PART I

INTRODUCTION TO SOLAR CELLS

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SOLAR CELLS: A BRIEF HISTORY AND INTRODUCTION

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1.1 BRIEF HISTORY

The history of the solar cell is really quite interesting [1]. In 1839, Edmond Becquerel found that two different brass plates immersed in a liquid produced a continuous current when illuminated with sunlight. We now believe that he had made a copper-cuprous oxide thin-film solar cell. Later in the 1870s, Willoughby Smith, W. G. Adams, and R. E. Day discovered a PV effect in selenium. A few years later, an American named C. E. Fritts placed a sheet of amorphous selenium on a metal backing and covered the selenium with a transparent gold leaf film. He reported that this selenium array produced a current "that is continuous, constant, and of considerable force—with exposure to sunlight." At the time, there was no quantum theory and there was considerable skepticism about his claim of converting sunlight into electricity. So he sent a sample to Werner Siemens in Germany, who was one of the most respected experts in electricity at the time. Siemens's observation verified Fritts's claims. However, the conversion efficiencies of both the thin-film cuprous oxide and the amorphous selenium solar cells were less than 1%.

Around 75 years passed while quantum mechanics was discovered, the importance of single-crystal semiconductors was recognized, and p/n junction behavior was explained (see Chapter 3). By 1954, Chapin et al. [2] at Bell Labs had discovered, invented, and demonstrated the silicon single-crystal solar cell with 6% efficiency. Over the few following years, researchers brought the silicon solar cell efficiency up to 15%. The timing was fortunate because Sputnik was launched in 1957 and solar cells were the perfect lightweight low-maintenance remote electric power source. Today, silicon solar cells are being used to power the space station.

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The solar cell industry remained small until the first Arab oil embargo in 1973. Up until that time, the solar cell industry established a firm foothold with low-level but consistent cell and array production and performance. During those first 20 years, reliability was the driver and cost was not as important. After 1973, the flat-plate silicon module was brought down to earth and modified for weather resistance. This transition also included major improvements in cell and module fabrication that brought down costs dramatically (Fig. 2.3, chapter 2). Flat-plate "champion" silicon cell efficiencies (defined in Section 2.1, Chapter 2) have improved to values as high as 25%. Production module efficiencies have improved from around 10% for early modules to as high as 19% today (SunPower Corporation). Most important, annual production quantities have grown dramatically. Worldwide production exceeded 1 GW/year in 2002 and rose to over 3.8 GW/year by 2006 (Fig. 2.1, Chapter 2).

In the late 1970s, it was discovered that good cells could be made with multicrystalline wafers as long as the crystal size is at least 20 times larger than the optical absorption length [3]. Only those carriers within an optical absorption length from the crystal boundaries are lost. This is less than 5% of the carriers. Typical production quantity multicrystalline cell efficiencies are around 14%, whereas comparable single-crystal cells have efficiencies around 15%. By 2007, modules with multicrystalline cells accounted for about 45% of sales and modules with single-crystal cells accounted for about 40% of sales. Planar silicon cell modules dominated the market in 2007 because of their early well-funded foundation years for space satellites and their huge learning curve support (Fig. 2.3, Chapter 2) from single-crystal silicon and integrated circuit technology development.

While silicon-based cells still dominate the solar cell electricity market today, several other cell types have now entered the market. (Solar cells are also known as PV cells.) These newer cell types have added diversity in potential applications as well as offered alternate paths to lower-cost solar electric power. These alternate cell types include hydrogenated amorphous silicon, cadmium teluride and CIGS thin-film cells (Chapter 6), as well as concentrator cells with efficiencies as high as 41% (Chapters 13–17).

1.2 APPLICATIONS AND MARKETS

In the late 1970s and early 1980s, the traditional solar cell electricity applications [4] were at remote locations where utility power was unavailable, for example, campers and boats, temporary power needs for disaster situations, and power for remote communication station repeaters. In the late 1980s and early 1990s, solar cells began to be routinely used to provide site-specific energy for urban and suburban homes, office buildings, and a multitude of other mainstream grid-connected applications. Also, solar cell electricity systems have become very important sources of energy in the developing world. Today, for an increasing number of power needs, solar cell electricity is the cheapest and best way to generate electricity.

