Chapter 1

Introduction

1.1 Solar Energy

According to well-established measurements, the average power density of solar radiation just outside the atmosphere of the Earth is 1366 W/m^2, widely known as the *solar constant*. The definition of the meter is one over 10,000,000 of Earth's meridian, from the North Pole to the equator, see Fig. 1.1. This definition is still pretty accurate according to modern measurements. Therefore, the radius of Earth is $(2/\pi) \times 10^7$ m. The total power of solar radiation reaching Earth is then

$$\text{Solar power} = 1366 \times \frac{4}{\pi} \times 10^{14} \cong 1.73 \times 10^{17}\ \text{W}. \tag{1.1}$$

Each day has 86,400 s, and on average, each year has 365.2422 days. The total energy of solar radiation reaching Earth per year is

$$\text{Annual solar energy} = 1.73 \times 10^{17} \times 86400 \times 365.2422 \cong 5.46 \times 10^{24}\ \text{J}. \tag{1.2}$$

Or 5,460,000 EJ/year. To have an idea of how much energy that is, let us compare it with annual global energy consumption; see Fig. 1.2. In the years 2005–2010, the annual energy consumption of the entire world was about 500 EJ. A mere 0.01% of the annual solar energy reaching Earth can satisfy the energy need of the entire world.

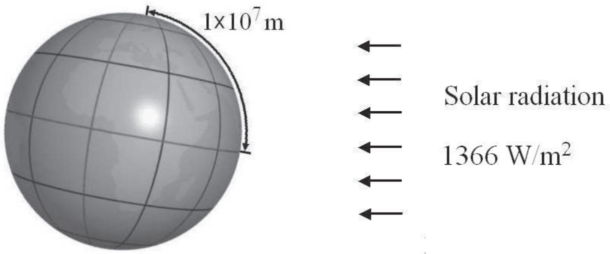

Figure 1.1 Annual solar energy arriving at surface of Earth. The average solar power on the Earth is 1366 W/m^2. The length of the meridian of Earth, according to the definition of the meter, is 10,000,000 m. The total solar energy that arrives at the surface of Earth per year is 5,460,000 EJ.

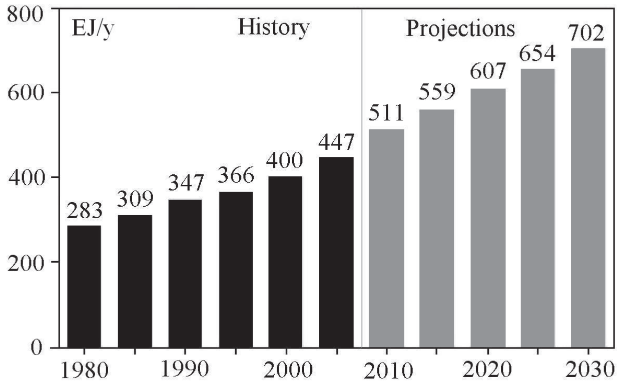

Figure 1.2 World marketed energy consumption, 1980–2030. *Source:* Energy Information Administration (EIA), official energy statistics from U.S. government. History: *International Energy Annual 2004* (May–July 2006), website www.eia.doe.gov/iea. Projections: EIA, *International Information Outlook 2007.*

Not all solar radiation falls on Earth's atmosphere reaches the ground. About 30% of solar radiation is reflected into space. About 20% of solar radiation is absorbed by clouds and molecules in the air; see Chapter 5. About three quarters of the surface of Earth is water. However, even if only 10% of total solar radiation is utilizable, 0.1% of it can power the entire world.

It is interesting to compare the annual solar energy that reaches Earth with the proved total reserve of various fossil fuels; see Table 1.1. The numbers show that the total proved reserves of fossil fuel is approximately 1.4% of the solar energy that reaches the surface of Earth each year. Fossil fuels are solar energy stored as concentrated biomass over many millions of years. Actually, only a small percentage of solar energy was able to be preserved for mankind to explore. The current annual consumption of fossil fuel energy is approximately 300 EJ. If the current level of consumption of fossil

Table 1.1: Proved Resources of Various Fossil Fuels

Item	Quantity	Unit Energy	Energy (EJ)
Crude oil	1.65×10^{11} tons	4.2×10^{10} J/ton	6,930
Natural gas	1.81×10^{14} m^3	3.6×10^7 J/m^3	6,500
High-quality coal	4.9×10^{11} tons	3.1×10^{10} J/ton	15,000
Low-quality coal	4.3×10^{11} tons	1.9×10^{10} J/ton	8,200
Total			36,600

Source: BP Statistical Review of World Energy, June 2007, British Petroleum.

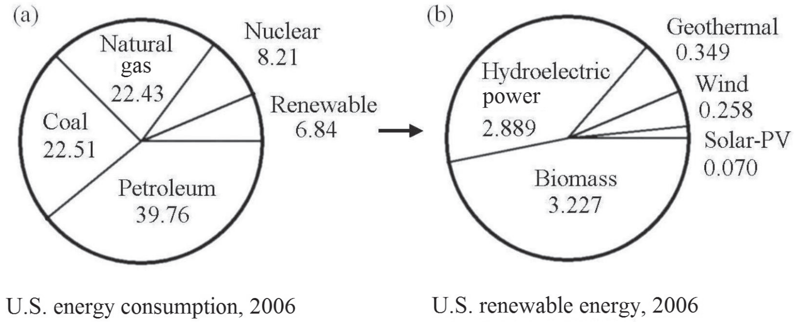

Figure 1.3 U.S. energy consumption, 2006. *Source: Annual Energy Review 2006*, Energy Information Administration (EIA). The unit of energy in the original report is quad, approximately 10^{18}J, or EJ. See Appendix A. In 2006, total U.S. energy consumption was 99.87 quad, almost exactly 100 EJ. Therefore, the energy value in exajoules is almost exactly its percentage. Solar photovoltaic (PV) energy only accounts for 0.07% of total energy consumption in 2006.

fuel continues, the entire fossil energy reserve will be depleted in about 100 years.

Currently, the utilization of renewable energy is still a small percentage of total energy consumption; see Table 1.2. Figure 1.3 shows the percentage of different types of energy in the United States in 2006. The utilization of solar energy through photovoltaic (PV) technology only accounts for 0.07% of total energy consumption. However, globally, solar photovoltaic energy is the fastest growing energy resource. As we will analyze in Section 1.5.4, solar photovoltaics will someday become the dominant source of energy. Figure 1.4 is a prediction by the German Solar Industry Association.

The inevitability that fossil fuel will eventually be replaced by solar energy is simply a geological fact: The total recoverable reserve of crude oil is finite. For example, the United States used to be the largest oil producer in the world. By 1971, about one-half of the recoverable crude oil reserve in the continental United States (the lower 48 states) was depleted. Since then, crude oil production in this area started to decline.

Table 1.2: Renewable Energy Resources

Type	Resource (EJ/year)	Implemented (EJ/year)	Percentage Explored
Solar	2,730,000	0.31	0.0012%
Wind	2,500	4.0	0.16%
Geothermal	1,000	1.2	0.10%
Hydro	52	9.3	18%

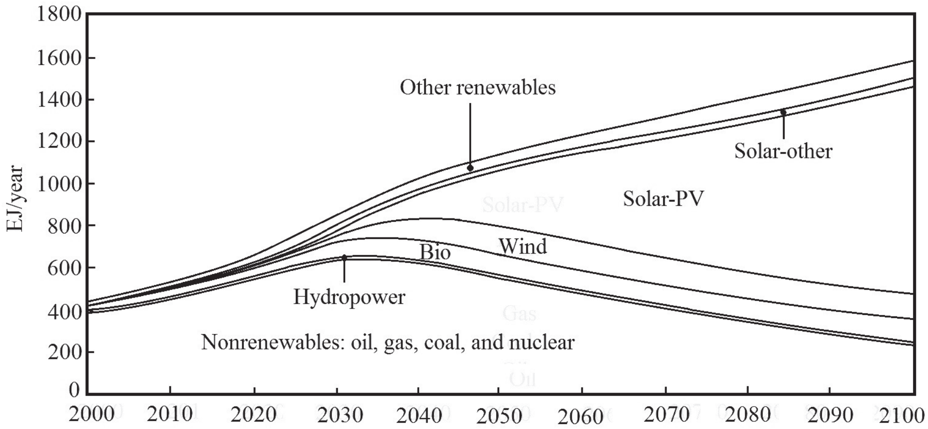

Figure 1.4 Energy industry trend in the twenty-first century. Source of information: German Solar Industry Association, 2007; see www.solarwirtschaft.de. The driving force of twenty-first century energy revolution is economy. Because natural resources of fossil fuels and nuclear materials are finite, the cost of production will increase with time. Solar radiation energy and the raw material to make solar cells, silicon, are inexhaustible. Mass production of solar cells will bring the cost down. At some time, the cost of solar electricity will be lower than that of conventional electricity, to reach *grid parity*. In 2007, it was estimated that grid parity would be reached between 2020 and 2030. After that, an explosive expansion of solar electricity would take place. Recent development indicates that grid parity will be reached around 2015. The rapid implementation of solar electricity will take place sooner than that 2007 prediction. See Section 1.5.4.

Therefore, crude oil production from more difficult geological and environmental conditions must be explored. Not only has the cost of oil drilling increased, but also the energy consumed to generate the crude oil has also increased. To evaluate the merit of an energy production process, the *energy return on energy invested* (EROI), also called *energy balance*, is often used: The definition is

$$\mathrm{EROI} = \frac{\text{energy return}}{\text{energy invested}} = \frac{\text{energy in a volume of fuel}}{\text{energy required to produce it}}. \tag{1.3}$$

In the 1930's, the EROI value to produce crude oil was around 100. In 1970, it was 25. For deep-sea oil drilling, typical value is around 10. Shale oil, shale gas, and tar sands also have low EROI values. If the EROI of an energy production process is decreased to nearly 1, there is no value in pursuing in the process.

On the other hand, although currently the cost of solar electricity is higher than that from fossil fuels, its technology is constantly being improved and the cost is constantly being reduced. As shown in Section 1.5.4, around 2015, the cost of of solar electricity will be lower than conventional electricity, to reach *grid parity*. After that, a rapid growth of solar electrcity will take place; see Fig. 1.4.

1.2 Go beyond Petroleum

Fossil energy resources, especially petroleum, are finite, and depletion will happen sooner or later. The transition to renewable energy is inevitable. This fact was first recognized and quantified by a highly regarded expert in the petroleum industry, Marion King Hubbert (1903–1989). His view is not unique in the oil industry. In 2000, recognizing the eventual depletion of petroleum, former British Petroleum changed its name to "bp beyond petroleum."

In 1956, M. King Hubbert, Chief Consultant of Shell Development Company, presented a widely cited report [40] based on the data available at that time, and predicted that crude oil production in the United States would peak around 1970, then start to decline. His bold and original predictions were scoffed but since then have been proven to be remarkably accurate and overwhelmingly recognized.[1]

His theory started with the discovery that the plots of x, the cumulative production of crude oil Q, versus y, the ratio of production rate P over Q, in the United States follows a straight line; see Fig. 1.5.

The two intersections of the straight line with the coordinate axes are defined as follows. The intersection with the x-axis, Q_0, is the total recoverable crude oil reserve. The value found from Fig. 1.5 is $Q_0 = 228$ billion barrels. The intersection with the y-axis, a, has a dimension of inversed time. The inverse of a is a measure of the duration of crude oil depletion; see below. The value in Fig. 1.5 is $a = 0.0536$/year. The straight line can be represented by the equation

$$\frac{P}{Q} = a\left(1 - \frac{Q}{Q_0}\right). \tag{1.4}$$

By definition, the relation between P and Q is

$$P = \frac{dQ}{dt}, \tag{1.5}$$

where t is time, usually expressed in years. Using Eq. 1.5, Eq. 1.4 becomes an ordinary differential equation

$$\frac{Q_0\, dQ}{Q(Q_0 - Q)} = a\, dt. \tag{1.6}$$

Equation 1.6 can be easily integrated to

$$\int \frac{Q_0\, dQ}{Q(Q_0 - Q)} = -\ln\left(\frac{Q_0}{Q} - 1\right) = a(t - t_{\mathrm{m}}), \tag{1.7}$$

where t_{m} is a constant of integration to be determined. From Eq. 1.7,

$$Q = \frac{Q_0}{1 + e^{-a(t - t_{\mathrm{m}})}}. \tag{1.8}$$

[1] The mathematics of Hubbert's theory is similar to the equations created by Pierre François Verhurst in 1838 to quantify Malthus's theory on population growth [85].

