Solar Energy Conversion

Richard C. Neville

THE SOLAR CELL

(SECOND EDITION)

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PREFACE

That the human race faced an energy crisis became painfully obvious during the 1970s. Since that time the blatant obviousness of the problem has waned, but the underlying technical and political problems have not disappeared. Humanity continues to increase in number (the world population is, at present, in excess of five billion) and, despite major efforts towards improving the efficiency of energy consumption, the overall per capita use of energy continues to increase.

Projections concerning the human population and its energy requirements during the next century estimate populations in excess of seven billion and energy consumption per person in excess of 40,000 kilowatt hours per year (approximately twice the current rate). This increasing energy use must be viewed in the light of the finite availability of conventional energy sources. When done so the energy crisis can be seen to be all too real for any long term comfort.

A frequently mentioned solution to the problem of increasing requirements for energy and dwindling energy sources is to tap the energy in sunlight. The solar energy falling on the earth's surface each year is over 20,000 times the amount presently required by the human race, making for a seemingly inexhaustible supply. For effective utilization of any energy source civilization requires an easily storable, easily transportable form of energy (after all, it is dark at night). This implies that the incoming solar energy should be transformed into electrical energy. In turn this means that we need to utilize photovoltaic (solar cell) conversion of the energy in sunlight.

Photovoltaic effects were initially observed more than a century and a half ago. In 1839 E. Becquerel observed a photovoltage (a voltage depending on the character and intensity of the illuminating light) when sunlight was allowed to shine on one of two electrodes in an electrolytic solution. The first scientific paper on photovoltage using solids was published in 1877 and concerned the semiconductor, selenium. In 1954 research groups at RCA and Bell Telephone Laboratories demonstrated the practical conversion of solar radiation into electrical energy by a silicon pn junction solar cell, and shortly thereafter Chapin, Fuller and Pearson reported on a six percent efficient solar cell (Journal of Applied Physics, Vol. 25, 1954, p. 676).

The modern solar cell is an electronic device, fabricated from semiconducting materials. It converts a fraction of the energy contained in sunlight directly to electrical energy at a voltage and current level determined by the properties of the semiconductor, the solar cell design and construction techniques, and the incident light. To gain an understanding of how solar cells work and to be in a position to design and construct energy conversion systems using solar cells requires a background covering such diverse areas as: the nature of solar radiation; semiconductor physics; quantum mechanics; the techniques of energy storage; optics; heat flow in solids; the nature of elemental, compound, single crystal, polycrystalline and amorphous semiconductors; the technology of semiconductor device fabrication; and the economics of energy flow. It is not physically possible to cover, in depth, all of these areas in a single work. In writing this volume, I have endeavored to create a survey text; a book that explores a number of critical background areas and then outlines the theory of operation of solar cells while considering their design and fabrication. Solar cell performance is treated both in the general sense and for some specific examples. These examples select semiconductor, junction type, optical orientation and fabrication technology and then highlight the problems encountered in solar cell design and illustrate, both in general and specific fashion, areas of promising future research and development. References are provided to facilitate deeper investigations of the various topics of interest--from quantum mechanics to economics.

This is the second edition of this work on solar cells. Historically, this book originated from a series of lectures on energy and solar cells given to engineering students at the University of California at Santa Barbara. These lectures culminated in the first edition of this work, in 1978. Since that time there has been much change in the fields of energy generation and consumption, solar energy and solar cells. Additional lectures at UCSB and at Northern Arizona University, coupled with considerable research into aspects of photovoltaic and solar energy have modified the original work. This, the second edition, is thus the result of more than 20 years of interest in solar energy and solar cells coupled with steady changes in these fields and our understanding of these fields. Since it is virtually impossible to separate design and operating theory, engineering, economics and politics in considering the use of solar cells in addressing the energy problem facing humanity, the systems aspect is present throughout this volume.

The first chapter is a broad (and brief) survey of the elements which make up the "energy crisis". It is devoted to illustrating the limited nature of presently utilized energy sources and to a discussion of the various "non-conventional" energy sources proposed for the future: biological, wind, wave and solar. It has, as its major purpose, three points to make: (1) that our conventional energy sources will be exhausted at some point in the not-too-distant future, (2) that solar energy is capable of supplying the energy requirements of humanity for the foreseeable future, and (3) that photovoltaic energy conversion is a major candidate for supplying mankind with its required energy; perhaps the prime candidate.

