SOLAR CELLS
From Basics to Advanced Systems

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SOLAR CELLS

From Basics to Advanced Systems

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Part 2 Concentrators and Complete Photovoltaic Systems

PREFACE

This book began as a set of notes for two University Extension courses presented by the authors for heterogeneous groups that included college teachers and students, solar cell researchers, utility company engineers, government agency staff, a lawyer, investment counselors, and two people interested in installing a solar cell system in their Nevada ranch house. Success of the courses with such a diverse audience suggested making the material available, considerably reworked and augmented, in book form.

This book is intended both as a self-learning resource or professional reference and as a text for use in an undergraduate or first-year graduate course. A key feature of the book is modular organization. The twelve chapters, each containing problems and a reference list, may be read in almost any order, though they are grouped in three parts in order of increasing depth and complexity. The three parts discuss fundamentals, complete systems, and possibilities for improvements, respectively.

In Part One, Solar Cell Fundamentals, Chapter 1 gives an overview of photovoltaic power generation and its appeals. After the nature and the geographical distribution of sunlight is examined in Chapter 2, principles of operation of solar cells are developed in Chapter 3, starting from a discussion of the properties of semiconductors. For this the reader needs no more background than introductory college courses in mathematics and physics, although additional knowledge of semiconductors will be helpful. Chapter 4 concludes Part One with an examination of the materials and processing methods used in making conventional *pn*-junction cells.

Concentrators and Complete Photovoltaic Systems are the subject of Part Two. Concentrators (Chapter 5) and power conditioning and energy storage equipment (Chapter 6) may be used with solar cells for increased efficiency, convenience, and reduced cost. Examples of solar cell applications are given in Chapter 7, and the economics of photovoltaic electricity are discussed in Chapter 8.

Imaginative new approaches for further reducing the cost of solar cells are discussed in Part Three, Solar Cell Improvements. Chapter 9 describes new techniques for manufacturing semiconductors, and Chapter 10 examines thin-film approaches. Novel cell structures and unconventional cell systems are summarized in Chapters 11 and 12, respectively.

In addition, nine appendixes provide such information as an annotated bibliography, a list of solar cell suppliers, and a compilation of operational photovoltaic systems and their key design features. There is a table of recent laboratory cell efficiencies arranged by cell material and design. Several solar cell experiments that can be done with simple laboratory equipment are described in one appendix. Some readers may find useful the list of abbreviations and acronyms, and the discussion of computer simulations of solar cells and photovoltaic systems.

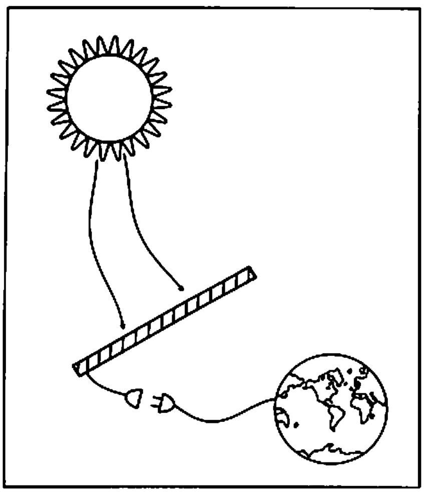
Perhaps no book can claim completeness in the coverage of a topic so interdisciplinary and fast-advancing; ours certainly does not. We have tried to stimulate thinking in addition to giving information, and hope to provide a foundation and framework upon which the reader can build further.

While writing this book, we have enjoyed the support and counsel of many friends whom we wish to acknowledge. Alex Kugushev of Lifetime Learning Publications suggested to us the idea of writing the book. Professor Ned Birdsall and many other colleagues urged us on. Joan Stern was the able editor. Bettye Fuller typed the manuscript. Finally, our families' support was invaluable.

Chenming Hu
Richard M. White

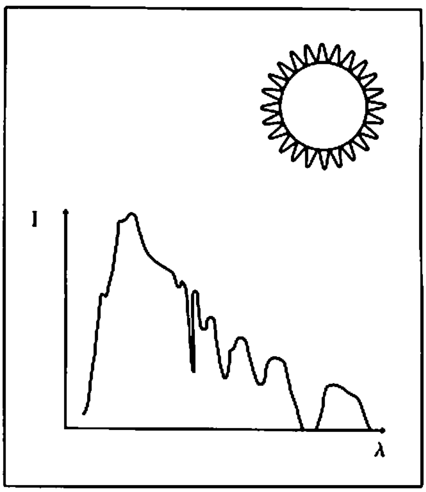
CHAPTER ONE
OVERVIEW

Components of a solar cell system, types of cells that exist or are proposed, and global power needs



CHAPTER TWO
NATURE AND AVAILABILITY OF SOLAR ENERGY

Characteristics of solar energy and ways of estimating, measuring, and collecting it

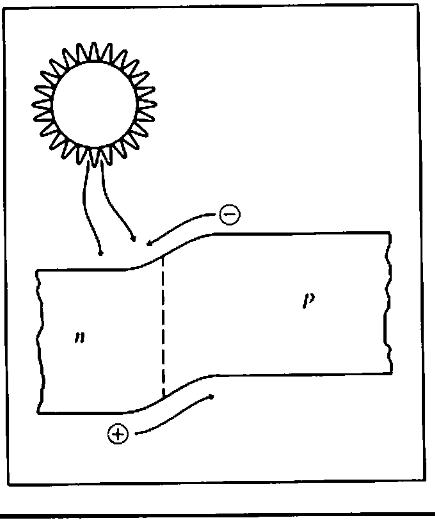


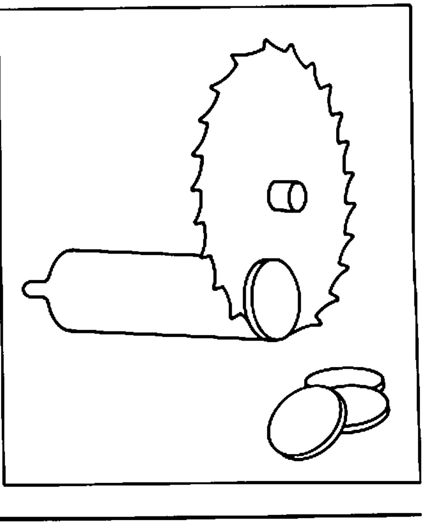
PART ONE

SOLAR CELL FUNDAMENTALS

CHAPTER THREE
PRINCIPLES OF SOLAR CELL OPERATION
Nature of semiconductors and the theory and efficiencies of solar cells

CHAPTER FOUR
SOLAR CELL MATERIALS AND PROCESSING
Making of conventional cells with wafers cut from single-crystal ingots



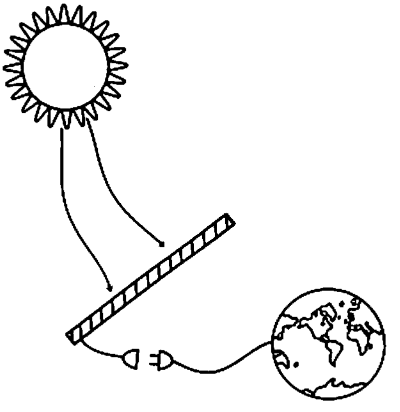


CHAPTER

ONE

OVERVIEW

CHAPTER OUTLINE



Solar cells are devices in which sunlight releases electric charges so they can move freely in a semiconductor and ultimately flow through an electric load, such as a light bulb or a motor. The phenomenon of producing voltages and currents in this way is known as the *photovoltaic* effect.

The fuel for solar cells—sunlight—is free and abundant. The intensity of sunlight at the surface of the earth is at most about one thousand watts per square meter. Thus the area occupied by the cells in a photovoltaic power system may be relatively large, and its cost must be considered in calculating the cost of the electricity produced. The primary factor that determines whether solar cells will be used to supply electricity in a given situation is the cost per unit output, relative to that of alternative power sources, of acquiring, installing, and operating the photovoltaic system.

Solar cells are already being used in terrestrial applications where they are economically competitive with alternative sources. Examples are powering communications equipment, pumps, and refrigerators located far from existing power lines. It is expected that the markets for solar cells will expand rapidly as the cost of power from conventional sources rises, and as the cost of solar cells falls because of technological improvements and the economies of large-scale manufacture. The first of these economic forces—the rising price of conventional sources, particularly those employing fossil fuels—continues automatically, in part because the resource is limited. The second—reducing the cost of electricity from solar cell systems—is the

HOW MUCH OIL?

It is sometimes argued that our energy problems would disappear if we just looked harder for oil. The inherent fallacy of this argument can be shown by the following example.

Suppose that geologists have been mistaken about our oil reserves, and have grossly underestimated the amount of oil that is in the earth. In fact, suppose that the earth consists *entirely* of oil, except for a thin solid shell on which we live.

The radius of the earth is 6.4×10^6 meters, and the volume of oil consumed worldwide in the year 1970 was 1.67×10^{10} barrels. You can show from these figures that if we continued to consume oil at that rate each year, the oil would last a comfortable 4.1×10^{11} years. But if consumption increased each year by 7 percent, as it did from 1890 to 1970, then the earthful of oil would be drained in only 344 years.

This example (Barnett, 1978) shows the devastating effect of an exponentially growing rate of consumption. For the record, the oil that is believed to be in the earth now will be used up in only a few decades if our present rate of consumption continues.

subject of worldwide research and development efforts today. To increase the economic attractiveness of the solar cell option, one or more of the following must be done:

- Increase cell efficiencies.
- Reduce cost of producing cells, modules, and associated equipment, and the cost of installing them.
- Devise new cell or system designs for lower total cost per unit power output.

1.1 HOW SOLAR CELL SYSTEMS WORK

The most important physical phenomena employed in all solar cells are illustrated schematically in Fig. 1.1. Sunlight enters the semiconductor and produces an electron and a hole—a negatively charged particle and a positively charged particle, both free to move. These particles diffuse through the semiconductor and ultimately encounter an energy barrier that permits charged particles of one sign to pass but reflects those of the other sign. Thus the positive charges are collected at the upper contact in Fig. 1.1, and the negative charges at the lower contact. The electric currents caused by this charge collection flow through metal wires to the electric load shown at the right side of Fig. 1.1.

The current from the cell may pass directly through the load, or it may be changed first by the power-conditioning equipment to alternating current at voltage and current levels different from those provided by the cell. Other sub-systems that may also be used include energy-storage devices such as batteries, and concentrating lenses or mirrors that focus the sunlight onto a

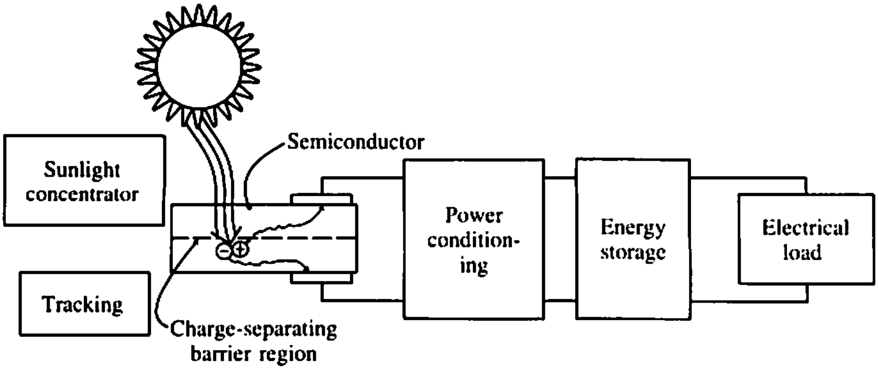


Figure 1.1 Sketch showing functional elements of solar cell system.

smaller and hence less costly semiconductor cell. If concentration is employed, a tracking subsystem may be required to keep the array pointed at the sun throughout the day.

