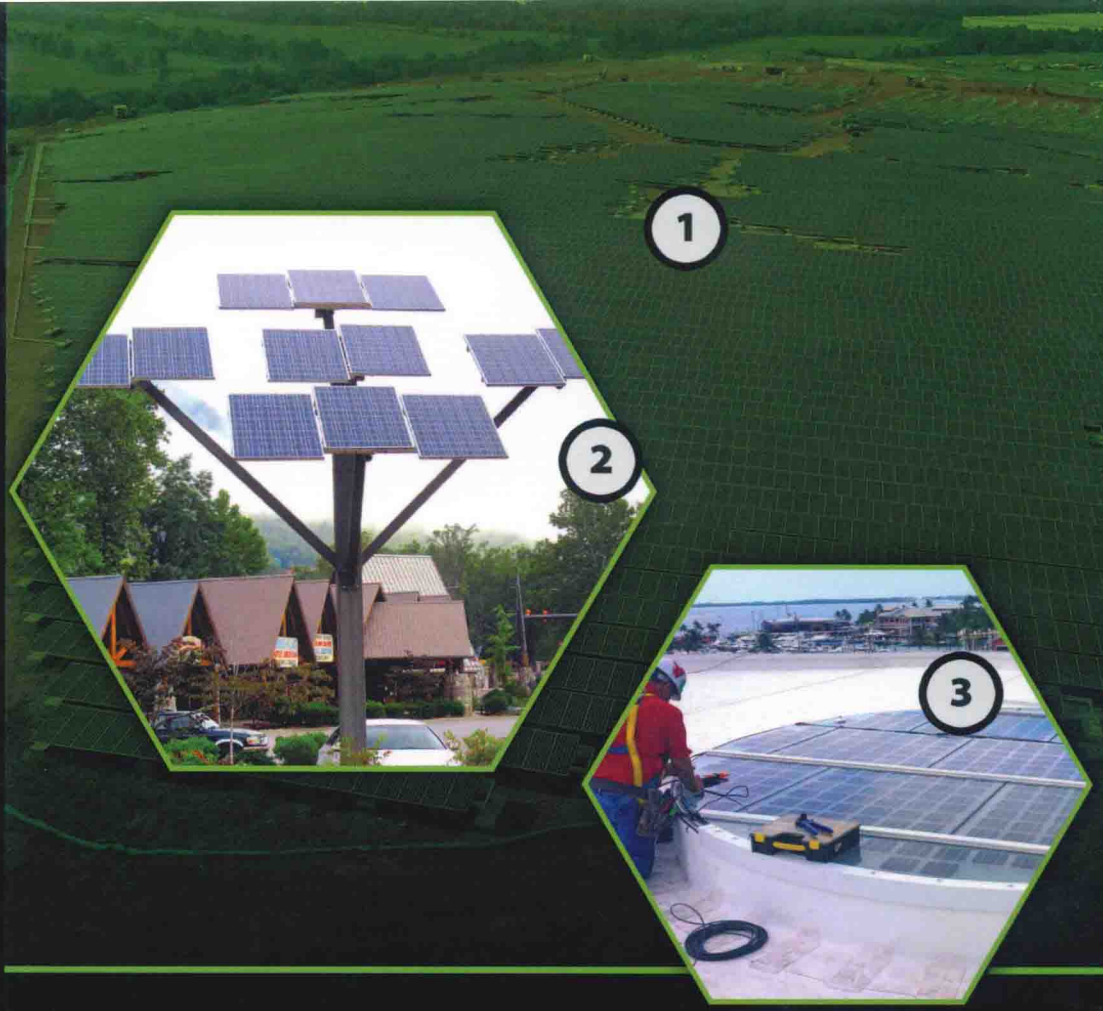
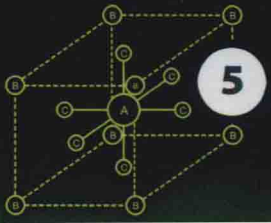


Fourth Edition

Photovoltaic Systems Engineering

Roger Messenger
Amir Abtahi



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Photovoltaic Systems Engineering

The primary purpose of PV Systems Engineering is to provide a comprehensive set of PV knowledge and understanding tools for the design, installation, commissioning, inspection, and operation of PV systems. During recent years in the United States, more PV capacity was installed than any other electrical generation source. In addition to practical system information, this new edition includes explanation of the basic physical principles upon which the technology is based and a consideration of the environmental and economic impact of the technology. The material covers all phases of PV systems from basic sunlight parameters to system commissioning and simulation, as well as economic and environmental impact of PV. With homework problems included in each chapter and numerous design examples of real systems, the book provides the reader with consistent opportunities to apply the information to real-world scenario.

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Photovoltaic Systems Engineering

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Fourth Edition

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Homayoon "Amir" Abtahi

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Photovoltaic Systems Engineering

Fourth Edition

We did not inherit this world from our parents. . . .

We are borrowing it from our children.

(Author unknown)

It is our fervent hope that the engineers
who read this book
will dedicate themselves to the creation of a world
where children and grandchildren will be left
with air they can breathe and water they can drink,
where humans and the rest of nature
will nurture one another.

