Contents

Preface XXV
About the Editors XXVII
List of Contributors XXIX

1 Electrochemical Technologies for Energy Storage and Conversion 1
   Neelu Chouhan and Ru-Shi Liu
   1.1 Introduction 1
   1.2 Global Energy Status: Demands, Challenges, and Future Perspectives 1
   1.3 Driving Forces behind Clean and Sustainable Energy Sources 5
       1.3.1 Local Governmental Policies as a Potential Thrust 6
       1.3.2 Greenhouse Gases Emission and the Associated Climate Changes 7
       1.3.3 Public Awareness about Environmental Protection Rose around the World 7
       1.3.4 Population Growth and Industrialization 8
       1.3.5 Security and Safety Concerns Arising from Scarcity of Resources 9
       1.3.6 Platforms Advocating in Favor of Sustainable and Renewable Resources 9
       1.3.7 Economic Risk Generated from Price Pressure of Natural Resources 10
       1.3.8 Regulatory Risk from Governmental Action and Legislation 10
       1.3.9 Fear of Reputational Risk to Strengthen Corporate Social Responsibility 11
       1.3.10 Operational and Supply Chain Risks from Inefficiencies and Environmental Changes 11
   1.4 Green and Sustainable Energy Sources and Their Conversion: Hydro, Biomass, Wind, Solar, Geothermal, and Biofuel 11
       1.4.1 Solar PV Plants 13
       1.4.2 Wind Power 14
       1.4.3 Geothermal Power 14
       1.4.4 Concentrating Solar Thermal Power (CSP) Plants 14
       1.4.5 Biomass 15
       1.4.6 Biofuel 15
1.5 Electrochemistry: a Technological Overview 15
1.6 Electrochemical Rechargeable Batteries and Supercapacitors (Li Ion
Batteries, Lead-Acid Batteries, NiMH Batteries, Zinc–Air Batteries,
Liquid Redox Batteries) 17
1.6.1 Lead-Acid Batteries 19
1.6.2 NiMH Batteries 20
1.6.3 Li-Ion Batteries 21
1.6.4 Zinc–Air Batteries 22
1.6.5 Liquid Redox Batteries 24
1.7 Light Fuel Generation and Storage: Water Electrolysis,
Chloro-Alkaline Electrolysis, Photoelectrochemical and Photocatalytic
H₂ Generation, and Electroreduction of CO₂ 25
1.7.1 Water Electrolysis 26
1.7.2 Electrochemistry of Water Splitting 27
1.7.3 Chlor-Alkaline Electrolysis 27
1.7.4 Photoelectrochemical and Photocatalytic H₂ Generation 28
1.7.5 Carbon Dioxide Reduction 30
1.8 Fuel Cells: Fundamentals to Systems (Phosphoric Acid Fuel Cells,
PEM Fuel Cells, Direct Methanol Fuel Cells, Molten Carbon Fuel
Cells, and Solid Oxide Fuel Cells) 32
1.8.1 Alkaline Fuel Cells 33
1.8.2 Direct Methanol Fuel Cells 33
1.8.3 Phosphoric Acid Fuel Cells (PAFCs) 34
1.8.4 Proton Exchange Membrane Fuel Cells 35
1.8.5 High-Temperature Molten Carbonate Fuel Cells 36
1.8.6 Solid Oxide Fuel Cells 37
1.9 Summary 38
Acknowledgments 39
References 39
Further Reading 43

