# **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







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



This edition first published 2024 © 2024 John Wiley and Sons Ltd

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at http://www.wiley.com/go/permissions.

The right of Wilfried van Sark, Bram Hoex, Angèle Reinders, Pierre Verlinden, and Nicholas J. Ekins-Daukes to be identified as the editorial material in this work has been asserted in accordance with law.

#### 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.

Trademarks: Wiley and the Wiley logo are trademarks or registered trademarks of John Wiley & Sons, Inc. and/or its affiliates in the United States and other countries and may not be used without written permission. All other trademarks are the property of their respective owners. John Wiley & Sons, Inc. is not associated with any product or vendor mentioned in this book.

#### Limit of Liability/Disclaimer of Warranty

#### While the publisher and authors have used their best efforts in preparing

this work, they make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials or promotional statements for this work. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

#### 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 xxiii List of Contributors xxvii Preface xxxiii Acknowledgments xxxv About the Companion Website xxxvii

#### Part One Introduction to the Book 1

#### **1** Introduction *3*

Wilfried van Sark, Bram Hoex, Angèle Reinders, Pierre Verlinden, and Nicholas J. Ekins-Daukes

- 1.1 Introduction to Photovoltaic Solar Energy, Volume 2 3
- 1.2 The First Terawatt 5
- 1.3 Structure of the Book 6 References 7

#### Part Two Solar Irradiance Resources 9

#### 2 Solar Irradiance Resources 11

Joshua S. Stein

- 2.1 Introduction 11
- 2.2 Earth–Sun System 11
- 2.3 Sun Position Calculations 11
- 2.4 Extraterrestrial Irradiance 13
- 2.5 Solar Radiation at the Earth's Surface 14
- 2.6 Spectral Content of Sunlight 15
- 2.7 Clear Sky Irradiance Models 16
- 2.8 Conclusion/Summary 17
  - Author Biography 17

References 17

viii Contents

3 Irradiance and Weather Datasets for PV Modeling 19 Joshua S. Stein Introduction 19 3.1 3.2 Measurements of Irradiance Data 19 3.3 Satellite Irradiance Datasets 20 Modeled or Processed Irradiance Datasets 21 3.4 3.5 Conclusion 22 Author Biography 23 References 23 4 Irradiance on the Plane of the Array 25 Joshua S. Stein and Clifford W. Hansen Introduction 25 4.1 4.2 Modeling POA Irradiance 25 Array Orientation 26 4.3 4.3.1 Fixed Tilt Array Orientation 27 4.3.2 Tracking Schemes and Algorithms 28 4.3.3 Backtracking 29 4.4 Plane-of-Array Beam Irradiance 29 4.5 Angle of Incidence 29 4.6 Plane-of-Array Ground Reflected Irradiance 30 4.7 Albedo 30 4.8 Plane-of Array Sky Diffuse Irradiance 32 4.8.1 Isotropic Model 32 4.8.2 Circumsolar Brightening (e.g. Hay and Davies Model) 32 Horizon Brightening (e.g. Reindl Model) 33 4.8.3 4.8.4 Empirical Models (e.g. Perez Model) 33 4.9 Conclusion 36 Author Biographies 37

References 37

#### Part Three Crystalline Silicon Technologies 39

#### 5 Crystalline Silicon Ingot Pulling and Wafering Technology 41

Nannan Fu and Jiarui Fan

- 5.1 Origin of Czochralski-Growth Technology 41
- Technical Principles and Application 44 5.2
- 5.3 Status of Recharge-Cz (RCz) Ingot Pulling Technology 44
- 5.4 Development of Continuous Crystal Pulling Technology (CCz) 48
- N-Type Mono-Wafer Slicing Technology 50 5.5
- Conclusion 52 5.6

Abbreviations and Acronyms 52 Author Biographies 53 References 53

#### Contents ix

#### 6 Tunnel Oxide Passivated Contact (TOPCon) Solar Cells 55

Bishal Kafle and Armin Richter

- 6.1 Introduction 55
- 6.2 Concept 56
- 6.3 Both Side Contacted Cells with TOPCon 57
- 6.3.1 Cell Architectures 57
- 6.3.2 Industrial TOPCon (i-TOPCon) 59
- 6.3.2.1 Formation of Interfacial Oxide 61
- 6.3.2.2 Deposition and Doping of Polysilicon 61
- 6.3.2.3 Hydrogenation and Contact Formation 62
- 6.4 Challenges 62
- 6.4.1 Technological Challenges 62
- 6.4.2 Alternative to Ag Contacts 63
- 6.4.3 Economic Competitiveness to *p*-PERC Cells 64
- 6.5 Conclusion 64 List of symbols 64 Author Biographies 65 References 65

