1

INTRODUCTION—WHY SOLAR ENERGY?

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1.1 THE ERA OF FOSSIL ENERGY

The Industrial Revolution that began with the invention of the steam engine in 1765 by James Watt reshaped the role of labor in human history. From the 18th to the 21st centuries, machines gradually replaced human labor and animal power. As a result, energy consumption due to the increased types and numbers of machines continues to grow, so fossil fuels, including coal, oil, and natural gas, have become the major supplies of energy. The growth of energy consumption became even more significant in the 20th century. From 1900 to 2000, energy consumption grew nearly 40 times and this trend will not stop in future decades.

As it became known that the use of fossil fuels would result in emission of carbon dioxide, gasoline engines that emitted less carbon dioxide became dominant in 20th century. Oil began to be used around 1900 and natural gas around 1950. The pollutant factors for electricity generation from coal, oil, and natural gases are 322.8, 258.5, and 178, respectively [1]. However, the emission of carbon dioxide continued to grow dramatically because of the huge demands for fossil energy in general. Natural gas has a pollutant factor about half that of coal but this reduction in carbon dioxide emission is still not significant enough. Therefore, although the recovery of the global economy was slow in 2010, emissions of carbon dioxide still reached the historical record of 30,600 million tons, whereas it was less than 15,000 million tons in 1970 [2, 3]. The United States and the OECD countries used to generate most of the carbon dioxide but China surpassed United States in the emission of carbon dioxide in 2007 [2]. Other non-OECD countries also generated more carbon dioxide than OECD countries after 2004 [2]. The fact that those newly developing countries consume even more fossil fu-

els than economically developed countries certainly worsens the emission of carbon dioxide.

1.1.1 Possible Depletion of Fossil Fuels

After centuries of consuming fossil fuels, people are now facing three major problems, although some controversies over the causes exist. First, some predict that reserves of petroleum will last for only 40 years and natural gases for only 60 years. Such a time span seems long for people who are over 40 years old but could become a serious issue for young people. In addition, there are two hidden problems in such a time span. First, mining technologies are becoming more difficult and challenging because some fossil fuels are buried deep in the ground. Mining cost will consequently increase. Second, as the foreseeable depletion of fossil energy approaches, countries will compete for the limited resources. Then large-scale wars might occur unless other huge resources of energy supplies become ready for use.

1.1.2 Global Warming

The second problem is global warming due to the emission of greenhouse gases such as carbon dioxide. According to a recent report from NASA [4], global temperature has obviously been increasing since 1980. As shown in Figure 1.1, the average temperature has increased 0.5–0.6 °C, compared to the average temperature between 1951 and 1980. The increase of temperature in the northern hemisphere is even worse for the past ten years: 0.5–2.5 °C. As indicated in Figure 1.2, the worst area is around the Arctic Ocean. The significant increase of global temperature has caused the disappearance of glaciers in many areas, such as North America, South America, Africa, Europe, and
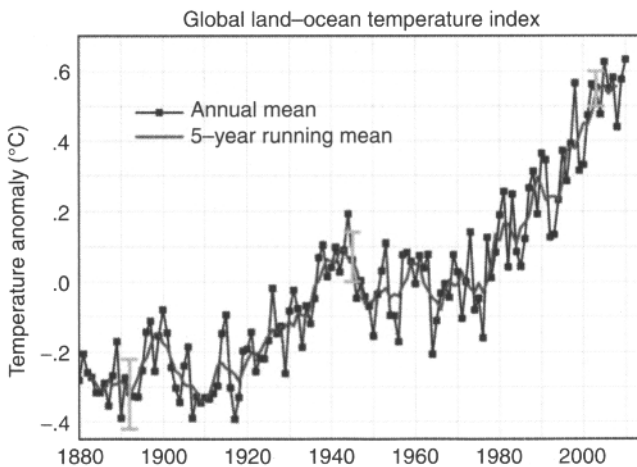
Figure 1.1. Relative variation of global temperature in recent decades [4].

Temperature anomaly (°C)

-2.5   -1.5   -0.5   0   +0.5   +1.5   +2.5
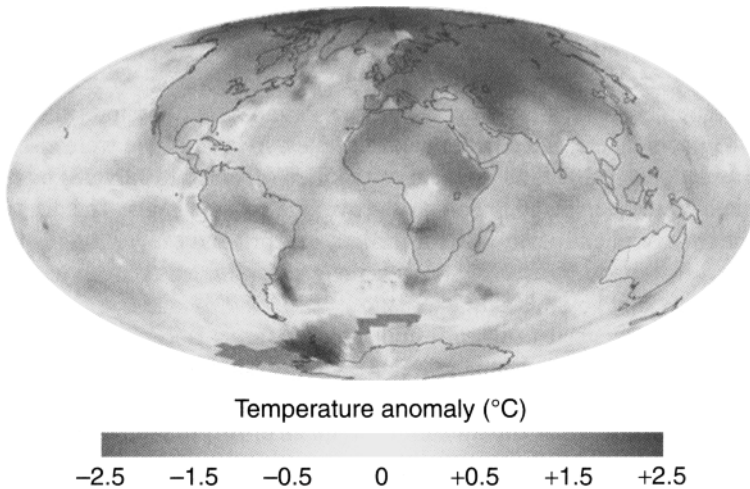
Figure 1.2. Geometrical distribution of temperature variation on earth [4].

