

Contents

List of Contributors *xxxii*

Volume 1

Part 1 Industrial Utilization of Hydrogen 1

1 Hydrogen in Refineries 3

James G. Speight

1.1 Introduction 3

1.2 Hydroprocesses 4

1.2.1 Hydrotreating Processes 6

1.2.2 Hydrocracking Processes 8

1.2.3 Slurry Hydrocracking 10

1.2.4 Process Comparison 10

1.3 Refining Heavy Feedstocks 11

1.4 Hydrogen Production 12

1.5 Hydrogen Management 14

References 17

2 Hydrogen in the Chemical Industry 19

Florian Ausfelder and Alexis Bazzanella

2.1 Introduction 19

2.2 Sources of Hydrogen in the Chemical Industry 22

2.2.1 Synthesis Gas-Based Processes 22

2.2.2 Steam Reforming 23

2.2.3 Process Variations 25

2.2.3.1 Partial Oxidation 25

2.2.3.2 Autothermal Reforming 25

2.2.3.3 Pre-reforming 25

2.2.3.4 Water–Gas Shift Conversion 26

2.2.3.5 Gasification 26

2.2.3.6 Other Waste and Coupled Streams 26

2.2.4 Electrolytic Processes 26

2.2.4.1 Alkaline Electrolysis 27

2.2.4.2	PEM Electrolysis	27
2.2.4.3	High-Temperature Electrolysis	27
2.2.5	Hydrogen Production Steam Reforming versus Electrolysis	28
2.2.6	Hydrogen as Coupled Stream in the Electrolytic Production of Chlorine	28
2.2.6.1	Membrane Cell Process	29
2.2.6.2	Mercury Cell Process	30
2.2.6.3	Daphragm Cell Process	31
2.2.6.4	New Developments	31
2.3	Utilization of Hydrogen in the Chemical Industry	32
2.3.1	Ammonia	32
2.3.2	Methanol	34
2.3.3	Other Uses and Applications of Hydrogen	36
2.3.4	Current Developments and Outlook	37
	References	38
3	Chlorine-Alkaline Electrolysis – Technology and Use and Economy	41
	<i>Alessandro Delfrate</i>	
3.1	Introduction	41
3.2	Production Technologies	42
3.2.1	Electrochemistry of Chlorine Production	42
3.2.2	Mercury Electrolyzer Technology	43
3.2.3	Diaphragm Electrolyzers	45
3.2.4	Ion Exchange Membrane Electrolyzers	46
3.2.5	Research	49
3.2.6	Breakthrough Technologies: Chlorine-Alkali Production with Oxygen Depolarized Cathode (ODC)	49
3.3	Use of Chlorine and Sodium Hydroxide	52
3.3.1	Chlorine	52
3.3.2	Sodium Hydroxide	53
3.3.3	Economy of Chlorine and Caustic Soda	53
3.3.4	Energy Savings	55
	References	56

Part 2 Hydrogen as an Energy Carrier 57

Part 2.1 Introduction and National Strategies 57

4	Hydrogen Research, Development, Demonstration, and Market Deployment Activities	59
	<i>Jochen Linssen and Jürgen-Friedrich Hake</i>	
4.1	Introduction	59
4.2	Germany	60

- 4.2.1 Energy Framework and Relevant Policies 60
- 4.2.2 Hydrogen Related Energy Policy Strategies 60
- 4.2.3 Hydrogen Research, Development, Demonstration, and Deployment Activities 61
 - 4.2.3.1 Transportation 61
 - 4.2.3.2 Hydrogen Production 63
 - 4.2.3.3 Stationary and Residential Applications 63
 - 4.2.3.4 Special Markets 64
 - 4.2.3.5 Industry Activity 64
- 4.3 Norway 65
 - 4.3.1 Energy Framework and Relevant Policies 65
 - 4.3.2 Hydrogen Related Energy Policy Strategies 65
 - 4.3.3 Hydrogen Research, Development, Demonstration, and Deployment Activities 66
 - 4.3.3.1 HyNor Project 67
 - 4.3.3.2 ZEG Power 67
 - 4.3.3.3 Transnova Hydrogen Projects 68
- 4.4 European Union 68
 - 4.4.1 Energy Framework and Relevant Policies 68
 - 4.4.2 Hydrogen Related Energy Policy Strategies 69
 - 4.4.3 Hydrogen Research, Development, Demonstration, and Deployment Activities 69
- 4.5 Canada 70
 - 4.5.1 Energy Framework and Relevant Policies 70
 - 4.5.2 Hydrogen Related Energy Policy Strategies 74
 - 4.5.3 Hydrogen Research, Development, Demonstration, and Deployment Activities 74
- 4.6 United States of America 76
 - 4.6.1 Energy Framework and Relevant Policies 76
 - 4.6.2 Hydrogen Related Energy Policy Strategies 76
 - 4.6.3 Hydrogen Research, Development, Demonstration, and Deployment Activities 77
- 4.7 Japan 78
 - 4.7.1 Energy Framework and Relevant Policies 78
 - 4.7.2 Hydrogen Related Energy Policy Strategies 79
 - 4.7.3 Hydrogen Research, Development, Demonstration, and Deployment Activities 80
- 4.8 International Networks 80
 - 4.8.1 Hydrogen Implementing Agreement of the IEA 81
 - 4.8.2 IPHE 81
 - 4.8.3 EHA 81
 - 4.8.4 International Association for Hydrogen Energy 82
- Acknowledgment 82
- References 82

