Contents

Preface to the First International Edition  xv
Preface to the Second International Edition  xvii
Abbreviations  xix

1  Introduction  1
1.1  Introduction  1
1.1.1  Why Photovoltaics?  1
1.1.2  Who Should Read This Book?  2
1.1.3  Structure of the Book  2
1.2  What Is Energy?  3
1.2.1  Definition of Energy  3
1.2.2  Units of Energy  4
1.2.3  Primary, Secondary, and End Energy  5
1.2.4  Energy Content of Various Substances  6
1.3  Problems with Today’s Energy Supply  7
1.3.1  Growing Energy Requirements  7
1.3.2  Tightening of Resources  8
1.3.3  Climate Change  9
1.3.4  Hazards and Disposal  11
1.4  Renewable Energies  11
1.4.1  The Family of Renewable Energies  11
1.4.2  Advantages and Disadvantages of Renewable Energies  12
1.4.3  Previous Development of Renewable Energies  13
1.5  Photovoltaics – The Most Important in Brief  13
1.5.1  What Does “Photovoltaics” Mean?  13
1.5.2  What Are Solar Cells and Solar Modules?  14
1.5.3  How Is a Typical Photovoltaic Plant Structured?  14
1.5.4  What Does a Photovoltaic Plant “Bring?”  15
1.6  History of Photovoltaics  16
1.6.1  How It all Began  16
1.6.2  The First Real Solar Cells  17
1.6.3  From Space to Earth  19
1.6.4  From Toy to Energy Source  20
2  Solar Radiation  23
   2.1  Properties of Solar Radiation  23
   2.1.1  Solar Constant  23
   2.1.2  Spectrum of the Sun  23
   2.1.3  Air Mass  25
   2.2  Global Radiation  25
   2.2.1  Origin of Global Radiation  25
   2.2.2  Contributions of Diffuse and Direct Radiation  26
   2.2.3  Global Radiation Maps  28
   2.3  Calculation of the Position of the Sun  30
   2.3.1  Declination of the Sun  30
   2.3.2  Calculating the Path of the Sun  32
   2.4  Radiation on Tilted Surfaces  35
   2.4.1  Radiation Calculation with the Three-component Model  35
   2.4.1.1  Direct Radiation  35
   2.4.1.2  Diffuse Radiation  36
   2.4.1.3  Reflected Radiation  37
   2.4.2  Radiation Estimates with Diagrams and Tables  38
   2.4.3  Yield Gain through Tracking  41
   2.5  Radiation Availability and World Energy Consumption  41
   2.5.1  The Solar Radiation Energy Cube  41
   2.5.2  The Sahara Miracle  45