1.2 TYPES OF CELLS

A glance at the recent literature (see "Annotated Bibliography," Appendix 1) shows that many different solar cell designs and materials are being studied. This situation is common in the early stages of a technical development, when many different approaches are explored. Incidentally, *terrestrial* use of cells to produce power is quite recent, even though the photovoltaic effect has been known since 1839. Silicon solar cells were first described in print in 1954, and solar cells have been used on most of the spacecraft launched since then. Cells for use in space are not discussed in this book because the hostile conditions those cells must withstand, together with the extreme reliability demanded, make the space cells far too costly and specialized for terrestrial use.

Although the details involve concepts of solid-state physics, chemistry, and materials science, some very simple observations underlie the different types of solar cells:

- Because silicon has been used so extensively for integrated circuits, its technology is well developed and it is a natural choice for use in solar cells now, while other approaches are being developed.
- Making thin-film or polycrystalline cells instead of single-crystal cells, which require extensive heating and careful crystal growth and slicing, may be economical in terms of both monetary cost and energy expended in the production process.
- Since focusing lenses and mirrors cost much less per unit area than do most semiconductors, it can be cost-effective to use "concentrator" systems in which sunlight is focused onto relatively small semiconductor cells.
- Since cells can be designed to work particularly well with light of one wavelength, it may be economical to split the spectrum and direct different portions onto cells optimized for those spectral components ("split spectrum" or "multicolor" cells).
- Since both available sunlight and the demand for energy fluctuate, cells providing inherent energy storage by electrolysis within the cell may be attractive ("photoelectrochemical" cells).

The cell types shown in Fig. 1.2 are arranged according to material and form of the semiconductor used and the degree of sunlight concentration employed. Some characteristics of the starting material or cell design are also indicated.

The cells produced in greatest quantity have been made of single-crystal

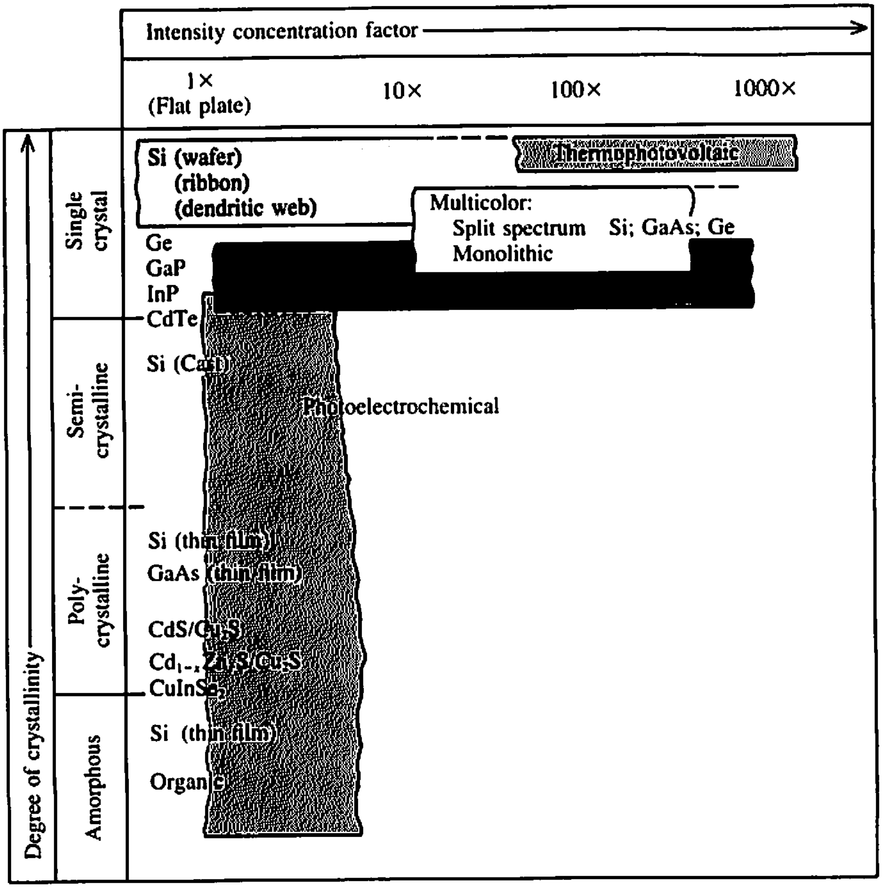


Figure 1.2 Types of solar cells, arranged according to degree of crystallinity of the semiconductor and degree of sunlight concentration used, if any. Single-crystal silicon and gallium arsenide, and thin-film CdS/Cu_2S cells are discussed in Part I of this book, while the other cell types and materials are discussed in Part III.

silicon, and used without sunlight concentration (upper left corner, Fig. 1.2). Silicon cells have been made of wafers sawed from large single-crystal ingots, and from thin ribbons or thin webs of silicon that do not require slicing. Of the many other single-crystal cell materials that have been studied, the compound semiconductor gallium arsenide has been most used in experiments because of its high efficiency and its ability to operate at high temperatures. Concentrator cell systems have been made with both silicon and gallium arsenide. Concentrator cell configurations differ from those for nonconcentrator use ("flat-plate" cells); concentrator cells must withstand higher temperatures and must have lower resistive losses because of their relatively higher cell currents. Since the split-spectrum cells involve several cells, one expects that to achieve low system cost such cells will be used initially with concentrating lenses or mirrors. Another concentrator cell involving spectral alteration in the interest of high efficiency is the "thermophotovoltaic" cell, which is illuminated by relatively long wavelength radiation from a plate heated by concentrated sunlight.

Most cells employ so-called *pn* junctions, that is, two adjacent regions of a semiconductor such as silicon that contain different impurities within them so they have different electrical characteristics. An alternative structure is the Schottky-barrier cell, in which a thin, fairly transparent metal film replaces one of the semiconductor regions of the *pn*-junction cell. Another promising cell design contains in addition a very thin insulating region between the metal and the semiconductor, forming the "metal-insulator-semiconductor" (MIS) or "metal-oxide-semiconductor" (MOS) structure.

Polycrystalline cells generally have lower production and material costs than do conventionally made single-crystal cells. Alternatives to the conventional methods of making single-crystal ingots have been developed, as will be discussed in Chap. 9. These include the edge-defined film-fed growth (EFG) and dendritic web cells. Thin-film cells, in which a semiconducting film is deposited on a substrate, include commercial cadmium sulfide cells, which actually have a *pn* junction between layers of cadmium sulfide and copper sulfide, and cells made of thin films of amorphous semiconductors. Experimental cells made from organic constituents are also under investigation. Studies predict that it will be possible to make thin-film cells that are efficient and inexpensive enough to become the cells of choice for many terrestrial applications.

1.3 HOW MUCH POWER, AND WHEN?

When one considers that the power rating of a modern central electricity-generating plant is typically 1000 megawatts, the present annual world production of solar cells of only a few megawatts seems very small indeed. (A *megawatt* is one million watts.) What reasons are there to think that solar cells may be important components in the world energy picture of the next few decades?

First, one must not judge significance solely on the basis of total power output. Even a 100-watt solar cell power supply in any one of the several million small villages in the world could be of enormous importance to the villagers, for whom it would provide power for water pumping, refrigeration, and communication with the surrounding world. Second, photovoltaic power generation is relatively free from the problems facing fossil-fueled or nuclear power plants—escalating fuel costs, disposal of wastes, disposal of heat, major concerns over safety, and potential modification of weather due to release of carbon dioxide. Third, photovoltaic systems are modular and can be installed near points of use and put on line quickly as the demand for electricity rises. These inherent advantages, plus the experience and expectations of a steady reduction in solar cell system cost, lead to the prediction that solar cell systems can make a significant contribution to the world energy supply.

Figure 1.3 summarizes energy supply and utilization in the United States in 1978. The unit standing for usage is the "quad," for quadrillion or 10^{15} Btu (British thermal units), a very large amount of energy. Several details are worth observing on this "spaghetti" diagram. In 1978, 54 percent of the energy was wasted, as can be seen by comparing the two energy amounts at the extreme right side of Fig. 1.3. Electricity production consumed 28 percent of the total energy input, and the production of electricity was on the average only about 33 percent efficient. The average rate of consumption of electrical energy in the United States in 1978 was about 260 GW (1 GW = 1 gigawatt = 10^9 watts, where 1 watt = 1 joule per second) and the total world rate of consumption of electrical energy was about three times the figure for the United States.

Predicting is always uncertain, but current U.S. government predictions say that when the cost of power from photovoltaic systems drops to \$1.60 to \$2.20/W_{pk} for residential consumers, the annual U.S. market will be 3 to 10 GW_{pk}, and the electric utility market for photovoltaic power will range from 10 to 20 GW_{pk} per year. (The symbol \$/W_{pk} in this book means the cost in 1980 U.S. dollars of acquiring a solar cell array that produces 1 watt of peak electrical power when illuminated with sunlight at an intensity of 1 kilowatt per square meter. Because the sunlight intensity varies through the day, the peak output of a cell is, of course, greater than the power output averaged over a 24-hour day.)

When might photovoltaic electricity reach this price level? Active solar cell research and development is underway in industrial and governmental laboratories in nearly every developed country and in many developing countries. The detailed goals of the U.S. Department of Energy (DOE) effort appear in Table 1.1. The overall goal is to replace one quad per year of primary fuels by photovoltaics by the year 2000. In the recent past, commercial solar cell costs have dropped faster than the DOE goals, as shown in Fig. 1.4. Since 1980 the price of oil has actually fallen, and federal funding for photovoltaics has been cut back in the United States. Funding for energy research in several countries has increased (examples are West Germany, Japan, and Italy), and it is hoped that the industry will maintain the momentum for achieving the cost goals of Fig. 1.4. If the goals are met or exceeded, vast quantities of solar cells will be manufactured and used.

