

## Contents

**Acknowledgments** *XI*

**Preface** *XIII*

**List of Abbreviations** *XV*

**1 Introduction** *1*

- 1.1 Global Energy Flow *1*
- 1.2 Natural and Anthropogenic Greenhouse Effect *1*
- 1.3 Limit to Atmospheric CO<sub>2</sub> Concentration *5*
- 1.4 Potential Remedies *6*
  - 1.4.1 Energy Conservation *6*
  - 1.4.2 Rational Energy Production and Use *7*
  - 1.4.3 Carbon Capture and Storage (CCS) *7*
  - 1.4.4 Nuclear Energy *8*
  - 1.4.5 Renewable Energies *8*
- References *9*
- Solutions *10*

**2 Energy Conservation with Thermal Insulation** *11*

- 2.1 Opaque Insulations *11*
  - 2.1.1 Conventional Opaque Insulation: Three Contributions to Heat Transfer *14*
  - 2.1.2 Advanced Opaque Insulations: Vacuum Insulation Panels (VIPs) *21*
  - 2.1.3 Switchable Thermal Insulations *24*
  - 2.1.4 Thermal Measurement Methods *25*
- 2.2 Transparent and Translucent Insulations *28*
  - 2.2.1 Radiative Transfer *28*
  - 2.2.2 Convective Heat Transfer *30*
  - 2.2.3 Windows *37*
  - 2.2.4 Switchable Glazings *42*
  - 2.2.5 Translucent Insulations *43*
- References *44*
- Solutions *45*

|          |  |            |
|----------|--|------------|
| <b>3</b> | <b>Thermodynamic Energy Efficiency</b>                         | <b>47</b>  |
| 3.1      | Carnot's Law   | 47         |
| 3.2      | Stirling Engine  | 49         |
| 3.3      | Irreversibilities  | 52         |
| 3.4      | Exergy and Anergy  | 52         |
| 3.5      | Compression Heat Pumps and Air-Conditioning Systems            | 54         |
| 3.6      | Absorption Heat Transformers                                   | 61         |
| 3.7      | Energy and Exergy Efficiency                                   | 62         |
|          | References   | 64         |
|          | Solutions  | 65         |
| <br>     |  |            |
| <b>4</b> | <b>Fossil Fuel-Fired Energy Converters</b>                     | <b>67</b>  |
| 4.1      | Power Plants   | 67         |
| 4.1.1    | The Rankine Steam Process                                      | 68         |
| 4.1.2    | Gas Turbines   | 74         |
| 4.1.3    | Combined-Cycle Power Plants                                    | 76         |
| 4.1.4    | Turbine and Cooling Tower                                      | 78         |
| 4.1.5    | Scrubber: Dust Removal, Desulfurization, and DeNO <sub>x</sub> | 80         |
| 4.1.6    | Carbon Dioxide Capture and Storage (CCS)                       | 83         |
| 4.1.7    | Fossil-Fired Back-Up Power Plants                              | 89         |
| 4.2      | Internal Combustion Engines                                    | 89         |
| 4.2.1    | The Otto, Diesel, and Seiliger Processes                       | 90         |
| 4.2.2    | Fuels for Transportation                                       | 95         |
| 4.3      | Thermoelectric Converters (TECs)                               | 96         |
| 4.4      | Exotic Energy Converters                                       | 101        |
| 4.4.1    | Thermionic Converters  | 101        |
| 4.4.2    | Alkali Metal Thermal Energy Converter (AMTEC)                  | 102        |
| 4.4.3    | Magneto-Hydro-Dynamic (MHD) Converter                          | 103        |
| 4.5      | Absorption Cycles  | 104        |
| 4.6      | Condensation Boilers   | 108        |
|          | References   | 108        |
|          | Solutions  | 110        |
| <br>     |  |            |
| <b>5</b> | <b>Nuclear Fission Energy and Power Plants</b>                 | <b>113</b> |
| 5.1      | Binding Energy and Mass Defect                                 | 113        |
| 5.1.1    | Volume Term  | 114        |
| 5.1.2    | Surface Term   | 116        |
| 5.1.3    | Coulomb Term   | 116        |
| 5.1.4    | Asymmetry Term   | 116        |
| 5.1.5    | Pairing Term   | 117        |
| 5.2      | Fission  | 118        |
| 5.3      | The Multiplication Factor                                      | 124        |
| 5.3.1    | Neutron Emission Factor $k_1$                                  | 124        |
| 5.3.2    | Fast Neutron Enhancement Factor $k_2$                          | 125        |
| 5.3.3    | Resonance Escape Probability $k_3$                             | 127        |

