

Contents

Preface	xiii
1 Introduction	1
1.1 General Introduction to Renewable Energy Technologies	1
1.2 Energy Demand and Renewable Energy	3
1.3 Energy-Related Environmental Problems	8
1.3.1 Acid Rain	11
1.3.2 Ozone Layer Depletion	11
1.3.3 Global Climate Change	12
1.3.4 Nuclear Energy	13
1.3.5 Renewable Energy Technologies	15
1.4 State of the Climate in 2005	18
1.4.1 Global Temperature	18
1.4.2 Carbon Dioxide	19
1.4.3 Methane	20
1.4.4 Carbon Monoxide	21
1.4.5 Nitrous Oxide and Sulfur Hexafluoride	21
1.4.6 Halocarbons	22
1.4.7 Sea Level	22
1.5 Brief History of Solar Energy	22
1.5.1 Photovoltaics	26
1.5.2 Solar Desalination	28
1.5.3 Solar Drying	32
1.5.4 Passive Solar Buildings	33
1.6 Other Renewable Energy Systems	33
1.6.1 Wind Energy	33
1.6.2 Biomass	38
1.6.3 Geothermal Energy	41
1.6.4 Hydrogen	41
1.6.5 Ocean Energy	43
Exercise	45
References	46
2 Environmental Characteristics	49
2.1 Reckoning of Time	50
2.1.1 Equation of Time	50
2.1.2 Longitude Correction	51

2.2 Solar Angles	52
2.2.1 The Incidence Angle for Moving Surfaces	62
2.2.2 Sun Path Diagrams	68
2.2.3 Shadow Determination	70
2.3 Solar Radiation	72
2.3.1 General	72
2.3.2 Thermal Radiation	73
2.3.3 Transparent Plates	80
2.3.4 Radiation Exchange Between Surfaces	84
2.3.5 Extraterrestrial Solar Radiation	88
2.3.6 Atmospheric Attenuation	91
2.3.7 Terrestrial Irradiation	93
2.3.8 Total Radiation on Tilted Surfaces	97
2.3.9 Solar Radiation Measuring Equipment	104
2.4 The Solar Resource	106
2.4.1 Typical Meteorological Year	106
2.4.2 Typical Meteorological Year, Second Generation	108
Exercises	117
References	119
3 Solar Energy Collectors	121
3.1 Stationary Collectors	121
3.1.1 Flat-Plate Collectors (FPCs)	122
3.1.2 Compound Parabolic Collectors (CPCs)	129
3.1.3 Evacuated Tube Collectors (ETCs)	131
3.2 Sun-Tracking Concentrating Collectors	135
3.2.1 Parabolic Trough Collectors (PTCs)	138
3.2.2 Fresnel Collectors	144
3.2.3 Parabolic Dish Reflectors (PDRs)	147
3.2.4 Heliostat Field Collectors (HFCs)	149
3.3 Thermal Analysis of Flat-Plate Collectors	150
3.3.1 Absorbed Solar Radiation	151
3.3.2 Collector Energy Losses	156
3.3.3 Temperature Distribution Between the Tubes and Collector Efficiency Factor	166
3.3.4 Heat Removal Factor, Flow Factor, and Thermal Efficiency	172
3.4 Thermal Analysis of Air Collectors	175
3.5 Practical Considerations for Flat-Plate Collectors	180
3.6 Concentrating Collectors	181
3.6.1 Optical Analysis of a Compound Parabolic Collector	183
3.6.2 Thermal Analysis of Compound Parabolic Collectors	186
3.6.3 Optical Analysis of Parabolic Trough Collectors	191
3.6.4 Thermal Analysis of Parabolic Trough Collectors	199

3.7 Second-Law Analysis	206
3.7.1 Minimum Entropy Generation Rate	208
3.7.2 Optimum Collector Temperature	210
3.7.3 Non-Isothermal Collector	211
Exercises	212
References	214
4 Performance of Solar Collectors	219
4.1 Collector Thermal Efficiency	221
4.1.1 Effect of Flow Rate	225
4.1.2 Collectors in Series	226
4.1.3 Standard Requirements	227
4.2 Collector Incidence Angle Modifier	230
4.2.1 Flat-Plate Collectors	230
4.2.2 Concentrating Collectors	231
4.3 Concentrating Collector Acceptance Angle	232
4.4 Collector Time Constant	233
4.5 Dynamic System Test Method	235
4.6 Collector Test Results and Preliminary Collector Selection	236
4.7 Quality Test Methods	239
4.7.1 Internal Pressure Test	240
4.7.2 High-Temperature Resistance Test	240
4.7.3 Exposure Test	241
4.7.4 External Thermal Shock Test	241
4.7.5 Internal Thermal Shock Test	241
4.7.6 Rain Penetration	242
4.7.7 Freezing Test	242
4.7.8 Impact Resistance Test	243
4.8 European Standards	243
4.8.1 Solar Keymark	245
4.9 Data Acquisition Systems	246
4.9.1 Portable Data Loggers	248
Exercises	249
References	250
5 Solar Water Heating Systems	251
5.1 Passive Systems	252
5.1.1 Thermosiphon Systems	252
5.1.2 Integrated Collector Storage Systems	260
5.2 Active Systems	263
5.2.1 Direct Circulation Systems	264
5.2.2 Indirect Water Heating Systems	266
5.2.3 Air Water-Heating Systems	268
5.2.4 Heat Pump Systems	269
5.2.5 Pool Heating Systems	270