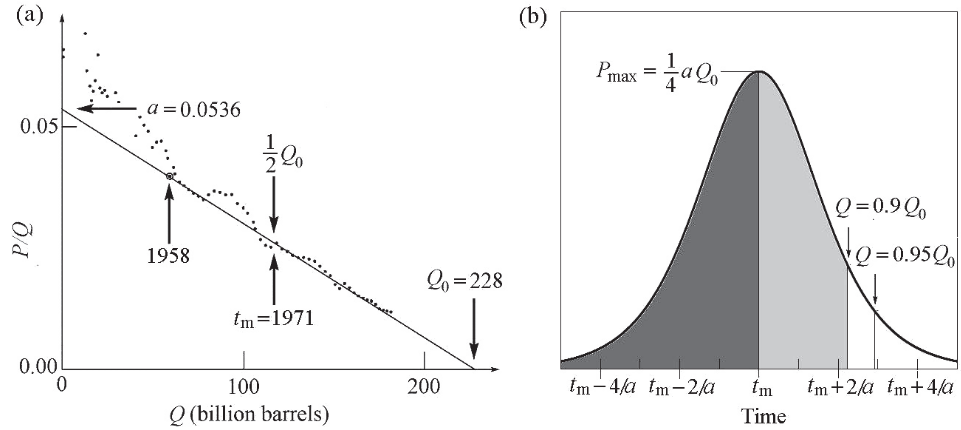

Figure 1.5 Hubbert's curve. (a) In 1956, Merion King Hubbert of Shell Oil studied the data of the cumulative production of crude oil, Q, and the rate of production, P, in the United States. He discovered a linear dependence between P/Q and Q. After Ref. [21]. (b) A curve of Q versus time can be derived from the linear relation, Hubbert's curve (Eq. 1.9). The peak of production occurs at time t_{m} when one-half of the crude oil is depleted. At time $t_{\mathrm{m}} + 2.197/a$, 90% of the recoverable crude oil is depleted. At time $t_{\mathrm{m}} + 2.944/a$, 95% of the recoverable crude oil is depleted.

The initial and final conditions, $Q = 0$ at $t = -\infty$ and $Q = Q_0$ at $t = +\infty$, are satisfied. The time at which one half of the crude oil is depleted, $Q = Q_0/2$ at $t = t_{\mathrm{m}}$, can be determined from historical data.

The rate of production P can be obtained using Eqs. 1.5 and 1.8,

$$P = \frac{dQ}{dt} = \frac{1}{4}aQ_0\,\mathrm{sech}^2\,\frac{a(t-t_{\mathrm{m}})}{2}\,. \tag{1.9}$$

Equation 1.9 represents a bell-shaped curve[2] symmetric with respect to t at $t = t_{\mathrm{m}}$, see Fig. 1.5(b). Therefore, $t = t_{\mathrm{m}}$ is also the time (year) of maximum production rate, $P_0 = aQ_0/4$. The quantity a is a measure of the rate of oil field depletion. Actually, the time when 90% of crude oil is depleted can be determined by Eq. 1.8,

$$\frac{Q_0}{1+e^{-a(t_{0.9}-t_{\mathrm{m}})}} = 0.9\,Q_0, \tag{1.10}$$

which yields $t_{0.9} = t_{\mathrm{m}} + 2.197/a$. Defining depletion time as the time when 95% of crude oil is depleted yields $t_{0.95} = t_{\mathrm{m}} + 2.944/a$.

Figure 1.6 shows the crude oil production rate in the United States from 1920 to 2010. The solid curve is a least-squares fitting with a Hubbert curve; Eq. 1.9. The peak reached in 1971 represents the crude oil production of the lower 48 states (excluding Alaska and Hawaii). There is another peak at around 1989. In 1977, the U.S. Congress passed a law to start drilling for crude oil in Alaska. Because Alaska did not produce

[2]By definition, $\mathrm{sech}\,x = 1/\cosh x = 2/(e^x + e^{-x})$.

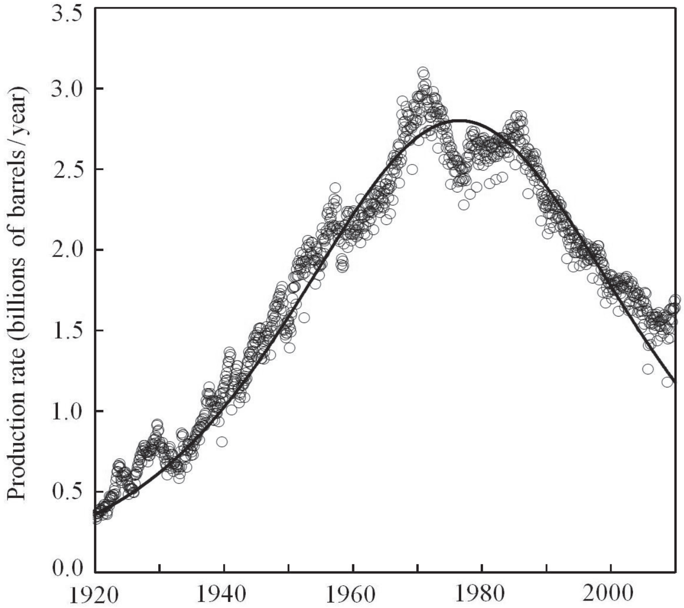

Figure 1.6 Rate of U.S. production of crude oil. Circles: actual U.S. production rate of crude oil. *Source:* EIA (U.S. Energy Information Administration). Solid curve: Hubbert function, using a least-squares fit to actual data. The sudden increase of production in 1977 and the second peak in 1989 are due to oil production in Alaska; see Fig. 1.7.

any crude oil before the 1970s, according to the theory of Hubbert, it should be treated as a stand-alone case independent of the lower 48 states. Plotting the data of crude oil production in Alaska published by the EIA, except for the earlier years, the ratio P/Q shows a rather accurate linear dependence on the accumulative production Q; see Fig. 1.7. From the plot $Q_0 = 17.3$ billion barrels, $a = 0.1646$, and $t_{\mathrm{m}} = 1989.38$, at about May 1989. Using those parameters, a Hubbert curve is constructed; see Fig 1.7(b). As shown, except in the early years, the production data follow the Hubbert curve rather accurately.

The date of depletion can be estimated from the parameters. For the entire United States, $a = 0.0536$. The date of 95% depletion is

$$t_{0.95} = 1971 + \frac{2.944}{0.0536} \approx 2026. \tag{1.11}$$

For Alaska, the date of 95% depletion is

$$t_{0.95} = 1989 + \frac{2.944}{0.1646} \approx 2007. \tag{1.12}$$

The depletion date of Alaska crude oil is sooner than the depletion date for the entire United States. Although crude oil in Alaska started to produce much later than the

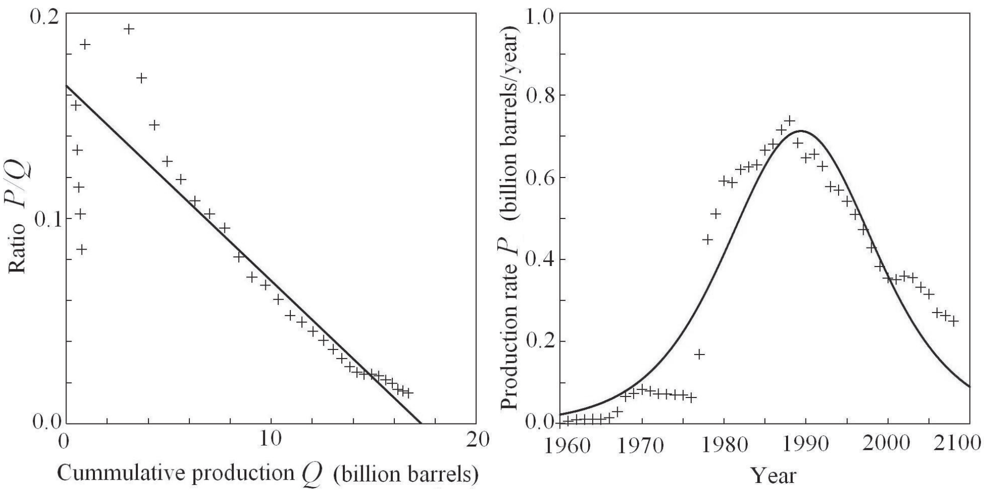

Figure 1.7 Production of crude oil in Alaska. (a) The ratio of P/Q versus Q for Alaska. *Source:* EIA. (b) A Hubbert curve constructed accordingly. As shown, except in the early years, the production data follows the Hubbert curve rather accurately.

lower 48 states, it is extracted much more aggressively there than in the other U.S. states.

Because different countries started crude oil production at different times, a better way of applying the Hubbert theory is to look at each country individually. Hubbert made an estimate based on the data available in the 1950s for the entire world and predicted a peak of crude oil production in the 2000s. Estimates based on more recent data came up with similar results. Recent data show that this peak actually already occurred. The process of discovery and depletion of other nonrenewable energy resources, such as natural gas and coal, follows a similar pattern. As resources are dwindling, the engineering and environmental costs of fossil fuel exploration are increasing rapidly. The Deepwater Horizon oil spill was a wakeup call that in the twenty-first century we must find and utilize renewable energy resources to gradually replace fossil energy resources.

1.3 Other Renewable Energy Resources

Because of the limited reserve of fossil fuel and the cost, from the beginning of the industrial age, renewable energy resources have been explored. Although solar energy is by far the largest resource of renewable energy, other renewable energy resources, including hydropower, wind power, and shallow and deep geothermal energy, have been extensively utilized. Except for deep geothermal energy, all of them are derived from solar energy.

1.3.1 Hydroelectric Power

Hydroelectric power is a well-established technology. Since the late nineteenth century, it has been producing substantial amounts of energy at competitive prices. Currently, it produces about one sixth of the world's electric output, which is over 90% of all renewable energy. As shown in Fig. 1.8, for many countries, hydropower accounts for a large percentage of total electricity. For example, Norway generates more than 98% of all its electricity from hydropower; in Brazil, Iceland, and Colombia, more than 80% of electricity is generated by hydropower. Table 1.3 lists the utilization of hydropower in various regions on the world.

The physics of hydropower is straightforward. A hydropower system is characterized by the *effective head*, the height H of the water fall, in meters; and the *flow rate*, the rate of water flowing through the turbine, Q, in cubic meters per second. The power carried by the water mass is given as

$$P(\mathrm{kW}) = g \times Q \times H, \tag{1.13}$$

where g, 9.81 m/s^2, is the gravitational acceleration. Because a 2% error is insignificant, in the engineering community, it always takes $g \approx 10\,\mathrm{m/s}^2$. Thus, in terms of kilowatts,

$$P(\mathrm{kW}) = 10 \times Q \times H. \tag{1.14}$$

The standard equipment is the Francis turbine, invented by American engineer James B. Francis in 1848. With this machine, the efficiency η of converting water power to mechanical power is very high. Under optimum conditions, the overall efficiency of converting water power into electricity is greater than 90%, which makes it one of the most efficient machines. The electric power generated by the hydroelectric system is

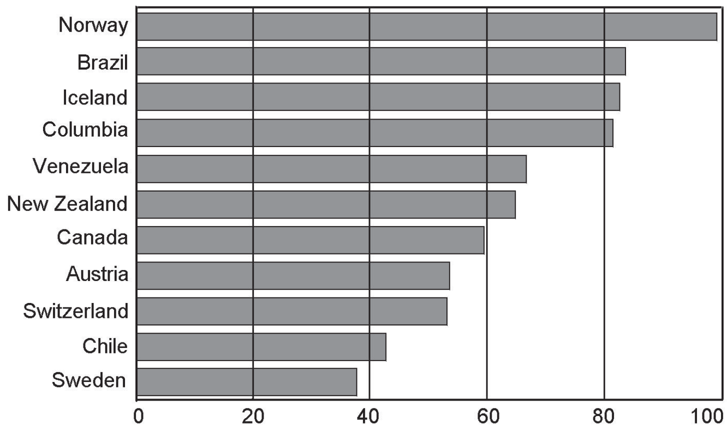

Figure 1.8 Percentage of electricity generation from hydropower in various countries. Norway generates virtually all its electricity from hydropower; in Brazil, Iceland, and Colombia, more than 80% of electricity is generated by hydropower. .

