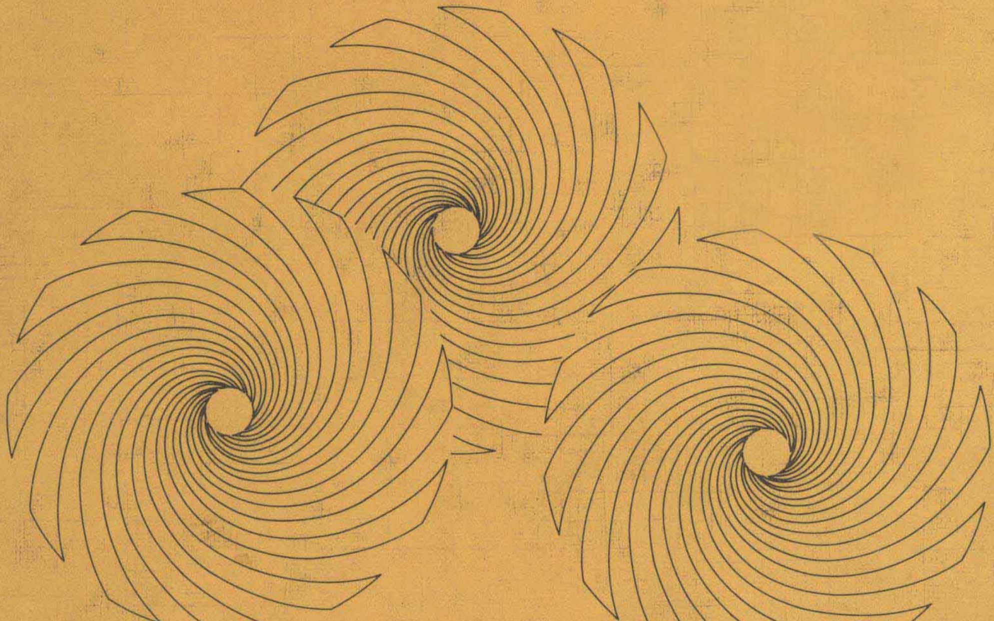
STUDIES IN ELECTRICAL AND ELECTRONIC ENGINEERING 1

Solar Energy Conversion: The Solar Cell

RICHARD C. NEVILLE



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Vol. 1 Solar Energy Conversion: The Solar Cell (Neville)

Preface

The existence of an "energy source" crisis has become all too clear during this seventh decade of the twentieth century. A frequently mentioned solution to the problem of obtaining an adequate source of energy for the future is the use of photovoltaic, or solar cell, conversion of the energy contained in sunlight.

Photovoltaic effects were first noticed more than a century ago. In 1839, E. Becquerel observed a photovoltage (a voltage that depends on light) when sunlight was allowed to shine on one electrode in an electrolytic solution. The first scientific paper to report on photovoltage in a solid was published in 1877 and concerned selenium. In 1954, an RCA group demonstrated practical conversion of radiation into electrical energy by a silicon PN junction cell, and shortly thereafter Chapin, Fuller and Pearson reported on a 6% efficient solar cell (J. Appl. Phys., 25(1954)676).

The modern solar cell is an electronic device, fabricated from semiconductors, that converts a fraction of the energy contained in sunlight directly to electrical energy. To understand how solar cells work and to be able 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 materials, 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 book I have endeavored to create a survey-text, a book that explores a number of critical background fields or areas and then outlines the theory of operation of solar cells. Solar cell performance is treated both in the general sense and for some specific cases. These specific cases select semiconductor, junction type, optical orientation and fabrication technology and serve as vehicles in highlighting the problems encounted in solar cell design and to point out, in both general and specific fashion, areas for future research and development. References are provided that enable the reader to investigate more deeply the various topics of interest, from quantum mechanics to economics.

Historically, this book grew from a series of course lectures given at the University of California at Santa Barbara, to undergraduate and graduate students in the Electrical Engineering and Computer Science Department, and from my interest in all aspects of solar energy. Since it is impossible to separate engineering, economics and politics in considering the solution to such a major problem as energy supply, the systems aspect is present throughout the work.