Asia. For example, the area of the Tsho Rolpha Glacier Lake in Nepal increased from 0.23 km^2 before 1960 to 1.65 km^2 in 1997 because glacier ice melted and flowed into this lake. Also, Arctic Ocean ice has been decreasing at a rate of 9% per decade as the ice of frozen freshwater in glaciers on Greenland melts and dilutes the salinity of the Arctic Ocean, significantly influencing the conveyed ocean currents.

1.1.3 Dramatic Changes in Weather

Global warming has led to dramatic changes in weather. In Australia, record or near-record temperatures at the sea surface were recorded off the Queensland coast in late 2010. Then a series of floods hit Queensland, beginning in December 2010 and lasting until January 2011. The flood took over about three-quarters of the state and affected over 70 towns and 200,000 people. Thirty-five deaths were reported due to these floods. The state rainfall of 209.45 mm was the highest since 1900. Kevin Trenberth attributed the flood to a half-degree Celsius rise in ocean temperature around Australia as a result of global warming. [5] Thus, extra water vapor was produced and intensified the rainfall. Some scientists do not agree with this point of view, but such global debate cannot be verified by experiments in the laboratory [6]

Like Australia, Taiwan was also hit by a huge rainfall in summer 2008. The mountain area of south Taiwan experienced a record of about 3000 mm rainfall in just two days when the center of Typhoon Morakot landed in the north part of Taiwan. The huge amount of rainfall further caused a dramatic mudslide. An 80-meter layer of dirt and stone slid off the mountain and buried the entire Shiao-Lin Village in south Taiwan. More than 500 people were killed. From 2000 to 2010, Taiwan has experienced over four times the number of huge rainfalls that used to occur only once every 50 or 100 years.

Even the most powerful country, the United States, is not able to escape from the flood. In April and May 2011, the Mississippi River had catastrophic floods as two major storms gave rise to record levels of rainfall. The floods affected several states, including Missouri, Illinois, Kentucky, Tennessee, Arkansas, Mississippi, and Louisiana. At least 383 people were killed in these seven states. In 2011, there were also most destructive tornadoes. In 2011, 546 people were killed (counted to July 28) by tornadoes in the United States, compared to 564 deaths over the past ten years. The disasters were mainly due to several extremely large tornadoes in April and May. A huge and intense multiple-vortex tornado, rated EF5, badly damaged Joplin, Missouri in May 22. Over 100 people were killed by this single tornado.

It is still controversial to directly link the disastrous floods and tornadoes with global warming. The global change in weather cannot be experimentally verified in the laboratory but the coincidence between the temperature rise in the recent decade and recently detrimental weather should alert us to make efforts to reduce global warming. Therefore, replacing fossil fuels with other energy resources that do not emit greenhouse gases should be considered seriously.

1.2 RENEWABLE ENERGIES

Nuclear power had been thought of as a good alternative to replace fossil fuels. For example, Japan has 54 nuclear power plants that generate 30% of its electricity. In the beginning of 2011, Japan planned to build another 14 nuclear power plants by 2030 and hoped to have 50% of its electricity generated by nuclear power. Nevertheless, the earthquake on March 11, 2011 induced a giant tsunami that destroyed several Fukushima nuclear power reactors, causing nuclear pollutants to spread over a very large area. This disaster made Japan abandon its plans and stopped the operation of several other nuclear power plants. Other countries also reconsidered their plans to build new nuclear power plants and have given more thought to renewable energies that are more environmentally friendly.

The renewable energies include solar, hydropower, ocean wave, tide, biomass, wind, and geothermal energies. Although hydropower had been well developed and currently generates 15% of global electricity, it can only be built in regions that have large rivers with steady water streams. Not much more hydropower can be developed. On the other hand, among all other renewable energies, wind and solar are the two most developed technologies and have the potential to generate significant portions of electricity worldwide. The potential wind power is about 1.3×10^{12} kW globally, which is about 3000 times the power generated by fossil fuels and approximately 850 times global power consumption, 15–16 TW (1 TW = 1×10^{12} W). However, it has two major drawbacks: (1) wind power is not stable and (2) wind is strongly influenced by regional geography. The windy areas are not equally distributed on earth. Quite a few countries do not have sufficiently strong winds.

In addition to wind power, solar power could produce much more electricity than human beings need. The solar power that the earth receives every day is 174,000 TW, which is about 11,600 times human needs. In comparison with wind power, solar power has two

major advantages. First, sunlight is most intense in summer and around noon, when most electricity is needed. It well matches the daily activities of human beings. Second, the sun shines almost everywhere, and the area required to generate electricity for human needs from sunshine is small compared to the entire land area. As mentioned previously, the total power demand of human beings is 15–16 TW. Solar intensity is approximately 1 kW/m^2. With 15% efficiency of solar panels, a square meter will generate 150 W of power. Therefore, the area that is required to generate the total power needed by human beings is 16×10^{12} W/(150 W/m^2) = 1.07×10^{11} m^2 = 1.07×10^5 km^2. This area is only 0.0723% of the total land area on earth, which is 1.48×10^8 km^2. Take the United States as an example. The United States consumes about 20% of total global power, 3.2 TW, so it will need an area of 3.2×10^{12} W/(150 W/m^2) = 2.14×10^{10} m^2 = 2.14×10^4 km^2. This area is only 0.234% of the United States land area, which is about 9.16×10^6 km^2.