Preface

The goal of this textbook is to present a comprehensive engineering basis for photovoltaic (PV) system design so that the engineer can understand the *what*, the *why*, and the *how* associated with the electrical, mechanical, economic, and aesthetic aspects of PV system design. This book is intended to *educate* the engineer in the design of PV systems so that when engineering judgment is needed, the engineer will be able to make intelligent decisions based upon a clear understanding of the parameters involved. This goal differentiates this textbook from the many design and installation manuals that are currently available that *train* the reader *how* to do it but not *why*.

Widespread acceptance of the first three editions, coupled with significant growth and new ideas in the PV industry, along with additional years of experience with PV system design and installation for the authors, and, for that matter, a bit of nudging from the publisher, have led to the publication of this Fourth Edition. In recent years, annual installed renewable capacity has exceeded annual installed nonrenewable capacity in the United States. So who knows, there might even be jobs waiting out there for many who learn the material in this book.

The *what* question is addressed in the first three chapters, which present an updated background of energy production and consumption, some mathematical background for understanding energy supply and demand, a summary of the solar spectrum, how to locate the sun, and how to optimize the capture of its energy, as well as the various components that are used in PV systems. Chapter 3 has been shortened a bit so actual design work can begin by about the fifth week of a three-credit course, but it also introduces lithium and a few other emerging battery technologies.

The *why* and *how* questions are dealt with in the remaining chapters in which every effort is made to explain why certain PV designs are done in certain ways as well as how the design process is implemented. Included in the *why* part of the PV design criteria are economic and environmental issues that are discussed in Chapters 8 and 9. Chapter 5 has been embellished with additional practical considerations added to the theoretical background associated with mechanical and structural design.

Chapters 4, 6, and 7 have once again have been updated, including updated homework problems, to incorporate the most recently available technology and design and installation practice. In particular, Chapter 4 incorporates more emphasis on higher voltage systems, new developments in IEEE 1547, new fire code requirements, and *National Electrical Code* changes in the 2014 Edition, such as rapid shutdown and arc fault protection. New sections on Arc Flash Calculations and System Commissioning have been added to Chapter 4.

By the end of Chapter 4, instructors can assign relevant design problems earlier in the course to avoid having designs due at final exam time. We have found when significant design projects are due just before final exams, students tend to spend time on design projects that might better be spent studying for the final exam, especially if

the final exam counts more toward the overall course grade. Paradoxically, the better designers have sometimes ended up with lower course grades.

Since the publication of the previous edition in 2009, a nearly overwhelming wealth of new research on old and new technologies has been underway. We try to cover the highlights of some of this activity in Chapter 11 but have eliminated some of the historical content to make room for the new stuff.

The Appendix presents a recommended format for submittal of a PV design package for permitting or for design review that has been widely used in Florida by the authors and their associates.

A modified top-down approach is used in the presentation of the material. The material is organized to present a relatively quick exposure to all of the building blocks of PV systems followed by design, design, and design. Even the physics of PV cells of Chapter 10 and the material on emerging technologies of Chapter 11 are presented with a design flavor. The focus is on adjusting the parameters of PV cells to optimize their performance as well as on presenting the physical basis of PV cell operation.

Homework problems are incorporated that require both analysis and design, since the ability to perform analysis is the precursor to being able to understand how to implement good design. Many of the problems have multiple answers, such as "Calculate the number of daylight hours on the day you were born in the city of your birth." We have eliminated a few homework problems based on old technology and added a number of new problems based on contemporary technology. Hopefully there are a sufficient number to enable students to test their understanding of the material.

We recommend the course be presented so that by the end of Chapter 4 students will be able to engage in a comprehensive, relevant design project and by the end of Chapter 7 they will be able to design relatively complex systems. We like to assign two design projects: a straight grid-connected system based on Chapter 4 material and a battery-backup grid-connected system based on Chapter 6 material. At the discretion of the instructor, an additional design of a stand-alone system might be considered at the end of Chapter 7, or the stand-alone design might be assigned rather than the battery-backup grid-connected system.

While it is possible to cover all the material in this textbook in a three-credit semester course, it may be necessary to skim over some of the topics. This is where the discretion of the instructor enters the picture. For example, each of the design examples of Chapter 4 introduces something new, but a few examples might be left as exercises for the reader with a preface by the instructor as to what is new in the example. Alternatively, by summarizing the old material in each example and then focusing on the new material, the *why* of the new concepts can be emphasized.

The order of presentation of the material actually seems to foster a genuine reader interest in the relevance and importance of the material. Subject matter covers a wide range of topics, from chemistry to circuit analysis to electronics, solid-state device theory and economics. *The material is presented at a level that can best be understood by those who have reached the upper division at the engineering undergraduate level and have also completed the coursework in circuits and in electronics.*

We recognize that the movement to reduce credit toward the bachelor's degree has left many programs with less flexibility in the selection of undergraduate elective courses, but note the material in this textbook can also be used for a beginning graduate level course.

While the primary purpose of this material is for classroom use, with an emphasis on the electrical components of PV systems, we have endeavored to present the material in a manner sufficiently comprehensive that it will also serve practicing engineers as a useful reference book.

