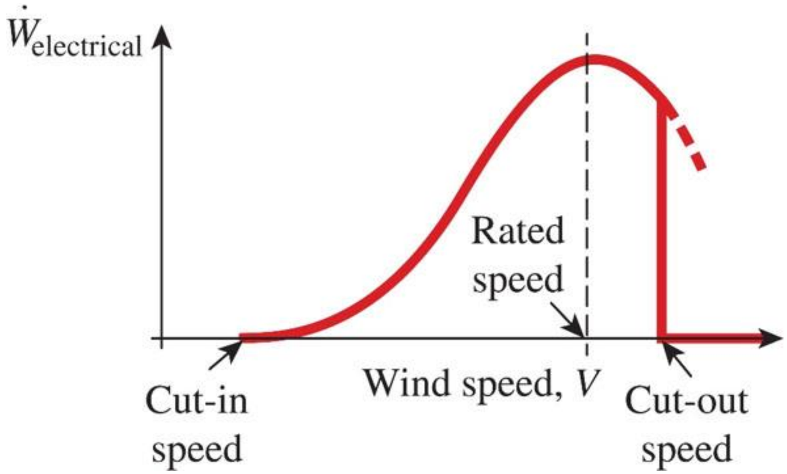
18–3 Wind Energy [6]

- Every wind turbine has a characteristic power performance curve. Electrical power output is plotted as a function of wind speed *V* at the height of the turbine's axis.
- We identify three key locations on the wind-speed scale:

Cut-in speed is the minimum wind speed at which useful power can be generated.
Rated speed is the wind speed that delivers the rated power, usually the maximum power.
Cut-out speed is the maximum wind speed at which the wind turbine is designed to produce power. At wind speeds greater than the cut-out speed, the turbine blades are stopped by some type of braking mechanism to avoid damage and for safety issues.

- The short dashed line indicates the power that would be produced if cut-out were not implemented.

Figure 18–31
Typical qualitative wind-turbine power performance curve with definitions of cut-in, rated, and cut-out speeds.



The design of HAWT turbine blades includes tapering and twist to maximize performance.

While the fluid mechanics of wind turbine design is critical, the power performance curve also is influenced by the electrical generator, the gearbox, and structural issues. Inefficiencies appear in every component.

18–3 Wind Energy [7]

Wind power potential

The mechanical energy can be defined as the form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.

$$\dot{E}_{mech} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

$\frac{P}{\rho}$ is the flow energy,

$\frac{V^2}{2}$ is the kinetic energy

gz is the potential energy of the fluid

$\dot{m}$ is the mass flow rate of the fluid.

The pressures at the inlet and exit of a wind turbine are both equal to the atmospheric pressure and the elevation does not change across a wind turbine.

Therefore, flow energy and potential energy do not change across a wind turbine.

A wind turbine converts the kinetic energy of the fluid into power.

18–3 Wind Energy [8]

$$\dot{W}_{available} = \frac{1}{2}\dot{m}V^2 \qquad \text{(kW)}$$

Available wind power: The maximum power a wind turbine can generate for the given wind velocity V.

$$\dot{m} = \rho AV \quad \text{(kg/s)}$$

Mass flow rate

$$\dot{W}_{available} = \frac{1}{2}\rho AV^3$$

Wind power potential

ρ is the density

A is the disk area of a wind turbine (the circular area swept out by the turbine blades as they rotate).

18–3 Wind Energy [9]

The available power relation indicates that the power potential of a wind turbine is proportional to density of air. As a result, cold air has a higher wind power potential than the warm air.

$P = \rho RT$ Ideal gas relation Gas constant R = 0.287 kPa · m³/kg · K

$A = \pi D^2 / 4$ The disk area. D is the blade diameter.

$$\dot{W}_{available} = \frac{1}{2}\rho A V^3 \qquad \dot{W}_{available} = \frac{\pi P D^2 V^3}{8RT}$$

The power potential of a wind turbine is proportional to cubic power of the wind velocity.

The power potential of a wind turbine is proportional to the square of the blade diameter.

As a result, doubling blade diameter increases the power potential by a factor of four.

18–3 Wind Energy 10

Consider a location where the wind with a density of 1.2 kg/m^3 is blowing at a velocity of 4 m/s. The maximum power a wind turbine with a rotor diameter of 1 m can generate is

$$\dot{W}_{avilable} = \frac{1}{2}\rho A V^3 = \frac{1}{2}(1.2 kg/m^3)\frac{\pi(1m^2)}{4}(4m/s)^3 = 30kW$$

If the wind velocity is doubled, the available power becomes 242 kW.

Doubling the wind velocity will increase the power potential by a factor of 8.

For this cubical relationship, a wind turbine investment is usually not justified if the location does not have a steady wind at a velocity of about 6 m/s or higher.

Figure 18–32

The power potential of a wind turbine is proportional to the cubic power of the wind velocity. Therefore, doubling the wind velocity will increase the power potential by a factor of 8.

Wind velocity, m/s	*Available power, kW*
1	0.5
2	4
3	13
4	30
5	59
6	102
7	162
8	242
9	434
10	471

Wind power Density

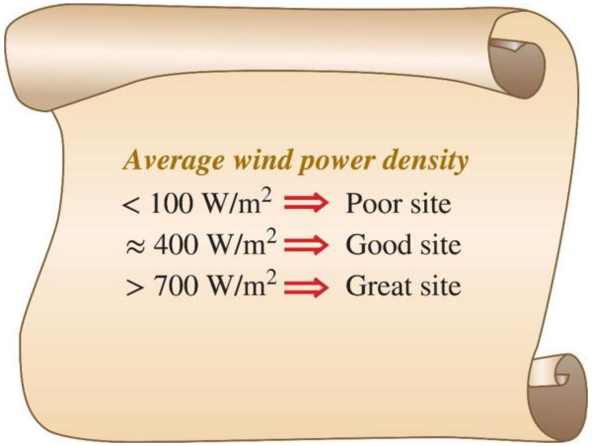
For comparison of various wind turbines and locations, it is more useful to think in terms of the available wind power per unit area, which we call the wind power density, typically in units of W/m^2.

$$wind\ power\ density: \frac{\dot{W}_{available}}{A} = \frac{1}{2}\rho V^3$$

The average wind power density should be calculated based on hourly wind speed averages for the entire year.
As a general rule of thumb, the *quality* of a location is assessed using the criteria in figure 18.33

Figure 18–33

A rule of thumb criteria for construction of wind turbines in a proposed site.



Note that a wind power density of $100\ \text{W/m}^2$ corresponds to a wind speed of 5.5 m/s for an air density of $1.2\ \text{kg/m}^3$.

Other factors affect the choice of a wind turbine site, such as atmospheric turbulence intensity, terrain, obstacles (buildings, trees, etc.), environmental impact, etc.

18–3 Wind Energy 12

Wind Turbine Efficiency

An actual wind turbine can produce only a percentage of available power potential into actual shaft power. This percentage is called the wind turbine efficiency.

$$\eta_{wt} = \frac{\dot{W}_{shaft}}{\dot{W}_{available}} = \frac{\dot{W}_{shaft}}{\frac{1}{2}\rho A V^3}$$

The efficiency of a wind turbine is usually referred to as the **power coefficient** *Cp*. Here, we use the notation η_{wt}

A gearbox/generator connected to the turbine converts shaft power into electrical power output:

$$\dot{W}_{electric} = \eta_{gearbox/generator} \dot{W}_{shaft} \quad \text{(kW)}$$

$\eta_{gearbox/generator}$ is the gearbox/generator efficiency, and is typically above 80 percent.

$$\eta_{wt,overall} = \frac{\dot{W}_{electric}}{\dot{W}_{available}} = \frac{\dot{W}_{electric}}{\frac{1}{2}\rho A V^3}$$

Overall wind turbine efficiency

The efficiency of wind turbines usually ranges between 30 and 40 percent.

18–3 Wind Energy [14]

If we neglect frictional effects in a wind turbine and take the wind velocity as the average velocity of air at the turbine inlet, we can state that the portion of incoming kinetic energy not converted to shaft power leaves the wind turbine as outgoing kinetic energy. That is,

$$\dot{m}\frac{V_1^2}{2} = \dot{W}_{shaft} + \dot{m}\frac{V_2^2}{2}$$

$$\eta_{wt} = \frac{\dot{W}_{shaft}}{\dot{m}\frac{V_1^2}{2}}$$

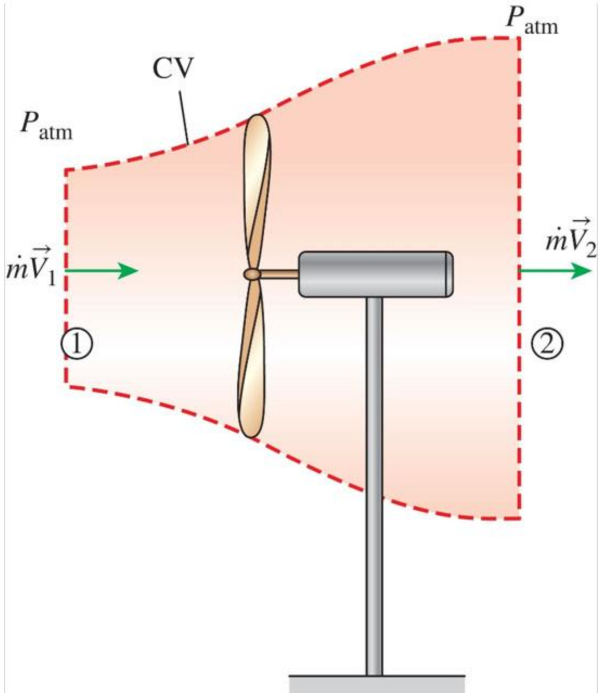
$$\dot{m}\frac{V_2^2}{2} = \dot{m}\frac{V_1^2}{2}(1-\eta_{wt})$$

$$V_2 = V_1\sqrt{1-\eta_{wt}}$$

This relation enables us to determine the exit velocity when the turbine efficiency is known and the frictional effects are neglected.

Figure 18–34

The flow of air across a wind turbine.



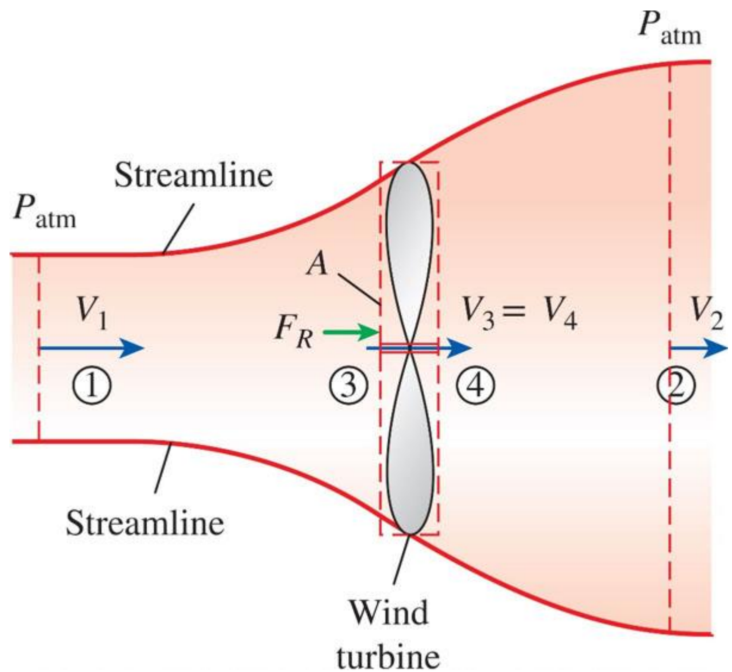
18–3 Wind Energy 15

Betz Limit for Wind Turbine Efficiency

- A wind turbine converts kinetic energy of air into work.
- Since $V_2 > 0$, this turbine cannot be 100% efficient
- It turns out that there is a maximum possible efficiency for a wind turbine.
- This was first calculated by Albert Betz (1885–1968) in the mid 1920s.
- We consider two control volumes surrounding the disk area: a large control volume and a small control volume as sketched in Fig. 18–35, with upstream wind speed V taken as V_1.

Figure 18–35

The large and small control volumes for analysis of ideal wind turbine performance bounded by an axisymmetric diverging stream tube.



18–3 Wind Energy 16

Since far field pressure is atmospheric, there is no net pressure force acting on the large control volume

$$F_R = \dot{m}(V_2 - V_1)$$

Assuming the turbine disk is infinitely thin, we have

$$F_R + (P_3 - P_4) = 0$$

Bernoulli's equation applies upstream and downstream of the disk (neglect potential terms)

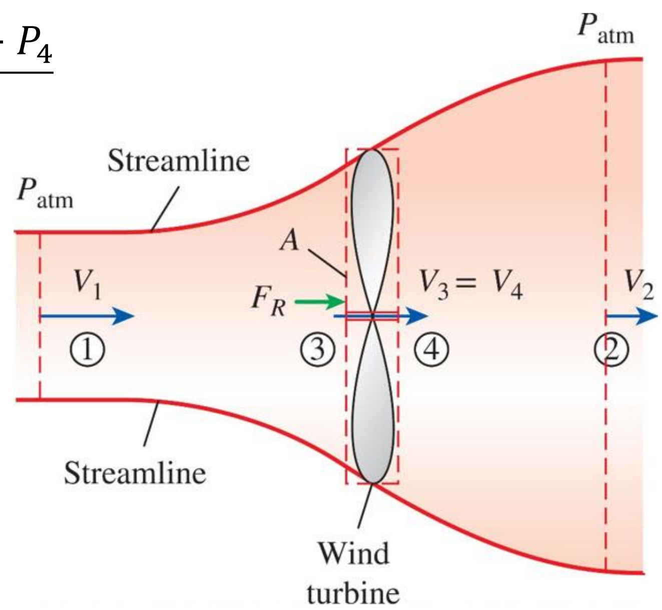
$$\frac{P_{atm}}{\rho g} + \frac{V_1^2}{2g} = \frac{P_3}{\rho g} + \frac{V_3^2}{2g} \qquad \frac{P_4}{\rho g} + \frac{V_4^2}{2g} = \frac{P_{atm}}{\rho g} + \frac{V_2^2}{2g}$$

Combine the two Bernoulli equations

$$\frac{V_1^2 - V_2^2}{2} = \frac{P_3 - P_4}{\rho}$$

Introduce $a = (V_1 - V_3)/V_1$

$$\left.\begin{aligned} V_3 &= V_1(1-a) \\ V_2 &= V_1(1-2a) \\ \dot{m} &= \rho V_3 A \end{aligned}\right\} \quad V_3 = \frac{V_1 + V_2}{2}$$



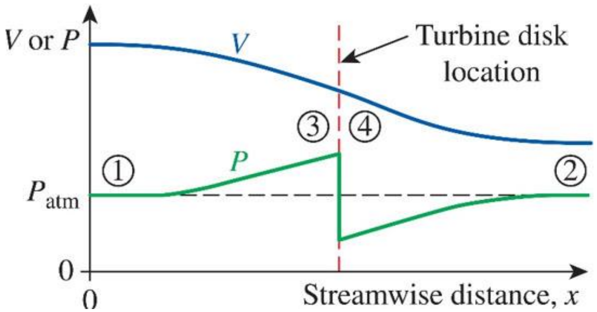


Figure 18–36

Qualitative sketch of average streamwise velocity and pressure profiles through a wind turbine.