The first chapter is a broad and brief survey of the "energy crisis" and is devoted to showing the limited nature of presently utilized energy sources as well as to a discussion of the various "non-conventional" energy sources of the future; biological, wind and wave and, in very general terms, solar energy. 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 the human race for the foreseeable future; and (3), that photovoltaic energy conversion is a major candidate, perhaps the prime candidate for utilizing solar energy.

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

The third chapter is also background. Solar cells are made from semiconductors and depend for their performance 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 toward outlining the principal properties of semiconductors as they affect solar cell performance and the manner in which these properties may vary with device processing, with temperature of operation and with illumination. Because the physics of single-crystal semiconductors is best understood, the emphasis is on single-crystal solar cells as opposed to cells made from amorphous or polycrystalline materials. It is in this chapter that certain specific example semiconductor materials are first introduced.

In Chapter IV, the interaction of light and semiconductors is treated, including absorption, reflection and transmission. The generation of hole-electron pairs is treated both in the abstract and in detail using the example semiconductors introduced in the preceding chapter. The maximum potential power density (output power per unit area of solar cell) and optimum output current density are displayed for solar cells fabricated from six example semiconductors.

Chapter V is devoted to a general discussion of methods for solar cell construction. The current-voltage characteristics of PN, Heterojunction, MOS junction and Schottky barrier solar cells are considered and a general expression for the output power density 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 is derived. This is displayed as a function of the saturation current of the solar cell.

In Chapter VI the six example semiconductors are utilized to provide specific values of solar cell performance based on particular technologies of junction fabrication and solar cell optical orientation. The solar cell performance data calculated in this chapter, and the succeeding chapter, are not meant as predictions of maximum performance. Rather, they are intended to provide indications of "typical" performance as structured by technology and materials limitations. My hope is that they will suggest areas in need of research and development.

Chapter VII considers the effects upon solar cell operation of increased (above 300°K) temperature and the use of concentrated sunlight. The power density in sunlight is relatively low (approximately 1 kW/m^2 at the earth's surface) and hence any sizeable energy requirement implies a large area of solar cells. By using mirrors or lenses to concentrate sunlight on solar cells a smaller area of expansive solar cell is required. The limits imposed on optical concentration by the solar cells and the improved performances possible are examined using the example semiconductors.

Chapter VIII is devoted to economics and systems problems inherent in the use of solar cells. Potential problems and their solutions are noted and briefly discussed. It is intended that the researcher treat this chapter as a single question mark whose main purpose is to provoke questioning thought.

The field of photovoltaic energy conversion is increasing rapidly in scope and complexity. Of necessity I have been forced to treat lightly many areas which deserve much deeper consideration. In particular, I have given little space to surface recombination effects, the inverted solar cell, to solar cells made from polycrystalline or amorphous materials, to Heterojunction solar cells and to those photovoltaic schemes involving an alteration in the photon spectra incident on the solar cell. To those readers whose specialty in research or development lies in these areas, my apologies. I can only plead lack of space and time.

I would like to thank Ms. C. Stadem and Mr. C. Iverson for typing many pages of many revisions and my wife for her patience, support and encouragement. Any errors are, of course, my responsibility.

Richard C. Neville
Santa Barbara, California
24 January 1978

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CHAPTER I: ENERGY NEEDS -- ENERGY SOURCES

Introduction

Before considering the theory and design of solar cells we should first inquire as to whether there is any real requirement for yet another energy source and another means of tapping that source. In the course of this inquiry we must consider for what purposes man uses energy, how efficiently he uses it and how much he uses. We must consider the various potential energy sources, how long each will last and the rate at which energy can be obtained from each source. We must consider the cost of energy, whether or not it can be used more efficiently or more sparingly, the size of the population using the energy and the limitations imposed on the use of any particular energy source by the availability of other materials. These questions concerning energy cannot be ignored for we require energy to live, even on an idyllic island in the South Pacific. We consume energy in the form of food, as clothing, shelter and tools. We use energy for transportation, for heating and cooling, and for entertainment. The amount of energy used by any one individual varies greatly depending on the individual's geographic location and lifestyle. Moreover, as the human population of the planet earth has increased, the rate of energy use by the human race has increased, both on a total and on a per capita basis, as our standard of living has increased.