#### 7 Heterojunction Silicon Solar Cells: Recent Developments 71

Mathieu Boccard and Jun Zhao

- 7.1 Introduction 71
- 7.2 Material Evolutions 71
- 7.2.1 Thin Silicon Layers 71
- 7.2.2 Transparent Electrodes 72
- 7.2.3 Alternative Materials 73
- 7.3 Device Processing 74
- 7.3.1 Contacting Strategies 74
- 7.3.2 Wafer Type *74*
- 7.3.3 Post-processing Improvements 75
- 7.4 Revolution in Industry 75
- 7.4.1 Research and Development 75
- 7.4.2 Status of Production 77
- 7.5 Conclusions 78 References 79

#### 8 Update on Non-silicon-based Low-Temperature Passivating Contacts for Silicon Solar Cells 81

Md. Anower Hossain and Bram Hoex

- 8.1 Introduction 81
- 8.2 TMOs as Passivating Electron Contacts 85
- 8.2.1  $TiO_{2-x}$  as Passivating Electron Contact 86
- 8.2.2 Nb<sub>2</sub>O<sub>5-x</sub> as Passivating Electron Contact 88
- 8.2.3  $Ta_2O_{5-x}$  as Passivating Electron Contact 88
- 8.2.4  $Sc_2O_{3-x}$  as Passivating Electron Contact 89

- x Contents
  - 8.2.5 ZnO as Passivating Electron Contact 89
  - 8.3 Non-TMOs as Electron-Selective Contacts 89
  - 8.3.1  $MgO_x$  as Passivating Electron Contact 89
  - 8.3.2  $SnO_{2-x}$  as Passivating Electron Contact 90
  - 8.3.3 Other Metal Compounds as Electron-Selective Contacts 90
  - 8.4 TMOs as Passivating Hole Contacts for c-Si Solar Cells 90

96

- 8.4.1  $MoO_{3-x}$  as Passivating Hole Contact 91
- 8.4.2  $V_2O_{5-x}$  as Passivating Hole Contact 92
- 8.4.3  $WO_{3-x}$  as Passivating Hole Contact 92
- 8.4.4 Non-conventional  $TiO_x Si_v/c$ -Si Stack as Passivating Hole Contact 92
- 8.4.5 Other Passivating Hole Contacts 94
- 8.5 Summary 95
  - Author Biographies References 97

#### 9 Carrier-Induced Degradation 103

Michelle Vaqueiro Contreras

- 9.1 Introduction 103
- 9.2 Boron–Oxygen Related Recombination 103
- 9.3 Light and Elevated Temperature Degradation (LeTID) 107
- 9.4 Copper-Related Degradation 111
- 9.5 Surface-Related Degradation 113
- 9.6 Conclusions 116 Author Biography 116 References 117

#### **10 Hydrogenation** *123*

Alison Ciesla

- 10.1 Introduction 123
- 10.2 Typical Hydrogenation Methods 123
- 10.2.1 Forming Gas Anneal and "Alneal" 124
- 10.2.2 Hydrogen Containing Dielectrics 124
- 10.2.2.1 Thermal Activation 125
- 10.2.3 Hydrogen Plasma 125
- 10.2.4 Bulk Silicon Hydrogen Passivation 125
- 10.3 Advanced Hydrogenation 126
- 10.3.1 Background 126
- 10.3.2 Atomic Hydrogen Behavior in Silicon 126
- 10.3.3 The Impact of Temperature and Carrier Injection 127
- 10.3.4 The Benefit of Charge State Control 128
- 10.3.5 Industrial Advanced Hydrogenation Processes 129
- 10.4 Hydrogenation in Record Solar Cells 129
- 10.5 Passivation of Specific Defects 129
- 10.5.1 Surfaces and Grain Boundaries 130
- 10.5.2 Dislocations 130

