Sunlight is a spectrum of photons distributed over a range of energy. Photons whose energy is greater than the band gap energy (the threshold energy) can excite electrons from the valence to conduction band where they can exit the device and generate electrical power. Photons with energy less than the energy gap fail to excite free electrons. Instead, that energy travels through the solar cell and is absorbed at the rear as heat. Solar cells in direct sunlight can be somewhat (20–30°C) warmer than the ambient air temperature. Thus, PV cells can produce electricity without operating at high temperature and without mobile parts. These are the salient characteristics of photovoltaics that explain safe, simple, and reliable operation.

At the heart of any solar cell is the *pn* junction. Modeling and understanding is very much simplified by using the *pn* junction concept. This *pn* junction results from the "doping" that produces conduction-band or valence-band selective contacts with one becoming the *n*-side (lots of negative charge), the other the *p*-side (lots of positive charge). The role of the *pn* junction and of the selective contacts will be explained in detail in Chapters 3 and 4. Here, *pn* junctions are mentioned because this term is often present when talking of solar cells, and is used occasionally in this chapter.

Silicon (Si), one of the most abundant materials in the Earth's crust, is the semiconductor used in crystalline form (c-Si) for 90% of the PV applications today (Chapter 5). Surprisingly, other semiconductors are better suited to absorb the solar energy spectrum. This puzzle will be explained further in Section 1.10. These other materials are in development or initial commercialization today. Some are called thin-film semiconductors, of which amorphous silicon (a-Si) (Chapter 12), copper indium gallium diselenide ($Cu(InGa)Se_2$ or CIGS) (Chapter 13), and cadmium telluride (CdTe) (Chapter 14) receive most of the attention. Solar cells may operate under concentrated sunlight (Chapter 11) using lenses or mirrors as concentrators allowing a small solar cell area to be illuminated with the light from larger area. This saves the expensive semiconductor but adds complexity to the system, since it requires tracking mechanisms to keep the light focused on the solar cells when the sun moves in the sky. Silicon and III-V semiconductors (Chapter 9), made from compounds such as gallium arsenide (GaAs) and gallium indium phosphide (GaInP) are the materials used in concentrator technology that is still in its demonstration stage.

For practical applications, a large number of solar cells are interconnected and encapsulated into units called PV modules, which is the product usually sold to the customer. They produce DC current that is typically transformed into the more useful AC current by an electronic device called *an inverter*. The inverter, the rechargeable batteries (when storage is needed), the mechanical structure to mount and aim (when aiming is necessary) the modules, and any other elements necessary to build a PV system are called the *balance of the system* (BOS). These BOS elements are presented in Chapters 17 to 19.

1.3 SIX MYTHS OF PHOTOVOLTAICS

Borrowing a format for discussing photovoltaics from Kazmerski [2], in this section, we will briefly present and then dispel six common myths about photovoltaics. In the following sections, we identify serious challenges that remain despite 40 years of progress in photovoltaics.

The six myths are as follows:

1. *Photovoltaics will require too much land area to ever meet significant fraction of world needs*:

   Solar radiation is a rather diffuse energy source. What area of PV modules is needed to produce some useful amounts of power? Let's make some very rough estimates to give answers that will be accurate within a factor of 2. Using methods described in detail in Chapter 20 (especially equations 20.50 and 20.51 and Table 20.5), one can calculate how much sunlight falls on a square meter, anywhere in the world, over an average day or a year. We will use an average value of 4 kilowatt-hrs (kWh) per m^2 per day to represent a conservative worldwide average. Now, a typical PV module is approximately 10% efficient in converting the sunlight into electricity, so every square meter of PV module produces, on average, $4 \times 0.1 = 0.4$ kWh of electrical energy per day. We can calculate the area in m^2 needed for a given amount of electrical energy E in kWh by dividing E by 0.4 kWh/m^2. (Chapter 20 contains much more detailed methods to calculate the incident sunlight and the PV module output as a function of time of day, month of year, etc.)

   Let us consider three different-sized PV applications: a family's house in an industrialized country, replacing a 1000 MW (megawatt) coal or nuclear powered generating plant, or providing all the electricity used in the USA.