2 Electrochemical Engineering Fundamentals 45
Zongwei Chen, Fathy M. Hassan, and Aiping Yu
2.1 Electrical Current/Voltage, Faraday’s Laws, Electric Efficiency, and
Mass Balance 45
2.1.1 Current Efficiency 46
2.1.2 Mass Balance 47
2.2 Electrode Potentials and Electrode–Electrolyte Interfaces 48
2.2.1 Potential Difference 49
2.2.2 Electrode–Electrolyte Interfaces 51
2.3 Electrode Kinetics (Charger Transfer (Butler–Volmer Equation) and
Mass Transfer (Diffusion Laws)) 53
2.3.1 Limitations of Butler–Volmer Equation 55
2.4 Porous Electrode Theory (Kinetic and Diffusion) 55
2.4.1 Theories of Porous Electrode 56
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5.2.1</td>
<td>Core Construction</td>
<td>86</td>
</tr>
<tr>
<td>3.5.2.2</td>
<td>Welding</td>
<td>86</td>
</tr>
<tr>
<td>3.5.2.3</td>
<td>Injecting</td>
<td>87</td>
</tr>
<tr>
<td>3.5.2.4</td>
<td>Sealing</td>
<td>87</td>
</tr>
<tr>
<td>3.5.3</td>
<td>Formation and Aging</td>
<td>87</td>
</tr>
<tr>
<td>3.6</td>
<td>Li Ion Battery Performance, Testing, and Diagnosis</td>
<td>88</td>
</tr>
<tr>
<td>3.6.1</td>
<td>Characteristics of Energy</td>
<td>88</td>
</tr>
<tr>
<td>3.6.1.1</td>
<td>Specific Energy of Cathode Materials</td>
<td>88</td>
</tr>
<tr>
<td>3.6.1.2</td>
<td>Specific Energy of Anode Materials</td>
<td>88</td>
</tr>
<tr>
<td>3.6.2</td>
<td>Working Characteristics</td>
<td>89</td>
</tr>
<tr>
<td>3.6.2.1</td>
<td>Discharge Rate Capability</td>
<td>89</td>
</tr>
<tr>
<td>3.6.2.2</td>
<td>Cycle Life</td>
<td>91</td>
</tr>
<tr>
<td>3.6.2.3</td>
<td>Storage Performance</td>
<td>92</td>
</tr>
<tr>
<td>3.6.2.4</td>
<td>Temperature Effects on Performance</td>
<td>94</td>
</tr>
<tr>
<td>3.6.3</td>
<td>Test and Evaluation of Li Battery Materials</td>
<td>94</td>
</tr>
<tr>
<td>3.7</td>
<td>Degradation Mechanisms and Mitigation Strategies</td>
<td>96</td>
</tr>
<tr>
<td>3.7.1</td>
<td>Degradation Mechanisms</td>
<td>96</td>
</tr>
<tr>
<td>3.7.1.1</td>
<td>The Effect of Anode Materials</td>
<td>96</td>
</tr>
<tr>
<td>3.7.1.2</td>
<td>The Effect of Cathode Materials</td>
<td>97</td>
</tr>
<tr>
<td>3.7.1.3</td>
<td>The Effect of Electrolyte</td>
<td>98</td>
</tr>
<tr>
<td>3.7.1.4</td>
<td>The Effect of Charging and Discharging States</td>
<td>98</td>
</tr>
<tr>
<td>3.7.1.5</td>
<td>The Effect of Current Collector</td>
<td>98</td>
</tr>
<tr>
<td>3.7.2</td>
<td>Mitigation Strategies</td>
<td>99</td>
</tr>
<tr>
<td>3.7.2.1</td>
<td>The Surface Treatment</td>
<td>99</td>
</tr>
<tr>
<td>3.7.2.2</td>
<td>Replacement of LiPF₆ by Salts and the Use of Additives</td>
<td>101</td>
</tr>
<tr>
<td>3.7.2.3</td>
<td>Developing a New System of Electrolyte</td>
<td>101</td>
</tr>
<tr>
<td>3.8</td>
<td>Current and Potential Applications of Secondary Li Ion Batteries</td>
<td>101</td>
</tr>
<tr>
<td>3.8.1</td>
<td>Portable Electronic Devices</td>
<td>101</td>
</tr>
<tr>
<td>3.8.2</td>
<td>Applications of Lithium Ion Batteries in Electric Vehicle (EV) Industry</td>
<td>102</td>
</tr>
<tr>
<td>3.8.3</td>
<td>Application Prospect of Lithium Ion Battery in the Aerospace Industry</td>
<td>103</td>
</tr>
<tr>
<td>3.8.4</td>
<td>As Energy Reserves</td>
<td>106</td>
</tr>
<tr>
<td>3.8.5</td>
<td>Application of Military Equipment</td>
<td>106</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>107</td>
</tr>
</tbody>
</table>

4 **Lead-Acid Battery** 111

Joey Jung

4.1 General Characteristics and Chemical/Electrochemical Processes in a Lead-Acid Battery 111

4.1.1 General Characteristics 111

4.1.2 Major Milestones in the Development of the Lead-Acid Battery 111

4.1.2.1 Chemistry/Electrochemistry 111

4.2 Battery Components (Anode, Cathode, Separator, Endplates (Current Collector), and Sealing) 115
5.6.1 Surface Corrosion of Negative Electrode 222
5.6.2 Decrepitation of Alloy Particles 222
5.6.3 Loss of Water in the Electrolyte 222
5.6.4 Crystalline Formation 223
5.6.5 Cell Reversal 223
5.6.6 High Self-Discharge 223
5.6.7 Shorted Cells 223
5.7 Applications (Portable, Backup Power, and Transportation) 224
5.7.1 Electric Tools 224
5.7.2 Electric Bicycles 225
5.7.3 Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) 226
5.7.3.1 The Toyota Prius 226
5.7.3.2 The Honda Insight 227
5.7.3.3 The Ford Escape Hybrid 228
5.7.4 UPS and Energy Storage Battery 229
5.7.5 Recycling of Ni-MH Batteries 230
5.8 Challenges and Perspectives of Ni-MH Rechargeable Batteries 231
References 232

