

# Table of Contents

Preface . . . . .	xvii
<b>Chapter 1. Photovoltaic Electricity Production. . . . .</b>	
Jean-Claude MULLER	
1.1. Introduction . . . . .	2
1.2. Photovoltaic conversion . . . . .	3
1.2.1. I-V characteristics of a cell and conversion output . . . . .	4
1.3. Cells with a crystalline silicon base. . . . .	5
1.3.1. Raw silicon . . . . .	5
1.3.2. Monocrystalline silicon . . . . .	5
1.3.2.1. Techniques for growing monocrystals . . . . .	5
1.3.2.2. Record for cells on monocrystals . . . . .	5
1.3.3. Multicrystalline silicon . . . . .	6
1.3.3.1. Techniques for growing multicrystals . . . . .	6
1.3.3.2. Improvement in performance of cells created from multicrystals . . . . .	7
1.3.4. Silicon in self-supported ribbon . . . . .	9
1.3.4.1. Growing techniques . . . . .	9
1.3.4.2. Prospects . . . . .	9
1.4. Cells in thin films . . . . .	10
1.4.1. Polycrystalline silicon . . . . .	10
1.4.2. Nanocrystalline and amorphous silicon . . . . .	12
1.4.2.1. State of the art and new prospects . . . . .	12
1.4.2.2. Industrial applications . . . . .	13
1.4.3. Marriage of crystalline and amorphous technologies . . . . .	14

1.4.4. Other emerging thin-film materials . . . . .	15
1.4.4.1. Materials with a cadmium–tellurium base . . . . .	15
1.4.4.2. Materials with a base of indium–copper–selenium (CIS) (copper selenate) . . . . .	15
1.4.5. Prospects for thin films . . . . .	16
1.5. Photovoltaic market . . . . .	17
1.5.1. Stimulation of production by political intervention . . . . .	18
1.5.2. First beneficial effects on production and power of the installations . . . . .	19
1.5.3. Adaptation of the product to the market: cost of watt and kilowatt hour PV . . . . .	21
1.6. Prospects for photovoltaic electricity development . . . . .	22
1.7. Bibliography . . . . .	23
<b>Chapter 2. Photovoltaic Systems Connected to the Grid . . . . .</b>	<b>25</b>
Seddik BACHA and Daniel CHATROUX	
2.1. Problems of photovoltaic power generation connected to the grid . . . . .	25
2.2. General remarks on connection . . . . .	28
2.2.1. Interfacing with the grid . . . . .	28
2.2.2. General remarks on control . . . . .	30
2.3. Physical architectures . . . . .	30
2.3.1. Central inverter . . . . .	32
2.3.2. Individual inverter . . . . .	32
2.3.3. Row inverters . . . . .	32
2.3.4. Multiple row inverters . . . . .	32
2.3.5. Conclusion . . . . .	33
2.4. Constraints related to supplying energy to the utility grid . . . . .	34
2.4.1. Quality of the energy supplied . . . . .	34
2.4.2. Security . . . . .	34
2.4.2.1. Security regarding the grid . . . . .	35
2.4.2.2. Security with respect to installation . . . . .	35
2.5. Algorithmic architectures . . . . .	38
2.5.1. The search for MPPT . . . . .	38
2.5.2. Control of the inverter grid and the global chain . . . . .	41
2.6. Conclusion . . . . .	42
2.7. Bibliography . . . . .	43

<b>Chapter 3. Solar Heating . . . . .</b>	<b>45</b>
Christophe MARVILLET	
3.1. Introduction . . . . .	45
3.1.1. Some history . . . . .	45
3.1.2. Some basic calculations . . . . .	47
3.1.3. The performance of solar heating devices . . . . .	48
3.2. Available energy from the sun . . . . .	49
3.2.1. The apparent motion of the sun . . . . .	49
3.2.2. Evaluation of sunlight received by a collector . . . . .	52
3.3. Flat solar panels . . . . .	53
3.3.1. Different technologies of thermal solar collectors . . . . .	54
3.3.2. Evaluation of the performance of solar collectors . . . . .	55
3.3.3. Selective coatings for collectors and glazing . . . . .	58
3.4. Solar heating systems . . . . .	58
3.4.1. Individual and collective solar water heaters . . . . .	58
3.4.2. Combined solar systems for the heating of buildings . . . . .	61
3.5. Bibliography . . . . .	62
<b>Chapter 4. Solar Thermodynamic Power Stations . . . . .</b>	<b>63</b>
Alain FERRIÈRE	
Introduction . . . . .	63
4.1. Concentrating solar power technologies . . . . .	65
4.1.1. Why concentrate solar radiation? . . . . .	65
4.1.2. Concentrating systems . . . . .	67
4.1.2.1. The parabolic concentrator (or dish) . . . . .	68
4.1.2.2. The tower concentrator . . . . .	71
4.1.2.3. The cylindrical-parabolic concentrator (or trough concentrator) . . . . .	72
4.1.3. Components for production of heat and conversion into electricity . . . . .	75
4.1.3.1. The solar receiver . . . . .	76
4.1.3.2. Heat transfer fluid . . . . .	77
4.1.4. Storage and hybridization . . . . .	82
4.2. The state of the art . . . . .	84
4.2.1. First generation solar stations and exploratory work . . . . .	84
4.2.2. Second generation solar power stations: precommercial prototypes . . . . .	90
4.3. Prospects . . . . .	94
4.3.1. Strategy for penetrating the market . . . . .	94
4.3.1.1. Power stations of the future and research efforts . . . . .	98
4.3.1.2. Conclusions . . . . .	101
4.4. Bibliography . . . . .	102