- 10.5.3 Vacancies 131
- 10.5.4 Process Induced Defects 131
- 10.5.5 Boron–Oxygen (BO) Defects 131
- 10.5.6 Transition Metals 132
- 10.6 Negative Effects of Hydrogen 132
- 10.7 Conclusion 133 Acknowledgments 133 Author Biography 133 References 133

#### Part Four Perovskite Solar Cells 139

#### **11 Perovskite Solar Cells** 141

- Anita Ho-Baillie, Md Arafat Mahmud, and Jianghui Zheng
- 11.1 Introduction 141
- 11.2 Metal Halide Perovskites 142
- 11.3 Evolution of Perovskite Solar Cell Design 144
- 11.4 Optical Properties of Perovskites 145
- 11.5 Defects and Defect Tolerance of Perovskite 147
- 11.6 Outlook 149 Author Biographies 150 References 151

#### Part Five Tandem Structures 157

#### **12** Perovskite/Silicon Tandem Photovoltaics 159

Thomas G. Allen, Erkan Aydin, Anand S. Subbiah, Michele De Bastiani, and Stefaan De Wolf

- 12.1 Introduction 159
- 12.2 Monolithic Tandems: Evolution of Record Devices and Key Developments 161
- 12.3 Four Terminal Tandems 167
- 12.4 Packaging, Stability, and Field Testing 169
- 12.5 Outlook 171 Abbreviations and Acronyms 171 Author Biographies 172 References 173

## **13** An Overview of Chalcogenide Thin Film Materials for Tandem Applications 179

Bart Vermang

- 13.1 Chalcogenide Thin Film Materials With Tuneable Bandgap 179
- 13.2 Tandem Applications 180
- 13.3 Bottom Cell Candidates 182
- 13.4 Top Cell Candidates 183
- 13.5 Tandem Results 186

- xii Contents
  - 13.6 Conclusions and Outlook 188 Author Biography 188 References 188

#### Part Six Nanophotonics 193

#### **14** Nanoscale Photovoltaics 195

Sander A. Mann and Esther Alarcón-Lladó

- 14.1 Introduction 195
- 14.2 Absorption and Scattering by Nanoscale Objects 195
- 14.2.1 Localized Resonances 196
- 14.2.2 Guided Modes 198
- 14.2.2.1 Arrays of Absorbing Nanoparticles 201
- 14.3 Nanophotovoltaics 201
- 14.3.1 The Internal and External Quantum Efficiency 201
- 14.3.2 The Short-Circuit Current 202
- 14.3.3 The Open-Circuit Voltage 202
- 14.3.3.1 Radiative Recombination 202
- 14.3.3.2 Nonradiative Recombination 203
- 14.3.4 Conversion Efficiency 204
- 14.3.4.1 Efficiency Limits 204
- 14.3.4.2 Concentration 204
- 14.3.5 Angle Restriction 205
- 14.4 Nanowire Solar Cells 205
- 14.4.1 Nanowire Synthesis 206
- 14.4.2 Single Nanowire Solar Cells 206
- 14.4.3 Nanowire Array Solar Cells 207

14.5 Conclusion 210
Abbreviations and Acronyms 210
Nomenclature 210
Author Biographies 211
References 212

#### **15 Quantum Dots Solar Cells** 217

Han Wang and Maria Antonietta Loi

- 15.1 Introduction 217
- 15.2 Colloidal Quantum Dots Generalities 219
- 15.3 Ligand Exchange Methods 222
- 15.4 Evolution of CQDs Solar Cells 224
- 15.5 Recent Progress in Solar Cells 227
- 15.6 Solvents for CQDs Inks 234
- 15.7 Device Structure 235
- 15.7.1 Electron Transport Layer 235
- 15.7.2 Hole Transport Layer 240

15.8 Conclusion 242 Author Biographies 243 References 243

#### **16** Singlet Fission for Solar Cells 255

Timothy W. Schmidt and Murad J. Y. Tayebjee

- 16.1 Introduction 255
- 16.2 Molecular Electronic Structure and Photophysics 256
- 16.3 Davydov Splitting 258
- 16.4 Singlet Fission 259
- 16.5 The Potential Benefits of Singlet Fission 262
- 16.6 Materials for Singlet Fission 264
- 16.7 Devices Reported to Date 266
- 16.8 Prospects 266 Author Biographies 267 References 268