Part 2.2 Thermochemical Hydrogen Production 85

5	Solar Thermal Water Decomposition 87
	<i>Christian Sattler, Nathalie Monnerie, Martin Roeb, and Matthias Lange</i>
5.1	Introduction 87
5.2	Historical Development 88
5.3	Present State of Work 89
5.3.1	Metal/Metal Oxide Thermochemical Cycles 89
5.3.1.1	FeO/Fe ₃ O ₄ 90
5.3.1.2	Ferrites 91
5.3.1.3	Hercynite Cycle 93
5.3.1.4	Manganese Ferrite plus Activated Sodium Carbonate 94
5.3.1.5	Zn/ZnO 94
5.3.1.6	CeO ₂ /Ce ₂ O ₃ 95
5.3.2	Sulfur Cycles 96
5.3.2.1	Hybrid Sulfur Cycle (Westinghouse, Ispra Mark 11) 96
5.3.2.2	Mark 13 V2 98
5.3.2.3	Mark 13A 98
5.3.2.4	Sulfur–Iodine or General Atomics Process (ISPRA Mark 16) 99
5.3.3	Other Cycles 100
5.3.3.1	UT3 (Ca/Fe/Br Cycle) 101
5.3.3.2	Hybrid Copper–Chlorine Cycle 101
5.3.3.3	Uranium–Europium Cycle 102
5.4	Conclusion and Outlook 102
	Nomenclature 103
	References 103
6	Supercritical Water Gasification for Biomass-Based Hydrogen Production 109
	<i>Andrea Kruse</i>
6.1	Introduction 109
6.1.1	Hydrothermal Biomass Conversions 109
6.1.2	Properties of Water 111
6.2	Model Compounds 113
6.2.1	Glucose 113
6.2.2	Cellulose 115
6.2.3	Amino Acids 115
6.2.4	Phenols 115
6.2.5	Others 116
6.3	Biomass 116
6.3.1	Influence of Salts 118
6.3.2	Influence of Proteins 118
6.3.3	Influence of Lignin 118
6.4	Catalysts 119

6.5	Challenges	119
6.5.1	Heating-Up	119
6.5.2	Heat Recovery	120
6.5.3	Yields	120
6.5.4	Salt Deposition	121
6.5.5	Material Choice	121
6.5.6	Catalyst Stability	122
6.6	Scale-Up and Technical Application	122
6.7	New Developments	122
6.8	Conclusion	123
	References	123
7	Plasma-Based Production of Hydrogen from Hydrocarbons	131
	<i>Abdullah Aitani, Shakeel Ahmed, and Fahad Al-Muhaish</i>	
7.1	Introduction	131
7.2	Non-thermal Plasma	132
7.2.1	Gliding-Arc Plasma	132
7.2.2	Microwave Plasma	136
7.2.3	Dielectric Barrier Discharge (DBD) Plasma	139
7.2.4	Corona Discharge	142
7.2.5	Spark and Pulsed Plasmas	142
7.3	Thermal Plasma	144
7.3.1	DC Torch Plasma	144
7.3.2	Three-Phase AC Plasma	145
7.3.3	DC-RF Plasma	145
7.4	Concluding Remarks	146
	Acknowledgment	147
	References	147
8	Solar Thermal Reforming	151
	<i>Christos Agrafiotis, Henrik von Storch, Martin Roeb, and Christian Sattler</i>	
8.1	Introduction	151
8.2	Hydrogen Production via Methane Reforming	152
8.2.1	Thermochemistry and Thermodynamics of Reforming	152
8.2.2	Current Industrial Status	153
8.3	Solar-Aided Methane Reforming	154
8.3.1	Solar Concentration Systems	154
8.3.2	Coupling Reforming with Solar Energy: Solar Receiver–Reactor Concepts	154
8.3.3	Worldwide Research into Solar Thermal Reforming of Methane	157
8.3.3.1	Indirectly Heated Reactors	159
8.3.3.2	Directly Irradiated Reactors	163
8.4	Current Development Status and Future Prospects	167
	References	169

9	Fuel Processing for Utilization in Fuel Cells	173
	<i>Ralf Peters</i>	
9.1	Introduction	173
9.2	Scope of the Work and Methodical Approach	174
9.3	Chemical Engineering Thermodynamics	175
9.3.1	Thermodynamic Property Relations	175
9.3.2	Chemical Equilibrium	178
9.4	Unit Operations	180
9.4.1	Catalytic Reactors	180
9.4.1.1	Hydrogen Generation	181
9.4.1.2	Water–Gas Shift Reaction	184
9.4.1.3	Preferential Oxidation	186
9.4.1.4	Selective CO Methanation	187
9.4.1.5	Catalytic Combustion	188
9.4.2	Separation Devices	189
9.4.2.1	Adsorption Process	189
9.4.2.2	Membrane Process	189
9.4.3	Balance-of-Plant Components	191
9.4.3.1	Pumps and Compressors	191
9.4.3.2	Heat Exchangers and Evaporators	192
9.5	Subsystems of Fuel Processing	192
9.5.1	Optimization of the Subsystem Reforming	193
9.5.1.1	Process Selection and Optimization	193
9.5.1.2	Catalyst Development	200
9.5.1.3	Current Challenges in Fuel Processing	201
9.5.1.4	Technical Outlook	204
9.5.2	Design of Complete Gas Cleaning System	205
9.6	Conclusion	208
	Acknowledgments	209
	References	209
10	Small-Scale Reforming for On-Site Hydrogen Supply	217
	<i>Ingrid Schjølberg, Christian Hulteberg, and Dick Liefink</i>	
10.1	Introduction	217
10.2	Definition	218
10.3	Reforming Technologies	219
10.3.1	Steam Methane Reforming (SMR)	219
10.3.2	Partial Oxidation	220
10.3.3	Hydrogen Purity	221
10.4	Feedstock Options	223
10.4.1	Upgraded Biogas	223
10.4.2	Biomethanol and bioDME	224
10.4.3	Biodiesel	224
10.4.4	Biopropane	225
10.5	Suppliers and Products	225

10.5.1	Cost Trends	225
10.5.1.1	Central Plant Production	225
10.5.1.2	On-Site SR	226
10.5.1.3	Economics: On-Site versus Central Plant Production	227
10.6	Emerging Technologies	228
10.6.1	Material Development	229
10.6.2	Reactor Improvements and Design Aspects	230
10.6.3	Clean-Up Technology	230
10.6.4	Small-Scale CO ₂ Capture	231
10.7	Process Control	232
10.7.1	Condition Monitoring	232
10.7.2	Control Structures	233
10.8	Safety	234
10.9	Conclusion	235
	References	235

11	Industrial Hydrogen Production from Hydrocarbon Fuels and Biomass	237
	<i>Andreas Jess and Peter Wasserscheid</i>	
11.1	Options to Produce Hydrogen from Fuels—An Overview	237
11.2	Hydrogen Production from Solid Fuels (Coal, Biomass)	242
11.2.1	Basic Principles and Reactions of Syngas Production from Solid Fuels	242
11.2.2	Hydrogen Production by Gasification of Solid Fuels	242
11.3	Syngas by Partial Oxidation of Heavy Oils	244
11.4	Syngas by Steam Reforming of Natural Gas	246
11.5	Conclusions	249
	References	251