<b>Chapter 5. Wind Systems Technology . . . . .</b>	<b>103</b>
Régine BELHOMME, Daniel ROYE and Nicolas LAVERDURE	
5.1. Introduction: wind power today . . . . .	103
5.2. Description of a wind generator . . . . .	104
5.2.1. Principle . . . . .	104
5.2.2. Constitution . . . . .	105
5.3. Operation of a wind turbine . . . . .	106
5.3.1. Controls of energy conversion . . . . .	106
5.3.2. Control at the turbine level . . . . .	108
5.3.2.1. Action of the wind on the turbine blades . . . . .	108
5.3.2.2. Control methods at the turbine level . . . . .	111
5.3.3. Mechanical system – transmission of the power . . . . .	116
5.3.4. Controls at generator and transmission network levels – different types of wind power generator systems . . . . .	119
5.3.4.1. Fixed speed systems – squirrel cage asynchronous machines . .	119
5.3.4.2. Variable speed systems . . . . .	123
5.4. Bibliography . . . . .	136
<b>Chapter 6. Integration of Wind Turbine Generators into the Grid . . . . .</b>	<b>143</b>
Régine BELHOMME, Daniel ROYE and Nicolas LAVERDURE	
6.1. Connection to the grid . . . . .	143
6.1.1. Voltage at the point of connection . . . . .	144
6.1.2. Currents in steady state . . . . .	145
6.1.3. Short circuit currents . . . . .	145
6.1.4. Voltage profile . . . . .	147
6.1.5. Voltage quality . . . . .	148
6.1.5.1. Slow variations in voltage . . . . .	148
6.1.5.2. Sudden changes in voltage . . . . .	148
6.1.5.3. Flicker . . . . .	149
6.1.5.4. Harmonics . . . . .	149
6.1.5.5. Disturbances of signals transmitted on the grid . . . . .	151
6.1.6. Stability and protection design . . . . .	151
6.1.6.1. Management in normal and abnormal regimes . . . . .	152
6.1.6.2. Managing voltage sags (FRT “fault-ride-through” or LVRT) .	152
6.1.6.3. Interaction with the protection design . . . . .	155
6.1.7. Auxiliary system . . . . .	156
6.1.7.1. Regulation of voltage and reactive compensation . . . . .	157
6.1.7.2. Regulation of frequency . . . . .	159
6.1.7.3. Operating on a separate grid and reconstitution of grids . . .	161
6.1.8. Variability and unpredictability of production . . . . .	162