6 Metal–Air Technology 239
Bruce W. Downing
6.1 Metal–Air Technology 239
6.1.1 Metal–Air Technologies 241
6.2 Introduction to Aluminum–Air Technology 242
6.2.1 Aluminum–Air Cell Structure 243
6.2.2 Electrochemical Processes 244
6.2.2.1 Reaction Products 245
6.2.3 Degradation Mechanisms and Mitigation Strategies 246
6.2.3.1 Anode 246
6.2.3.2 Cathodes 246
6.2.4 Applications 246
6.3 Introduction to Lithium–Air Technology 246
6.3.1 Aqueous Lithium–Air Cell Structure 247
6.3.2 Electrochemical Processes 247
6.3.3 Nonaqueous Lithium–Air Cell Structure 248
6.3.4 Degradation Mechanisms and Mitigation Strategies 248
6.3.4.1 Anodes 248
6.3.4.2 Electrolyte 248
6.3.4.3 Cathodes 249
6.3.5 Manufacturing 249
6.3.6 Applications 249
6.4 Introduction to Zinc–Air Technology 249
6.4.1 Zinc–Air Cell Structure 249
6.4.2 Electrochemical Processes 249
6.4.2.1 Reaction Products 250
Contents

6.4.3 Degradation Mechanisms and Mitigation Strategies 250
6.4.3.1 Anode 250
6.4.3.2 Hydrogen Evolution 251
6.4.3.3 Electrolyte 251
6.4.3.4 Cathode 251
6.4.3.5 Regeneration 251
6.4.4 Applications 252
6.5 Introduction to Magnesium–Air Technology 252
6.5.1 Magnesium 252
6.5.1.1 Sources 253
6.5.1.2 Production 254
6.5.1.3 Uses 254
6.5.2 Associations 255
6.6 Structure of Magnesium–Air Cell 255
6.7 Electrochemical Processes 255
6.8 Components 258
6.8.1 Electrolyte 258
6.8.2 Cathode 258
6.8.3 Anode 261
6.8.4 Reaction Products 263
6.9 Manufacturing 263
6.10 Magnesium–Air Battery Performance 267
6.11 Degradation Mechanisms and Mitigation Strategies 269
6.11.1 Hydrogen Problem 269
6.11.2 Magnesium Utilization Efficiency (MUE) 271
6.11.3 Electrolyte 271
6.11.4 Cathode 273
6.11.5 Precipitate 273
6.12 Applications 273
6.13 Challenges and Perspectives of Magnesium–Air Cells 274