#### Part Seven Characterization and Measurements Methods 271

#### 17 Temperature-Dependent Lifetime and Photoluminescence Measurements 273 Ziv Hamoiri and Yan Zhu

Ziv Hameiri and Yan Zhu

- 17.1 Temperature-Dependent Lifetime Spectroscopy 273
- 17.1.1 Lifetime Spectroscopy 273
- 17.1.2 Analysis Methods 274
- 17.1.2.1 Defect Parameterization Solution Surface 274
- 17.1.2.2 Defect Parameter Contour Map 276
- 17.1.2.3 Linearization-Based Methods 277
- 17.1.2.4 The Newton–Raphson Method 278
- 17.1.2.5 Machine Learning-Based Methods 278
- 17.1.3 Challenges 279
- 17.1.3.1 Extraction of the Defect-Associated Lifetime 279
- 17.1.3.2 Temperature Dependencies of Capture Cross Sections 279
- 17.1.3.3 Two-Level (or More) Defects 279
- 17.1.4 T-IDLS Like Measurements 280
- 17.1.4.1 Suns-V<sub>oc</sub>(T) 280
- 17.1.4.2 Investigation of Surface Passivation 280
- 17.2 Temperature-Dependent Photoluminescence Imaging 280
- 17.2.1 Photoluminescence Imaging 280
- 17.2.2 T-IDLS Using Photoluminescence Imaging 281
- 17.2.3 Spatially Resolved Temperature Coefficients 281
- 17.3 Summary 284 Author Biographies 284 References 284

xiv Contents

#### 18 Advanced Flash Testing in High-Volume Manufacturing 291 Karoline Dapprich and Ronald A. Sinton 18.1 Capacitive Devices 291 Bifacial Devices 293 18.2 18.3 Aggregate $J_{0s}$ 294 18.4 Power Loss Analysis 296 18.5 Conclusion 299 Abbreviations and Acronyms 300 Nomenclature 300 Author Biographies 301 References 301 19 Machine Learning for Photovoltaic Applications 303 Priya Dwivedi and Ziv Hameiri Machine Learning 303 19.1 Types of Machine Learning 303 19.1.1 19.1.1.1 Supervised Learning 303 19.1.1.2 Unsupervised Learning 303 19.1.1.3 Reinforcement Learning 305 Machine Learning-based Process Optimization 305 19.1.2 19.2 Applications of Machine Learning in Photovoltaics 306 Ingot 306 19.2.1 19.2.2 Wafer 306 19.2.2.1 Process Optimization 306 19.2.2.2 Defect Inspection 307 19.2.2.3 Quality Rating 307 19.2.3 Solar Cells 307 19.2.3.1 Process Optimization 307 19.2.3.2 Defect Inspection 308 19.2.3.3 Quality Rating 310 19.2.4 Module 311 19.2.5 New Materials 311 Conclusions 312 19.3 Author Biographies 313 References 313 20 Non-Destructive, Spatially Resolved, Contactless Current Measurement 319 Kai Kaufmann, Tino Band, and Dominik Lausch 20.1 Introduction 319 20.2 Theory and Practical Application to PV Modules 319 Application to Solar Modules 321 20.3 20.3.1 Cross and Interconnectors 321 20.3.2 Soldering Joints 322 20.3.3 Shingled Modules 323 Diode Analysis in Junction Boxes 324 20.3.4

- 20.3.5 Solder Joint Analysis in Junction Boxes 325
- 20.3.6 Inverse Problem, Quantitative Current Analysis 328
- 20.3.7 Conclusion 329 Author Biographies 330 References 330

#### Part Eight PV Modules 333

#### 21 Advanced Industrial High-Efficiency Silicon PV Module Design 335

Shu Zhang, Xue Chen, Jianmei Xu, and Pierre J. Verlinden

- 21.1 Introduction 335
- 21.2 Large Silicon Wafers 336
- 21.3 Multi-Busbar (MBB) 338
- 21.4 Diversified Layout Design 341
- 21.5 Non-Destructive Cutting (NDC) Technology 342
- 21.6 High-Density Assembly 344
- 21.7 Bifacial Modules 346
- 21.8 Advanced Materials *347*
- 21.9 Summary 350 Abbreviations and Acronyms 351 Nomenclature 352 Author Biographies 352 References 354