Part 2.3 H₂ from Electricity 253

12	Electrolysis Systems for Grid Relieving	255
	<i>Filip Smeets and Jan Vaes</i>	
12.1	Introduction	255
12.2	Energy Policies around the Globe Drive Demand for Energy Storage	256
12.3	The Options for Integration of Intermittent Renewable Energy Sources	261
12.4	The Evolution of the Demand for Energy Storage	268
12.5	The Role of Electrolyzers in the Energy Transition	270
12.6	The Overall Business Case and Outlook	274
12.6.1	De-carbonization of all Energy Sectors and the Chemical Industry	275
12.6.2	Combination of Low-Cost Power Generation with Low-Cost Gas Infrastructure	276

12.6.3	Grid-Scale Renewable Energy Storage	276
12.6.4	Optimization of Power System Operation with Intermittent Generators	277
12.7	Conclusions	278
	References	279
13	Status and Prospects of Alkaline Electrolysis	283
	<i>Dongke Zhang and Kai Zeng</i>	
13.1	Introduction	283
13.2	Thermodynamic Consideration	285
13.2.1	Theoretical Cell Voltages	285
13.3	Electrode Kinetics	287
13.3.1	Hydrogen Generation Overpotential	288
13.3.2	Oxygen Generation Overpotential	290
13.3.3	Cell Overpotential	291
13.4	Electrical and Transport Resistances	292
13.4.1	Electrical Resistances	292
13.4.2	Bubble Phenomena	293
13.4.2.1	Bubble Departure Diameter Predictions	293
13.4.2.2	Comparison of Model Predictions with Experimental Observations	296
13.5	Research Trends	297
13.5.1	Electrodes	297
13.5.2	Electro-Catalysts	298
13.5.3	Electrolyte and Additives	302
13.5.4	Bubble Management	302
13.6	Summary	303
	References	304
14	Dynamic Operation of Electrolyzers – Systems Design and Operating Strategies	309
	<i>Geert Tjarks, Jürgen Mergel, and Detlef Stolten</i>	
14.1	Introduction	309
14.2	Process Steps and System Components	310
14.2.1	Alkaline Electrolysis	311
14.2.2	PEM Electrolysis	312
14.2.3	Gas Separation	313
14.2.4	Compression	314
14.2.5	Gas Drying	316
14.2.6	Power Supply	317
14.3	Dynamic Operation of Electrolyzers	317
14.3.1	Operation Range	318
14.3.2	Dynamic System Response	320
14.3.3	Startup and Shutdown	322
14.4	System Design Criterion	322

14.4.1	System Efficiency	322
14.4.2	Investment Cost and Hydrogen Production Costs	325
14.4.3	Lifetime	326
14.4.4	Safety	327
14.5	Conclusion	327
	References	328
15	Stack Technology for PEM Electrolysis	331
	<i>Jürgen Mergel, David L. Fritz, and Marcelo Carmo</i>	
15.1	Introduction to Electrolysis	331
15.1.1	History of PEM Electrolysis	333
15.1.2	Challenges Facing PEM Electrolysis	334
15.2	General Principles of PEM Electrolysis	335
15.2.1	State-of-the-Art	335
15.2.2	Stack Design	338
15.2.2.1	Catalyst Coated Membranes (CCMs)	338
15.2.2.2	Porous Transport Layer (PTL)	340
15.2.2.3	Separator Plates	343
15.2.2.4	Stack Operation	345
15.2.3	Future Trends in PEM Electrolysis	349
15.2.3.1	Cost Reduction	350
15.3	Summary	355
	References	356
16	Reversible Solid Oxide Fuel Cell Technology for Hydrogen/Syngas and Power Production	359
	<i>Nguyen Q. Minh</i>	
16.1	Introduction	359
16.2	Reversible Solid Oxide Fuel Cell Overview	359
16.2.1	Operating Principles	359
16.2.2	Features	361
16.3	Solid Oxide Fuel Cell Technology	366
16.4	Solid Oxide Electrolysis Cell Technology	372
16.5	Reversible Solid Oxide Fuel Cell Technology	379
16.6	Summary	383
	References	383
Part 2.4 H₂ from Biomass 391		
17	Assessment of Selected Concepts for Hydrogen Production Based on Biomass	393
	<i>Franziska Müller-Langer, Konstantin Zech, Stefan Rönsch, Katja Oehmichen, Julia Michaelis, Simon Funke, and Elias Grasemann</i>	
17.1	Introduction	393
17.2	Characteristics of Selected Hydrogen Concepts	394

17.2.1	Concepts under Discussion	394
17.2.2	Concepts for Further Assessment	398
17.2.2.1	Concept A – Wood Chip Gasification	398
17.2.2.2	Concept B – Biogas Reforming	398
17.2.2.3	Concept for Hydrogen Distribution of Produced Hydrogen	399
17.3	Concept Assessment of Technical Aspects	401
17.3.1	Methodical Approach	401
17.3.2	Overall Efficiencies	401
17.4	Concept Assessment of Environmental Aspects	402
17.4.1	Methodical Approach	403
17.4.2	GHG Emissions	403
17.4.3	Cumulated Non-renewable Energy Demand	405
17.5	Concept Assessment of Economic Aspects	406
17.5.1	Methodical Approach	406
17.5.2	Total Capital Investments of Hydrogen Production	407
17.5.3	Hydrogen Production Costs	408
17.5.4	Hydrogen Distribution Costs	410
17.6	Summary	411
	Acknowledgment	411
	References	412
18	Production Process via Fermentation	417
	<i>Balachandar G., Shantonu Roy, and Debabrata Das</i>	
18.1	Introduction	417
18.1.1	Current Energy Scenario	417
18.1.2	Importance and Applications of Hydrogen as a Fuel	419
18.1.3	Conventional Hydrogen Production	419
18.1.4	Biological Hydrogen Production	419
18.1.4.1	Biochemistry behind Thermophilic Biohydrogen Production via Dark Fermentation	420
18.1.4.2	Microbial Characteristics of Thermophilic Hydrogen Producing Bacteria	421
18.2	Hydrogen Production from Biomass as Feedstock	422
18.2.1	Agricultural Residues	423
18.2.2	Municipal Solid Waste and Sewage	424
18.2.3	Industrial Residues	424
18.2.3.1	Distillery Industry Waste	425
18.2.3.2	Food Industry Waste	425
18.3	Reactor Configurations and Scale-Up Challenges	427
18.3.1	Reactor Configurations	427
18.3.2	Current Status of Technologies Available on Scale Up	429
18.4	Economics and Barriers	430
18.5	Future Prospects	431
18.6	Conclusion	431
	Acknowledgment	432
	References	432