References 275

7 Liquid Redox Rechargeable Batteries 279
Huamin Zhang
7.1 Introduction 279
7.1.1 Summary 279
7.1.2 Background 279
7.1.3 Development 280
7.2 Electrochemical Processes in a Redox Flow Battery 284
7.2.1 Basic Electrochemical Principles 284
7.2.1.1 Apparent Current Density 284
7.2.1.2 Electromotive Force and Open Circuit Potential 284
7.2.1.3 Polarization of Redox Flow Battery 285
7.2.2 Introduction to Electrochemical Processes [7] 286
7.2.2.1 Vanadium Redox Battery (VRB) 286
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2.2.2</td>
<td>Zinc/Bromine Flow Battery</td>
<td>286</td>
</tr>
<tr>
<td>7.2.2.3</td>
<td>Sodium Polysulfide/Bromine Flow Battery</td>
<td>286</td>
</tr>
<tr>
<td>7.2.2.4</td>
<td>Vanadium/Bromine Flow Battery</td>
<td>287</td>
</tr>
<tr>
<td>7.2.2.5</td>
<td>Fe/Cr Flow Battery</td>
<td>288</td>
</tr>
<tr>
<td>7.2.2.6</td>
<td>Zinc/Cerium Flow Battery</td>
<td>288</td>
</tr>
<tr>
<td>7.2.2.7</td>
<td>Soluble Lead-Acid Flow Battery</td>
<td>288</td>
</tr>
<tr>
<td>7.2.2.8</td>
<td>Zinc/Nickel Flow Battery</td>
<td>288</td>
</tr>
<tr>
<td>7.3</td>
<td>Materials and Properties of Redox Flow Battery</td>
<td>288</td>
</tr>
<tr>
<td>7.3.1</td>
<td>Introduction</td>
<td>288</td>
</tr>
<tr>
<td>7.3.2</td>
<td>Electrodes</td>
<td>289</td>
</tr>
<tr>
<td>7.3.3</td>
<td>Bipolar Plates</td>
<td>290</td>
</tr>
<tr>
<td>7.3.4</td>
<td>Ion Exchange Membranes</td>
<td>292</td>
</tr>
<tr>
<td>7.3.5</td>
<td>Electrolyte Solutions</td>
<td>294</td>
</tr>
<tr>
<td>7.4</td>
<td>Redox Flow Battery System</td>
<td>295</td>
</tr>
<tr>
<td>7.4.1</td>
<td>Introduction</td>
<td>295</td>
</tr>
<tr>
<td>7.4.2</td>
<td>Single Cell</td>
<td>295</td>
</tr>
<tr>
<td>7.4.3</td>
<td>Battery Module</td>
<td>296</td>
</tr>
<tr>
<td>7.4.4</td>
<td>The Composition of the Battery System</td>
<td>297</td>
</tr>
<tr>
<td>7.4.5</td>
<td>Battery System Scale-Up</td>
<td>298</td>
</tr>
<tr>
<td>7.5</td>
<td>Performance Evaluation of Redox Flow Battery</td>
<td>298</td>
</tr>
<tr>
<td>7.5.1</td>
<td>Introduction</td>
<td>298</td>
</tr>
<tr>
<td>7.5.2</td>
<td>Performance Indicators</td>
<td>299</td>
</tr>
<tr>
<td>7.5.2.1</td>
<td>Rated Output Power</td>
<td>299</td>
</tr>
<tr>
<td>7.5.2.2</td>
<td>Energy Storage Capacity</td>
<td>299</td>
</tr>
<tr>
<td>7.5.2.3</td>
<td>Efficiencies of Charge–Discharge Cycles</td>
<td>300</td>
</tr>
<tr>
<td>7.5.2.4</td>
<td>Voltage Uniformity of Single Battery</td>
<td>300</td>
</tr>
<tr>
<td>7.5.2.5</td>
<td>Self-Discharge</td>
<td>300</td>
</tr>
<tr>
<td>7.5.2.6</td>
<td>Cycle Life</td>
<td>301</td>
</tr>
<tr>
<td>7.5.3</td>
<td>Evaluation of Battery System Performance</td>
<td>301</td>
</tr>
<tr>
<td>7.5.3.1</td>
<td>Evaluation Method</td>
<td>301</td>
</tr>
<tr>
<td>7.5.3.2</td>
<td>Evaluation Instruments</td>
<td>301</td>
</tr>
<tr>
<td>7.5.4</td>
<td>Factors Influencing Battery Performance</td>
<td>301</td>
</tr>
<tr>
<td>7.5.4.1</td>
<td>Battery Materials</td>
<td>301</td>
</tr>
<tr>
<td>7.5.4.2</td>
<td>Battery Structures</td>
<td>302</td>
</tr>
<tr>
<td>7.5.4.3</td>
<td>Concentration and Composition of Electrolyte</td>
<td>302</td>
</tr>
<tr>
<td>7.5.4.4</td>
<td>Charge–Discharge Conditions</td>
<td>302</td>
</tr>
<tr>
<td>7.5.4.5</td>
<td>Temperature</td>
<td>303</td>
</tr>
<tr>
<td>7.5.4.6</td>
<td>Flow Rate of Electrolyte</td>
<td>303</td>
</tr>
<tr>
<td>7.5.5</td>
<td>Control and Management of the Battery System</td>
<td>303</td>
</tr>
<tr>
<td>7.5.5.1</td>
<td>Operational Parameter Control</td>
<td>303</td>
</tr>
<tr>
<td>7.5.5.2</td>
<td>Safety Management of RFB</td>
<td>303</td>
</tr>
<tr>
<td>7.5.5.3</td>
<td>Power Management</td>
<td>304</td>
</tr>
<tr>
<td>7.5.5.4</td>
<td>Heat Management</td>
<td>304</td>
</tr>
<tr>
<td>7.5.5.5</td>
<td>System Failure Diagnosis</td>
<td>304</td>
</tr>
<tr>
<td>7.6</td>
<td>Degradation Mechanisms and Mitigation Strategies</td>
<td>305</td>
</tr>
</tbody>
</table>
8 Electrochemical Supercapacitors 317