#### 22 Smart Modules for Shade Resilience 357

- Wilfried van Sark
- 22.1 Introduction 357
- 22.2 Shade Mitigation Strategies 358
- 22.2.1 Module Level 358
- 22.2.1.1 Increasing Module Granularity 358
- 22.2.1.2 Increasing Cell Granularity 361
- 22.2.2 System Level 365
- 22.3 Commercial Applications *367*
- 22.4 Conclusion 367 Acknowledgments 367
  - Author Biography 368
    - Abbreviations and Acronyms 368
  - Nomenclature 368
  - References 369

#### 23 Colored PV Modules 373

Lenneke Slooff-Hoek and Angèle Reinders

- 23.1 Introduction 373
- 23.1.1 What is Color? 373
- 23.1.2 CIE Color Space *375*
- 23.1.3 Relevance of Color in Photovoltaic Applications 375

- xvi Contents
  - 23.1.4 Structure of This Chapter 376
  - 23.2 Physics of Colors in PV Modules Explained 377
  - 23.2.1 Photons 377
  - 23.2.2 Reflectance and Transmittance 378
  - 23.2.3 Thin Film Interference 379
  - 23.2.4 Multilayer Interference, Plasmonic Coatings 380
  - 23.2.5 Photoluminescence 381
  - 23.3 Options to Realize Colored Silicon PV Modules 381
  - 23.4 Colored Front Cover Design of Silicon PV Modules 382
  - 23.4.1 Coloring Techniques 382
  - 23.4.2 Printing of Patterns 384
  - 23.5 Energy Performance of Colored PV Modules 386
  - 23.5.1 Effect of Color or Ink/Pigment 388
  - 23.5.2 Effect of Ink Coverage 388
  - 23.5.3 Effect of Front Side Structure of the Module 388
  - 23.5.4 Performance of Commercial Panels 389
  - 23.6 Conclusions 390 Acknowledgments 390 Nomenclature 390 Abbreviations and Acronyms 390 Author Biographies 390 References 391

#### 24 Building Integrated Photovoltaic Products and Systems 393

Francesco Frontini

- 24.1 Introduction 393
- 24.2 Evolution of BIPV 393
- 24.3 BIPV as a Part of the Building Skin Elements *396*
- 24.4 BIPV Performances 397
- 24.4.1 Design and Aesthetics of BIPV 397
- 24.4.2 Consideration About the BIPV Module Temperature 398
- 24.4.3 Consideration About the Orientation and Shadows 400
- 24.4.4 Daylighting Properties and Energy Protection 400
- 24.4.5 Design with Photovoltaic: Mechanical Performances and Safety 402
- 24.5 Conclusion and Outlook 403
  - List of Acronyms 404 Author Biography 404
    - References 405

#### 25 PV Module /-V Models 407

Clifford W. Hansen

- 25.1 Introduction 407
- 25.2 Overview of PV Cell, Module, and Array Physics 408
- 25.3 *I–V* Curve Models 409
- 25.3.1 The Single-Diode Equation 409

- 25.3.2 Computing Solutions to the Single Diode Equation 411
- 25.3.3 The Two-Diode Equation 412
- 25.4 All-Condition Single-Diode *I–V* Models 412
- 25.4.1 De Soto Model 412
- 25.4.2 The CEC Model 413
- 25.4.3 PVsyst Model 413
- 25.5 Parameter Estimation for *I–V* Models 414
- 25.5.1 Single *I–V* Curve Fitting *415*
- 25.5.2 All-Condition Model Fitting 416
- 25.6 Module Performance Characterization 417
- 25.6.1 Standard Test Conditions (STC) 418
- 25.6.2 Normal Operating Cell Temperature (NOCT) 418
- 25.6.3 IEC 61853 Standard 419
- 25.7 Conclusion 419 Author Biography 419 References 419

#### Part Nine PV Systems and Applications 423

#### 26 Photovoltaic Performance 425

- Dirk C. Jordan and Kevin Anderson
- 26.1 Introduction 425
- 26.2 Performance 425
- 26.3 Failures and Availability 426
- 26.4 Performance Loss Rates and Degradation 430
- 26.5 Conclusion 431 Acknowledgments 431 Author Biographies 432
  - References 432
- 27 Deployment of Solar Photovoltaic Systems in Distribution Grids in Combination with Batteries 435