The second chapter considers the nature of sunlight, discusses the solar spectrum, the effects of latitude, the earth's rotation and axial tilt, and atmosphere and weather. A brief discussion of optics is included as a background for those individuals interested in this aspect of energy conversion.

The third chapter surveys the nature of semiconductors. Solar cells are theoretically constructed of various semiconductors and their performance is shown to depend upon the properties of these materials. These properties are best understood within the framework of quantum mechanics and solid state physics. Chapter III discusses crystals, quantum mechanics and semiconductor physics with a view towards outlining the principal properties of semiconductors and the manner in which these properties vary with device processing technology, temperature of operation, and the characteristics of the illumination. Because the physics of single crystal semiconductors is best understood (as contrasted with polycrystalline or amorphous structured semiconductors), the emphasis in this chapter is on solar cells constructed from single crystal semiconductors. It is in this chapter that certain specific example semiconductor materials are first introduced.

Chapter IV treats the interaction of light semiconductors including absorption, reflection and transmission. The generation of hole-electron pairs is treated both in the abstract and in detail using the example semiconducting materials introduced in Chapter III. The maximum potential output power density and the optimum output current density for photovoltaic cells are displayed for solar cells fabricated from six sample single crystal semiconductors.

The fifth chapter is devoted to a general discussion of solar cell performance as a function of the junction employed. The current versus voltage characteristics of pn, heterojunctions, mos junctions and Schottky barrier solar cells are considered and a general expression for the output power density as delivered to an optimum external load is obtained. From this expression, the maximum expectable output power density for solar cells, as a function of the energy gap of the semiconductor employed, is derived. This is displayed as a function of the saturation current of the solar cell.

In Chapter VI the six example semiconductors are employed to provide specific values of estimated solar cell performance, based on various technologies of junction fabrication and upon the optical orientation of the solar cells. The solar cell performance levels computed in this chapter, and in later chapters, are not meant as absolute predictions of maximum performance. Rather, they are intended to provide indications of "typical" solar cell performance as structured by technology and materials limitations. It is intended that they will suggest areas in need of research and development.

The seventh chapter considers the effects upon solar cell operation of changes in junction temperature and the use of concentrated sunlight. The power density in natural sunlight is very low (approximately one kw/m^2 at sea level) and hence any sizeable energy requirement implies a large area of solar cells. By utilizing relatively inexpensive mirrors or lenses to concentrate sunlight upon expensive solar cells a significant reduction in cost can be effected. This chapter examines the limits imposed on optical concentration levels by the solar cells and shows that improved solar cell performance is possible using the six example single crystal semiconductors.

Chapter VIII carries the materials of the preceding chapter a step further. In addition to considering the electrical energy output for solar cells operating under concentrated sunlight, the thermal energy available from such a situation is considered. Thus a complete systems approach to producing energy from photovoltaic cells is developed. Later in this chapter various approaches to further improving overall energy output (both electrical and thermal) from photovoltaic systems are considered. Most of these systems involve modifying the spectral characteristics of the light used to illuminate the solar cells. The altered light is a better match for the semiconductors used in fabricating the solar cells and so overall efficiency is improved.

In the ninth chapter the solar cells are constructed using polycrystalline and amorphous semiconductors. The operation of these devices depends strongly on the crystal interfaces and the properties of unsaturated chemical bonds. As a result, the theory of operation of polycrystalline and amorphous material solar cells is not well understood. Thus, this chapter is less theoretical and more empirical in nature than the previous chapters. Numerous examples of polycrystalline and amorphous solar cell operations and materials are provided.

The final chapter, Chapter X, is devoted to a brief survey of such topics as economics, energy storage, and overall systems effects. Potential problems and proposed solutions are noted and briefly discussed. It is intended that the reader treat this chapter as a question mark whose main purpose is to provoke inquiry.

The energy "problem" has not gone away, and will not go away. Without strenuous and continuing efforts on the part of humanity we will see a continuing series of "crises". Fortunately, the field of photovoltaic energy conversion is growing rapidly, both in scope and complexity. Of necessity I have been forced to treat lightly many areas which deserve considerably more intense study. To those readers whose specialty in research or development lies in these areas, my apologies. I can but plead lack of space and time.

In closing I would like to thank my fellow faculty members and my students for many hours of stimulating discussion and my wife, Laura Lou for her encouragement, patience, support and proof reading. In the final analysis, any errors are, of course, my responsibility.

