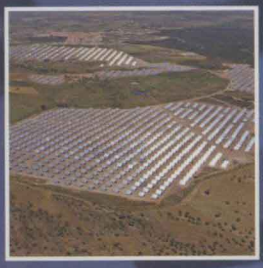
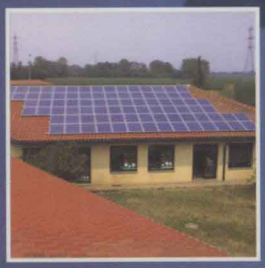
Electricity from Sunlight

An Introduction to Photovoltaics

Paul A. Lynn





WILEY

Electricity from Sunlight

An Introduction to Photovoltaics

Paul A. Lynn ***BSc(Eng), PhD***

formerly

Imperial College London

WILEY

A John Wiley & Sons, Ltd., Publication

This edition first published 2010

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

Library of Congress Cataloging-in-Publication Data
Lynn, Paul A.
Electricity from sunlight : an introduction to photovoltaics / Paul A. Lynn.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-470-74560-1 (cloth)
1. Photovoltaic power generation. 2. Solar cells. 3. Solar energy. I. Title.
TK1087.L96 2010
621.31′244–dc22

2009054395

A catalogue record for this book is available from the British Library.

ISBN: 978-0-470-74560-1

Set in 10/12 pt Times New Roman by Toppan Best-set Premedia Limited
Printed in Singapore by Fabulous Printers Pte Ltd

Electricity from Sunlight

About the author

Paul A. Lynn obtained his BSc(Eng) and PhD degrees in electrical engineering from Imperial College London. After several years in the electronics industry he lectured at Imperial College and the University of Bristol. In 1993 he was appointed founding Managing Editor of the Wiley international journal *Progress in Photovoltaics: Research and Applications*, which he managed for 14 years. His previous publications include 5 textbooks, more than 50 technical papers and articles, and 2 short books on English country pubs. In his spare time Paul maintains a strong interest in environmental matters and is a long-time member of *Friends of the Earth*. He has designed and built three prize-winning solar catamarans and in 2003 he and his wife Ulrike made the first-ever solar-powered voyage along the entire River Thames from Gloucestershire to London.

Preface

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

Acknowledgements

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)

The EPIA is the world's largest industry association devoted to Photovoltaics, with more than 200 business members representing about 95% of the European PV industry. EPIA members are active across the whole field of PV, from silicon producers, cell and module manufacturers, to system providers. Amongst the Association's many activities promoting a higher awareness and penetration of the technology, it represents the European PV industry in contact with political institutions and key decision makers.

The Association's informative website (www.epia.org) includes an excellent photo gallery with a comprehensive selection of images provided by business members. The author acknowledges use of the following photographs, which are reproduced by permission of the EPIA:

Figures 1.3, 1.12, 2.1, 2.3, 2.22, 2.23, 2.29, 3.1, 3.16, 3.18, 4.9, 4.11, 4.12, 4.14, 4.15, 4.16, 4.17, 4.18, 4.20, 4.21, 4.23, 4.24, 4.25, 4.26, 4.27, 5.2, 5.25, 5.27, 5.28, 5.33, 5.34, 5.35, 5.36, 5.37, 6.3, 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, 6.10, 6.11, 6.12, 6.14, 6.16

Permission to use two of these photographs (Figures 1.3 and 4.20) for the front cover is also gratefully acknowledged.

At a personal level it is a pleasure to thank Michel Bataille, IT Manager of the EPIA, for his advice and technical assistance.

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

The International Energy Agency (IEA), founded in 1974 as part of the Organisation for Economic Co-operation and Development (OECD), encourages energy cooperation among member countries. Its Photovoltaic Power Systems Programme (IEA PVPS), begun in 1993, now has 23 members worldwide and organises international projects to accelerate the development and deployment of Photovoltaics.

The IEA PVPS website (www.iea-pvps.org) includes a series of excellent Annual Reports giving up-to-date information about PV developments in the various member countries. The author acknowledges use of the following photographs from these Annual Reports, which are reproduced by permission of IEA PVPS.

Figures 1.1, 1.4, 1.8, 1.13, 1.14, 1.15, 2.2, 2.27, 3.3, 3.14, 4.2, 4.3, 4.6, 4.7, 4.10, 4.13, 4.19, 4.22, 4.28, 4.30, 4.31

Permission to use three of these photographs (Figures 1.4, 1.13, and 4.6) for the front cover is also gratefully acknowledged.

At a personal level it is a pleasure to thank Mary Brunisholz, Executive Secretary of IEA PVPS, for her enthusiastic advice and encouragement.