On the other hand, if solar cells can be used on the roof of a house, even with an efficiency of only 10%, a regular house with 100 m^2 of roof area will be able to generate 10 kW of power capability. For 3.5-hour equivalent daily sunlight, which is common in many areas, such a house will generate about 35 kWh of electricity each day and 1050 kWh every month. This is sufficient for a regular household with usual power consumption.

It looks as if solar energy is very promising and should be a good solution to the problems caused by the fossil energy. However, solar energy is still not popular. The reason will be discussed in the following section.

1.3 SOLAR ENERGY AND ECONOMY

Four aspects are important for solar cells: cost, efficiency, lifetime, and productivity, as illustrated in Figure 1.3. In the past, efficiency has been thought of as the key factor that indicates the advancement of solar cells. However, the cells that have the best efficiency may not be practical because of high production cost. Thus, cost is the core issue of solar cells. Solar energy has to be competitive with fossil energy in order to make the solar industry self-sustainable without government subsidies. On the other hand, the importance of efficiency cannot be ignored because it influences the cost. If the efficiency is doubled while other factors remain the same, the same area of land will generate twice the electricity. It means that the cost per watt is reduced by half.

As to the aspect of lifetime, its requirement depends on the applications. If the solar cells will be used for power plants, their lifetime is expected to be 20 years, or at least 10 years. With all other factors remaining the same, 20-year lifetime costs are almost half of the 10-year lifetime, including solar-cell cost and installation cost. Only the cost of land is not increased. If solar cells are used for consumer products, the lifetime can be lowered to much less than 10 years. For productivity, it is well known that mass production will reduce the cost significantly. For example, the cost of dynamic random access memory (DRAM) becomes one quarter as its production increases one order of magnitude. Therefore, the technology of solar cells has to be compatible with mass-production techniques for the cost and deployment of solar panels to be practical.
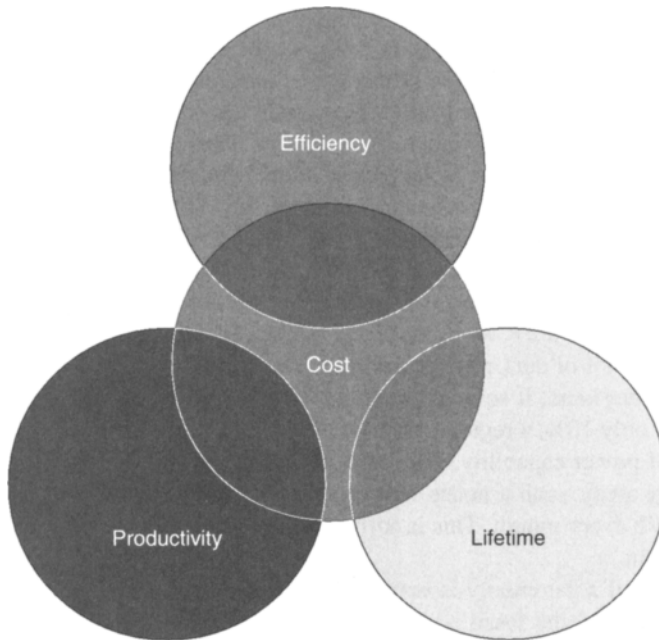
Figure 1.3. Four important aspects of solar cells.

1.3.1   Production Issue

Although the area for solar cells to generate all energy needs for human beings is only 0.0723% of the total area of earth's surface land, this area of 1.07×10^5 km^2 is still large compared to the area of integrated circuits (ICs). The IC industry produces ICs with an area of 10 km^2 per year. Therefore, if the solar panels are manufactured with IC technology, it will take 1.07×10^4 years. From the material point of view, the IC industry uses 7×10^6 kg of silicon. If silicon with a similar wafer thickness will be used for solar panels to generate all energy, the total amount will be 7.5×10^{10} kg. Even if the thickness is reduced to only one-third and the replacement of fossil energy with solar is only 20%, the total amount is still 5×10^9 kg. The large amount of material demand means that current means of material production will have to evolve very quickly or different solutions from the IC industry will be necessary to achieve the goal of using sunlight as one of the major energy supplies. Therefore, in the evaluation of solar technology, a very different scenario for the production volume has to be taken into account.

1.3.2   Types of Solar Cells

Solar energy had been applied as early as the seventh century B.C., but the photovoltaic effect was first recognized in 1839 by the French physicist A. E. Becquerel. The first solar cell was built much later. In 1883, Charles Fritts coated selenium with a very thin

layer of gold to form junctions and obtained about 1% of power conversion efficiency from sunlight to electricity. Only after Albert Einstein explained the photoelectric effect in 1905 were human beings able to gradually realize the working principle of power conversion from light to electricity. More progress was made after the modern photovoltaic cell was developed at Bell Laboratories in 1954. Since then, many types of solar cells have been developed, including single-crystalline Si solar cells, multicrystalline Si solar cells, single-junction III-V solar cells, multijunction III-V solar cells, and several types of thin-film solar cells.

