

# Contents

<b>Preface</b>	<b>xi</b>
<b>Abbreviations</b>	<b>xiii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Introduction	1
1.1.1 <i>Why Photovoltaics?</i>	1
1.1.2 <i>Who Should Read this Book?</i>	2
1.1.3 <i>Structure of the Book</i>	2
1.2 What is Energy?	3
1.2.1 <i>Definition of Energy</i>	3
1.2.2 <i>Units of Energy</i>	4
1.2.3 <i>Primary, Secondary and End Energy</i>	5
1.2.4 <i>Energy Content of Various Substances</i>	6
1.3 Problems with Today's Energy Supply	7
1.3.1 <i>Growing Energy Requirements</i>	7
1.3.2 <i>Tightening of Resources</i>	8
1.3.3 <i>Climate Change</i>	9
1.3.4 <i>Hazards and Disposal</i>	10
1.4 Renewable Energies	11
1.4.1 <i>The Family of Renewable Energies</i>	11
1.4.2 <i>Advantages and Disadvantages of Renewable Energies</i>	12
1.5 Photovoltaic – The Most Important in Brief	12
1.5.1 <i>What Does "Photovoltaic" Mean?</i>	13
1.5.2 <i>What are Solar Cells and Solar Modules?</i>	13
1.5.3 <i>How is a Typical Photovoltaic Plant Structured?</i>	14
1.5.4 <i>What Does a Photovoltaic Plant "Bring?"</i>	14
1.6 History of Photovoltaics	15
1.6.1 <i>How it all Began</i>	15
1.6.2 <i>The First Real Solar Cells</i>	16
1.6.3 <i>From Space to Earth</i>	18
1.6.4 <i>From Toy to Energy Source</i>	18

<b>2</b>	<b>Solar Radiation</b>	<b>21</b>
2.1	Properties of Solar Radiation	21
2.1.1	<i>Solar Constant</i>	21
2.1.2	<i>Spectrum of the Sun</i>	22
2.1.3	<i>Air Mass</i>	23
2.2	Global Radiation	24
2.2.1	<i>Origin of Global Radiation</i>	24
2.2.2	<i>Contributions of Diffuse and Direct Radiation</i>	25
2.2.3	<i>Global Radiation Maps</i>	25
2.3	Calculation of the Position of the Sun	29
2.3.1	<i>Declination of the Sun</i>	29
2.3.2	<i>Calculating the Path of the Sun</i>	31
2.4	Radiation on Tilted Surfaces	33
2.4.1	<i>Radiation Calculation with the Three-Component Model</i>	33
2.4.2	<i>Radiation Estimates with Diagrams and Tables</i>	37
2.4.3	<i>Yield Gain through Tracking</i>	38
2.5	Radiation Availability and World Energy Consumption	40
2.5.1	<i>The Solar Radiation Energy Cube</i>	40
2.5.2	<i>The Sahara Miracle</i>	41
<b>3</b>	<b>Fundamentals of Semiconductor Physics</b>	<b>43</b>
3.1	Structure of Semiconductors	43
3.1.1	<i>Bohr's Atomic Model</i>	43
3.1.2	<i>Periodic Table of the Elements</i>	45
3.1.3	<i>Structure of the Silicon Crystal</i>	46
3.1.4	<i>Compound Semiconductors</i>	47
3.2	Band Model of the Semiconductor	47
3.2.1	<i>Origin of Energy Bands</i>	47
3.2.2	<i>Differences in Isolators, Semiconductors and Conductors</i>	48
3.2.3	<i>Intrinsic Carrier Concentration</i>	49
3.3	Charge Transport in Semiconductors	50
3.3.1	<i>Field Currents</i>	50
3.3.2	<i>Diffusion Currents</i>	52
3.4	Doping of Semiconductors	53
3.4.1	<i>n-Doping</i>	53
3.4.2	<i>p-Doping</i>	54
3.5	The p-n Junction	54
3.5.1	<i>Principle of Method of Operation</i>	55
3.5.2	<i>Band Diagram of the p-n Junction</i>	56
3.5.3	<i>Behavior with Applied Voltage</i>	58
3.5.4	<i>Diode Characteristics</i>	59
3.6	Interaction of Light and Semiconductors	60
3.6.1	<i>Phenomenon of Light Absorption</i>	60
3.6.2	<i>Light Reflection on Surfaces</i>	64