Table 1.3: Regional Hydropotential and Output

Region	Output (EJ/year)	Resource (EJ/year)	Percentage Explored
Europe	2.62	9.74	27%
North America	2.39	6.02	40%
Asia	2.06	18.35	11%
Africa	0.29	6.80	4.2%
South America	1.83	10.05	18%
Oceania	0.14	0.84	17%
World	9.33	51.76	18%

Source: Ref. [14], Chapter 5.

$$P(\mathrm{kW}) = 10\,\eta\,QH. \tag{1.15}$$

A significant advantage over other renewable energy resources is that hydropower provides an energy storage mechanism of very high round-trip efficiency. The energy loss in the storage process is negligible. Therefore, the hydropower station together with the reservoir makes a highly efficient and economic energy storage system. Figure 1.9 is a photo of one of the world's largest hydropower station, the Itaipu hydropower station, which supplies about 20% of Brazil's electricity.

Figure 1.9 Itaipu hydropower station at border of Brazil and Paraguay. With a capacity of 14.0 GW, the Itaipu hydropower station is one of the world's largest and generates about 20% of Brazil's electricity.

1.3.2 Wind Power

The kinetic energy in a volume of air with mass m and velocity v is

$$\text{Kinetic energy} = \frac{1}{2}mv^2. \tag{1.16}$$

If the density of air is ρ, the mass of air passing through a surface of area A perpendicular to the velocity of wind per unit time is

$$m = \rho v A. \tag{1.17}$$

The wind power P_0, or the kinetic energy of air moving through an area A per unit time, is then

$$P_0 = \rho v A \times \frac{1}{2}v^2 = \frac{1}{2}\rho v^3 A. \tag{1.18}$$

Under standard conditions (1 atm pressure and 18°C), the density of air is 1.225 kg/m^3. If the wind speed is 10 m/s, the wind power density is

$$P_0 \approx 610\ \text{W/m}^2. \tag{1.19}$$

It is of the same order of magnitude as the solar power density.

However, the efficiency of a wind turbine is not as high as that of hydropower. Because the air velocity before the rotor, v_1, and the air velocity after the rotor, v_2, are different, see Figure 1.10, the air mass flowing through area A per unit time is determined by the *average wind speed* at the rotor,

$$m = \rho A\, \frac{v_1 + v_2}{2}. \tag{1.20}$$

Thus, the kinetic energy picked up by the rotor is

$$\text{Kinetic energy difference} = \frac{1}{2}mv_1^2 - \frac{1}{2}mv_2^2. \tag{1.21}$$

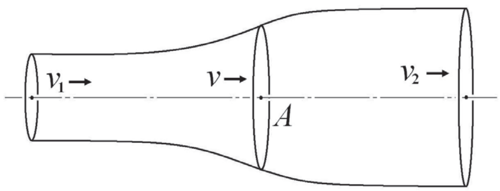

Figure 1.10 Derivation of Betz theorem of wind turbine. Wind velocity before the turbine rotor is v_1, and wind velocity after the turbine rotor is v_2. The velocity at the rotor is the average velocity, and the power generated by the rotor is related to the difference in kinetic energy.

Combining Eqs. 1.20 and 1.21, we obtain an expression of the wind power P picked up by the rotor,

$$P = \frac{1}{4}\rho A(v_1 + v_2)\left[v_1^2 - v_2^2\right]. \tag{1.22}$$

Rearranging Eq. 1.22, we can define the fraction C of wind power picked up by the rotor, or the *rotor efficiency*, as

$$P = \frac{1}{2}\rho v_1^3 A \left[\frac{1}{2}\left(1 + \frac{v_2}{v_1}\right)\left(1 - \frac{v_2^2}{v_1^2}\right)\right] = P_0\, C. \tag{1.23}$$

Hence,

$$C = \frac{1}{2}\left(1 + \frac{v_2}{v_1}\right)\left(1 - \frac{v_2^2}{v_1^2}\right). \tag{1.24}$$

Let $x = v_2/v_1$ be the ratio of the wind speed after the rotor and the wind speed before the rotor. Then we have

$$C = \frac{1}{2}\left(1 + x\right)\left(1 - x^2\right). \tag{1.25}$$

The dependence of rotor efficiency C with speed ratio x is shown in Fig. 1.11. It is straightforward to show that the maximum occurs at $x = 1/3$ where $c = 16/27 = 59.3\%$. This result was first derived by Albert Betz in 1919 and is widely known as Betz's theorem or the Betz limit.

The estimate of worldwide available wind power varies. A conservative estimate shows that the total available wind power, 75 TW, is more than five times the world's total energy consumption. In contrast to hydropower, currently, only a small fraction of wind power has been utilized. However, it is growing very fast. From 2000 to 2009,

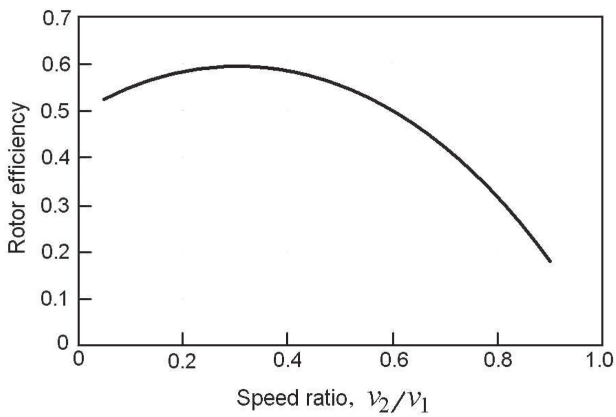

Figure 1.11 Efficiency of wind turbine. See Eq. 1.26. As shown, the maximum efficiency is 16/27, which occurs at a speed ratio of $v_2/v_1 = 1/3$.

Figure 1.12 Wind turbines in Copenhagen. A photo taken by the author in Copenhagen, Denmark, 2006. The statue of the little mermaid, a national symbol of Denmark, is staring at a dense array of wind turbines rather than the Prince.

total capacity grew nine fold to 158.5 GW. The Global Wind Energy Council expects that by 2014, total wind power capacity will reach 409 GW.

Because of a shortage of conventional energy resources, in the late nineteenth century, Denmark began to developed wind power and accelerated production after the 1970 energy crisis. Denmark is still the largest manufacturer of wind turbines, led by Vestas Cooperation, and it has about 20% of wind power in its electricity blend. Figure 1.12 is a photo the author took in Copenhagen. The little mermaid is staring at a dense array of wind turbines instead of the Prince.

However, Denmark's success in wind energy could not be achieved without its neighbors: Norway, Sweden, and Germany [45]. Because wind power is intermittent and irregular, a stable supply of electricity must be accomplished with a fast-responding power generation system with energy storage. Fortunately, almost 100% of the electricity in Norway is generated by hydropower, and the grids of the two countries share a 1000-MW interconnection. In periods of heavy wind, the excess power generated in Denmark is fed into the grid in Norway. By using the reversible turbine, the surplus electrical energy is stored as potential energy of water in the reservoirs. In 2005, the author visited the Tonstad Hydropower Station in Norway on a Sunday afternoon. I asked a Norwegian engineer why the largest turbine was sitting idle. He explained that one of the missions of that power station is to supply power to Denmark. On Monday morning, when the Danes brew their coffee and start to work, that turbine would run full speed.

1.3.3 Biomass and Bioenergy

Over the many thousands of years of human history, until the industrial revolution when fossil fuels began to be used, the direct use of biomass was the main source of energy. Wood, straw, and animal waste were used for space heating and cooking. Candle (made of whale fat) and vegetable oil were used for light. The mechanical power of the horse was energized by feeding biomass. In less developed countries of the world, this situation remains the norm. Even in well-developed countries, direct use of biomass is still very common: for example, firewood for fireplaces and wood-burning stoves.

Biomass is created by photosynthesis from sunlight. For details, see Section 10.1. Although the efficiency of photosynthesis is only about 5% and land coverage by leaves is only a few percent, the total energy currently stored in terrestrial biomass is estimated to be 25,000 EJ, roughly equal to the energy content of the known fossil fuel reserve of the world, see Table 1.1. The energy content of the annual production of land biomass is about six times the total energy consumption of the world; see Table 1.4.

Currently there is a well-established industry to generate liquid fuel using biomass for transportation. Two approaches are widely used: produce ethanol from sugar and produce biodiesel from vegetable oil or animal oil.

Ethanol from Sugar Fermentation

The art of producing wine and liquor from sugar by fermentation has been known for thousands of years. Under the action of the enzymes in certain yeasts, sugar is converted into ethanol and CO_2:

$$C_6H_{12}O_6 \longrightarrow 2(C_2H_5OH) + 2(CO_2). \tag{1.26}$$

At the end of the reaction, the concentration of ethanol can reach 10–15% in the mixture, using specially cultured yeast, it can be up to 21%. Ethanol is then extracted by distillation.

One of the most successful examples is the production of ethanol from sugarcane in Brazil. An important number in the energy industry is *energy balance*, or EROI,

Table 1.4: Basic Data of Bioenergy

Item	in EJ/year	in TW
Rate of energy storage by land biomass	3000 EJ/year	95 TW
Total worldwide energy consumption	500 EJ/year	15 TW
Worldwide biomass consumption	56 EJ/year	1.6 TW
Worldwide food mass consumption	16 EJ/year	0.5 TW

Source: Ref. [14], page 107.

Figure 1.13 Costa Pinto Production Plant of sugar ethanol. The foreground shows the receiving operation of the sugarcane harvest; on the right in the background is the distillation facility where ethanol is produced. Courtesy of Mariordo.

the ratio of energy returned over energy invested; see Eq. 1.3. According to various studies, the energy balance in Brazil for sugar ethanol is over 8, which means that, in order to produce 1 J equivalent of ethanol, about 0.125 J of input energy is required. Also, the cost to produce 1 gal of ethanol in Brazil is about \$0.83, much less than the cost of 1 gal of gasoline. This is at least partially due to the climate and topography of São Paulo, the south-east state of Brazil, a flat subtropical region with plenty of rainfall and sunshine. Since the advance of the flex-fuel automobiles in 2003 which can efficiently use an mixture of gasoline and ethanol of any proportion, the consumption of ethanol dramatically increased because of its low price. In 2008, as a world first, ethanol overtook gasoline as Brazil's most used motor fuel [49]. Figure 1.13 is a panoramic view of the Costa Pinto Production Plant for producing ethanol located in Piracicaba, São Paulo state. The foreground shows the receiving operation of the sugarcane harvest. On the right side, in the background, is the distillation facility where ethanol is produced. This plant produces all the electricity it needs from the bagasse of sugarcane left over by the milling process, and it sells the surplus electricity to public utilities.

Although the Brazil government makes no direct subsidy for the use of ethanol, there is continuous government-supported research to improve the efficiency of production and mechanization of the process. It is an important factor for the success of the Brazilian sugar-ethanol project. From 1975 to 2003, yield has grown from 2 to 6 m^3/ha. Recently, in the state of São Paulo, it has reached 9 m^3/ha. Figure 1.14 shows the annual production of fuel-grade ethanol in Brazil from 1975 to 2010. Although Brazil currently produces more than 50% of the fuel for domestic automobiles and about 30% of the world's traded ethanol, it only uses 1.5% of its arable land.

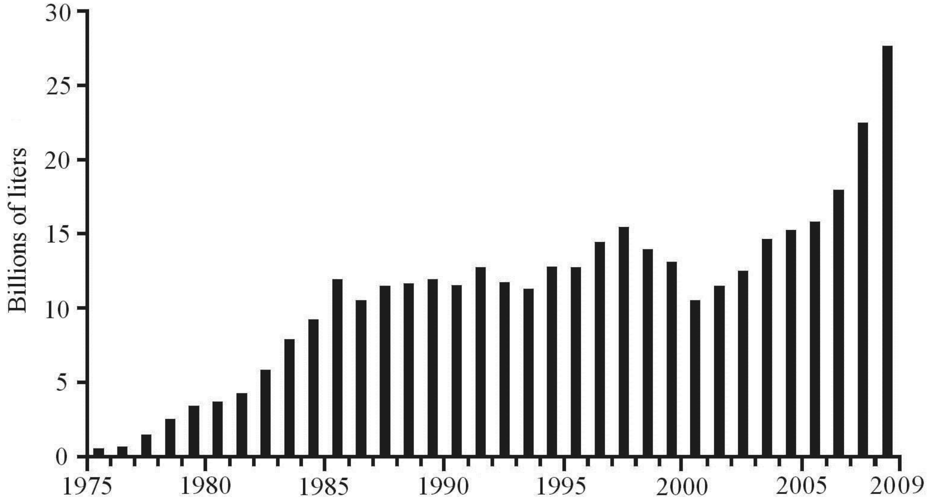

Figure 1.14 Annual production of ethanol in Brazil. *Source: Anuário Estatístico da Agroenergia* 2009, Ministério da Agricultura, Pecuária e Abastecimento, Brazil.

