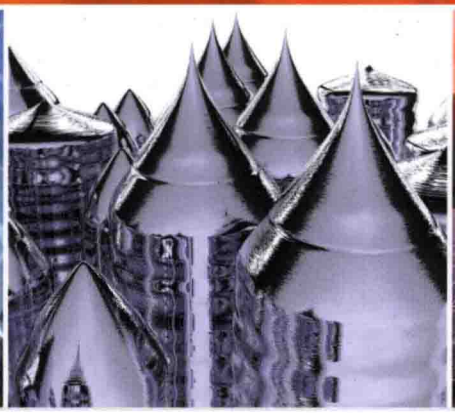
ELECTRICITY FROM SUNLIGHT

PHOTOVOLTAIC-SYSTEMS INTEGRATION AND SUSTAINABILITY


SECOND EDITION

VASILIS FTHENAKIS
PAUL A LYNN

with website

WILEY

A technically authoritative overview of photovoltaics and its practical applications – now including sections on large-scale PV and the sustainability of its growth

Praised for its visual appeal, conversational style and clear explanation of complex ideas with minimal mathematics, *Electricity from Sunlight* has been thoroughly revised and updated to reflect advances in the global PV market, economics and installed capacity.

Key features of the 2nd edition include:

- A timely update of the advances of photovoltaics (PV), with major new material on grid-connected systems.
- More in-depth treatment of PV scientific principles, solar cells, modules, and systems.
- Up-to-date coverage of the PV market including conversion efficiencies and the expansion of grid-friendly power plants.
- End-of-chapter questions to support instructors and students through guided self-study.
- New chapters on manufacturing processes and on materials and other resources availability.
- New large-scale PV section covering the growth of global capacity, utility-scale PV and affordable solutions for intermittency.
- Systems analysis of new applications empowered by low-cost PV, such as energy storage and water desalination.
- Significantly expanded economics and environmental section explaining leveled cost of electricity versus upfront costs, energy return on investments, and lifecycle analysis.

Electricity From Sunlight: Photovoltaic-Systems Integration and Sustainability, Second Edition is an essential primer for new entrants to the PV industry, needing a basic appreciation of complete PV systems, and to students on undergraduate and graduate courses on renewable energy and photovoltaics. It also offers a unique treatise of the sustainability of emerging transformative technologies, which makes it useful to both system analysts and energy policy strategists.

VASILIS FTHENAKIS, Center for Life Cycle Analysis (CLCA), Department of Earth & Environmental Engineering, Columbia University, New York, USA

Vasilis Fthenakis, the founder and director of the CLCA, also leads the National PV Environmental Health and Safety (EHS) Research Center operating at Brookhaven National Lab (BNL). He specializes in the area of PV and the environment and his current research is focused on: recycling, life-cycle environmental impact analysis, air pollution prevention and control, and modeling of accidental chemical releases. Vasilis Fthenakis has authored one book and numerous conference proceedings, book chapters and journal articles.

PAUL A LYNN, formerly Imperial College London, UK

Paul A Lynn obtained his BSc(Eng) and PhD degrees from Imperial College London, UK. After several years in the electrical/electronics industry he lectured at Imperial College and the University of Bristol, latterly as Reader in Electronic Engineering. In 1993 he became Founding Managing Editor of the prestigious Wiley journal "Progress in Photovoltaics" and held this position for 14 years. As a retired academic, Paul Lynn's continued interest in renewable energy has led to a trilogy of Wiley books and, in his spare time, three solar-powered boats. He is the author of nine other books and numerous technical papers and articles.

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Second Edition

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UK

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Electricity from Sunlight

About the Authors

Vasilis M. Fthenakis is the founder and director of the Center for Life Cycle Analysis (CLCA), Department of Earth and Environmental Engineering, Columbia University, New York, USA. He is also a senior scientist emeritus at Brookhaven National Laboratory (BNL) where he conducted research for 36 years and directed the National Photovoltaics (PV) Environmental Research Center and several international networks. Dr. Fthenakis is the coauthor and editor of four books and about 400 scientific publications on topics at the interface of energy life cycles and the environment. Currently, he is leading research on solar desalination, energy systems modeling, life-cycle analysis, and PV recycling.