Aiping Yu, Aaron Davies, and Zhongwei Chen

8.1 Introduction to Supercapacitors (Current Technology State and Literature Review) 317

8.1.1 Historical Overview 319

8.1.2 Current Research and Industry Development 319

8.2 Main Types and Structures of Supercapacitors 322

8.2.1 Electric Double-Layer Capacitors (EDLCs) 322

8.2.2 Pseudocapacitor 324

8.2.3 Asymmetric Hybrid Capacitors 324

8.3 Physical/Electrochemical Processes in Supercapacitors 325

8.3.1 Physical/Electrochemical Processes for EDLC 325

8.3.1.1 Analysis of the Diffuse Layer 326

8.3.2 Physical/Electrochemical Processes for the Pseudocapacitor 328

8.3.2.1 Thermodynamic Approach 329

8.3.2.2 Kinetic Approach 330

8.3.2.3 Redox Pseudocapacitance 331

8.3.3 Physical/Electrochemical Processes for AHCs 331

8.3.4 Electrolyte Processes: Conductance and Dissociation 333

8.3.5 Modeling of Electrochemical Behavior 334

8.3.5.1 Effects of Pore Size and Pore-Size Distribution 335

8.4 Supercapacitor Components 338

8.4.1 Electrode 338

8.4.1.1 Carbon as an EDLC Material 339
### Contents

8.4.1.2 Pseudocapacitive Electrode Materials 346  
8.4.2 Electrolytes for Use in Electrochemical Supercapacitors 352  
8.4.2.1 Aqueous Electrolytes 353  
8.4.2.2 Organic Electrolytes 353  
8.4.2.3 Ionic Liquid Electrolytes 353  
8.4.3 Separators 354  
8.4.4 Current Collector and Sealant Components 357  
8.5 Assembly and Manufacturing of Supercapacitors 357  
8.5.1 Electrode Fabrication from Carbon Materials 358  
8.5.2 Concerns with Cell Assembly 359  
8.6 Supercapacitors Stacking and Systems 359  
8.6.1 Bipolar Electrodes 361  
8.7 Supercapacitor Performance, Testing, and Diagnosis 362  
8.7.1 Cyclic Voltammetry 362  
8.7.2 Charge or Discharge Chronopotentiometry 363  
8.7.3 Impedance Measurement 364  
8.7.4 Energy and Power Density 367  
8.7.4.1 Energy Density 367  
8.7.4.2 Power Density 367  
8.7.5 Leakage Current and Self-Discharge Behavior 368  
8.7.6 Durability Test and Additional Procedures 369  
8.8 Supercapacitor Configurations 369  
8.9 Applications 371  
8.9.1 Use in Memory Backup 371  
8.9.2 Improved Battery Systems 372  
8.9.3 Hybrid Electric Vehicles and Transport 372  
8.9.4 Military Applications 373  
8.9.5 Current Marketed Applications 374  
8.9.6 Future Applications 374  
8.10 Challenges and Perspectives of Electrochemical Supercapacitors 375  
References 376  

---

9 Water Electrolysis for Hydrogen Generation 383  
  
Pierre Millet  

9.1 Introduction to Water Electrolysis 383  
9.1.1 Brief Historical Review 383  
9.1.2 Cell Technologies 383  
9.2 Thermodynamics 385  
9.2.1 Gibbs Free Energy of the Water-Splitting Reaction and Cell Voltage 385  
9.2.2 Role of pH on Cell Voltage 387  
9.2.3 Role of Operating Temperature on Cell Voltage 388  
9.2.4 Role of Operating Pressure on Cell Voltage 391  
9.3 Kinetics 393  
9.3.1 Current–Voltage Relationships 393
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.3.2</td>
<td>Cell Impedance</td>
<td>396</td>
</tr>
<tr>
<td>9.3.3</td>
<td>Role of Operating Temperature on the Kinetics</td>
<td>398</td>
</tr>
<tr>
<td>9.3.4</td>
<td>Role of Operating Pressure on the Kinetics</td>
<td>399</td>
</tr>
<tr>
<td>9.3.5</td>
<td>Cell Efficiencies</td>
<td>399</td>
</tr>
<tr>
<td>9.3.5.1</td>
<td>Energy Consumption and Cell Efficiency</td>
<td>399</td>
</tr>
<tr>
<td>9.3.5.2</td>
<td>Faradaic Efficiency</td>
<td>401</td>
</tr>
<tr>
<td>9.4</td>
<td>Alkaline Water Electrolysis</td>
<td>401</td>
</tr>
<tr>
<td>9.4.1</td>
<td>Basic Principles</td>
<td>401</td>
</tr>
<tr>
<td>9.4.2</td>
<td>Cell Components</td>
<td>402</td>
</tr>
<tr>
<td>9.4.3</td>
<td>Cell Assembly and Manufacturing</td>
<td>403</td>
</tr>
<tr>
<td>9.4.4</td>
<td>Cell Stacking and Systems</td>
<td>403</td>
</tr>
<tr>
<td>9.4.5</td>
<td>Cell Performance, Testing, and Diagnosis</td>
<td>404</td>
</tr>
<tr>
<td>9.4.6</td>
<td>Degradation Mechanisms and Mitigation Strategies</td>
<td>406</td>
</tr>
<tr>
<td>9.4.7</td>
<td>Challenges and Perspectives</td>
<td>406</td>
</tr>
<tr>
<td>9.5</td>
<td>PEM Water Electrolysis</td>
<td>406</td>
</tr>
<tr>
<td>9.5.1</td>
<td>Basic Principles (Electrochemical Processes)</td>
<td>406</td>
</tr>
<tr>
<td>9.5.2</td>
<td>Cell Components</td>
<td>407</td>
</tr>
<tr>
<td>9.5.3</td>
<td>Cell Assembly and Manufacturing</td>
<td>407</td>
</tr>
<tr>
<td>9.5.4</td>
<td>Cell Stacking and Systems</td>
<td>408</td>
</tr>
<tr>
<td>9.5.5</td>
<td>Cell Performance, Testing, and Diagnosis</td>
<td>410</td>
</tr>
<tr>
<td>9.5.6</td>
<td>Degradation Mechanisms and Mitigation Strategies</td>
<td>411</td>
</tr>
<tr>
<td>9.5.7</td>
<td>Challenges and Perspectives</td>
<td>412</td>
</tr>
<tr>
<td>9.5.7.1</td>
<td>Replacement of Platinum with Non-Noble Electrocatalysts</td>
<td>412</td>
</tr>
<tr>
<td>9.5.7.2</td>
<td>Replacement of Iridium with Non-Noble Electrocatalysts</td>
<td>414</td>
</tr>
<tr>
<td>9.5.7.3</td>
<td>Development of Polymeric Proton Conductors for Operation at More Elevated Temperatures</td>
<td>414</td>
</tr>
<tr>
<td>9.5.7.4</td>
<td>Development of Proton-Conducting Ceramics for Operation at More Elevated Temperatures</td>
<td>415</td>
</tr>
<tr>
<td>9.6</td>
<td>High Temperature Water Electrolysis</td>
<td>415</td>
</tr>
<tr>
<td>9.6.1</td>
<td>Basic Principles (Electrochemical Processes)</td>
<td>415</td>
</tr>
<tr>
<td>9.6.2</td>
<td>Cell Components</td>
<td>417</td>
</tr>
<tr>
<td>9.6.3</td>
<td>Cell Assembly and Manufacturing</td>
<td>417</td>
</tr>
<tr>
<td>9.6.4</td>
<td>Cell Stacking and Systems</td>
<td>417</td>
</tr>
<tr>
<td>9.6.5</td>
<td>Cell Performance, Testing, and Diagnosis</td>
<td>417</td>
</tr>
<tr>
<td>9.6.6</td>
<td>Degradation Mechanisms and Mitigation Strategies</td>
<td>419</td>
</tr>
<tr>
<td>9.6.7</td>
<td>Challenges and Perspectives</td>
<td>420</td>
</tr>
<tr>
<td>9.7</td>
<td>Conclusion</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>List of Symbols and Abbreviations</td>
<td>421</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>422</td>
</tr>
</tbody>
</table>