3  Fundamentals of Semiconductor Physics  47
   3.1  Structure of a Semiconductor  47
   3.1.1  Bohr’s Atomic Model  47
   3.1.2  Periodic Table of Elements  49
   3.1.3  Structure of the Silicon Crystal  49
   3.1.4  Compound Semiconductors  49
   3.2  Band Model of a Semiconductor  51
   3.2.1  Origin of Energy Bands  51
   3.2.2  Differences in Isolators, Semiconductors, and Conductors  53
   3.2.3  Intrinsic Carrier Concentration  53
   3.3  Charge Transport in Semiconductors  55
   3.3.1  Field Currents  55
   3.3.2  Diffusion Currents  56
   3.4  Doping of Semiconductors  57
   3.4.1  n-Doping  57
   3.4.2  p-Doping  58
   3.5  The p–n Junction  59
   3.5.1  Principle of Method of Operation  59
   3.5.2  Band Diagram of the p–n Junction  61
   3.5.3  Behavior with Applied Voltage  62
   3.5.4  Diode Characteristics  63
   3.6  Interaction of Light and Semiconductors  64
   3.6.1  Phenomenon of Light Absorption  64
   3.6.1.1  Absorption Coefficient  65
   3.6.1.2  Direct and Indirect Semiconductors  65
4 Structure and Method of Operation of Solar Cells 71
4.1 Consideration of the Photodiode 71
4.1.1 Structure and Characteristics 71
4.1.2 Equivalent Circuit 73
4.2 Method of Function of the Solar Cell 73
4.2.1 Principle of the Structure 73
4.2.2 Recombination and Diffusion Length 74
4.2.3 What Happens in the Individual Cell Regions? 75
4.2.3.1 Absorption in the Emitter 75
4.2.3.2 Absorption in the Space Charge Region 76
4.2.3.3 Absorption Within the Diffusion Length of the Electrons 76
4.2.3.4 Absorption Outside the Diffusion Length of the Electrons 76
4.2.4 Back-surface Field 77
4.3 Photocurrent 77
4.3.1 Absorption Efficiency 78
4.3.2 Quantum Efficiency 79
4.3.3 Spectral Sensitivity 79
4.4 Characteristic Curve and Characteristic Parameters 80
4.4.1 Short-circuit Current $I_{SC}$ 81
4.4.2 Open-circuit Voltage $V_{OC}$ 82
4.4.3 Maximum Power Point (MPP) 82
4.4.4 Fill Factor (FF) 82
4.4.5 Efficiency $\eta$ 83
4.4.6 Temperature Dependence of Solar Cells 83
4.5 Electrical Description of Real Solar Cells 85
4.5.1 Simplified Model 85
4.5.2 Standard Model (Single-diode Model) 86
4.5.3 Two-diode Model 86
4.5.4 Determining the Parameters of the Equivalent Circuit 88
4.6 Considering Efficiency 90
4.6.1 Spectral Efficiency 91
4.6.2 Theoretical Efficiency 94
4.6.3 Losses in Real Solar Cells 96
4.6.3.1 Optical Losses, Reflection on the Surface 96
4.6.3.2 Electrical Losses and Ohmic Losses 98
4.7 High-efficiency Cells 99
4.7.1 Buried-contact Cell 99
4.7.2 Point-contact Cell (IBC Cell) 99
4.7.3 PERL and PERC Cell 101

5 Cell Technologies 103
5.1 Production of Crystalline Silicon Cells 103
5.1.1 From Sand to Silicon 103
5.1.1.1 Production of Polysilicon 103
5.1.1.2 Production of Monocrystalline Silicon 105
5.1.1.3 Production of Multicrystalline Silicon 106
5.1.2 From Silicon to Wafer 107
5.1.2.1 Wafer Production 107
5.1.2.2 Wafers from Ribbon Silicon 107
5.1.3 Production of Standard Solar Cells 108
5.1.4 Production of Solar Modules 111
5.2 Cells of Amorphous Silicon 112
5.2.1 Properties of Amorphous Silicon 112
5.2.2 Production Process 113
5.2.3 Structure of the Pin Cell 113
5.2.4 Staebler–Wronski Effect 115
5.2.5 Stacked Cells 116
5.2.6 Combined Cells of Micromorphous Material 118
5.2.7 Integrated Series Connection 119
5.3 Further Thin Film Cells 120
5.3.1 Cells of Cadmium-Telluride 120
5.3.2 CIS Cells 121
5.4 Hybrid Wafer Cells 123
5.4.1 Combination of c-Si and a-Si (HIT Cell) 123
5.4.2 Stacked Cells of III/V Semiconductors 124
5.5 Other Cell Concepts 125
5.6 Concentrator Systems 126
5.6.1 Principle of Radiation Bundling 126
5.6.2 What Is the Advantage of Concentration? 127
5.6.3 Examples of Concentrator Systems 128
5.6.4 Advantages and Disadvantages of Concentrator Systems 128
5.7 Ecological Questions on Cell and Module Production 129
5.7.1 Environmental Effects of Production and Operation 129
5.7.1.1 Example of Cadmium-Telluride 129
5.7.1.2 Example of Silicon 129
5.7.2 Availability of Materials 130
5.7.2.1 Silicon 130
5.7.2.2 Cadmium-Telluride 131
5.7.2.3 Cadmium Indium Selenide 131
5.7.2.4 III/V Semiconductors 132
5.7.3 Energy Amortization Time and Yield Factor 132
5.8 Summary 135