Paul A. Lynn obtained his B.Sc. (Eng) and Ph.D. degrees from Imperial College London, UK. After several years in the electrical/electronics industry, he lectured at Imperial College and the University of Bristol, latterly as Reader in Electronic Engineering. In 1993 he became the founding managing editor of the prestigious Wiley journal *Progress in Photovoltaics* and held this position for 14 years. As a retired academic, Dr. Lynn's continued interest in renewable energy has led to a trilogy of Wiley books and, in his spare time, three solar-powered boats. He is the author of nine other books and numerous technical papers and articles.

Foreword

Just over 40 years ago, the idea that solar power could make the leap from powering satellites in space to powering the planet was the vision of only a few people brought together by the shock of the first oil embargo. Today, almost everyone sees solar panels on a daily basis. *Electricity from Sunlight: Photovoltaic-Systems Integration and Sustainability* describes the journey from the sun's use in earliest times to tomorrow's continuum of recyclable materials employed in producing energy from a manufactured good, rather than by consuming Mother Earth's resources. The exponential increase in applications powered by solar is shown to be directly tied to the predictable cost reduction experienced through economies of scale and continuous technology performance improvements. The book delivers insights that are both inspirational and quantitatively informative by thoroughly documenting many of the pathways for achieving scale that have been established upon foundations of science and experience proven over decades.

Electricity from Sunlight describes the quantification and consideration given to every dimension of the solar value chain: how feedstocks are prepared, how factories consistently operate, how manufacturing environmental health and safety is planned and audited, how life-cycle benefits are quantified, and how our planet wins at the same time business wins. We now have an existence proof. It is possible to have sustainable development that is economically sustainable.

Sunlight is freely distributed across our planet. The combination of information technology with low-cost solar technology has established the foundation for an irreversible growth connecting the dots between the supply of cost-competitive electricity and the need for power everywhere. The book is a roadmap to understanding the cornerstones upon which an industry has been framed so that ideas for totally optimizing that early vision can be explored and accelerated to meet real-world needs. Here in one place is the guidebook to a clean energy future.

Charlie Gay, Ph.D.
Director, Solar Energy Technology Office
U.S. Department of Energy
Washington, DC

Preface to the First Edition

Photovoltaics (PV), the 'carbon-free' technology that converts sunlight directly into electricity, has grown dramatically in recent years. Unique among the renewable energies in its interaction with the built environment, PV is becoming part of the daily experience of citizens in developed countries as millions of PV modules are installed on rooftops and building facades. People living in sunshine countries will increasingly live in solar homes or receive their electricity from large PV power plants. Many governments around the world are now keen to promote renewable electricity as an essential part of the 21st century's energy mix, and PV is set for an exciting future.

This book is designed for students and professionals looking for a concise, authoritative, and up-to-date introduction to PV and its practical applications. I hope that it will also appeal to the large, and growing, number of thoughtful people who are fascinated by the idea of using solar cells to generate electricity and wish to understand their scientific principles. The book covers some challenging concepts in physics and electronics, but the tone is deliberately lighter than that of most academic texts, and there is comparatively little mathematics. I have included many colour photographs, gathered from around the World, to illustrate PV's huge and diverse range of practical applications.

In more detail, Chapter 1 introduces PV's scientific and historical context, suggests something of the magic of this new technology, and summarises its current status. The treatment of silicon solar cells in Chapter 2 includes material in semiconductor physics and quantum theory, described by a few key equations and supported by plenty of discussion. The new types of thin-film cell that have entered the global PV market in recent years are also introduced. Chapter 3 covers the characteristics of PV modules and arrays, discusses potential problems of interconnection and shading, and outlines the various types of system that track the sun, with or without concentration. The two major categories of PV system, grid-connected and stand-alone, provide the material for Chapters 4 and 5 respectively, and Chapter 6 concludes the story with some of the most important economic and environmental issues surrounding PV's remarkable progress.

Photovoltaic technology seeks to work with nature rather than to dominate or conquer it, satisfying our growing desire to live in tune with Planet Earth. I trust that this book will inspire as well as inform, making its own small contribution to an energy future increasingly based on 'electricity from sunlight'.