5.3 Heat Storage Systems	275
5.3.1 Air System Thermal Storage	276
5.3.2 Liquid System Thermal Storage	277
5.3.3 Thermal Analysis of Storage Systems	280
5.4 Module and Array Design	287
5.4.1 Module Design	287
5.4.2 Array Design	288
5.5 Differential Temperature Controller	297
5.5.1 Placement of Sensors	301
5.6 Hot Water Demand	301
5.7 Solar Water Heater Performance Evaluation	304
5.8 Simple System Models	307
5.9 Practical Considerations	308
5.9.1 Pipes, Supports, and Insulation	308
5.9.2 Pumps	309
5.9.3 Valves	309
5.9.4 Instrumentation	311
Exercises	312
References	314
6 Solar Space Heating and Cooling	315
6.1 Thermal Load Estimation	315
6.1.1 The Heat Balance Method	316
6.1.2 The Transfer Function Method	318
6.1.3 Heat Extraction Rate and Room Temperature	322
6.1.4 Degree Day Method	323
6.1.5 Building Heat Transfer	325
6.2 Passive Space Heating Design	328
6.2.1 Building Construction: Thermal Mass Effects	328
6.2.2 Building Shape and Orientation	338
6.2.3 Insulation	339
6.2.4 Windows: Sunspaces	339
6.2.5 Overhangs	341
6.2.6 Natural Ventilation	345
6.3 Solar Space Heating and Cooling	347
6.3.1 Space Heating and Service Hot Water	348
6.3.2 Air Systems	350
6.3.3 Water Systems	352
6.3.4 Location of Auxiliary Heater	357
6.3.5 Heat Pump Systems	358
6.4 Solar Cooling	360
6.4.1 Adsorption Units	365
6.4.2 Absorption Units	367

6.5 Solar Cooling with Absorption Refrigeration	381
Exercises	383
References	386
7 Industrial Process Heat, Chemistry Applications, and Solar Dryers	391
7.1 Industrial Process Heat: General Design Considerations	391
7.1.1 Solar Industrial Air and Water Systems	395
7.2 Solar Steam Generation Systems	397
7.2.1 Steam Generation Methods	397
7.2.2 Flash Vessel Design	399
7.3 Solar Chemistry Applications	400
7.3.1 Reforming of Fuels	400
7.3.2 Fuel Cells	402
7.3.3 Materials Processing	408
7.3.4 Solar Detoxification	409
7.4 Solar Dryers	410
7.4.1 Active Solar Energy Dryers	411
7.4.2 Passive Solar Energy Dryers	413
7.5 Greenhouses	416
7.5.1 Greenhouse Materials	417
Exercises	418
References	419
8 Solar Desalination Systems	421
8.1 Introduction	421
8.1.1 Water and Energy	421
8.1.2 Water Demand and Consumption	422
8.1.3 Desalination and Energy	423
8.2 Desalination Processes	424
8.2.1 Desalination Systems Exergy Analysis	427
8.2.2 Exergy Analysis of Thermal Desalination Systems	432
8.3 Direct Collection Systems	433
8.3.1 Classification of Solar Distillation Systems	434
8.3.2 Performance of Solar Stills	436
8.3.3 General Comments	439
8.4 Indirect Collection Systems	440
8.4.1 The Multi-Stage Flash (MSF) Process	441
8.4.2 The Multiple-Effect Boiling (MEB) Process	444
8.4.3 The Vapor Compression (VC) Process	448
8.4.4 Reverse Osmosis (RO)	450
8.4.5 Electrodialysis (ED)	452
8.5 Review of Renewable Energy Desalination Systems	453
8.5.1 Solar Thermal Energy	453
8.5.2 Solar Ponds	454

