Lewis M. Fraas

Low-Cost Solar Electric Power

Springer

Lewis M. Fraas

Low-Cost Solar Electric Power

Springer

Lewis M. Fraas
JX Crystals Inc.
Bellevue, WA
USA

ISBN 978-3-319-07529-7 ISBN 978-3-319-07530-3 (eBook)
DOI 10.1007/978-3-319-07530-3
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014940920

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Low-Cost Solar Electric Power

This photograph shows a 300 kW solar cell field near Shanghai China designed and installed by the authors company in 2008. The largest solar field in operation at the end of 2013 is one thousand times larger at 300 MW. In 2018, there will be multiple GW sized solar fields in operation around the world

Foreword

This latest solar cell technology book by Lewis Fraas is a rich resource of understanding, explanation, and simplification of developments to date as well as analysis of future opportunities. It is based on a deep history of Dr. Fraas' pioneering contributions to the field, his extensive experience working on and helping resolved key challenges, as well as his visionary projections of where we can go in the future.

Chapter 1 crisply summarizes the over 175 years of history it has taken to go from the first scientific observation of the photovoltaic effect until the modern era of economic conversion of sunlight into electricity on a large scale. He details all the key scientific and engineering developments and struggles over the almost 200 years it has taken to come this far.

Chapter 2 explains the amazing growth in the market for solar cells since the start of the twenty-first century to become a cost-effective way to provide large amounts of electricity at competitive prices to not only help address the energy shortage problem but also the related problems of global warming and air pollution.

Chapter 3 illustrates his unique and crisp skill of surveying the complex field of all solar cell technologies to explain why we are where we are now and what the opportunities are for the future many of which are currently being overlooked. Chapter 4 presents the most eloquent, accurate but non-mathematical description of the quantum mechanics of semiconductors I have ever seen. This makes underlying key scientific concepts more accessible to those without a deep theoretical physics background.

Chapter 5 is one of the most amazing. It makes dramatically clear what China's planned investment commitments have done to Japan's and the US's free-market-based solar cell industries with Germany's just barely hanging on. It is just the Sputnik versus Vanguard space rocket and satellites development process revisited once again. The catch up in space was not the US free market system but the planned and substantial investment by the US military. Eventually, the free market system has won out by 2014 with commercial space rockets just now becoming the most practical solutions soon expected to dominate. However Sputnik 1 was launched in 1957. One can just imagine the military risks—ballistic missiles, etc.—of the intervening 60 or so years had the US waited until the free-market approach eventually won.

There are present national and international interests in energy strategy, energy security, and energy independence, if not in global warming and pollution, that warrant wisely planned early investments well beyond just what a free market system can initially generate, particularly if the end result can become economically competitive. Many of the US-led pioneering technical innovations have come from the planned, largely military or NASA funded developments like commercial jet airliners, integrated circuits for electronics, the Internet, satellites, or landing men-on-the-moon not to mention infrastructure like the US Interstate Highway system.

Chapter 6 is a very nice, even handed, balanced, and brief treatment of thin films. The CdTe thin film solar cell modules have played a key role in leading the reduction of solar module prices below $2/W but eventually their inherently limited efficiency has proved problematic.

Chapter 7 provides a good introduction to the advantages of concentrated sunlight solar cell systems. Chapter 8 is a totally fascinating, compelling, and very personal description of the development of solar cells with 40 % efficiencies.

Chapter 9 is an excellent description of solar photovoltaics in the larger context of large-scale electric power generation. Particularly striking is the description of the potential of the vehicle-to-grid storage approach that makes the combination of solar and wind a truly reliable displacement for coal, oil, natural gas, and even nuclear utility power generation.

Chapter 10 is a delightfully novel presentation of how concentrated sunlight can provide lighting and some electricity generation whose future development should be interesting to follow. Chapter 11 was very useful for me to begin to understand for the first time some of the important elements and potential advantages of thermophotovoltaics.

Chapter 12 is perhaps the most visionary of all the chapters in its explanation of many of the complex details of how solar mirrors in space could provide one of the future's most promising advances in low-cost solar electric power.

Los Altos, CA Larry Partain

Preface

The 1973 Arab oil embargo with its associated gas lines was the first energy shock for the US. This led to President Gerald Ford launching a government funded program dedicated to US energy independence. This energy independence program was continued under President Jimmy Carter with an emphasis on renewable nonpolluting energy sources such as solar and wind. In 1975, Solar Technology International was formed in California to bring silicon solar cells down from space for terrestrial applications.

In a solar cell, sunlight is converted directly into electric power, the most valuable form of energy. This is a very elegant option with two outstanding advantages.