10 Hydrogen Compression, Purification, and Storage 425

Pierre Millet

10.1 Introduction 425
10.2 Pressurized Water Electrolysis 425
10.2.1 Principles 425
10.2.1.1 Thermodynamics 426
10.2.1.2 Kinetics 428
10.2.2 Technical Developments 430
10.2.2.1 HP Stack 430
10.2.2.2 Ancillary Equipment 431
10.2.3 Electrochemical Performances 432
10.2.4 Current Limitations and Perspectives 434
10.3 Hydrogen Electrochemical Compression 438
10.3.1 Principles 438
10.3.1.1 Compression Cell 438
10.3.2 Thermodynamics 439
10.3.2.1 Kinetics 440
10.3.3 Technical Developments 441
10.3.4 Electrochemical Performances 443
10.3.5 Current Limitations and Perspectives 446
10.4 Hydrogen Electrochemical Extraction and Purification 447
10.4.1 Principles 447
10.4.1.1 Concentration Cell 447
10.4.1.2 Thermodynamics 448
10.4.1.3 Kinetics 448
10.4.2 Technical Developments 448
10.4.3 Electrochemical Performances 449
10.4.4 Current Limitations and Perspectives 449
10.5 Hydrogen Storage in Hydride-Forming Materials 450
10.5.1 Principles 450
10.5.1.1 Thermodynamics 450
10.5.1.2 Insertion Mechanisms 451
10.5.1.3 Hydriding Kinetics 454
10.5.2 Electrochemical Storage (see Ni-MH batteries Chapter 5) 457
10.5.3 Gas-Phase Storage 457
10.5.3.1 Selection of Storage Materials 457
10.5.3.2 Hydride Reactor Technology 457
10.5.4 Current Limitations and Perspectives 459
10.6 Conclusion and Perspectives 460
List of Symbols and Abbreviations 460
References 461