6.1.9. Other solutions for connection problems . . . . .	162
6.1.9.1. Reinforcement of the grid . . . . .	162
6.1.9.2. Power shedding . . . . .	163
6.1.9.3. Coordination with other production methods . . . . .	163
6.1.9.4. Load control . . . . .	164
6.1.9.5. Systems of reactive compensation and of voltage control . . . . .	165
6.1.9.6. Systems for managing voltage sags . . . . .	167
6.1.9.7. Systems for energy storage . . . . .	168
6.1.9.8. Short circuit current limiting devices . . . . .	168
6.1.9.9. Other equipment . . . . .	169
6.2. Comparison of technologies and conclusion . . . . .	169
6.3. Bibliography . . . . .	171
6.4. Appendix: symbol table . . . . .	177
6.4.1. Parameters and physical variables . . . . .	177
6.4.1.1. Time variable . . . . .	177
6.4.1.2. Turbine, blades . . . . .	178
6.4.1.3. Mechanical system . . . . .	178
6.4.1.4. Induction and synchronous generators . . . . .	178
6.4.1.5. DC bus . . . . .	180
<b>Chapter 7. Marine Energy Resources Conversion Systems . . . . .</b>	<b>181</b>
Bernard MULTON, Alain CLÉMENT, Marie RUELLAN, Julien SEIGNEURBIEUX and Hamid BEN AHMED	
7.1. Introduction . . . . .	181
7.2. Electricity productivity from marine resources . . . . .	183
7.2.1. Energy sources from the sea . . . . .	183
7.2.1.1. Solar heat . . . . .	183
7.2.1.2. Wind energy . . . . .	183
7.2.1.3. Ocean wave energy . . . . .	184
7.2.1.4. Tidal currents . . . . .	184
7.2.1.5. Continuous ocean currents . . . . .	185
7.2.1.6. Osmotic energy . . . . .	185
7.2.1.7. Ocean biomass . . . . .	186
7.2.1.8. Evaluation . . . . .	186
7.2.2. General technical-economic aspects . . . . .	186
7.3. Ocean wave generator systems (WEC: wave energy converters) . . . . .	188
7.3.1. Wave energy characteristics . . . . .	188
7.3.2. Diversity in conversion systems . . . . .	192
7.3.3. Systems with breakwater ramps . . . . .	193
7.3.4. Oscillating water column (OWC) systems . . . . .	195
7.3.5. Systems with wave activated bodies . . . . .	198

7.4. Tidal energy converters (TEC) . . . . .	202
7.4.1. Characteristics of tides and other marine currents . . . . .	202
7.4.2. Tidal power production systems with dams . . . . .	203
7.4.3. Systems for recovering energy from marine currents . . . . .	206
7.5. Other conversion systems . . . . .	214
7.5.1. Offshore wind power generators . . . . .	214
7.5.2. Ocean thermal energy converter (OTEC). . . . .	218
7.6. Conclusion . . . . .	221
7.7. Bibliography . . . . .	223
<b>Chapter 8. Small Hydropower . . . . .</b>	<b>227</b>
Raymond CHENAL, Aline CHOULOT, Vincent DENIS and Norbert TISSOT	
8.1. Introduction . . . . .	227
8.2. What is small hydropower? . . . . .	229
8.3. Hydraulic energy . . . . .	231
8.4. The exploitation of hydraulic force . . . . .	233
8.4.1. Description of a typical scheme . . . . .	234
8.4.2. Different types of schemes encountered . . . . .	234
8.4.3. Different kinds of turbines . . . . .	236
8.4.3.1. The Pelton turbine . . . . .	236
8.4.3.2. The Francis turbine . . . . .	237
8.4.3.3. The diagonal turbine . . . . .	238
8.4.3.4. The Kaplan turbine . . . . .	238
8.4.3.5. The waterwheel for water from above. . . . .	239
8.4.3.6. The Banki or crossflow turbine. . . . .	240
8.4.3.7. The inverted Archimedes screw . . . . .	240
8.4.4. Particular applications of small hydro . . . . .	240
8.4.4.1. Turbines in drinking water networks . . . . .	241
8.4.4.2. Turbines in wastewater networks . . . . .	242
8.4.4.3. Recovery of energy in desalination plants . . . . .	244
8.5. Potential . . . . .	244
8.5.1. Worldwide small hydropower . . . . .	244
8.5.2. European-wide small hydropower . . . . .	244
8.5.3. Possibilities for development of small hydropower in Europe . . . . .	245
8.6. Research & Development in small hydropower . . . . .	245
8.6.1. Development of equipment adapted to each site. . . . .	246
8.6.2. Development of variable speed. . . . .	246
8.6.3. Development in generators . . . . .	247
8.6.4. Development in control-command. . . . .	247
8.6.5. Inflatable weirs . . . . .	248
8.6.6. Water intake . . . . .	248

8.7. Environmental aspects of small hydropower . . . . .	249
8.7.1. Initial state of the milieu. . . . .	249
8.7.2. Setting phase. . . . .	249
8.7.2.1. Setting of a small power plant for its integration into the ecosystem . . . . .	249
8.7.2.2. Flow of materials and equipment . . . . .	253
8.7.3. Principal inputs and outputs during the operating phase . . . . .	253
8.7.3.1. Water . . . . .	254
8.7.3.2. Materials carried by the watercourse . . . . .	254
8.7.3.3. Noise . . . . .	254
8.7.3.4. Electricity production . . . . .	254
8.8. Policies favoring small hydropower . . . . .	254
8.8.1. R & D program . . . . .	255
8.8.2. Rate measures . . . . .	256
8.9. Conclusions. . . . .	257
8.10. Bibliography . . . . .	258