- There are no moving parts and semiconductor devices have almost no need for maintenance.
- No fuel is necessary eliminating almost all negative environmental impacts.

By 1980, Solar Technology International was the first to manufacture 1 MW of terrestrial solar modules per year. However, unfortunately, while President Carter had installed solar panels on the White House rooftop, President Ronald Reagan then removed them in 1980 and launched a new unspoken energy policy for the US where the US would defend access to the oil in the Middle East with military action if necessary. The first Middle East oil war eventually followed in 1991 when Iraq invaded Kuwait.

Meanwhile there was a Green Movement in Germany, Japan, and the US with homeowners buying terrestrial solar modules for off grid and grid connected applications. By 1999, terrestrial solar modules generating 1 GW of electricity were in operation around the world.

By the end of 2012, 100 GW of solar electric power had been installed around the world using solar cells including now large utility central power stations. We are now in the middle of a solar revolution. Chapter 1 herein recites the history of this solar cell revolution noting not just the history of the scientific cell and module research innovations but also noting the important roles played in policy and financial investments made by different governments at different times during this revolution up to today.

The arguments in favor of renewable energy are described in Chap. 2 with a discussion of Peak Oil and even the potential of a natural gas bubble over the next 5–10 years. Climate change is obvious with evidence of the glaciers melting and environment impacts such as Super Storm Sandy and Typhoon Haiyan. For evidence of pollution from coal, one only needs to look at the pictures of haze in Beijing and Shanghai on the TV news.

The technical aspects of solar cells are presented in Chaps. 3 and 4. Chapter 3 discusses the various types of solar cells and modules and systems and their production status today and Chap. 4 describes how solar cells work and emphasizes the importance of single crystal semiconductors for achieving high cell efficiencies.

The dominant solar cell module in the market today is the crystalline silicon (c-Si) solar module. That core technology is described in detail in Chap. 5. Installed system prices for that c-Si technology have now fallen to $2.50 per W and are continuing to fall. There are clear technical paths for continued cost reductions.

A dream for over 30 years now has been the idea that noncrystalline thin film cells will lead to even lower installed solar residential and utility system prices. Unfortunately, for scientific reasons explained in Chap. 4, this dream has not turned into reality because the conversion efficiencies of noncrystalline thin film cells are limited. Nevertheless, there have been outstanding achievements in this field. I have been using an Eco-Drive wristwatch as well as a simple calculator for years now powered by amorphous silicon photovoltaic cells. There has also been another outstanding spinoff application of amorphous silicon semiconductor devices as large area Field Effect Transistor drive circuits for liquid crystal displays. These displays are in our I-Pads, Cell phones, flat screen, TV and computer screens. This technology is described in Chap. 6. This is an example of two interacting revolutions in solar cells and displays.

Chapters 1–6 in this book describe an unstoppable solar cell revolution that is already well underway. The second half of this book describes things that are technically possible but still will require political will and financing to come to full completion.

One path for cost reduction for solar utility systems is by the use of concentrated sunlight systems. The idea is that optical elements like mirrors and plastic or glass lenses are cheaper as large area collectors than single crystal cells and that they can be used to dilute the cost of still higher efficiency solar cells at the focus of these optical elements. This Concentrating PhotoVoltaic (CPV) technology can take one of two forms with either low concentrating systems (LCPV) using 24 % efficient silicon cells or with high concentration systems (HCPV) using 44 % efficient multijunction cells. These concepts are described in Chap. 7. SunPower Corp. is having notable success with the LCPV concept with a recent announcement of an order for 70 MW of solar electric power. Chapter 8 tells the story of the development of the 40 % efficient multijunction solar cell from this author's point of view.

As noted in Chap. 1 and 2, there has been a continuing debate between the oil, gas, coal, and nuclear main stream energy groups, the incumbency, and the renewable energy advocates, the insurgency. The incumbency group has been very strong in the US as evidenced by the second Iraq war in 2003 and the unfortunate fact that the US lost its initial leading position in c-Si PV to China in 2005. The criticism by the incumbency has been that renewable energy is too expensive. This argument is now losing ground, as the first eight chapters of this book hopefully illustrate.

The incumbency argument is now shifting to the statement that solar and wind are both too intermittent. Energy storage is a solution to this problem and is already being implemented. However, there is potential help from a second ongoing revolution, the introduction of electric vehicles (EVs) as commute vehicles replacing gasoline powered cars. EVs are driven approximately 2 h to work and back each day. For the remaining 22 h, they are either sitting in a parking lot at work or they are in the home garage. Solar and/or wind can be used to charge their batteries at work and then those batteries can be used to power the home appliances at night. This vehicle to grid idea is described in Chap. 9.