In addition to the solar power arrays on space satellites, there are now many different types of PV systems used here on Earth including

1. remote stand-alone without battery storage,
2. remote stand-alone with battery storage,
3. small modules for calculators and toys,
4. residential grid connected with DC to AC inverter,
5. commercial grid connected with inverters, and
6. PV fields for utility power generation.

Remote solar water pumping is a nice example of stand-alone solar cell electricity where batteries are not needed. Solar water pumping is very desirable for crop irrigation, livestock watering, and clean water for remote villages. Solar water pumping systems are now installed around the world. The nice thing about this application is that underground water is pumped when the sun is shining. It can be immediately used for crop irrigation. In other areas, it can be pumped into tanks for livestock to drink. In third world countries, pumping underground water for people to drink provides cleaner water than surface water thereby limiting disease. This application is quite economical because the system is simple. Battery storage or DC to AC conversion is not necessary. Simple solar trackers are used to maximize pumping time. The electric motors driving the pumps have a threshold current that must be provided before they will operate. By tracking the sun, this power is provided from dawn to dusk, not just at around noon as would be the case without tracking. Another application where there is a good match with demand is for air conditioning in developed countries like the United States.

For many remote applications, storage is needed to store electric energy for when it is needed. Examples of these applications include off-grid cabins and remote communication repeater stations. For most solar cell applications where storage is needed, secondary or storage batteries are the best alternative. Generally, batteries should be deep discharge batteries such as marine batteries or motive power batteries. Forklift trucks and golf carts use large-capacity deep discharge batteries that are designed for long life and many discharge cycles. In addition to batteries, combination systems can be used to compensate for the fact that the sun does not always shine. A solar/wind combination is particularly good since quite often, either one or the other is available. Another combination system can be a solar–thermal cell electricity system. In this case, solar cells are located on your roof for generating electricity in the summer and infrared-sensitive PV cells (also known as TPV cells) are integrated into your heating furnace to generate electricity when it is cold and dark outside and you need heat to keep warm. In a TPV cell electricity system, a ceramic element is heated in the furnace flame and its glow in the infrared is converted to electricity by infrared-sensitive TPV cells [5].

Solar-powered calculators are another familiar application for solar cells. While the efficiencies of amorphous silicon solar cells are much lower than either single or multicrystalline cells, an advantage for thin-film cells is that they can be made with cell interconnections built into the process. This means that for applications like powering calculators where voltage but little current is required to run the calculator, amorphous silicon circuits are preferred to save on the cost of interconnecting multiple cells to provide voltage. Credit is due to the Japanese for recognizing this advantage and to the inventors of the amorphous silicon solar cell for making solar cells a common household item [6].

Today, more and more homes on the grid are using solar cell arrays to generate electricity to save on costs of peak electric power. The passage of the PURPA by the U.S. Congress made it possible for a small producer to install generating systems and to sell the power to the utility at a favorable price without the enormous amount of red tape usually required of a new electric power producer. Most states have now also passed net metering laws that allow the electric meter at a home to run both directions. However, at least in California, the utility charge can at most be reduced to zero and they never pay any net money to their customers who produce more electricity than they consume. This allows homeowners generating solar cell electricity to send energy to the grid if they are producing excess electricity with a credit from the utility so that they can use electric power from the grid on days without sufficient sunlight. An example of real cost savings with a solar cell electricity installation for a homeowner in San Jose, California, is shown in Figure 1.1 [7].