Elham Shirazi, Wilfried van Sark, and Angèle Reinders

- 27.1 Introduction 435
- 27.2 Challenges 437
- 27.3 PV, Battery, and Grid Interactions 439
- 27.3.1 Demand-side Management 440
- 27.3.2 PV-battery Systems Integrated in Grids 441
- 27.3.3 Control Measures 444
- 27.3.4 PV-battery Systems Deployment in Transport 445
- 27.3.4.1 PV-battery Systems Integrated in Electric Vehicles 445
- 27.3.4.2 PV-battery Systems Integrated in Charging Stations 446
- 27.4 Conclusion 449 List of Symbols and Acronyms 450 Author Biographies 451 References 451

xviii Contents

28	Floating PV Systems 455
	Sara M. Golroodbari and Josefine Selj
28.1	Introduction 455
28.2	Structure and Design 456
28.2.1	Floating Platform 456
28.2.1.1	Pontoon-Type 456
28.2.1.2	Pontoon Concept 456
28.2.1.3	Rafts Concept 456
28.2.1.4	Truss Concept 457
28.2.1.5	Superficial 458
28.2.1.6	Rigid 458
28.2.1.7	Flexible 458
28.2.2	Mooring System 458
28.2.3	Electrical Components 459
28.2.3.1	Solar PV Module 459
28.2.3.2	Cables and Connectors 459
28.3	Performance and Reliability 460
28.3.1	Soiling and Shading 460
28.3.2	Mismatch 460
28.3.3	Operating Temperatures 460
28.3.4	Dynamic Albedo 462
28.3.5	Reliability 462
28.3.6	OFPV in Worldwide Perspective 463
28.4	FPV System Modeling 464
28.4.1	Irradiation and Dynamic Albedo 464
28.4.2	Dynamic Tilt 466
28.4.3	Heat Transfer 467
28.5	Conclusions 468
	Author Biographies 469
	References 469
29	Agrivoltaics 475
	Christian Braun and Matthew Berwind
29.1	History and Status 475
29.1.1	Introduction 475
29.1.2	Goetzberger/Zastrow 475
29.1.3	First Practical Experiences in Germany 475
29.1.4	Solar Sharing, Japan 476
29.1.5	France 476
29.1.6	Italy 477
29.1.7	USA 478
29.1.8	China 478
29.2	Technology and Classifications 478
29.2.1	APV System Types 478
29.2.2	Overhead Agrivoltaics 479

- 29.2.2.1 Arable Land Use 480
- 29.2.2.2 Greenhouse Photovoltaics 480
- 29.2.3 Interspace Agrivoltaics 481
- 29.2.4 Module Technologies 481
- 29.2.5 Emerging Technological Approaches 481
- 29.2.5.1 Wavelength Selective Solar Cells 483
- 29.2.5.2 Dynamic Module Technologies/Solar Trackers 483
- 29.3 Benefits from Dual Land Use 484
- 29.4 Conclusion 485
- 29.4.1 Research Prospects 485
- 29.4.2 Outlook 485 List of Symbols 486 Author Biographies 486 References 487

#### **30** Vehicle Integrated Photovoltaics 491

Neel Patel, Karsten Bittkau, Kaining Ding, Wilfried van Sark, and Angèle Reinders

- 30.1 Introduction 491
- 30.2 State-of-the-Art: Industry 492
- 30.3 State of the Art: Academia 493
- 30.3.1 Module Technology 493
- 30.3.2 Control Electronics 494
- 30.3.3 Measurement Campaigns 494
- 30.3.4 Energy Yield 495
- 30.3.5 Testing and Standardization 495
- 30.3.6 Social Acceptance and Sustainability 495
- 30.4 Potential Impact 496
- 30.5 Energy Yield Modeling 497
- 30.5.1 Input Data 498
- 30.5.2 Effective Irradiance 498
- 30.5.3 Cell Temperature 499
- 30.5.4 Module Power 500
- 30.5.5 Loss Factors 500
- 30.5.6 Uncertainties 500
- 30.6 Outlook 501
  - List of Acronyms 501
    - Author Biography 502
    - References 502

