

# Contents

List of Contributors  
Preface

xvii  
xxi

## Part A Introduction

### 1. The Role of Energy Storage in Low-Carbon Energy Systems

*Paul E. Dodds, Seamus D. Garvey*

1. Introduction	3
2. The Need for New Types of Storage	4
2.1. Impact of Demands on Generation Imbalances	5
2.2. Strategies to Cope with Electricity System Imbalances	6
3. Storage Technologies	8
3.1. Gravitational/Mechanical/Thermomechanical	9
3.2. Electrochemical	10
3.3. Thermal	11
3.4. Chemical	11
4. Comparing Storage Systems	12
5. Challenges for Energy Storage	13
5.1. Integrating Energy Storage into Low-Carbon Energy Systems	14
5.2. Innovation to Reduce Technology Costs	17
5.3. Public Acceptance	18
5.4. Finding the Most Appropriate Roles for Energy Storage Technologies	18
5.5. Adapting Energy Markets to Realize the Value of Energy Storage	19
6. Conclusions	19
References	21

## Part B

# Electrical Energy Storage Techniques Gravitational/Mechanical/Thermomechanical

## 2. Pumped Hydroelectric Storage

*Chi-Jen Yang*

1. Introduction	25
2. Pros and Cons	27
3. Historical Development	28
4. Prospects	34
4.1. Revival of Conventional PHES	34
4.2. Alternative and Novel PHES Designs	35
4.3. Retrofits of Existing PHES and Conventional Hydropower Stations	36
References	37

## 3. Novel Hydroelectric Storage Concepts

*Frank Escombe*

1. Introduction	39
1.1. Scope and Purpose	39
1.2. Constraints	39
1.3. How Did We Get Here?	41
1.4. Novel Hydroelectric Storage Categories	41
1.5. Future Applications and Markets	41
2. Piston-in-Cylinder Electrical Energy Storage	42
2.1. Background and Operating Principle	42
2.2. Piston versus PHES?	45
2.3. Piston Storage Economic Performance	50
2.4. Markets and Competition for Piston Storage	54
3. Energy Membrane–Underground Pumped Hydro Storage	57
3.1. The Energy Membrane Concept	57
3.2. Energy Losses due to Soil Deformation	59
3.3. Soil Migration	59
3.4. Membrane and Water Cavity	60
3.5. Efficiency and Economic Performance	61
4. Novel Land-Based and Seabed Pumped Hydro Configurations	61
4.1. Background	61
4.2. Surface Reservoir Systems	61
4.3. Subterranean Reservoir Systems	62
4.4. Seabed Hydroelectric Storage	62
5. Offshore Lagoon and Island Storage Systems	63
5.1. Background	63
5.2. Shallow-Water Lagoon Energy Storage	64
5.3. Deeper Water Energy Island Storage	65
6. Conclusions	66
Acknowledgment	66
References	66

#### 4. **Advanced Rail Energy Storage: Green Energy Storage for Green Energy**

*Francesca Cava, James Kelly, William Peitzke, Matt Brown, Steve Sullivan*

1. Introduction	69
2. Market for Utility-Scale Energy Storage	70
3. How Much Storage is Needed for Renewable Energy?	71
4. Value and Storage Market	72
5. Competitive Storage Technologies	73
6. Advanced Rail Energy Storage	74
6.1. Shuttle Vehicle	75
6.2. Rail	77
6.3. Power System	78
7. ARES Operational Control System	79
8. Advantages of ARES	81
8.1. Large-Scale Load Shifting and Power Quality Services	81
8.2. Siting and Permitting	81
8.3. Cost	81
9. Potential Sites in the Southwestern United States	81
10. ARES Pilot and First Commercial Project	82
10.1. ARES Nevada Project—System Description	83
11. Conclusions	85
Acknowledgment	86
References	86

#### 5. **Compressed Air Energy Storage**

*Seamus D. Garvey, Andrew Pimm*

1. Introduction	87
2. CAES: Modes of Operation and Basic Principles	89
2.1. The Basic Equations Governing CAES	89
2.2. Electrical Energy, Work, and Heat in CAES	93
3. Air Containment for CAES	95
3.1. Isobaric Air Containment	96
3.2. Isochoric Air Containment	98
3.3. Air Containment in Tanks	100
3.4. The Case for Underground or Underwater Storage	101
4. System Configurations and Plant Concepts	102
4.1. Diabatic Concepts	103
4.2. Adiabatic Concepts	105
5. Performance Metrics	108
6. Integrating CAES with Generation or Consumption	109
7. Concluding Remarks	110
References	110