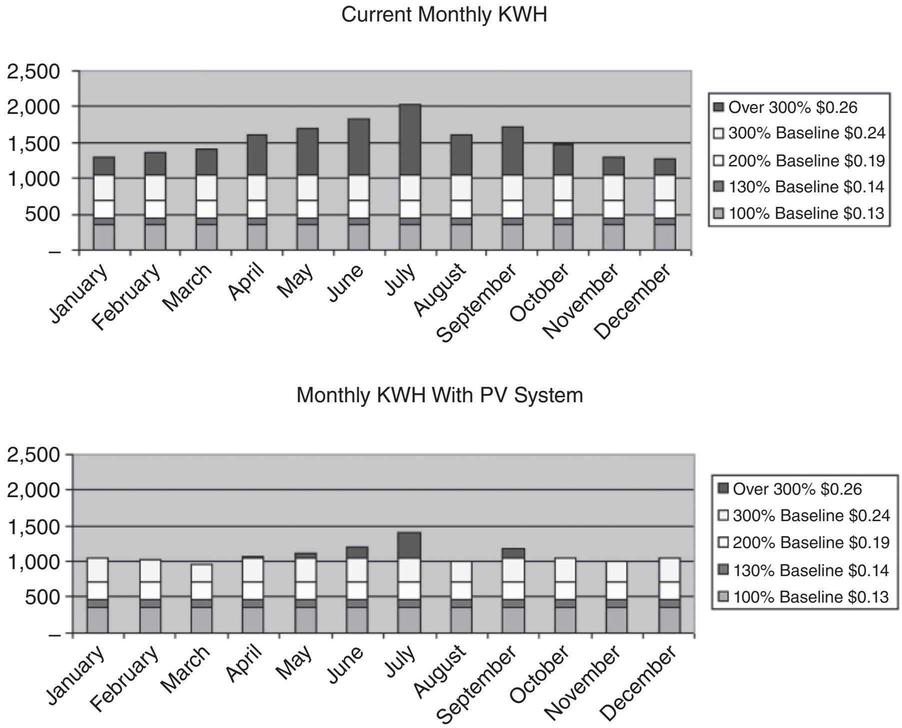

Figure 1.1. When electric utility rates are staged, a homeowner with solar can displace electricity at the peak power rate as illustrated here. This example was originally presented by Akeena Solar on their web site in 2003 and then published in reference [7].

Figure 1.1 is for an actual case in 2003. Note in this figure that the utility electric rates are staged. While the homeowner pays a base rate of 13¢ per kilowatt hour that in itself is well above the national average. More importantly, the homeowner is paying twice that or 26¢ per kilowatt hour for his peak power. So his solar electric system is saving him money at the 26¢ per kilowatt hour rate.

While the grid-connected solar cell electricity market started with residential customers, commercial customers are now starting to use solar arrays on their flat building rooftops. Figure 1.2 shows a photograph of two 1-kW solar cell arrays on a flat rooftop in Spokane, Washington. These arrays are mounted on carousel solar trackers (Chapter 9).

People have been dreaming of the potential of solar cell electricity systems as a major electric power source for over 100 years. Now with the existence of solar power fields such as the one in China shown in Figure 1.3, this dream is becoming reality.

Figure 1.2. Two-kilowatt PV array from JX Crystals Inc on a commercial building flat rooftop.

Figure 1.3. Solar cell electricity generating field in Shanghai, China. System designed by JX Crystals Inc.

1.3 TYPES OF SOLAR CELLS AND MODULES

Unfortunately, solar cell electricity is still too expensive for widespread economical use (Section 2.4, Chapter 2). While it is hoped that traditional crystalline silicon module prices will continue to fall, there are other alternatives under development as shown in Figure 1.4.

Figure 1.4 shows the three types of solar modules in use today [8]. The upper section (Figure 1.4a) of this figure shows the planar single-crystal silicon modules and fabrication procedure. This approach dominates the solar market today with over 85% of solar modules sold. As shown in Figure 1.5, retail module prices have