## **Chapter 9. Geothermal Energy Production . . . . .** 261

Florence JAUDIN and Laurent LE BEL

9.1. Introduction. . . . .	261
9.2. Geothermal energy: why, for whom and how? . . . . .	262
9.2.1. The types of resources used. . . . .	262
9.2.1.1. Fissured and/or porous volcanic formations . . . . .	264
9.2.1.2. Aquifers of sedimentary basins. . . . .	265
9.2.1.3. Superficial formations . . . . .	266
9.2.1.4. Deep formations (with low permeability). . . . .	266
9.2.2. End-use. . . . .	266
9.2.2.1. Heat network system. . . . .	267
9.2.2.2. Heat pump (HP) system . . . . .	267
9.2.2.3. Electricity production . . . . .	268
9.2.3. Other uses . . . . .	268
9.3. Geothermal heat pump systems . . . . .	269
9.3.1. Current situation and tendencies . . . . .	269
9.3.2. The principle of the heat pump . . . . .	270
9.3.2.1. Classification of heat pumps . . . . .	270
9.3.2.2. Coefficient of performance (COP). . . . .	273
9.3.3. Extracting heat from the ground . . . . .	275
9.3.3.1. Drawing calories from groundwater. . . . .	276
9.3.3.2. Horizontal and vertical in-ground heat exchangers . . . . .	277
9.3.4. Development prospects and potential . . . . .	285

9.4. Direct production of heat . . . . .	286
9.4.1. Current situation . . . . .	286
9.4.2. Geothermal heating networks . . . . .	288
9.4.2.1. The theoretical doublet and the associated heating network . . . . .	288
9.4.2.2. Geothermy experience in the Paris basin . . . . .	289
9.4.2.3. Technological developments . . . . .	291
9.4.3. Prospects and potential for development . . . . .	300
9.4.3.1. The objectives of the revival in Ile-de-France . . . . .	301
9.5. Electricity production . . . . .	301
9.5.1. Current contribution of geothermal energy to the production of electricity . . . . .	301
9.5.2. Exploitation of geothermal resources . . . . .	302
9.5.2.1. Naturally producing reservoirs . . . . .	302
9.5.2.2. Enhanced geothermal systems . . . . .	312
9.5.3. Development potential . . . . .	318
9.6. Glossary . . . . .	320
9.7. Bibliography . . . . .	325
<b>Chapter 10. Biofuels . . . . .</b>	<b>329</b>
Frédéric MONOT, Jean-Luc DUPLAN, Nathalie ALAZARD-TOUX and Stéphane HIS	
10.1. The place of biofuels in the energy environment . . . . .	329
10.1.1. A favorable environment . . . . .	330
10.1.2. Principal characteristics of systems today . . . . .	331
10.1.3. Main advantages and disadvantages associated with biofuel use .	333
10.1.4. The situation of biofuels in the world . . . . .	335
10.1.4.1. The influence of the Common Agricultural Policy (CAP) . . . . .	343
10.1.5. Prospects . . . . .	345
10.2. Current systems . . . . .	345
10.2.1. Biodiesel systems . . . . .	345
10.2.1.1. Raw materials . . . . .	345
10.2.1.2. Production processes . . . . .	346
10.2.2. The bioethanol system . . . . .	352
10.2.2.1. Raw materials . . . . .	352
10.2.2.2. Production procedures . . . . .	353
10.3. Future systems: use of lignocellulose . . . . .	358
10.3.1. Characteristics of components in vegetable lignocellulose . . . . .	358
10.3.2. The BtL system . . . . .	361
10.3.2.1. Main constraints of the process . . . . .	361
10.3.2.2. Conditioning of biomass . . . . .	362
10.3.2.3. Gasification . . . . .	366
10.3.2.4. Treatment of syngas . . . . .	370