The anticipated rapid growth of solar cell use raises questions about the

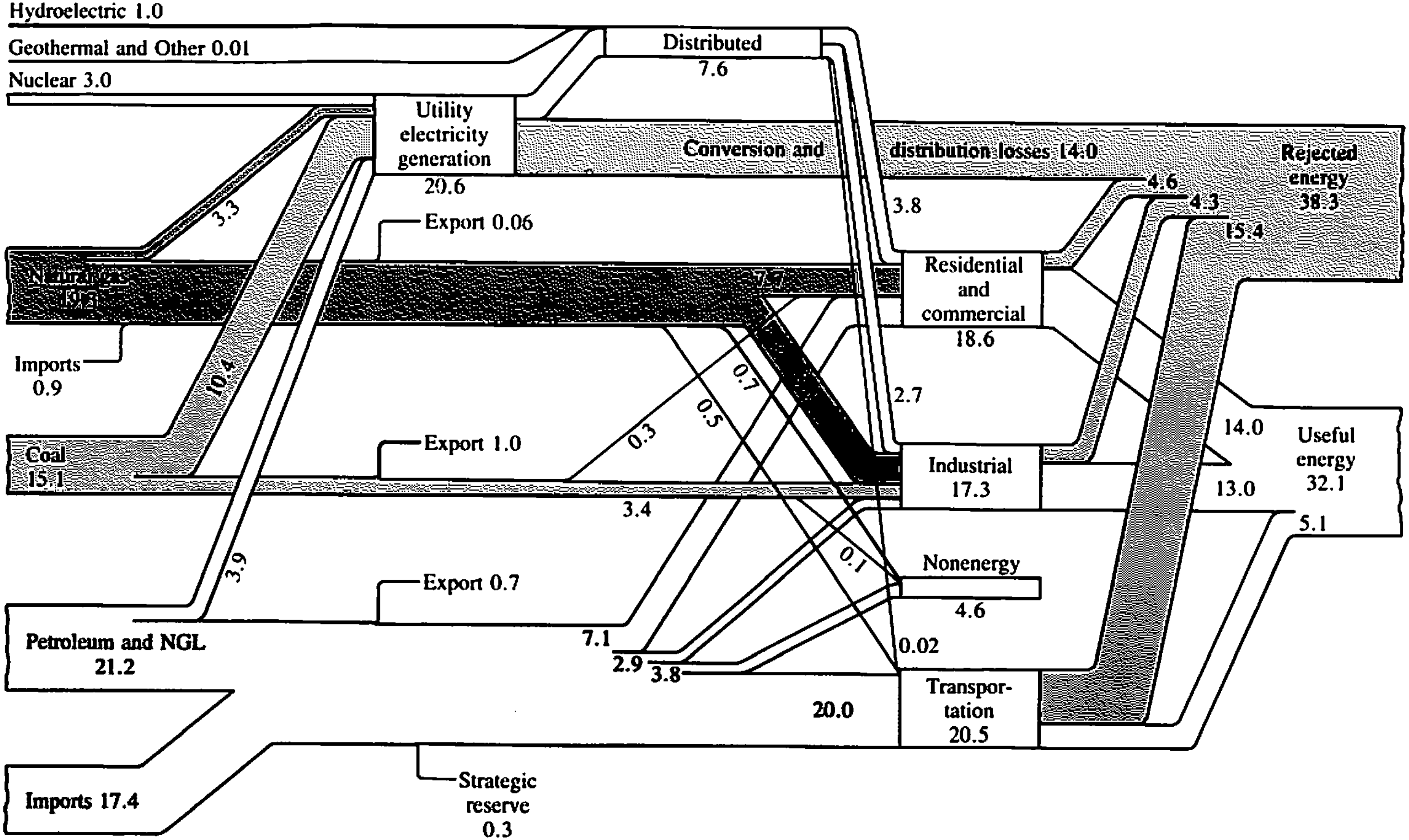


Figure 1.3 Energy flow in the United States in 1978 *(Ramsey, 1979)*. Numbers are quads (quadrillions of Btu's).

Table 1.1 Solar cell development and production goals of the U.S. DOE National Photovoltaics Program

Costs per W_{pk} delivered with illumination at 1 kW/m^2 in 1980 U.S. dollars (DOE, 1980). System prices in third column include balance-of-system components required in addition to solar cells, whose prices appear in column 2.

Application and year	Collector price (FOB), \$/W_{pk}	System price, \$/W_{pk}	Production scale, MW_{pk}/yr	User energy price, ¢/kWh
Remote stand-alone (1982)	≤ 2.80	6–13		
Residential (1986)	≤ 0.70	1.60–2.20	100–1000	3.5–10.5
Intermediate load center (1986)	≤ 0.70	1.60–2.60	100–10,000	5.0–13.5
Central power station (1990)	0.15–0.40	1.10–1.30	500–2500	4.0–10.0

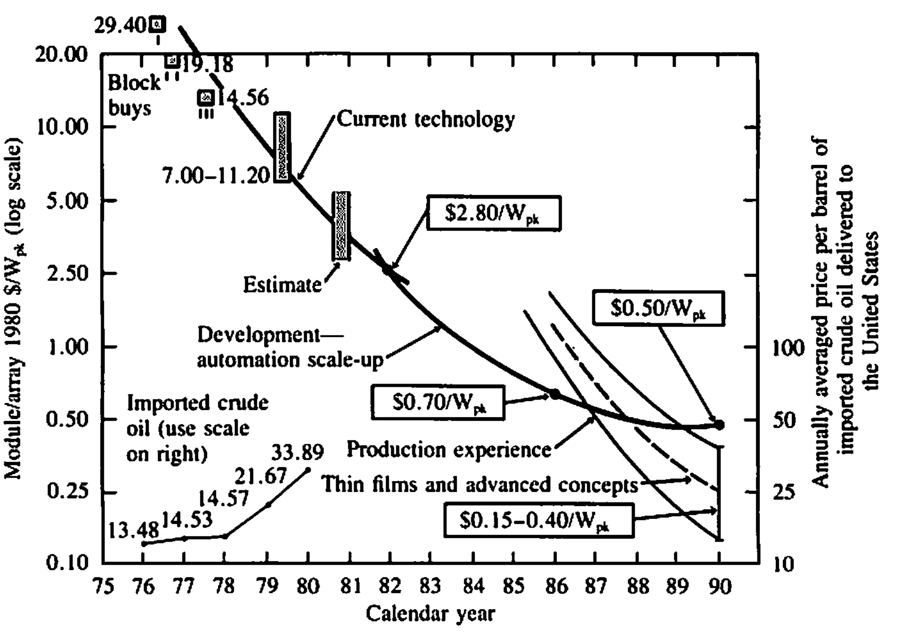


Figure 1.4 Price goals and cost history for terrestrial solar cell modules and arrays, in 1980 dollars. Shaded regions represent actual purchase prices. Block buys I, II, and III were large U.S. government purchases for demonstration projects. *(From DOE, 1980.)* The prices for a barrel of imported crude oil delivered at U.S. ports, averaged over suppliers and through the year, are also plotted in current year dollars. *(DOE, 1981)*

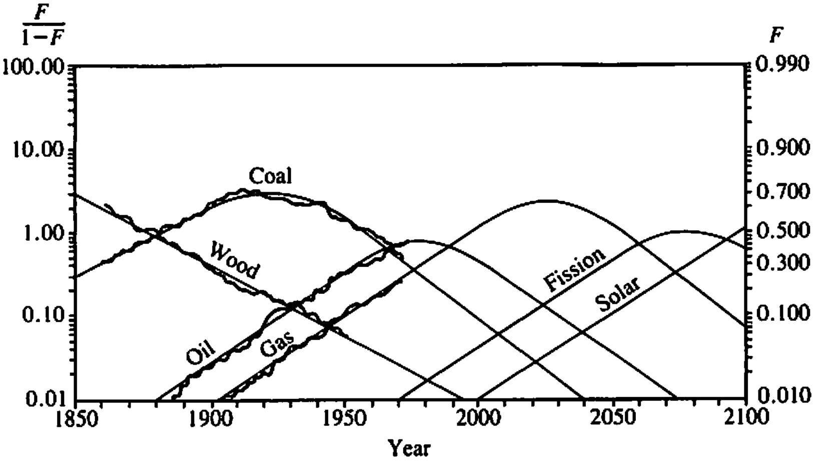


Figure 1.5 History and projection of energy sources for the world plotted versus year. F is the fraction of the total market supplied by a given energy source *(Weingart, 1978)*. The plot shows how similar the histories have been for all the major sources.

possible rates of expansion of manufacturing facilities, availability of materials, and so on. Encouraging answers have been obtained, as discussed in Chap. 4. The possible rate of growth of the solar energy supply is suggested by the curves in Fig. 1.5, where the growth in the market fraction commanded by a given energy source is plotted for both conventional and the newer alternative energy sources. If those logistic growth curves for wood, coal, natural gas, and oil also apply to solar sources, we should see a growth rate for all solar sources—solar cell and solar thermal power plants, and heating and cooling of buildings—that causes those sources to become dominant over a 40- to 50-year period.

Realizing that these predictions and trends are only suggestive of a possible future, let us begin our study.

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PROBLEMS

1.1 *Energy payback time* The energy payback time is the time required for an energy-producing system to produce the amount of energy used in making the system. Suppose that by the introduction of new thin-film solar cells the energy required to make a solar cell system of given area is reduced by 50 percent from that required for a single-crystal system. Assume that the system's efficiency is also reduced, say, from 14 to 12 percent. What is the energy payback time of the new thin-film system if that for the single-crystal system is 6 years?

1.2 *Doubling time* Verify the results given in the box entitled "How Much Oil?" in Chap. 1. As a related exercise, suppose that you have a financial investment in which the amount of money increases by P percent each year. Show that the time in years for your money to double is approximately $70/P$.

1.3 *Efficiency of energy use* From Fig. 1.3 calculate the approximate percentage of total energy that is used in each of the major sectors listed below, together with the energy efficiency of each:

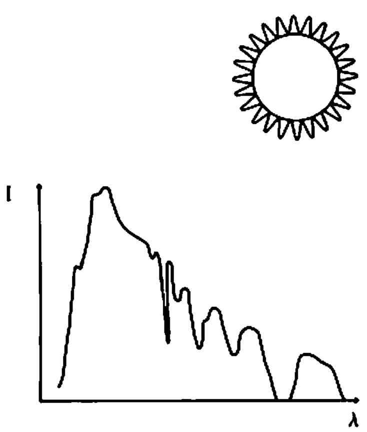
Sector	Approximate % of total energy input for sector	Approximate efficiency (%) of energy usage in sector
Utility electricity generation		
Industrial		
Residential and commercial		
Transportation		
Overall	(100%)	

CHAPTER

TWO

NATURE AND AVAILABILITY OF SOLAR ENERGY

CHAPTER OUTLINE



The sun, the energy source of all solar cell systems, is the subject of this chapter. A rather thorough description of the temporal and geographical variations of solar insolation is presented. It is hoped that, after studying this chapter, one can estimate the solar energy available to flat-plate and tracking concentrator collectors (solar cells) and the best ways of mounting them at a given location.

2.1 THE SUN AND THE SUN–EARTH RELATIVE MOTION

The sun is located in one of the spiral arms, the Orion arm, of our galaxy. It is believed that hydrogen nuclei are converted into helium nuclei under high temperature and pressure near the center of the sun by thermonuclear fusion. The fusion energy is transferred outward by radiation and convection and finally radiated into space in the form of electromagnetic waves in and near the visible spectrum. The spectrum of solar radiation is close to that of a black-body heated to 5743 K.

A sun-centered view of the sun–earth system is shown in Fig. 2.1*a*. The earth's orbit is slightly elliptical and eccentric. The sun–earth distance varies

THE SUN AS A FUSION REACTOR

For thermonuclear fusion both high temperature and high concentration (density or pressure) of reacting gases are desirable. Near the center of the sun, the temperature is on the order of 10^7 K and the density (of hot gases!) is about 100 times that of water. The high density is maintained by the gravitational forces resulting from the sun's large mass. Current estimates of the power released from the sun are around 3.8×10^{26} W. At this rate, 2×10^{19} kg of hydrogen is consumed by fusion each year. This huge mass is only $1/10^{11}$ of the sun's weight.

To achieve controlled fusion as an energy source on earth in imitation of the sun, other means of confining the hot gases must be found. One method being investigated is called *magnetic* confinement. A low but sufficient gas pressure is maintained by confining the ionized gases in a "bottle" formed with a magnetic field. The other, newer method under study is called *inertial* confinement. A small, hollow glass bubble holding fusion gases is irradiated from several symmetrical directions with beams of intense laser light for less than one billionth of a second. The resultant implosion compresses the gases to a density comparable to that of lead for the brief duration of the fusion process.

Question: Is the gravitational force larger or smaller near the center of the sun than near its surface? How do you reconcile this with the fact that density (pressure) is larger near the center? (*Hint:* Force per unit volume is the gradient of pressure.)