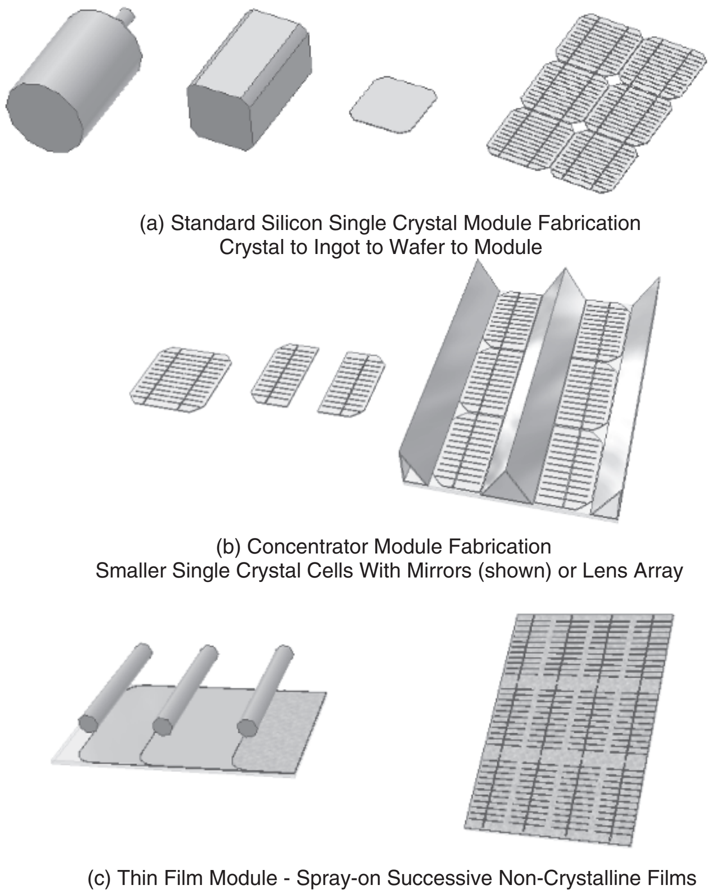

Figure 1.4. Alternate PV module types: (a) standard silicon single-crystal module fabrication, crystal to ingot to wafer to module; (b) concentrator module fabrication, smaller single-crystal cells with mirrors (shown) or lens array; and (c) thin-film module, spray-on successive noncrystalline films.

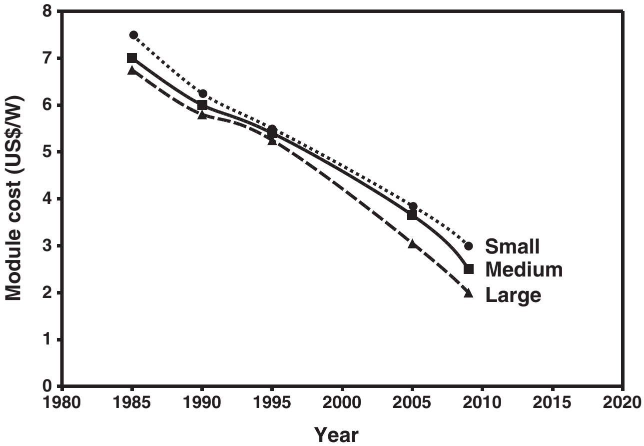

Figure 1.5. Solar module prices for small, medium, and large volumes from 1985 through 2009. All values in then current dollars without inflation adjustments (from Photovoltaics World, September 2009).

been falling dramatically recently. Wholesale module prices are substantially lower than retail prices. The silicon cell cost accounts for about 75% of the module cost with the cost of the glass, frame, junction box, and labor accounting for the remaining approximately 25%.

The lower section of Figure 1.4c shows a thin-film module. This concept is attractive because thin films require up to 100× less semiconductor material and offer a promise of lower costs per watt. Since single-crystal material is expensive, why not replace it with inexpensive thin films? The challenge is accommodating their lack of crystallinity. The latter degrades conversion efficiency, which, if too severe, limits their abilities to compete economically in the marketplace (Figs. 2.8 and 2.9 and accompanying text, Chapter 2). An appeal of multicrystalline silicon solar cells is that they offer lower manufacturing costs while still maintaining a conversion efficiency at least two-thirds that of the single-crystal ones [9] of similar Jet Propulsion Laboratory-like configurations (see Chapter 2). However, there are other useful thin-film applications, particularly for amorphous silicon, where its unique properties offer particular advantages and where high quantum efficiency but not high light conversion efficiency is a dominant factor. An example of this is use of amorphous silicon cells in medical imaging (Chapters 22–25) as shown in Figure 1.6. Here, the complete absence of crystallinity in amorphous silicon provides strong radiation damage resistance, and its higher bandgap (than crystalline silicon) gives lower dark currents. These are two strong advantages in the field of flat-plate, digital X-ray imagers that have almost totally replaced analog X-ray film. Recently, amorphous silicon imagers have also begun to displace many of the vacuum tube-based image intensifiers traditionally used in X-ray fluoroscopy. Both X-ray film and intensifier fluoroscopy replacements typically use a thin scin-