   First, for a typical family, let us assume that there are four people in the house. Figure 1.1 shows a range of electricity usage for the industrialized countries. Let us use 6000 kWh/person/year as an average. But, this includes all their electrical needs including at work, at school, as well as the electricity needed for manufacturing the products they buy, powering their street lights, pumping water to their homes, and so on. Since people spend about a third of the day awake in their home, let us assume that a third of their electrical needs are to be supplied in their home, or 2000 kWh/person/year. Dividing this by 365 days in a year gives about 5 kWh/person/day, or 20 kWh/day per family of four. This is consistent with household data from various sources for the US and Europe. Thus, they would need 20 kWh/0.4 kWh/m^2 or 50 m^2 of solar modules to provide their electrical power needs over the year. Thus, a rectangular area of solar modules of 5 by 10 meters will be sufficient. In fact, many roofs are about this size, and many homes have sunny areas of this size around them, so it is possible for a family of four, with all the conveniences of a typical modern home, to provide all their power from PV modules on their house or in their yard.

   Next, how much land would it take to replace a 1000 MW coal or nuclear power plant that operates 24 hours/day and might power a large city? This would require 10^6 kW $\times$ 24 hr/(0.4 kWh/m^2) or 6×10^7 m^2. So, with 60 km^2 (or 24 square miles) of photovoltaics we could replace one of last century's power plants with one of this century's power plants. This is a square 8 km (or 5 miles) on a side. For the same electricity production, this is equivalent to the area for coal mining during the coal powered plant's life cycle, if it is surface mining, or three times the area for a nuclear plant, counting the uranium mining area [3]. This is also the same area required to build a 600 km (373 miles) long highway (using a 100 m wide strip of land).

   Finally, we can calculate how much land is needed to power the entire US with photovoltaics (neglecting the storage issue). The US used about 3.6×10^{12} kWh of electricity in 2000. This could be met with 2×10^{10} m^2. If we compare with the area of paved roads across the country, of about 3.6×10^6 km and assume an average width of 10 m this leads to 3.6×10^{10} m^2. It is to be concluded that all the electricity needed in the US can be met by covering the paved roads with PV modules. Of course, no one is seriously proposing this action. We use the road analogy to show that if society wanted, it could establish land use priorities favorable to photovoltaics just as it has done to accommodate the ubiquitous automobile. We are certain that each state could find areas of unused land around airports, parking spaces, rooftops, highway dividing strips, or desert land that could be used for photovoltaics.

These simplistic "back-of-the-envelope" calculations show that having enough area for PV modules is not a limit for a homeowner or a large city. Certainly, there are sunny places in every country that could be used for generating significant amounts of PV power. As will be evident in other chapters, it is the initial cost of the photovoltaics, not the amount of land that is the primary barrier to be overcome.

2. *Photovoltaics can meet all of the world's needs today if we would just pass laws requiring photovoltaics and halting all fossil and nuclear plants*:

   Besides the difficulty of convincing the people's representatives to pass such a law, the first technical problem faced would be the intermittent nature of the solar radiation, available only during the day and strongly reduced in overcast skies. Energy storage would solve this problem but no cheap storage method appears on the horizon. Nevertheless, well-developed electric grids may accept large amounts of PV electricity by turning off some conventional power plants when PV plants are delivering power. Adequate grid management would allow up to 20 to 30% of the electric production to be intermittent [4].

   But now for a dose of reality. The cumulative production of PV modules up to the year 2002 is about 2000 MW. Thus, if you took all of the PV panels that were ever made up to and including the year 2002, and put them all in the same sunny place at the same time, they would generate enough electricity to displace about one of last century's 500 MW smoke- or radioactive-waste–producing power plants. (This assumes that the solar plant would operate at full output for an equivalent of six hours per day owing to the daily variation in sunlight). Clearly, if we want photovoltaics to make any meaningful contribution to the world's energy supply, very massive increases in manufacturing capacity are needed. Additionally, PV electricity is very expensive, presently between 5 to 10 times more expensive than conventional alternatives. Mass use of PV electricity today could produce significant negative distortion of the economic system.