By considering the complex interaction of energy sources, energy consumption and human politics, we will see that a new, reliable answer to the energy-source problem must be found. Furthermore, solar energy as tapped with solar cells will be found to have a high potential as a solution to the energy-source problem.

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

Table I.1

Energy Sources

Energy Capital	Energy Income
Fossil Fuels (coal, oil, gas)	Biological (wood, plants)
Nuclear Fission	Hydropower (dams, tidal)
Geothermal Energy	Wind Power
	Solar Energy
	Nuclear Fusion

The division in energy sources indicated in Table I.1 is not inflexible. For example, if we burn wood from trees faster than the trees can be grown, then wood becomes an energy capital source. As another example, it is theoretically possible to extract geothermal energy so slowly that it is replaced by heat flow from the earth's core. This would make geothermal energy an energy income source.

The balance of this introductory chapter is devoted to a closer look at the amount of energy the human race consumes, the sources from which this energy is obtained at present, and the energy potentially available from both currently used, currently under-utilized, and virtually unused sources. Much of the data is presented in estimated form since we still do not really "know" our own planet. We will reach the conclusion that a change in our pattern of energy source utilization must be made, and that the time scale for doing so is certainly very short on a geologic scale, and probably so on a human scale.

Consumption

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

The consumption of energy for the United States alone is in excess of 10^{13} kWh per year. Rather than continue to write of energy in such unwieldly numbers, Q will be used as the fundamental unit of energy, defining Q by:

$$1\ Q = 10^{18}\ \text{Btu} = 2.93\times10^{14}\ \text{kWh}, \tag{I.1}$$

where one Q is approximately the amount of energy required to bring Lake Michigan to a boil.

Table I.2

United States Per Capita Energy Use [1,2]

Year	Per Capita Energy Use kWh/year	Remarks
1920	54,500	The "Roaring 20's"
1930-40	53,000	The Depression
1950	66,200	The Affluent Society (total U.S. use $\simeq 10^{13}$ kWh)
1960	72,000	(est.total use, 1.3×10^{13} kWh)
1970	97,500	(est.total use, 2×10^{13} kWh)

Over the past two millennia the total world energy consumption has been approximately 18 Q [3], corresponding to an average annual use of 0.009 Q. However, over the past century (during the Industrial Revolution), approximately 9 Q of energy were used, corresponding to a rate ten times the overall average. The world rate of use has increased from 0.01 Q per year in 1850, to 0.17 Q per year in 1970, to an estimated rate of 0.24 Q per year in 1977 [3]. During this period the world's population increased from approximately one billion to four billion [4]. This implies that the average annual energy consumption for each person in the world rose from 2930 kWh in 1850, to approximately 17,600 in 1970.

The average energy consumption rate figures for the world in 1977 are much lower than the U.S. average energy consumption figures in 1970 (from Table I.2). Indeed, with about 6% of the world's population [4], the U.S. now consumes an estimated 0.082 Q of energy each year -- roughly 34% of the world's total usage. What does this imply for the future? If the human race were to stay at its present four billion, and if the rest of the world were to "live as well" as the U.S. citizen, the world's annual energy consumption would rise to 1.33 Q. If we allow for population growth to eight billion or 12 billion, then the required energy to live the "good life" rises to 2.66 Q or to 4.00 Q each year. Of course, it is possible to reduce energy consumption by a combination of more efficient energy use and completely abandoning certain energy-using processes. The name normally given to this is conservation. Carried to an extreme limit we could envisage a world where each year each individual used no more energy than in 1850 (2930 kWh). This is a consumption rate one-sixth the average current world usage and about one-thirty-third the present U.S. usage. If the world lived at the average level of 1850, the energy required annually would range from 0.04 Q/year (a population of four billion) to 0.12 Q/year (a 12-billion population level).

It is instructive to consider the various energy uses and the efficiency of their utilization. In doing this we must face the fact that food energy is measured in kilocalories, heat energy frequently in Btu, and electrical energy in kWh. Electrical energy is the most easily portable form, and for this reason energy units will be converted into watt-hours or kilowatt-hours, with power measured in watts or kilowatts. For large values this book will use Q as the unit of energy, with power (rate of energy expenditure) being expressed in Q/year.