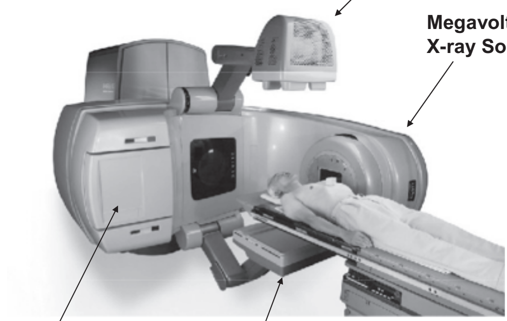

Figure 1.6. Medical imaging system using amorphous silicon solar cell modules.

tillator film to convert the incident X-ray photons into visible light that the underlying amorphous silicon cells efficiently convert into electronic signals that are readily digitized. Frequently, the amorphous silicon solar cells (or pixels) measure a few hundred microns on a side, and millions of them form the rows and columns of a single X-ray imager plate. Such plates provide the digitized X-ray images at up to 30 frames/s and higher.

The difficulty with module approaches (a) and (c) in Figure 1.4 is that one tries to obtain both low cost and high efficiency with the same element. In the approach shown in Figure 1.4b, one separates the two requirements of low cost and high performance into two separate elements. The single-crystal cells are the high-efficiency converters used sparingly, while mirrors or lenses are used to concentrate the sunlight onto the cells. The aluminum mirrors (or alternately glass or plastic lenses) are relativley inexpensive. For the case shown in Figure 1.4b, the cell cost is halved. The aluminum mirrors cost at least 10 times less than the single-crystal cells. In this approach, the sunlight is concentrated onto the expensive high-efficiency single-crystal cells diluting their cost. This approach is now termed CPV. In Figure 1.4b, the sunlight intensity on the cell is doubled; that is, the concentration ratio is 2. Chapter 12 describes a configuation similar to the mirror configuration in Figure 1.4b with a concentration ratio of 3. Various concentration ratios are possible up to as high as 1000. A negative for this approach is that the modules must be aimed at the sun using solar trackers. Trackers by themselves are not a negative as the additional kilowatt per hour per installed kilowatt pays for the trackers. However, when high-concentration optical elements are used, only the direct sunlight is collected. This limits CPV to very sunny locations. However, in any case, solar cell electricity in general will be most economical first in very sunny locations such as the Southwestern United States.

1.4 ARGUMENTS FOR SOLAR CELL ELECTRIC POWER

While solar cell electricity is still expensive today, there are three strong arguments for national programs to accelerate its transition into a mainstream power source. The first argument is that there is a logical path for future lower costs for solar electricity. There are three simple steps that will lead to lower cost given development and manufacturing scale-up. These steps are based on technical breakthroughs that have now been made.

In step 1, given that the cost of solar electricity today (August 2009) is about 20¢ per kilowatt hour (Solarbuzz) for commercial-sized systems for fixed flat-plate systems in the sunny Southwestern United States, by implementing solar trackers where the modules continuously point at the sun, one can gain 1.3 times more kilowatt hour per installed kilowatt, reducing the cost of solar electricity to about 16¢ per kilowatt hour. This is already being done as evidenced in Figures 1.2 and 1.3 [10].

Step 2 is then to decrease the module cost while maintaining its performance by using lower-cost optical elements as shown in Figure 1.4b. This CPV approach by itself can potentially reduce the system cost for solar electricity to under 10¢ per kilowatt hour (see Chapter 12) [10].

In step 3, one then increases the module efficiency in the CPV approach to well over 20%. As described in Chapter 3, this should reduce the cost of solar electricity still further. "Champion" CPV module efficiencies as high as 31% [11] have now been demonstrated including the one shown in Figure 1.7. While logic suggests these lower costs, this will depend on funding for manufacturing scale-up and government top-down commitment.

