



**Matthew Buresch**

**PHOTOVOLTAIC  
ENERGY SYSTEMS**

Design and Installation

**McGraw-Hill Book Company**

New York St. Louis San Francisco Auckland  
Bogotá Hamburg Johannesburg London Madrid  
Mexico Montreal New Delhi Panama Paris  
São Paulo Singapore Sydney Tokyo Toronto

*Library of Congress Cataloging in Publication Data*

Buresch, Matthew.

Photovoltaic energy systems.

Bibliography: p.

Includes index.

1. Photovoltaic power generation. I. Title.

TK2960.B87 1983 621.31'244 82-17150

ISBN 0-07-008952-3

Copyright © 1983 by McGraw-Hill, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

1234567890 KGP KGP 89876543

**ISBN 0-07-008952-3**

The editors for this book were Jeremy Robinson and Susan Thomas, the designer was Elliot Epstein, and the production supervisor was Teresa F. Leadon. It was set in Baskerville by J.M. Post Graphics Corp.

Printed and bound by The Kingsport Press.

# **PHOTOVOLTAIC ENERGY SYSTEMS**

## **About the Author**

Matthew E. Buresch received his B.A. degree in the History of Science from Antioch University and his A.S. degree in Electronic Engineering Technology from Wentworth Institute of Technology. Since then he has worked for three years at M.I.T. Lincoln Laboratory in a research group developing photovoltaic applications at remote sites and in utility-interactive homes. His major work has involved assisting in the final checkout and turn-on of the standalone 100-kWp PV system at the Natural Bridges National Monument in Utah. He has also acted as site engineer for the utility-interactive Northeast Residential Photovoltaic Experiment Station in Massachusetts.

# Preface

Until recently, solar cells have been little more than a popular curiosity to anyone but those specialists involved in related theoretical and laboratory work. The literature about solar cells has therefore been either esoteric or visionary. Books of all types have been published which explain the physics of light and its impact on different PN junctions, or which eloquently discuss the value of renewable resources and the important role that solar energy can play in the future of mankind. The state of photovoltaic technology has been such that little has been written to bridge the gap between hopeful ideals and practical reality. Recent progress in the field, however, is changing the picture. A combination of government and business efforts has brought the price of photovoltaic electricity down substantially and has led to the formation of small-scale industries that are pioneering the terrestrial application of solar cells and establishing a market for their wares. Concomitant with these developments is a growing demand for basic information about how solar cells can be integrated into a power system that will satisfy real energy demands. This book is based on the practical and theoretical experience developed at M.I.T. Lincoln Laboratory, Sandia Laboratory, and the Jet Propulsion Laboratory in the field of photovoltaic-system design and is intended to aid this dawning industry.

The widespread application of photovoltaic systems will require that the price be competitive with other forms of energy. The most expensive and important element in such a system is the solar cell. Most photovoltaic

cells are composed of basic materials that are abundant throughout the world (commercial solar cells, to date, are generally made from silicon, which is the second most plentiful element on earth). The cost of a solar cell is largely determined by the manufacturing process, which itself requires energy. Various industries and governments are committing large amounts of money and talent to the scientific and technical innovation needed to develop a more efficient manufacturing technique. Other significant photovoltaic system expenses are for power conditioning equipment; wiring and mounting hardware; and labor costs for design and installation. The last cost factor can be reduced by simplifying and standardizing system designs so that the design, manufacturing, and installation process becomes easy to understand and implement. Ultimately, cost-effectiveness will be achieved only through mass production.

Photovoltaic electricity will make a significant contribution to a nation's energy demand when the installation of photovoltaic systems becomes as routine as the installation of electrical wiring in a building. Standard designs could be made for different regions of the country, and builders and electricians could perform both the layout and the installation work. The objective of this book is to simplify and organize the extensive information available on photovoltaic system design in a way that facilitates the standardization process.