The course can be successfully taught as an Internet course with a preference for live participation open to all. Those remote students who were sufficiently motivated to keep up with the course generally reported that they found the text to be very readable and a reasonable replacement for lectures. We highly recommend that if the Internet is tried that quizzes be given frequently to coerce students into feeling that this course is just as important as their linear systems analysis course. Informal discussion sessions can also be useful in this regard.

The PV field is evolving rapidly. While every effort has been made to present contemporary material in this work, the fact that it has evolved over a period of a year almost guarantees that by the time it is adopted, some of the material will be outdated. For engineers who wish to remain current in the field, many of the references and websites listed will keep them up to date. Proceedings of the many PV conferences, symposia, and workshops, along with manufacturers' data, are especially helpful.

This textbook should provide engineers with the intellectual tools needed for understanding new technologies and new ideas in this rapidly emerging field. The authors hope that at least one in every 4.6837 students will make their own contribution to the PV knowledge pool.

We apologize at the outset for the occasional presentation of information that may be considered to be practical or, perhaps, even interesting or useful. We fully recognize that engineering students expect the material in engineering courses to be of a highly theoretical nature with little apparent practical application. We have made every effort to incorporate heavy theory to satisfy this appetite whenever possible.

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Disclaimer

It's been said that no two snowflakes are the same. And, for that matter, it is unlikely that the weather on any 2 days at any location will be exactly the same. The minute-by-minute temperature and cloud cover will differ between any 2 days, whether they are one after the other or the same date on two successive or nonsuccessive years. As a result, estimating the performance of a PV system is, at best, an inexact science, since performance is critically weather dependent.

However, the longer the period included in a prediction or simulation of PV system performance, the more reliable the prediction becomes, since weather conditions tend to average out over the long term. Still, predicting the future is not nearly as reliable as recording the past. As a result, *when system performance is simulated in this text* using the System Advisory Model (SAM) developed by the U.S. National Renewable Energy Laboratory, because of the careful modeling tools used by NREL, SAM is one of the most reasonable tools to use to estimate annual energy production for a PV system. But no claim has been made that SAM is exact or perfect, and thus when SAM is used to estimate system performance, it must be done with the understanding of the following disclaimer:

> "USER AGREES TO INDEMNIFY DOE/NREL/ALLIANCE AND ITS SUBSIDIARIES, AFFILIATES, OFFICERS, AGENTS, AND EMPLOYEES AGAINST ANY CLAIM OR DEMAND, INCLUDING REASONABLE ATTORNEYS' FEES, RELATED TO USER'S USE OF THE DATA. THE DATA ARE PROVIDED BY DOE/NREL/ALLIANCE "AS IS," AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING BUT NOT LIMITED TO THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL DOE/NREL/ALLIANCE BE LIABLE FOR ANY SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES OR ANY DAMAGES WHATSOEVER, INCLUDING BUT NOT LIMITED TO CLAIMS ASSOCIATED WITH THE LOSS OF DATA OR PROFITS, THAT MAY RESULT FROM AN ACTION IN CONTRACT, NEGLIGENCE OR OTHER TORTIOUS CLAIM THAT ARISES OUT OF OR IN CONNECTION WITH THE ACCESS, USE OR PERFORMANCE OF THE DATA."

In other words, using SAM for educational purposes is just fine, but blaming SAM if a system is built and does not work as predicted by SAM is not okay.

Acknowledgments

Thanks to a long list of PV pioneers for making this publication possible. Only a few years ago, PV was considered to be an emerging technology. Some thought it would never make it on a large scale. But others with more persistence have persevered over the years such that PV is no longer a hobby but a mature, widely accepted, large-scale, worldwide technology that is growing faster than most advocates ever imagined.

One of these PV pioneers is Jerry Ventre, who coauthored the first three editions of this text. Jerry has been retired for a while now and has spent much of his time doing volunteer work with organizations that focus on PV job growth. It has been an honor and a privilege to work with Jerry over the years, and we wish him the best in his current and future activities.

We are convinced that it is virtually impossible to undertake and complete a project such as this without the encouragement, guidance, and assistance from a host of friends, family, and colleagues.

For this edition, we again asked many questions of many people as we rounded up information for the wide range of topics contained herein. A wealth of information flowed our way from the National Renewable Energy Laboratory (NREL) as well as from many manufacturers and distributors of a diverse range of PV system components. We feel confident that had we asked, we would have been able to obtain additional cooperation and materials from many more.

Special thanks to Kimandy Lawrence of VB Engineering for the many discussions during and after normal work hours on various nuances associated with certain systems, including, but not limited to, ac-coupled battery-backup systems, three-phase battery-backup PV systems, microinverter systems, and other experimental designs as well as the latest administrative and permitting issues. We would also like to thank Ms. Hadis Moradi, PhD Candidate, for her review and comments on the latest developments in microgrid systems.

Last, but not least, we thank Mimi Abtahi and Jane Caputi for encouraging us to work on this manuscript rather than play golf, tennis, watch TV, or pay attention to them.

Roger Messenger
Homayoon "Amir" Abtahi
August 2016