Actually, there are multiple approaches for CPV ranging from LCPV systems using linear mirrors with silicon cells as shown in Figure 1.4b to HCPV systems

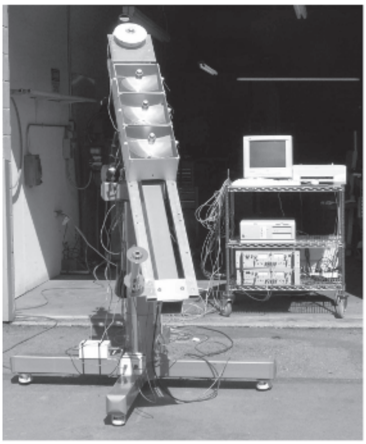

Table III: Performance Summary

	Packaged Cells at STC	Projected STC with 90% Optical Effic	Measure at Operate Temp (April 28)	Measure Module at STC (April 28)
DJ Cell Power	17.4 W	15.7 W	14.4 W	15.1 W
DJ Cell Effic.	31.5%	28.4%	26.1%	27.3%
IR Cell Power	3.64 W	3.28 W	2.6 W	3.1 W
IR Cell Effic.	6.6%	5.9%	4.7%	5.6%
Sum Power	21 W	19 W	17 W	18.7 W
Sum Effic.	38.1%	34.3%	30.8%	32.9%

NIP DNI = 0.92; Area = 600 cm2; Input Power = 55.2 W

Figure 1.7. Prototype CPV module with demonstrated outdoor module efficiency of 31%.

with newer semiconductor materials [12] such as the one shown in Figure 1.7. These LCPV and HCPV systems will be described in more detail in Chapters 12–17.

Of course, while the above three steps can be implemented, this still requires investment and political commitment. This leads us to our next two arguments in favor of national programs to accelerate the penetration of solar cell electricity into the mainstream energy mix.

The second reason relates to the fact that oil and natural gas resources are being depleted. Quoting from Kenneth Deffeyes's [13] book titled *Hubbert's Peak: The Impending World Oil Shortage*, "In 1956, the geologist M. King Hubbert predicted that U. S. oil production would peak in the early 1970s. Almost everyone inside and outside the oil industry rejected Hubbert's analysis. The controversy raged until 1970 when the U.S. production of crude oil started to fall. Around 1995, several analysts began applying Hubbert's method to world oil production, and most of them estimated that the peak year for world oil will be between 2004 and 2008. These analyses were reported in some of the most widely circulated sources: *Nature*, *Science*, and *Scientific American*" [14]. The 2008 peaking of world oil prices to record levels above $140 per barrel seems to support these predictions. The war in Iraq that began in 2003 was likely influenced, at least in part by the shortage of proven U.S. oil and natural gas reserves that could only last 3.0 and 7.5 years, respectively, should the United States have to depend only on its own reserves [15].

The consequence of this "impending world oil shortage" is that electricity prices are going to be rising probably abruptly within the next 5–10 years. This affects the economics of solar cell electricity as solar modules based on semiconductor devices will last for 25 years or longer. Today's cost competition calculations for solar cell electricity usually assume a short-term payback and non-escalating energy prices.

The third argument in favor of bringing solar cell electricity into the mainstream is the environmental and moral argument. It is desirable to avoid global warming as well as oil related war.

When one thinks about conventional electric power production, one thinks about oil, natural gas, nuclear, and coal as fuel sources. Solar cell electricity is not on this list because it is currently too expensive. However, these conventional fuel sources have hidden unintentional costs.

For example, nuclear fuels are coupled with nuclear waste management and nuclear weapons. Then nuclear waste and nuclear weapons are coupled with the cost of homeland security and our fear of weapons of mass destruction. There are hidden costs involved in attempting to guarantee that nuclear materials do not find their way into the hands of terrorists.

Another example of hidden costs is the world's dependence on oil from the Middle East that is linked unavoidably, particularly in the United States and in other developed countries, with terrorists from the Middle East. It can arguably be claimed that wars have now been fought in the Middle East to secure oil supplies.