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29 March 1994

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CHAPTER I: ENERGY NEEDS--ENERGY SOURCES

Introduction

This work is concerned with the theory, design and operation of solar cells. However, we need to first ask the fundamental question--why consider solar cells at all? The answer to this question involves energy. As a form of life Homo sapiens sapiens requires, as do all other living things, energy in the form of food and energy in the form of heat (ofttimes supplied by food, but sometimes by sunlight or hot water or...). We also use energy for a number of other purposes, such as clothing, shelter, transportation, entertainment, cooling and the construction of tools.

There is a large number of energy sources available to our species and we make use of most of them. In this chapter we will consider, briefly, a number of these energy sources, examine how we utilize them to supply us with energy, how this energy is used to provide us with a lifestyle, how much energy we use, what problems are or may be associated with this use, and describe several scenarios for the future. Note that how much energy a particular human being uses depends on where she/he lives and the nature of her/his lifestyle. Thus the overall quantity of energy used by our species is the net result of a complex interaction between energy sources, energy uses, human interaction (politics), human aspirations and engineering talent. There is no way in which we can obtain complete understanding of this subject in a single chapter. Such a complete understanding involves an exhaustive description of the energy resources available on the planet Earth, a thorough knowledge of the potential ecological interactions and an ability to forecast the numbers and lifestyles of humanity for at least the next thousand years...

What we shall do is to undertake a brief examination of the types of energy we use, how and how much we use them, and the availability of these energy sources. While doing so we will look, very briefly, into politics, ecology and demographics. We will discover that the energy crisis does exist, and, depending on our definitions of such items as satisfactory lifestyle* and our selection of energy sources, serious ecological consequences can develop for a planet whose problems are driven by a large and expanding population.

The sources of energy available to mankind on this planet are commonly divided into two broad categories: (1) energy capital sources, i.e., those sources of energy which, once used, cannot be replaced on any time scale less than millions of years (details to follow); and (2) energy income sources, i.e. those sources of energy which are more or less continuously refreshed (by nature or by man assisting nature) and which may be considered to be available, at potentially their current levels of supply, for millions of years. A listing of energy sources under these two categories would include:

Table I.1

Energy source types

Energy Capital	Energy Income
Fossil fuels (coal, oil and gas)	Biological sources (wood, plants)
Geothermal	Hydropower (dams, tides)
Nuclear fission	Wind energy
Nuclear fusion	Solar energy

The division in energy sources indicated in Table I.1 is not inflexible. For example, if we burn our trees very rapidly, we will outstrip the ability of our forests to grow new trees; making wood a capital energy source. The divisions indicated in Table I.1 are consistent with the way in which we are likely to make use of the energy sources--the capital sources will eventually become exhausted while the income sources will

* The reader should understand that, in this text as elsewhere in the literature, it is often implied that an improved lifestyle requires a greater expenditure of energy. Depending on one's viewpoint, this is not necessarily the case.

not. (Note, if our understanding of the physics of the universe is correct, all of the energy sources will eventually fail as the stars use up their fuel and turn dark. This is unlikely to be a problem during the next twenty billion years and will be ignored in this work).

The questions we need to ask are: (1) How long will the capital energy sources last? and (2) How many people can the energy income sources support? To answer these questions we need to consider how much energy the human race uses.

Consumption

In Table I.2 the per capita rate of energy use in the United States is presented for selected years.

Table I.2

Per capita energy use in the United States [1, 2, 3, 4]

Year	Per Capita energy use (kwh/year)	Year	Per Capita energy use (kwh/year)
1800	12,000	1950	66,200
1850	17,000	1960	72,000
1900	32,200	1970	97,000
1925	52,800	1980	96,700
1940	53,000	1990	99,600

The energies in Table I.2 were used for food, transportation, clothing, tools, housing, etc. and the units in which the energy is expressed for each usage varies (see Appendix A for a listing of the various units of energy). The annual consumption of energy for the United States alone is currently in excess of 10^{13} kwh. It is possible to represent this number in Btus, in calories, in barrels of oil equivalent, horsepower-years, or any one of a number of equivalent energy units. For relatively small amounts of energy we will use the kilowatt hour (kwh). For very large amounts of energy, such as the amount annually used in the United States, we shall utilize the Q. The Q is defined by:

$$1\ Q = 1 \times 10^{18}\ \text{Btu} = 2.93 \times 10^{14}\ \text{kwh}. \qquad (I.1)$$

Note that one Q is approximately the amount of energy required to bring Lake Michigan (North America) to a boil.