Part 2.5 Hydrogen from Solar Radiation and Algae 439

- 19 Photoelectrochemical Water Decomposition 441**
Sebastian Fiechter
- 19.1 Introduction 441
19.2 Principles of Photoelectrochemical Water Splitting 442
19.2.1 Photoelectrochemical Cells with a Single Photoelectrode 443
19.2.2 Photoelectrochemical Cells with Two Photoelectrodes 446
19.2.3 Electrocatalysts and Overvoltage 448
19.3 Design of Water Splitting Devices 448
19.4 Nano- and Microstructured Photoelectrodes 455
19.5 Economic Aspects 457
19.6 Concluding Remarks 457
References 458
- 20 Current Insights to Enhance Hydrogen Production by Photosynthetic Organisms 461**
Roshan Sharma Poudyal, Indira Tiwari, Mohammad Mahdi Najafpour, Dmitry A. Los, Robert Carpentier, Jian-Ren Shen, and Suleyman I. Allakhverdiev
- 20.1 Introduction 461
20.2 Biological H₂ Production 463
20.3 Physiology and Biochemistry of Algae and Cyanobacteria for H₂ Production 465
20.4 Hydrogenase and Nitrogenase for H₂ Production 466
20.4.1 Hydrogenase and H₂ Production 466
20.4.2 Uptake Hydrogenase and Hydrogen Production 467
20.4.3 Nitrogenase and H₂ Production 469
20.5 Photosystems and H₂ Production 469
20.6 Factors Affecting Hydrogen Production 470
20.7 Designing the Photosynthetic H₂ Production 471
20.8 Leaf and Solar H₂ Production 472
20.9 Biofuel and Hydrogen Production by Other Organisms 473
20.10 Available Methods to Enhance Photosynthetic Hydrogen Production 474
20.10.1 Photolytic H₂ Production by Microorganisms 474
20.10.2 Photosynthetic Bacterial H₂ Production 475
20.10.3 Dark Fermentative H₂ Production 475
20.10.4 Genetic Engineering to Enhance Hydrogen Production 476
20.11 Application of Biohydrogen 477
20.12 Conclusion and Future Prospectus 477
Acknowledgments 478
Abbreviations 478
References 478

Part 2.6 Gas Clean-up Technologies 489

- 21 PSA Technology for H₂ Separation 491**
Carlos A. Grande
- 21.1 Introduction 491
21.2 Basics of PSA Technology 492
21.3 Selective Adsorbents; Commercial and New Materials 499
21.4 Improving the PSA Cycle 501
21.5 Summary 503
Acknowledgments 504
References 504
- 22 Hydrogen Separation with Polymeric Membranes 509**
Torsten Brinkmann and Sergey Shishatskiy
- 22.1 History 509
22.2 Basics of Membrane Gas Separation 510
22.3 Hydrogen Separation and Fractionation by Gas Permeation 516
22.3.1 Hydrogen/Nitrogen Separation 517
22.3.2 Hydrogen/Carbon Monoxide Separation 517
22.3.3 Hydrogen/Hydrocarbon Separation 518
22.3.4 Hydrogen Separation and Fractionation Applications in Renewable Hydrogen Production 519
22.4 Membrane Materials and Modules 519
22.4.1 Membrane Classification 519
22.4.1.1 Morphological Classification 520
22.4.1.2 Geometrical Classification 523
22.4.2 Membrane Defect Curing 524
22.4.3 Membrane Module Classification 525
22.4.3.1 Hollow Fiber Modules 525
22.4.3.2 Flat Sheet Modules 526
22.4.4 Membrane Material Classification 528
22.4.4.1 Membranes Based on Rubbery Polymers 528
22.4.4.2 Glassy Polymer Based Membranes 530
22.5 Process Examples 531
22.5.1 Hydrogen Separation from Purge Streams in Ammonia Production 531
22.5.2 Hydrogen Separation from Hydrocracker Flash Gas 532
22.5.3 Carbon Dioxide Removal from Biomass Gasification Product Gas 534
22.6 Conclusions 535
Nomenclature 536
References 537

23	Gas Clean-up for Fuel Cell Systems – Requirements & Technologies	543
	<i>Matthias Gaderer, Stephan Herrmann, and Sebastian Fendt</i>	
23.1	Introduction	543
23.2	Background	543
23.3	Fuel and Pollutants	545
23.3.1	Main Gas Components	545
23.3.1.1	Hydrogen	546
23.3.1.2	Carbon Monoxide	546
23.3.1.3	Methane	546
23.3.1.4	Carbon Dioxide	547
23.3.1.5	Nitrogen	547
23.3.1.6	Steam	547
23.3.2	Trace Gas Components	547
23.3.2.1	Tars	547
23.3.2.2	Particulate Matter (Particles)	549
23.3.2.3	Alkali Compounds	549
23.3.2.4	Sulfur Compounds	549
23.3.2.5	Nitrogen Compounds	550
23.3.2.6	Halogen Compounds	550
23.3.2.7	Siloxanes	550
23.3.2.8	Other Potential Contaminants	550
23.4	Pollutant Level Requirements	550
23.5	Technologies to Remove Pollutants	551
23.5.1	Cold Gas Clean-Up	552
23.5.2	Hot Gas Clean-Up	552
23.5.3	Particulate Matter	552
23.5.4	Alkali Components	555
23.5.5	Tars and Higher Hydrocarbons	555
23.5.5.1	Thermal Cracking	556
23.5.5.2	Catalytic Reduction	557
23.5.6	Sulfur Components	558
	References	559

Volume 2

Part 3	Hydrogen for Storage of Renewable Energy	563
24	Physics of Hydrogen	565
	<i>Carsten Korte, Tabea Mandt, and Timm Bergholz</i>	
24.1	Introduction	565
24.2	Molecular Hydrogen	565
24.2.1	The H ₂ Molecule	565
24.2.1.1	Covalent Bonding and Molecular Orbitals	565
24.2.1.2	Natural Isotopes	566
24.2.1.3	Nuclear Spin-States, Ortho- and Para-H ₂	566