#### 31 Yield Assessments for PV Bankability 507

David Moser

- 31.1 Introduction 507
- 31.2 Introduction to Yield Assessment 508
- 31.3 The Key Elements of Yield Assessments 509
- 31.3.1 Long-Term Insolation and Trends 509

- **xx** Contents
  - 31.3.2 Annual Insolation Variability 511
  - 31.3.3 Temperature 511
  - 31.3.4 Parameters Used in Power Calculation 511
  - 31.3.5 Availability 512
  - 31.3.6 Degradation and Performance Loss Rates for LTYP 512
  - 31.3.7 Yield Assessments of Novel PV System Typologies 513
  - 31.3.7.1 Irradiance Variability 513
  - 31.3.7.2 Temperature Effects 514
  - 31.4 The Impact of Yield Assessments on Bankability 514
  - 31.4.1 Impact of Decisions on Yield Assessments 514
  - 31.4.2 Uncertainty Scenarios 515
  - 31.4.3 The Link with Economic KPIs 516
  - 31.4.4 The Impact on LCOE and NPV 517
  - 31.5 Conclusions 517 List of Acronyms 517 Nomenclature and Definitions 518 Author Biography 518 References 519

#### Part Ten Sustainability 523

#### **32 Terawatt Sustainability** 525

Masafumi Yamaguchi

- 32.1 Introduction 525
- 32.2 Brief Overview of Sustainability of Photovoltaics 525
- 32.3 Discussion About Sustainability of Material Resources 531
- 32.4 Effectiveness of CPV to Overcome Limitation of Solar Cell Module Production Capacity 534
- 32.5 Conclusion 536 Acknowledgments 537 Author Biography 537 References 537

#### 33 Life Cycle Assessment of Photovoltaics 541

Vasilis Fthenakis and Enrica Leccisi

- 33.1 Introduction 541
- 33.2 Methodology 541
- 33.3 Cumulative Energy Demand (CED) During the Life of a PV System 542
- 33.3.1 Energy Payback Time (EPBT) 542
- 33.3.2 Energy Return on Investment (EROI) 544
- 33.3.3 Greenhouse Gas (GHG) Emissions and Global Warming Potential (GWP) 544
- 33.4 Results 545
- 33.4.1 Energy Payback Time and Energy Return on Investment 545
- 33.4.2 Greenhouse Gas Emissions 546
- 33.4.3 Toxic Gas Emissions 548

33.5 Conclusion 550 Acknowledgment 550
Disclaimer 551 List of symbols 551 List of acronyms 551 Author Biographies 551 References 552
34 PV Recycling – Status and Perspectives 555
Frank Lenzmann
34.1 Introduction 555
34.2 Evolution of PV Waste in the Coming Decades 556
34.3 Compositional and Economic Characteristics of EoL PV Modules 557
34.4 Challenges Versus Need for PV Recycling 559
34.5 Current Downcycling Technologies 561
34.6 Future High-Value PV Recycling Technology 562
34.6.1 Delamination 562
34.6.1.1 Mechanical Methods 563
34.6.1.2 Thermal Methods 563
34.6.1.3 Chemical Methods 564
34.6.2 Recovery of Materials from Solar Cell Residues 564
34.7 First Industrial Initiatives for High-Value PV Recycling 564
34.8 Conclusions 565
Author Biography 565
References 565
75 Environmental Impacts of Integrated Distance Itals Medulas in Light
JS Environmental impacts of integrated Photovollaic Modules in Light
Olaa Kanz Karsten Bittkau Kaining Ding Johanna May and Angèle Reinde
35.1 Introduction 567
35.2 Methodology 568
35.2.1 Life Cycle Assessment Method 568
35.2.2 Functional Unit. Goal. and Scope 569
35.2.3 Input Parameters of the Inventory 569
35.2.4 Input Parameters for the Energy Flow Model 571
35.2.5 Input Parameters of the Grid Charging 571

- 35.3 Results 572
- 35.3.1 Manufacturing Process of the VIPV 572
- 35.3.2 Operation Phase of the VIPV 572
- 35.3.3 Sensitivity Analysis 573
- 35.3.4 Reliability of the Data 575
- 35.4 Discussion and Conclusions 575 Author Biography 576 References 576

**Index** 579

#### 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 12000 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

#### xxiv About the Editors

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 xxviii List of Contributors

#### **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