## 6. Compressed Air Energy Storage in Underground Formations

*Sabine Donadei, Gregor-Sönke Schneider*

1. Introduction	113
2. Mode of Operation	114
3. Plant Concept	117
3.1. Diabatic Concept	117
3.2. Single-Stage Adiabatic Concept	118
3.3. Multistage Adiabatic Concept	119
3.4. Performance Metrics	120
4. Underground Storage	120
4.1. Depleted Oil and Gas Fields	122
4.2. Aquifers	122
4.3. Salt Caverns	123
4.4. Rock Caverns	124
4.5. Abandoned Mines	125
4.6. Conclusions	126
4.7. Existing and Proposed Plants	126
5. Conclusions	129
References	130

## 7. Underwater Compressed Air Energy Storage

*Andrew Pimm, Seamus D. Garvey*

1. Introduction	135
2. Storage Vessels for UWCAES	136
2.1. Flexible Vessels	137
2.2. Rigid Vessels	140
3. Anchorage and Installation	142
4. System Configurations	143
5. Locations	146
6. Cost and Efficiency	148
7. State of Development	152
8. Concluding Remarks	153
References	153

## 8. A Novel Pumped Hydro Combined with Compressed Air Energy

*Erren Yao, Huanran Wang, Guang Xi*

1. Introduction	155
2. Storage System	156
3. Characteristics of a PHCA System	157
4. A Novel Constant Pressure PHCA Energy Storage System	158
5. The Influences of Work Density	160

<b>6. Energy and Exergy Analysis</b>	<b>160</b>
6.1. Energy Analysis	161
6.2. Exergy Analysis	162
<b>7. Simulation Analysis</b>	<b>162</b>
<b>References</b>	<b>165</b>

## **9. Liquid Air Energy Storage**

*Yulong Ding, Lige Tong, Peikuan Zhang, Yongliang Li,  
Jonathan Radcliffe, Li Wang*

<b>1. Introduction</b>	<b>167</b>
<b>2. Energy and Exergy Densities of Liquid Air</b>	<b>168</b>
<b>3. Liquid Air as Both a Storage Medium and an Efficient Working Fluid</b>	<b>170</b>
<b>4. Applications of LAES Through Integration</b>	<b>172</b>
4.1. Integration of LAES with Gas Turbine-Based Peaking Plants	172
4.2. Integration of LAES with Concentrated Solar Power Plants	174
4.3. Integration of LAES with Nuclear Power Plants	175
4.4. Integration of LAES with Liquefied Natural Gas Regasification Process	179
<b>5. Technical and Economic Comparison of LAES with Other Energy Storage Technologies</b>	<b>179</b>
5.1. Technical Comparison	179
5.2. Economic Comparison	180
<b>References</b>	<b>181</b>

## **10. Flywheels**

*Donald Bender*

<b>1. Introduction</b>	<b>183</b>
<b>2. Physics</b>	<b>183</b>
<b>3. History</b>	<b>185</b>
<b>4. The Design of Modern Flywheels</b>	<b>186</b>
4.1. Rotor Design	187
4.2. Bearings	188
4.3. Motor/Generator	189
<b>5. Cost and Comparison with Other Technologies</b>	<b>189</b>
<b>6. Applications</b>	<b>191</b>
6.1. Grid-Connected Power Management	191
6.2. Industrial and Commercial Power Management	193
6.3. Pulsed Power	194
6.4. Uninterruptible Power Supplies	196
6.5. Mobile	196
<b>7. Outlook</b>	<b>198</b>
<b>Acknowledgments</b>	<b>199</b>
<b>References</b>	<b>199</b>

## Part C

### Electrochemical

#### 11. Rechargeable Batteries with Special Reference to Lithium-Ion Batteries

*Matthias Vetter, Stephan Lux*

1. Introduction	205
2. Physical Fundamentals of Battery Storage	206
2.1. Lead–Acid Batteries	206
2.2. Lithium-Ion Batteries	207
3. Development of Lithium-ion Battery Storage Systems	207
3.1. Design of Battery Modules and Systems for Stationary Applications	208
3.2. Battery Management Systems	212
4. System Integration	221
4.1. Configuration	221
4.2. Communication Infrastructure	223
5. Conclusions	224
References	224

#### 12. Vanadium Redox Flow Batteries

*Christian Doetsch, Jens Burfeind*

1. Introduction and Historic Development	227
2. The Function of the VRFB	230
3. Electrolytes of VRFB	233
4. VRFB Versus Other Battery Types	234
5. Application of VRFB	235
5.1. Applications	236
5.2. Current Large-Scale Applications	237
6. Recycling, Environment, Safety, and Availability	239
7. Other Flow Batteries	240
7.1. Iron–Chromium Flow Battery	240
7.2. Polysulfide Bromine Flow Battery	241
7.3. All-Organic Redox Flow Battery	242
7.4. Hybrid Flow Batteries	242
References	245