Biodiesel from Vegetable Oil or Animal Fat

Another example of using biomass for liquid fuel is the production of biodiesel from vegetable oil or animal fat. The chemical structures of vegetable oil and animal fat molecules are identical: triglyceride formed from a single molecule of glycerol and three molecules of fatty acid; see Fig. 1.15. A fatty acid is a carboxylic acid (characterized by a —COOH group) with a long unbranched carbon hydride chain. With different types of fatty acids, different types of triglycerides are formed. Although vegetable oil can be used in diesel engines directly, the large molecule size and the resulting high viscosity as well as the tendency of incomplete combustion could damage the engine. Commercial biodiesel is made from reacting triglyceride with alcohol, typically methanol or ethanol. Using sodium hydroxide or potassium hydroxide as catalyst, the triglyceride is transesterified to form three small esters and a free glycerin; see Fig. 1.15. The ester is immiscible with glycerin, and its specific gravity (typically 0.86–0.9 g/cm^3) is much lower than that of glycerin (1.15 g/cm^3). Therefore, the biodiesel can be easily separated from the mixture of glycerin and residuals.

The biodiesel thus produced has a much smaller molecule size than the triglycerides, which provides better lubrication to the engine parts. It was reported that the property of biodiesel is even better than petroleum-derived diesel oil in terms of lubricating properties and cetane ratings, although the calorific value is about 9% lower. Another advantage of biodiesel is the absence of sulfur, a severe environmental hazard of petroleum-derived diesel oil.

The cost and productivity of biodiesel depend critically on the yield and cost of the feedstock. Recycled grease, for example, used oil in making French fries and grease re-

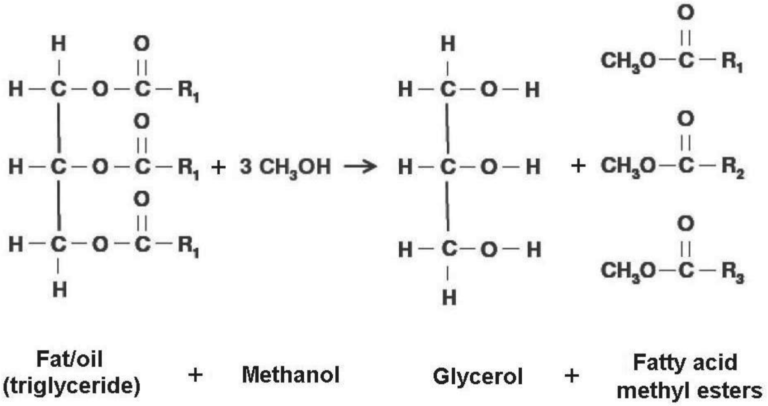

Figure 1.15 Production process of biodiesel. By mixing triglyceride with alcohol, using a catalyst, the triglyceride is transesterified to form three esters and a free glycerin. The ester, or the biodiesel, has a much smaller molecule size, which provides better lubrication to the engine parts.

covered from restaurant waste, is a primary source of the raw materials. Byproducts of the food industry, such as lard and chicken fat, often considered unhealthy for humans, are also frequently used. However, the availability of those handy resources is limited. Virgin oil is thus the bulk of the feedstock of biodiesel. The yield and cost of virgin oil vary considerably from crop to crop; see Table 1.5.

In Table 1.5, several crops for producing biofuels are listed, including those for producing ethanol. Two of them are sugar-rich roots (sugar beet and sweet sorghum). Harvesting these roots takes much more energy and is more labor intensive than harvesting sugarcane. Therefore, the energy balance (the ratio of energy produced versus the energy required to produce it) is often around 2, much lower than the case of sugarcane, which is higher than 8. The energy balance of corn is also lower (around 2), because the first step is to convert corn starch into sugar, which requires energy and labor. Palm oil, originally from Africa, has the highest yield per unit area of land.

Table 1.5: Yield of Biofuel from Different Crops

For Ethanol	m^3/ha	For Biodiesel	m^3/ha
Sugar beet (France)	6.67	Palm oil	4.75
Sugarcane (Brazil)	6.19	Coconut	2.15
Sweet sorghum (India)	3.50	Rapeseed	0.95
Corn (U.S.)	3.31	Peanut	0.84

Source: Ref. [14], Chapter 4.

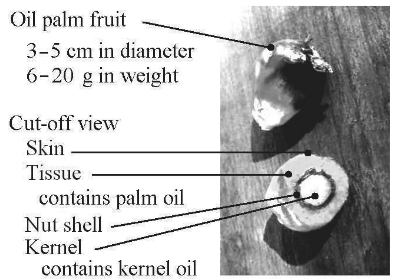

Figure 1.16 Oil palm fruit. The size and structure of oil palm fruit are similar to a peach or a plum. However, the soft tissue of the fruit contains about 50% palm oil. The yield of palm oil per unit plantation area is much higher than any other source of edible oil. The kernel is also rich in oil but of a different type. The oil palm kernel oil is a critical ingredient of soap.

A photograph of the oil palm fruit is shown in Fig. 1.16. The fruit is typically 3–5 cm in diameter. The soft tissue of the fruit contains about 50% palm oil. The kernel contains another type of oil, the palm kernel oil, a critical ingredient for soap. Under favorable conditions, the yield of palm oil could easily reach 5 tonnes per hectare per year, far outstriping any other source of edible oil. Because it contains no cholesterol, it is also a healthy food oil. Currently, palm oil is the number one vegetable oil on the world market (48 million tonnes, or 30% of the world market share), with Malaysia and Indonesia the largest producers. Unlike other types of oil-producing plants (such as soybean and rapeseeds), which are annual, oil palms are huge trees; see Fig. 1.17. Once planted, an oil palm can produce oil for several decades.

Figure 1.17 Wild oil palms in Africa. Oil palms are native trees in Africa which have supplied palm oil for centuries. Shown is a photo of wild oil palms taken by Marco Schmidt on the slopes of Mt. Cameroon, Cameroon, Africa.

1.3.4 Shallow Geothermal Energy

By definition, geothermal energy is the extraction of energy stored in Earth. However, there are two distinct types of geothermal energy depending on its origin: shallow and deep geothermal energy. Shallow geothermal energy is the solar energy stored in Earth, the origin of which will be described in Section 5.4. The temperature is typically some 10°C off that of the surface. The major application of shallow geothermal energy is to enhance the efficiency of the electrical heater and cooler (air conditioner) by using a vapor compression heat pump or refrigerator. Deep geothermal energy is the heat stored in the core and mantel of Earth. The temperature could be hundreds of degrees Celsius. It can be used for generating electricity and large-scale space heating. In this section, we will concentrate on shallow geothermal energy. Deep geothermal energy is presented in the following section.

The general behavior of the underground temperature distribution is shown in Fig. 1.18. At a great depth, for example, 20–30 m underground, the temperature is the annual average temperature of the surface, for example, $\overline{T} = 10°\text{C}$. At the surface, the temperature varies with the seasons. In January, the temperature is the lowest, for example, $\overline{T} - \Delta T = 0°\text{C}$. In July, the temperature is the highest, for example, $\overline{T} + \Delta T = 20°\text{C}$. There are diurnal variations, but the penetration depth is very small. Because of the finite speed of heat conduction, at certain depth, typically -5 to -10 meters below the surface, the temperature profile is *inverted.* In other words, in the summer, the temperature several meters underground is *lower* than the annual average; and in the winter, the temperature several meters underground is *higher* than the annual average.

The solar energy stored in Earth is universal and of very large quantity. In much of the temperate zone, it can be used directly for space cooling. By placing heat exchange structures underground and guiding the cool air through ducts to the living space, a virtually free air-conditioning system can be built. In areas with average temperature

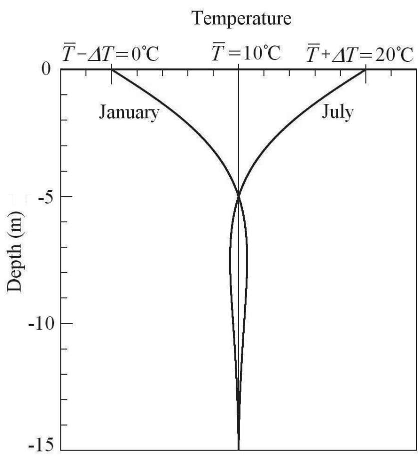

Figure 1.18 Shallow geothermal energy. Seasonal variation of underground temperature. On the surface, the summer temperature is much higher than the winter temperature. Deeply underground, e.g., minus 20 m, the temperature is the annual average temperature of the surface. In the Summer, the temperature several meters underground is *lower* than the annual average; in the winter, the temperature several meters underground is *higher* than the annual average. The energy stored in Earth can be used for space heating and cooling, to make substantial energy savings.

close to or slightly below 0°C, underground caves can be used as refrigerators, also virtually free of energy cost.

The major application of the shallow geothermal energy is the space heating and cooling systems using vapor-compression heat pump or refrigerator, taking the underground mass as a heat reservoir. Details will be presented in Chapter 6.

1.3.5 Deep Geothermal Energy

The various types of renewable energies presented in the previous sections are derivatives of solar energy. Deep geothermal energy, on the other hand, is the only major energy source not derived from solar energy. At the time Earth was formed from hot gas, the heat and gravitational energy made the core of Earth red hot. After Earth was formed, the radioactive elements continuously supplied energy to keep the core of Earth hot. Figure 1.19 is a schematic cross section of Earth. The crest of Earth, a relatively cold layer of rocks with a relatively low density (2–3 g/cm^3), is divided into several *tectonic plates*. The thickness varies from place to place, from 0 to some 30 km. Underneath the crest is the *mantle*, a relatively hot layer of partially molten rocks with relatively high density (3–5.5 g/cm^3). It is the reservoir of magna for volcanic activities. From about 3000 km and down is the core of Earth, which is believed to be molten iron and nickel, with the highest density (10–13 g/cm^3).

The heat content of the mantle and the core is enormous. In principle, by drilling a deep well to the hot part of Earth, injecting water, superheated steam can be produced to drive turbines to generate electricity. In general, such operation is prohibitively expensive and difficult.

Most current geothermal power stations are located either in the vicinity of edges of tectonic plates or in regions with active volcanoes, where the thickness of Earth's crest is less than a few kilometers and drilling to hot rocks is practical. Figure 1.20 shows the regions on Earth where deep geothermal energy can be extracted.

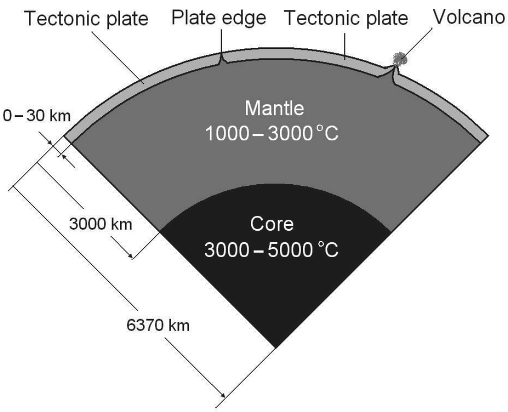

Figure 1.19 Deep geothermal energy. The origin of deep geothermal energy is the core of Earth. First, during the formation of Earth, gravitational contraction generated heat. Then, nuclear reactions in Earth continuously supplied energy. Because of the thickness of the tectonic plates, deep geothermal energy is economical only at the edges of the plate or near the volcanoes.