This book focuses on the design and installation of small to intermediate-scale photovoltaic systems (100 to 100,000 peak watts) with fixed, flat-plate photovoltaic modules. Techniques involving sunlight concentration, sun tracking, and combined photovoltaic-thermal collection are not discussed here for reasons listed below. The potential applications of photovoltaic power in remote locations and on the low-cost roof space of many buildings will be great as the price of solar cells becomes increasingly competitive. Fixed flat-plate photovoltaic arrays will prove most attractive in the latter designs because of their simplicity, reliability, and low maintenance cost. Sun tracking is considered attractive because it can increase the solar energy received by as much as 50 percent. Sunlight concentration is heralded because the presently expensive cell area can be reduced. Combined photovoltaic-thermal collection at first makes good sense because most of the energy not converted into electricity goes into heat. Why not simultaneously tap this additional resource? Despite all these favorable features, the three techniques mentioned have major flaws.

Sun tracking and concentrator systems typically need a mechanical assembly to follow the sun's direct-beam rays. This assembly uses additional energy to operate and will involve considerable maintenance. Photovoltaic systems involving high concentration ratios or combined photovoltaic-thermal collection require pumps and plumbing to circulate

the liquid used to store heat. Such systems can only heat the fluid significantly by forcing the solar cell to operate at a high temperature, and therefore at a low efficiency. There is a trade-off in a PV/T collector between obtaining maximum heat and maximum electric power; since both cannot be optimized simultaneously, the value of such a system decreases. Solar heating and solar electricity are best generated side by side or together in a special integral-mount passive design, discussed in Chapter 9. The fixed flat-plate photovoltaic collector does not track the sun, taps only a percentage of the heat received from the sun, and requires large amounts of cell area. It does, however, afford a simple design that can be reliable and virtually maintenance-free. Once the expected photovoltaic cell cost reductions are achieved, the value of simplicity will be critical, especially to the manufacturing, construction, and housing industries.

This book discusses the performance and design of photovoltaic systems involving *silicon* solar cells (be they single-crystal, polycrystalline, or amorphous). The photovoltaic effect can be produced using other materials, such as gallium arsenide or cadmium sulfide; to date, however, silicon is by far the most common material used in commercially available solar cells. Most of the principles presented here will be transferable to other types of PN junctions.

While this book is written at a level that is instructive to the professional engineer and architect, it is also comprehensible to the educated layperson and skilled craftsperson. The first three chapters present an introductory review of electricity demand, the photovoltaic effect, and solar energy. The major technical discussion is found in chapters four through nine and in the appendixes.



# Acknowledgments

My three years of work with notable engineers involved in the research and development of standalone and utility-interactive photovoltaic systems at M.I.T. Lincoln Laboratory has formed the basis for much of the material presented here. Many of the systems developed in this research group have successfully operated for three or more years and could become models for a potentially large industry. The information presented in this book is based on the accomplishments of such pioneering scientists and engineers as Drs. Charles Cox, Steve Forman, Edward Kern, Emmanuel Landsman, Marvin Pope, Ron Ross, Al Millner, Ron Matlin, Larry Bucciarelli, John Cremin, Bud Lyon, Carl Much, P. Raghuraman, and John Solman, along with Burt Nichols, Niel Rasmussen, Tom Warner, Bonwyn Brench, Miles Russell, Susan Hendrie, Howard Branz, Joseph Doucet, Henry Bulwinkel, Michael Wong, George Hart, Rick Cadieux, Pat Phemelis, Ray Hopkinson, Harvey Fenton, Jack Helfrich, Tom Emberly, Steven Strong, and Peter Mahoney. The latter half of chapter 2 was ably written by Robert Lempert. The manuscript was carefully read and influenced by Dr. Charles Cox of M.I.T. Lincoln Laboratory and Dr. Ron Ross of the Jet Propulsion Laboratory; I am most grateful for their technical advice and editorial comments, which immeasurably improved this work. Additional reviewers were Jeffrey Cook, Richard Livingstone, and Martin Self.

I am especially thankful to Dr. Charles Cox, Victoria Cox, and my mother for their continuous moral support, and to Bob Harris for his initial ideas and encouragement. Above all, I must dedicate this work to my Lord and Author, who prepared for me the opportunity to write this book and sustained me throughout the years it took to complete the task.