   Thus, requesting the immediate and exclusive use of photovoltaics is not feasible technically or, probably, economically. It would also be socially unacceptable.

3. *Photovoltaics cannot meet any significant fraction of world needs. It will remain a small-scale "cottage" industry that will only meet the needs of specialty markets like remote homes in developing countries or space satellites*:

   Figure 1.3 shows the evolution of markets associated with different applications [5]. Some used to be considered as *specialty* markets, for example, the category of "world off-grid power" which is trying to supply power to the $\sim$1/3 of the world's citizens who lack it. The grid-connected market, whose growth has been meteoric in the past decade, is by no means a small market. Ironically it is the large-scale (recently awakened) centralized power plant market which is the smallest "specialty" application in today's world. Thus, evidence from the recent past tends to refute

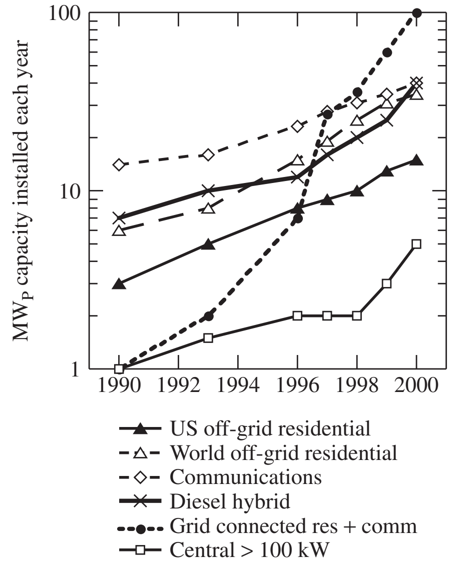

Figure 1.3 Trend in worldwide PV applications (From Reference [5] Maycock P, *Renewable Energy World* **3**, 59–74 (2000)

the modest forecasts that some attribute to photovoltaics. We shall come to this point again.

4. *No more R/D is needed since PV technology has demonstrated the technical capability to perform, so we should stop all public funding and let the economic markets decide if it is worthwhile*:

    The present cost of photovoltaics is affordable for certain markets but it is still too high to actually compete with conventional electricity. If PV technology is to be promoted for environmental or social reasons, public subsidy to R&D and to installation will be necessary to stimulate production and thereby reduce costs. Without continued subsidies, photovoltaics will probably remain as a specialty cottage industry for the next half century.

    Public support for photovoltaics is one of the major factors compelling politicians to fund R&D. This funding had been comparable to PV sales in the 1980s, as shown in Figure 1.4. Private funding has doubled this public support so that PV companies themselves have also heavily supported the development of photovoltaics. After two decades of constant investment in a promising market that was slow to actually start, the market finally awoke and became one of the fastest growing in the world by the beginning of the twentieth century, with sales now greatly exceeding public investment.

    But, this fast growing market is still dependent on public/government funding. As with many goods and services (e.g. military hardware, commercial air travel), photovoltaics is partly publicly financed. In Germany or in Japan, for instance, significant public support is being given to grid-connected installations. If photovoltaics is going to become a major energy contender, the countries where the support has been lacking will remain technologically inferior with respect to those, where the support has

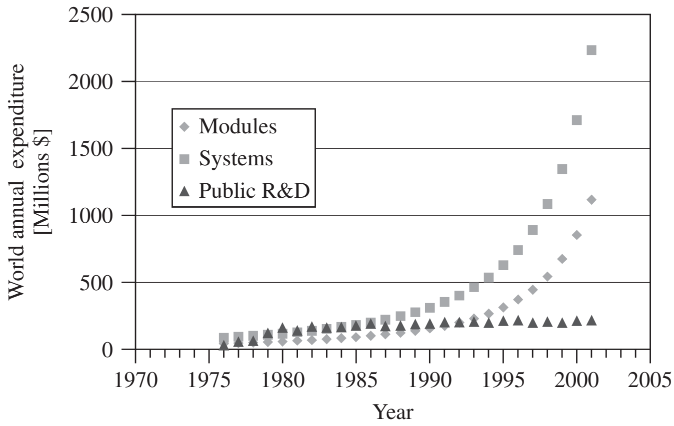

Figure 1.4 Public funding for R&D (triangles) compared to module (diamonds) and system (squares) sales. (This curve is drawn from the data of Eckhart *et al*. in Chapter 24, "Financing PV Growth", in this book)

been stronger. This should be taken into account while making decisions about energy policy and public or private financing.