18–3 Wind Energy [17]

We are now in a position to calculate the work and efficiency

$$\dot{W}_{ideal} = \dot{m}\frac{V_1^2 - V_2^2}{2} = 2\rho A V_1^3 a(1-a)^2$$

$$\eta_{wt} = \frac{\dot{W}_{ideal}}{\frac{1}{2}\rho V_1^3 A} = 4a(1-a)^2$$

To find maximum efficiency, evaluate $\dfrac{\partial \eta_{wt}}{\partial a} = 0 \Longrightarrow a = 1, \dfrac{1}{3}$

$a = 1$ is the trivial case (no power generation – see first equation)

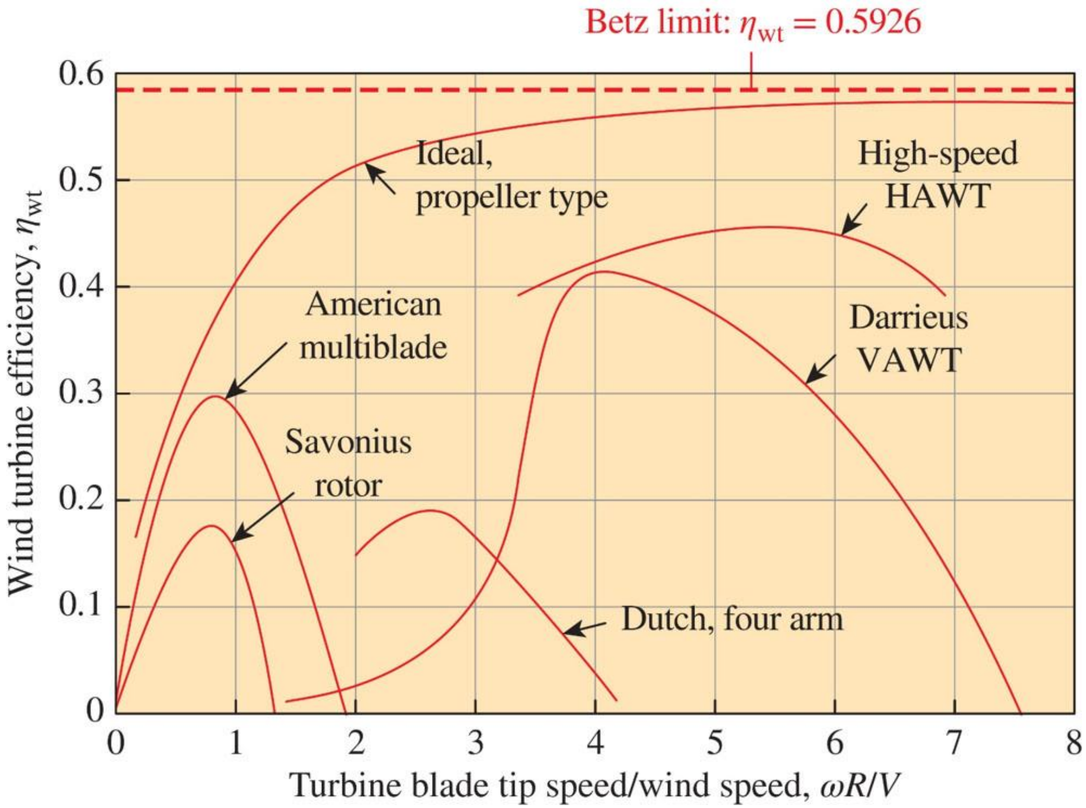
$a = 1/3$ provides the condition for maximum efficiency

$$\eta_{wt,max} = \frac{4}{3}\left(1 - \frac{1}{3}\right)^2 = \frac{16}{27}$$

This Is the *Betz limit*

Figure 18–37

Efficiency of various types of wind turbines as a function of the ratio of turbine blade tip speed to wind speed. So far, no design has achieved better performance than the horizontal axis wind turbine (HAWT).



18–3 Wind Energy [20]

- From the wind turbine efficiency plot, we see that an ideal propeller-type wind turbine approaches the Betz limit as $\omega R/V$ approaches infinity.
- However, the efficiency of real wind turbines reaches a maximum at some finite value of $\omega R/V$ and then drops beyond that.
- In practice, three primary effects lead to a maximum achievable efficiency that is lower than the Betz limit:
- Rotation of the wake behind the rotor (swirl)
- Finite number of rotor blades and their associated tip losses (tip vortices are generated in the wake of rotor blades for the same reason they are generated on finite airplane wings since both produce "lift").
- Non-zero aerodynamic drag on the rotor blades (frictional drag as well as induced drag)
- In addition, mechanical losses due to shaft friction lead to even lower maximum achievable efficiencies.
- Other mechanical and electrical losses in the gearbox, generator, etc., also reduce the overall wind turbine efficiency.
- As seen in Figure:18–37, the "best" wind turbine is the high-speed HAWT, and that is why you see this type of wind turbine being installed throughout the world.

18–4 Hydropower 1

Turbines have been used for centuries to convert freely available mechanical energy from rivers and water bodies into useful mechanical work, usually through a rotating shaft.

The rotating part of a hydroturbine is called the runner. When the working fluid is water, the turbomachines are called hydraulic turbines or hydroturbines.

Large dams are built in the flow path of rivers to collect water.

The water having potential energy is run through turbines to produce electricity. Such an installation is called a hydroelectric power plant.

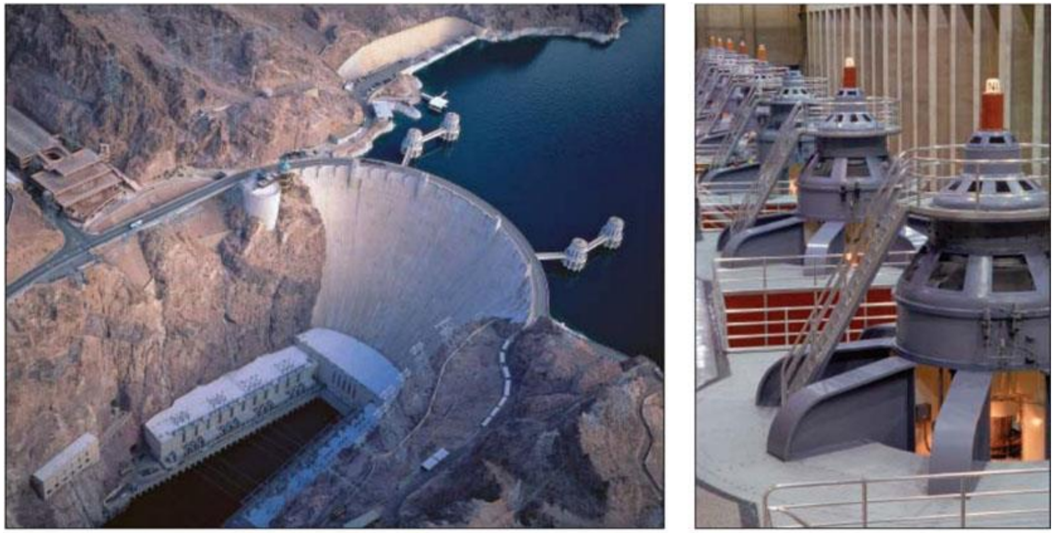
Some dams are also used for irrigation of farms and flood control.

The large dam takes a long time and a large amount of investment to build but the cost of producing electricity by hydropower is much lower than the cost of electricity production by fossil fuels.

Most large hydroelectric power plants have several turbines arranged in parallel.

This offers the power company the opportunity to turn off some of the turbines during times of low power demand and for maintenance.

18–4 Hydropower 2



(a) (b)

Figure 18–37

(*a*) An aerial view of Hoover Dam and (*b*) the top (visible) portion of several of the parallel electric generators driven by hydraulic turbines at Hoover Dam.

Hoover Dam in Boulder City, Nevada, for example, has 17 parallel turbines, 15 of which are identical large Francis turbines that can produce approximately 130 MW of electricity each. The maximum gross head is 180 m. The total peak power production of the power plant exceeds 2000 MW while about 4 billion kWh electricity is produced every year.

18–4 Hydropower 3

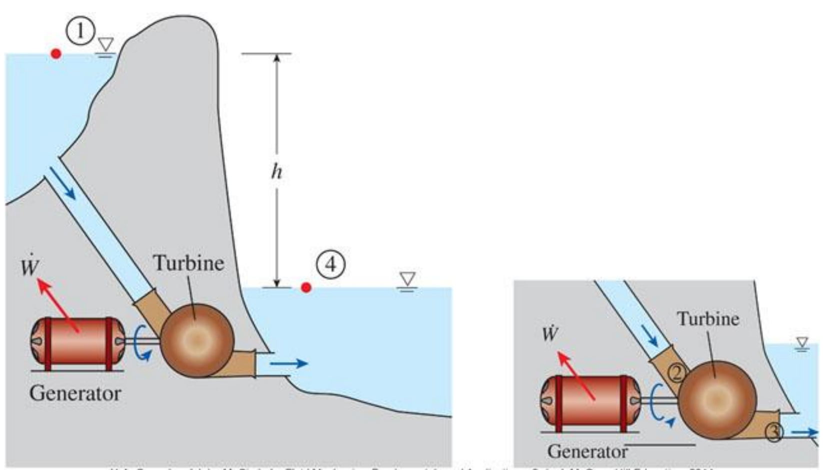
Analysis of Hydroelectric Power Plant

Applying the SFEE to the hydroturbine: $\cancel{\dot{Q}} - \dot{W} = \dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right)$

But! $h_2 - h_1 = c(T_2 - T_1) + p_2 v_2 - p_1 v_1 = \frac{P_2 - P_1}{\rho}$ for an isothermal incompressible flow

$$\dot{W}_{max} = \dot{m}\left\{\frac{P_1 - P_2}{\rho} + \frac{V_1^2 - V_2^2}{2} + g(z_2 - z_1)\right\}$$

Choosing '1' and '2' to be the upstream and downstream free surfaces, then $P_1 = P_2 = P_{atm}$, $V_1 = V_2 \approx 0$ and $\dot{W}_{max} = \dot{m}g(z_1 - z_2)$



Y. A. Çengel and John M. Cimbala, Fluid Mechanics: Fundamentals and Applications, 3rd ed. McGraw-Hill Education, 2014

Figure 18–39

In the absence of irreversible losses, the maximum produced power is proportional to :

(a) the change in water surface elevation from the upstream to the downstream reservoir or:

(b) (close-up view) the drop in water pressure from just upstream to just downstream of the turbine.

