

# Contents

<b>1</b>	<b>What Is Photovoltaics?</b> .....	1
1.1	What Is Photovoltaics? .....	1
1.2	Short History of Photovoltaics .....	2
1.2.1	Technology .....	2
1.2.2	Applications .....	5
1.3	Relevance of PV, Now and in the Future .....	6
1.4	Markets, Economics .....	8
<b>2</b>	<b>Physics of Solar Cells</b> .....	11
2.1	Basic Mechanisms of Energy Conversion .....	11
2.2	The Silicon Solar Cell .....	18
<b>3</b>	<b>Silicon Solar Cell Material and Technology</b> .....	23
3.1	Silicon Material .....	23
3.2	Monocrystalline and Multicrystalline Silicon .....	23
3.2.1	Technology of Czochralski and Float Zone Silicon .....	23
3.2.2	The Silicon Supply Problem .....	27
3.3	Ribbon Silicon .....	28
3.3.1	Principle .....	28
3.3.2	The Main Approaches in Ribbon Silicon Production .....	28
3.4	Silicon Cell Technology .....	30
3.4.1	Production of pn and pp <sup>+</sup> Junctions .....	30
3.4.2	Oxidation Process .....	31
3.4.3	Electrical Contacts .....	31
3.4.4	Antireflection Technologies .....	31
3.4.5	Status Today .....	32
3.5	Advanced Si-Solar Cells .....	33
3.5.1	High Efficiency Cells .....	33
3.5.2	Bifacial Solar Cells .....	35
3.5.3	Buried Contact Cells .....	35
3.5.4	Interdigitated Back Contact Cells .....	36
3.5.5	OEKO Cell .....	37

- 3.5.6 a-Si/c-Si Heterostructures ..... 37
- 3.5.7 Rear Side Contacted Cells ..... 38
- 3.5.8 Laser-Fired Contact Cells ..... 40
- 4 Crystalline Thin-Film Silicon ..... 43**
  - 4.1 History ..... 43
  - 4.2 The Basic Components  
of a Crystalline Silicon Thin-Film Solar Cell ..... 44
  - 4.3 The Present Status  
of the Crystalline Silicon Thin-Film Solar Cell ..... 47
    - 4.3.1 Si Layers Deposited Directly onto Glass ..... 47
    - 4.3.2 Si Layers on High-Temperature  
Resistant Substrates ..... 49
    - 4.3.3 Transfer Technologies of Monocrystalline  
Thin Si Films onto Glass ..... 51
- 5 Other Materials, New Concepts,  
and Future Developments ..... 57**
  - 5.1 Theoretical Efficiencies and Requirements  
for Solar Cell Materials ..... 57
  - 5.2 Thin-Film Materials ..... 59
    - 5.2.1 Amorphous Silicon ..... 59
    - 5.2.2 Copper Indium Diselenide  
and Related Compounds ..... 65
    - 5.2.3 Cadmium Telluride ..... 69
  - 5.3 Other Materials and Concepts ..... 73
    - 5.3.1 Tandem Cells, Concentrating Systems ..... 73
    - 5.3.2 Dye-Sensitized Cells ..... 75
    - 5.3.3 Organic Solar Cells ..... 77
  - 5.4 Theoretical Concepts for New High Efficiency  
Semiconductor Materials ..... 78
    - 5.4.1 Auger Generation Material ..... 78
    - 5.4.2 Intermediate Metallic Band Material  
and Up and Down Conversion ..... 79
  - 5.5 Past and Future Development of Solar Cell Efficiency ..... 81
- 6 Solar Cells and Solar Modules ..... 85**
  - 6.1 Characteristic Curves and Characteristics of Solar Cells .... 85
    - 6.1.1 Characteristic Curves of Solar Cells ..... 85
    - 6.1.2 Characteristics of Solar Cells ..... 86
  - 6.2 Module Technologies ..... 91

- 7 PV Systems** ..... 95
  - 7.1 Stand-Alone PV Systems ..... 95
    - 7.1.1 Consumer Applications ..... 96
    - 7.1.2 Solar Home Systems ..... 97
    - 7.1.3 Residential Systems ..... 100
    - 7.1.4 Hybrid Systems ..... 102
    - 7.1.5 Photovoltaic Water Pumping ..... 105
  - 7.2 Grid-Connected PV Systems ..... 107
    - 7.2.1 Decentralized Grid-Connected PV Systems ..... 107
    - 7.2.2 Central Grid-Connected PV Systems ..... 109
    - 7.2.3 Inverter ..... 109
  
- 8 PV Systems: Installation Possibilities** ..... 113
  - 8.1 Geometrical Considerations ..... 113
  - 8.2 PV Systems in Connection with Buildings ..... 115
    - 8.2.1 Advantages and Potential ..... 115
    - 8.2.2 Installation on the Roof ..... 118
    - 8.2.3 Roof-Integrated Systems ..... 120
    - 8.2.4 Facade-Integrated Systems ..... 123
  - 8.3 PV Sound Barriers ..... 126
  - 8.4 Solar Power Plants ..... 130
    - 8.4.1 Examples of Large PV Power Plants ..... 130
    - 8.4.2 PV and Plant Growth ..... 130
  - 8.5 Sun-Tracked and Concentrating Systems ..... 132
    - 8.5.1 Sun-Tracked Systems ..... 132
    - 8.5.2 Concentrating Systems ..... 133
  