10.3.2.5. Fuel synthesis: Fischer–Tropsch and hydrocracking . . . . .	371
10.3.2.6. Conclusion . . . . .	372
10.3.3. The bioethanol system . . . . .	373
10.3.3.1. Main constraints of the process . . . . .	373
10.3.3.2. Pretreatment . . . . .	374
10.3.3.3. Enzyme hydrolysis . . . . .	375
10.3.3.4. Ethanol fermentation . . . . .	377
10.3.3.5. Conclusion . . . . .	379
10.4. Economic and environmental balance of biofuel production systems . . . . .	380
10.4.1. Economic aspects . . . . .	380
10.4.1.1. The competitiveness of biofuels . . . . .	380
10.4.1.2. The ethanol system . . . . .	382
10.4.1.3. Cost of ETBE production . . . . .	387
10.4.1.4. Biodiesel . . . . .	387
10.4.1.5. New fuel systems . . . . .	389
10.4.2. Results of analyses of life cycle of biofuels . . . . .	390
10.5. Bibliography . . . . .	394
<b>Chapter 11. Biogas . . . . .</b>	<b>397</b>
Pierre LABEYRIE	
11.1. Introduction: biogas, “the renewable natural gas” . . . . .	397
11.2. Naturally occurring biogas . . . . .	397
11.3. Production organized by humans . . . . .	398
11.4. History of anaerobic digestion . . . . .	399
11.5. Anaerobic digestion . . . . .	400
11.5.1. Management of the anaerobic digestion process . . . . .	401
11.5.1.1. The effect of temperature . . . . .	402
11.5.1.2. Effect of pH . . . . .	403
11.5.1.3. Dynamics of the bacteria populations . . . . .	403
11.5.1.4. Mixtures of substrates or codigestion . . . . .	403
11.6. Anaerobic digestion installations or biogas units . . . . .	405
11.6.1. Techniques . . . . .	405
11.6.1.1. Digesters functioning with a continuous introduction of substrates . . . . .	405
11.6.1.2. Discontinuously functioning digesters (batch) . . . . .	408
11.6.2. Examples of recent agricultural anaerobic digestion installations . . . . .	408
11.6.2.1. Mr Claudepiere’s installation: liquid system . . . . .	408
11.6.2.2. The GAEC Oudet installation: liquid system . . . . .	411

11.6.2.3. GAEC of the Chateau installation (under completion): mixed system . . . . .	413
11.6.2.4. Pierre Lebbe installation: solid system . . . . .	414
11.7. Uses of biogas . . . . .	419
11.7.1. Thermal engine cogeneration . . . . .	419
11.7.2. Exclusively thermal use . . . . .	421
11.7.2.1. Use of a boiler . . . . .	421
11.7.2.2. Use of a production system for cooling . . . . .	422
11.7.3. Fuel production . . . . .	422
11.7.3.1. PSA (pressure swing adsorption) purification . . . . .	423
11.8. Conclusion: renewable natural gas and its challenges . . . . .	424
11.9. Bibliography . . . . .	425
 <b>Chapter 12. Energy Production from Wood</b> . . . . .	427
Frédéric DOUARD	
12.1. Introduction: what is wood energy? . . . . .	427
12.2. Overview of wood fuels. . . . .	429
12.2.1. Logs . . . . .	429
12.2.2. Densified wood logs or compacted logs . . . . .	430
12.2.3. Briquettes . . . . .	431
12.2.4. Wood pellets . . . . .	432
12.2.5. Wood chips . . . . .	434
12.2.6. Industrial chips . . . . .	435
12.2.7. Grindings from recycled wood . . . . .	436
12.2.8. Ground bark . . . . .	438
12.2.9. Sawdust and wood chips . . . . .	439
12.2.10. Wood powder . . . . .	440
12.2.11. Roasted wood . . . . .	440
12.2.12. Wood charcoal . . . . .	440
12.2.13. Spent pulping liquors and paper mill sludge . . . . .	441
12.3. Principles of conversion of wood into energy . . . . .	442
12.3.1. Combustion . . . . .	442
12.3.2. Pyrolysis . . . . .	445
12.3.3. Gasification . . . . .	447
12.4. Generators of thermal energy from wood . . . . .	450
12.4.1. Domestic technologies . . . . .	450
12.4.1.1. Hearths, ovens and other open fireplaces . . . . .	450
12.4.1.2. Closed hearth fireplaces . . . . .	451
12.4.1.3. Heating and cooking stoves . . . . .	453
12.4.1.4. Wood-fired boilers . . . . .	455
12.4.1.5. Pellet stoves . . . . .	457

12.4.1.6. Pellet boilers . . . . .	459
12.4.1.7. Domestic wood chip boilers . . . . .	460
12.4.2. Housing complexes or industrial technologies . . . . .	461
12.4.2.1. Hot air boilers and generators with fixed grilles . . . . .	461
12.4.2.2. Boilers with moving or mobile grilles . . . . .	463
12.4.2.3. Boilers with rotating conical grilles . . . . .	464
12.4.2.4. Boilers with vibrating grilles . . . . .	466
12.4.2.5. Boilers with rolling grilles . . . . .	466
12.4.2.6. Bottom draft or air injection boilers . . . . .	467
12.4.2.7. Boilers with boiling fluidized beds . . . . .	468
12.4.2.8. Boilers with circulating fluidized beds . . . . .	469
12.5. Conclusion . . . . .	470
12.6. Bibliography . . . . .	471
 <b>List of Authors</b> . . . . .	473
 <b>Index</b> . . . . .	475