The critical question then is: Should the support be focused in R&D, or is PV technology already mature enough (as many claim) to focus on the cost reduction via the economy of scale permitted by the larger volume of production required by a subsidized market? This point will be discussed latter in this chapter.

5. *Photovoltaics is polluting just like all high-technology or high-energy industries only with different toxic emissions*:

   One of the most valuable characteristics of photovoltaics is its well-deserved image as an environmentally clean and "green" technology. This healthy image obviously results from the cleaner operation of a PV electricity generator compared to a fossil-fuel fired generator, but this must also extend to the manufacturing process itself as well as the recycling of discarded modules. Manufacturing of PV modules on a large scale requires the handling of large quantities of hazardous or potentially hazardous materials (e.g. heavy metals, reactive chemical solutions, toxic gases). Let it be stated at the beginning that the present Si-based PV technology which dominates the market has few environmental concerns and is considered totally safe to the public.

   The PV industry is very aware of the value of its clean "green" image and has worked hard over the years to establish and maintain high standards of environmental responsibility [6, 7]. Conferences on PV Safety and Environmental Issues have been held since the late 1980s and their proceedings have been published [8, 9]; the PV Environmental Health Safety Assistance Center at Brookhaven National Laboratory in New York, USA provides worldwide leadership in risk analysis and safety recommendations for the PV industry [10].

   Safe handling procedures for some of the materials and processes were already well established from the integrated circuit or glass coating industries. But in the case of unique materials and processes, safety procedures had to be developed by the PV industry. This is especially true of the thin-film technologies [11]. The PV industry recognized early that being proactive and designing safety into the process, from the beginning, was the responsible thing to do and would ultimately result in reduced costs. The international nature of the PV industry introduces some variability in the standards which must be met.

Hazards can be classified by whether they affect workers at a PV manufacturing plant, customers with photovoltaics on or near their homes, or the public who consumes air and water near the PV plant. The population with greatest potential health risks are employees in PV manufacturing. Very little risk is associated with the public or the PV owner or installer. Among the most heavily studied issues unique to the PV industry is the potential toxicity of semiconductor CdTe and the safe usage of hydride gases AsH_3, SiH_4, GeH_4, PH_3, B_2H_6, and H_2Se, which are used in the growth of GaAs, a-Si, a-SiGe, and $Cu(InGa)Se_2$ layers. There has been considerable research and risk analysis of CdTe as a PV material [12–14]. The general conclusion is that CdTe in modules does not pose a risk to the public. Similarly, procedures and hardware ensuring safe usage of the hydride gases listed above have been well established in both the electronics and PV industries [15].

Environmental monitoring of the workplace for hazardous levels in the air or on surfaces, and biological monitoring of the employee for evidence of exposure should be routine. Once the module is manufactured, the only way for the public to be exposed to hazardous materials existing in some kind of modules is by absorbing them via ingestion or inhalation. Accordingly, accidental human absorption is not at all likely. Even in event of a house fire, studies have shown that PV modules do not release any potentially hazardous materials [16].

A related issue is what to do with thin film PV modules at the end of their projected 25- to 30-year life. An excellent strategy is to recycle the modules. This solves two problems at once, namely, keeping potentially hazardous materials out of the environment and reducing the need for additional mining and/or refining of new materials. Semiconductor vendors have indicated a willingness to accept used modules, and to extract and purify the CdTe, CdS, or $Cu(InGa)Se_2$ for resale and reuse [17, 18].

Thus, we can say with confidence that photovoltaics is nearly the cleanest and safest technology with which to generate electricity. It is especially true of the present Si technology.