Matthew Buresch

# Contents

<b>Preface</b>	ix
<b>Acknowledgments</b>	xiii
<b>1 The Demand for Electricity</b>	1
Energy Needs in an Industrialized Society	1
Photovoltaic Energy	5
The Residential Electric Load	11
<b>2 Generating Electricity from Sunlight</b>	25
The Atomic Structure of Matter	26
Radiation and the Sun	28
The PN Junction: A Built-In Electromotive Force	29
Photovoltaic Conversion Efficiency	38
Other Types of Photovoltaic Cells	40
<b>3 Solar Energy</b>	43
The Sunlight Experienced on Earth	43
Surface Orientation and Solar Intensity	45
Locating the Sun's Position	46
<i>Hour Angle</i>	47
<i>Declination Angle</i>	48
<i>The Sun Chart: Solar Altitude versus Azimuth</i>	48

The Optimum Surface Orientation	51	
Calculating Solar Energy and Power	55	
<i>Average Daily Solar Energy</i>	57	
<i>Daily Solar Power</i>	63	
<b>4 The Silicon Solar-Cell Response</b>		71
A Solar-Cell Experiment	71	
<i>The Light Variable</i>	72	
<i>The Temperature Variable</i>	74	
<i>The Cell Area Variable</i>	78	
<i>The Load Variable</i>	78	
The Solar-Cell Response Under Normal Conditions	81	
Solar-Cell Simulation	84	
<b>5 Building a Solar-Cell Array</b>		89
A Solar-Cell Array Experiment	89	
<i>Solar Cells Connected in Series</i>	90	
<i>Solar Cells Connected in Parallel</i>	90	
<i>Array Output under a Changing Load</i>	91	
<i>Array Problems and Their Resolution</i>	92	
Array Configuration	97	
Array Energy Calculations	100	
<i>Array Design Exercise</i>	104	
<b>6 Array Protection and Failure Detection</b>		107
Protecting the Array from Stray Electricity	108	
<i>Static Electricity</i>	108	
<i>Induced Electricity</i>	110	
Array Troubleshooting and Protection Strategies	112	
<i>The Array Problem</i>	112	
The Short-Circuit Fault	113	
The Open-Circuit Fault	114	
The Development of Short- and Open-Circuit Faults	115	
<i>A Problem-Solving Circuit</i>	116	
<i>Solving the Array Problem</i>	123	
Detecting Shorts to Ground Using a Multimeter	125	
Detecting Open- or Short-Circuited Modules Using a Multimeter	128	
Detecting Faults Using an <i>I-V</i> Curve Tracer	128	
<b>7 The Photovoltaic-Energy System</b>		131
The Need for Energy Storage	132	
<i>Photovoltaic Output and Load Input throughout the Day</i>	132	
<i>Photovoltaic Output and Load Input throughout the Year</i>	134	

<i>Electricity Storage</i>	137	
Utility Grid Storage	137	
Battery Storage	142	
Voltage Regulation	152	
<i>The Need for Load-Voltage Regulation</i>	152	
<i>The Need for Solar-Cell Voltage Regulation</i>	154	
<i>Locating the System Operating Voltage</i>	155	
<i>Maintaining the Optimum System Operating Voltage</i>	158	
Direct Connection	158	
Fixed-Voltage Operation	159	
Maximum-Power Tracking	160	
Direct-Current-to-Alternating-Current Conversion	162	
<i>The Relative Advantages of DC and AC Electricity</i>	162	
<i>The Basic DC-to-AC Inverter Circuit Design</i>	167	
<b>8 System Design Procedures</b>		175
Photovoltaic-System Energy Calculations	175	
Photovoltaic-System Sizing	177	
<i>Battery Storage</i>	180	
<i>Utility Storage</i>	182	
<i>System Design Sample Problem</i>	183	
Photovoltaic-System Costs versus Benefits	189	
<i>System Costs</i>	190	
<i>System Benefits</i>	192	
<i>Net Present Value</i>	196	
<b>9 Photovoltaic-Array Installation</b>		201
Physical Installation	201	
<i>Rack Mount</i>	203	
<i>Standoff Mount</i>	206	
<i>Direct Mount</i>	208	
<i>Integral Mount</i>	210	
Electrical Installation	212	
<i>Electrical Wire</i>	212	
Wire Resistance and Gauge	213	
Wire Insulation	213	
Ampacity	215	
Wire Selection Procedure	220	
Wire Routing	221	
<i>Electrical Connections</i>	222	
<i>Terminal Lugs</i>	222	
<i>Connectors</i>	223	
<i>Circuit Protection and Interruption Devices</i>	225	
Switching	226	
Overcurrent Protection	228	