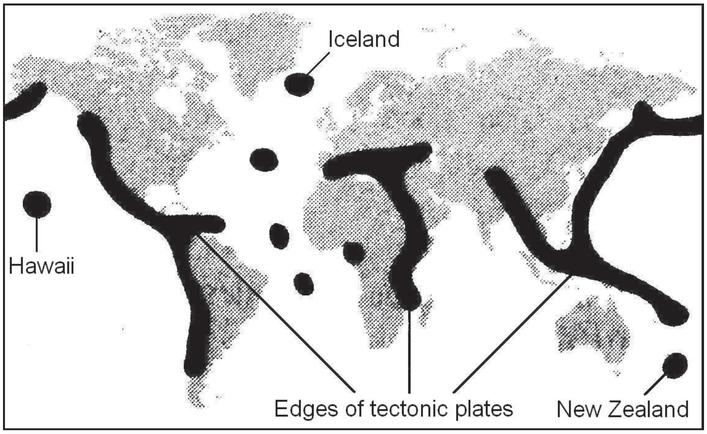

Figure 1.20 Regions for deep geothermal energy extraction. At the edges of tectonic plates and regions with active volcanoes, deep geothermal energy can be extracted economically.

Being rich in active volcanoes, Iceland has an unusual advantage in the utilization of deep geothermal energy. In 2008, about 24% of Iceland's electricity was geothermal and 87% of the buildings were heated by geothermal energy. Figure 1.21 is a photograph of the Nesjavellir Geothermal Power Station, the second largest in Iceland, with a capacity of 120 MW.

Figure 1.21 Nesjavellir geothermal power station, Iceland. Due the high concentration of volcanoes, Iceland has an unusual advantage of utilizing geothermal energy. Shown here is Nesjavellir Geothermal Power Station with a capacity of 120 MW.

1.4 Solar Photovoltaics Primer

It is clear that in the first half of the twenty-first century, fossil fuel will be depleted to an extent that it cannot support the energy demand of human society. There are various types of renewable energy resources. Many of them have limitations, including hydropower, wind energy, and geothermal energy. Solar thermal applications such as solar water heaters can fill only a small part of the total energy demand. Solar photovoltaics is the single most promising substitute for fossil energy. In this section, we will present an elementary conceptual overview of photovoltaics. Details will be presented in Chapters 2–4 and 7–10.

1.4.1 Birth of Modern Solar Cells

In 1953, Bell Labs set up a research project for devices to provide energy source to remote parts of the world where no grid power was available. The leading scientist, Darryl Chapin, suggested using solar cells, and his proposal was approved by his supervisors.

At that time, the photovoltaic effect in selenium, discovered in the 1870s, was already commercialized as a device for the measurement of light intensity in photography. Figure 1.22(a) is a schematic. A layer of Se is applied on a copper substrate, then covered by a semitransparent film of gold. When the device is illuminated by visible light, a voltage is generated, which in turn generates a current. The intensity of electric current depends on the intensity of light. It has been a standard instrument in the first half of the twentieth century for photographers to measure light conditions. This device is much more rugged and convenient than photoresistors because there are no moving parts and no battery is required.

Chapin started his experiment with selenium photocells. He found that the efficiency, 0.5%, is too low to generate sufficient power for telephony applications. Then, a stroke of unbelievable luck, two Bell Lab scientists involved in the pioneering effort to develop silicon transistors, Calvin Fuller and Gerald Pearson, joined Chapin in using

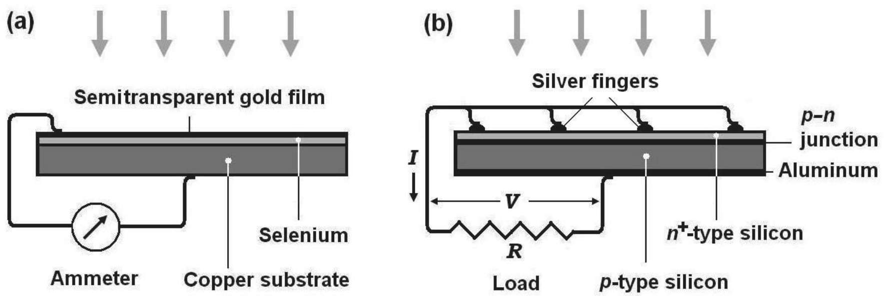

Figure 1.22 Selenium solar cell and silicon solar cell. (a) The selenium photovoltaic cell was discovered in the middle of the nineteenth century and was used for measuring light intensity in photography. (b) The silicon photovoltaic cell was invented at Bell Labs in 1954 using the technology for silicon transistors.

Figure 1.23 Inventors of silicon solar cells. Left to right: Gerald Pearson (1905–1987), Darryl Chapin (1906–1995), and Calvin Fuller (1902–1994). In 1953 Bell Labs set up a research project to provide energy sources for remote parts of the world where no grid power was available. Utilizing the nascent technology to make silicon transistors, in 1954, they designed and demonstrated the first silicon solar cells. The efficiency achieved, 5.7%, makes the solar cell a useful power source. Courtesy of AT&T Bell Labs.

the nascent silicon technology for solar cells; see Fig 1.23. In 1954, a solar cell with 5.7% efficiency was demonstrated [67]. A schematic is shown in Fig. 1.22(b).

The silicon solar cell was made from a single crystal of silicon. By judicially controlling the doping profile, a p–n junction is formed. The n-side of the junction is very thin and highly doped to allow light to come to the p–n junction with very little attenuation, but the lateral electric conduction is high enough to collect the current to the front contact through an array of silver fingers. The back side of the silicon is

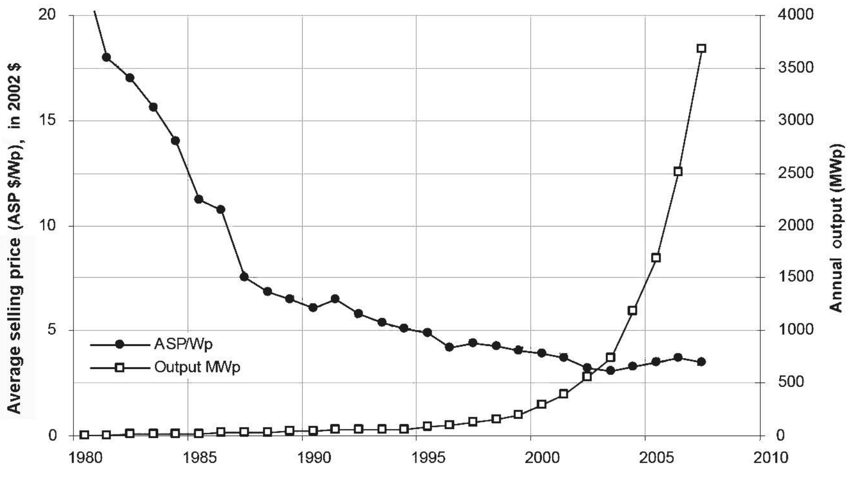

Figure 1.24 Average price and installation of solar cells: 1980–2007. The average price of solar cells dropped threefold from more than $20 per peak watt in 1980 to $6.5 per peak watt in 1990. The installation of solar cells steadily increased during that period. *Source: Solar Photovoltaic Industry, 2008 Global Outlook*, Deutsch Bank.

covered with a metal film, typically aluminum. The basic structure of the silicon solar cell has remained almost unchanged until now.

The initial demonstration of the solar cell to the public in New York City was a fanfare. And the cost of building such solar cells was very high. From the mid 1950s to the early 1970s, photovoltaics research and development were directed primarily toward space applications and satellite power. In 1976, the U.S. Department of Energy (DOE) was established. A Photovoltaics Program was created. The DOE, as well as many other international organizations, began funding research in photovoltaics at appreciable levels. A terrestrial solar cell industry was quickly established. Economies of scale and progress in technology reduced the price of solar cells dramatically. Figure 1.24 shows the evolution of price and annual PV installation from 1980 to 2007.

1.4.2 Some Concepts on Solar Cells

Following are a list of key terms and concepts regarding solar cells.

Standard Illumination Conditions

The efficiency and power output of a solar module (or a solar cell) are tested under the following standard conditions: 1000 W/m^2 intensity, 25°C ambient temperature, and a spectrum that relates to sunlight that has passed through the atmosphere when the sun is at 42° elevation from the horizon [defined as air mass (AM) 1.5, see Plate 1].

Fill Factor

The *open-circuit voltage* V_{op} is the voltage between the terminals of a solar cell under standard illumination conditions when the load has infinite resistance that is open. In this situation, the current is zero. The *short-circuit current* I_{sc} is the current of a solar cell under standard illumination conditions when the load has zero resistance. In this case, the voltage is zero. By using a resistive load R, the voltage V will be smaller than V_{op}, and the current I is smaller than I_{sc}. The power $P = IV$. The maximum power output is determined by the condition

$$dP = d(IV) = IdV + VdI = 0. \tag{1.27}$$

Figure 1.25 shows the relation among these quantities. Denoting the point of maximum power by I_{mp} and V_{mp}, we have $P_{\max} = I_{\text{mp}}V_{\text{mp}}$.

The fill factor of a solar cell FF is defined as

$$\text{FF} = \frac{P_{\max}}{I_{\text{sc}}V_{\text{oc}}} = \frac{I_{\text{mp}}V_{\text{mp}}}{I_{\text{sc}}V_{\text{oc}}}. \tag{1.28}$$

The typical value of the fill factor is between 0.8 and 0.9.

Efficiency

The efficiency of a solar cell is defined as the ratio of the output electric power over the input solar radiation power under standard illumination conditions at the maximum power point. Efficiencies for various solar cells are shown in Plate 5.

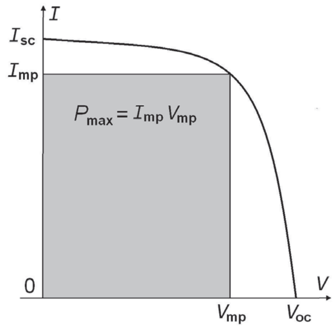

Figure 1.25 Maximum power and fill factor. By connecting a load resistor to the two terminals of a solar cell, the solar cell supplies power to the load. The maximum power point occurs when $P = IV$ reaches maximum. At that point, $P_{\text{max}} = I_{\text{mp}} V_{\text{mp}}$. Obviously, there is always $I_{\text{mp}} < I_{\text{sc}}$ and $V_{\text{mp}} < V_{\text{oc}}$. The fill factor of a solar cell is defined as $\text{FF} = P_{\text{max}}/I_{\text{sc}} V_{\text{oc}} = I_{\text{mp}} V_{\text{mp}}/I_{\text{sc}} V_{\text{oc}}$.

Peak Watt

The "peak watt" (Wp) rating of a solar module is the power (in watts) produced by the solar module under standard illumination conditions at the maximum power point. The actual power output of a solar cell obviously depends on the actual illumination conditions. For a discussion of solar illumination, see Chapter 4.

1.4.3 Types of Solar Cells

The crystalline silicon solar cell was the first practical solar cell invented in 1954. The efficiency of such solar cells as mass produced is 14–20%, which is still the highest in single-junction solar cells. It also has a long life and a readiness for mass production. To date, it still accounts for more than 80% of the solar cell market. There are two versions of the crystalline silicon solar cell: monocrystalline and polycrystalline. Amorphous silicon thin-film silicon solar cells are much less expensive than the crystalline ones. But the efficiency is only 6–10%. In between are CIGS (copper indium gallium selenide) and CdTe–CdS thin film solar cells, with a typical efficiency of around 10% and account for about 15% of the market. Because of the very high absorption coefficient, the amount of materials required is small, and the production process is simpler; thus the unit price per peak watt is lower than crystalline silicon solar cells. To date, organic solar cells still have low efficiency and a short lifetime, and the market share is insignificant, see Plate 5. Table 1.6 summarizes several significant types of solar cells.

1.4.4 Energy Balance

It takes energy to produce solar cells. Therefore, a study of the EROI is important. Here we discuss the energy balance for the most expensive case, crystalline silicon solar cells. The energy investment includes that for producing silicon feedstock, ingot and wafers, cell production, module assembly, and installation. A standard benchmark number to evaluate the energy balance of photovoltaics is *payback time*. By setting the solar cells in a given solar illumination condition, the solar cells will generate energy in the form of electricity. Payback time is the number of years it takes for the electricity

Table 1.6: Types of Solar Cells

Type	Efficiency (%)	Cost ($/Wp)	Market share (%)
Monocrystalline Si	17–20	3.0	30
Polycrystalline Si	15–18	2.0	40
Amouphous Si	5–10	1.0	5
CIGS	11–13	1.5	5
CdTe-CdS	9–11	1.5	10

generated by the solar cell to compensate for the energy invested in the production and installation process.