18–4 Hydropower 4

We use the maximum possible shaft power for our definition of turbine efficiency

$$\eta_{turbine} = \frac{\dot{W}_{shaft}}{\dot{W}_{max}} = \frac{\dot{W}_{shaft}}{\dot{m}gh}$$

If the turbine is connected to a generator with some efficiency $\eta_{generator} = \frac{\dot{W}_{electric}}{\dot{W}_{shaft}}$

$$\eta_{turbine-generator} = \eta_{turbine}\eta_{generator} = \frac{\dot{W}_{electric}}{\dot{m}gh}$$

When there are losses in the system, we can modify the SFEE in this case to:

$$-\dot{W} = \dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) + \dot{E}_{mech,loss\ total}$$

Or, using the same (incompressible, isothermal) assumptions previously

$$\dot{m}\left(\frac{P_1}{\rho} + \frac{V_1^2}{2} + gz_1\right) = \dot{m}\left(\frac{P_2}{\rho} + \frac{V_2^2}{2} + gz_2\right) + \dot{W} + \dot{E}_{mech,loss\ total}$$

By convention, losses in the turbine and the ***penstock*** (or other piping losses) are separated

$$\dot{E}_{mech,loss\ total} = \dot{E}_{mech,loss\ turbine} + \dot{E}_{mech,loss\ piping}$$

18–4 Hydropower [6]

We can apply the SFEE in terms of *pressure head* form – this allows us to take into account losses from the turbine and the supply pipework etc.

$$\left(\frac{P_1}{\rho g}+\frac{V_1^2}{2g}+z_1\right)=\left(\frac{P_2}{\rho g}+\frac{V_2^2}{2g}+z_2\right)+\frac{w+e_{mech,loss\ turbine}}{g}+\frac{e_{mech,loss\ piping}}{g}$$

Losses in the pipe system mean that the turbine does not see P_1 and P_2 directly, since there is a pressure drop between (say) the penstock inlet and the turbine inlet

$$\frac{w+e_{mech,loss\ turbine}}{g}=h_{turbine,e}=\frac{w}{g\eta_{turbine}}$$

$$\left(\frac{P_1}{\rho g}+\frac{V_1^2}{2g}+z_1\right)=\left(\frac{P_2}{\rho g}+\frac{V_2^2}{2g}+z_2\right)+h_{turbine,e}+h_L$$

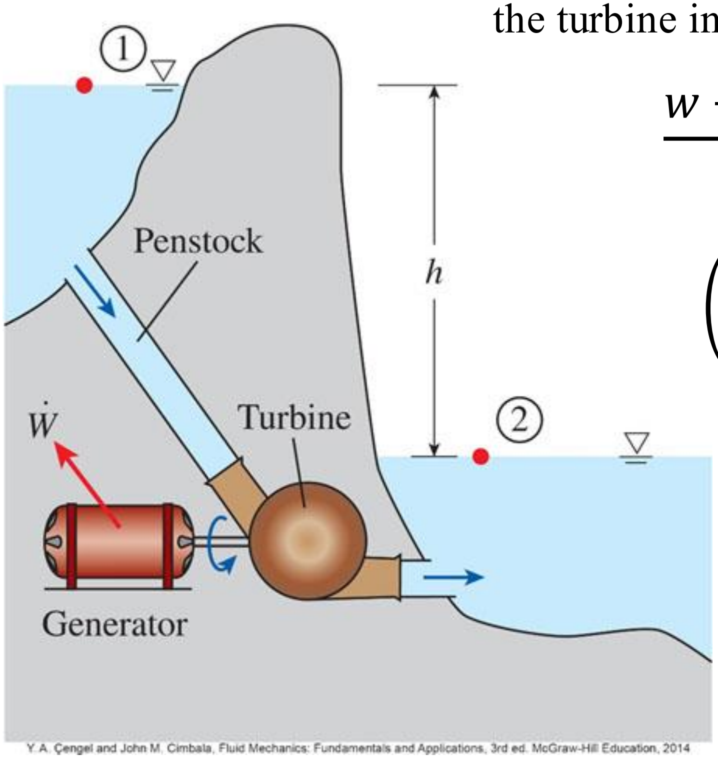


Figure 18–41

The analysis of a hydroelectric power plant involves that of the turbine and the penstock.

18–4 Hydropower [7]

$$\left(\frac{P_1}{\rho g}+\frac{V_1^2}{2g}+z_1\right)=\left(\frac{P_2}{\rho g}+\frac{V_2^2}{2g}+z_2\right)+h_{turbine,e}+h_L$$

h_L is the irreversible head loss between points 1 and 2 due to the components of the piping system (i.e. everything *that is **not** the turbine*), i.e. losses from pipes, and from bends, valves, T-Junctions, etc.

$$(h_L)_{pipe} \equiv h_{L,major} = f\frac{L}{D}\frac{V^2}{2g}$$

- f is the Darcy friction factor.
- L is the length of the penstock.
- D is the diameter of the penstock.
- V is the velocity of water in the penstock.

$$(h_L)_{component} \equiv h_{l,minor} = K_L\frac{V^2}{2g}$$

K_L is the coefficient for minor losses

And so, for the combined pipe system

$$h_L = \left(f\frac{L}{D}+\sum K_L\right)\frac{V^2}{2g}$$

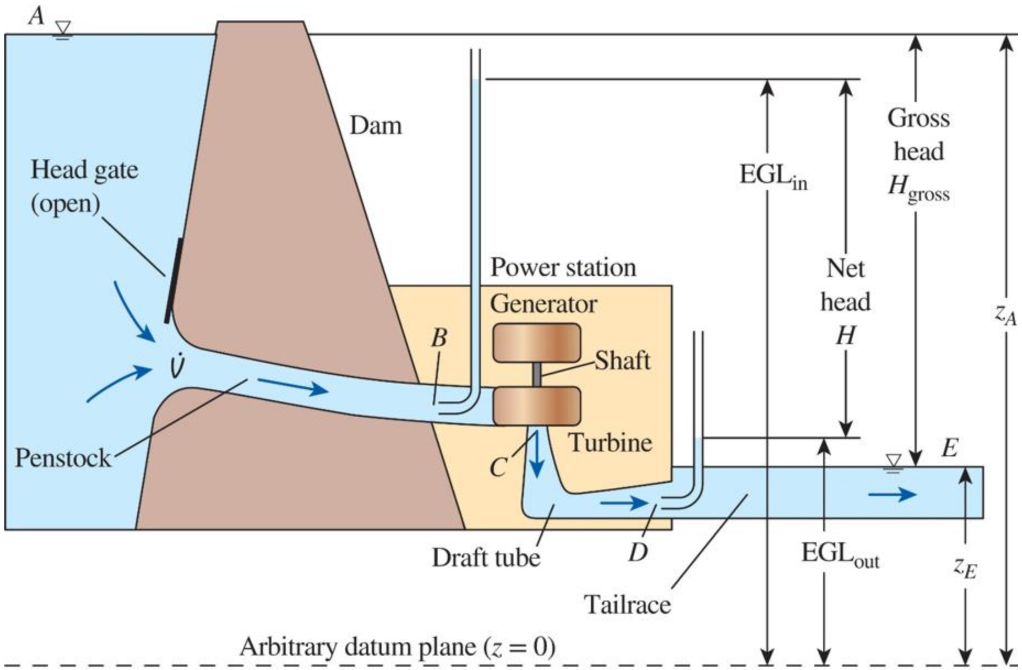
18–4 Hydropower [9]

Putting the pieces together, define $H_{gross} = z_A - z_E$ and as before $\dot{W}_{max} = \rho g \dot{\mathcal{V}} H_{gross}$

Define the ***Energy Grade Line*** (EGL) $= \frac{P}{\rho g} + \frac{V^2}{2g} + z$ and $H_{net} = EGL_{in} - EGL_{out}$

Incorporating potential head losses in the supply $\eta_{turbine} = \frac{\dot{W}_{shaft}}{\rho g \dot{\mathcal{V}} H_{net}} = \frac{\dot{W}_{shaft}}{\rho g \dot{\mathcal{V}}(H_{gross} - h_L)}$

Define a *piping efficiency*: $\eta_{piping} = 1 - \frac{\rho g \dot{\mathcal{V}} h_L}{\dot{W}_{max}}$



$$\eta_{plant} = \frac{\dot{W}_{electric}}{\dot{W}_{max}}$$

$$= \eta_{generator}\eta_{turbine}\eta_{piping}$$

Figure 18–42

Setup and terminology for a hydroelectric plant.

Tutorial Questions

Tutorial Questions

End

Supplementary material – Solar power

18–1 Introduction [1]

To meet its energy needs, the world community currently depends heavily on fossil fuels that are non-renewable and unfriendly to the environment.

In 2007, fossil fuels accounted for 85 percent (27% coal, 35% oil, 23% natural gas) of the total energy use and 68 percent of total electricity generation in the world.

Renewable energy (including hydroelectric power), which is environment friendly and can be harvested indefinitely, was responsible for 10 percent of the total energy use and 18 percent of electricity generation globally.

Nuclear power supplied the remaining 5 percent of the total energy use and 14 percent of electricity generation.

18–1 Introduction 2

Table 18–1

Total world delivered energy consumption by end-use sector and fuel in 2007.

All values are in quadrillion (Quad) Btu. (1 quadrillion Btu = 10^{15} Btu and 1 kJ = 0.95 Btu)

Fuel	Total	Electricity	Residential	Commercial	Industrial	Transportation	All end-use sectors
Oil**	174.7	10.2	9.7	4.3	57.0	93.4	164.4
Natural gas	112.1	37.3	20.3	7.8	43.2	3.5	74.8
Coal	132.4	84.5	3.8	0.8	43.1	0.1	47.9
Nuclear	27.1	27.1					
Electricity			15.8	13.5	27.6	0.9	57.8*
Renewables	48.8	34.8	0.4	0.1	13.4		13.9
Total	495.2	194.1*	50.1	26.5	184.4	97.9	359.0*

18–1 Introduction 3

* The difference between the total energy value of fuel consumption to produce electricity (194.1 Quad Btu) and the actual amount of electricity consumed by all end-use sectors (57.8 Quad Btu) is equal to the energy lost during the production of electricity, which is equal to 194.1 − 57.8 = 136.2 Quad Btu. As a result, the difference between the totals in the second and last column is also equal to 495.2 − 359.0 = 136.2 Quad Btu.

** The values given for oil also include other nonpetroleum liquid fuels such as ethanol, biodiesel, coal-to-liquids, natural gas liquids, and liquid hydrogen.

Source: Energy Information Administration (EIA), International Energy Outlook 2010, *DOE/EIA-0484(2010), Washington, DC, 2010.*

18–1 Introduction [6]

Fossil fuels have been powering the industrial development and the amenities of modern life since the 1700s, but this has not been without the undesirable side effects.

Pollutants emitted during the combustion of fossil fuels are responsible for smog, acid rain, and global warming. The environmental pollution has reached such high levels that it has become a serious threat to vegetation, wild life, and human health.

Air pollution has been the cause of numerous health problems including asthma and cancer.

But this fossil fuel based economy is not sustainable since the estimated life of known reserves is roughly 250 years for coal, 60 years for oil, and 80 years for natural gas.

Therefore, the switch to renewable energy sources is inevitable.

18–1 Introduction 7

The concern over the depletion of fossil fuels and pollutant and greenhouse emissions associated by their combustion can be tackled by essentially two methods:

- Using renewable energy sources such as solar, wind, hydroelectric, biomass, and geothermal to replace fossil fuels.
- Implementing energy efficiency practices in all aspects of energy production, distribution, and consumption so that less fuel is used while obtaining the same useful output.

Energy efficiency is to reduce energy use to the minimum level, but to do so without reducing the standard of living, the production quality, and the profitability.

Energy efficiency is an expression for the most effective use of the energy resources, and it results in energy conservation.

Energy efficiency can only reduce the fossil fuel use while renewable energy can directly replace fossil fuels.

18–1 Introduction [9]

Wind: The conversion of kinetic energy of wind into electricity via wind turbines represenst wind energy, and it is the fastest growing renewable.

Hydro: The collection of river water into large dams at some elevation and directing the collected water into a hydraulic turbine is the common method of converting water energy into electricity. Hydro or water energy represents the greatest amount of electricity production, and it supplies most of electricity needs of some countries.

Geothermal: Geothermal energy refers to heat of earth. High temperature underground geothermal fluid found in some locations is extracted and the energy of geothermal fluid is converted to electricity or heat. Geothermal energy conversion is one of the most mature renewable energy technologies. Geothermal energy is mostly used for electricity generation and district heating.

Biomass: Organic renewable energy is referred to as biomass and a variety of sources (agriculture, forest, residues, crops, etc.) can be used to produce biomass energy. Biomass is becoming more popular with the help of the variety of available sources.

18–1 Introduction [10]

Figure 18–6

Renewable energies such as solar hot water collectors seen on top of buildings are called "green energy" since they emit no pollutants or greenhouse gases.

18–1 Introduction 11

Are electric cars zero emission vehicles?

Electric cars (and other electricity-driven equipment) are often touted as — zero emission - vehicles and their widespread use is seen by some as the ultimate solution to the air pollution problem.

It should be remembered, however, that the electricity used by the electric cars is generated somewhere else mostly by burning fuel and thus emitting pollution.

Therefore, each time an electric car consumes 1 kWh of electricity, it bears the responsibility for the pollutants emitted as 1 kWh of electricity (plus the conversion and transmission losses generated elsewhere).

The electric cars can be claimed to be zero emission vehicles only when the electricity they consume is generated by emission-free renewable resources such as hydroelectric, solar, wind, and geothermal energy.

Therefore, the use of renewable energy should be encouraged worldwide, with incentives, as necessary, to make the earth a better place in which to live in.

18–2 Solar Energy 4

The several dips on the spectral distribution of radiation on the earth's surface are due to absorption by the gases O_2, O_3 (ozone), H_2O, and CO_2.

Another mechanism that attenuates solar radiation as it passes through the atmosphere is scattering or reflection by air molecules and the many other kinds of particles such as dust, smog, and water droplets suspended in the atmosphere.

This molecular scattering in all directions is what gives the sky its bluish color.

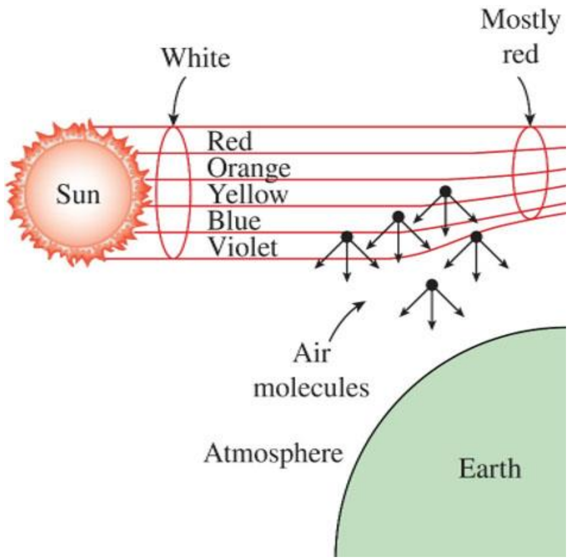
The same phenomenon is responsible for red sunrises and sunsets.

The violet and blue colors of the light encounter a greater number of molecules by the time they reach the earth's surface, and thus a greater fraction of them are scattered .

Consequently, the light that reaches the earth's surface consists primarily of colors corresponding to longer wavelengths such as red, orange, and yellow.

Figure 18–8

Air molecules scatter blue light much more than they do red light. At sunset, light travels through a thicker layer of atmosphere, which removes much of the blue from the natural light, allowing the red to dominate.