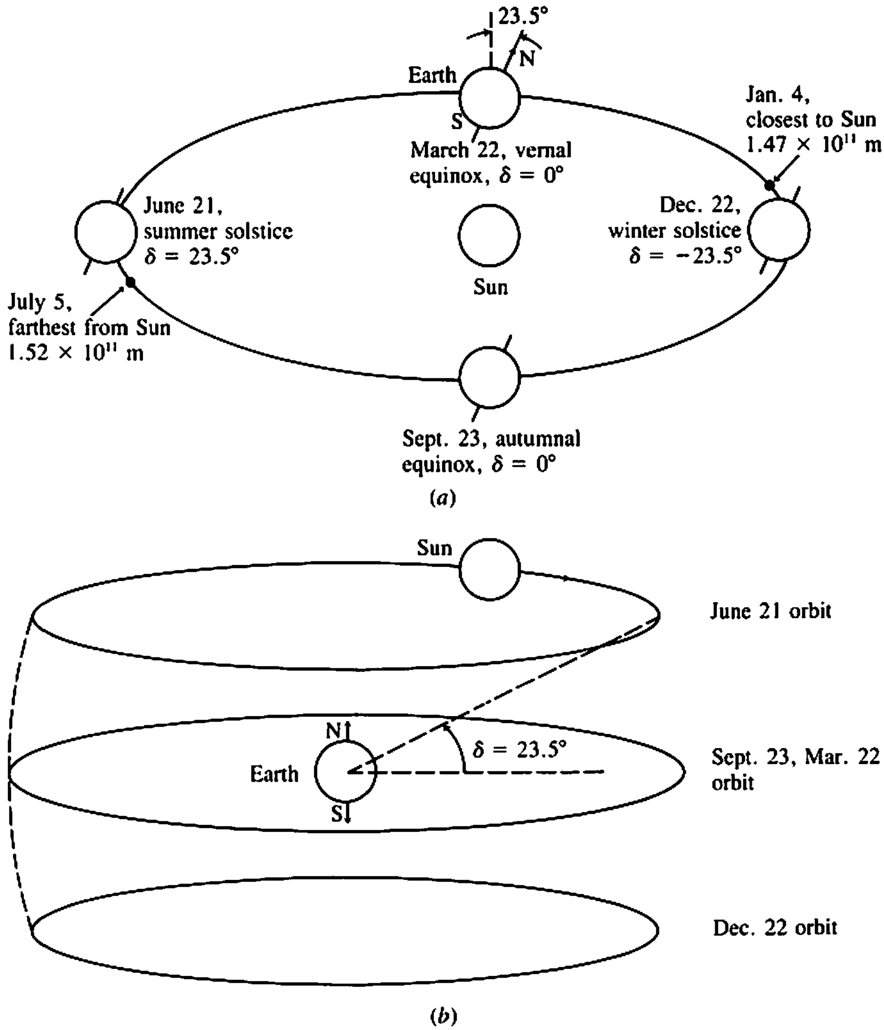


Figure 2.1 (*a*) The conventional sun-centered view of the sun-earth system. (*b*) An earth-centered view, which is easier to visualize. For example, the declination angle δ between the sun ray and the plane of the equator is better illustrated in *b*. The date given may vary by one day or so.

seasonally about the mean by 1.7 percent. At the mean distance of 1.495×10^{11} m, known as one *astronomical unit*, the solar flux outside the earth's atmosphere is 1.353 kW/m^2, a quantity known as the *solar constant*. The earth spins around its own polar axis once every space day. Its polar axis is tilted by 23.45° from the normal of the orbital plane. This causes seasonal variations of the sunlight incidence angle.

The sun–earth relationship can be visualized more easily in an earth-centered view, which is shown in Fig. 2.1*b*. The two views, of course, are equivalent through coordinate transformations. In Fig. 2.1*b*, the earth is motionless with its polar axis pointing upward. The sun moves around the earth exactly once every day at constant angular speed (15° per hour) tracing an almost perfectly centered and circular path. The solar path is highest over the north pole with the sun rays making a 23.5° angle with the plane of the equator around June 21. Around September 23 and March 22, the sun rays arrive parallel to the plane of the equator; around December 22, the solar path is lowest below the south pole, making a −23.5° angle with the plane of the equator. On the nth day of the year, the declination δ can be found from the approximate equation

$$\delta = 23.45° \sin\left[2\pi \cdot \frac{n - 80}{365}\right] \qquad (2.1.1)$$

The radii of the solar paths also vary through the year so that the earth–sun distance varies as in Fig. 2.1*a*, or approximately

$$\text{Earth-sun distance} = 1.5 \times 10^{11}\left[1 + 0.017 \sin\left(2\pi \frac{n - 93}{365}\right)\right] \text{m} \qquad (2.1.2)$$

To visualize the geometrical factors of solar flux at a certain location on earth, imagine a tangent plane touching the earth at that location, as shown in Fig. 2.2. The plane is an extension of the earth's horizon at that point. The angle between this plane and the polar axis is equal to the latitude. The sun is visible to an observer at that location only when the sun's path is above the plane. Point A corresponds to sunrise and point B, sunset. The midpoint between A and B corresponds to the "solar noon." Clearly, for any location in the northern hemisphere, days are longer in June than in December. Moreover, a horizontal collector (such as the earth's surface) is closer to being normal to the solar flux in June than in December. Therefore, June is warmer than December. To enhance solar energy collection in the winter months, one can tilt the collector surface toward the south. It can be shown that the total annual collection is maximized when the collector is approximately parallel to the polar axis, i. e., the collector is tilted to the south by ϕ (see Sec. 2.5). The following are examples of the many questions that can be answered using Figs. 2.1*b* and 2.2.

Imagine a tracking solar collector in front of you. Can you visualize the motions it must go through in order to face the sun directly at all daytime hours throughout a year?

From the symmetry in Fig. 2.2 (the earth's radius is negligible in comparison with the sun–earth distance), can you see that the annual average length

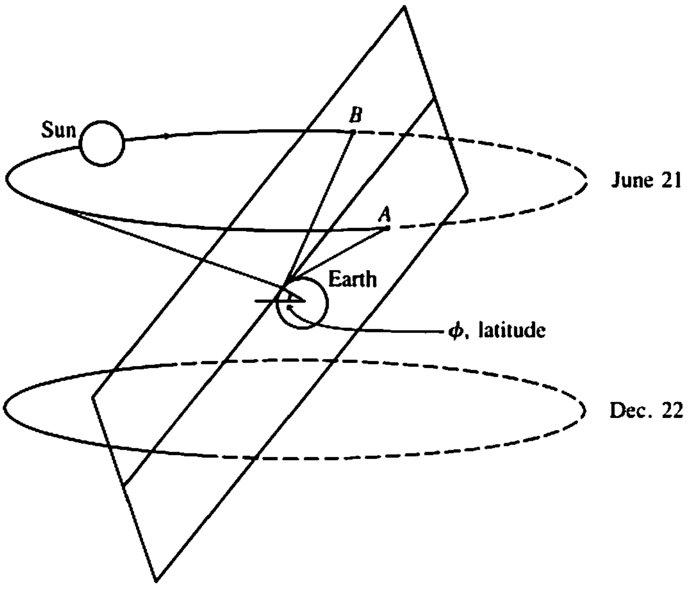


Figure 2.2 A tangent plane touching the earth is but an enlargement of the horizontal plane at that location. This plane can help one visualize the seasonal variation of the length of the day, the motions a tracking solar collector must go through in a day and a year, and so forth.

of day is equal to the average length of night? If so, what is the average length of day? (Answer: 12 hours.)

Around the polar regions, the sun may be invisible for an entire day. In which portions of the world will this phenomenon occur on at least one day each year? (Answer: north of 66.5°N and south of 66.5°S.)

2.2 ATMOSPHERIC EFFECTS ON SOLAR RADIATION

On a clear day and when the sun is directly overhead, 70 percent of the solar radiation incident to the earth's atmosphere reaches the earth's surface undisturbed. Another 7 percent or so reaches the ground in an approximately isotropic manner after scattering from atmospheric molecules and particulates. The rest is absorbed or scattered back into space. Figure 2.3 illustrates the situation. (For a review of the various processes see DOE Report HCP/T2552-01.) Clearly, both the direct and scattered fluxes vary with time and location because the amounts of dust and water vapor in the atmosphere are not constant even on clear days. A commonly accepted set of solar fluxes

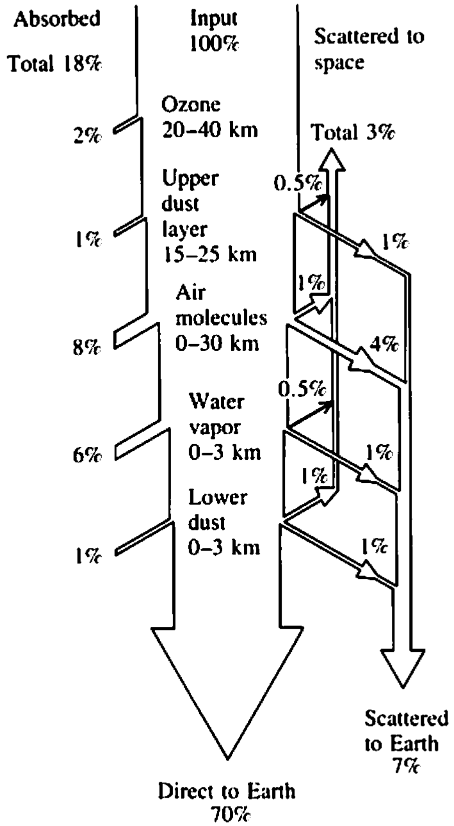


Figure 2.3 Typical air mass one (AM1) clear sky absorption and scattering of incident solar energy. Clouds can significantly reduce the direct transmission and increase scattering.

for air mass one (AM1) sun is shown in Table 2.1. A more complete table of units and numerical constants can be found in Appendix 2.

Air mass one refers to the thickness of the atmosphere a sunbeam passes through if the beam is normal to the horizon. The angle between the sunbeam and the horizon, α, is called the *solar altitude*. For any solar altitudes other than 90°, the air mass number is of course larger and is equal to csc α except for very small α's, for which the curvature of the atmosphere makes the air mass smaller than csc α. Since an AM1 atmosphere reduces the direct flux by the factor 0.7 (see Table 2.1), one would expect the direct intensity at an arbitrary air mass number to be

$$I = 1.353 \times 0.7^{\text{air mass}} = 1.353 \times 0.7^{\csc \alpha} \text{ kW/m}^2 \qquad (2.2.1)$$

Meinel and Meinel (1976) have found, however, that actual observations by Laue (1970) can be fitted better with

$$I = 1.353 \times 0.7^{(\csc \alpha)^{0.678}} \text{ kW/m}^2 \qquad (2.2.2)$$

Table 2.1 Solar fluxes of AM1 sun
Sunbeam normal to horizon, as at solar noon on summer solstice at 23.5°N latitude [Meinel and Meinel (1976)]

Above atmosphere (direct/total):	1.353 kW/m^2
Desert sea level (direct):	0.970 kW/m^2
Desert sea level (total):	1.050 kW/m^2
Standard sea level (direct):	0.930 kW/m^2

1 kW/m^2 = 1.433 langley/min (cal/cm^2 · min)
= 316.9 Btu/ft^2 · hr

There is no known explanation for the additional exponent. Equations (2.2.1) and (2.2.2) can be used to estimate the clear sky direct normal (collector facing sun) flux at arbitrary solar altitude.

Besides intensity, the spectral distributions of solar fluxes are also affected by the atmosphere. This fact is important to photovoltaic solar energy conversion since the conversion efficiencies of solar cells depend on the spectrum of the incident light. Figure 2.4 shows the solar spectrum outside the atmosphere (air mass zero, or AM0), which is close to the 5743 K blackbody radiation spectrum, and the AM1 (air mass one) direct and estimated diffuse radiation spectra at sea level. The AM1 direct radiation spectrum is from Thekaekara (1974). Absorption by ozone is essentially complete below 0.3 μm wavelength. The relatively large attenuation below 0.8 μm is due to scattering by molecules and particulates. These scattering processes become weaker at longer wavelengths, as has been shown by both theory and observation. This also explains the spectrum of the diffuse radiation, which is richer than the direct radiation in the blue portion of the spectrum. The many notches in the sea-level spectrum can be attributed to the absorption bands of various atmospheric gases. Some of the attributions are shown in Fig. 2.4.