Figure 1.26 represents a conservative estimate of payback time for crystalline silicon solar cells based on European insolation conditions [4]. For Central Europe, with annual insolation of 1000 W/m^2, the payback time is 3.6 years. Its lifetime is typically 25 years, which results in an EROI of 7. In Southern Europe and most places in the United States, the EROI is above 10. The EROI for thin-film solar cells is even better. However, because of lower efficiency, these require more space to generate the same power.

1.5 Above Physics

Good physics does not always lead to successful industrial implementation and to conferring a great benefit to mankind. Solar energy is no exception. Economics and politics play a significant role. In this section, we will review some important historical lessons and analyze the economical and political context for which the utilization of solar energy can become a success and thus benefit mankind.

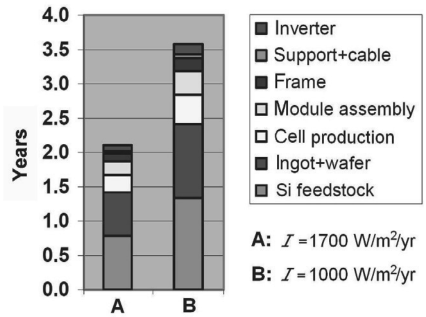

Figure 1.26 Payback time for crystalline silicon solar cells. The energy invested for a solar cell includes the energy for producing silicon feedstock, ingot and wafers, cell production, and installation. Even under unfavorable insolation conditions, such as central Europe, the payback time is less than 15% of its lifetime, which results in an EROI of 7 (see Ref. [4]).

1.5.1 Economics of Solar Energy

The early history of solar water heaters in the United States vividly illustrates the interplay of physics, engineering and economics [17]. In the nineteenth century, before the invention of modern hot-water systems, making hot water for a bath was expensive and difficult. Water had to be heated in a large pot over fire, then scooped into the bathtub. It was especially expensive in California, where fuel such as coal had to be imported and wood was precious. Artificial gas and electricity were very expensive. However, sunlight is plenty there, and the weather is mild.

In 1891, Clarence Kemp patented an effective and usable solar water heater, named Climax (U.S. Patent 451,384). First marketed in Maryland, Kemp's business was not very successful. Then he sold the exclusive right to two Pasadena businessmen and made a great commercial success in California. By 1900, 600 units were sold in southern California alone. However, the Climax water heater had a drawback in that it took a few hours of sunlight to heat up the water and after sunset the water temperature would drop quickly. Therefore, it could only be used in the afternoon of a sunny day.

In 1910, William J. Bailey invented and patented the Day-and-Night solar water heater (U.S. Patent 966,070), which resolved the major problems and became the prototype of later solar water heaters; see Fig. 1.27. First, the heat collector A is made of a parallel grid of copper pipes welded on a flat piece of copper plate. Second, it uses a water tank C placed above the heat collector, heavily insulated by cork, D. Such an arrangement enables water circulation by *natural convection* and effective *energy storage*. When water is heated by sunlight, the specific gravity decreases. It flows automatically upward through pipe B into water tank C. The colder water then flows automatically downwards through pipe E back into the heat collector A. If the insulation is sufficient, the water can stay hot overnight. Therefore, it works in the day as well as in the night. Although the Day-and-Night system cost about $180 at that time, much higher than a Climax system, it quickly conquered the consumers. Climax was forced out of business. By the end of World War I, more than 4000 Day-and-Night solar water heaters were

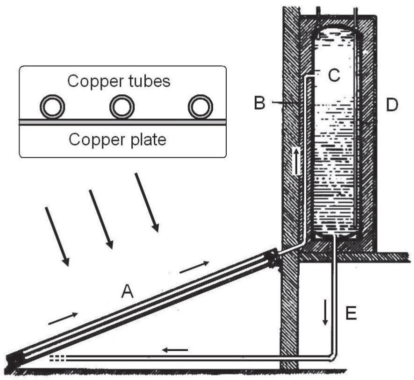

Figure 1.27 Day-and-Night solar water heater. The inset shows the copper tubes and copper plate of the solar heat collector A. The system works under natural convection: the water heated by sunlight in collector A rises to the insulated tank C. The cold water flows down from tank C through pipe E back to the solar heat collector A. *Source*: U.S. Patent 966,070, 1911.

sold.

In the early 1920s, abundant natural gas was discovered in the Los Angeles Basin. The price of natural gas in 1927 was only a quarter of that in 1900 for town gas. The gas-operated water heater, much cheaper in initial investment than the solar heater and more convenient to use, gradually replaced the once popular solar water heaters. Bailey's company, being quite experienced in water heater systems, quickly adapted into a gas heater business. Still keeping Day-and-Night as the company name, it soon became one of the largest producers of gas water heaters in the nation.

The downfall of the solar water heater business in California was not the end of it. Florida, with a real estate boom in the 1920s through the 1940s and no natural gas available, became the sweet spot of solar water heaters; see Fig. 1.28. It is estimated that from 25,000 to 60,000 solar water heaters were installed in Miami during 1920–1941. During World War II, price of copper skyrocketed. After the war, the price of electricity plummeted. The result was the gradual replacement of solar water heaters by electric water heaters. In the United States, the solar water heater had lost its glory.

However, after World War II, elsewhere in the world, solar water heaters gained momentum, especially in Israel. A desert area without energy resources similar to California in the late nineteenth century, solar water heaters could bring sizeable economic benefit. A significant advance in solar thermal technology, selective absorption coating, was invented in Israel in the 1950s, which greatly improved the efficiency of solar water heaters. Later, Israel became the first country to require that all new buildings must have solar water heaters.

Figure 1.28 A Day-and-Night solar water heater in Florida. From 1920 to 1941, more than 25,000 solar water heaters were manufactured and installed in Florida. After 80 years, thousands of them are still working. The photo, taken by the author in Miami in August 2010, is a solar water heater installed in 1937. The insulated water tank is disguised as a chimney. Even with a broken pane, it is still working properly.

1.5.2 Moral Equivalence of War

Government policies on energy have a major effect on renewable energy development. In the United States, the new energy policies during the Carter administration in the 1970s created a golden period for renewable energy research and development.

After World War II, the United States enjoyed cheap crude oil, staying below $20 per barrel (inflation adjusted in January 2008 dollars) for three decades. In 1973, an oil embargo triggered the first energy crisis. The price of crude oil jumped dramatically; see Fig. 1.29.

Coincidentally, the timing of the energy crisis matched the prediction of M. King Hubbert in 1956 that shortly after 1970 the production of crude oil in the United States would peak and start to decline; see Section 1.2. The coincidence is not accidental. As crude oil production in the United States started to decline, consumption was still growing. In 1971, the United States paid $3.7 billion for importing crude oil; in 1977, it increased 10-fold to $37 billion (in 1977 dollars). Obviously, excessive dependence on foreign oil poses severe economic and security threats.

On April 18, 1977, then President Jimmy Carter delivered a televised speech about his new energy policy. He called the struggle for greater energy independence the *moral equivalence of war* — one that "will test the character of the American people." He said:

> Tonight I want to have an unpleasant talk with you about a problem unprecedented in our history. With the exception of preventing war, this is the greatest challenge our country will face during our lifetimes. The energy

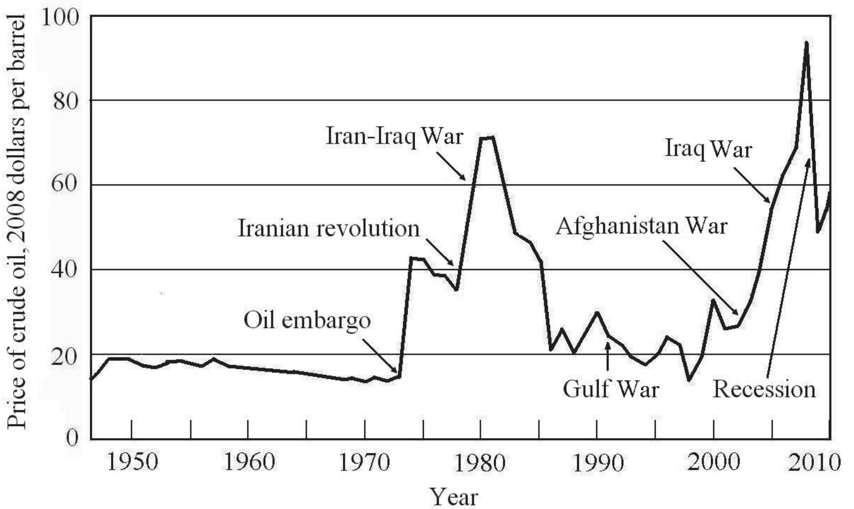

Figure 1.29 History of crude oil price, 2008 dollars. *Source:* U.S. Energy Information Administration.

> crisis has not yet overwhelmed us, but it will if we do not act quickly.
>
> It is a problem we will not solve in the next few years, and it is likely to get progressively worse through the rest of this century.
>
> We must not be selfish or timid if we hope to have a decent world for our children and grandchildren.
>
> We simply must balance our demand for energy with our rapidly shrinking resources. By acting now, we can control our future instead of letting the future control us.

The major points of Carter's energy policy included energy conservation, increasing domestic traditional energy exploration, and developing renewable energy resources. In his words, "we must start now to develop the new, unconventional sources of energy we will rely on in the next century." A few days later President Carter signed the Department of Energy Organization Act and on August 4, 1997, formed the U.S. Department of Energy. Then, the National Energy Act (NEA) was established in 1978 with tax incentives for renewable energy projects, especially solar energy. This legislation initiated a significant boost to the research, development, and installation of solar water heaters, solar cells, and solar-operated buildings.

To lead the public by example, on June 20, 1979, Carter installed a solar water heater with 32 panels on the roof of the White House; see Fig. 1.30. At the ceremony, Carter reflected upon his own idealism:

> A generation from now, this solar heater can either be a curiosity, a museum piece, an example of a road not taken, or it can be a small part of one of the greatest and most exciting adventures ever undertaken by the American people . . . to harness the power of the sun to enrich our lives as we move away from our crippling dependence on foreign oil.

In 1978, the Carter administration enacted the first National Energy Act (NEA) to promote fuel efficiency and renewable energy. The research and development funding for renewable energy is greatly increased. Part of the 1978 NEA is an Energy Tax Act that gave an income tax credit to private residents who use solar, wind, or geothermal sources of energy. The 1978 Energy Tax Act was expired in 1986. However, many other countries followed the example of the United States and provided government financial support for renewable energy utilization.

As anticipated by Jimmy Carter, during the rest of the twentieth century, several factors made the energy problem "progressively worse": Due to a steady decline and an increasing consumption, crude oil import into the United States increased from 1.8 billion barrels in 1980 to 5.0 billion barrels in 2000s. The price of crude oil (in 2008 dollars) increased from about $20 to more than $100 a barrel in late 2000s; see Fig. 1.29. The petroleum crisis in the 1970s reappeared, but with an even more gruesome context: According to Hubbert, in the early 2000s, the world's crude oil production peaked and started to decline; see Section 1.2. The world's two most populous countries, India and China, are experiencing rapid economic development, which consume a growing

Figure 1.30 Jimmy Carter dedicates solar water heater on top of the White House, June 20, 1979. He hoped that this would be "a small part of one of the greatest and most exciting adventures ever undertaken by the American people, ... to harness the power of the sun to enrich our lives as we move away from our crippling dependence on foreign oil". Courtesy of Jimmy Carter Library, Atlanta, GA.

proportion of the dwindling production of the world's crude oil. Both India and China have very limited crude oil resource and therefore have an even more severe energy problem.

1.5.3 Solar Water Heaters over the World

As we have presented, the solar water heater was invented in the United States and it was quite popular in the first half of the twentieth century. However, despite the energy crisis and strong government incentive in the 1970s, the installation volume in the United States is still very low. Nevertheless, in recent decades, the solar water heater has enjoyed an explosive growth globally, especially in China. As shown in Fig. 1.31, in 2007, China installed 80% of the new solar water heaters with 16 GW capacity; the total installation capacity of solar water heaters is 84 GW, accounting for two-thirds of the world's total.