|          |   |            |
|----------|---|------------|
| 5.3.4    | Thermal Utilization Factor $k_4$                | 127        |
| 5.4      | Reactor Control                                 | 127        |
| 5.5      | Neutron Flux                                    | 129        |
| 5.6      | Reactivity Changes during Power Plant Operation | 134        |
| 5.7      | Fuel Conversion and Breeding                    | 135        |
| 5.8      | Nuclear Reactor Types                           | 139        |
| 5.9      | The Fuel Question                               | 145        |
| 5.10     | U235 Enrichment                                 | 146        |
| 5.11     | Spent Fuel                                      | 147        |
| 5.12     | Reactor Safety and Accidents                    | 152        |
|          | References                                      | 156        |
|          | Solutions                                       | 158        |
| <b>6</b> | <b>Hydropower</b>                               | <b>161</b> |
| 6.1      | Water Runoff from Mountains                     | 161        |
| 6.2      | Laminar and Turbulent Flow in Pipes             | 166        |
| 6.3      | Running Water from Oceans                       | 170        |
| 6.4      | Ocean Tides                                     | 172        |
| 6.4.1    | Equilibrium Theory of Tides                     | 172        |
| 6.4.2    | Dynamical Theory of Tides                       | 176        |
| 6.4.3    | Basin Resonances and Seiches                    | 180        |
| 6.4.4    | Tidal Power Plants                              | 183        |
| 6.5      | Ocean Waves                                     | 185        |
| 6.5.1    | Characterization of Ocean Waves                 | 185        |
| 6.5.2    | Energy from Ocean Waves                         | 189        |
| 6.6      | Ocean Thermal Energy Conversion (OTEC)          | 191        |
| 6.7      | Energy from Osmotic Pressure                    | 192        |
|          | References                                      | 195        |
|          | Solutions                                       | 197        |
| <b>7</b> | <b>Wind Power</b>                               | <b>201</b> |
| 7.1      | Wind Velocity                                   | 201        |
| 7.2      | Using the Drag                                  | 203        |
| 7.3      | Using the Lift                                  | 205        |
| 7.4      | Technical Questions                             | 213        |
| 7.5      | Electricity from Wind on Demand                 | 215        |
| 7.6      | Small-Scale Wind Energy Conversion              | 216        |
| 7.7      | Alternative Wind Energy Converters              | 218        |
| 7.8      | Wind Energy Concentration                       | 219        |
|          | References                                      | 220        |
|          | Solutions                                       | 221        |
| <b>8</b> | <b>Photovoltaics (PV)</b>                       | <b>223</b> |
| 8.1      | Diodes and Solar Cells                          | 224        |
| 8.2      | Transport Phenomena, $I_{sc}$ and $U_{oc}$      | 229        |

|           |  |            |
|-----------|--|------------|
| 8.3       | Temperature Effects  | 233        |
| 8.4       | Equivalent Circuit   | 234        |
| 8.5       | Absorption Process and Transitions                           | 235        |
| 8.6       | Advanced Solar Cells   | 237        |
| 8.7       | Si Production and Energy Amortization                        | 238        |
| 8.8       | Other Solar Materials  | 241        |
| 8.9       | From Solar Cells to Modules                                  | 241        |
| 8.10      | Future Prospects for Photovoltaics                           | 242        |
| 8.11      | Wet Solar Cells  | 244        |
|           | References   | 247        |
|           | Solutions  | 248        |
| <b>9</b>  | <b>Solar Space and Hot Water Heating</b>                     | <b>249</b> |
| 9.1       | Solar Radiation  | 249        |
| 9.2       | Flat Plate Collectors  | 252        |
| 9.2.1     | Gains, Losses, and Efficiency                                | 252        |
| 9.2.2     | Temperature Rise along a Solar Flat Plate Collector          | 258        |
| 9.2.3     | Temperature Distribution across a Solar Flat Plate Collector | 262        |
| 9.3       | Evacuated Thermal Collectors                                 | 264        |
| 9.4       | Compound Parabolic Concentrator (CPC)                        | 267        |
| 9.5       | Solar Thermal Heating Systems                                | 269        |
| 9.5.1     | Active Solar Heating Systems                                 | 269        |
| 9.5.2     | Thermosiphon   | 271        |
|           | References   | 276        |
|           | Solutions  | 277        |
| <b>10</b> | <b>Electricity and Fuels from Solar Heat</b>                 | <b>281</b> |
| 10.1      | Concentration of Solar Radiation                             | 281        |
| 10.2      | Solar Troughs  | 286        |
| 10.3      | Fresnel Systems  | 288        |
| 10.4      | Solar Dish and Solar Tower                                   | 289        |
| 10.5      | Solar Thermic Power Plants                                   | 291        |
| 10.6      | Solar Fuels  | 295        |
|           | References   | 297        |
|           | Solutions  | 298        |
| <b>11</b> | <b>Biomass Energy</b>  | <b>301</b> |
| 11.1      | Growth of Biomass  | 301        |
| 11.2      | Direct Use of Solid Biomass                                  | 304        |
| 11.3      | Biogas   | 306        |
| 11.4      | Biofuel  | 309        |
| 11.4.1    | First Production Method                                      | 309        |
| 11.4.2    | Second Production Method                                     | 309        |
| 11.4.3    | Third Production Method                                      | 310        |