24.2.2	Thermodynamic Properties	569
24.2.2.1	Pressure–Temperature Phase Diagram	569
24.2.2.2	Pressure–Volume Phase Diagram	571
24.2.2.3	Joule–Thomson Effect	572
24.2.3	Reaction Kinetics	574
24.2.3.1	Reaction with O ₂ – Thermodynamics	574
24.2.3.2	Reaction with O ₂ – Microscopic Mechanisms	574
24.2.3.3	Reaction with O ₂ – Explosion Limits	577
24.2.4	Transport Kinetics	578
24.2.4.1	Thermal Conductivity	578
24.2.4.2	Diffusion in Gasses	579
24.2.4.3	Permeation and Diffusion in Polymers	580
24.2.4.4	Permeation and Diffusion in Metals	583
24.3	Hydrides	588
24.3.1	Classification and Properties of Hydrides	588
24.3.1.1	Ionic Hydrides	588
24.3.1.2	Covalent Hydrides	590
24.3.1.3	Complex Hydrides (Hydrido Complexes)	591
24.3.1.4	Interstitial (Metallic) Hydrides	592
24.3.2	Formation of Hydrides	593
24.3.2.1	Ionic and Covalent Hydrides	593
24.3.2.2	Interstitial (Metallic) Hydrides	594
24.3.3	Clathrates	597
	References	598
25	Thermodynamics of Pressurized Gas Storage	601
	<i>Vanessa Tietze and Detlef Stolten</i>	
25.1	Introduction	601
25.2	Calculation of Thermodynamic State Variables	602
25.2.1	Ideal Gases	602
25.2.2	Real Gases	603
25.3	Comparison of Thermodynamic Properties	606
25.3.1	Compressibility Factor	606
25.3.2	Joule–Thomson Coefficient	607
25.3.3	Isentropic Exponent	609
25.4	Thermodynamic Analysis of Compression and Expansion Processes	610
25.4.1	Isothermal and Isentropic Compression	611
25.4.2	Isenthalpic and Isentropic Expansion	615
25.5	Thermodynamic Modeling of the Storage Process	617
25.5.1	Governing Equations	617
25.5.2	Heat Transfer Equations	619
25.6	Application Examples	620
25.6.1	Refueling of a Vehicle Storage Tank	620
25.6.2	Salt Cavern	622
25.7	Conclusion	624
	References	625

26	Geologic Storage of Hydrogen – Fundamentals, Processing, and Projects	629
	<i>Axel Liebscher, Jürgen Wackerl, and Martin Streibel</i>	
26.1	Introduction	629
26.2	Fundamental Aspects of Geological Hydrogen Storage	631
26.2.1	Physicochemical Properties of Hydrogen and Hydrogen Mixtures	631
26.2.2	Interaction between Hydrogen and Microbial Inventories	634
26.2.3	General Types of Geological Storage Option	635
26.2.4	Hydrogen Storage in Porous Rocks	636
26.2.5	Hydrogen Storage in Caverns	640
26.3	Process Engineering	642
26.3.1	Gas Transport: Pipelines and Tubing	642
26.3.2	Compressors	643
26.3.3	Metering	644
26.3.4	Controlling and Safety Components	644
26.3.5	Geologic Storages: Survey	645
26.3.6	Geologic Storages: Construction	646
26.3.7	Geologic Storages: Initial Testing	647
26.3.8	Geologic Storages: Operation	648
26.4	Experiences from Storage Projects	649
26.4.1	Hydrogen Storage Projects	650
26.4.2	Pure Hydrogen Storage Projects	650
26.4.2.1	Clemens Dome, Texas, USA	650
26.4.2.2	Moss Bluff, Texas, USA	650
26.4.2.3	Teesside Project, Yorkshire, UK	651
26.4.3	Town Gas Storages	651
26.4.3.1	Town Gas Storage at Ketzin, Germany	652
26.4.3.2	Town Gas Storage at Lobodice, Czech Republic	652
26.4.3.3	Town Gas Storage at Beynes, Ile de France, France	654
26.5	Concluding Remarks	654
	References	655
27	Bulk Storage Vessels for Compressed and Liquid Hydrogen	659
	<i>Vanessa Tietze, Sebastian Luhr, and Detlef Stolten</i>	
27.1	Introduction	659
27.2	Stationary Application Areas and Requirements	660
27.3	Storage Parameters	661
27.4	Compressed Hydrogen Storage	662
27.4.1	Hydrogen Compression	662
27.4.2	Hydrogen Pressure Vessels	663
27.4.2.1	Conventional Small-Scale Bulk Storage	663
27.4.2.2	Current and Potential Small- to Medium-Scale Bulk Storage	665
27.4.2.3	New Ideas for Medium-Scale Bulk Storage	669
27.5	Cryogenic Liquid Hydrogen Storage	670
27.5.1	Hydrogen Liquefaction	670

27.5.2	Liquid Hydrogen Storage Tanks	671
27.6	Cost Estimates and Economic Targets	675
27.7	Technical Assessment	678
27.8	Conclusion	683
	References	684
28	Hydrogen Storage in Vehicles	691
	<i>Jens Franzen, Steffen Maus, and Peter Potzel</i>	
28.1	Introduction: Requirements for Hydrogen Storage in Vehicles	691
28.2	Advantages of Pressurized Storage over Other Storage Methods	693
28.3	Design of a Tank System	695
28.3.1	Flow Diagram and Description of the Components	695
28.3.2	Container	697
28.4	Specific Requirements for Compressed Gas Systems for Vehicles	699
28.4.1	Legal and Normative Requirements	699
28.4.2	Refueling	700
28.5	Special Forms of Compressed Gas Storage	704
28.5.1	Parallel Hydride and Compressed Gas Storage	704
28.5.2	Metal Hydride-Filled Pressure Containers	705
28.5.3	Conformable Containers	705
28.6	Conclusion	707
	References	707
29	Cryo-compressed Hydrogen Storage	711
	<i>Tobias Brunner and Oliver Kircher</i>	
29.1	Motivation for Cryo-compressed Hydrogen Vehicle Storage	711
29.2	Thermodynamic Opportunities	714
29.3	Refueling and Infrastructure Perspectives	717
29.4	Design and Operating Principles	719
29.4.1	System Design	720
29.4.2	Operating Principles	722
29.5	Validation Challenges of Cryo-compressed Hydrogen Vehicle Storage	725
29.5.1	Validation Procedure	726
29.5.2	Validation Challenges and Opportunities	729
29.5.3	Hydrogen Safety Validation	730
29.6	Summary	731
	References	731
30	Hydrogen Liquefaction	733
	<i>Alexander Alekseev</i>	
30.1	Introduction	733
30.2	History of Hydrogen Liquefaction	734
30.3	Hydrogen Properties at Low Temperature	735
30.3.1	Thermodynamic Properties	735
30.3.2	Ortho and Para Modifications of Hydrogen	735