Now the energy we use is spent for transportation, industry and commerce, heating, electricity, etc. An exact assessment of how much for each category depends on geography, lifestyle and weather. As a potential prototype for the future, let us consider the distribution of energies 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.). Note that the present division in energy usage is projected to remain constant for several decades.

A more detailed viewpoint for a specific year can be obtained by reference to Table I.3.

How efficient is our use of energy in each of these areas? On the average, the efficiency is about 32% [6], with individual area efficiencies ranging from approximately 60% for heating usage to 15% for the energy efficiency of transportation. Some improvement in efficiencies is possible, but it must be noted that most of man's machines are heat engines and their efficiencies are bounded by those of the Carnot cycle (see section on

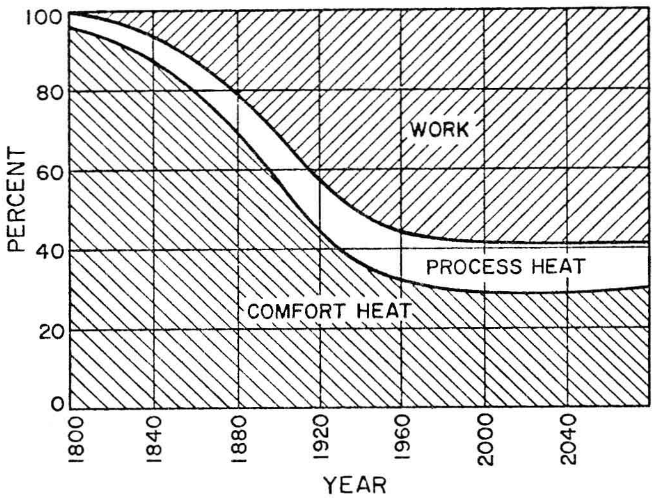

Fig. I.1. Projection of the relative proportions of three components of the energy system to the year 2050 for the United States. After Putnam [5], with permission.

Table I.3

Energy Usage in the United States (1968) [1,2,6]

Energy Area of Use	Percent of Total National Energy Use
Residential Use	19.2
-- Heating (and cooling)	12.9
-- Electrical	6.3
Commercial Use	14.4
--Heating (and cooling)	6.2
--Electrical	4.9
--Miscellaneous	3.3
Industrial Use	41.2
--Heat (steam or direct)	28.0
--Electrical	9.3
--Miscellaneous	3.9
Transportation	25.2
--Fuel	24.9
--Raw Material	0.3
National Total	100.0%

thermodynamics of this chapter). This implies a realistic upper bound on efficiencies of approximately 40-50%. This is not a significant improvement in the sense that the improved efficiency, while reducing the energy use, does no more than postpone the day on which capital energy resources are exhausted. It will be seen that new energy sources are still required.

Consider the "political" and "lifestyle" aspects of conservation. An example of extreme conservation might be to use energy at the 1850 level (2930 kWh per capita) rather than the 1977 U.S. level (97,500 kWh per capita). For most people in the world this represents a sharp decrease in the amount of energy consumed, and, therefore, a major reduction in "quality-of-life". It is clear from history that any such abrupt change will be accompanied by major political upheavals. A less "violent" form of conservation might be a reduction in average U.S. usage from 97,500 kWh to 17,600 kWh, the current world average for energy conservation. The change in "lifestyle" dictated by this degree of conservation would affect citizens of industrialized nations far more than those of an underdeveloped nation. To this degree, the "political" problems are simpler than those for the extreme conservation case. Clearly, both of these conservation techniques would of necessity be accompanied by a change in lifestyle of major proportions for the average U.S. citizen. Generally, however, conservation is considered to be an improvement in energy use efficiency, and the decrease in energy consumption rate is of the order of 5-20%, thus much less than the extreme examples considered above.

As an example of the problems facing us in achieving improved energy use efficiencies, consider the generation of light. An ordinary (incandescent) electric light bulb is approximately 2% efficient, and fluorescent bulbs are about ten times better. Saving lighting energy in major ways would clearly require either a new technology or a major reduction in the amount of light required.

Conventional Sources of Energy

Today mankind depends on a wide range of energy sources. Table I.4 presents a short list of the more important sources.