Supplementary material – Wind power

18–3 Wind Energy [1]

- We note the distinction between the terms windmill used for mechanical power generation (grinding grain, pumping water, etc.) and wind turbine used for electrical power generation, although technically both devices are turbines since they extract energy from the fluid.
- The rotation speed of rotors of wind turbines is usually under 40 rpm (under 20 rpm for large turbines).
- Altamont Pass in California is the world's largest wind farm with 15,000 modern wind turbines). This farm and two others in California produce about 3 billion kWh of electricity per year, which is enough power to meet the electricity needs of San Francisco.
- The United States, Germany, Denmark, and Spain account for over 75 percent of current wind energy generating capacity worldwide.
- Denmark uses wind turbines to supply 10 percent of its national electricity.
- Commercial wind turbines generate from 100 kW to 3.2 MW of electric power each at peak design conditions.
- The blade span (or rotor) diameter of the 3.2 MW wind turbine built by Boeing Engineering is 320 ft (97.5 m).

18–3 Wind Energy [2]

Figure 18–29

(*a*) Wind farms are popping up all over the world to help reduce the global demand for fossil fuels. (*b*) Some wind turbines are even being installed on buildings! (These three turbines are on a building at the Bahrain World Trade Center.)

- Wind turbines produce power only when the wind is blowing, and the power output of a wind turbine is unsteady.
- Wind turbines need to be located where the wind blows, which is often far from traditional power grids, requiring construction of new high-voltage power lines.
- Wind turbines are expected to play an ever increasing role in the global supply of energy for the foreseeable future.

Supplementary material – hydropower

18–4 Hydropower [11]

In hydroelectric power plants, large dynamic turbines are used to produce electricity.

Hydroturbines utilize the large elevation change across a dam to generate electricity, and wind turbines generate electricity from blades rotated by the wind. There are two basic types of dynamic turbine—*impulse* and *reaction*.

Impulse turbines require a higher head, but can operate with a smaller volume flow rate.

Reaction turbines can operate with much less head, but require a higher volume flow rate.

In an impulse turbine, the fluid is sent through a nozzle so that most of its available mechanical energy is converted into kinetic energy.

The high-speed jet then impinges on bucket-shaped vanes that transfer energy to the turbine shaft.

The modern and most efficient type of impulse turbine is Pelton turbine and the rotating wheel is now called a Pelton wheel.

18–4 Hydropower 12

The other main type of energy-producing hydroturbine is the reaction turbine, which consists of fixed guide vanes called stay vanes, adjustable guide vanes called wicket gates, and rotating blades called runner blades.

Flow enters tangentially at high pressure, is turned toward the runner by the stay vanes as it moves along the spiral casing or volute, and then passes through the wicket gates with a large tangential velocity component.

There are two main types of reaction turbine—*Francis* and *Kaplan*.

The Francis turbine is somewhat similar in geometry to a centrifugal or mixed-flow pump, but with the flow in the opposite direction.

The Kaplan turbine is somewhat like an *axial-flow* fan running backward.

We classify reaction turbines according to the angle that the flow *enters* the runner. If the flow enters the runner radially, the turbine is called a Francis radial-flow turbine.

18–4 Hydropower 13

Figure 18–45

A view from the bottom of an operating Pelton wheel illustrating the splitting and turning of the water jet in the bucket. The water jet enters from the left, and the Pelton wheel is turning to the right.

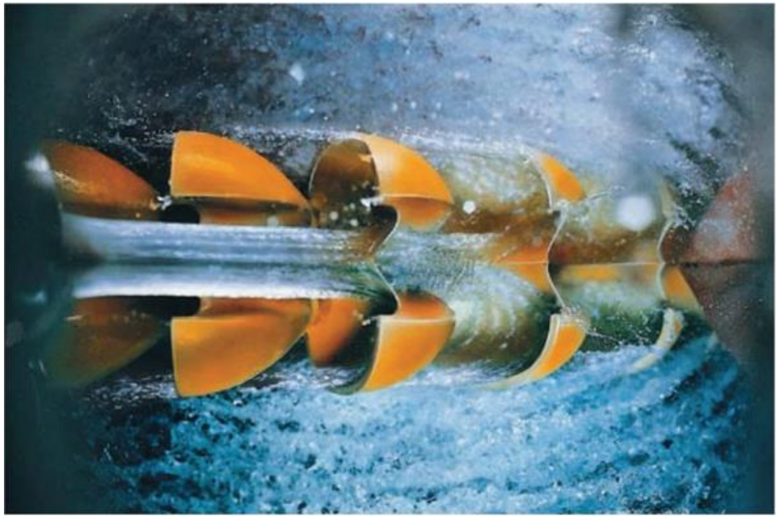


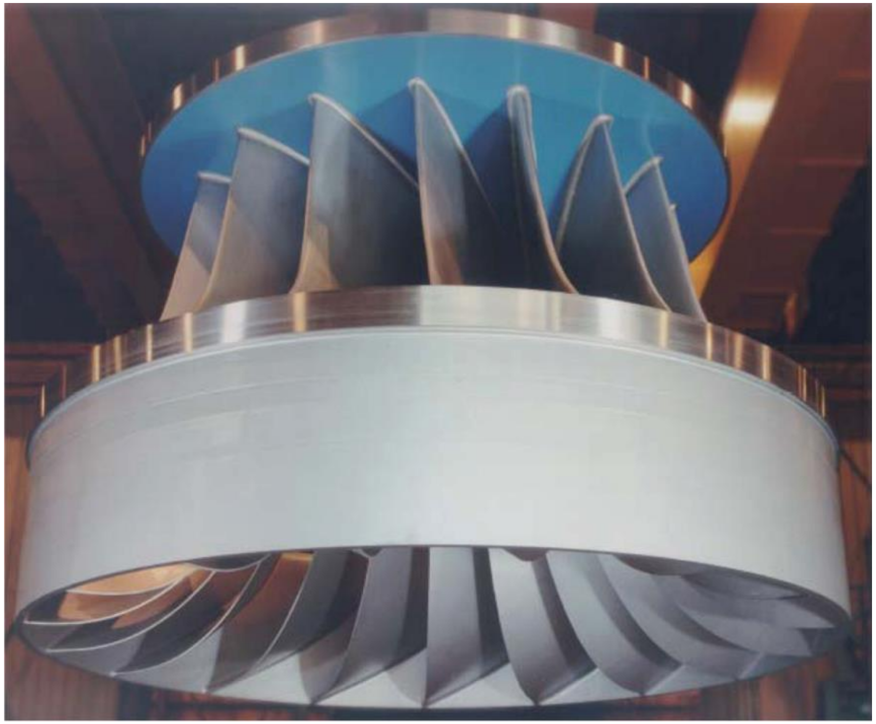
Figure 18–46

The runner of a Francis radial-flow turbine used at the Round Butte hydroelectric power station in Madras, OR. There are 17 runner blades of outer diameter 11.8 ft (3.60 m). The turbine rotates at 180 rpm and produces 119 MW of power at a volume flow rate of 127 m^3/s from a net head of 105 m.

18–4 Hydropower [14]

Figure 18–47

The runner of a Francis mixed-flow turbine used at the Smith Mountain hydroelectric power station in Roanoke, VA. There are 17 runner blades of outer diameter 20.3 ft (6.19 m). The turbine rotates at 100 rpm and produces 194 MW of power at a volume flow rate of 375 m^3/s from a net head of 54.9 m.



18–4 Hydropower [15]

Figure 18–48

The five-bladed propeller turbine used at the Warwick hydroelectric power station in Cordele, GA. There are five runner blades of outer diameter 12.7 ft (3.87 m). The turbine rotates at 100 rpm and produces 5.37 MW of power at a volume flow rate of 63.7 m^3/s from a net head of 9.75 m.

Tutorial Questions

1. Solar radiation is incident on a flat-plate collector at a rate of 930 W/m^2. The glazing has a transmissivity of 0.82 and the absorptivity of absorber plate is 0.94. Determine the maximum efficiency of this collector.

2. Solar radiation is incident on a flat-plate collector at a rate of 880 W/m^2. The product of the transmissivity of glazing and the absorptivity of absorber plate is 0.82. The collector has a surface area of 33 m^2. This collector supplies hot water to a facility at a rate of 6.3 L/min. Cold water enters the collector at 18°C. If the efficiency of this collector is 70 percent, determine the temperature of hot water provided by the collector. *Answer:* 64.3°C

3. A solar cell has an open circuit voltage value of 0.55 V with a reverse saturation current density of $J_o = 1.9 \times 10^9$ A/m^2. For a temperature of 25°C, determine (*a*) the current output density J_s, (*b*) the load voltage at which the power output is maximum, and (*c*) the maximum power output of the cell for a unit cell area.

4. A typical winter day in Reno, Nevada (39°N latitude), is cold but sunny, and thus the solar heat gain through the windows can be more than the heat loss through them during daytime. Consider a house with double-door-type windows that are double paned with 3-mm-thick glasses and 6.4 mm of air space and have aluminum frames and spacers. The overall heat transfer coefficient for this window is 4.55 $W/m^2\cdot°C$. The house is maintained at 22°C at all times. Determine if the house is losing more or less heat than it is gaining from the sun through an east window on a typical day in January for a 24-h period if the average outdoor temperature is 10°C. *Answer:* less

5. A wind turbine with a blade diameter of 50 m is to be installed in a location where average wind velocity is 7.5 m/s. The average temperature and pressure of ambient air in this location are 23°C and 96 kPa, respectively. Determine the wind power potential.

6. The measurements over an entire week period indicates that a wind turbine with a blade diameter of 40 m has produced 11,000 kWh of electricity. If the overall efficiency of the wind turbine is estimated to be 28 percent, determine the average wind velocity during this period. Take the density of air to be 1.16 kg/m^3. *Answer:* 6.85 m/s

7. River water is collected into a large dam whose height is 65 m. How much power can be produced by an ideal hydraulic turbine if water is run through the turbine at a rate of 1500 L/min?

8. The irreversible losses in the penstock and its inlet and those after the exit of the draft tube are estimated to be 7 m. The elevation difference between the reservoir surface upstream of the dam and the surface of the water exiting the dam is 140 m. If the flow rate through the turbine is 4000 L/min, determine (*a*) the power loss due to irreversible head loss, (*b*) the efficiency of the piping, and (*c*) the electric power output if the turbine-generator efficiency is 84 percent.

9. A hydroelectric power plant consists of 18 identical turbine-generator units with an overall plant efficiency of 90 percent. The gross head of the dam is 150 m and the flow rate through each turbine is 3300 L/min. The plant operates 80 percent of time throughout the year and the electricity generated is sold to the utility company at a rate of \$0.095/kWh. How much revenue can this plant generate in a year? *Answer:* \$873,000

Supplementary material – Geothermal and biomass

18–5 Geothermal Energy [1]

Geothermal energy is the thermal energy within the earth's interior.

It is a renewable energy source because heat is continuously transferred from within the earth to the water recycled by rainfall or reinjected back to the ground after use.

The origin of geothermal energy is earth's core. The core is made up of inner core (iron center) and outer core made up of very hot magma.

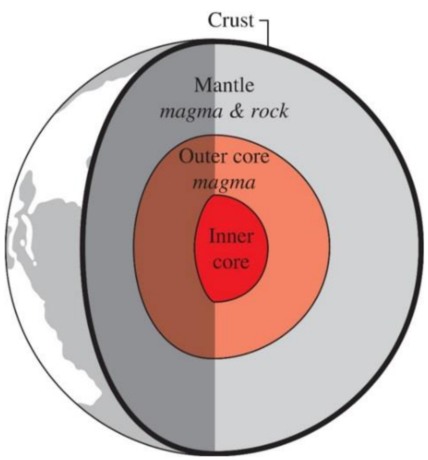
At some reasonable depths, the rocks and water absorb heat from magma. These sites are characterized as geothermal resources. By digging wells and pumping the hot water to the surface, we make use of geothermal energy.

18–5 Geothermal Energy [2]

MANCHESTER 1824
The University of Manchester

Figure 18–49

The interior of the earth.



- The origin of geothermal energy is earth's core, and it is about 6500 km deep. The core is made up of inner core (iron center) and outer core made up of very hot magma.
- The temperature in the magma remains very high due to decay of radioactive particles. The outer core is surrounded by the mantle whose thickness is about 3000 km. The mantle is made of magma and rock.

- The layer of the earth housing continents and ocean floors is called the crust. The thickness of the crust is 25 to 55 km on the continents and 5 to 8 km under the oceans. The crust is made up of tectonic plates. Volcanoes occur near the edges of these plates due to magma getting close to it.
- At some reasonable depths, the rocks and water absorb heat from this magma. These sites are characterized as geothermal resources. By digging wells and pumping the hot water to the surface, we make use of geothermal energy.

18–5 Geothermal Energy [3]

Geothermal resources can be classified based on their thermal and compositional characteristics:

Hydrothermal These are known geothermal fields containing high temperature water in vapor, mixture, or liquid phases.

Geopressurized These resources contain hot liquid water at 150°C to 180°C at very high pressures (up to 600 bar). The fluid in these deposit-filled reservoirs also contains methane and high levels of dissolved solids. The fluid is highly corrosive and thus very difficult to harvest and handle.

Magma They are also called molten rock, and typically contained under active volcanoes at temperatures above 650°C.

Enhanced They are also called hot, dry rock geothermal systems. These are not natural geothermal resources. The idea is injecting water into hot rock formation at high pressure and bringing the resulting hot water to the surface.

Only hydrothermal resources are being exploited. Other three are estimated to have enormous energy potentials but current technologies do not allow feasible energy production from these resources.

The quality and life of a hydrothermal resource can be prolonged by reinjecting the waste fluid back to the gorund.

18–5 Geothermal Energy [4]

A geothermal resource contains geothermal water at a temperature higher than that of the environment. One common classification of geothermal resources is based on the resource temperature.