A Huge Virgin Market

The market for water heaters in China is quite similar to that in California in the late nineteenth century. Up to the 1980s, nearly one billion people in China had no running

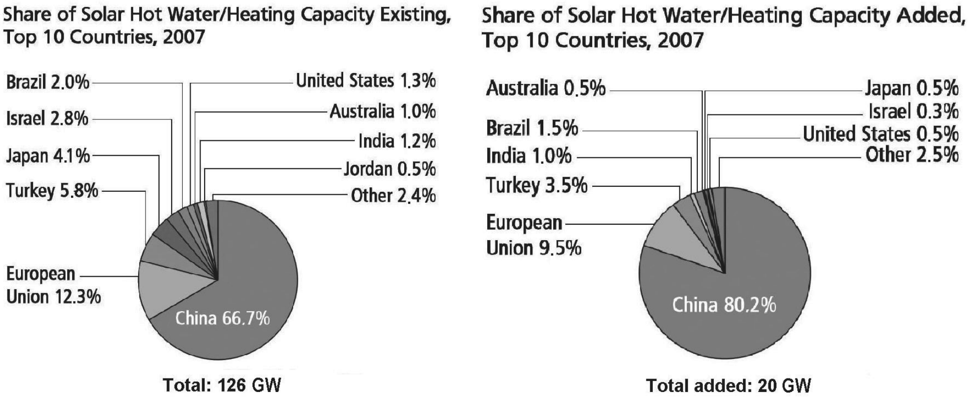

Figure 1.31 Global installations of solar water heater. Globally, solar water heater installation is increasing rapidly. The most growth is in China. *Source:* Renewables Global Status Report, 2009 Update, (http://www.ren21.net).

hot water. Improvement in the standard of living has made hot water a necessity of life. However, natural gas and heating oil are expensive and not generally available. Electricity is very expensive. The cost of equipment for making hot water using fossil fuel is comparable with that using sunlight. China represents perfect soil in which the solar water heater industry can grow.

Advances in Technology and Economy of Scale

Until recently, most solar water heaters in the Western world used flat-plate heat collectors similar to the Day-and-Night system (Fig 1.28) and the White House solar panels (Fig 1.30). However, the structure is rather inconvenient for mass production. It uses a lot of copper, a major factor of its demise during and after World War II. The heat loss due to conduction through the glass window and the back plate is significant. A lot of metal parts exposed to the elements limit its lifetime. The vacuum tube heat collector, invented by American engineer William L. R. Emmet in 1911 (U.S. Patent 980,505) has superb properties. However, for several decades, it was expensive and complicated to produce. In early 1980s, vacuum tube solar heat collectors were improved. An extremely simple and effective solar water heater was invented and perfected; see Fig 1.32.

Figure 1.32(a) shows the design of evacuated-tube solar water heater. Each heat collector is a double-walled glass tube. The space between the outer tube and the inner tube is evacuated to a high vacuum, similar to a Dewar flask. On the outer surface of the inner tube, a *selective absorption film* is applied. For sunlight, which is mostly visible and near infrared, the absorption coefficient is around 95%. For far-infrared radiation from the hot water (80–100°C), the emission coefficient is around 5%. The vacuum sleeve perfectly blocks thermal conduction. The entire system works automatically under the principle of natural convection. The water heated by sunlight, having a lower specific gravity, flows upward to the insulated tank. Similarly, the cold water flows downward from the tank into the heat collector tubes. A photo is shown in Fig 1.32(b). Typically, 10–40 evacuated tubes are used in one system. The water tank is insulated by foam polyurethane. The temperature only drops a few degrees overnight. Therefore, it can provide hot water day and night.

The design also facilitates shipping and storage. The tubes, the tank, and the parts of the frame are shipped in three separate rectangular cardboard boxes. The system is then assembled at the installation site.

Because the evacuated tubes are made of borosilicon glass (Pyrex), the selective absorption film is under high vacuum, and the tank is usually made of high-grade stainless steel. Unless it is broken by brute force, the system could work for decades. In addition, these parts are suitable for automatic mass-production. Currently, some 200 million evacuated tubes and some 10 million insulated water tanks are being manufactured every year.

The huge market enables cost advantages by the economies of scale. The producer's average cost per unit falls as scale is increased. Due to relentless effort of automation, the manufacturing cost of evacuated tubes is reduced to a few dollars per piece, unimaginable a few decades ago. The reduced price of solar water heaters further increases the size of the market. The expansion of the market further provides grounds to improve the manufacturing process. As a result, the solar water heater business in China is sustainable *without government financial incentives*.

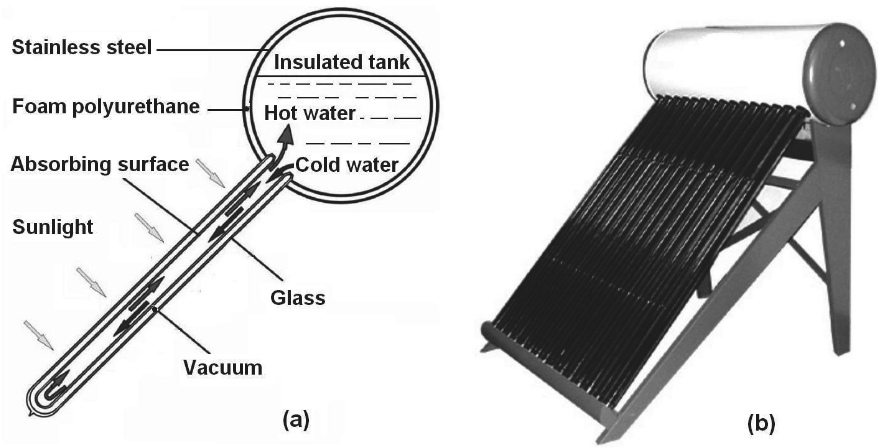

Figure 1.32 Evacuated-tube solar water heater. (a) Schematic of evacuated-tube solar water heater. Each heat collector is a double-walled glass tube. The system works automatically under the principle of natural convection. (b) Photograph of system.

Himin Model of Solar Energy Business

It is instructive to learn how the colossal solar water heater industry has been able to grow over such a short period of time. For that purpose, I visited the world's largest manufacturer of solar water heaters, Himin Solar Energy Group, and met the founder and CEO, Mr. Huang Ming in Beijing, when he attended the Plenary Meeting of People's Congress. A number of internal documents of this company were then collected.

In 1978, when Huang Ming was a student at East China Petroleum Institute, he learned that the crude oil reserve in the world would be depleted within 50 years. China's crude oil would be depleted even sooner. Several years after graduation, he became a highly regarded research engineer specializing in oil well drilling. However, his personal experience reinforced his pessimism about the future of petroleum.

In 1987, by chance, he found Duffie and Beckman's book *Solar Energy Thermal Processes*. Reading it from cover to cover and doing hands-on experiments using funds from the sale of a patent, he became convinced that sunlight is the ultimate solution to the energy problem. Solar energy became his lifetime passion. Since then, he spends 8 h at the Petroleum Institute, 8 h working at home on solar energy projects, and 8 h sleeping and eating. He gave his hand-made solar water heater to friends and relatives as gifts and installed a system at a children's entertainment center.

In 1995, he quitted his job in petroleum industry, and started his own business. He chose the Chinese name of the company, Huangming, as a homophone of his personal name, to symbolize his dedication. Within ten years, his company has grown into one of the largest solar water heater manufacturers on the world without government subsidy. In 2009, Himin produced more than two million square meters of solar heat collectors, equivalent to 2 GW of peak solar energy utilization. In May 2006, Huang Ming was

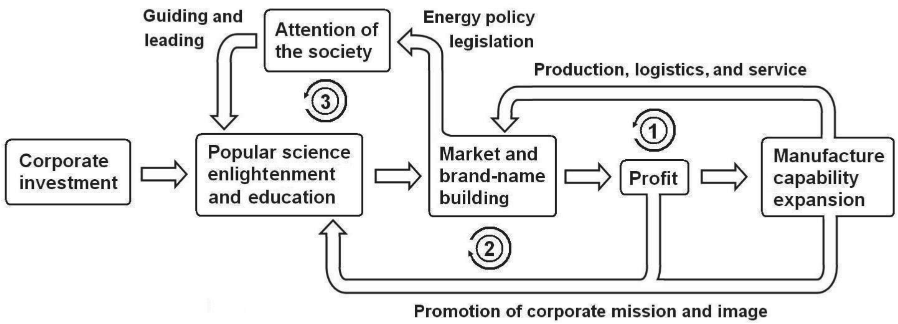

Figure 1.33 Himin model of solar energy business. The Himin model consists of three loops. Loop 1 is similar to a conventional business cycle. Strict quality control and good after sale service build up the brand name. Large-scale mass production reduces unit cost. Loop 2 is to invest heavily in popular science education as the major marketing method. Loop 3 is to push energy policy legislation to favor renewable energy and to promote public awareness. *Source:* Minutes of the 14th Conference of United Nations Commission on Sustainable Development, New York, 2006.

invited by United Nations to present Himin's business mode at the 14th Meeting of United Nations Commission on Sustainable Development, 2006. It was later known as the "Himin model of solar energy business".

Figure 1.33 is a sketch of the Himin model. A central point is to create a new market through popular science enlightenment and education. In 1996, right after the birth of Himin, the weekly newsletter *Popular Solar Energy* was established. It became Himin's continuing marketing tool, with accumulated distribution of 300 million copies in 2010. Himin organized numerous popular science tours, traveling 80 million kilometers over China. Because for an average Chinese family a solar water heater is still a major capital investment, the decision to purchase a set must be based on careful thinking. Such educated people were the first customers and then became volunteer marketers for the product. The Himin model is represented by three loops; see Fig. 1.33.

Loop 1 is the main production cycle. Himin's strategy is to pursue the highest standard of excellence. The retail price of their product is among the most expensive on the market. However, because of their extensive research and quality control, the products have less trouble and last a long time. The quality ensures their reputation in the marketplace.

Loop 2 emphasizes the importance of popular science enlightenment and education. In addition to corporate investment, a substantial portion of the profit is invested in science education to ensure that customers understand how the system works and how to choose a good product or part.

Loop 3 emphasizes the importance of pushing for energy policy legislation and raising public attention to renewable energy. This is also a significant factor of its success. In 2003, local city folks, especially Himin employees, elected Huang Ming to become a member of the People's Congress. He then mobilized 60 fellow congressmen to propose a Renewable Energy Act, which was passed in the spring of 2005. The legislation has motivated central and local governments to set up renewable-energy projects and raises public support to solar energy technology and products.

In 2008, the International Solar Energy Society (ISES) chose Dezhou, the location of Himin, to host the 2010 International Solar City Congress. Around that time, Huang Ming was elected as the vice president of the ISES. The venue of the congress, the Dezhou Apollo Temple, an 800,000-ft^2 museum, ballroom, and hotel with 65% of its energy supplied by solar, was completed in 2009; see Plate 17.

1.5.4 Photovoltaics: Toward Grid Parity

Because water heaters consume less than 10% of total energy, the bulk of energy needed, especially electricity, can only be supplied through photovoltaics or other means of solar electricity generation. Compared with solar water heaters, the total power of solar PV installed in the world is much smaller. In 2008, 6.08 GWp of PV was installed in the world. The accumulative installation in 2008 is 15 GWp. Figure 1.34 shows the yearly installation and growth rate of the entire world from 1990 to 2008.

As shown, the installation in terms of peak watts of PV is only about one tenth of solar water heaters. The limiting factor is simply economics. As shown in Section 1.4.1,

Table 1.7: Cost Per Kilowatt-Hour of Solar Electricity for Various Cases

Insolation $kWh/m^2/day$	By Cost of Installed PV per Peak Watt $ 2	$ 4	$ 6	$ 8	$ 10
3	$ 0.073	$ 0.146	$ 0.219	$ 0.292	$ 0.365
4	$ 0.054	$ 0.109	$ 0.164	$ 0.219	$ 0.273
5	$ 0.043	$ 0.087	$ 0.131	$ 0.175	$ 0.219
6	$ 0.036	$ 0.073	$ 0.109	$ 0.146	$ 0.182

although practically usable solar cells were invented in 1954, the manufacturing cost was very high. The major applications were space and military fields. In the late 1970s and early 1980s, stimulated by the National Energy Act, dramatic improvement in efficiency and reduction in cost were achieved; see Fig. 1.24. The gradual reduction in the manufacturing cost of solar cells continues in the 1990s and early 2000s. In 2003, the price of solar cell per peak watt has dropped to $6.50. However, solar electricity is still much more expensive than the electricity generated by traditional energy resources, especially by coal and hydropower, which is $0.05 to $0.10 per kWh. Including the supporting structure, inverters and necessary instruments, the cost of installed solar panels per peak watt in 2003 was about $10. Table 1.7 shows the cost of generating 1 kWh of electric energy by solar cells in regions with different insolation.