From the AM0 and AM1 spectra, one may estimate the spectrum for an arbitrary air mass AMK by assuming that the attenuation at each wavelength follows the form of Eq. (2.2.1) or Eq. (2.2.2). For example,

$$I_{\mathrm{AM}K}(\lambda) = I_{\mathrm{AM0}}(\lambda)\left|\frac{I_{\mathrm{AM1}}(\lambda)}{I_{\mathrm{AM0}}(\lambda)}\right|^{K^{0.678}} \qquad (2.2.3)$$

In analyzing the performance of solar cell systems, the cell output is usually assumed to be proportional to the solar radiation intensity with no regard to the variations in the spectral distributions. This practice should be satisfactory for engineering purposes.

So far only the clear sky condition has been considered. The amount of sky cover in the form of clouds is a dominant factor in determining the transmission and scattering of solar radiation. Although the amount of water

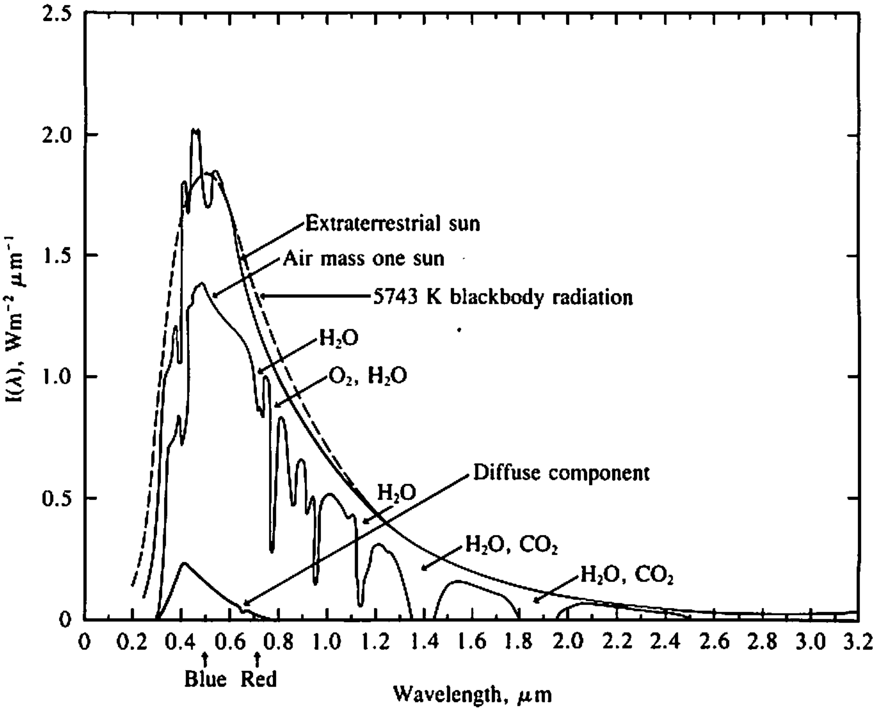


Figure 2.4 Spectral intensities of the extraterrestrial and air mass one (sun directly overhead, measured at sea level) direct solar radiation. A typical spectrum of clear sky scattered radiation is also shown.

in the clouds is usually a small fraction of the total water content in the air, the condensed droplets or ice crystals have much stronger effects on light than does water vapor. Unlike the sun–earth geometry and the air mass number, the amount of sky cover defies simple modeling. As a result, insolation may fluctuate unpredictably over intervals of minutes. Even longer-term average insolation can be obtained only through measurements, as discussed in the next two sections.

2.3 SOLAR RADIATION MEASUREMENT AND INSTRUMENTATION

Many different types of instruments are used for measuring solar radiation, including the following:

Pyranometer: Total (direct and diffuse) radiation
Shading-ring pyranometer: Diffuse radiation

Moving shadow-bar pyranometer: Both total and diffuse radiation
Pyrheliometer: Direct radiation at normal incidence
Sunshine recorder: Hours of bright sunshine

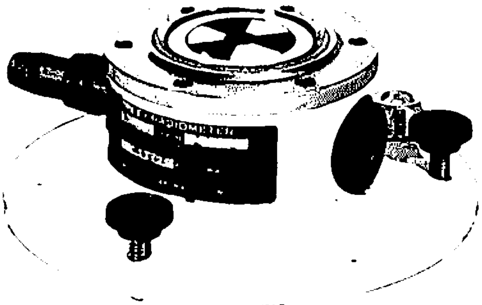
Pyranometer Also known as a *solarimeter*, the pyranometer is generally mounted in a horizontal position away from tall objects so that the 2π field of view of the instrument covers the entire sky. It responds equally to the energy in all wavelengths. The Eppley pyranometer (see Fig. 2.5*a*) is the type most commonly used in the United States. It employs metal wedges arranged into a circular disk and alternately painted with Parson's black for black and magnesium oxide for white. The disk is protected by one or two layers of dome-shaped glass covers. The temperature difference between the black and white wedges is sensed by multiple thermocouple junctions whose output voltage is measured. Similar instruments are manufactured in Europe as Kipp and Zonen pyranometers.

Because of the ease of operating pyranometers, the vast majority of solar insolation data is gathered with this type of instrument. In some parts of the world, the data are mainly gathered with a simpler kind of instrument based on the differential expansion of bimetal elements. The principles and the calibration characteristics of many pyranometers are discussed by Robinson (1966).

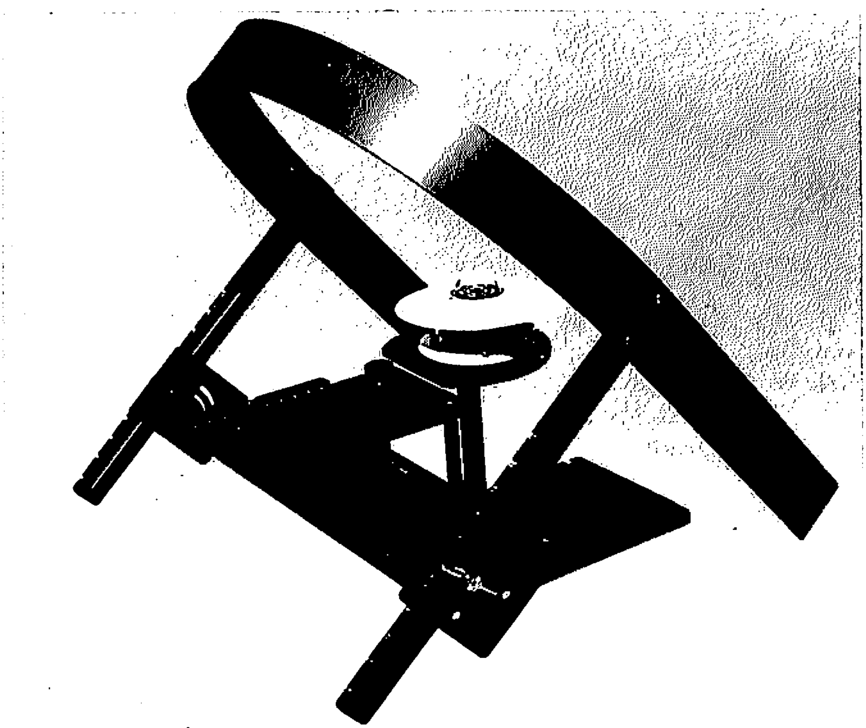
Shading-ring pyranometer A ring-shaped hoop sunshield may be added to a pyranometer to exclude direct sunlight and thereby permit measurement of the diffuse components. When this reading is subtracted from that of a standard pyranometer, the result is the direct solar radiation. To keep the obstruction of the sky small, the ring is made narrow, shading only about 5°, and the position of the ring is changed every few days (see Fig. 2.5*b*).

Moving shadow-bar pyranometer This instrument is a clever combination of the standard pyranometer and the shading-ring pyranometer. Instead of the quasi-stationary shading ring, a narrow shadow bar is moved over the sensor every few minutes, shading the direct radiation and causing a drop in the recorder trace. The upper envelope of the trace thus provides a record of the total radiation versus time, and the lower envelope is a record of the diffuse radiation. The sensor is a small silicon diode (solar cell) having a short response time.

Pyrheliometer The pyrheliometer has a small field of view, around 6°, and tracks the sun continuously and thus measures the direct normal radiation. Since the field of view is larger than the 0.53° subtended by the solar disk, the reading is higher than the true direct flux by a few percent. Pyrheliometer stations are relatively rare. For example, among the approximately 100 sta-

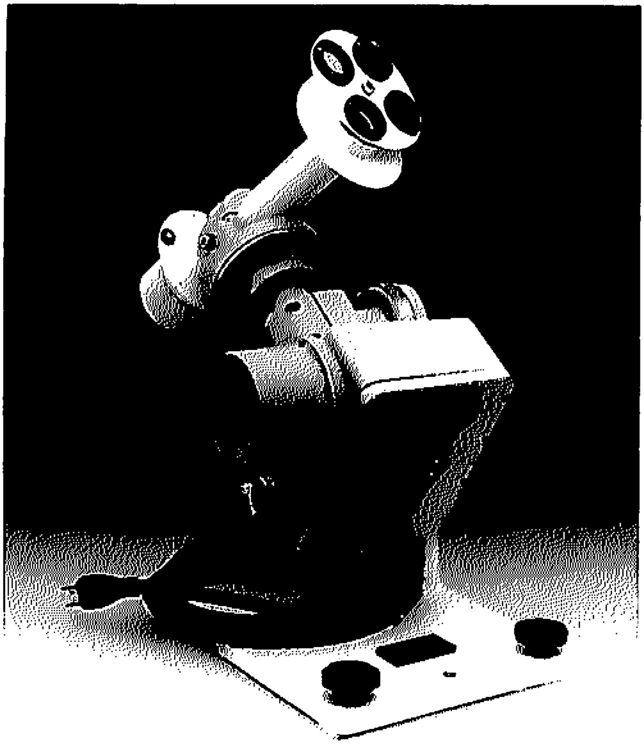


(*a*)



(*b*)

Figure 2.5 (*a*) Pyranometer. (*b*) Pyranometer with shading ring. (*Courtesy Eppley Laboratory, Inc.*)



(c)

Figure 2.5 *(continued)* (*c*) Pyrheliometer. (*Courtesy Eppley Laboratory, Inc.*)

tions that record solar radiation in the United States, only about 18 record direct normal insolation. Pyrheliometer measurements are needed to predict the performance of tracking concentrator photovoltaic systems. Figure 2.5*c* shows a pyrheliometer with filters.

Sunshine recorder The sunshine recorder measures the duration of "bright sunshine," the number of hours per day that the sunlight intensity is above some chosen level. An older instrument, the Campbell-Stokes recorder, uses a spherical lens that focuses the sunlight on an advancing treated paper. The paper is burned whenever the beam radiation is above a critical level. This type of recorder is used in many hundreds of stations throughout the world. The standard U.S. Weather Bureau instrument uses two photocells, one of which is shaded from the direct radiation. When the reading difference between the two cells is above a set threshold, "bright sunshine" is assumed to be present. Although sunshine-recorder data does not provide direct information on the incident solar energy, it is widely available and may be used to estimate the solar radiation (Duffie and Beckman, 1974).

2.4 GEOGRAPHICAL DISTRIBUTION OF AVERAGE INSOLATION

In designing a photovoltaic system the temporal variability of solar radiation needs to be considered for the following reasons.

Daily and hourly variations Daily variations are important for the design of storage capacity in totally self-sufficient systems. The variations from hour to hour, or even from minute to minute, should be considered when accurately calculating the system output since the output power of the cells and the system in general is not linearly proportional to the solar radiation. For example, one hour of 1 kW/m^2 radiation and three hours of zero radiation generally would not produce the same electrical energy as four hours of 0.25 kW/m^2 radiation.

Unfortunately, variations on such fine time scales are difficult to record, present, and adequately deal with in design. The data of these variations will not be presented here. Statistical techniques will no doubt be used in this area more extensively in the future. Interested readers might note that the U.S. National Oceanic and Atmospheric Administration (Asheville, North Carolina) keeps on tape or punched cards the daily and (for some 40 stations) hourly radiation data recorded at many locations for varying periods, starting from 1952.