- High temperature resource: $T > 150°C$
- Medium temperature resource:

$90°C < T < 150°C$

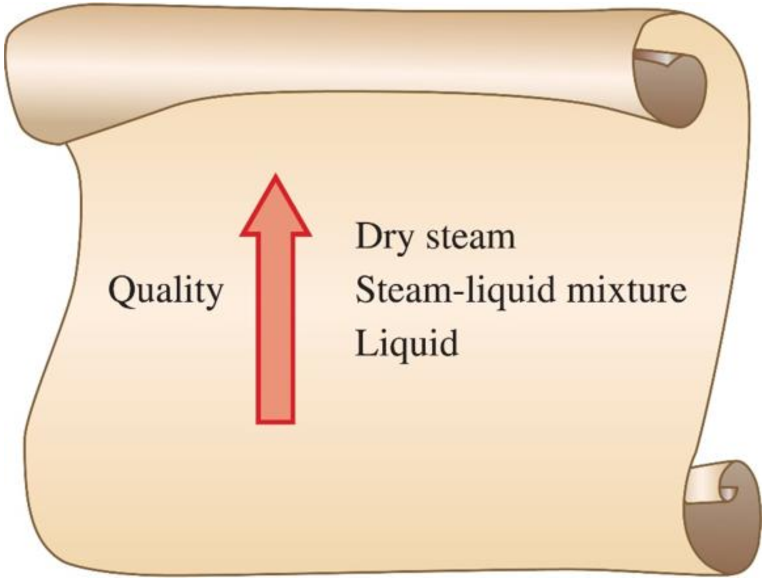
- Low temperature resource: $T < 90°C$

The state of geothermal water in the reservoir may be superheated or saturated steam (dry steam), saturated steam-liquid mixture, or liquid (usually compressed liquid).

Steam-dominated resources are of the higher quality than liquid-dominated resources due to their higher enthalpy and exergy (work potential) values.

Figure 18–50

The quality of a geothermal resource depends on its phase (and temperature) in the reservoir. The higher the quality, the higher the work potential.



18–5 Geothermal Energy 5

There are several options for utilizing the thermal energy produced from geothermal energy systems.

Electricity production Geothermal energy is most commonly used for base-load electric power generation. The technology for producing power from geothermal resources is well-established and there are numerous geothermal power plants operating worldwide. The temperature of geothermal resource should be about 150°C or higher for economic power production.

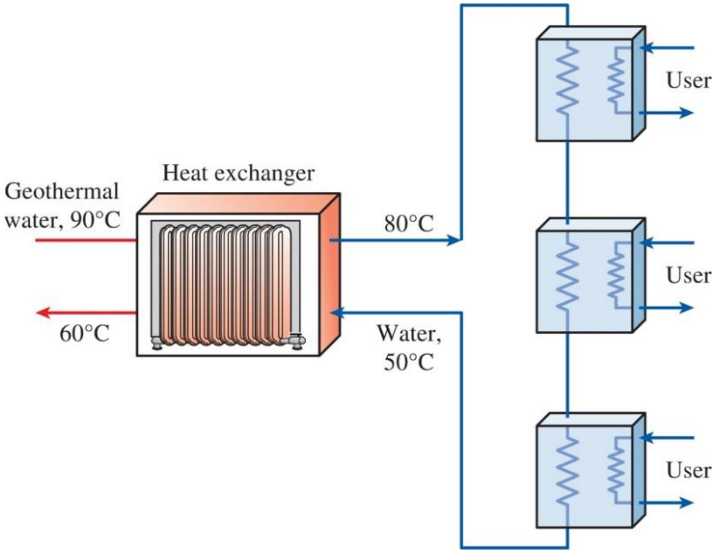
Space heating A large number of residential and commercial districts are effectively heated in winter by low-cost geothermal heat in many parts of the world. Some of the largest district heating installations are in China, Sweden, Iceland, Turkey, and USA. Almost 90 percent of buildings in Iceland (a small country) are heated in winter by geothermal heat. The annual amount of space heating supplied in the world by geothermal is estimated to be about 60,000 TJ

18–5 Geothermal Energy 6

Geothermal heat is used for space heating mostly in a district heating scheme. Normally, hot geothermal water is not directly circulated to the district due to undesirable chemical composition and characteristics of geothermal brine. Heat exchangers are used to transfer the heat of geothermal water to fresh water and this heated fresh water is sent to the district. This heat is supplied to the buildings through individual heat exchangers.

Figure 18–51

A common operating mode for geothermal district space heating systems. Temperature values are representative.



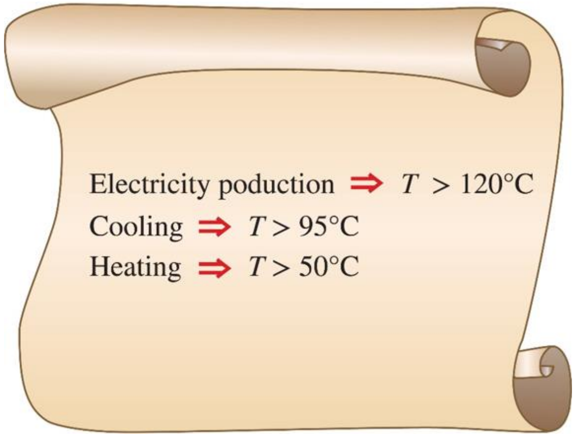
18–5 Geothermal Energy 7

Cogeneration A cogeneration system utilizing a geothermal resource and producing electricity and heat allows an enhanced use of the resource. This is a cascaded application in which the used geothermal water leaving the power plant is used for heating before being reinjected back to the ground. Geothermal brine is reinjected back to the ground at much lower temperatures in cogeneration applications in comparison to single power production. This represents a much higher utilization rate for a given resource corresponding to higher potential revenues.

Cooling Geothermal heat may be supplied to an absorption refrigeration system for space cooling applications. The temperature of geothermal water should be above 95°C for absorption cooling for reasonable coefficient of performance values. A district cooling system utilizing geothermal heat may be feasible depending on the annual cooling load of the district. The use of geothermal heat for cooling is not common. A geothermal cooling system installed in Oregon Institute of Technology was estimated to pay for itself in about 15 years.

Figure 18–52

Approximate temperature requirements for geothermal applications.



18–5 Geothermal Energy 8

Heat pump Ground-source heat pumps represent perhaps the most common use of geothermal energy in terms of the number of units installed. These heat pumps are called geothermal heat pumps as they utilize the heat of the earth. Ground-source heat pumps provide higher values of coefficient performance (COP) compared to air-source units. The ground at a few meters depth is at a higher temperature than the ambient air in winter and it is at a lower temperature than the ambient in summer. These systems use higher ground temperatures in winter for heat absorption (heating mode) and cooler ground temperatures in summer for heat rejection (cooling mode), and this is the reason for higher COPs.

Other utilization of geothermal energy includes growing plants and crops (greenhouses), drying of lumber, fruits and vegetables, spas, desalination, and fish farming.

Ancient people used geothermal energy for heating and bathing. In many parts of the world, hot springs are used for bathing since many people believe health benefits of minerals in hot geothermal water.

18–5 Geothermal Energy 9

Geothermal Power Production

Only a fraction of geothermal resources have relatively high temperatures making them suitable for electricity production. Geothermal power plants have been in operation for decades in many parts of the world.

The first geothermal power plant was built in Italy in 1904. In the U.S., the first plant was built in 1960 in the Geysers in northern California.

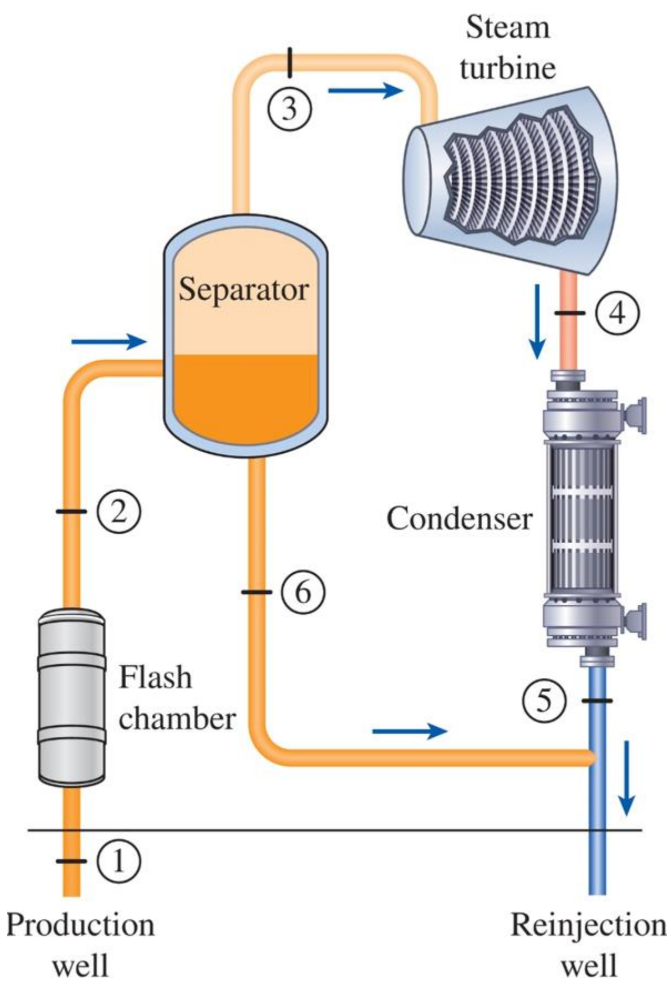
There are about 60 geothermal power plants in the U.S. located in California, Nevada, Utah, Montana, Idaho, and Hawaii. Currently, more than 12,000 MW of geothermal electricity are produced in 24 countries.

FIGURE 18–53
A small-sized geothermal power plant in Nevada. The source temperature for this plant is only 120°C.

18–5 Geothermal Energy 10

Figure 18–54

Single-flash geothermal power plant.



The simplest geothermal cycle is the direct steam cycle. Steam from the geothermal well is passed through a turbine and exhausted to the atmosphere or to a condenser.

Flash steam plants are used to generate power from liquid-dominated resources that are hot enough to flash a significant proportion of the water to steam in surface equipment, either at one or two pressure stages.

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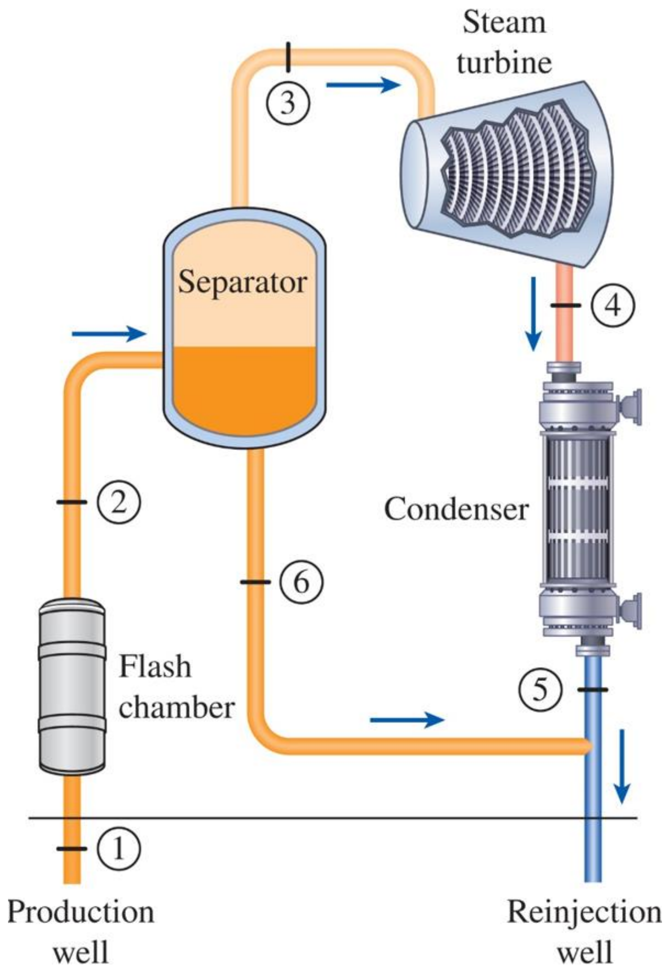
18–5 Geothermal Energy 11

Figure 18–54

Single-flash geothermal power plant.



$$\dot{W}_{\text{out}} = \dot{m}_3\left(h_3 - h_4\right)$$

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{out}}}{\dot{E}_{\text{in}}}$$

$$\dot{E}_{\text{in}} = m_1\left(h_1 - h_0\right)$$

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{out}}}{\dot{E}_{\text{in}}} = \frac{\dot{m}_3\left(h_3 - h_4\right)}{\dot{m}_1\left(h_1 - h_0\right)}$$