The III-V single-junction and multijunction solar cells are made of III-V crystals, which are much more expensive than other materials. Thus, they are usually combined with concentrators, which are lenses to focus sunlight to a small spot. As a consequence, a large area of sunlight can be collected and concentrated to a III-V solar cell with a much smaller area, so much less III-V materials are required. The single-junction III-V solar cells with concentrated sunlight have efficiency of nearly 30%. Experimentally, the multijunction III-V solar cells with concentrated sunlight are able to convert 43.5% of sunlight to electricity [7]. In principle, the multijunction III-V solar cells can have power conversion efficiency of more than 60% [8], but the fabrication of solar cells with over three junctions is very difficult and is still under development.

The crystalline Si solar cells are the most used ones commercially. The best Si solar cell has a power conversion efficiency of 27.6% [9]. Because cost is the major concern, the commercial solar cells are mainly made of multicrystalline Si that is slightly cheaper than the single-crystalline Si. However, the cost of multicrystalline Si solar cells is still too high and cannot compete with fossil fuels for electricity generation. Government subsidies are necessary to keep this industry alive.

In comparison, thin-film solar cells that consume much less materials are considered to offer the hope of future development without the necessity of government subsidies. The thin-film solar cells include amorphous Si solar cells, nanocrystalline or microcrystalline Si solar cells, $Cu(In, Ga)Se_2$ (CIGS) solar cells, CdTe solar cells, dye-sensitized solar cells, organic solar cells, and organic–inorganic hybrid solar cells. As mentioned before, if solar cells will be used as a major energy supply, the total area required will be very large, so the production capability and material consumption have to be considered. Roll-to-roll production and ease of conveyance will be important issues for future production and deployment. From this point of view, those that can be fabricated with solution processes or under atmospheric pressure will have an advantage over those that need high-vacuum apparatus. From the material point of view, those that use abundant chemical elements will be more beneficial than those that use rare-earth chemical elements.

1.3.3 Cost Analysis—Grid Parity

To make solar electricity attractive, the first step is to make it comparable in price to what people pay to power companies, which varies among countries, from 3.05 US cents/kWh (Ukraine) to 42.89 US cents/kWh (Denmark). Table 1.1 lists the prices of grid electricity in many countries. Within each country, the price also varies depending

TABLE 1.1.   Prices of grid electricity in different countries

Country	Price, US cents/kWh
Argentina	5.74
Australia	18.55
Belgium	11.43
Canada	6.18
Denmark	42.89
France	19.25
Germany	30.66
Italy	37.23
Netherlands	34.70
Russia	9.49
Singapore	20.69
Spain	19.69
South Africa	17.10
Sweden	27.34
Taiwan	8.80
United Kingdom	18.59
Ukraine	3.05
United States	11.20

on the region and the amount of consumption. For example, the average price in the US is 11.2 US cents/kWh, but the highest price is 31.04 US cents/kWh in Hawaii and the lowest price is 7.31 US cents/kWh in North Dakota. Both New York and California have higher prices than the national average, 17.45 cents/kWh and 14.83 cents/kWh, respectively. Thus, each country or each state will vary in the degree to which the cost of solar electricity is comparable with the price of regular electricity.

In addition, the total amount of solar energy received in different regions also varies. For the same power output of solar panels, a region that has the equivalent of 6 hours of sunlight each day generates twice the electricity of a region that has 3 hours of sunlight each day. The following formula can be used to calculate the cost of solar electricity for grid parity, meaning that the cost is equal to the price of regular grid electricity:

$$\text{Cost of solar electricity } \$/\text{kWh} = \frac{\text{Cost of solar system }(\$/\text{Wp}) \times \text{Capacity of plant (W)}}{\text{Average daily electricity generated (kWh)} \times \text{lifetime of system (days)}}$$
$$= \frac{\text{Cost of solar system }(\$/\text{Wp})}{\text{lifetime of system (years)}} \times \frac{\text{Capacity of plant (W)}}{\text{Average daily electricity generated (kWh)} \times 365 \text{ (days)}}$$

$$(1\text{-}1)$$

From Eq. (1-1), the cost of solar electricity clearly depends on the average electricity generated. For example, the UK has only 800 kWh of solar energy annually per kW of solar plant, whereas Australia receives 1500 kWh of solar energy per kW.

Both countries have similar prices of grid electricity: 18.59 US cents/kWh for UK and 18.55 US cents/kWh for Australia. To make the cost of solar electricity have grid parity, that is, the cost of solar electricity equals the price of grid electricity, the cost of the solar system has to be as low as US$2.94/$W_p$ for UK, whereas it can be as high as US$5.56/$W_p$ for Australia, assuming that the solar system will be used for 20 years. This means that a high-price solar system can be more easily adapted by Australia than the UK. Figure 1.4 shows the relation of system cost to average price of grid electricity in different countries or regions; capital interests are not taken into account.

In this figure, the annual solar energy yield equals the effective hours of sunshine (1 kW/m^2) in one year times 1 kW of solar system power. If the annual solar energy yield is 1000 kWh/kW, the effective hours per year is 1000, so each day has 2.74 hours of average effective sunshine. For countries with low annual solar energy yield, the curve at constant system cost moves up, indicating that a lower system cost has to be achieved to make the price of solar electricity competitive with grid electricity. Most countries in Europe are located in the region of low annual solar energy yield.