While the US lost its position in PV manufacturing to China, there is still innovation going on in the US and Europe. As described in Chaps. 10 and 11, PV cells can also be used in multiple hybrid applications. For example, infrared sensitive PV cells or Thermo Photo Voltaic (TPV) cells can be used to convert infrared thermal energy from glowing objects into electricity in cogeneration applications. Natural gas heated glowing ceramic elements in home heating furnaces in cold climates can be used in homes to generate heat and electricity with 90 % conversion efficiencies. In addition, these IR cells can capture radiation from glowing steel billets in steel mills to generate electricity reducing the amount of coal burned in China.

A last very imaginative augmentation of solar energy is described in Chap. 12. This application is another example of potential interactions between two ongoing revolutions with surprising potential benefits. One of the challenges that solar energy faces is associated with the fact that solar energy is limited to daytime hours. A Space Power Satellite (SPS) capable of providing solar electric power economically for 24 h per day has been a dream for decades. However, the SPS concept is very complex since it assumes multiple energy conversion steps and includes specially constructed ground microwave receiver stations. In Chap. 12, an alternative is described. A constellation of 10 km diameter mirror arrays in a sun synchronous orbit at an altitude of 1,000 km deflecting sunbeams down to terrestrial solar power fields at dawn and dusk can provide 3 additional hours in the morning and another 3 additional hours in the evening. The key is that larger and larger terrestrial solar fields, photovoltaic or trough concentrated solar power, are already being built all around the world. Mirrors deflecting sunbeams down to earth is a much simpler concept. A surprising convergence of two technologies under development is now possible, i.e., lower cost access to space and the ongoing construction of larger and larger solar power fields. If this concept is implemented in the future, the hours of solar electricity production in sunny PV fields around the world can be potentially increased to 14 h per day with an increase in the solar field capacity factor to 58 % and a reduction in the cost of renewable pollution-free solar electricity to below 6 cents per kWh.

The second half of this book describes some exciting possibilities. An outstanding problem has been access to financing for these new ideas. The money in the hands of the financial community has tended to favor the status quo incumbency energy technologies (as most recently, "fracking," for example). Hopefully the young and older educated readers of this book will find the new ideas presented here intriguing enough to work for the political will and financing to make them become a reality. We can all strive for a peaceful bright and sunny energy future.

March 2014 Dr. Lewis M. Fraas

Contents

Chapter 1
History of Solar Cell Development

It has been 175 years since 1839 when Alexandre Edmond Becquerel observed the photovoltaic (PV) effect via an electrode in a conductive solution exposed to light [1]. It is instructive to look at the history of PV cells [2] since that time because there are lessons to be learned that can provide guidance for the future development of PV cells.

The Discovery Years

This 175 year history can be divided into six time periods beginning with the discovery years from 1839 to 1904. Table 1.1 gives the most significant events during this first period. In 1877, Adams and Day observed the PV effect in solidified selenium [3] and in 1904, Hallwachs made a semiconductor-junction solar cell with copper and copper oxide. However, this period was just a discovery period without any real understanding of the science behind the operation of these first PV devices.

Theoretical Foundation

A theoretical foundation for PV device operation and potential improvements was formulated in the second phase of the history of PV in the period from 1905 to 1950 as summarized in Table 1.2. Key events in this period were Einstein's photon theory [4], the adaptation of the Czochralski crystal growth method for single crystal silicon and germanium growth [5] and the development of band theory for high purity single crystal semiconductors [6, 7]. The PV cell theory developed emphasized the importance of high purity single crystal semiconductors for high efficiency solar cells. This theoretical foundation will be reviewed in Chap. 4 in this book. These developments laid the foundations for the third phase of PV device development.

L. M. Fraas, *Low-Cost Solar Electric Power*, DOI: 10.1007/978-3-319-07530-3_1,

Table 1.1 1800–1904: Discovery years

1839—Alexandre Edmond Becquerel observes the photovoltaic effect via an electrode in a conductive solution exposed to light [1]
1877—W.G. Adams and R.E. Day observed the photovoltaic effect in solidified selenium, and published a paper on the selenium cell [3]. 'The action of light on selenium', in "Proceedings of the Royal Society", A25, 113
1883—Charles Fritts develops a solar cell using selenium on a thin layer of gold to form a device giving less than 1 % efficiency
1904—Wilhelm Hallwachs makes a semiconductor-junction solar cell (copper and copper oxide)