<b>4</b>	<b>Structure and Method of Operation of Solar Cells</b>	<b>67</b>
4.1	Consideration of the Photodiode	67
4.1.1	<i>Structure and Characteristics</i>	67
4.1.2	<i>Equivalent Circuit</i>	69
4.2	Method of Function of the Solar Cell	69
4.2.1	<i>Principle of the Structure</i>	69
4.2.2	<i>Recombination and Diffusion Length</i>	70
4.2.3	<i>What Happens in the Individual Cell Regions?</i>	71
4.2.4	<i>Back-Surface Field</i>	73
4.3	Photocurrent	73
4.3.1	<i>Absorption Efficiency</i>	74
4.3.2	<i>Quantum Efficiency</i>	75
4.3.3	<i>Spectral Sensitivity</i>	76
4.4	Characteristic Curve and Characteristic Dimensions	77
4.4.1	<i>Short Circuit Current <math>I_{SC}</math></i>	78
4.4.2	<i>Open Circuit Voltage <math>V_{OC}</math></i>	78
4.4.3	<i>Maximum Power Point (MPP)</i>	79
4.4.4	<i>Fill Factor <math>FF</math></i>	79
4.4.5	<i>Efficiency <math>\eta</math></i>	80
4.4.6	<i>Temperature Dependency of Solar Cells</i>	80
4.5	Electrical Description of Real Solar Cells	82
4.5.1	<i>Simplified Model</i>	82
4.5.2	<i>Standard Model (Single-Diode Model)</i>	83
4.5.3	<i>Two-Diode Model</i>	83
4.5.4	<i>Determining the Parameters of the Equivalent Circuit</i>	85
4.6	Considering Efficiency	87
4.6.1	<i>Spectral Efficiency</i>	87
4.6.2	<i>Theoretical Efficiency</i>	90
4.6.3	<i>Losses in Real Solar Cells</i>	92
4.7	High Efficiency Cells	95
4.7.1	<i>Buried-Contact Cells</i>	96
4.7.2	<i>Point-Contact Cell</i>	96
4.7.3	<i>PERL Cell</i>	97
<b>5</b>	<b>Cell Technologies</b>	<b>99</b>
5.1	Production of Crystalline Silicon Cells	99
5.1.1	<i>From Sand to Silicon</i>	99
5.1.2	<i>From Silicon to Wafer</i>	103
5.1.3	<i>Production of Standard Solar Cells</i>	104
5.1.4	<i>Production of Solar Modules</i>	106
5.2	Cells of Amorphous Silicon	108
5.2.1	<i>Properties of Amorphous Silicon</i>	108
5.2.2	<i>Production Process</i>	108
5.2.3	<i>Structure of the pin Cell</i>	109
5.2.4	<i>Staebler–Wronski Effect</i>	110
5.2.5	<i>Stacked Cells</i>	112

5.2.6	<i>Combined Cells of Micromorphous Material</i>	113
5.2.7	<i>Integrated Series Connection</i>	114
5.3	<b>Further Thin Film Cells</b>	115
5.3.1	<i>Cells of Cadmium-Telluride</i>	115
5.3.2	<i>CIS Cells</i>	116
5.4	<b>Hybrid Wafer Cells</b>	118
5.4.1	<i>Combination of c-Si and a-Si (HIT Cell)</i>	118
5.4.2	<i>Stacked Cells of III/V Semiconductors</i>	119
5.5	<b>Other Cell Concepts</b>	120
5.6	<b>Concentrator Systems</b>	120
5.6.1	<i>Principle of Radiation Bundling</i>	120
5.6.2	<i>What is the Advantage of Concentration?</i>	120
5.6.3	<i>Examples of Concentrator Systems</i>	122
5.6.4	<i>Advantages and Disadvantages of Concentrator Systems</i>	123
5.7	<b>Ecological Questions on Cell and Module Production</b>	123
5.7.1	<i>Environmental Effects of Production and Operation</i>	123
5.7.2	<i>Availability of Materials</i>	124
5.7.3	<i>Energy Amortization Time and Yield Factor</i>	126
	<b>Summary</b>	129
<b>6</b>	<b>Solar Modules and Solar Generators</b>	<b>133</b>
6.1	<b>Properties of Solar Modules</b>	133
6.1.1	<i>Solar Cell Characteristic Curve in All Four Quadrants</i>	133
6.1.2	<i>Parallel Connection of Cells</i>	134
6.1.3	<i>Series Connection of Cells</i>	135
6.1.4	<i>Use of Bypass Diodes</i>	136
6.1.5	<i>Typical Characteristic Curves of Solar Modules</i>	141
6.1.6	<i>Special Case Thin Film Modules</i>	143
6.1.7	<i>Examples of Data Sheet Information</i>	145
6.2	<b>Connecting Solar Modules</b>	145
6.2.1	<i>Parallel Connection of Strings</i>	145
6.2.2	<i>What Happens in Case of Cabling Errors?</i>	147
6.2.3	<i>Losses Due to Mismatching</i>	148
6.2.4	<i>Smart Installation in Case of Shading</i>	148
6.3	<b>Direct Current Components</b>	150
6.3.1	<i>Principle Plant Build-Up</i>	150
6.3.2	<i>Direct Current Cabling</i>	151
6.4	<b>Types of Plants</b>	153
6.4.1	<i>Open Air Plants</i>	153
6.4.2	<i>Flat Roof Plants</i>	155
6.4.3	<i>Pitched Roof Systems</i>	157
6.4.4	<i>Façade Systems</i>	159
<b>7</b>	<b>Photovoltaic System Technology</b>	<b>161</b>
7.1	<b>Solar Generator and Load</b>	161
7.1.1	<i>Resistive Load</i>	161