30.3.2.1	Underlying Physics	735
30.3.2.2	Ortho-to-Para Conversion and Liquefaction of Hydrogen	737
30.3.2.3	Available Data	738
30.3.2.4	Some Useful Thermodynamics	738
30.4	Principles of Hydrogen Liquefaction	739
30.4.1	Power Requirements	739
30.4.2	General Principle	740
30.4.3	Simple Joule–Thomson Process with Nitrogen Precooling	742
30.4.3.1	Basic Process	742
30.4.3.2	Integration of Ortho-to-Para Conversion	744
30.4.4	Evolution of the Hydrogen Liquefaction Processes	745
30.4.5	Process Design of the Precooling Part	745
30.4.6	Precooling by Nitrogen Brayton Cycle	746
30.4.6.1	Process Description	746
30.4.6.2	Evaluation	748
30.4.7	Mixed Gas Refrigeration for Precooling Purposes	748
30.4.8	Final Cooling	749
30.5	Key Hardware Components	751
30.5.1	Compression	752
30.5.1.1	Impact of the Isentropic Exponent	752
30.5.1.2	Low Density	753
30.5.1.3	Screw Compressor	753
30.5.1.4	Reciprocating (Piston) Compressors	755
30.5.2	Expansion Turbine (or Expander or Turbine)	755
30.5.2.1	Oil Bearing	756
30.5.2.2	Gas Bearing	757
30.5.3	Heat Exchangers	758
30.6	Outlook	760
	References	761
31	Hydrogen Storage by Reversible Metal Hydride Formation	763
	<i>Ping Chen, Etsuo Akiba, Shin-ichi Orimo, Andreas Zuettel, and Louis Schlapbach</i>	
31.1	Introduction	763
31.2	Summary of Energy Relevant Properties of Hydrogen and its Isotopes	764
31.3	Hydrogen Interaction with Metals, Alloys and Other Inorganic Solids	764
31.4	Hydrogen Storage in Intermetallic Compounds	767
31.4.1	AB ₅ Type Compounds	771
31.4.2	AB ₂ Type Hydrogen Absorbing Alloys	771
31.4.3	AB Type Alloy TiFe	772
31.4.4	Intermetallic Hydrides	773
31.5	Hydrogen Storage in Complex Hydrides	773
31.5.1	Alanates (tetrahydroaluminate)	774

31.5.2	Amides	775
31.5.3	Borohydrides (Tetrahydroborate)	779
31.6	Physisorption and High Open-Porosity Structures for Molecular Hydrogen Storage	781
31.7	Other Energy Relevant Applications of Hydrogen Interacting Materials	784
31.8	Conclusions and Outlook	785
	References	786
32	Implementing Hydrogen Storage Based on Metal Hydrides	791
	<i>R.K. Ahluwalia, J.-K. Peng, and T.Q. Hua</i>	
32.1	Introduction	791
32.2	Material Requirements	792
32.2.1	Operating Temperatures	792
32.2.2	Material Thermodynamics	794
32.2.3	Containment Tank	794
32.2.4	Buffer Hydrogen	796
32.2.5	Desorption Kinetics	797
32.2.6	Sorption Kinetics	798
32.2.7	Material Compaction and Heat Transfer	799
32.3	Reverse Engineering: A Case Study	800
32.3.1	MH Refueling: Temperature Profile and Conversion	802
32.3.2	System Analysis Model	803
32.3.3	Reference Targets	804
32.3.4	Sensitivity Study	805
32.4	Summary and Conclusions	807
	Acknowledgments	808
	References	808
33	Transport and Storage of Hydrogen via Liquid Organic Hydrogen Carrier (LOHC) Systems	811
	<i>Daniel Teichmann, Wolfgang Arlt, Eberhard Schlücker, and Peter Wasserscheid</i>	
33.1	Hydrogen Storage and Transport for Managing Unsteady Renewable Energy Production	811
33.2	Liquid Organic Hydrogen Carrier (LOHC) Systems	814
33.3	Development of LOHC-Based Energy Storage Systems	819
33.4	Applications of LOHC-Based Energy Storage Systems	822
33.4.1	LOHC Systems for the Storage of Renewable Energy Equivalents, in Particular for Decentralized Storage in Heat–Storage Coupling	823
33.4.2	Energy Transport over Long Distances with LOHC	824
33.4.2.1	Import of Solar Energy from Northern Africa	825
33.4.2.2	Import of Renewable Energy from Iceland	826
33.4.3	Mobile Applications	827
33.5	Conclusions	828
	References	829

Part 4 Traded Hydrogen 831

34	Economics of Hydrogen for Transportation 833
	<i>Akiteru Maruta</i>
34.1	Introduction 833
34.2	Hydrogen Transportation System 833
34.2.1	FCEVs 833
34.2.2	Hydrogen Infrastructure 835
34.3	Economics of Hydrogen for Transportation 836
34.3.1	Hydrogen Cost 836
34.3.1.1	Two Approaches for Hydrogen Cost Calculation 836
34.3.1.2	Bottom-Up Approach for Hydrogen Cost 836
34.3.1.3	Top-Down Approach for Hydrogen Cost 839
34.3.1.4	Total Cost of Ownership (TCO) Approach 841
34.3.2	Economics of Social Cost and Benefits 841
34.3.2.1	Social Costs 842
34.3.2.2	Social Benefits 843
34.4	Conclusion 845
	References 846
35	Challenges and Opportunities of Hydrogen Delivery via Pipeline, Tube-Trailer, LIQUID Tanker and Methanation-Natural Gas Grid 849
	<i>Krishna Reddi, Marianne Mintz, Amgad Elgowainy, and Erika Sutherland</i>
35.1	Introduction 849
35.2	Variation in Demand for Hydrogen 850
35.3	Refueling Station Components and Layout 852
35.3.1	Gaseous Hydrogen Refueling Station 852
35.3.2	Cryo-Compressed and Gaseous Refueling Station with Liquid Delivery 854
35.3.3	Refueling Station Challenges 854
35.4	Distributed Production of Hydrogen 856
35.5	Central or Semi-central Production of Hydrogen 857
35.5.1	Gaseous Hydrogen Delivery 857
35.5.1.1	Pipeline Delivery Pathway 857
35.5.1.2	Tube-Trailer Delivery Pathway 860
35.5.1.3	Challenges 863
35.5.2	Liquid Hydrogen Delivery Pathway 864
35.5.2.1	Components Layout 864
35.5.2.2	Cost Estimates 864
35.5.2.3	Challenges 865
35.6	Power-to-Gas Mass Energy Solution (Methanation) 866
35.6.1	Hydrogen Methanation Process 866
35.6.2	Current Applications 867
35.6.3	Challenges and Opportunities 869
35.7	Outlook and Summary 870
	Note 871
	References 872