To jump start the utilization of solar energy, in the 1990s, many European countries established the *feed-in tariff (FIT) law*, which guarantees a solar photovoltaic system

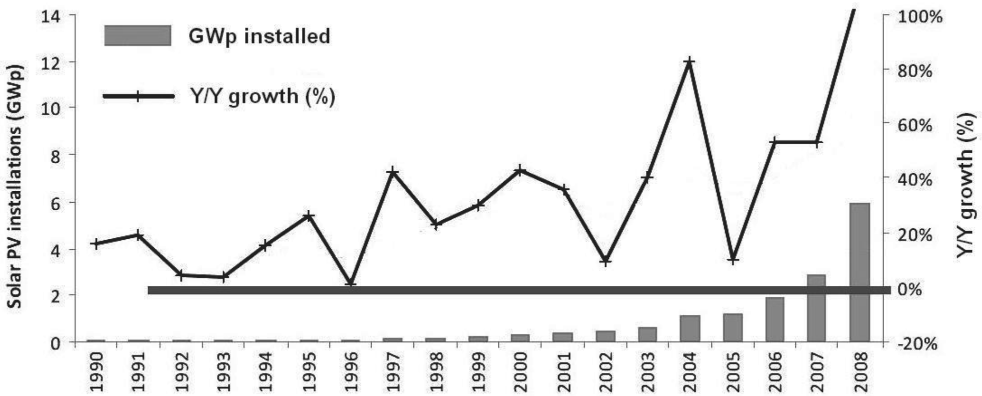

Figure 1.34 Installation of solar photovoltaics: 1990 to 2008. Bar graph: world annual installation of solar photovoltaic panels. Solid curve: growth rate by year. *Source*: After *Solar Photovoltaic Industry, 2008 Global Outlook*, Deutsch Bank.

access to the grid with the purchase price of thus generated electricity based on cost. The purchase guarantees could be extended to 20 or 25 years, but the rate could decline based on expected cost reductions. The law significantly expended the market for solar photovoltaics. However, it also caused unexpected gyrations. For example, in 2007, Spain raised the date for large PV systems from €0.18/kWp to €0.42/kWp. Immediately, the installation surged from 61 mWp in 2006 to 591 mWp in 2007, then to 2700 mWp in 2008. The Spanish government suddenly found that the rate was not sustainable and reduced it to €0.32/kWp, to take effect in 2009. In 2009, the installation is reduced to less than 200 MWp.

The dramatic increase of demand in 2007–2008 nevertheless gave a thrust to an unprecedented boom in the solar cell industry, especially in the United States and Asia. The economy of scale, in the form of vertical integration, again works. First Solar in the Unites States is vertically integrated in a sense that it designs and manufactures equipment for solar cell production by themselves, thus its production capability is quickly expended. Yingli Solar in Baoding, China, and Renewable Energy Corporation in Norway, both manufacturers of polycrystalline silicon solar cells, are so vertically integrated that they start with producing pure silicon from silica mines and end up with solar panel installation. In 2009, 49% of the world's solar cells were produced in China and Taiwan, mostly crystalline silicon solar cells with high efficiency. Figure 1.35 shows the statistics from two manufacturers. As shown, in 2009, the manufacturing

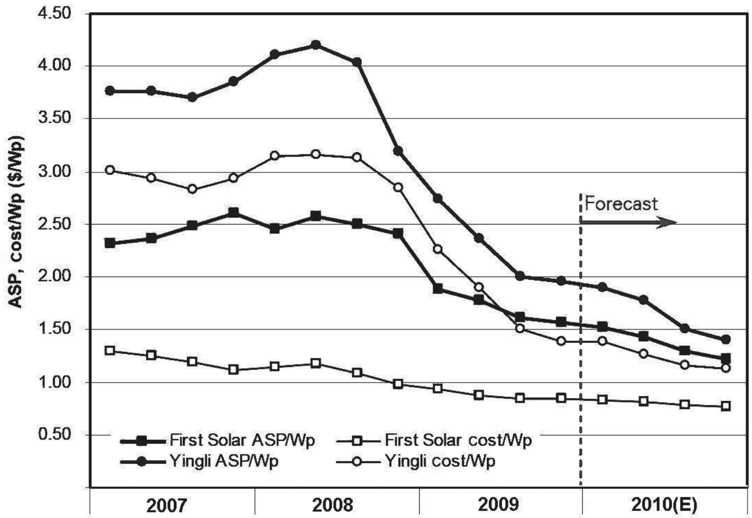

Figure 1.35 Price of solar cells from two major suppliers: 2007 to 2010. Existing data and forecast for two representative solar cell manufacturers. First Solar is the world's largest manufacturer of CdTe-CdS thin film solar cells. Yingli is the world's largest manufacturer of polycrystalline solar cells, which is also one of the world's most vertically integrated solar cell manufacturers. After *Solar Photovoltaic Industry, 2008 global outlook*, Deutsch Bank.

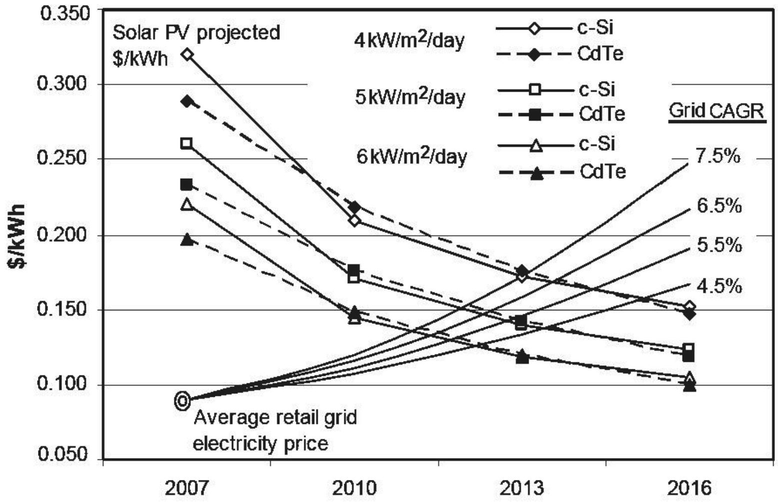

Figure 1.36 Prediction of grid parity. According to a forecast by the Deutsch Bank, the two most promising solar cells, crystalline silicon solar cells and CdTe thin-film solar cells, will arrive at grid parity around year 2013. Beyond 2013, the cost of solar electricity could be lower than that of traditional sources of electricity for many places in the world. *Source*: After *Solar Photovoltaic Industry, 2008 Global Outlook*, Deutsch Bank.

cost of First Solar's CdTe thin-film solar cells dropped to \$0.80 per peak watt, and the retail price is \$1.50 per peak watt. Yingli's polycrystalline silicon solar cells, with an efficiency close to 20%, is manufactured with \$1.50 per peak watt, and a and the retail price of \$2 per peak watt. The cost and price is expected to decrease continuously in the years to come. (Recently, Yingli announced a selling price of polycrystalline silicon solar panels of less than \$1 per peak watt.)

According to statistics and analysis by Deutsch Bank, because of the combined effect of explosive expansion of solar cell production capability and the recession, in 2009, the price of solar cells on the international market dropped significantly. A brutal shake-up of the industry, suppliers of both pure silicon and solar cells, took place. After a brief period of oversupply, the price of solar cells will be reduced to a level where the cost of solar electricity will be comparable to electricity generated by, for example, coal-burning power stations, that is, will reaches *grid parity*; see Fig. 1.36. The pace of grid parity depends on the local situation and thus varies from place to place. For places with high electricity cost, such as Hawaii, Connecticut, California, and New York, especially those places with high insolation, grid parity will take place earlier. For areas with low electricity prices, for example, West Virginia and central-west China, especially places with low insolation, grid parity will be reached later. However, the trend that the cost of fossil fuel electricity will increase and the cost of solar electricity will decrease is inevitable. Solar electricity will gradually replace fossil fuel electricity.

Figure 1.37 shows the average annual growth rates of renewables from 2002 to

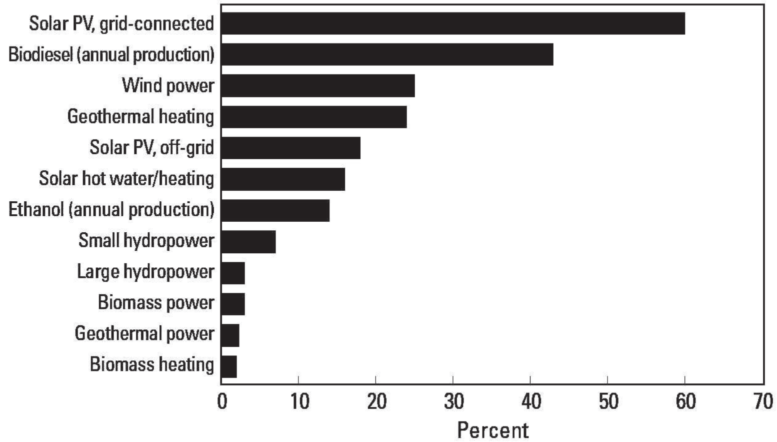

Figure 1.37 Average annual growth rates of renewables: 2002–2006. The average growth rate for grid-connected solar photovoltaics far exceeds other renewable energy capacities, even more for traditional energy resources. If in the future the rate of growth of photovoltaics can maintain 40%, in 20 years, or by 2030, solar photovoltaics will account for 50% of the energy supply and become the dominant energy source. *Source*: After *Renewables 2007 Global Status Report*, REN21 [1].

2006, as reported by REN21 [1]. As shown, the average growth rate for grid-connected solar photovoltaics, more than 60%, far exceeds other energy resources. In 2006, the percentage of solar photovoltaics was only a miserable 0.07%. However, if in the future the rate of growth of photovoltaics can maintain 40%, in 20 years, or by 2030, solar photovoltaics will supply more than 50% of the energy consumption.

Problems

1.1. In the United States, the British thermal unit (Btu) is defined as the energy to raise the temperature of one pound water by one degree Fahrenheit. Show that to a good approximation, 1 Btu equals 1 kJ.

1.2. Approximately (to $\pm 5\%$), how much energy is in one billion barrels of petroleum in gigajoules (GJ) and megawatt-hours (MWh)?

1.3. The area of New Mexico is 121,666 square miles. The average annual insolation (hours of equivalent full sunlight on a horizontal surface) is 2200 h. If one-half of the area of New Mexico is covered with solar panels of 10% efficiency, how much electricity can be generated per year? What percentage of US energy needs can be satisfied? (The total energy consumption of the United States in 2007 was 100 EJ).

1.4. The area of Tibet is 1,230,000 km^2. The average annual insolation (hours of equivalent full sunlight on a horizontal surface) is 3000 h. If one-half the area of Tibet is covered with solar panels of 10% efficiency, how much electricity per year can be generated? What percentage of the world's energy needs can be satisfied? (The total energy consumption of the world in 2007 was 500 EJ.)

1.5. A solar oven has a concentration mirror of 1 m^2 with a solar tracking mechanism. If the efficiency is 75%, on a sunny day, how long will it take to melt one kg of ice at 0°C at the same temperature? How long will it take to heat it to the boiling point? How long will it take to evaporate it at 100°C?

1.6. For wind speeds of 20, 30, 40, ..., up to 100 mph, calculate the wind power density (in watts per square meter).

1.7. The distance from the equator to the North Pole along the surface of Earth is 1.00×10^7 m. If the average solar radiation power density on Earth is one sun, how much energy is falling on Earth annually? If the annual energy consumption of the entire world in 2040 is 800 EJ, what percentage of solar energy is required to supply the world's energy need in 2040? (*Hint*: One day equals $24\times60\times60$=86,400 seconds.)

1.8. Using a solar photovoltaic field of 1 square mile (2.59 km^2) with efficiency of 15%, how many kilowatt-hours will this field generate annually at locations of average daily insolation (on flat ground) of 3 h (Alaska), 4 h (New York), 5 h (Georgia), and 6 h (Arizona)? An average household consumes 1000 kWh per month. How many households can this field support in the four states, respectively?