From Figure 1.4, the cost of solar electricity ($/kWh) can also be obtained for a constant system cost according to the annual solar energy yield or the average effective hours of sunshine per day. For example, if the system cost is US$3.00/$W_p$ and is expected to be used for 20 years, the cost of solar electricity is US$0.1644/kWh if the average effective sunshine is 2.5 hours per day and reduces to US$0.0685/kWh for 6 hours of average effective sunshine per day. Table 1.2 shows the relation between the cost of solar electricity and the effective hours of sunshine per day.
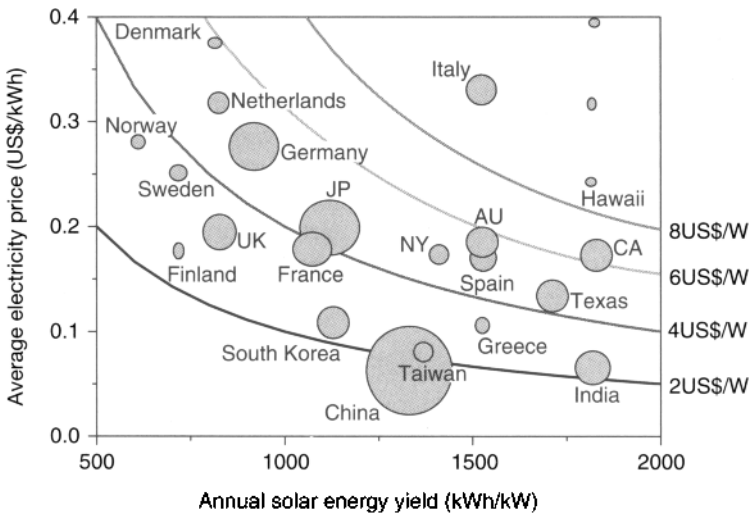
Figure 1.4. Relation of system cost with the average price of grid electricity (modified from [10]).

TABLE 1.2.   Cost of solar electricity versus effective hours
of sunshine per day for system cost of US$3.00/Wp used for
20 years

Effective hours of sunshine per day (hours)	Cost of solar electricity (US$)
2.5	0.1644
3.0	0.1370
3.5	0.1174
4.0	0.1027
4.5	0.0913
5.0	0.0822
6.0	0.0685

1.3.4   Cost Analysis—Breakdown of System Cost

The cost of a solar system includes the raw material, wafer formation, cell fabrication, lamination of modules, electrical accessories, and the balance of the system. Here we take crystalline-Si solar cells as an example for evaluation, which can be easily compared with other types of solar cells. The cost of raw materials for Si is typically no lower than US$25.0/kg. With 180 μm of the wafer thickness and 130 μm thickness of cutting loss, each wafer will consume 310-μm-thick material. Then the material cost converts to US$34.6/$m^2$. Wafer formation is US$0.70/piece of 6-inch wafer, which converts to US$30.0/$m^2$. Cell fabrication is about US$0.80/piece of 6-inch wafer, equivalent to US$34.7/$m^2$. The cost of lamination for modules is approximately US$70.0/$m^2$. Therefore, the above costs add up to give the overall module cost of US$169.3/$m^2$, named cost I here.

The electrical accessories include the inverter, mounting cable, meter, and transformer, which add up to give about US$1.0/$W_p$, named cost II. The balance of the system consists of labor cost, EPC (engineering, procurement, and construction) cost, fencing, and land cost, which sums to US$50/$m^2$ approximately, named cost III. Cost I and cost III are given in units of USD/m^2. They depend on the efficiency after being converted to USD/W_p. For efficiency of η, each square meter will generate p W of power if the intensity of sunlight is 1 kW/m^2, where $p = 1000$ W $\times \eta \times 100\%$. The final cost in units of USD/W_p is hence given by

$$(\text{cost I} + \text{cost III})/p + \text{cost II} (= 1.0) \qquad (1\text{-}2)$$

If the module efficiency is 16%, each square meter will generate 160 W of power, so the total cost in units of USD/W_p will be (cost I + cost III)/160 + 1.0 = 2.37. Table 1-3 lists the total cost of solar system in units of USD/W_p at different module efficiencies for crystalline-Si solar cells.

For other types of solar cells, cost I could be significantly different. For example, the module cost of the amorphous-Si (a-Si) solar cells is expected to be no more than

TABLE 1.3.   Cost of solar system at different module
efficiencies for crystalline-Si solar cells

| Efficiency (%)	Cost of solar system (US$/$W_p$)
10	3.19
11	2.99
12	2.83
13	2.69
14	2.57
15	2.46
16	2.37
20	2.10

US$65/m^2. Then the cost of the solar system could be further reduced. With 12% efficiency of the a-Si solar-cell module, (cost I + cost III)/p + 1.0 = 1.958, and the cost of solar systems will be less than US$2.00/$W_p$. For printed solar cells such as organic or organic–inorganic hybrid solar cells, cost I will be further reduced because much lower material and equipment costs are expected, less than US$35.0/m^2. If the solar-cell module has 10% efficiency, (cost I + cost III)/p + cost II = 1.85. Thus, the cost of the solar system is expected to be less than US$1.85/$W_p$. According to Figure 1.4, this cost will make the solar electricity cheaper than the grid electricity in most countries.

In addition to cost I, cost II should be expected to further decrease as mass production of the inverters, mounting cables, meters, and transformers is achieved and cheaper ways of fabrication are invented. Probably, only cost III will not change much with time.