6. *PV modules never recover all of the energy required in making them, thus they represent a net energy loss*:

The focus of photovoltaics is on generating energy (specifically electrical energy) with many beneficial characteristics as noted in Table 1.1. Among those who envision photovoltaics having an increasingly larger role in producing the world's electricity, there is awareness that photovoltaics must produce much more energy than was required to produce the PV system. Otherwise, it would be a net energy loss not a net energy source. The "energy payback" has been widely studied. It is described in terms of how many years the PV system must operate to produce the energy required for its manufacture. After the payback time, all of the energy produced is truly new energy.

This topic is discussed in Chapter 21. An excellent review has been given by Alsema [19]. In general, results of several studies have arrived at some general conclusions. Specific payback times have ranged from 3 to 5 years for crystalline Si and 1 to 4 years for thin films. For crystalline Si, forming the crystalline Si wafers is the major energy requirement. For thin films, the semiconductor layers are 100 times thinner, and deposited at ~1000°C lower temperature, so their energy requirement is negligible, in comparison. Instead, it is the energy embodied in the glass or stainless steel substrate, which is the major energy sink. Also, a seemingly insignificant component, the cosmetic Al frame around the module, is responsible for a surprisingly large fraction of energy. In fact, this can be the dominant energy sink for thin-film a-Si or $Cu(InGa)Se_2$ modules [20, 21]. Although thin-film modules have a shorter energy payback, they also have lower efficiency, which means a larger BOS is needed to support the larger number of modules. Thus, a larger amount of energy is embodied in the BOS for thin-film photovoltaics compared to crystalline Si photovoltaics.

The case of concentrators is less studied, but again the use of semiconductor is reduced and the BOS becomes more important than even for the thin films because the concentrating structures are very massive. However, their efficiency is higher. In summary, we can guess that in this case the situation will be similar to the case of thin films.

1.4 HISTORY OF PHOTOVOLTAICS

The history of photovoltaics goes back to the nineteenth century, as shown in Table 1.2. The first functional, intentionally made PV device was by Fritts [22] in 1883. He melted Se into a thin sheet on a metal substrate and pressed a Au-leaf film as the top contact. It was nearly 30 cm^2 in area. He noted, "the current, if not wanted immediately, can be either stored where produced, in storage batteries, ... or transmitted a distance and there used." This man foresaw today's PV technology and applications over a hundred years ago. The modern era of photovoltaics started in 1954 when researchers at Bell Labs in the USA accidentally discovered that *pn* junction diodes generated a voltage when the room lights were on. Within a year, they had produced a 6% efficient Si *pn* junction solar cell [23]. In the same year, the group at Wright Patterson Air Force Base in the US published results of a thin-film heterojunction solar cell based on Cu_2S/CdS also having 6% efficiency [24]. A year later, a 6% GaAs *pn* junction solar cell was reported by RCA Lab in the US [25]. By 1960, several key papers by Prince [26], Loferski [27], Rappaport and Wysoski [28], Shockley (a Nobel laureate) and Queisser [29], developed the fundamentals of *pn* junction solar cell operation including the theoretical relation between band gap, incident spectrum, temperature, thermodynamics, and efficiency. Thin films of CdTe were also producing cells with 6% efficiency [30]. By this time, the US space program was utilizing Si PV cells for powering satellites. Since space was still the primary application for photovoltaics, studies of radiation effects and more radiation-tolerant devices were made using Li-doped Si [31]. In 1970, a group at the Ioffe Institute led by Alferov (a Nobel laureate), in the USSR, developed a heteroface GaAlAs/GaAs [32] solar cell which solved one of the main problems that affected GaAs devices and pointed the way to new device structures. GaAs cells were of interest due to their high efficiency and their resistance to the ionizing radiation in outer space. The year 1973 was pivotal for photovoltaics, in both technical and nontechnical areas. A significant improvement in performance occurring in 1973 was the "violet cell" having an improved short wavelength response leading to a 30% relative increase in efficiency over state-of-the-art Si cells [33]. GaAs heterostructure cells were also developed at IBM in