- 11.5 Hydrothermal Carbonization of Biomass 311
  - References 311
  - Solutions 312
  
- 12 Geothermal Energy 315**
  - 12.1 The Origin of Geothermal Energy 315
  - 12.2 Geothermal Anomalies 318
  - 12.3 Geothermal Power Plants 319
  - 12.4 Hot Dry Rock 321
    - References 322
    - Solutions 324
  
- 13 Energy Storage 325**
  - 13.1 Mechanical Energy Storage 325
    - 13.1.1 Flywheels 325
    - 13.1.2 Compressed Air Storage 329
  - 13.2 Electric Energy Storage 335
    - 13.2.1 Capacitors 335
    - 13.2.2 Supercaps 336
    - 13.2.3 Superconducting Magnetic Energy Storage (SMES) 337
  - 13.3 Electrochemical Energy Storage 338
    - 13.3.1 General Considerations 338
    - 13.3.2 Accumulators 341
      - 13.3.2.1 Lead-Acid Accumulator 341
      - 13.3.2.2 Ni–Cd Accumulator 342
      - 13.3.2.3 Ni–Metal–Hydride Accumulator 343
      - 13.3.2.4 Li–Ion and Li–Polymer Accumulator 343
      - 13.3.2.5 Na–NiCl<sub>2</sub> Accumulator 344
      - 13.3.2.6 Na–S Accumulator 345
    - 13.3.3 Redox Flow Systems (RFS) 346
  - 13.4 Chemical Energy Storage 348
  - 13.5 Thermal Energy Storage 350
    - 13.5.1 Sensible Heat 350
    - 13.5.2 Solid–Liquid Phase Change Materials (PCMs) 354
    - 13.5.3 Liquid–Vapor and Solid–Vapor Phase Transitions 357
      - References 361
      - Solutions 362
  
- 14 Energy Transport 365**
  - 14.1 Mechanical Energy Transport 365
  - 14.2 Transporting Electricity 367
    - 14.2.1 AC Transmission Lines 367
    - 14.2.2 DC Transmission Lines 375
    - 14.2.3 Superconductivity 376
  - 14.3 Heat Transport 382

|           |  |            |
|-----------|--|------------|
| 14.3.1    | Heat Pipes   | 382        |
| 14.3.2    | District Heating   | 387        |
| 14.3.3    | Daily and Annual Temperature Variations near the Earth's Surface | 389        |
| 14.3.4    | Radiative Transfer   | 393        |
|           | References   | 395        |
|           | Solutions  | 396        |
| <b>15</b> | <b>Fuel Cells</b>  | <b>401</b> |
| 15.1      | General Considerations   | 401        |
| 15.2      | Polymer Electrolyte Membrane Fuel Cell (PEMFC)                   | 404        |
| 15.3      | Solid Oxide Fuel Cell (SOFC)                                     | 407        |
| 15.4      | Other Fuel Cells   | 408        |
|           | References   | 408        |
|           | Solutions  | 409        |
| <b>16</b> | <b>Nuclear Fusion Energy</b>                                     | <b>411</b> |
| 16.1      | Introduction   | 411        |
| 16.2      | Fuel for Fusion  | 412        |
| 16.3      | Break-Even and the Lawson Criterion                              | 413        |
| 16.4      | Magnetic Confinement Fusion (MCF)                                | 416        |
| 16.5      | International Thermonuclear Experimental Reactor (ITER)          | 421        |
| 16.6      | Inertial Confinement Fusion (ICF)                                | 423        |
| 16.7      | The National Ignition Facility (NIF)                             | 426        |
|           | References   | 430        |
|           | Solutions  | 431        |
|           | <b>Index</b>   | <b>435</b> |