6 Solar Modules and Solar Generators 139
6.1 Properties of Solar Modules 139
6.1.1 Solar Cell Characteristic Curve in All Four Quadrants 139
6.1.2 Parallel Connection of Cells 139
6.1.3 Series Connection of Cells 141
6.1.4 Use of Bypass Diodes 142
6.1.4.1 Reducing Shading Losses 142
6.1.4.2 Prevention of Hotspots 144
6.1.5 Typical Characteristic Curves of Solar Modules 147
6.1.5.1 Variation of the Irradiance 147
6.1.5.2 Temperature Behavior 147
6.1.6 Special Case Thin-film Modules 149
6.1.7 Examples of Data Sheet Information 150
6.2 Connecting Solar Modules 150
6.2.1 Parallel Connection of Strings 150
6.2.2 What Happens in Case of Cabling Errors? 152
6.2.3 Losses Due to Mismatching 153
6.2.4 Smart Installation in Case of Shading 153
6.3 Direct Current Components 156
6.3.1 Principle of Plant Construction 156
6.3.2 Direct Current Cabling 156
6.4 Types of Plants 158
6.4.1 Ground-mounted Plants 158
6.4.2 Flat-roof Plants 161
6.4.3 Pitched-roof Systems 162
6.4.4 Facade Systems 164