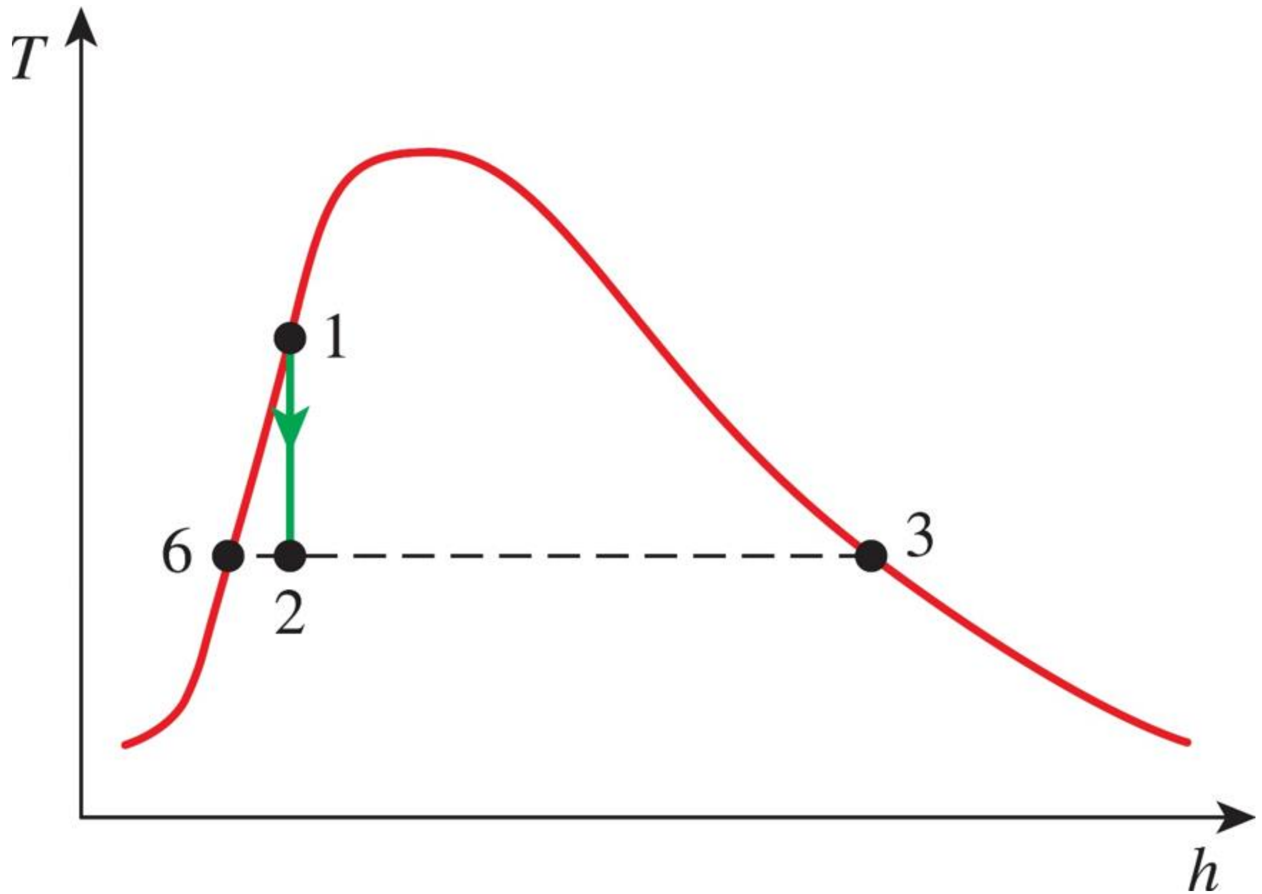
$$\eta_{\text{th}} = \frac{\dot{W}_{\text{out}}}{\dot{E}_{\text{in}}} = 1 - \frac{\dot{E}_{\text{out}}}{\dot{E}_{\text{in}}}$$

$$\dot{E}_{\text{out}} = \dot{m}_6\left(h_6 - h_0\right) + \dot{m}_4\left(h_4 - h_0\right)$$

18–5 Geothermal Energy [12]

Figure 18–55

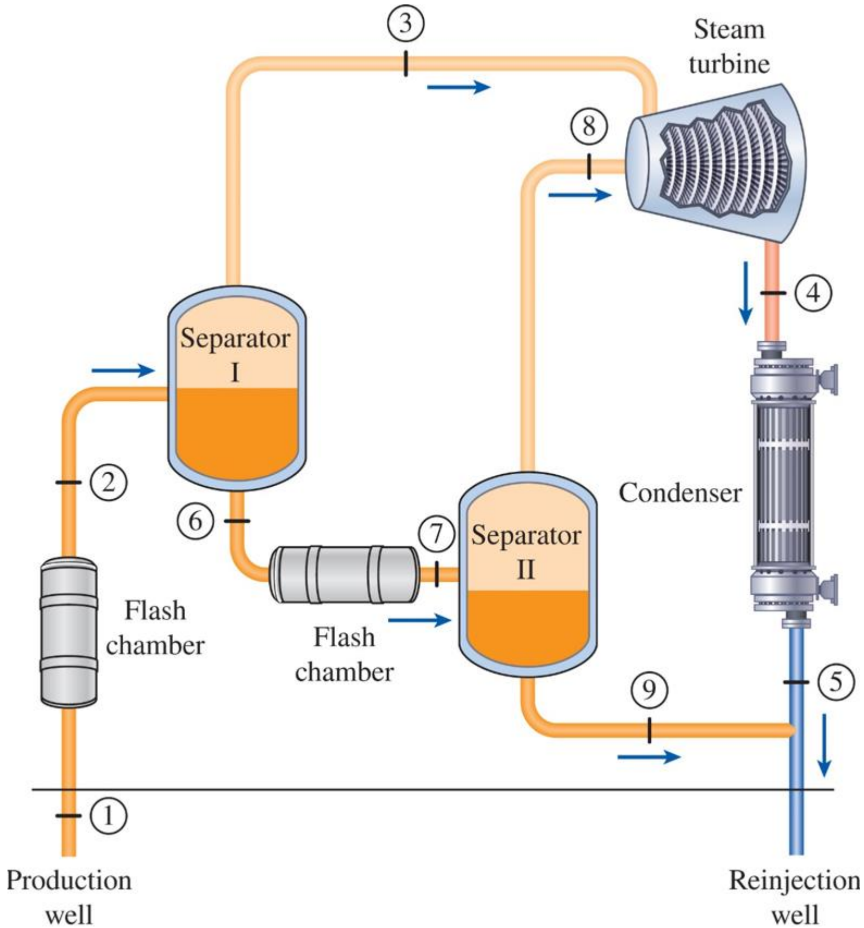
Flashing process in temperature–enthalpy diagram.



18–5 Geothermal Energy [13]

Figure 18–56

Double-flash geothermal power plant.



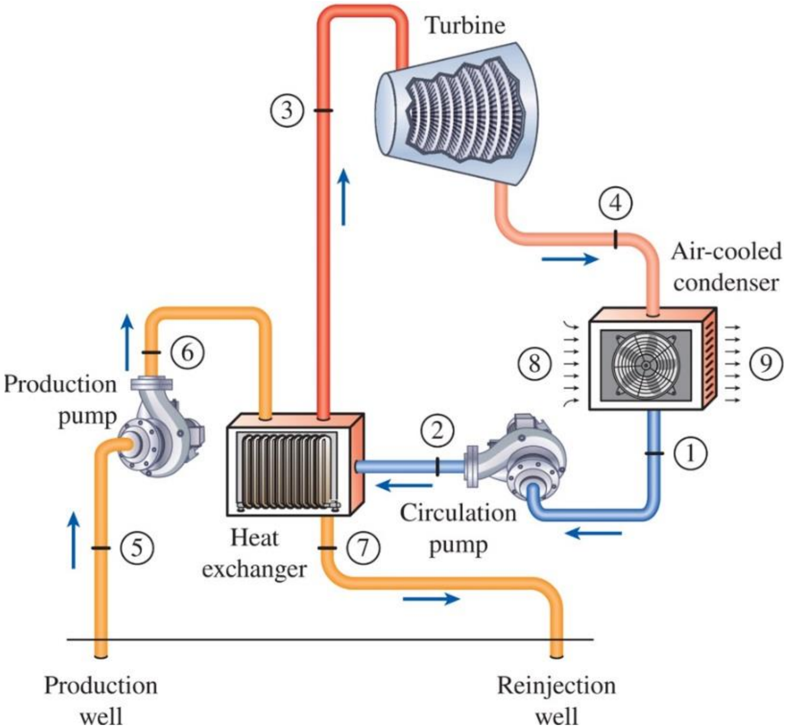
$$\eta_{th} = \frac{\dot{W}_{out}}{\dot{E}_{in}} = \frac{\dot{m}_3(h_3 - h_4) + \dot{m}_8(h_8 - h_4)}{\dot{m}_1(h_1 - h_0)}$$

Access the text alternative for this image.

18–5 Geothermal Energy 14

Figure 18–57

Binary cycle geothermal power plant.



Binary cycle plants use the geothermal brine from liquid-dominated resources at relatively low temperatures. These plants operate on a Rankine cycle with a binary working fluid (isobutane, pentane, isopentane, R-114, etc.) that has a low boiling temperature.

Access the text alternative for this image.

18–5 Geothermal Energy 15

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{E}_{\text{in}}} = \frac{\dot{W}_{\text{turbine}} - \dot{W}_{\text{pump}} - \dot{W}_{\text{fan}}}{\dot{E}_{\text{in}}}$$

$$\dot{E}_{\text{in}} - \dot{m}_5 (h_5 - h_0)$$

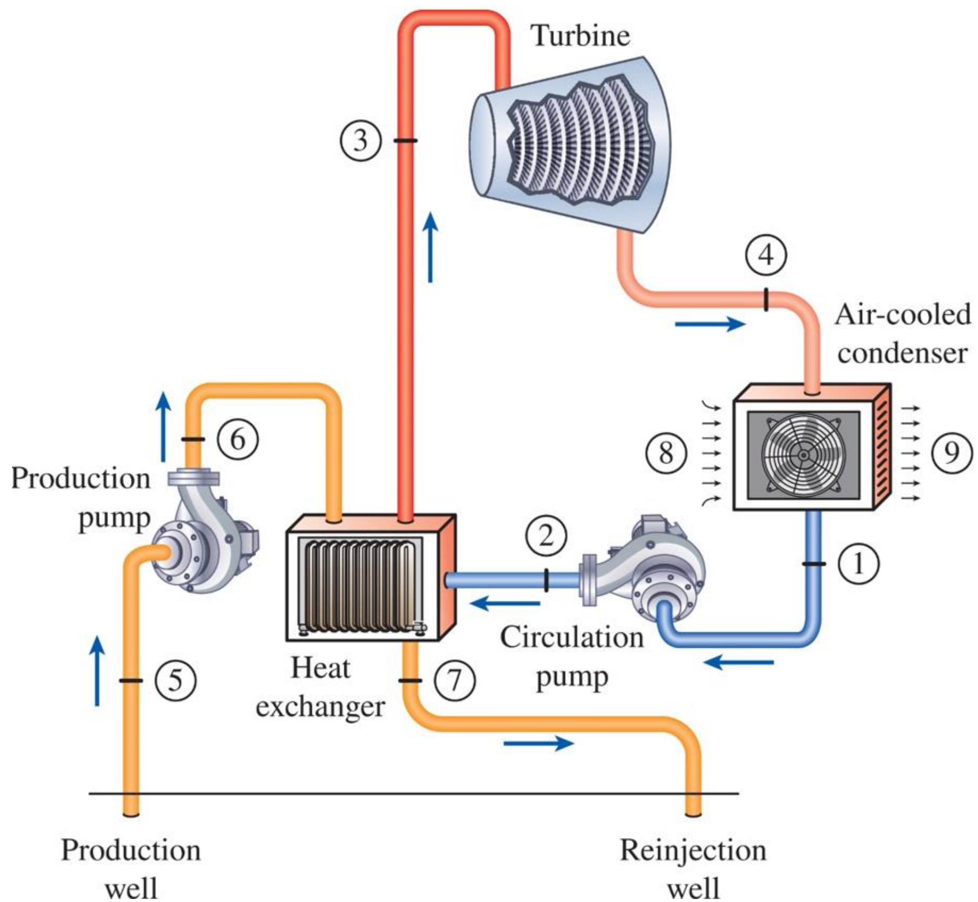
$$\dot{W}_{\text{turbine}} = \dot{m}_3 (h_3 - h_4)$$

$$\dot{W}_{\text{pump}} = \dot{m}_1 (h_2 - h_1)$$

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{Q}_{\text{in}}}$$

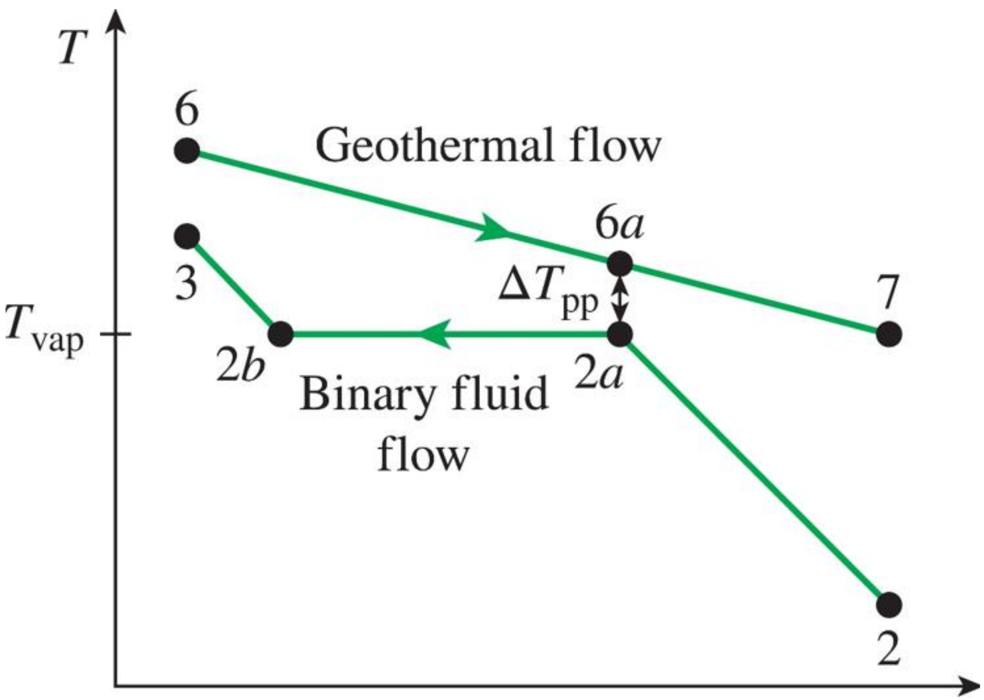
$$\dot{Q}_{\text{in}} = \dot{m}_6 (h_6 - h_7) = \dot{m}_2 (h_3 - h_2)$$

Figure 18–57
Binary cycle geothermal power plant.