36	Pipelines for Hydrogen Distribution	875
	<i>Sabine Sievers and Dennis Krieg</i>	
36.1	Introduction	875
36.2	Overview	875
36.2.1	Pipelines in Comparison to Other Transportation Possibilities	875
36.2.2	An Overview of Existing Hydrogen Pipelines	876
36.2.3	Some Material Concerns	877
36.3	Brief Summary of Pipeline Construction	879
36.3.1	Planning and Approval	879
36.3.2	Assessment of Preferred Pipeline Routes and Alternative Routes	880
36.3.3	Project Execution, Construction and Commissioning	883
36.4	Operation of an H ₂ Pipeline	886
36.4.1	The Control Center	886
36.4.2	Operations	887
36.5	Decommissioning/Dismantling/Reclassification	888
36.6	Conclusion	888
	References	889
37	Refueling Station Layout	891
	<i>Patrick Schnell</i>	
37.1	Introduction	891
37.2	Basic Requirements for a Hydrogen Refueling Station	892
37.2.1	Car Refueling	892
37.2.2	Bus Refueling	894
37.3	Technical Concepts for Hydrogen Filling Stations	895
37.3.1	Hydrogen Production	895
37.3.1.1	Hydrogen Production from Biomass	896
37.3.1.2	Electrolysis	897
37.3.1.3	Steam Reforming	900
37.3.1.4	Byproduct Hydrogen	900
37.3.1.5	Biological Hydrogen Production	900
37.3.2	Hydrogen Delivery	900
37.3.2.1	CGH ₂ Delivery	901
37.3.2.2	LH ₂ Delivery	901
37.3.2.3	Pipeline Delivery	901
37.3.3	Major Components of Hydrogen Refueling Stations	902
37.3.3.1	Production	902
37.3.3.2	Hydrogen Storage	902
37.3.3.3	Compressors	903
37.3.3.4	Pre-cooling	904
37.3.3.5	Dispenser	905
37.3.3.6	Controls	905
37.3.4	Integration of Hydrogen Refueling Stations	906
37.3.5	Facility Size/Space Requirements	907
37.4	Challenges	907

37.4.1	Standardization	907
37.4.2	Costs	909
37.4.3	Reliability	910
37.4.4	Approval Processes	910
37.4.5	Gauged H ₂ -Metering	911
37.4.6	Refueling According to Technical Guidelines	911
37.4.7	Hydrogen Quality	912
37.5	Conclusion	913
	References	914

Part 5 Handling of Hydrogen 917

38	Regulations and Codes and Standards for the Approval of Hydrogen Refueling Stations	919
	<i>Reinhold Wurster</i>	
38.1	Introduction	919
38.1.1	Explanation of the term “Regulations, Codes and Standards (RCS)”	919
38.1.1.1	Regulations	919
38.1.1.2	Codes of Practice	920
38.1.1.3	Standards	921
38.1.1.4	Referencing of standards	922
38.1.1.5	Why Globally Harmonized Standards are Needed	923
38.1.2	General Requirements for the Approval of Hydrogen Refueling Stations (HRSs)	923
38.2	European Union and Germany	924
38.2.1	Europe	924
38.2.2	Germany	928
	References	930
39	Safe Handling of Hydrogen	933
	<i>William Hoagland</i>	
39.1	Introduction	933
39.2	Hydrogen Safety and the Elements of Risk	934
39.2.1	Assessing Risk	935
39.2.2	Current Shortcomings of QRA for Hydrogen Safety	935
39.3	The Unique, Safety-Related Properties of Hydrogen	937
39.4	General Considerations for the Safe Handling of Hydrogen	938
39.4.1	Gaseous Hydrogen	939
39.4.2	Liquid Hydrogen	939
39.4.3	Handling Emergencies	940
39.5	Regulations, Codes, and Standards	940
39.6	International Collaborations to Prioritize Hydrogen Safety Research	942

39.6.1	Survey of Hydrogen Risk Assessment Methods, 2008	942
39.6.2	Knowledge Gaps White Paper, 2008	942
39.6.3	Comparative Risk Assessment Studies of Hydrogen and Hydrocarbon Fueling Stations, 2008	943
39.7	Current Directions in Hydrogen Safety Research [6]	943
39.7.1	Research on the Physical Behavior of Leaked or Leaking Hydrogen	943
39.7.2	Hydrogen Storage Systems Safety Research	944
39.7.3	Research that Supports Early Market Applications	945
39.7.4	Research on Risk Mitigation Measures	945
39.7.5	Simplified Tools to Assess and Mitigate Risk	947
39.8	Summary	947
	References	948
	Bibliography	948

Part 6 Existing and Emerging Systems 949

40	Hydrogen in Space Applications	951
	<i>Jérôme Lacapere</i>	
40.1	Liquid Hydrogen for Access to Space	951
40.1.1	Liquid Storage	951
40.1.2	Constraints Due to Liquid Hydrogen Use	952
40.1.3	Insulation	953
40.2	To Go Beyond GTO	954
40.2.1	Coasting Phase	954
40.2.2	Re-ignition Preparation Phase	955
40.3	Relevant Tests in Low Gravity Environment	958
40.4	In-Space Propulsion	960
40.5	Conclusion	961
	References	963
41	Transportation/Propulsion/Demonstration/Buses: The Design of the Fuel Cell Powertrain for Urban Transportation Applications (Daimler)	965
	<i>Wolfram Fleck</i>	
41.1	Introduction	965
41.2	Operational Environment	966
41.3	Requirements	967
41.3.1	Propulsion Power to Drive	967
41.3.2	Auxiliary Power Demand	970
41.3.3	Heating and Air Condition Power Demand	971
41.4	Design Solutions	973
41.4.1	NEBUS	973
41.4.1.1	Design Solution	973
41.4.2	CUTE and HyFleet: CUTE Program	975
41.4.3	Citaro FuelCELL-Hybrid	978