7 System Technology of Grid-connected Plants 165
7.1 Solar Generator and Load 165
7.1.1 Resistive Load 165
7.1.2 DC/DC Converter 166
7.1.2.1 Idea 166
7.1.2.2 Buck Converter 166
7.1.2.3 Boost Converter 169
7.1.3 MPP Tracker 171
7.2 Construction of Grid-connected Systems 172
7.2.1 Feed-in Variations 172
7.2.2 Plant Concepts 173
7.3 Construction of Inverters 174
7.3.1 Tasks of the Inverter 175
7.3.2 Line-commutated and Self-commutated Inverter 175
7.3.3 Inverters Without Transformers 175
7.3.4 Inverters with Mains Transformer 177
7.3.5 Inverters with HF Transformer 178
7.3.6 Three-phase Feed-in 179
7.3.7 Further Clever Concepts 180
7.4 Efficiency of Inverters 181
7.4.1 Conversion Efficiency 181
7.4.2 European Efficiency 184
7.4.3 Clever MPP Tracking 185
7.5 Dimensioning of Inverters 186
7.5.1 Power Dimensioning 186
7.5.2 Voltage Dimensioning 187
7.5.3 Current Dimensioning 188
7.6 Requirements of the Grid Operators 188
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6.1 Prevention of Stand-Alone Operation</td>
<td>188</td>
</tr>
<tr>
<td>7.6.2 Maximum Feed-in Power</td>
<td>190</td>
</tr>
<tr>
<td>7.6.3 Reactive Power Provision</td>
<td>191</td>
</tr>
<tr>
<td>7.7 Safety Aspects</td>
<td>194</td>
</tr>
<tr>
<td>7.7.1 Earthing of the Generator and Lightning Protection</td>
<td>194</td>
</tr>
<tr>
<td>7.7.2 Fire Protection</td>
<td>194</td>
</tr>
<tr>
<td>8 Storage of Solar Energy</td>
<td>197</td>
</tr>
<tr>
<td>8.1 Principle of Solar Storage</td>
<td>197</td>
</tr>
<tr>
<td>8.2 Batteries</td>
<td>198</td>
</tr>
<tr>
<td>8.2.1 Lead-acid Battery</td>
<td>199</td>
</tr>
<tr>
<td>8.2.1.1 Principle and Build-up</td>
<td>199</td>
</tr>
<tr>
<td>8.2.1.2 Types of Lead Batteries</td>
<td>201</td>
</tr>
<tr>
<td>8.2.1.3 Battery Capacity</td>
<td>203</td>
</tr>
<tr>
<td>8.2.1.4 Voltage Progression</td>
<td>203</td>
</tr>
<tr>
<td>8.2.1.5 Summary</td>
<td>204</td>
</tr>
<tr>
<td>8.2.2 Charge Controllers</td>
<td>204</td>
</tr>
<tr>
<td>8.2.2.1 Series Controller</td>
<td>204</td>
</tr>
<tr>
<td>8.2.2.2 Shunt Controller</td>
<td>205</td>
</tr>
<tr>
<td>8.2.2.3 MPP Controller</td>
<td>205</td>
</tr>
<tr>
<td>8.2.2.4 Examples of Products</td>
<td>206</td>
</tr>
<tr>
<td>8.2.3 Lithium Ion Battery</td>
<td>206</td>
</tr>
<tr>
<td>8.2.3.1 Principle and Build-up</td>
<td>207</td>
</tr>
<tr>
<td>8.2.3.2 Reactions During Charging and Discharging</td>
<td>208</td>
</tr>
<tr>
<td>8.2.3.3 Material Combinations and Cell Voltage</td>
<td>209</td>
</tr>
<tr>
<td>8.2.3.4 Safety Aspects</td>
<td>210</td>
</tr>
<tr>
<td>8.2.3.5 Charging Procedures</td>
<td>211</td>
</tr>
<tr>
<td>8.2.3.6 Battery Design</td>
<td>211</td>
</tr>
<tr>
<td>8.2.3.7 Lifespan</td>
<td>212</td>
</tr>
<tr>
<td>8.2.3.8 Application Areas</td>
<td>213</td>
</tr>
<tr>
<td>8.2.3.9 Summary</td>
<td>213</td>
</tr>
<tr>
<td>8.2.4 Sodium Sulfur Battery</td>
<td>213</td>
</tr>
<tr>
<td>8.2.4.1 Principle and Build-up</td>
<td>213</td>
</tr>
<tr>
<td>8.2.4.2 Peculiarities of the High Temperature Battery</td>
<td>214</td>
</tr>
<tr>
<td>8.2.4.3 Sodium Sulfur Batteries in Practice</td>
<td>215</td>
</tr>
<tr>
<td>8.2.4.4 Summary</td>
<td>216</td>
</tr>
<tr>
<td>8.2.5 Redox Flow Battery</td>
<td>216</td>
</tr>
<tr>
<td>8.2.5.1 Principle and Build-up</td>
<td>216</td>
</tr>
<tr>
<td>8.2.5.2 Behavior in Practice</td>
<td>218</td>
</tr>
<tr>
<td>8.2.5.3 Concrete Applications</td>
<td>219</td>
</tr>
<tr>
<td>8.2.5.4 Summary</td>
<td>220</td>
</tr>
<tr>
<td>8.2.6 Comparison of the Different Battery Types</td>
<td>220</td>
</tr>
<tr>
<td>8.3 Storage Use for Increase of Self-consumption</td>
<td>220</td>
</tr>
<tr>
<td>8.3.1 Self-consumption in Domestic Households</td>
<td>221</td>
</tr>
<tr>
<td>8.3.1.1 Solution Without Storage</td>
<td>222</td>
</tr>
<tr>
<td>8.3.1.2 Solution with Storage</td>
<td>223</td>
</tr>
<tr>
<td>8.3.1.3 Examples of Storage Systems</td>
<td>223</td>
</tr>
</tbody>
</table>
8.3.1.4 How Much Cost a Kilowatt-Hour? 225
8.3.1.5 The Smart Home 226
8.3.2 Self-consumption in Commercial Enterprises 227
8.3.2.1 Example Production Factory 227
8.3.2.2 Example Hospital 227
8.4 Storage Deployment from the Point of View of the Grid 228
8.4.1 Peak-shaving with Storages 229
8.4.2 Governmental Funding Program for Solar Storages 229
8.5 Stand-alone Systems 232
8.5.1 Principal Structure 232
8.5.2 Examples of Stand-alone Systems 232
8.5.2.1 Solar Home Systems 232
8.5.2.2 Hybrid Systems 234
8.5.3 Dimensioning Stand-alone Plants 235
8.5.3.1 Acquiring the Energy Consumption 235
8.5.3.2 Dimensioning the PV Generator 236
8.5.3.3 Selecting the Battery 238