1.3.5   Forecast and Practical Trends

Solar-cell development is actually progressing faster than had been forecast. Before 2007, most people agreed with the prediction of McKinsey & Company that solar electricity in Japan would have the same price as grid electricity in 2020 [10]. However, the progress has moved ahead by about 5–10 years. Now, more people believe that the goal, predicted by Fuji Keizai, for the price of solar electricity to be comparable to the grid price can be achieved by 2015 [11]. Figure 1.5 shows that the price of a solar-cell module dropped significantly during 2006–2010, so the original prediction has changed. The movement is 5–10 years ahead of the prior forecast. CdTe, CIGS, a-Si, and multicrystalline Si solar cells all have their module prices falling very fast. Organic and organic–inorganic hybrid solar cells are not included in Figure 1.5, but their module price is expected to be lower than US$0.35/$W_p$ in the future.

Grid parity can be achieved first in areas that have abundant sunshine and high prices of grid electricity, such as California and Hawaii. Grid parity has been reached in Hawaii because of the high price of grid electricity. The United States had set 2015 as the year for grid parity [12, 13]. The Chief Engineer of General Electric also predict-
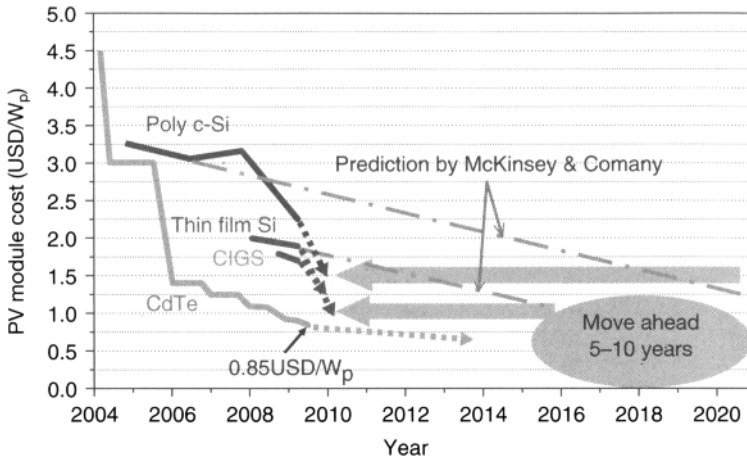
Figure 1.5. Cost of solar cells is decreasing faster than predicted. The progress has moved ahead by 5–10 years. The figure shows the trend of the fabrication cost of PV modules. CdTe solar cells defeated others by 2009, due to their low cost [11].

ed grid parity without government subsidies in sunny regions of the United States by 2015 approximately, as shown in Figure 1.6. Because the cost of solar electricity decreases very fast, while the price of grid electricity gradually increases, both values will meet around 2015 to give grid parity [14]. In brief, the progress of solar energy is moving forward at a fast pace. We should be optimistic about the replacement of fossil energy by solar energy in the near future.

1.4 MOVE TOWARD THIN-FILM SOLAR CELLS

From the above analysis, we know that the cost of crystalline-Si solar cells is higher than that of thin-film solar cells. The main reason is that the material consumption of crystalline-Si solar cells is large. Many types of thin-film solar cells have been developed. They can be categorized into two areas: inorganic semiconductor and organic ones.

1.4.1 Inorganic Versus Organic

The inorganic thin-film solar cells include the most popular a-Si solar cells, nanocrystalline or microcrystalline Si solar cells, and other compound semiconductor thin-film solar cells that combine several chemical elements, such as group I elements (Cu, Ag, Au), group III elements (Al, Ga, In), and group VI elements (S, Se, Te). Recently, CdTe thin-film solar cells have also proved to exhibit high efficiency and low-cost production. No matter how many chemical elements are involved in the inorganic semiconductor solar cells, a p–n junction is usually required. Their working principles will
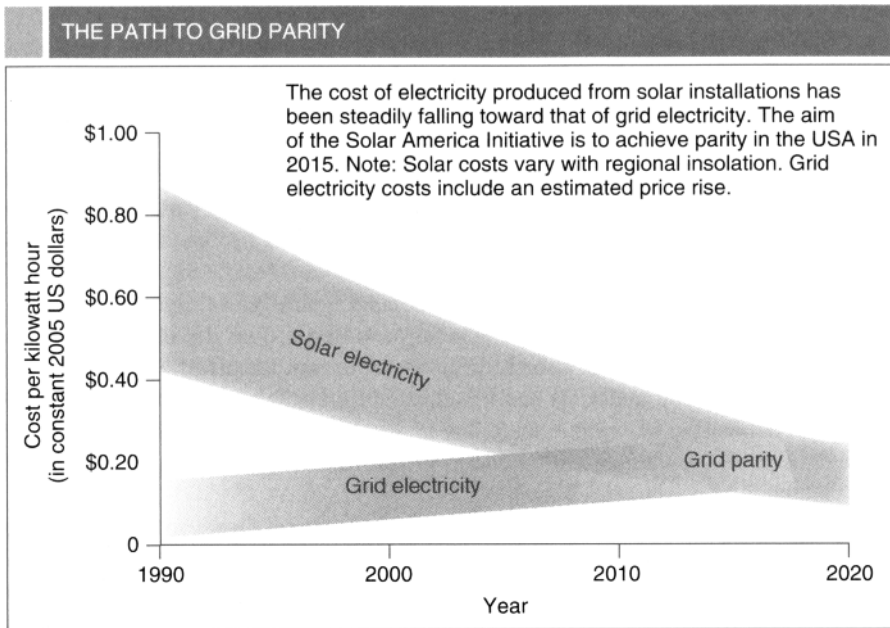
Figure 1.6. Cost of solar electricity will decrease rapidly and the price of grid electricity will gradually increase. Both values will meet around 2015 to achieve grid parity [14].