Monthly variations Monthly variations result from the seasonal changes of both the sun–earth relationships (Figs. 2.1 and 2.2) and weather, particularly cloudiness. With the average monthly sunshine data, one may estimate the monthly outputs of a photovoltaic system for comparison with the expected monthly electricity demands.

Yearly variations The yearly average insolation is normally used to analyze the average energy cost, the energy payback time (defined in Chap. 4), and other such information about a system. At a given location, the average insolation varies from the mean from year to year by less than 10 percent. There is no clear pattern (cycles) in the year-to-year variations. However, after major volcanic eruptions, large temporary decreases in yearly insolation have been observed.

Figure 2.6 shows the average insolation by month at selected sites in the United States. The averages are for periods of many years and are expressed in terms of kWh/m$^2\cdot$day. Both direct normal radiation (excluding diffuse radiation, collector normal to sunbeams at all times), corresponding to the flux on tracking concentrators, and the radiation on horizontal surfaces are shown. The monthly variations can be explained by Fig. 2.7. In the northern hemisphere, the radiation on a horizontal surface generally peaks in June and reaches a minimum in December because of the seasonal changes in the

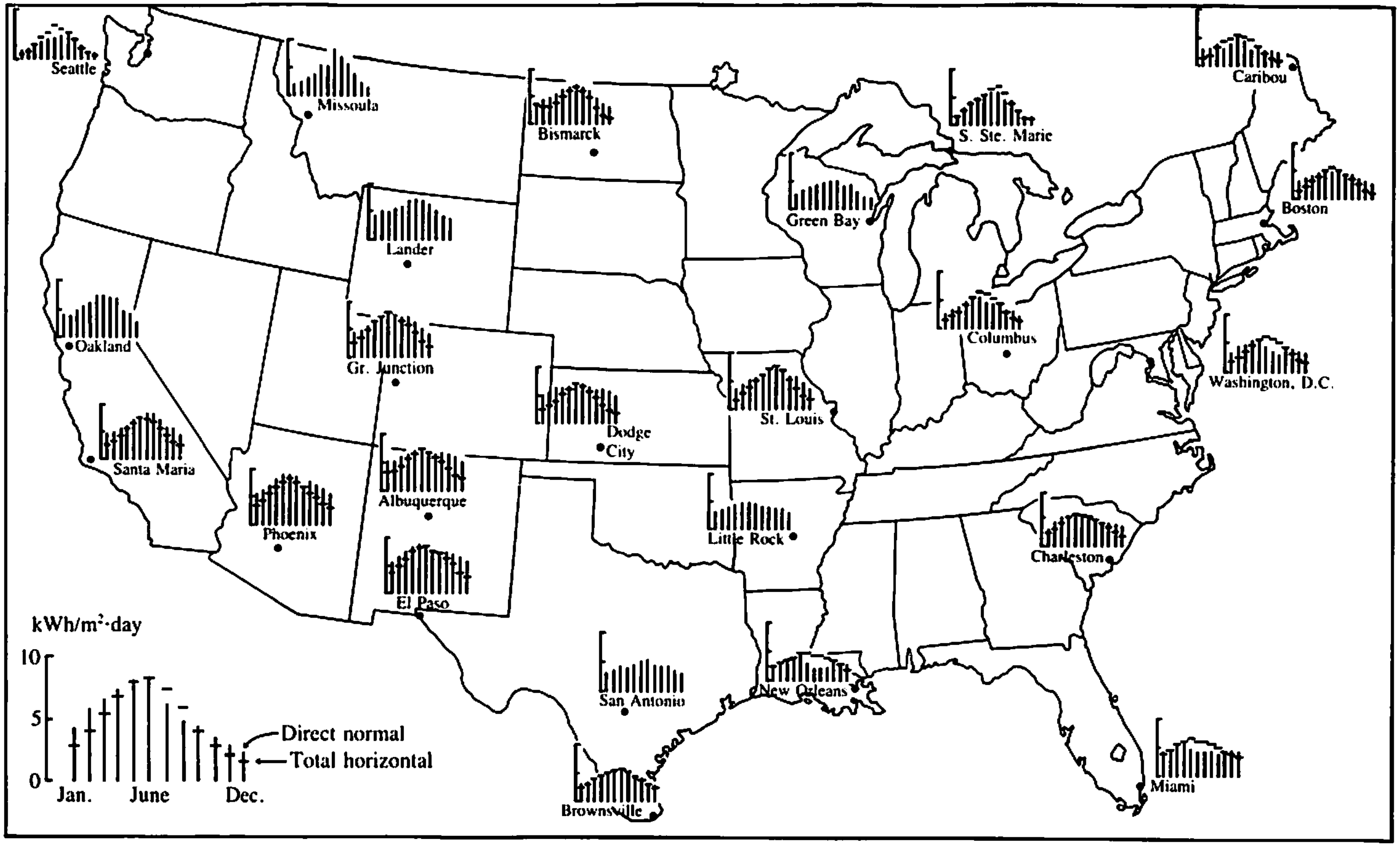


Figure 2.6 Daily direct normal and total (direct plus diffuse) horizontal radiation in selected United States cities. *(DOE Report HCP/T2252-01, 1978, and HCP/T-4016/1, 1979)*. Total horizontal insolation data are not available at some of the locations shown.

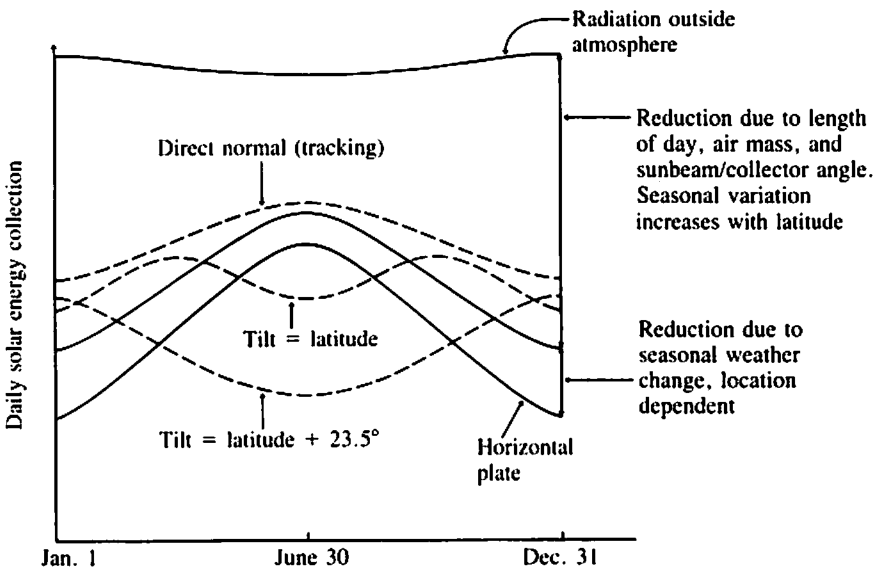


Figure 2.7 Qualitative plots of seasonal variations of daily solar energy collection for a location north of 23.5°N. "Tilt" (see Sec. 2.5) is the angle between the collector plate and the horizontal plane. The plate is tilted due south.

length of the day (Fig. 2.2), the average air mass, and the average angle between sunbeam and the horizontal surface (collector). The peak-to-valley ratio increases with increasing latitude. At the same latitude, the insolation tends to be lower in the eastern regions of the United States because of the weather conditions. The average direct normal radiation is usually greater than the radiation on horizontal surfaces because the angle between sunbeam and collector is always 90° in the case of direct normal radiation. The west–east difference is even clearer with the direct normal radiation because the direct normal flux is more sensitive to cloudiness.

Figures 2.8 and 2.9 show contour drawings of annual radiation on a horizontal surface and the direct normal radiation in the United States, respectively, in units of $kWh/m^2 \cdot day$. It is worth remembering that the average energy received on a horizontal surface per day is between 3.5 and 6 kWh/m^2, or the equivalent of 4 to 6 hours of the clear-sky noontime sun every day of the year. The energy received by a tracking collector ranges between 3.5 and 7.5 kWh/m^2.

Figures 2.10*a* through *d* are world maps of energy received daily on a horizontal surface in four months of the year. Notice the high insolation in the desert zones around 30°N and 30°S where the sky coverages are statistically low. Table 2.2 shows the daily energy density averaged over a month and a year at selected cities.

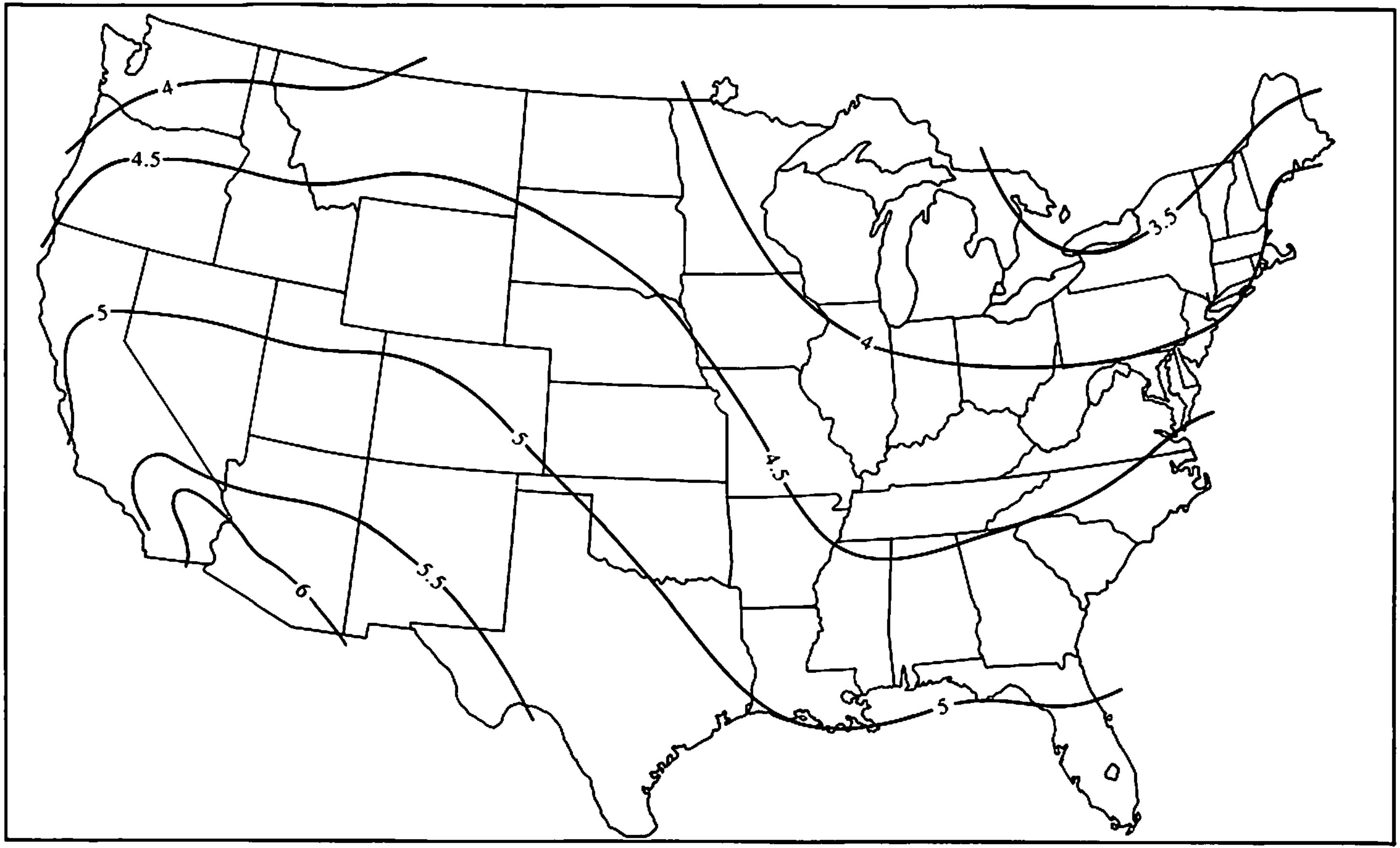


Figure 2.8 Contour map of daily radiation (direct plus diffuse) on a horizontal surface in the United States. The values are averaged over many years and expressed in kWh/m^2 · day. *(From DOE Report HCP/T2252-01.)*