## Part D

### Thermal

#### 13. Phase Change Materials

*John A. Noël, Samer Kahwaji, Louis Desgrosseilliers,  
Dominic Groulx, Mary Anne White*

1. Introduction	249
1.1. Thermal Energy Storage	249

1.2. Properties of Phase Change Materials	251
1.3. Sustainability	253
<b>2. Heat Storage at Subambient Temperatures</b>	254
<b>3. Heat Storage at Ambient Temperature</b>	256
<b>4. Heat Storage at Moderate Temperatures</b>	257
4.1. Moderate-Temperature PCMs	257
4.2. Applications of Moderate-Temperature Phase Change Materials	259
<b>5. Heat Storage at High Temperatures</b>	262
5.1. High-Temperature PCMs	262
5.2. High-Temperature Applications	263
<b>6. Heat Transfer in PCM-Based Thermal Storage System</b>	264
<b>7. Gaps in Knowledge</b>	266
<b>8. Outlook</b>	268
<b>References</b>	268

## **14. Solar Ponds**

*César Valderrama, José Luis Cortina, Aliakbar Akbarzadeh*

<b>1. Introduction</b>	273
<b>2. Types of Solar Ponds</b>	274
2.1. Salinity Gradient Solar Pond	275
2.2. Saturated Solar Ponds	281
2.3. Solar Gel and Membrane Ponds	281
2.4. Shallow Solar Pond	282
<b>3. Investment and Operational Cost</b>	283
<b>4. Applications of Solar Ponds</b>	284
4.1. Industrial Process Heating	284
4.2. Desalination	284
4.3. Electrical Power Production	285
4.4. Salinity Mitigation	286
4.5. Production of Chemicals	287
4.6. Aquaculture and Biotechnology	287
4.7. Buildings and Domestic Heating	287
<b>References</b>	288

## **15. Sensible Thermal Energy Storage: Diurnal and Seasonal**

*Cynthia Ann Cruickshank, Christopher Baldwin*

<b>1. Introduction: Storing Thermal Energy</b>	291
<b>2. Design of the Thermal Storage and Thermal Stratification</b>	292
2.1. Heat Exchangers	293
2.2. Destratification in Storage Tanks	294
<b>3. Modeling of Sensible Heat Storage</b>	294
3.1. Modeling Stratified Thermal Energy Storage	295
<b>4. Second Law Analysis of Thermal Energy Storage</b>	298

5. Solar Thermal Energy Storage Systems	299
6. Cold Thermal Energy Storage	300
7. Seasonal Storage	302
7.1. Applications	303
7.2. Storage Methods	304
8. Concluding Remarks	309
References	309

## Part E Chemical

### 16. Hydrogen From Water Electrolysis

*Greig Chisholm, Leroy Cronin*

1. Introduction	315
2. Hydrogen as an Energy Vector and Basic Principles of Water Electrolysis	317
2.1. Hydrogen as an Energy Vector	317
2.2. History of Water Electrolysis	318
2.3. Electrochemistry and Thermodynamics	319
3. Hydrogen Production Via Water Electrolysis	321
3.1. Water Electrolysis	321
3.2. Alkaline Water Electrolysis	321
3.3. Proton Exchange Membrane Electrolysis	323
3.4. Solid Oxide Water Electrolysis	324
4. Strategies for Storing Energy in Hydrogen	326
4.1. Properties of Hydrogen Related to Storage	326
4.2. Gaseous Hydrogen Storage	327
4.3. Cryogenic Liquid Hydrogen Storage	329
4.4. Cryocompressed Hydrogen Storage	329
4.5. Hydrogen Storage by Physisorption	329
4.6. Hydrogen Storage by Chemisorption	329
4.7. Power-to-Gas	331
5. Technology Demonstrations Utilizing Hydrogen as an Energy Storage Medium	332
5.1. System Engineering	332
5.2. Renewable Energy Storage	333
6. Emerging Technologies and Outlook	335
6.1. Electron-Coupled Proton Buffers and Decoupling of Hydrogen Gas Generation	335
6.2. Flow Battery/Electrolyzer Hybrids	338
References	339

### 17. Thermochemical Energy Storage

*Henner Kerskes*

1. Introduction	345
2. Physical Fundamentals of Thermochemical Energy Storage	346

2.1. Thermochemical Energy Storage (reaction)	346
2.2. Prototype of the Combined Hot Water and Sorption Store	348
<b>3. Storage Materials</b>	351
3.1. Adsorption Materials	352
3.2. Salt Hydrates	354
3.3. Composite Materials	356
<b>4. Thermochemical Storage Concepts</b>	357
4.1. Closed-System Operation Mode	358
4.2. Open-System Operation Mode	360
<b>5. Selected Examples</b>	362
5.1. Closed Adsorption Storage Systems	362
5.2. Open Adsorption Storage Systems	365
<b>References</b>	369