✖ Contents

8.5.3 Solar Photovoltaic Technology	454
8.5.4 Wind Power	455
8.5.5 Hybrid Solar PV-Wind Power	455
8.5.6 Geothermal Energy	456
8.6 Process Selection	457
Exercises	463
References	463
9 Photovoltaic Systems	469
9.1 Semiconductors	470
9.1.1 p-n Junction	472
9.1.2 Photovoltaic Effect	474
9.1.3 PV Cell Characteristics	476
9.2 Photovoltaic Panels	483
9.2.1 PV Arrays	485
9.2.2 Types of PV Technology	486
9.3 Related Equipment	488
9.3.1 Batteries	488
9.3.2 Inverters	489
9.3.3 Charge Controllers	490
9.3.4 Peak-Power Trackers	491
9.4 Applications	491
9.4.1 Direct Coupled PV System	492
9.4.2 Stand-Alone Applications	492
9.4.3 Grid-Connected Systems	493
9.4.4 Hybrid-Connected Systems	493
9.4.5 Types of Applications	494
9.5 Design of PV Systems	495
9.5.1 Electrical Loads	495
9.5.2 Absorbed Solar Radiation	498
9.5.3 Cell Temperature	503
9.5.4 Sizing of PV Systems	505
9.6 Concentrating PV	511
9.7 Hybrid PV/T Systems	512
9.7.1 Hybrid PV/T Applications	515
Exercises	517
References	518
10 Solar Thermal Power Systems	521
10.1 Introduction	521
10.2 Parabolic Trough Collector Systems	524
10.2.1 Description of the PTC Power Plants	528
10.2.2 Outlook for the Technology	531
10.3 Power Tower Systems	533
10.3.1 System Characteristics	535

10.4 Dish Systems	537
10.4.1 Dish Collector System Characteristics	538
10.5 Thermal Analysis of Solar Power Plants	539
10.6 Solar Ponds	545
10.6.1 Practical Design Considerations	547
10.6.2 Transmission Estimation	549
10.6.3 Applications	550
Exercises	551
References	551
11 Designing and Modeling Solar Energy Systems	553
11.1 <i>f</i> -Chart Method and Program	553
11.1.1 Performance and Design of Liquid-Based Solar Heating Systems	557
11.1.2 Performance and Design of Air-Based Solar Heating Systems	568
11.1.3 Performance and Design of Solar Service Water Systems	574
11.1.4 General Remarks	576
11.1.5 <i>f</i> -Chart Program	577
11.2 Utilizability Method	578
11.2.1 Hourly Utilizability	578
11.2.2 Daily Utilizability	580
11.2.3 Design of Active Systems With the Utilizability Method	585
11.3 The $\bar{\Phi}$, <i>f</i> -Chart Method	591
11.3.1 Storage Tank Losses Correction	598
11.3.2 Heat Exchanger Correction	600
11.4 Unutilizability Method	602
11.4.1 Direct Gain Systems	603
11.4.2 Collector Storage Walls	608
11.4.3 Active Collection with Passive Storage Systems	614
11.5 Modeling and Simulation of Solar Energy Systems	618
11.5.1 TRNSYS Simulation Program	619
11.5.2 WATSUN Simulation Program	624
11.5.3 Polysun Simulation Program	626
11.6 Artificial Intelligence in Solar Energy Systems	627
11.6.1 Artificial Neural Networks	629
11.6.2 Genetic Algorithms	644
11.6.3 Fuzzy Logic	648
11.6.4 Hybrid Systems	656
11.7 Limitations of Simulations	658
Exercises	658
References	661

12 Solar Economic Analysis	665
12.1 Life Cycle Analysis	666
12.1.1 Life Cycle Costing	667
12.2 Time Value of Money	671
12.3 Description of the Life Cycle Analysis Method	674
12.3.1 Fuel Cost of Non-Solar Energy System Examples	679
12.3.2 Hot Water System Example	681
12.3.3 Hot Water System Optimization Example	684
12.3.4 Payback Time	686
12.4 The P_1, P_2 Method	688
12.4.1 Optimization Using P_1, P_2 Method	692
12.5 Uncertainties in Economic Analysis	696
Assignment	698
Exercises	699
References	701
Appendix 1: Nomenclature	703
Appendix 2: Definitions	711
Appendix 3: Sun Diagrams	717
Appendix 4: Terrestrial Spectral Irradiance	723
Appendix 5: Thermophysical Properties of Materials	727
Appendix 6: Equations for the Curves of Figures 3.34 to 3.36	733
Appendix 7: Meteorological Data	737
Appendix 8: Present Worth Factors	747
Index	755