be described in later chapters. Briefly, the semiconductor thin-film solar cells operate similarly to the crystalline-Si solar cells except that materials with direct-bandgap properties are usually chosen because direct-bandgap materials have a larger absorption coefficient than indirect-bandgap ones like Si. However, the thin-film semiconductors are usually not single crystals. Many grain boundaries and voids are formed, leading to significant defects and surface states, so there are lots of recombination centers to reduce the extraction of carriers to external electrodes. It is always a challenging task to reduce the grain boundaries and voids.

Most of the thin-film semiconductors are deposited in vacuum chambers. In particular, the commercial modules of thin-film semiconductor solar cells are fabricated with entire large panels placed in vacuum chambers, which are thus very large. Solution processes with printing capability are also under development for easy fabrication and possibility of roll-to-roll production. Currently, CIGS thin-film solar cells and CdTe thin-film solar cells have attracted significant attention due to their high efficiencies and low costs. However, they will face the challenge of material supply as the solar power exceeds 100 GW [15]. Both In and Te are rare-earth elements. Shortages will develop as their demand continues to grow.

The organic solar cells are mainly divided into two types: dye-sensitized solar cells (DSSCs) and conventional organic solar cells. The dye-sensitized solar cells have proved to exhibit high efficiency (more than 10%) and low-cost production. In particu-

lar, they work in low-light conditions, so they are very suitable for cloudy weather. Unfortunately, the DSSCs have three major drawbacks. First, they use liquid electrolytes, which have temperature stability problems. In particular, when the temperature drops to 0°C, the liquid electrolyte freezes and becomes solid-state. Then the cell does not work and the expansion of solid-state electrolyte could cause damage to the cell. Second, the electrolyte contains iodine, which is toxic, so the cell has to be carefully sealed, leading to increased cost. Third, the most efficient DSSC uses a dye that contains ruthenium (Ru), a rare-earth element. When solar cells become the major supply of electricity, shortages of Ru will develop.

In comparison, conventional organic solar cells typically use organic materials in the light-absorption layer. They have several advantages over the inorganic ones or DSSCs: (1) they can be mostly made from the abundant chemical elements, (2) the bandgap of the organic materials can be adjusted by changing the chemical formula, and (3) the deposition of organic materials is usually done by a solution process and can be done in air, so the fabrication cost is lower. Roll-to-roll fabrication is deemed a great advantage of organic devices.

On the other hand, organic solar cells also have several disadvantages: (1) the organic semiconductors have low mobility, so most of organic materials with a film thickness more than 100 nm may lead to high series resistance, significantly decreasing the device performance; (2) organic semiconductors have a short exciton-diffusion distance, so complicated nanomorphology is required to assure efficient separation of electrons and holes, making the processing conditions very stringent and challenging; (3) organic materials usually degrade rapidly in air, so rigorous encapsulation is required, which may give rise to additional cost.

According to the above discussion, both inorganic semiconductor thin-film solar cells and organic solar cells have their own advantages and disadvantages. It would be great if both advantages could be utilized simultaneously while avoiding the disadvantages. Therefore, this book will particularly address the organic-inorganic hybrid solar cells.

With the combination of organic and inorganic semiconductors, the hybrid solar cells are expected to have the following major benefits: (1) improved stability, much better than organic solar cells; (2) solution process or good flexibility, so future development of roll-to-roll production can be easily adapted; (3) good conduction paths for collected carriers; (4) both organic and inorganic materials could be used for light absorption, increasing the choice of materials for light harvesting.

1.4.2   More Possible Applications

In the discussion in Section 1.3, we mainly focused on the possibility of replacing fossil energy with the solar energy from the viewpoint of power plants. However, there are also applications of solar cells that are not directly used in power plants. A few possibilities are listed below:

1. Consumer products such as calculators, watches, toys, cell-phone chargers, and notebook chargers

2. Power systems for remote villages and rural electrification
3. Telecommunications in remote areas and remote monitoring systems
4. Remote lighting lamps for houses
5. Electric fences
6. Water pumping powered by solar cells
7. Power systems for fish ponds
8. Emergency power systems
9. Portable power supplies for camping
10. Satellites and space vehicles

The above listed are niche applications that do not need very cheap solar cells. As the cost becomes very low, more applications will emerge. For example, one possible application is to place the solar panels on the outside wall of a building, like tile decoration. The entire wall area could be easily over 100 m^2. Even if the efficiency is only 3%, the overall power generated could be around 3 kW, which will give about 10 kWh of energy each day and 300 kWh each month. Another example could be use as a curtain or wallpaper if the solar cells are flexible. The overall area could also be easily more than 100 m^2. Then, even with low efficiency, probably over 10% of household electricity could be generated in this way. The key points are low cost and easy installation, so people would put up the solar cells like a curtain or wallpaper. If a city has 100,000 homes and offices generating solar electricity in this way, there will be 300 MW of solar power, which is equivalent to the power from a power plant. Therefore, a city that used to consume lots of energy could become a plant generating environmentally friendly power. Here we only consider 3% efficiency. When solar cells of higher efficiency and lower cost are developed, the generated power will be even more significant.

