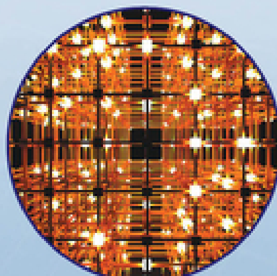
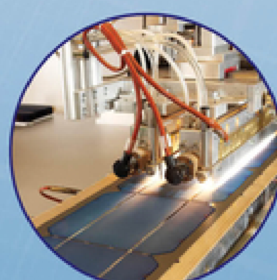
Photovoltaic Solar Energy

From Fundamentals to Applications

Volume 2





Edited by Wilfried van Sark • Bram Hoex
Angèle Reinders • Pierre J. Verlinden
Nicholas J. Ekins-Daukes

with website

IEEE Press

WILEY

Photovoltaic Solar Energy

Photovoltaic Solar Energy

From Fundamentals to Applications, Volume 2

Edited by

Wilfried van Sark
Utrecht University, Utrecht, The Netherlands

Bram Hoex
University of New South Wales
Sydney, Australia

Angèle Reinders
Eindhoven University of Technology
Eindhoven, The Netherlands

Pierre Verlinden
Chief Scientist of Yangtze Institute for Solar Technology (YIST)
Jiangyin, China

Nicholas J. Ekins-Daukes
University of New South Wales
Sydney, Australia

IEEE Press
WILEY

This edition first published 2024

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data:

Names: Sark, Wilfried van, editor. | Hoex, Bram, editor. | Reinders, Angèle, editor. | Verlinden, Pierre, editor. | Ekins-Daukes, Nicholas J., editor. | John Wiley & Sons, publisher.
Title: Photovoltaic solar energy : from fundamentals to applications, volume 2 / edited by Wilfried van Sark, Bram Hoex, Angèle Reinders, Pierre Verlinden, Nicholas J. Ekins-Daukes.
Description: Hoboken, NJ : Wiley, 2024. | "Since the publication of the book Photovoltaic Solar Energy, from Fundamentals to Applications (Reinders, 2017), we have been eager to compile another volume, in fact, to start a series that would appear every 5–10 years to showcase the advancement of the state-of-the-art in photovoltaics research, development and deployment. We are now proud to present the second volume, and we are very grateful to the many authors who committed time to write a new or updated chapter"–Introduction. | Includes bibliographical references and index.
Identifiers: LCCN 2024014706 (print) | LCCN 2024014707 (ebook) | ISBN 9781119578819 (hardback) | ISBN 9781119578833 (adobe pdf) | ISBN 9781119578840 (epub)
Subjects: LCSH: Photovoltaic power generation. | Photovoltaic cells. | Solar energy.
Classification: LCC TK1087 .P478 2024 (print) | LCC TK1087 (ebook) | DDC 621.31/244–dc23/eng/20240501
LC record available at https://lccn.loc.gov/2024014706
LC ebook record available at https://lccn.loc.gov/2024014707

Cover Design: Wiley
Cover Images: © Tom Penpark/Shutterstock, gerenme/Getty Images, © eunikas/Adobe Stock Photos, © Spectral-Design/Adobe Stock Photos, © dim86b/Getty Images, © Gyuszko/Getty Images, © An Qi Wang/Adobe Stock Photos

Set in 9.5/12.5pt STIXTwoText by Straive, Chennai, India

Solar is becoming the new king of the world's electricity markets

Fatih Birol,
IEA Executive Director, 2020

We dedicate this book to all the young students and entrepreneurs who are to take up the task of realizing 50+ terawatt PV by mid-century as a major building block of a sustainable society.

Contents

About the Editors

Prof. Dr. Wilfried van Sark is a full professor of "Integration of Photovoltaics" at the Copernicus Institute of Sustainable Development at Utrecht University, Utrecht, the Netherlands. He is an experimental physicist by training (MSc/PhD) and has 40 years of experience in the field of photovoltaics. He worked on various material systems such as crystalline and thin film silicon and III–V solar cells, both experimentally and theoretically. His current activities focus on employing spectrum conversion to increase solar cell conversion efficiency for next-generation photovoltaic energy converters such as luminescent solar concentrators, as well as performance analysis of building-integrated and standard PV systems in the field, including offshore floating PV. This links to the integration of PV systems in smart grids in the built environment, in which electrical vehicles, demand response, and self-consumption and self-sufficiency play a major role. He is the author of some 250 publications, cited more than 12 000 times, and various (text)books on photovoltaics. He is an associate editor of *Solar Energy and Frontiers in Energy Research* and a member of the editorial boards of *Renewable Energy*, *Energies*, and *Materials*. He is a member of the International Solar Energy Society, a senior member of the Institute of Electrical and Electronic Engineers (IEEE), and a member of scientific committees of various EU and IEEE PV conferences. He presently is the national representative for the International Energy Agency (IEA) PVPS Task 13 (PV Performance, Operation and Reliability of Photovoltaic Systems) and Task 16 (Solar Resource for High Penetration and Large Scale Applications).