<b>Bibliography</b>	233
<b>Appendixes</b>	237
<b>A</b> State of the Art: Photovoltaic Systems in Operation	237
<b>B</b> Handbook for Various Block III and Block IV Silicon Solar-Cell Modules	267
<b>C</b> Climatic Data for 20 Sites within the Continental United States	289
<b>D</b> Uniform Present Worth Tables	311
<b>E</b> Units and Conversion Factors	315
<b>F</b> DC Electrical Equations and Laws	319
<b>Glossary</b>	321
<b>Index</b>	327

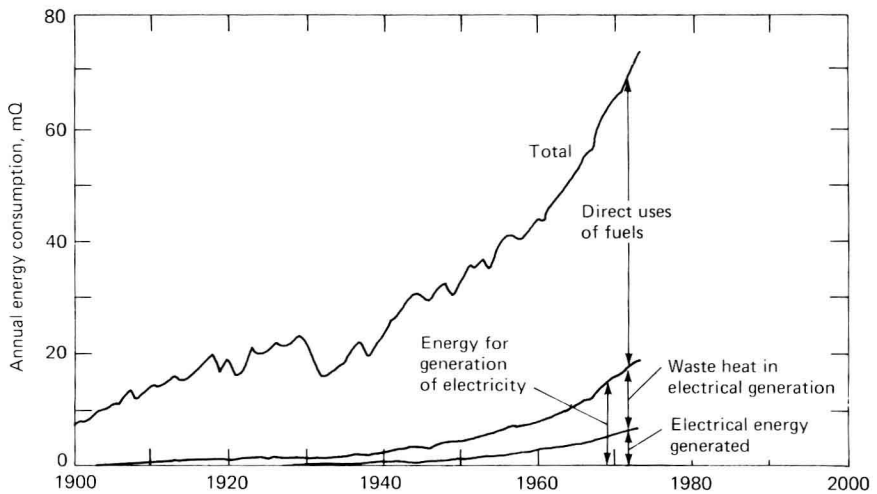
# **THE DEMAND FOR ELECTRICITY**

An assessment of where and how photovoltaic electricity could make a significant contribution to our energy needs is aided by obtaining an overview of energy uses as they differ throughout society. Electricity is a modern form of energy that has varied applications in four different sectors of our economy: industrial, transportation, commercial, and residential. Up until 1981, solar-cell electricity has been used for small-scale and special applications. If they are to play an appreciable part in supplying our energy needs, photovoltaic systems must be targeted toward one or more of the major electricity demand sectors. The size and distribution of the residential electrical load makes it particularly attractive for photovoltaic applications.

## **ENERGY NEEDS IN AN INDUSTRIALIZED SOCIETY**

Electricity was first generated and used on a significant scale in the early part of the twentieth century. Since that time, electricity use has increased at a steady rate that roughly parallels the overall increase in the U.S. demand for energy, as shown in Figure 1-1. In the coming decades, electricity needs are expected to grow more rapidly than the total energy demand, as a result of advances in technology that are resulting in widespread automation. The large energy losses that naturally occur when

## 2 PHOTOVOLTAIC ENERGY SYSTEMS



**Figure 1-1** Energy and electricity demand in the United States during the twentieth century. (From: Robert H. Romer, *Energy: An Introduction to Physics*, Freeman, San Francisco, copyright © 1976, p. 598.)

electricity is generated in a fuel-burning plant are often outweighed by the advantages of this versatile form of energy.

Energy demands in an industrialized society can be divided into four major sectors: industrial, transportation, commercial, and residential. The relative share of the energy "pie" that each different sector requires varies according to a country's resources, technical advancement, and political and economic structure. In the United States in 1973, for example, the industrial sector required about 40% of the total national energy output. Most of this energy went into the production of chemicals, metals, and petroleum products; secondary uses included the manufacture of food, paper products, and building materials. The next largest portion (about 26%) of the total national energy supply was required for transportation. Passenger automobiles and trucks carrying freight were the dominant users of fuel in this sector. The energy demand of the residential sector (about 19%) was mostly devoted to space heating, hot water, lighting, refrigeration, cooking, and air conditioning. The smallest portion (about 15%) was used in the commercial sector for space heating and cooling, refrigeration, and hot water. The residential and commercial needs are quite similar. Table 1-1 outlines the relative energy needs of each of the four sectors in greater detail.