Over the past two millennia, the total world energy consumption has been approximately 22 Q [5, 6], corresponding to an average annual use of 0.011 Q. However, during the past century and a half (the period of the industrial revolution) some 13 Q of energy has been consumed, corresponding to a rate more than eight times the average annual use above. The world rate of energy consumption has changed from approximately 0.01 Q in 1850 to 0.22 Q in 1970 and to an estimated value of 0.42 Q in 1990 [7]. During this time period, the world's population has increased from approximately one billion to five billion [8]. This implies that the average annual energy consumption for each person in the world rose from 2,930 kwh in 1850 to approximately 24,600 kwh in 1990.

The estimated average energy consumption rate for the world in 1990 is significantly lower than the average energy consumption in the United States (see Table I.2). Indeed, with about five percent of the world's population [8], the United States now consumes an estimated 0.085 Q of energy each year--roughly 20% of the world's usage. What does this imply for the future? If the human race were to remain at its present population of five billion, and if the rest of the world were to "live as well" as the average U. S. citizen, the world's annual energy consumption would increase to 1.7 Q. If we allow for a population increase to 10 billion, then the required energy to live "the good life" rises to an annual value of 3.4 Q. Of course, it is possible to reduce energy consumption by a combination of more efficient energy use and by completely abandoning certain energy-using processes. The name normally given to this type of behavior is conservation. Carried to an extreme limit, we could envisage a world where each year each individual uses no more energy than in 1850 (2,930 kwh). This level of energy consumption is some 12% of the current world usage and is approximately one thirty-fourth of the present usage in the United States.

If the world lived at the average consumption level of 1850, the energy required annually would range from 0.05 Q per year (for a population of five billion) to 0.10 Q/year (for a population of ten billion), much reduced from the several Q values of the preceding paragraph.

Now the energy we consume is spent for transportation, industry and commerce, space heating, electricity, etc. An exact assessment of how much is used in each category depends on geography, lifestyle and weather. As a potential prototype for the future, let us consider the distribution of the energy consumption as averaged over the United States. Figure I.1 presents one view of this problem, dividing energy into comfort heat (heating and cooling residences, stores, factories, hot water, etc.), process heat (in manufacturing) and work (electricity, transportation, etc.).

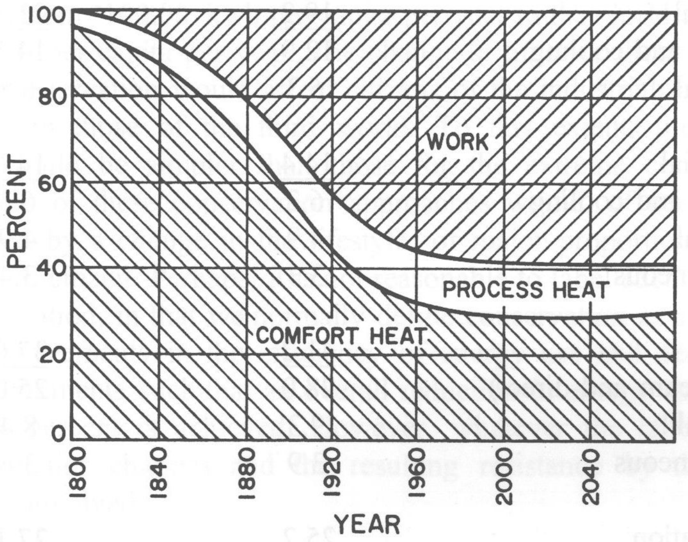

Figure I.1. A projection of the relative proportions of three components of the energy use system, to the year 2050, for the United States. After Putnam [9], with permission.

Note that the present division for energy allocation is predicted (by Figure I.1) to remain constant for several decades. Table I.3 provides a more detailed viewpoint for two selected years. Note the shift in how energy is used, and how the industrial sector is becoming more efficient.

Overall, how efficient is our use of energy? In 1968, the average efficiency appears to have been in the neighborhood of 32% [10] with individual area efficiencies ranging from 60% for heating usage to 15% for the energy efficiency of transportation. In 1990, the average efficiency of energy use was estimated to be 35%. Some additional improvement in efficiencies is possible (for example, replacing 100 watt incandescent light bulbs in homes with 15 watt fluorescent tubes which yield the same amount of light could improve the overall efficiency of energy use by one