- 9 Environmental Impacts by PV Systems** ..... 137
  - 9.1 Environmental Impacts Due to Manufacturing  
of PV Systems ..... 137
  - 9.2 Environmental Impacts from Operation of PV Systems ..... 137
  - 9.3 Energy Payback Time ..... 138
  - 9.4 Land Area Required by PV Systems ..... 139
  - 9.5 Recycling of PV Systems ..... 140
    - 9.5.1 Recycling of Crystalline Silicon PV Modules ..... 141
    - 9.5.2 Recycling of Amorphous Silicon PV Modules ..... 144
    - 9.5.3 Recycling of Compound Semiconductor  
Thin-Film PV Modules ..... 146
    - 9.5.4 Energy Demand for Recycling of PV Modules ..... 146

- 10 Efficiency and Performance of PV Systems** ..... 147
  - 10.1 Stand-Alone PV Systems ..... 147
  - 10.2 Grid-Connected PV Systems ..... 148
    - 10.2.1 Final Yield ..... 148
    - 10.2.2 Performance Ratio ..... 148
    - 10.2.3 Possibilities of Quality Control and Control  
of Energy Yield of Grid-Connected PV Systems .... 153
  - 10.3 Long-Term Behavior of Grid-Connected PV Systems ..... 155
    - 10.3.1 Solar Module ..... 155
    - 10.3.2 Inverter ..... 158
    - 10.3.3 Mounting Racks and Fixing Materials..... 158
    - 10.3.4 Cables ..... 159
  - 10.4 Electric Safety of Grid-Connected PV Systems ..... 159
  
- 11 PV Markets Support Measures and Costs** ..... 163
  - 11.1 Market Survey ..... 163
  - 11.2 Influences on the PV Market ..... 164
    - 11.2.1 Demonstration ..... 165
    - 11.2.2 General Investment Subsidy Programs ..... 168
    - 11.2.3 Sponsoring ..... 169
    - 11.2.4 Low Interest Loans ..... 171
    - 11.2.5 Tax Benefits ..... 173
    - 11.2.6 Rate-Based Incentives or Feed-In Tariffs ..... 173
    - 11.2.7 Green Pricing ..... 175
    - 11.2.8 Foundation ..... 175
    - 11.2.9 Solar Power Stock Exchange ..... 176
    - 11.2.10 Cooperatives ..... 176
    - 11.2.11 Green “Utility” ..... 176
    - 11.2.12 Tendering ..... 176
    - 11.2.13 Renewable Obligation Order  
or Renewable Portfolio Standard ..... 177
    - 11.2.14 Installation on Leased Roof Areas ..... 177
    - 11.2.15 Political Commitment ..... 177
    - 11.2.16 Information ..... 178
    - 11.2.17 Evaluation of Market Support Measures ..... 178
  - 11.3 Cost of Photovoltaics ..... 180
    - 11.3.1 Cost of PV Modules ..... 180
    - 11.3.2 Cost of PV Systems ..... 182
    - 11.3.3 Cost of Power Production ..... 184

**12 The Future of PV** ..... 187

12.1 Boundary Conditions for the Future Development  
of Photovoltaics ..... 187

12.1.1 Cost Development of Conventional Electricity ..... 187

12.1.2 Effects of Liberalization  
and Environmental Restrictions ..... 187

12.2 Cost and Market Development of Stand-Alone  
and Grid-Connected Systems ..... 188

12.3 PV in a Future Liberalized  
and Partly Decentralized Energy System ..... 189

12.3.1 Integration of PV  
into a Decentralized Energy System ..... 189

12.3.2 Fully Autonomous Systems,  
Autonomous House Concepts ..... 190

12.4 PV in a Centralized Energy System ..... 191

12.4.1 Electricity from the Desert ..... 191

12.4.2 Electricity from Space ..... 192

**13 Other (Perhaps Competing) CO<sub>2</sub>-Free Energy Sources** .... 195

13.1 Other Renewable Energy Sources ..... 195

13.1.1 Solar Thermal Energy ..... 195

13.1.2 Hydropower ..... 201

13.1.3 Wind Energy ..... 204

13.1.4 Biomass ..... 205

13.1.5 Ocean and Wave Energy ..... 206

13.1.6 Geothermal Energy ..... 209

13.2 Carbon-Free Combustion of Fossil Fuels:  
Carbon Sequestration ..... 212

13.2.1 What Is Carbon Sequestration? ..... 212

13.2.2 CO<sub>2</sub> Capture and Separation ..... 213

**14 Popular Killing Arguments Against PV  
and Why They Are Not Valid** ..... 215

14.1 Solar Modules Consume More Energy  
for Their Production Than They Ever Generate ..... 215

14.2 PV Produces More Greenhouse Gases Than It Saves ..... 216

14.3 Grid-Connected PV Requires Lots  
of Back-Up Fossil Power Plants ..... 216

14.4 PV Is Too Expensive ..... 216

14.5 PV Is Not Ready for Marketing, More Research  
Is Required ..... 217

- 14.6 Installation of PV in the Northern Half of Europe Does  
Not Make Sense Because the Same Solar Cells Generate  
Electricity Much Cheaper in the South ..... 217
- 14.7 PV Involves Toxic Materials ..... 218
- 14.8 PV Consumes Valuable Land Area ..... 218
- 14.9 PV Competes for Roof Space with Thermal Collectors ..... 219
- 14.10 A Feed-in Tariff Causes Unacceptably High  
Electricity Cost ..... 219
  
- References** ..... 221
  
- Index** ..... 229