9 Photovoltaic Metrology 241
9.1 Measurement of Solar Radiation 241
9.1.1 Global Radiation Sensors 241
9.1.1.1 Pyranometer 241
9.1.1.2 Radiation Sensors from Solar Cells 243
9.1.2 Measuring Direct and Diffuse Radiation 244
9.2 Measuring the Power of Solar Modules 245
9.2.1 Build-up of a Solar Module Power Test Rig 245
9.2.2 Quality Classification of Module Flashers 246
9.2.3 Determination of the Module Parameters 247
9.3 Peak Power Measurement at Site 248
9.3.1 Principle of Peak Power Measurement 248
9.3.2 Possibilities and Limits of the Measurement Principle 248
9.4 Thermographic Measuring Technology 249
9.4.1 Principle of Infrared Temperature Measurement 250
9.4.2 Bright Thermography of Solar Modules 251
9.4.3 Dark Thermography 254
9.5 Electroluminescence Measuring Technology 254
9.5.1 Principle of Measurement 254
9.5.2 Examples of Photos 255
9.5.3 Low-cost Outdoor Electroluminescence Measurements 257
9.6 Analysis of Potential Induced Degradation (PID) 259
9.6.1 Explanation of the PID Effect 260
9.6.2 Test of Modules for PID 262
9.6.3 EL Investigations to PID 263

10 Design and Operation of Grid-connected Plants 265
10.1 Planning and Dimensioning 265
10.1.1 Selection of Site 265
10.1.2 Shading 265
10.1.2.1 Shading Analysis 266
10.1.2.2 Near Shading 266
10.1.2.3 Self-shading 268
10.1.2.4 Optimized String Connection 269
10.1.3 Plant Dimensioning and Simulation Programs 270
10.1.3.1 Inverter Design Tools 270
10.1.3.2 Simulation Programs for Photovoltaic Plants 270
10.2 Economics of Photovoltaic Plants 272
10.2.1 The Renewable Energy Law 273
10.2.2 Return Calculation 273
10.2.2.1 Input Parameters 273
10.2.2.2 Amortization Time 274
10.2.2.3 Property Return 274
10.2.2.4 Profit Increase Through Self-consumption of Solar Power 276
10.2.2.5 Further Influences 276
10.3 Surveillance, Monitoring, and Visualization 277
10.3.1 Methods of Plant Surveillance 277
10.3.2 Monitoring PV Plants 278
10.3.2.1 Specific Yields 278
10.3.2.2 Losses 279
10.3.2.3 Performance Ratio 279
10.3.2.4 Concrete Measures for Monitoring 280
10.3.3 Visualization 280
10.4 Operating Results of Actual Installations 281
10.4.1 Pitched Roof Installation from 1996 281
10.4.2 Pitched Roof Installation from 2002 282
10.4.3 Flat Roof from 2008 283

11 Future Development 285
11.1 Potential of Photovoltaics 285
11.1.1 Theoretical Potential 285
11.1.2 Technically Useful Radiation Energy 285
11.1.2.1 Roofs 286
11.1.2.2 Facades 286
11.1.2.3 Traffic Routes 287
11.1.2.4 Free Areas 287
11.1.3 Technical Electrical Energy Generation Potential 287
11.1.4 Photovoltaics versus Biomass 288
11.2 Efficient Promotion Instruments 289
11.3 Price and Feed-in Tariff Development 290
11.3.1 Price Development of Solar Modules 290
11.3.2 Development of Feed-in Tariffs 292
11.4 Renewable Energies in Today’s Power Supply System 292
11.4.1 Structure of Electricity Generation 293
11.4.2 Types of Power Plants and Control Energy 293
11.4.3 Interplay Between Sun and Wind 294
11.4.4 Exemplary Electricity Generation Courses 295
11.5 Thoughts on Future Energy Supply 298
11.5.1 Consideration of Different Future Scenarios 298
11.5.2 Options to Store Electrical Energy 301
11.5.2.1 Pumped Storage Power Plants 301
11.5.2.2 Compressed Air Storage 301
11.5.2.3 Battery Storage 302
11.5.2.4 Electric Mobility 302
11.5.2.5 Hydrogen as Storage 302
11.5.2.6 Power to Gas: Methanation 303
11.5.3 Alternatives to Storage 304
11.5.3.1 Active Load Management by Smart Grids 304
11.5.3.2 Expansion of the Electricity Grids 304
11.5.3.3 Limitation of the Feed-in Power 304
11.5.3.4 Use of Flexible Power Plants 304
11.6 Conclusion 305

12 Exercises 307

A Solar Radiation Diagrams 317

B Checklist for Planning, Installing, and Operating a Photovoltaic Plant 327

C Physical Constants/Material Parameters 329

References 331

Further Information on Photovoltaics 339

Index 341