18–5 Geothermal Energy 16

Figure 18–58
Heat exchange process between the geothermal brine and the binary working fluid in the heat exchanger of binary cycle power plant.



$$\dot{m}_{geo}\left(h_6 - h_{6a}\right) = \dot{m}_{binary}\left(h_3 - h_{2a}\right)$$

$$\dot{m}_{geo}\left(h_{6a} - h_7\right) = \dot{m}_{binary}\left(h_{2a} - h_2\right)$$

$$h_{2a} = h_{f@Tvap} \qquad h_{2b} = h_{g@Tvap}$$

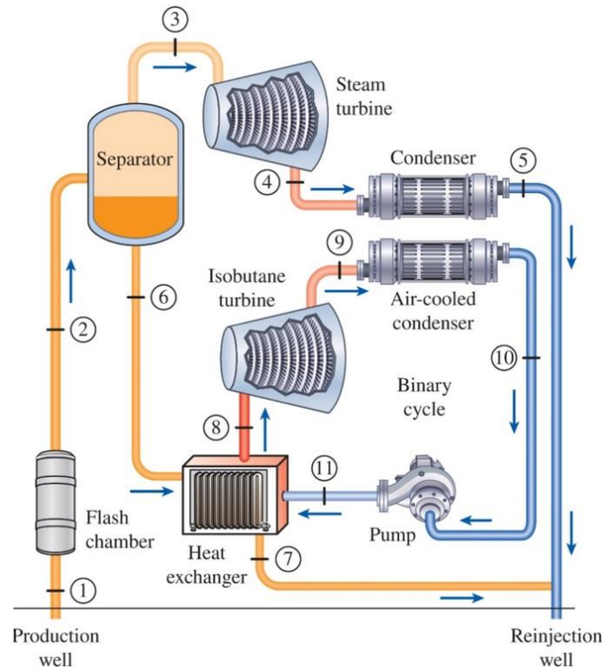
The temperature difference is called pinch-point temperature difference ΔT_{pp}.

The state 6a is called the pinch-point of geothermal water.

18–5 Geothermal Energy 17

Figure 18–59

Combined flash/binary geothermal power plant.



$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{E}_{\text{in}}} = \frac{\dot{W}_{\text{turbine}} - \dot{W}_{\text{pump}} - \dot{W}_{\text{fan}}}{\dot{E}_{\text{in}}}$$

$$= \frac{\dot{m}_3 (h_3 - h_4) + \dot{m}_8 (h_8 - h_9) - \dot{W}_{\text{pump}} - \dot{W}_{\text{fan}}}{\dot{m}_1 (h_1 - h_0)}$$

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18–6 Biomass Energy [1]

- Biomass is an organic renewable energy. It is mostly produced from agriculture and forest products and residues, energy crops, and algae.
- Organic component of municipal and industrial wastes and the fuel produced from food processing waste such as used cooking oil are also considered biomass.
- Despite relatively long period of times involved in growing crops and trees, they can be re-grown by planting, and therefore biomass is considered to be a renewable energy source.
- It is estimated that about half of all renewable energy consumed in the U.S. is biomass.

18–6 Biomass Energy 2

- Before coal, oil and natural gas replaced it as primary fuels, wood was the primary fuel for space heating in winter.
- Wood is still used in many parts of developing world for space heating.
- Liquid and gaseous fuels are generally more convenient forms of fuel compared to solid fuels. Therefore, crops and forest products are usually converted to liquid and gaseous fuels through some engineering processes.
- Growing of crops and trees as well as the conversion to liquid and gaseous fuels involve the consumption of energy in the form of electricity and fossil fuels such as coal, oil, and natural gas.
- The consumption of fossil fuels is accompanied by the pollutant and greenhouse emissions. Therefore, the renewability and cleanliness of biomass are not as good as other renewables such as solar, geothermal, or wind.

18–6 Biomass Energy 3

Biomass Resources

Biomass can be obtained from variety of resources called feedstocks.

Biomass resources can be listed as follows:

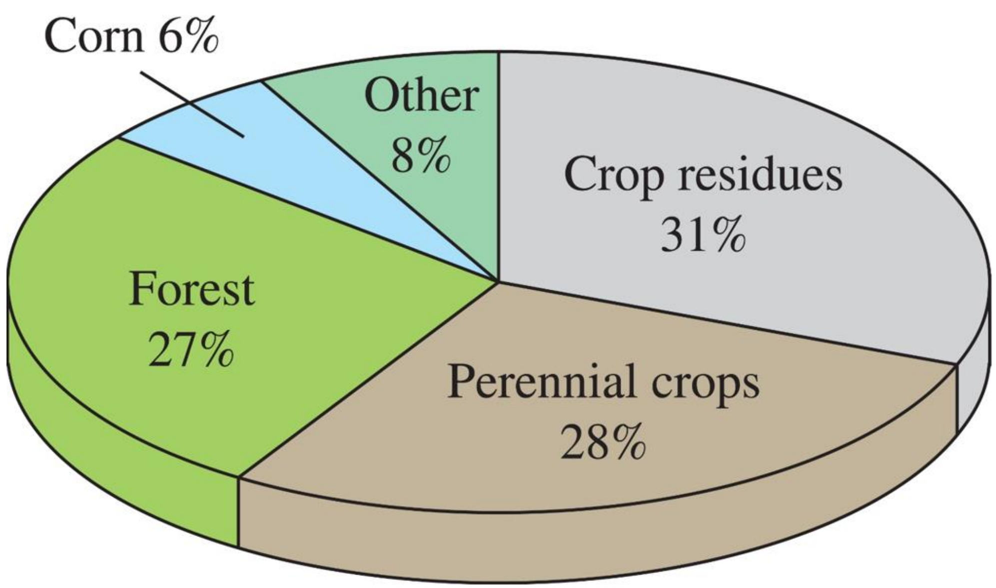
- Dedicated energy crops: These herbaceous energy crops are perennials that are harvested after reaching maturity. These include such grasses as switchgrass, miscanthus, bamboo, sweet sorghum, tall fescue, kochia, wheatgrass, and others.
- Agricultural Crops: These include cornstarch and corn oil, soybean oil and meal, wheat starch, and vegetable oils. They generally yield sugars, oils, and extractives.
- Agriculture Crop Residues: Biomass materials consisting primarily of stalks and leaves not used for commercial use such as corn stover (stalks, leaves, husks, and cobs), wheat straw, and rice straw are included in this resource. Approximately, 80 million acres of corn is planted annually.

18–6 Biomass Energy [4]

- Forestry Residues: These are biomass not harvested or used in commercial forest processes including materials from dead and dying trees.
- Aquatic Crops: Aquatic biomass resources include algae, giant kelp, other seaweed, and marine microflora.
- Biomass Processing Residues: Byproducts and waste streams produced by biomass processing are called residues, and they represent an additional biomass resource.
- Municipal Waste: Plant based organic material generated from industrial, residential, and commercial waste represents an important biomass source. Some examples include waste paper, wood waste, yard waste, and cooking oil.
- Animal Waste: Animal wastes consist of organic materials and are generated from farms and animal-processing operations. Animal waste is used as a heating fuel in some parts of the world.

18–6 Biomass Energy 5

Figure 18–61
Contribution of various feedstocks to biomass production in the United States



18–6 Biomass Energy [6]

Conversion of Biomass to Biofuel

Biomass can be converted into liquid or gaseous fuels through biochemical- and thermochemical-based conversion processes.

Biochemical conversion processes: Enzymes and microorganisms are used as biocatalysts to convert biomass or biomass-derived compounds into desirable products. Cellulase and hemicellulase enzymes break down the carbohydrate fractions of biomass to five- and six-carbon sugars in a process known as hydrolysis. Yeast and bacteria then ferment the sugars into products such as ethanol.

Thermochemical conversion processes: Heat energy and chemical catalysts are used to break down biomass into intermediate compounds or products. In gasification, biomass is heated in an oxygen-starved environment to produce a gas composed primarily of hydrogen (H2) and carbon monoxide (CO).

18–6 Biomass Energy [7]

Pyrolysis: Biomass is exposed to high temperatures without the presence of air, causing it to decompose. Solvents, acids, and bases can be used to fractionate biomass into an array of products including sugars, cellulosic fibers, and lignin.

Research is underway for an alternative conversion process called photobiological conversion process. Photobiological conversion processes use the natural photosynthetic activity of organisms to produce biofuels directly from sunlight. For example, the photosynthetic activities of bacteria and green algae have been used to produce hydrogen from water and sunlight.

18–6 Biomass Energy 8

Biomass Products

A major product of biomass is biofuels which are a replacement for petroleum-based fuels.

Biofuels can be liquid or gas. They are mostly used for transportation as the engine fuel but also used for heating and electricity generation.

The two most common biofuels are ethanol and biodiesel.

Other products include methanol, pyrolysis oil, biogas, producer gas, and synthesis gas.

Biomass is primarily used to produce biofuels such as ethanol and biodiesel but other products made from fossil fuels can also be made by biomass. Some of these products include antifreeze, plastics, glues, artificial sweeteners, and gel for toothpaste.

18–6 Biomass Energy [9]

Ethanol

Ethanol or ethyl alcohol (C_2H_5OH): HHV = 29,710 kJ/kg, LHV = 26,950 kJ/kg.

Gasoline: HHV = 47,300 kJ/kg, LHV = 43,000 kJ/kg.

A full tank of ethanol will get less mileage than that of gasoline.

Ethanol has less hydrocarbon (HC) emissions than gasoline, and is commonly added to gasoline for improved emission from the engines.

Its use also represents a renewable replacement for gasoline.

Adding ethanol to gasoline increases the octane number of gasoline allowing higher compression ratios and corresponding higher efficiencies for the engine.

Two common use of ethanol for automobiles in the U.S. include gasohol and E85:

Gasohol is a gasoline-ethanol mixture with 10 percent ethanol.

E85 contains 85 percent ethanol. A 15 percent gasoline is only added to eliminate operating problems with the use of pure ethanol.

About half of the gasoline used in the U.S. includes 5 percent to 10 percent ethanol.

Brazil is the leading user of ethanol with approximately 5 million vehicles operating with 93 percent ethanol.

18–6 Biomass Energy 10

Ethanol is made primarily from the starch in corn grain. Corn, sugar beets, sugar cane, and even cellulose (wood and paper) are some of the sources of ethanol.

Corn is the major source in the U.S. while sugar beets are primarily used in Brazil.

The feedstock used for ethanol should be high in sugar content. First, the feedstock is converted to sugar, and the sugar (glucose) is fermented into ethanol through the following reaction

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

The cost of producing ethanol is relatively high due to growing of corn and manufacturing and processing involved.

Some studies suggest that the energy consumed during the production of ethanol (plowing, planting, harvesting, fermenting, and delivery) can be quite high per unit mass of the ethanol produced and it is sometimes comparable to energy content of ethanol itself

18–6 Biomass Energy 11

Biodiesel

Biodiesel is ethyl or methyl ester that is produced through a process that combines organically-derived oils with ethanol or methanol in the presence of a catalyst.

Common sources of biodiesel include new and used vegetable oils, animal fats, and recycled restaurant greases.

HHV = 40,700 kJ/kg (17,500 Btu/lbm), which is about 9 percent less than that of petroleum diesel (HHV = 44,800 kJ/kg).

Biodiesel can be used in compression ignition engines as a single fuel or can be added to conventional diesel fuel.

The most common biodiesel mixture used in the U.S. is B20, which is 20 percent biodiesel and 80 percent conventional diesel.

Biodiesel is also used as a single fuel in compression ignition engines, called B100.

Due to lower heating values, B100 provides less power from the engine.

B100 could increase nitrogen oxides emissions while significantly reducing hydrocarbon, sulfur and carbon monoxide emissions.

18–6 Biomass Energy 12

Methanol

Methanol or methyl alcohol (CH_3OH): HHV = 22,540 kJ/kg, LHV = 20,050 kJ/kg.

Pure methanol and its blend with gasoline have been extensively tested as an alternative fuel to gasoline.

Two common mixtures are:

M85 (85 percent methanol, 15 percent gasoline)

M10 (10 percent methanol, 90 percent gasoline).

There is no noticeable emission reduction due to use of M10 in engines but M85 reduces hydrocarbon (HC) and carbon monoxide (CO) emissions significantly while also replacing more of gasoline consumption.

Methanol can be produced from fossil sources or biomass. Coal, oil and natural gas represent fossil sources.

Natural gas is the main feedstock in the U.S. for methanol production.

Synthesis gas produced from biomass can replace natural gas for this process.

18–6 Biomass Energy 13

Pyrolysis Oil

Pyrolsis oil is produced when biomass is exposed to high temperatures without the presence of air, causing it to decompose.

A possible reaction involves heating of cellulosic feedstock in grain form for a short period (less than half a second) to a temperature of 400°C - 600°C and quenching it.

The product is highly oxygenated and has considerable amounts of water. This makes these liquids corrosive and unstable with a low heating value.

Pyrolysis oil is not suitable as a replacement to conventional fuels such as gasoline or diesel. Further processes are needed to make this fuel compatible with conventional hydrocarbon fuels.

A chemical called phenol can be extracted from pyrolysis oil, and it is used to make wood adhesives, molded plastic, and foam insulation.

18–6 Biomass Energy 14

Biogas

Biogas, also called swamp gas, landfill gas, or digester gas, usually consists of 50 to 80 percent methane (CH_4) and 20 to 50 percent carbon dioxide (CO_2) by volume.

It also contains small amounts of hydrogen, carbon monoxide, and nitrogen.

Nothing that the HHV of methane is 55,200 kJ/kg, the HHV of biogas with 50 percent methane by volume is 14,700 kJ/kg and that of biogas with 80 percent methane is 32,700 kJ/kg. (Can you calculate these values by yourself?)

Biogas can be produced from biological waste such as animal manure, food waste, and agricultural waste.

The process is called anaerobic digestion which is the decomposition of organic waste into a gaseous fuel by bacteria action without the presence of oxygen.

It is possible to produce 200 to 400 m^3 of biogas from 1000 kg of organic waste with 50 to 75 percent methane by volume.

18–6 Biomass Energy 15

Biogas is basically a gaseous fuel similar to natural gas but with a lower heating value due to significant carbon dioxide fraction.

Biogas can be fed to a natural gas pipeline after carbon dioxide is removed.

It can be easily burned in a boiler for space, process, and water heating applications.