11 Solar Cell as an Energy Harvesting Device 463
Aung Ko Ko Kyaw, Ming Fei Yang, and Xiao Wei Sun
11.1 Introduction 463
11.2 Solar Radiation and Absorption 463
11.3 Fundamentals of Solar Cells 465
11.3.1 Working Principle of a p-n Junction Solar Cell 465
11.3.2 Equivalent Circuit Diagram (ECD) 466
11.3.3 Current–Voltage Characteristics 468
11.3.4 Quantum Efficiency 470
11.4 Silicon Solar Cell 470
11.4.1 Hydrogenated Amorphous Silicon Thin-Film Solar Cell 471
11.4.1.1 Hydrogenated Amorphous Silicon 472
11.4.1.2 Amorphous Silicon Thin-Film Solar Cell 474
11.4.1.3 Single-Junction Microcrystalline Silicon Thin-Film Solar Cell 475
11.4.2 Polycrystalline Silicon Thin-Film Solar Cell 475
11.4.2.1 Deposition of PolySi Thin Film 476
11.4.2.2 Enhanced Light Absorption and Suppressed Recombination 476
11.4.3 Single-Crystalline Silicon Solar Cell 477
11.4.3.1 Front Texturing 477
11.4.3.2 Diffusion and p-n Junction 478
11.4.3.3 Antireflection Coating (ARC) 479
11.4.3.4 Contact Formation 479
11.5 Other High-Efficiency Solar Cells 479
11.5.1 Copper Indium Diselenide (CIS or CuIn$_x$Ga$_{1-x}$Se) Solar Cell 479
11.5.1.1 Fundamental Characteristics 480
11.5.1.2 Development History 481
11.5.1.3 Typical Structure 481
11.5.1.4 The Active Layer – CIGS Thin Film 483
11.5.1.5 Future Researches 485
11.5.2 High-Efficiency III–V Compound Solar Cell 486
11.5.2.1 Cell Characteristics 486
11.5.2.2 Growth Method of Single-Crystal GaAs 488
11.5.2.3 Growth of III–V Thin Film 488
11.6 Dye-Sensitized Solar Cell 489
11.6.1 History of Dye-Sensitized Solar Cell 490
11.6.2 Basic Principle of Dye-Sensitized Solar Cell 492
11.6.2.1 Charge Transfer and Recombination Kinetics 494
11.6.2.2 Charge Separation at the Semiconductor–Dye Interface 495
11.6.2.3 Electron Percolation through the Nanocrystalline Film 497
11.6.2.4 Photovoltage in Dye-Sensitized Solar Cell 499
11.6.3 Photoanodes Other Than TiO$_2$ Nanoparticle Network 502
11.6.4 Photocathode and p-DSC 509
11.6.5 Improvement of Spectral Response by Tandem Structure and CoSensitization 513
11.6.5.1 Tandem-Structure DSC 514
11.6.5.2 Dye Cocktail or CoSensitization 517
11.6.6 Flexible Dye-Sensitized Solar Cell 521
11.7 Routes to Boost the Efficiency of Solar Cells 523
11.8 Current Ideas for Future Solar Cell 526
11.9 Summary 528
References 529
12 Photoelectrochemical Cells for Hydrogen Generation 541
Neelu Chouhan, ChihKai Chen, Wen-Sheng Chang, Kong-Wei Cheng, and Ru-Shi Liu

12.1 Introduction 541
12.2 Main Types and Structures of Photoelectrochemical Cells 544
12.2.1 Types of Photoelectrochemical Devices 544
12.2.1.1 Photoelectrolysis or Photosynthesis Cell 544
12.2.1.2 Photo-Assisted Electrolysis Cell 545
12.2.1.3 Photovoltaic Electrolysis Cell or Regenerative Cell 547
12.2.2 Photogalvanic Cells 548
12.2.3 Photoelectrochemical Solar Cells 548
12.2.4 Photoelectrochemical Cells Based on Inherently Conducting Polymers (ICPs) 549
12.3 Electrochemical Processes in Photoelectrochemical Cells 550
12.4 Photoelectrochemical Cell Components 553
12.4.1 Photoreactor 554
12.4.2 Photoelectrode 557
12.4.3 Counter Electrodes 560
12.4.4 Endplate/Current Collector 562
12.4.5 Electrolytes 563
12.5 Assembly of Photoelectrochemical Cells 566
12.6 Photoelectrochemical Cell Performance, Testing, and Diagnosis 572
12.6.1 Design and Construction of the PEC Test Assembly 574
12.6.1.1 Photoelectrodes 574
12.6.1.2 Light Calibration 574
12.6.1.3 Temperature Control 575
12.6.1.4 Solution Preparation 575
12.6.1.5 Gas Collection 575
12.6.1.6 Electrochemical Device Operation 575
12.7 Degradation Mechanisms and Mitigation Strategies 581
12.7.1 Staebler–Wronski Effect (SWE) in Si-Based PEC Devices 581
12.7.2 Degradation of Oxide Semiconductors and Corresponding Mitigation 582
12.7.3 Degradation of Chalcogenide Semiconductors and Corresponding Mitigation 584
12.7.4 Copper Chalcopyrites (CIS or CIGS) Electrode Degradation and Mitigation Strategies 586
12.8 Applications (Portable, Stationary, and Transportation) 586
12.8.1 Portable 588
12.8.2 Stationary 588
12.8.3 Transportation 589
12.9 Conclusions 589
Acknowledgments 590
References 590
14.2.2 Anode 680
14.2.3 Cathode 681
14.2.4 Interconnect 682
14.2.5 Sealant 683
14.3 Assembly and Manufacturing 684
14.4 Stacking and Balance of the Plant 685
14.5 Performance, Testing, and Diagnosis 688
14.6 Degradation Mechanisms and Mitigation Strategies 689
14.7 Applications 690
14.7.1 Large-Scale Power Generation 690
14.7.2 Small-Scale Stationary Applications 691
14.7.3 Auxiliary Power Units 692
14.7.4 Alternative Fuels 693
14.8 Challenges and Perspectives 694
Acknowledgments 694
References 694