Prof. Dr. Bram Hoex completed an MSc degree and a PhD degree in applied physics from the Eindhoven University of Technology (TU/e) in the Netherlands. His PhD work on functional thin films for high-efficiency solar cells was recognized by both the SolarWorld "Junior Einstein" and Leverhulme "Technology Transfer" awards. After completing his PhD degree in 2008, he joined the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) as head of the Photovoltaic Characterization group. From 2012 to the end of 2014, he was Director of the Silicon Materials and Solar Cells Cluster and Group Leader Monocrystalline Silicon Wafer Solar Cells. In 2015, he joined the School of Photovoltaic and Renewable Energy Engineering (SPREE) at University of New South Wales, Sydney, Australia where he is currently Deputy Head of School (Research). His research group focuses on developing and applying nanoscale thin films to a wide range of renewable energy devices to improve their performance, solar cell/module reliability, as well as financial and performance modeling of gigascale solar farms. He is best known for his groundbreaking work on aluminum oxide for crystalline silicon surface passivation, which is now the de facto standard for industrial PERC and TOPCon solar cells. He also pioneered the application of atomic layer deposition for silicon wafer solar cell manufacturing. During his career, he has raised over A$ 80 million in competitive research funding of which A$ 23 million as a lead investigator. He has published over 250 journal and conference papers, and he has an h-index of 42. In 2016, he was awarded the mid-career "IEEE PVSC Young Professional Award" for his significant contributions and his potential as a future leader in the field of photovoltaics, and in 2018, he was selected as one of the "Solar 40 under 40" by Renewable Energy World.

Prof. Dr. Angèle Reinders is a full professor of "Design of Sustainable Energy Systems" at the Department of Mechanical Engineering in Eindhoven University of Technology (TU/e), Eindhoven, the Netherlands. In her research, she focuses on the integration of solar energy technologies in buildings and mobility by means of simulation, prototyping, and testing. A strong interest exists in designs that enhance user acceptance and reduce environmental impact. Angèle Reinders studied experimental physics at Utrecht University, where she also received her doctoral degree in chemistry. Next, she developed herself in industrial design engineering. She was an associate professor at the University of Twente and a full professor in energy efficient design at TU Delft. In the past, she also worked at the Fraunhofer Institute of Solar Energy, World Bank, ENEA in Naples, and Center of Urban Energy in Toronto. She is known for her books: *Designing with Photovoltaics* (2020), *The Power of Design,* and *Photovoltaic Solar Energy from Fundamentals to Applications*. In 2010, she co-founded the *Journal of Photovoltaics*. She has also initiated many projects and has an extensive publication record.

Dr. Pierre Verlinden is currently Chief Scientist of Yangtze Institute for Solar Technology, China, and Adjunct Professor at the University of New South Wales, Sydney. He received the PhD degree in electrical engineering from the Catholic University of Louvain (UCL in Belgium) and was a visiting scholar at Stanford University (USA) thanks to a NATO Research Fellowship. Dr. Verlinden has been working in the field of photovoltaics since 1979 and has published over 200 technical papers and contributed to a number of books. Among several key positions in the PV industry, he was director of R&D at SunPower Corporation (USA) from 1991 to 2001 and Chief Scientist, Vice President, and Deputy Chair of the Academic Committee of the State Key Laboratory of PV Science and Technology at Trina Solar, Changzhou (China). He established the technical leadership of Trina Solar, allowing the company to become one of the largest PV manufacturers of cells and modules worldwide. Dr. Verlinden is the recipient of the 2016 William Cherry Award, awarded by the Institute of Electrical and Electronic Engineers (IEEE), and the 2019 Becquerel Prize, awarded by the EU Commission, for his dedication over the past three decades at the forefront of PV technology and commercialization, leading technology advances including the interdigitated back contact cell, silicon and multijunction III-V CPV cells, and his overall leadership of key R&D organizations. Dr. Verlinden is also a recipient of the 2017 Chinese Government Friendship Award, the highest award given by China to foreigners. In 2023, Dr. Verlinden was awarded a Doctor Honoris Causa degree from the University of New South Wales, Australia, and the Francqui Chair at the University of Hasselt, Belgium. He is a fellow member of the IEEE.