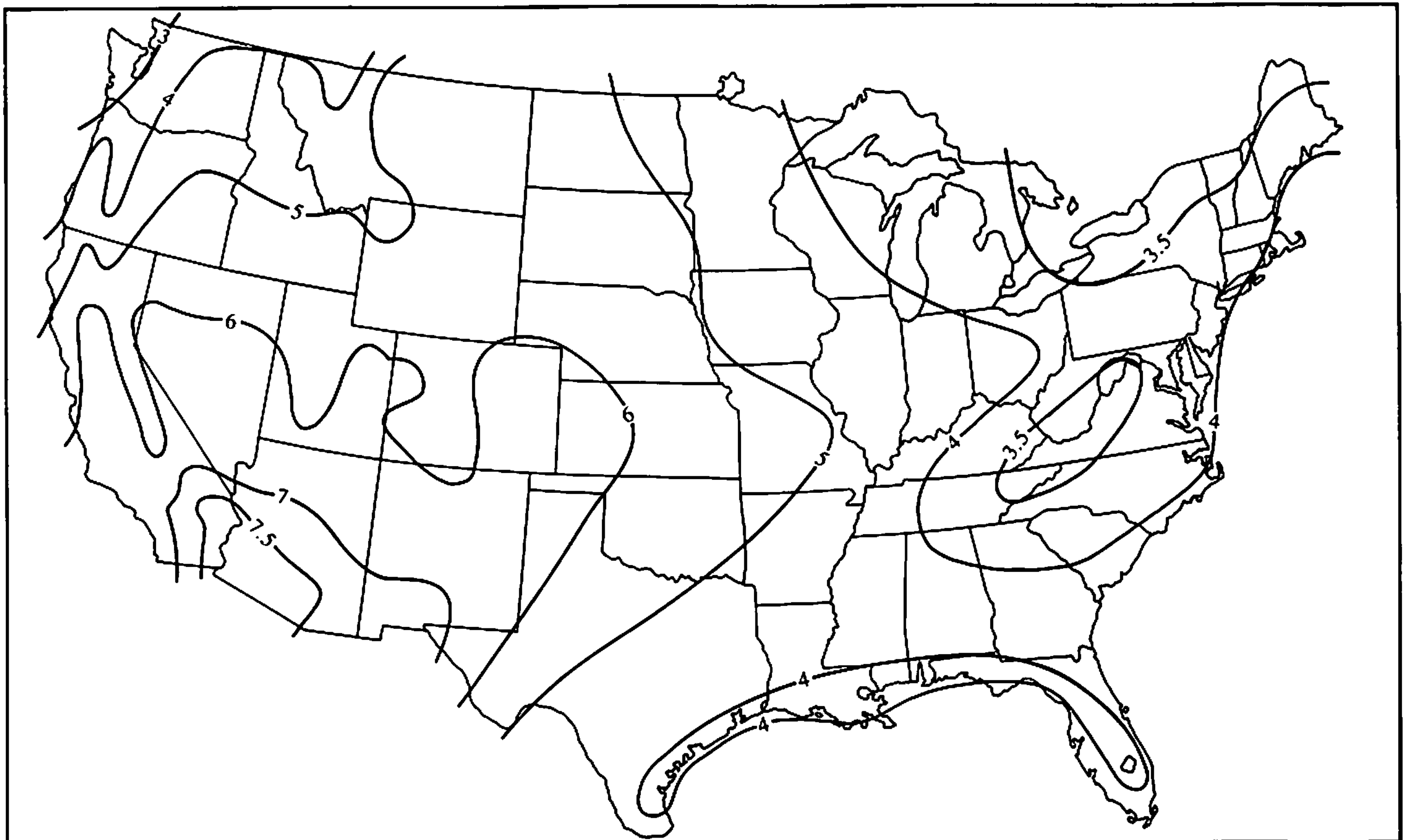
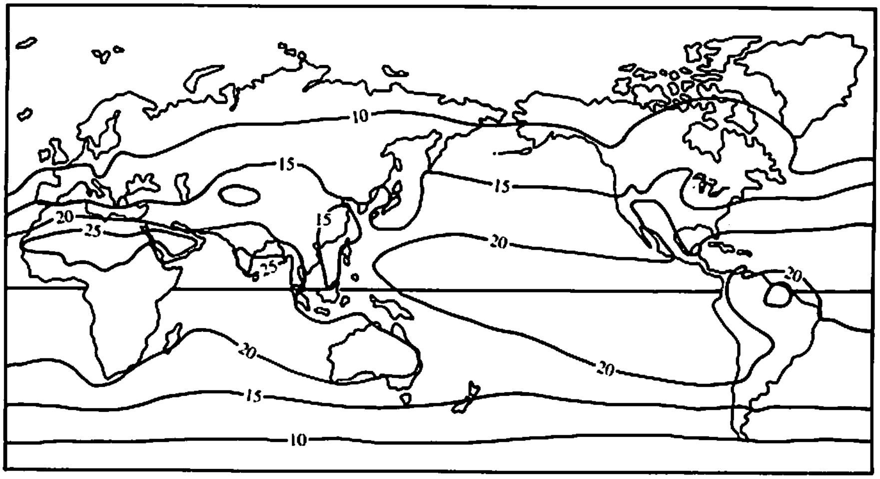
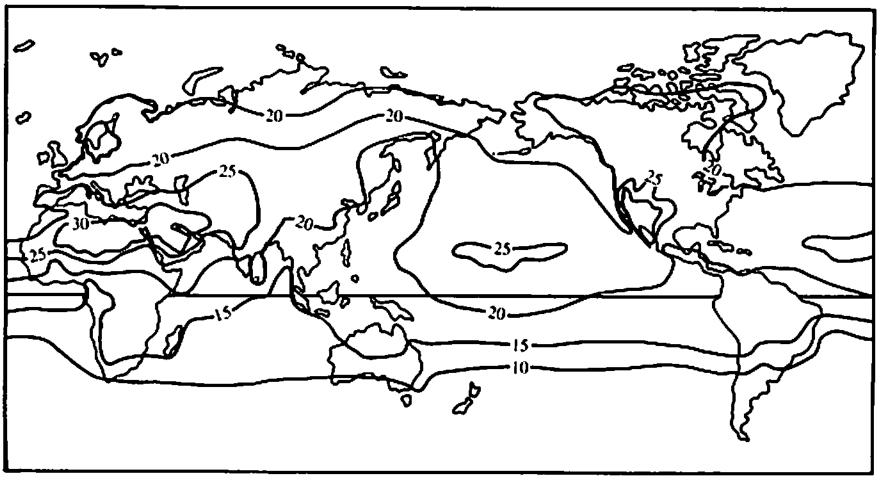


Figure 2.9 Contour map of daily radiation (direct only) on a tracking collector facing the sun at all times in the United States. The values are averaged over many years and expressed in $kWh/m^2 \cdot day$. *(From DOE Report HCP/T2252-01.)*

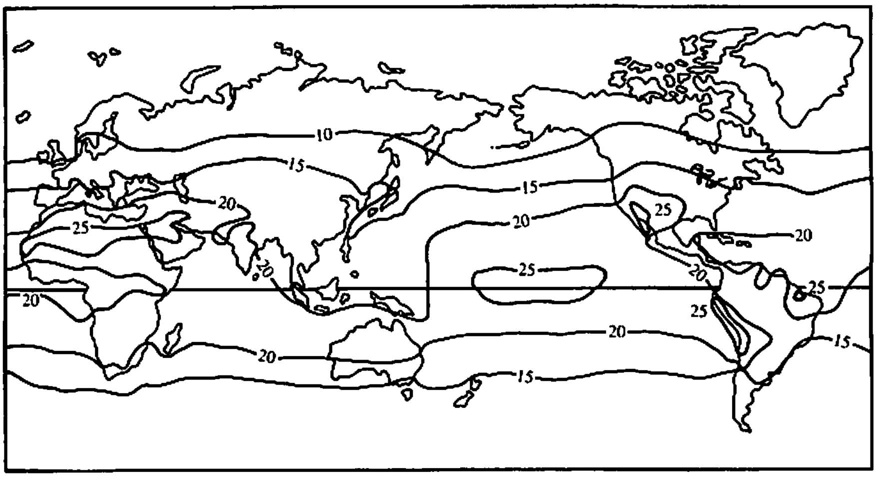


(*a*)



(*b*)

Figure 2.10 Global isoflux contours. Total insolation in MJ/m^2 · day on a horizontal surface in (*a*) March, (*b*) June, (*c*) September, and (*d*) December. 1 MJ/m^2 = 0.278 kWh/m^2. *(Meinel, 1978.)*



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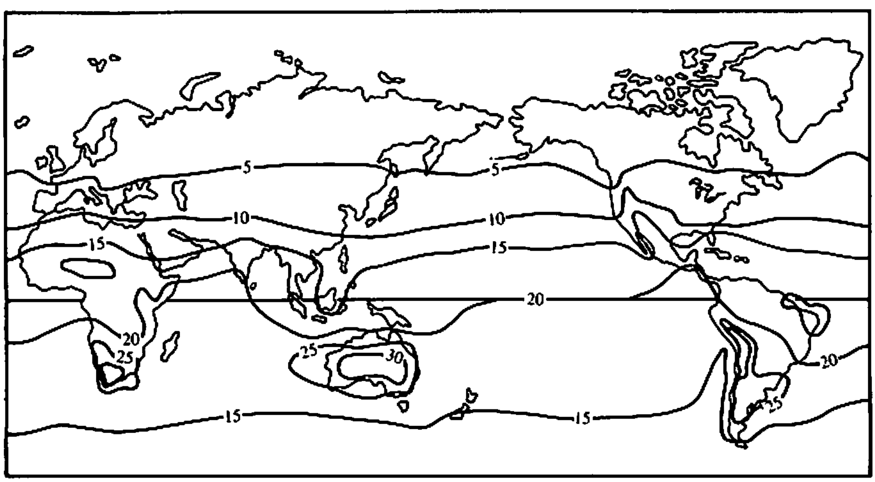

(d)

Figure 2.10 *(continued)*

Table 2.2 Daily direct and diffuse radiation energy on a horizontal surface in kWh/m^2 · day
The direct normal radiation energy in Albuquerque is also shown on the second line of entries for that city. [Meinel and Meinel (1976) and DOE Rept. HCP/T2552-01.]