Table 1.2 1905–1950: Scientific foundation

1905—Albert Einstein publishes a paper explaining the photoelectric effect on a quantum basis [4]
1918—Jan Czochralski, a Polish scientist, produces a method to grow single crystals of metal. Decades later, the method is adapted to produce single-crystal silicon
1928—F. Bloch develops band theory based on single crystal periodic lattice [5]
1931—A. H. Wilson develops theory of high purity semiconductor [6]
1948—Gordon Teal and John Little adapt the Czochralski method of crystal growth to produce single-crystalline germanium and, later, silicon [7]

The First Single Crystal Silicon Solar Cell

Table 1.3 summarizes the events between 1950 and 1959 leading to the practical silicon single-crystal PV device. The key events were the Bell Lab's announcement of the Silicon solar cell [8] in 1954 with the Pearson, Chapin, and Fuller patent in 1957 for the 8 % efficient Silicon solar cell [9]. The foundation was now laid for the development of a variety of markets for PV as will be discussed in more detail in Chaps. 2 and 3 herein.

Enthusiastic Support for PV in USA and New PV Devices

The next three phases of PV development can best be divided according to the political climate of the time. The 4th phase of PV history from 1960 to 1980 was defined by enthusiastic support in the US for PV solar cells first for applications on space satellites and then for initial terrestrial applications. Table 1.4 shows the timeline for significant events in this period.

This period began with the success of the first Telstar communication satellite [10] launched in 1962 and powered by silicon solar cells as shown in Fig. 1.1a. Then in the 1970s, silicon cells were evolved for use in terrestrial installations. Figure 1.1b shows a typical terrestrial silicon solar cell today. The present author began working in the solar field in 1973. This was the year of the Arab oil embargo [11] and the first gas lines in the US.

Table 1.3 1950–1959: First practical device demonstration

1950—Bell labs produce solar cells for space activities
1953—Gerald Pearson begins research into lithium-silicon photovoltaic cells
1954—Bell labs announces the invention of the first modern silicon solar cell [8]. These cells have about 6 % efficiency. The New York Times forecasts that solar cells will eventually lead to a source of "limitless energy of the sun"
1955—Western electric licences commercial solar cell technologies. Hoffman electronics-semiconductor division creates a 2 % efficient commercial solar cell for \$25/cell or \$1,785/Watt
1957—AT&T assignors (Gerald L. Pearson, Daryl M. Chapin, and Calvin S. Fuller) receive patent US2780765, "*Solar Energy Converting Apparatus*" [9]. They refer to it as the "solar battery". Hoffman electronics creates an 8 % efficient solar cell
1958—T. Mandelkorn, U.S. Signal Corps Laboratories, creates n-on-p silicon solar cells, which are more resistant to radiation damage and are better suited for space. Hoffman Electronics creates 9 % efficient solar cells. Vanguard I, the first solar powered satellite, was launched with a 0.1 W, 100 cm^2 solar panel
1959—Hoffman electronics creates a 10 % efficient commercial solar cell, and introduces the use of a grid contact, reducing the cell's resistance

Table 1.4 1960–1980: US enthusiastic support and new PV devices

1960—Hoffman electronics creates a 14 % efficient solar cell
1961—"Solar Energy in the Developing World" conference is held by the *United Nations*
1962—The *Telstar* communications satellite is powered by solar cells [10]
1967—*Soyuz 1* is the first *manned* spacecraft to be powered by solar cells
1970—First highly effective *GaAs heterostructure* solar cells are created by *Zhores Alferov* and his team in the *USSR* [12]
1971—*Salyut 1* is powered by solar cells
1972—Hovel and Woodall at IBM demonstrate AlGaAs/GaAs solar cell with 18–20 % efficiency [13]
1973—*Skylab* is powered by solar cells
1975—First JPL flat solar array block buy to transition silicon PV from space to terrestrial applications
1976—David Carlson and Christopher Wronski of RCA laboratories create first amorphous silicon PV cells, which have an efficiency of 1.1 % [16]
1977—The *Solar Energy Research Institute* is established at *Golden, Colorado*
1977—President *Jimmy Carter* installs *solar panels* on the *White House* and promotes incentives for solar energy systems
1977—The world production of photovoltaic cells exceeded 500 kW
1978—First amorphous silicon solar-powered calculator [17]
Late 1970—the "*Energy Crisis*" [11]; groundswell of public interest in solar energy use: *photovoltaic* and active and passive solar, including in architecture and off-grid buildings and home sites
1978—L. Fraas and R. Knechtli describe the InGaP/GaInAs/Ge triple junction concentrator cell predicting 40 % efficiency at 300 suns concentration [14]
1978—US public utilities regulation act (PURPA) passed [18]