The energy used to supply these different economic sectors can be divided into that devoted to direct use and that converted for electric

power. Table 1-2 shows how much energy was devoted to direct use and how much to electrical use in the U.S. economy in 1973. The direct use of energy involves burning fuels, such as wood, oil, gas, and coal, directly for the purpose of doing work. Direct burning of fuels is most notably used for heating space, water, or industrial materials, and for combustion in engines used for locomotion. Most electricity is created by converting energy from fossil fuels and nuclear reactions into electrical energy through the production of steam and the rotation of a generator. This conversion process is rather costly because energy is lost during generation and transmission, with over half the initial energy usually squandered in the

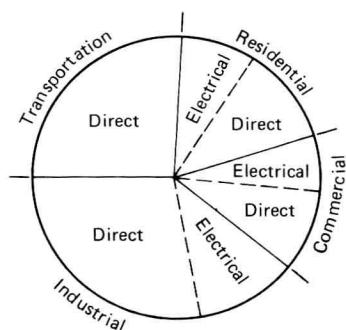
**Table 1-1 Energy Use for Four Major Sectors of the U.S. Economy, 1973.**

Sector	Direct uses of fuels,* mQ†	Electricity (including waste heat from generation),* mQ	Total energy consumption,* mQ	Percentage of national total, %
Residential	8.1 (+0.8%)	5.8 (+7.5%)	13.9 (+3.3%)	19.1
Commercial	6.7 (+3.0%)	4.5 (+7.0%)	11.2 (+4.6%)	15.4
Industrial	20.4 (+2.3%)	8.4 (+4.6%)	28.8 (+3.0%)	39.6
Transportation	18.9 (+4.4%)	0.04 (0%)	18.9 (+4.4%)	26.0
Total	54.1 (+2.9%)	18.7 (+6.0%)	72.8 (+3.7%)	100

Source: Robert H. Romer, *Energy: An Introduction to Physics*, W. H. Freeman & Co., San Francisco, © 1976, p. 603.

\*Figures in parentheses are average annual percentage rates of change during the period 1970–1973.

†Q = quad =  $10^{15}$  (or one quadrillion) Btu.



Distribution of total energy

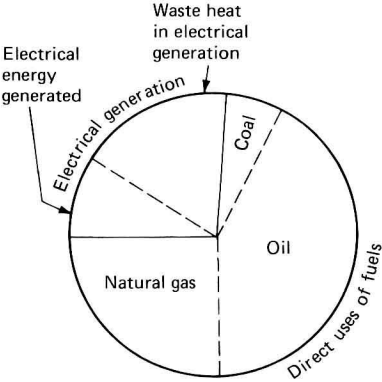


**Table 1-2 Percentages of Energy Used Directly and Converted to Electricity, United States, 1973**

Uses	Energy,* mQ	Percentage of national total, %
Direct uses of fossil fuels		
Coal	4.54 (−4.5%)	6.2
Oil	31.0 (+4.5%)	42.6
Natural gas	18.6 (+2.4%)	25.5
Total direct use	54.1 (+2.9%)	74.3
Electrical generation		
Electrical energy generated	6.64 (+5.9%)	9.1
Energy wasted in electrical generation	12.06 (+6.1%)	16.5
Total for electrical generation	18.7 (+6.0%)	25.7
Total energy consumption	72.8 (+3.7%)	100

Source: Robert H. Romer, *Energy: An Introduction to Physics*, W. H. Freeman & Co., San Francisco, © 1976, p. 603.

\*Figures in parentheses are average annual percentage rates of change during the period 1970–1973.



form of unused heat. Nevertheless, electricity is increasingly attractive because of its versatility for many applications that have developed since the invention of such devices as the motor, radio, and computer.

There is more use of directly burned fuel than of electricity in all four economic sectors. Transportation uses little electricity, especially in America, where electric trains and subways are not common. Most of