Prof. Dr. Nicholas J. Ekins-Daukes is a professor in the School of Photovoltaic and Renewable Energy Engineering at the University of New South Wales, Sydney, Australia. He holds a PhD and an MSc from Imperial College and an MSc in physics and electronics from the University of St Andrews. From 2008 to 2017, he worked in the physics department at Imperial College London, holding positions as Reader, Senior Lecturer, and Lecturer, as well as a Royal Society Industry Fellowship. From 2005 to 2017, he worked as a lecturer at the School of Physics at the University of Sydney. From 2003 to 2006, he was a JSPS research fellow at the Toyota Technological Institute, Japan. His research aims to fundamentally increase the efficiency of photovoltaic solar cells toward the ultimate efficiency limit for solar power conversion of 87%. This research begins by establishing conceptual thermodynamic boundaries for the processes that can (and cannot) lead to efficiency improvements in solar cells. This is followed by practical work to demonstrate working, proof-of-principle devices and often involves computer modeling and optical spectroscopy in addition to standard photovoltaic device measurements. Several "Advanced Concept" devices have emerged from this work, notably the quantum well solar cell that enabled a 32.9% III–V double junction solar cells to be made, photo-molecular up-conversion on amorphous silicon solar cells, photon ratchet sequential absorption photovoltaic device, and several demonstrations of a hot carrier solar cell. In 2022, he demonstrated electrical power from the thermal emission of light using a thermoradiative diode.

List of Contributors

Esther Alarcón-Lladó
Center for Nanophotonics
AMOLF
Amsterdam
The Netherlands

Thomas G. Allen
KAUST Solar Center (KSC), Physical Sciences and Engineering Division (PSE)
King Abdullah University of Science and Technology (KAUST)
Thuwal
Kingdom of Saudi Arabia

Kevin Anderson
Sandia National Laboratories
1515 Eubank Blvd SE
Albuquerque
USA

Erkan Aydin
KAUST Solar Center (KSC), Physical Sciences and Engineering Division (PSE)
King Abdullah University of Science and Technology (KAUST)
Thuwal
Kingdom of Saudi Arabia

Tino Band
DENKweit GmbH
Halle (Saale)
Germany

Michele De Bastiani
Department of Chemistry
INSTM Università di Pavia
Pavia
Italy

Matthew Berwind
Fraunhofer Institute for Solar Energy Systems
Division Photovoltaics
Freiburg
Germany

Karsten Bittkau
IEK-5 Photovoltaik
Forschungszentrum Jülich GmbH
Jülich
Germany

Mathieu Boccard
École Polytechnique Fédérale de Lausanne (EPFL)
Institute of Electrical and Micro Engineering (IEM)
Photovoltaics and Thin Film Electronics Laboratory (PV-LAB)
Neuchâtel
Switzerland

Christian Braun
Fraunhofer Institute for Solar
Energy Systems
Division Photovoltaics
Freiburg
Germany

Xue Chen
R&D Department
State Key Laboratory of Photovoltaic
Science and Technology, Trina Solar
Changzhou
Jiangsu
China

Alison Ciesla
School of Photovoltaic and Renewable
Energy Engineering
UNSW Sydney
Sydney, NSW
Australia

Karoline Dapprich
Sinton Instruments
Boulder, CO
USA

Kaining Ding
IEK-5 Photovoltaik
Forschungszentrum Jülich GmbH
Jülich
Germany

Priya Dwivedi
The University of New South Wales
Sydney, NSW
Australia

Nicholas J. Ekins-Daukes
School of Photovoltaic and Renewable
Energy Engineering
University of New South Wales
Sydney, NSW
Australia

Jiarui Fan
Longi, R&D Department
Wafer Business Unit
Xi'An, Shaanxi
China

Francesco Frontini
University of Applied Sciences and Arts of
Southern Switzerland (SUPSI)
Mendrisio
Switzerland

Vasilis Fthenakis
Earth and Environmental Engineering
Department
Center of Life Cycle Analysis
Columbia University
New York, NY
USA

Nannan Fu
Longi, R&D Department
Wafer Business Unit
Xi'An, Shaanxi
China

Sara M. Golroodbari
Copernicus Institute of Sustainable
Institute
Utrecht University
Utrecht
The Netherlands

Ziv Hameiri
The University of New South Wales
Sydney, NSW
Australia

Clifford W. Hansen
Photovoltaics and Materials Technologies
Sandia National Laboratories
Albuquerque, NM
USA