It can also be used to generate steam in a steam power plant to produce electricity.

Many municipalities in different countries have solid waste treatment facilities in which they produce biogas from the waste and use the biogas for electricity generation.

Some facilities produce both electricity and heat from biogas (i.e., cogeneration).

A gas-turbine or an internal combustion engine can be used as the power producing unit.

18–6 Biomass Energy [16]

Producer gas

Producer gas is produced by thermal gasification which is the partial oxidation of a solid biomass at high temperatures into a gaseous fuel.

Steam and oxygen interacts with solid biomass such as wood during a gasification process.

Most practical gasification systems can convert 70 to 80 percent of the heat of the biomass into energy of producer gas.

The resulting producer gas consists of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), nitrogen (N_2), and carbon dioxide (CO_2).

The composition of producer gas varies greatly. The heating value of producer gas depends on percentages of ingredient gases, and it varies between 15 percent and 50 percent of the heating value for natural gas.

Producer gas can be used as a feedstock for liquid fuels or it can be burned directly in a furnace.

18–6 Biomass Energy 17

Synthesis gas

Synthesis gas is also called biosynthesis gas or syngas, and is produced by thermal gasification using oxygen.

It consists of CO and H_2.

If a synthesis gas has 50 percent CO and 50 percent H_2 fraction by volume, its heating value will be 19,000 kJ/kg.

Synthesis gas is commonly produced from natural gas, coal, and heavy diesel.

However, we are more interested in its production from biomass feedstock.

Wood and other solid biomass can be used to produce syngas.

In addition to being used as the fuel for conversion to heat and electricity, synthesis gas can be used to make plastics and acids, which can then be used to make photographic films, textiles, and synthetic fabrics.

18–6 Biomass Energy 18

Electricity and Heat Production by Biomass

The production of electricity and heat from biomass is called biopower.

The installed capacity of biopower in the U.S. is about 10 gigawatts.

There are three technologies used to convert biomass energy to heat and electricity: direct combustion, co-firing, and anaerobic digestion.

Biomass consisting of waste wood products (i.e., wood pellet) can be burned in direct combustion in conventional boilers to generate steam or hot water. This steam is run through a turbine coupled with a generator to produce electricity.

Co-firing refers to replacing only a portion of fossil fuel in coal-fired boilers with biomass. This technology has been successfully demonstrated in most boiler technologies, including pulverized coal, cyclone, fluidized bed, and spreader stoker units. Sulfur dioxide emissions of coal-fired power plants can be reduced considerably by co-firing biomass.

Anaerobic digestion, or methane recovery, is a common technology used to convert organic waste to methane and heat. In this process, organic matter is decomposed by bacteria in the absence of oxygen to produce natural gas consisting primarily of methane and other byproducts such as carbon dioxide. This gas can be used for space and water heating or electricity production.

18–6 Biomass Energy 19

MANCHESTER 1824
The University of Manchester

Solid Municipality Waste

An important class of biomass is produced by households as trash or garbage.

This is referred to as municipal solid waste (MSW).

MSW includes mostly organic materials such as paper, food scraps, wood, and yard trimmings but some fossil content such as plastic also exists.

Most of MSW come from residences (55 to 65 percent) and 35 to 45 percent come from businesses, schools, and hospitals.

MSW does not include industrial, hazardous, or construction waste.

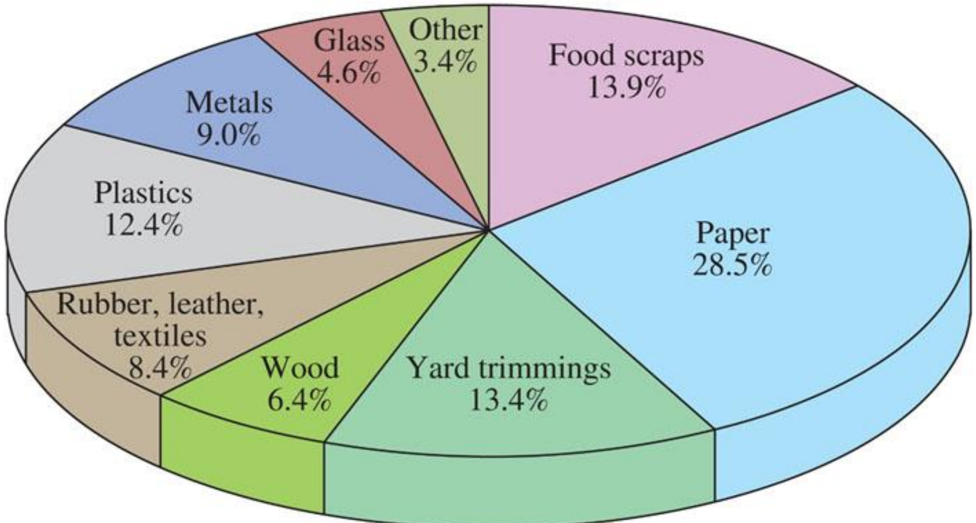
The U.S. Environmental Protection Agency (EPA) collects and reports data on the generation and disposal of waste in the United States.

This data is used to measure the success of waste reduction and recycling programs across the country.

18–6 Biomass Energy [20]

Figure 18–62

Materials in municipal solid waste and their percentages in the United States in 2010.

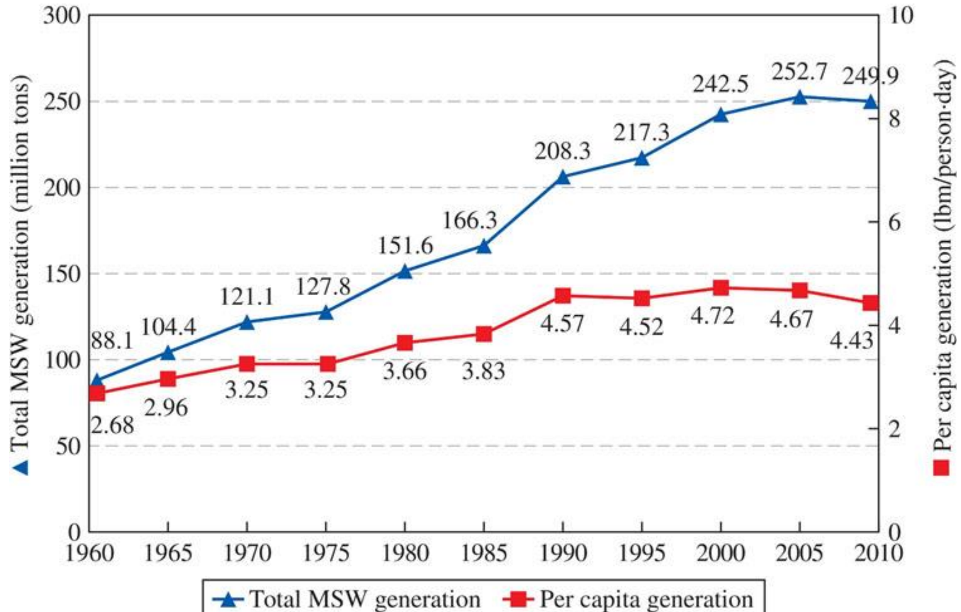


Environmental Protection Agency (EPA), Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2010. Washington, DC: U.S. Environmental Protection Agency, 2011

18–6 Biomass Energy 21

Figure 18–63

Municipal solid waste generation rates from 1960 to 2010 in the United States, total and per capita basis.



Environmental Protection Agency (EPA), Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2010. Washington, DC: U.S. Environmental Protection Agency, 2011

18–6 Biomass Energy [22]

About 250 million tons of municipal solid waste (MSW) was generated in the United States in 2010. 1 ton = 2000 lbm.

About a third of this waste (34.1 percent) was recycled or composted.

An average American produced 4.43 lbm (2 kg) of solid waste per day and only recycled or composted 1.52 lbm (0.7 kg) of this waste.

Total MSW production has increased steadily since 1960 but started to decrease between 2005 and 2010.

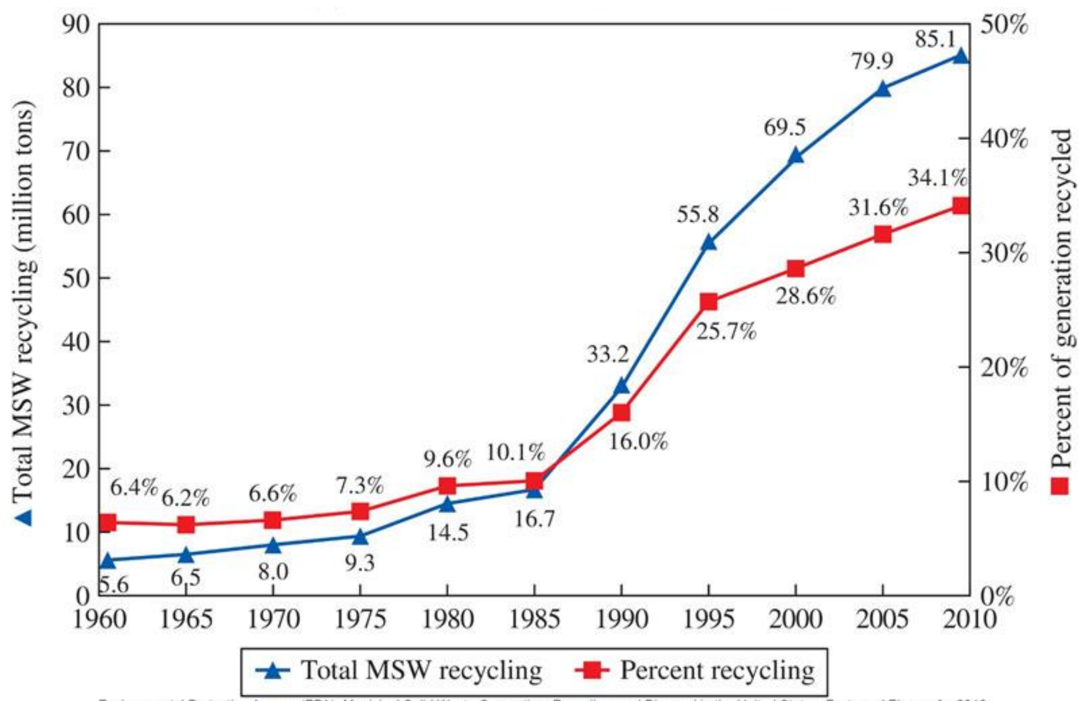
Per capita MWS production has increased since 1960 until 2000 when it reached the maximum value of 4.72 lbm per person per day.

It has decreased slightly between 2000 and 2005 but rather significantly after 2005.

18–6 Biomass Energy 23

Figure 18–64

Municipal solid waste recycling rates from 1960 to 2010 in the United States, total and per capita basis.



Environmental Protection Agency (EPA), Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2010. Washington, DC: U.S. Environmental Protection Agency, 2011.

18–6 Biomass Energy 24

The recycling culture in the U.S. has improved significantly after 1985 when only 10.1 percent of MSW was recycled. After dramatic increases between 1985 and 1995 in recycling rates, there is a steady increase in recycling since 1995.

In 2010, 85 million tons of MSW were recycled or composted representing 34.1 percent of all MSW.

About 65 million tons were recovered through recycling while 20 million tons were composted.

Recycling refers to recovery of useful materials such as paper, glass, plastic, and metals from the trash to use to make new products.

Composting refers to storing organic waste such as food scraps and yard trimmings under certain conditions to help it break down naturally. The resulting product can be used as a natural fertilizer.

The highest recycling rates are achieved in paper and paperboard, yard trimmings, and metals. More than 62 percent of the paper and paperboard (45 million tons) and 58 percent of yard trimmings (19 million tons) were recycled in 2010. Recycling paper, paparboard, and yard trimmings alone kept almost 29 percent of MSW out of landfills and combustion facilities.

18–6 Biomass Energy 25

Recycling reduces raw material use and associated energy consumption and greenhouse gas emissions, which cause global warming.

Air and water pollution associated with making new products are also avoided.

It is estimated that 85 million tons of MSW recycled in 2010 saved 205 million tons of carbon dioxide emissions.

This is equivalent to removal of 36 million cars from the roads.

In addition to recycling and composting, the amount of waste can also be reduced by waste prevention, which is the design of products to minimize the production of waste and making the resulting waste less toxic.

18–6 Biomass Energy 26

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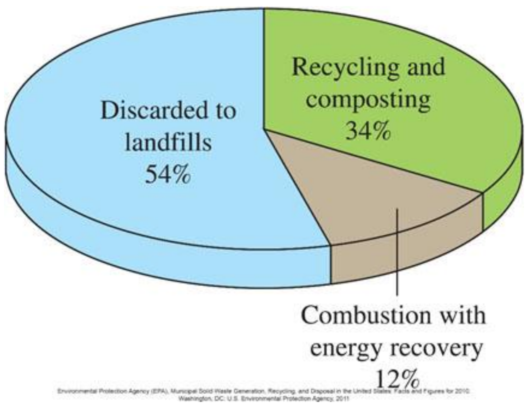
Figure 18–65

Use of municipal solid waste in the United States in 2010.



18–6 Biomass Energy 27

About 14 percent of renewable electricity generation excluding hydroelectric power comes from municipal waste facilities in the U.S.

Energy can be recovered in the form of electricity by both burying and burning options.

What is the best use of municipal solid waste? Is it better to burn or bury waste when trying to recover energy and minimize emissions?

A recent EPA research compared two options for producing electricity from MSW.

The first option is known as the waste to energy (WTE) where waste is burned directly for generating steam. This steam is run through a turbine to generate electricity.

The second option is known as landfill-gas-to-energy (LFGTE), and it involves harvesting biogas (mostly methane) from the buried waste as it decomposes. Biogas is then used as the fuel in an internal combustion engine or gas turbine to generate electricity.

The research indicates that burning waste through WTE method can produce up to 10 times more electricity than burying the same amount of waste through LFGTE method.

It is also determined that greenhouse gas emissions per unit electricity produced are two to six times higher in landfills than in waste burning plants