41.5	Test and Field Experience	982
41.5.1	NeBus	982
41.5.2	CTA, CMBC	982
41.5.3	CUTE and HyFleet:CUTE Program	984
41.5.4	NaBuz DEMO and CHIC	984
41.6	Future Outlook	986
41.6.1	Transit Bus Applications	986
41.6.2	Truck Applications	987
41.6.3	Life Time and Product Costs	989
41.6.4	Summary	989
	References	990
42	Hydrogen and Fuel Cells in Submarines	991
	<i>Stefan Krummrich and Albert Hammerschmidt</i>	
42.1	Background	991
42.1.1	When it All Began . . .	992
42.2	The HDW Fuel Cell AIP System	992
42.3	PEM Fuel Cells for Submarines	993
42.3.1	Introduction	993
42.3.2	The Oxygen/Hydrogen Cell Design	994
42.3.2.1	Constructive Features/Cell Design of Siemens PEM Fuel Cell	994
42.3.2.2	Results from Fuel Cell Operation	995
42.3.3	Constructive Feature of Fuel Cell Module for Submarine Use	995
42.3.3.1	Preconditions	995
42.3.3.2	Cascaded Fuel Cell Stacks [2]	996
42.3.3.3	Pressure Cushion for Uniform Current Distribution [4]	998
42.3.3.4	Fuel Cell Module	999
42.3.3.5	Results from Fuel Cell Module Operation	1000
42.3.3.6	Safety Features of Submarine Fuel Cell Modules	1001
42.4	Hydrogen Storage	1002
42.5	The Usage of Pure Oxygen	1004
42.6	System Technology – Differences Between HDW Class 212A and Class 214 Submarines	1005
42.7	Safety Concept	1006
42.8	Developments for the Future – Methanol Reformer for Submarines	1006
42.8.1	System Configuration	1006
42.8.2	Challenges of the Methanol Reformer Development	1007
42.8.3	Hydrogen Purification Membranes	1008
42.8.4	High Pressure Catalytic Oxidation	1008
42.8.5	Integration on Board a Submarine	1008
42.9	Conclusion	1009
	References	1010

43	Gas Turbines and Hydrogen	<i>Peter Griebel</i>	1011
43.1	Introduction	<i>1011</i>	
43.2	Combustion Fundamentals of Hydrogen relevant for Gas Turbines	<i>1012</i>	
43.2.1	Ignition Delay	<i>1014</i>	
43.2.2	Flame Speed	<i>1016</i>	
43.2.3	Flame Temperature, Stability, and Emissions	<i>1018</i>	
43.3	State-of-the-art Gas Turbine Technology for Hydrogen	<i>1019</i>	
43.4	Research and Development Status, New Combustion Technologies	<i>1022</i>	
43.4.1	New Combustion Technologies	<i>1024</i>	
43.4.1.1	MILD Combustion or Flameless Oxidation	<i>1024</i>	
43.4.1.2	Lean Direct Injection, Multi-injection, and Micro-mixing	<i>1026</i>	
43.5	Concluding Remarks	<i>1028</i>	
	References	<i>1028</i>	
44	Hydrogen Hybrid Power Plant in Prenzlau, Brandenburg	<i>Ulrich R. Fischer, Hans-Joachim Krautz, Michael Wenske, Daniel Tannert, Perco Krüger, and Christian Ziems</i>	1033
44.1	Introduction	<i>1033</i>	
44.2	Description of the Concept of the Hybrid Power Plant at Prenzlau	<i>1035</i>	
44.2.1	Overview	<i>1035</i>	
44.2.2	Alkaline Electrolyzer	<i>1036</i>	
44.2.3	Safety Engineering	<i>1039</i>	
44.3	Operating Modes of the Hybrid Power Plant	<i>1042</i>	
44.3.1	Hydrogen Production Mode	<i>1042</i>	
44.3.2	Base Load Mode	<i>1043</i>	
44.3.3	Forecast Mode	<i>1044</i>	
44.3.4	EEX Mode	<i>1045</i>	
44.4	Operational Management and Experiences	<i>1045</i>	
44.4.1	Dynamic Load Operation	<i>1045</i>	
44.4.2	Temperature Influence on Stack Voltage	<i>1047</i>	
44.4.3	Influence of Activated Electrodes	<i>1049</i>	
44.4.4	Voltage Efficiency of the Electrolyzer	<i>1050</i>	
44.5	Outlook	<i>1050</i>	
	References	<i>1051</i>	
45	Wind Energy and Hydrogen Integration Projects in Spain	<i>Luis Correas, Jesús Simón, and Milagros Rey</i>	1053
45.1	Introduction	<i>1053</i>	
45.2	The Role of Hydrogen in Wind Electricity Generation	<i>1055</i>	
45.2.1	Mini Grids	<i>1056</i>	
45.2.2	Electricity Storage	<i>1056</i>	

45.2.3	Fuel Production	1058
45.2.4	Comparison of the Three Configurations	1059
45.3	Description of Wind–Hydrogen Projects	1059
45.3.1	RES2H2 Project	1060
45.3.2	Hidráulica Project	1061
45.3.3	ITHER Project	1063
45.3.4	Sotavento Project	1064
45.4	Operation Strategies Tested in the Sotavento Project	1066
45.4.1	Peaking Plant Strategy	1067
45.4.2	Strategy of Deviation Correction	1069
45.4.3	Strategy for Increasing the Capacity Factor of the Wind Farm	1070
45.4.4	Load Leveling Enabling Distributed Generation or Island	1071
45.5	Conclusions	1071
	References	1072
46	Hydrogen Islands – Utilization of Renewable Energy for an Autonomous Power Supply	1075
	<i>Frano Barbir</i>	
46.1	Introduction	1075
46.2	Existing Hydrogen Projects on Islands	1077
46.3	System Design/Configuration	1082
46.4	Key Technologies	1083
46.4.1	Electrolyzer	1083
46.4.2	Hydrogen Storage	1085
46.4.3	Fuel Cell	1086
46.5	System Issues	1087
46.5.1	Capacity Factor	1087
46.5.2	Coupling Efficiency	1087
46.5.3	Intermittent Operation	1088
46.5.4	Water Consumption	1088
46.5.5	Performance Degradation with Time	1088
46.6	Sizing	1088
46.7	Energy Management	1090
46.8	Other Uses/System Configurations	1092
46.8.1	Demand Side Management	1092
46.8.2	Seawater Desalination	1092
46.8.3	Oxygen Use	1093
46.8.4	Fuel for Vehicles	1093
46.9	Conclusions	1093
	References	1094
	Index	1097