In contrast to the unintended costs just enumerated, consider solar energy. Solar energy is inevitable on the larger scale of time. Solar energy is really already a primary energy source through wind and hydroelectricity. Solar energy generated our coal, oil, and natural gas via photosynthesis a hundred million years ago. Solar cells are very much more efficient than plants at converting sunlight to useful energy. Finally, solar energy is benign and will benefit the whole world.

1.5 ABOUT THIS BOOK

The first edition of this book [16] was published in 1995 and can serve as a reference for this second edition. This second edition is divided into four main parts. Part I is an introduction to the current markets, cell and module types, and the physics of solar cell operation. The solar cell electricity market has grown appreciably over the last 14 years as described in Chapter 2. The basics of solar cell operation are presented for single-crystal cells and for thin-film cells in Chapters 3 and 4.

Part II of this book focuses on the status of solar cell systems today. Single and multicrystalline silicon and thin-film cells and modules are described in Chapters 5 and 6. Over the last 3 years, silicon module automated manufacturing is coming online with the promising major cost reductions. The traditional and currently dominant silicon module manufacturing, now with automation, is described in Chapter 7. Also, over the last 3 years, China has made a major commitment to solar module manufacturing, and the status of solar electricity in China is described in Chapter 8. A major cost reduction for solar cell electricity comes through the use of solar trackers as described in Chapter 9. Large multi-MW solar cell field installations are then described in Chapters 10 and 11.

Part III of this book then describes newer concentrated solar cell and system developments. Chapters 12–17 describe various concentrator solar cell electricity (also known as CPV) modules and system types and installations. Major developments have been taking place here over the last 3 years and that potentially could lead to major cost reductions over the next 5 years.

While it remains to be seen if thin-film solar modules can produce electricity at rates competitive with other mainstream electricity generating technologies, nevertheless, amorphous silicon thin-film panels have found a place in other applications and in major markets like flat panel displays and medical imagers. The fourth part of this book describes successful applications of thin film technology as a spin-off from solar cell electricity. Chapters 22–25 then discuss the newest and rapidly growing applications of amorphous silicon thin films in X-ray imaging.

The issue of the cost of solar cell electricity, solar modules, and solar systems is a very important subject addressed from various points of view in Chapters 2, 3, 10, 11, 20, and 26. Many believe that solar electricity prices will drop as a result of the recent investments in thin-film module manufacturing, and it is true that thin-film module prices have fallen. However, conversion efficiencies for these commercially available thin-film modules are still under 10%, and this means that

2.5–3.0 times more module area needs to be deployed relative to modules with over 19% conversion efficiencies. So, costs need to be compared at the system level, not just at the module level. Furthermore, the focus needs to be on the cost of the electricity produced in cents per kilowatt hour, not just the hardware cost.

A summary and conclusions are presented in Chapter 26. Features that distinguish this second edition from the first edition are the much larger number of solar field installations and the major advances in the concentrator arena using very high-efficiency cells as well as the advances in other novel uses of thin-film modules. The current magnitude and momentum of the solar cell electricity market development (as summarized in Chapter 2) makes its eventual success both inevitable and unstoppable. This is due to the certainty of its future development path with its inherent, major advantages along with the worldwide spread of the scientific knowledge and the manufacturing and engineering know-how (covered in Chapters 3–18), plus the national commitments (alluded to in the Public Policy section of Chapter 2) that will turn promise into reality. World fossil fuel energy production rates will decline in the near to medium time frames, and the current lifestyles of the developed world cannot continue without appropriate replacements. Thus, it is no longer a question of whether this solar cell electricity power transition will occur but one of who will lead this process, who will reap the most benefits, and on what time scale it will occur.

ABBREVIATIONS

AC—alternating current
CIGS—copper indium gallium deselenide
CPV—concentrating photovoltaic
DC—direct current
HCPV—high-concentration photovoltaic
LCPV—low-concentration photovoltaic
MW—megawatt
PURPA—Public Utilities Regulatory Power Act
PV—photovoltaic
TPV—thermophotovoltaic

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