Location	Latitude, degrees N	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Yearly average
Yangami, Congo	01	4.76	5.24	5.33	5.19	5.10	4.62	4.10	4.20	4.75	4.77	4.92	4.34	4.78
Dakar, Senegal	15	5.35	6.26	7.37	7.29	7.20	6.75	5.96	5.30	5.40	5.22	5.26	5.47	6.07
Calcutta, India	22	6.19	7.18	8.15	9.08	9.12	9.50	9.49	9.31	7.50	7.26	6.48	5.83	7.92
Honolulu, U.S.	22	4.22	4.91	6.00	6.50	7.18	7.15	7.15	7.12	6.66	5.90	4.95	4.31	6.00
Tucson, U.S.	32.5	3.66	4.55	5.28	7.61	8.47	8.12	7.28	6.88	6.63	5.14	4.14	3.54	5.94
Albuquerque, U.S.	35	3.57	4.24	5.78	7.05	7.86	8.67	7.89	7.25	6.36	5.40	4.05	3.42	5.96
		6.26	6.05	5.76	8.09	7.92	8.54	7.90	6.84	7.43	7.69	4.75	5.37	6.88
Tokyo, Japan	36	2.21	2.68	3.18	3.63	3.98	3.52	3.91	3.93	2.95	2.35	2.15	1.96	3.04
New York, U.S.	42	1.42	2.22	3.01	4.22	4.96	5.19	5.11	4.26	3.68	2.83	1.72	1.25	3.32
Brussels, Belgium	51	0.65	1.25	2.39	4.02	4.72	5.13	4.72	4.11	2.92	1.83	0.88	0.55	2.76

2.5 EFFECT OF COLLECTOR TILT

Except for locations near the equator, laying a flat photovoltaic-cell panel on a horizontal surface is not the best design. Tilting the plate toward the equator, i.e., toward the south for a northern hemisphere location, can increase the total annual solar energy collection and smooth out the difference between summer and winter collections.

By referring to Figs. 2.1*b* and 2.2, one can see that a horizontal collector at latitudes north of or near 23.5°N would collect the maximum daily energy on June 21 and the minimum on December 22 (as shown in Fig. 2.7). If the collector makes an angle with the horizontal plane equal to the latitude ϕ (see Fig. 2.2 and the inset of Fig. 2.11), the collector would be normal to the sun's orbit on September 23 and March 22 and the maximum energy collection would occur near these two dates (as shown in Fig. 2.7). Thus the seasonal variations in energy collection are reduced by tilting. If one tilted the collector by an additional 23.5°, one could maximize the energy collection on December 22. This may be desirable for a solar heating system, but usually offers no advantages for a photovoltaic system.

Most available insolation data are for horizontal collectors. The unknown directional distributions of the diffuse radiation make it impossible to calculate accurately energy collection by a tilted plate from the measured collection by a horizontal surface. Neglecting seasonal variations of weather, Morse and Czannecki (1958) calculated the relative annual insolation due to direct radiation only as a function of the tilt angle, s. They concluded that the maximum annual energy collection per collector area is achieved when $s \approx 0.9\phi$, as shown in Fig. 2.11. With s slightly less than ϕ, the plate faces the sun more directly in the summer, when days are longer, than in the winter, and the

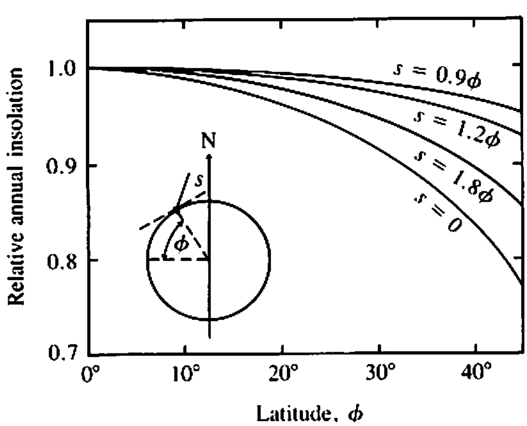

Figure 2.11 Relative annual insolation due to direct radiation on surfaces tilted at various degrees toward the equator. *(From Morse and Czarnecki, 1958.)*

annual collection is maximized. To estimate the insolation on a tilted collector, one can look up the annual insolation on a horizontal surface from the figures in Sec. 2.4 and multiply it by the ratio of the annual collection by a tilted plate to the collection by a horizontal plate ($s = 0$) obtained from Fig. 2.11. From the symmetry in Fig. 2.2, one can conclude that the collector should be tilted toward due south. However, Morse and Czannecki (1958) found that even a 22.5° tilt toward east or west causes less than 2 percent reduction in annual insolation for latitudes up to 45°.

Yet another alternative is to change the tilt angle s seasonally so that the envelope of the curves for fixed tilt angles in Fig. 2.7 is achieved. The annual insolation in this case would lie between the best fixed-tilt insolation and the direct normal insolation, which may be found from Fig. 2.9.

2.6 SUMMARY

The geometrical relationship between the earth and sun (Figs. 2.1*b* and 2.2) can help us understand the seasonal changes of insolation and the effect of tilting the solar collector and also to visualize the motions that a tracking mechanism must produce. The unpredictability of weather, particularly the cloud coverage of the sky, necessitates that measured insolation data be used for predicting and analyzing the performance of photovoltaic systems. The average (over a month and a year) daily collections of solar energy by a horizontal or tracking collector of unit area are presented in Figs. 2.6 through 2.10. Tilting the collector toward the equator to just short of paralleling the polar axis maximizes the total annual energy collection. In analyzing a photovoltaic system, it is usually assumed that its total or average electrical energy output is proportional to the total or average insolation, even though the electrical output actually varies with the solar intensity nonlinearly and also depends on the spectrum of the solar radiation (see Sec. 3.6).

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PROBLEMS

2-1 *Sun-earth relative motion* Answer the three questions at the end of Sec. 2.1. Give your reasoning.

2-2 *Atmospheric attenuation of solar radiation*
(*a*) Explain the rationale of Eq. (2.2.1).
(*b*) Sketch the approximate AM2 solar spectrum from the AM0 and AM1 spectra in Fig. 2.4 and Eq. (2.2.3).

2-3 *Shading-ring pyranometer* Based on your understanding, sketch the shading-ring arrangement of a shading-ring pyranometer. How should the ring be positioned relative to the earth's coordinates? How should it be adjusted every few days?

2-4 *Seasonal variation of solar insolation* Redraw Fig. 2.7 for a location at 23.5°S.

2-5 *Tilted collector* What needs to be known or what model information is necessary to convert pyranometer solar data to the flux on a tilted plane?

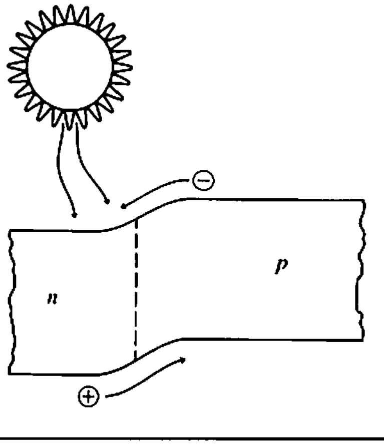
2-6 *Solar insolation in your location* What is the average daily total horizontal radiation in your location? Estimate the daily direct normal radiation, the total radiation on a flat plate tilted to maximize the annual collection, and the month-by-month changes of all these quantities. Where would you go for more information? If you were to supply about one third of the electricity use of a typical household with a 10 percent efficient photovoltaic system, how would you mount the solar cell panels and how large should they be?

CHAPTER

THREE

PRINCIPLES OF SOLAR CELL OPERATION

CHAPTER OUTLINE



In this chapter we shall explore the principles of operation, the electrical characteristics, and the limits of efficiency of solar cells. Silicon *pn*-junction solar cells will often be used as examples, but the principles presented here are general. The choices of cell materials and structures will be discussed in more detail in later chapters.

Mathematics is kept to a minimum in this chapter. The occasional long equations are included for reference purposes and may be bypassed by the reader. It is hoped that a conceptual, physical, and intuitive understanding of the operation of solar cells will emerge from studying this chapter. For more rigorous, mathematical, and formal treatments of this subject, readers should consult technical journals or other books, for example, Hovel (1975).

3.1 ELEMENTS OF SOLAR CELL OPERATION

Figure 3.1 illustrates the basic operation of a solar cell. Light photons are absorbed by the semiconductor and in the process generate electric-charge carriers called *electrons* and *holes*. Electrons and holes diffuse to a "junction," either a *pn* junction as illustrated in Fig. 3.1 or some other type of junction where a strong internal electric field exists. Electrons and holes are separated by the field and give rise to electric voltage and current in the external circuit. This scenario involves several topics that will now be discussed individually: semiconductors, light absorption and carrier generation, *pn* junction, cell current, cell voltage, and efficiency of energy conversion.

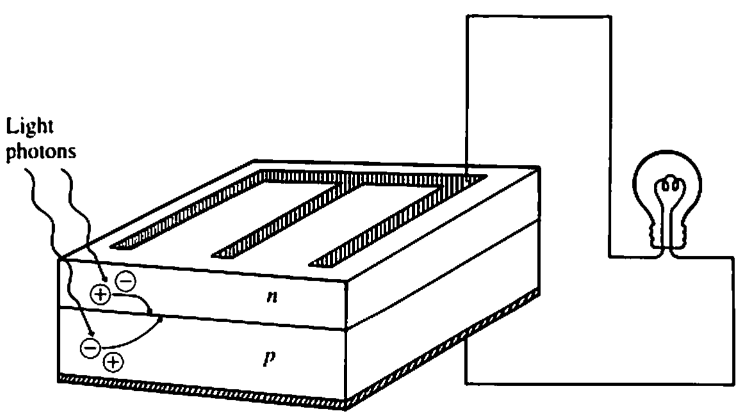


Figure 3.1 Positive and negative charge carriers are generated in a semiconductor as light photons are absorbed. These carriers, when collected by a *pn* junction, give rise to an electric current in the external circuit. Here, the current is shown to power a light bulb.

3.2 SEMICONDUCTORS

Good electrical conductors such as copper have conductivities in the range of 10^6 mho/cm (if 1 volt is applied to two opposing faces of a 1 cm × 1 cm × 1 cm copper cube, 10^6 amperes of current will flow between the faces). At the other extreme, good insulators such as quartz (SiO_2) have conductivities in the range of 10^{-16} mho/cm. Semiconductors have conductivities between these extremes in the range of 10^{-4} to 10^4 mho/cm. Furthermore, the conductivities of semiconductors may be changed within this range by adding small amounts of impurities, known as *dopants*, into the semiconductors. The conductivities of sufficiently pure semiconductors increase rapidly with rising temperature. These are the most easily identified traits of semiconductors.

Semiconductors may be elements such as silicon and germanium, or compounds such as cadmium sulfide (CdS) and gallium arsenide (GaAs), or alloys such as $Ga_xAl_{1-x}As$ where x may be any value between zero and one. Many organic compounds such as anthracene are also semiconductors (Gutmann and Lyons, 1967).

Many of the electronic properties of semiconductors can be explained with a simple model. Figure 3.2*a* shows the arrangement of silicon atoms in the silicon crystal. Silicon is a valence IV element and each atom has four electrons in the outermost shell. In a silicon crystal every atom has four nearest neighbor atoms, with each of which it shares two covalent electrons, thus completing the stable eight-electron shell. It takes 1.12 eV of energy, known as the *bandgap energy* of silicon, to separate an electron from the nuclei and create a free *conduction electron*. Conduction electrons are usually referred to simply as *electrons*. They can move freely and carry electric currents. The removal of an electron from a nucleus leaves behind a *hole* or a void. Electrons from neighboring atoms can fill this hole and thus cause the hole to move to a new site. This motion of the electrons naturally also carries electric current. It is easier to think of this conduction of current as due to the motion of positively charged holes in the opposite direction. The concept of a hole is analogous to that of a bubble in a liquid; although it is actually the

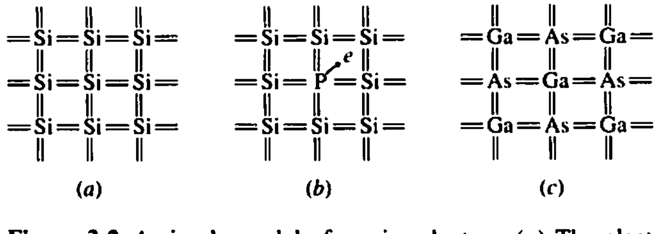


Figure 3.2 A simple model of semiconductors: (*a*) The electron bond diagram of pure Si. (*b*) The diagram of an *n*-type Si doped with phosphorous atoms. (*c*) The structure of GaAs.