15 Direct Methanol Fuel Cells 701
Kan-Lin Hsueh, Li-Duan Tsai, Chiou-Chu Lai, and Yu-Min Peng
15.1 Introduction to Direct Methanol Fuel Cells 701
15.2 Main Types and Structures of Direct Methanol Fuel Cells 703
15.3 Electrochemical Processes in Direct Methanol Fuel Cells 705
15.4 Fuel Cell Components 709
15.5 Assembly and Manufacturing of Direct Methanol Fuel Cells 712
15.6 Direct Methanol Fuel Cell Stacking and Systems 714
15.7 Direct Methanol Fuel Cells: Performance, Testing, and Diagnosis 718
15.8 Degradation Mechanisms and Mitigation Strategies 720
15.9 Applications 721
15.10 Challenges and Perspectives of Direct Methanol Fuel Cells 724
References 725

16 Molten Carbonate Fuel Cells 729
Xin-Jian Zhu and Bo Huang
16.1 Introduction to Molten Carbonate Fuel Cells 729
16.2 Current Technologic Status of Molten Carbonate Fuel Cells 730
16.3 Electrochemical Processes in Molten Carbonate Fuel Cells 733
16.4 Components of Molten Carbonate Fuel Cells 734
16.4.1 Anodes and Anode Materials 734
16.4.2 Cathode and Cathode Materials 735
16.4.3 The Electrolyte Matrix 738
16.4.3.1 Electrolyte Matrix Materials 740
16.4.3.2 Electrolyte Matrix Fabrication 740
16.4.3.3 Electrolyte Matrix Performance 741
16.4.4 Fabrication of Electrode–Electrolyte Assembly 743
16.4.5 Materials and Fabrication of the Bipolar Plate 744
16.5 Structure and Performance of MCFCs 744
16.5.1 Structure and Performance of MCFC Single Cell 744
16.5.2 Structure and Performance of MCFC Stack 747
16.6 Schematic of MCFC Power Generation Systems 750
16.7 Fabrication and Operation of MCFCs 752
16.7.1 Testing System of MCFCs 752
16.7.2 Performance of MCFCs 753
16.7.3 Operation of MCFCs 753
16.8 MCFC Power Plant 754
16.8.1 MCFC Power Plant for Natural Gas 754
16.8.2 Hybrid Coal-Gas-Fueled MCFC/GT (Gas Turbine) and ST (Steam Turbine) Systems 756
16.9 Major Factors Affecting the Performance and Lifetime of MCFCs 757
16.9.1 Electrode–Electrolyte Matrix Structure Effect 757
16.9.2 Electrolyte Composition Effect 758
16.9.3 Electrolyte Retention Effect 758
16.9.4 Reactant Crossover Effect 759
16.9.5 Temperature Effect 759
16.9.6 Pressure Effect 760
16.9.7 Effects of Reactant Gas Composition and Utilization 761
16.9.7.1 Oxidant Composition and Utilization 761
16.9.7.2 Fuel Composition and Utilization 762
16.9.8 Effect of Operating Current Density 763
16.9.9 Effect of Gas Impurities 763
16.9.9.1 Sulfides 764
16.9.9.2 Halides 764
16.9.9.3 Nitride 765
16.9.9.4 Particulates 765
16.9.9.5 Other Compounds 765
16.9.10 Consideration of MCFC Design 766
16.10 Challenges and Perspectives of MCFCs 767
16.10.1 High Cost of the MCFC Systems 767
16.10.2 Insufficient Durability of the MCFC Systems 768
16.10.3 Source and Storage of the Fuels for MCFCs 768
16.10.4 Low Volume Power Density of the MCFC Systems 768
16.10.5 Research and Development Directions 768
16.10.5.1 Cathode Material Development for Oxygen Reduction Reaction 768
16.10.5.2 Anode Material Development for Fuel Oxidation Reactions 769
16.10.5.3 Developing New Electrolyte Composition and the Additives 769
16.10.5.4 Improving Corrosion Resistance of MCFCs 769
16.10.5.5 Modeling, Failure Checking, and Automatic Control of MCFC Power Plants
References

Index