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:

Amonix Inc. (Nate Morefield) (Figure 3.21)
3425 Fujita Street, Torrance, CA 90505, USA

Boeing Images (Mary E. Kane), USA (Figure 2.32)
www.boeingimages.com

Dyesol Ltd (Viv Tulloch) (Figure 2.35)
P.O. Box 6212, Queanbeyan, NSW 2620, Australia

Dylan Cross Photographer (Dylan Cross), USA (Figure 5.31)
dylan@dylancross.com

First Solar Inc. (Brandon Michener) (Figure 2.31)
Rue de la Science 41, 1040 Brussels, Belgium

Isle of Eigg Heritage Trust (Maggie Fyffe) (Figure 5.23b)
Isle of Eigg, Inverness-shire PH42 4RL, Scotland

Padcon GmbH (Peter Perzl) (Figure 4.5)
Prinz-Ludwig-Strasse 5, 97264 Helmstadt, Germany

Steca Elektronik GmbH (Michael Voigtsberger) (Figures 5.9 and 5.12)
Mammostrasse 1, 87700 Memmingen, Germany

Tamarack Lake Electric Boat Company (Montgomery Gisborne) (Figure 5.30)
207 Bayshore Drive, Brechin, Ontario L0K 1B0, Canada

Wind and Sun Ltd (Steve Wade) (Figures 5.23(a) and 5.24)
Leominster, Herefordshire HR6 0NR, England

The publishers acknowledge use of the above photographs, which are reproduced by permission of the copyright holders.

The use of three photographs (Figures 5.18, 5.19 and 5.20) from the NASA website, and several pictures from the Wikipedia website (Figures 1.5, 1.9, 1.10 and 5.32), 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 (especially items 1, 2, 3, and 4 in the reference list to Chapter 5). 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. Dave's design sense and attention to detail are reflected in the many excellent colour figures that (as I trust my readers will agree) adorn the pages of this book.

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.

Finally I should like to thank the editorial team at Wiley UK in Chichester, and especially Simone Taylor, Nicky Skinner, Laura Bell, and Beth Dufour, for their enthusiasm and guidance during this project. They, and others, have eased into publication this account of an exciting new technology that magically, and quite literally, produces electricity from sunlight.

Paul A. Lynn

Contents

1 Introduction

1.1 The sun, earth, and renewable energy

We are entering a new solar age. For the last few hundred years humans have been using up fossil fuels that took around 400 million years to form and store underground. We must now put huge effort – technological and political – into energy systems that use the Sun's energy more directly. It is one of the most inspiring challenges facing today's engineers and scientists and a worthwhile career path for the next generation. Photovoltaics (PV), the subject of this book, is one of the exciting new technologies that is already helping us towards a solar future.

Most politicians and policymakers agree that a massive redirection of energy policy is essential if Planet Earth is to survive the 21st century in reasonable shape. This is not simply a matter of fuel reserves. It has become clear that, even if those reserves were unlimited, we could not continue to burn them with impunity. The resulting carbon dioxide emissions and increased global warming would almost certainly lead to a major environmental crisis. So the danger is now seen as a double-edged sword: on the one side, fossil fuel depletion; on the other, the increasing inability of the natural world to absorb emissions caused by burning what fuel remains.

Back in the 1970s there was very little public discussion about energy sources. In the industrialised world we had become used to the idea that electricity is generated in large centralised power stations, often out of sight as well as mind, and distributed to factories, offices, and homes by a grid system with far-reaching tentacles. Few people had any idea how the