Paul A. Lynn
Butcombe, Bristol, England
Spring 2010

Preface to the Second Edition

The eight years since *Electricity from Sunlight* first appeared have witnessed a remarkable development in the field of renewable energy—the explosive growth of photovoltaics (PV). Global installed capacity, which reached about 40 gigawatts (GW) in 2010, is approaching 400 GW. It is even possible to imagine 1000 GW by 2020—a thousand times greater than at the start of the new millennium.

PV's meteoric rise is due to a combination of factors: at the technical level, steady improvements in solar cells, modules, and systems; at the international political level, an ever-increasing awareness of the threats posed by global warming; and at the production level, a dramatic reduction in costs as PV exhibits the well-known "learning curve" of manufactured products experiencing exponential growth.

This new edition pays special attention to issues raised by PV's extraordinary progress, especially the integration of large amounts of solar electricity into existing grid networks and its sustainability in terms of markets, resources, and life-cycle impacts. Chapters 4, 5, and 7 have been revised and greatly expanded, and a brand new chapter on PV manufacturing has been inserted. The other chapters have all been updated.

We hope the new edition will act as an essential primer for entrants to the PV industry needing an up-to-date appreciation of the subject. It also offers a unique treatise on the sustainability of emerging transformative technologies, making it valuable to system analysts and energy policy strategists. Last but not least, we have included end-of-chapter questions and problems to support instructors and the ever-increasing number of college and university students taking courses in renewable energy and PV.

Vasilis Fthenakis
Columbia University and Brookhaven National Laboratory, USA

Paul A Lynn
formerly Imperial College London, UK
Spring 2018

Acknowledgment to the First Edition

There is nothing like a good set of pictures to illustrate PV's extraordinary progress and I have enjoyed enlivening the text with colour photographs obtained from around the world. I hope that my readers will regard them as an important and inspirational aspect of the book. They come from widespread sources and I have received generous cooperation from people in many organisations and companies who have provided copyright permissions and, in several cases, suggested stunning alternatives to illustrate particular topics.

I am especially grateful to the two international organisations that have provided the lion's share of the photographs reproduced in this book:

1. The European Photovoltaic Industry Association (EPIA)

2. The International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS)

3. Additional acknowledgements

I am also grateful to a further group of companies and organisations that have agreed to their photographs appearing in this book, and for help received in each case from the named individual:

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The use of three photographs from the NASA website, and several pictures from the Wikipedia website is also gratefully acknowledged.

The author of a comparatively short but wide-ranging book on PV – or any other technology – inevitably draws on many sources for information and inspiration. In my case several longer and more specialised books, valued companions in recent years, have strongly influenced my understanding of PV and I freely acknowledge the debt I owe their authors, often for clear explanations of difficult concepts that I have attempted to summarise. These books are included in the chapter reference lists, and you may notice that a few of them appear rather frequently. I have tried to give adequate and appropriate citations in the text.

My previous books on electrical and electronic subjects have been more in the nature of standard textbooks, illustrated with line drawings and a few black-and-white photographs. When the publishers agreed to my proposal for an introductory book on PV containing full-colour technical drawings and photographs, I realised that a whole new horizon was in prospect, and have enjoyed the challenge of trying to choose and use colour effectively. The photographs, many of them superb, have already been mentioned. It has also been a great pleasure to work closely with David Thompson, whose ability to transform my sometimes rough sketches into clear and attractive technical drawings has been something of an eye-opener.

For nearly 15 years my main involvement with PV was as Managing Editor of the Wiley international journal *Progress in Photovoltaics: Research & Applications*. Among the many editorial board members who gave valuable advice over that period, I should particularly like to mention Professor Martin Green of the University of New South Wales (UNSW), world-renowned for his research and development of silicon solar cells; and Professor Eduardo Lorenzo of the Polytechnic University of Madrid (UPM), whose encyclopaedic knowledge of PV systems and rural electrification was offered unstintingly. It was both a privilege and a pleasure to work with them for many years. And although any shortcomings in this book are certainly my own, any merits are at least partly due to them and other members of the board.