7.1.2	<i>DC/DC Converter</i>	162
7.1.3	<i>MPP-Tracker</i>	167
7.2	Grid-Connected Systems	168
7.2.1	<i>Feed-In Variations</i>	169
7.2.2	<i>Installation Concepts</i>	169
7.2.3	<i>Structure of Inverters</i>	171
7.2.4	<i>Efficiency of Inverters</i>	177
7.2.5	<i>Dimensioning of Inverters</i>	181
7.2.6	<i>Measures for Increasing Self-Consumption</i>	184
7.2.7	<i>Requirements of Grid Operators</i>	186
7.2.8	<i>Safety Aspects</i>	188
7.3	Stand-Alone Systems	189
7.3.1	<i>Principle of the Structure</i>	189
7.3.2	<i>Batteries</i>	190
7.3.3	<i>Charge Controllers</i>	194
7.3.4	<i>Examples of Stand-Alone Systems</i>	197
7.3.5	<i>Dimensioning Stand-Alone Plants</i>	199
<b>8</b>	<b>Photovoltaic Metrology</b>	<b>205</b>
8.1	Measurement of Solar Radiation	205
8.1.1	<i>Global Radiation Sensors</i>	205
8.1.2	<i>Measuring Direct and Diffuse Radiation</i>	207
8.2	Measuring the Power of Solar Modules	208
8.2.1	<i>Buildup of a Solar Module Power Test Rig</i>	209
8.2.2	<i>Quality Classification of Module Flashers</i>	210
8.2.3	<i>Determination of the Module Parameters</i>	211
8.3	Peak Power Measurement at Site	212
8.3.1	<i>Principle of Peak Power Measurement</i>	212
8.3.2	<i>Possibilities and Limits of the Measurement Principle</i>	213
8.4	Thermographic Measuring Technology	214
8.4.1	<i>Principle of Infrared Temperature Measurement</i>	214
8.4.2	<i>Bright Thermography of Solar Modules</i>	215
8.4.3	<i>Dark Thermography</i>	217
8.5	Electroluminescence Measuring Technology	218
8.5.1	<i>Principle of Measurement</i>	218
8.5.2	<i>Examples of Photos</i>	219
<b>9</b>	<b>Design and Operation of Grid-Connected Plants</b>	<b>223</b>
9.1	Planning and Dimensioning	223
9.1.1	<i>Selection of Site</i>	223
9.1.2	<i>Shading</i>	224
9.1.3	<i>Plant Dimensioning and Simulation Programs</i>	228
9.2	Economics of Photovoltaic Plants	230
9.2.1	<i>The Renewable Energy Law</i>	230
9.2.2	<i>Return Calculation</i>	231
9.3	Surveillance, Monitoring and Visualization	235

9.3.1	<i>Methods of Plant Surveillance</i>	235
9.3.2	<i>Monitoring PV Plants</i>	235
9.3.3	<i>Visualization</i>	238
9.4	<b>Operating Results of Actual Installations</b>	239
9.4.1	<i>Pitched Roof Installation from 1996</i>	239
9.4.2	<i>Pitched Roof Installation from 2002</i>	240
9.4.3	<i>Flat Roof from 2008</i>	241
<b>10</b>	<b>Outlook</b>	<b>243</b>
10.1	<b>Potential of Photovoltaics</b>	243
10.1.1	<i>Theoretical Potential</i>	243
10.1.2	<i>Technically Useful Radiation Energy</i>	243
10.1.3	<i>Technical Electrical Energy Generation Potential</i>	245
10.1.4	<i>Photovoltaics versus Biomass</i>	246
10.2	<b>Efficient Promotion Instruments</b>	247
10.3	<b>Price Development</b>	248
10.4	<b>Thoughts on Future Energy Supply</b>	249
10.4.1	<i>Current Development in Renewable Energies</i>	249
10.4.2	<i>Consideration of Future Scenarios</i>	249
10.4.3	<i>Options for Storing Electrical Energy</i>	251
10.4.4	<i>Requirements of the Grids</i>	254
10.5	<b>Conclusion</b>	255
<b>11</b>	<b>Exercises</b>	<b>257</b>
	<b>Appendix A</b>	<b>267</b>
	<b>Appendix B</b>	<b>269</b>
	<b>References</b>	<b>271</b>
	<b>Index</b>	<b>277</b>