Electricity from Sunlight By Paul A. Lynn

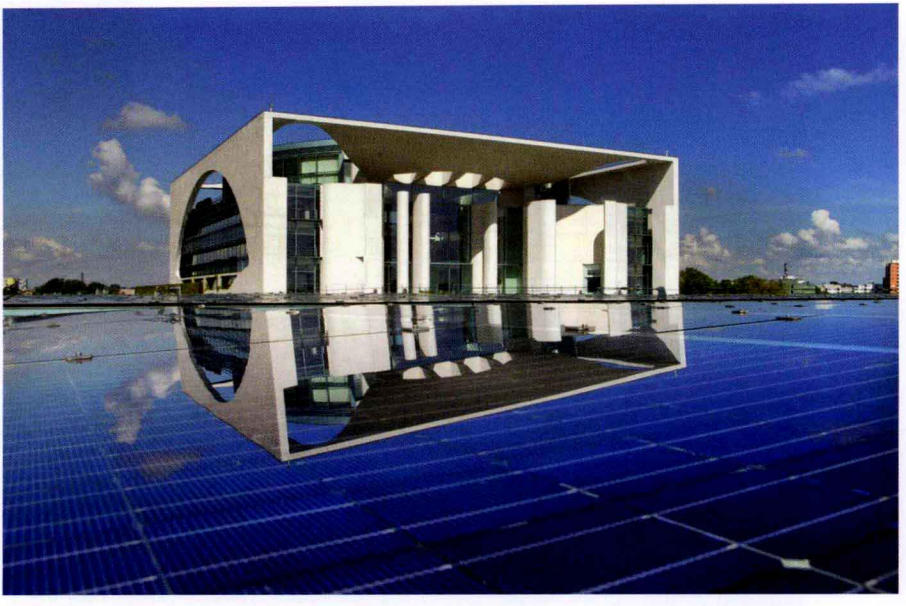


Figure 1.1 Towards the new solar age: this rooftop PV installation at the Mont-Cenis Academy in Herne, Germany, is on the site of a former coalmine (IEA-PVPS).

electricity they took for granted was produced, or that the burning of coal, oil, and gas was building up global environmental problems. Those who were aware tended to assume that the advent of nuclear power would prove a panacea; a few even claimed that nuclear electricity would be so cheap that it would not be worth metering! And university engineering courses paid scant attention to energy systems, giving their students what now seems a rather shortsighted set of priorities.

Yet even in those years there were a few brave voices suggesting that all was not well. In his famous book *Small is Beautiful*,[1] first published in 1973, E.F. Schumacher poured scorn on the idea that the problems of production in the industrialised world had been solved. Modern society, he claimed, does not experience itself as part of nature, but as an outside force seeking to dominate and conquer it. And it is the illusion of unlimited powers deriving from the undoubted successes of much of modern technology that is the root cause of our present difficulties. In particular, we are failing to distinguish between the capital and income components of the Earth's resources. We use up capital, including oil and gas reserves, as if

they were steady and sustainable income. But they are actually once-and-only capital. It is like selling the family silver and going on a binge.

Schumacher's message, once ignored or derided by the majority, is increasingly seen as mainstream. For the good of Planet Earth and future generations we have started to distinguish between capital and income, and to invest heavily in renewable technologies – including solar, wind and wave power – that produce electrical energy free of carbon emissions. In recent years the message has been powerfully reinforced by former US Vice President Al Gore, whose inspirational lecture tours and video presentation *An Inconvenient Truth*[2] have been watched by many millions of people around the world.

Whereas the fossil fuels laid down by solar energy over hundreds of millions of years must surely be regarded as capital, the Sun's radiation beamed at us day by day, year by year, and century by century, is effectively free income to be used or ignored as we wish. This income is expected to flow for billions of years. Nothing is 'wasted' or exhausted if we don't use it because it is there anyway. The challenge for the future is to harness such renewable energy effectively, designing and creating efficient and hopefully inspiring machines to serve humankind without disabling the planet.

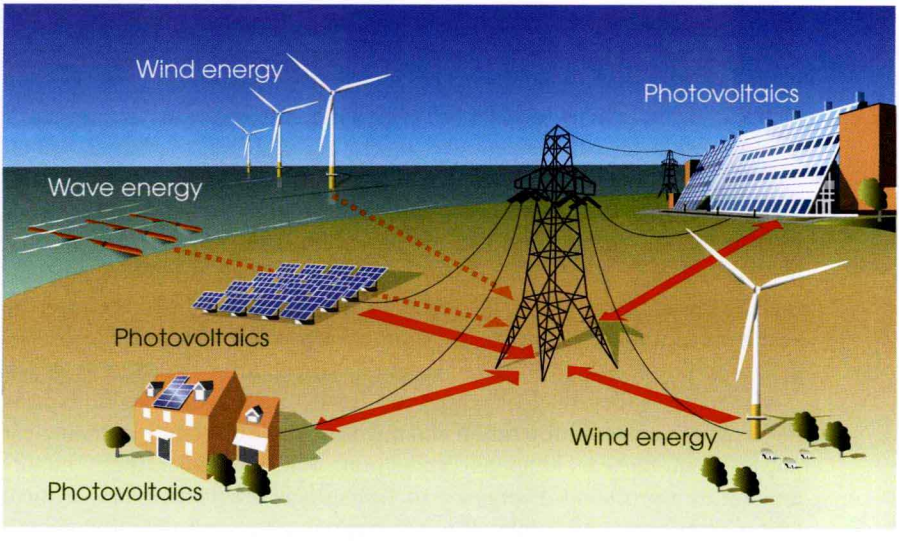


Figure 1.2 Three important renewable technologies: PV, wind and wave.