1.5 OUTLINE OF THIS BOOK

After the introduction in this chapter, Chapter 2, entitled "Light and Its Interaction with Matter," will discuss light properties and its interaction with materials. The different aspects of light will be introduced—rays, waves, and particles—followed by the physics of black-body radiation and the characteristics of solar light. Then the basic physics of light–matter interaction is described and discussed in detail, including reflection, transmission, dispersion, anisotropy, scattering, nonlinear optics, and light absorption. The theoretical derivation of some phenomena will also be given.

In Chapter 3, "Inorganic Materials," the properties of inorganic materials are introduced. The focus will be on semiconductors which are the most common materials for inorganic solar cells. The physics of band gap, conduction band and valence band, p-type semiconductors, n-type semiconductors, the formation of the p-n junction, carrier diffusion and drift, and light absorption in semiconductors will be discussed.

In Chapter 4, "Organic Materials," we will discuss the formation of small organic molecules as well as large molecules and how their chemical structures are related to

their physical properties, with emphasis on the electrical and optical properties of the organic materials.

In Chapter 5, "Interface between Organic and Inorganic Materials," some issues in combining organic and inorganic materials are discussed, including compatibility of deposition, adhesion problems, formation of surface states, and band-level realignment.

Once the basic knowledge of inorganic semiconductors and organic semiconductors as well as their interface is established, we are ready to examine the device characteristics. Therefore, Chapter 6 will start with a discussion of inorganic semiconductor solar cells. Inorganic semiconductor solar cells are the most common devices used commercially nowadays. Therefore, this chapter will introduce the functioning principles of those solar cells and also provide the basic knowledge for comparison with organic solar cells and organic–inorganic hybrid solar cells. The reasons for their high production cost will also be addressed, so readers can realize why the future trend will shift toward organic solar cells and organic-inorganic hybrid, thin-film solar cells.

Chapter 7 will address organic solar cells. The driving force for the organic solar cell is the prospect of having very low cost solar cells ($<US\$0.5/W_p$) due to the use of less materials compared to silicon solar cells (submicron thickness versus 100 micron thickness) and the ease of using low energy consumption fabrication processes such as printing and dip coating. At present, there are four kinds of organic solar cells under development: (1) dye-sensitized, (2) organic–molecule, (3) polymer–fullerene, and (4) polymer–semiconductor nanoparticle. The principle and performance of each type of organic solar cell is not the same and will be discussed in detail in this chapter.

With knowledge of both inorganic and organic solar cells, we are now prepared to explore the organic–inorganic hybrid solar cells, which are described in Chapter 8. The fundamental concepts of forming organic–inorganic hybrid solar cells will first be introduced. Then focus will be brought to the solution-processed sandwiched structure, in which the organic layer is protected by two inorganic oxide layers. The technique to overcome deposition difficulty of the inorganic layer on the organic layer using the solution process will be addressed. Detailed investigation of the deposited oxides will be provided. Device characterization and performance of such thin-film solar cells will be described. In addition to using organic materials for light absorption and inorganic materials for carrier transportation, an alternative to using inorganic semiconductors as the light-absorption materials and organic polymers as the carrier–transportation layer will be discussed.

Finally, Chapter 9 will discuss how the future technology of solar cells will be developed and what can be expected of electricity generation from solar cells in the future.

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EXERCISES

1. What problems did fossil fuels bring about after the Industrial Revolution?

2. What event caused Japan to give up the plan of building future nuclear power plants?

3. How much power does the earth receive from the sun each day? How much power do human beings consume each day?

4. To supply the overall power demand of United States, how much area of the land is required? (Assume that the United States consumes one-fifth of the total power

worldwide and that solar cells have 15% efficiency. The intensity of sunlight is considered to be 1 kW/m^2.)

5. List the types of solar cells that you know of.

6. What issues are important for solar cells?

7. How does efficiency influence the cost of solar cells?

8. How does lifetime influence the cost of solar cells?

9. List the costs of crystalline-Si solar cells.

10. What cost will be the same for most types of solar cells when they are used in a solar power plant?

11. What is grid parity?

12. To have grid parity in California, what is the cost of a solar system?

13. Compare Italy and Netherlands. Which country will more possibly use solar electricity? Why? (Provide scientific data.)

14. In a country with 5 effective hours of sunshine per day, what is the cost of solar electricity (in US$/kWh) if this country establishes a power plant costing US$4.00/W$_p$?

15. What are the advantages and disadvantages of inorganic solar cells?

16. What are the advantages and disadvantages of organic solar cells?

17. What are the major drawbacks of dye-sensitized solar cells?

18. What benefits are expected from hybrid solar cells?

19. Write down all the possible applications of solar cells that you can imagine.

20. For small projects: (1) estimate the area required to supply 50% of power consumption from solar-cell power plants in your country; (2) evaluate the cost of solar systems in your country to achieve grid parity, in the units of US$/W$_p$; (3) estimate how many years are required to achieve grid parity in your country or your state/province.

21. Explain why solar energy will be needed or not needed.