## **18. Power-to-Gas**

*Robert Tichler, Stephan Bauer*

1. Introduction	373
2. Dynamic Electrolyzer as a Core Part of Power-to-Gas Plants	376
3. Methanation Processes Within Power-to-Gas	378
4. Multifunctional Applications of the Power-to-Gas System	380
5. Underground Gas Storage in the Context of Power-to-Gas	385
<b>Acknowledgment</b>	387
<b>References</b>	387

## **19. Traditional Bulk Energy Storage—Coal and Underground Natural Gas and Oil Storage**

*Fritz Crotofino*

1. Introduction	391
2. Coal	393
3. Oil	394
3.1. Salt Caverns	396
3.2. Rock Caverns	398
4. Natural Gas Storage	400
4.1. Depleted Oil and Gas Fields	401
4.2. Aquifer Storage	403
4.3. Salt Caverns	404
5. Conclusions	409
<b>References</b>	409

## **20. Larger Scale Hydrogen Storage**

*Fritz Crotofino*

1. Hydrogen Economy—From the Original Idea to Today's Concept	411
2. Why Use Hydrogen Storage to Compensate for Fluctuating Renewables?	413
2.1. Storage Demand at Various Timescales	413

2.2. Estimate of Future Storage Demand	414
2.3. Which Storage Technologies Support Capacity in the High Gigawatt-Hour Range?	414
3. Hydrogen in the Chemical Industry	417
4. Options for Large-Scale Underground Gas Storage	418
4.1. Overview	418
4.2. Depleted Oil and Gas Fields	421
4.3. Aquifer Storage	422
4.4. Salt Caverns	423
4.5. Comparison of Storage Options	423
5. Underground Hydrogen Storage in Detail	424
5.1. Special Criteria for Storage Operations with a Focus on Fluctuating Injection or Withdrawal	424
5.2. Standard Engineering Practice	425
5.3. Dimensioning and Operational Metrics of Future Hydrogen Storage Caverns	427
5.4. Outlook	427
References	428

## Part F Integration

### 21. Energy Storage Integration

*Philip Taylor, Charalampos Patsios, Stalin Munoz Vaca,  
David Greenwood, Neal Wade*

1. Introduction	433
2. Energy Policy and Markets	434
2.1. Background	435
2.2. Business Models for Using Energy Storage	435
2.3. Review of National Policies, Regulation, and Electricity Market Arrangements Supporting Storage	436
2.4. Regulation, Electricity Markets, and Their Impact on Storage Implementation	438
3. Energy Storage Planning	441
3.1. Heuristic Techniques	442
3.2. Probabilistic Techniques	443
3.3. Planning Storage for Security of Supply	444
4. Energy Storage Operation	447
4.1. Balanced and Unbalanced Power Exchange Strategies	448
4.2. Combining Energy Storage and Demand Response	450
4.3. Coordination of Multiple Energy Storage Units	452
4.4. Summary	454
5. Demonstration Projects	454
5.1. Hemsby Energy Storage	454
5.2. Energy Storage in the Customer-Led Network Revolution	458
5.3. Smarter Network Storage	461

<b>6. Integrated Modeling Approach</b>	<b>464</b>
6.1. Methodology	465
6.2. Results and Discussions	468
<b>References</b>	<b>473</b>

## **22. Off-Grid Energy Storage**

*Catalina Spataru, Pierrick Bouffaron*

<b>1. Introduction: The Challenges of Energy Storage</b>	<b>477</b>
<b>2. Why is Off-Grid Energy Important?</b>	<b>478</b>
<b>3. Battery Technologies and Applications</b>	<b>480</b>
3.1. Battery Technologies	480
3.2. Battery Applications	483
<b>4. Dealing with Renewable Variability</b>	<b>485</b>
<b>5. The Emergence of Minigrids and Microgrids</b>	<b>486</b>
<b>6. Energy Storage in Island Contexts</b>	<b>487</b>
6.1. Island of Bonaire (The Netherlands)	487
6.2. Island of Miyakojima (Japan)	487
6.3. Island of Eigg (Scotland)	488
<b>7. Bring Clean Energy to the Poor</b>	<b>488</b>
<b>8. The Way Forward: Cost–Structure Evolution</b>	<b>489</b>
<b>9. International Examples</b>	<b>491</b>
9.1. Developing a Microgrid with Racks of Lead–Acid Batteries: Akkan (Morocco)	491
9.2. Developing a National Policy for NaS Batteries: The Case of Japan	491
9.3. An Example of New Microgrid Project in the West	492
9.4. Progress and Real Growth in Africa	492
9.5. Off-Grid Projects in Villages	493
9.6. Off-Grid Projects on Islands	493
<b>10. Conclusions</b>	<b>494</b>
<b>References</b>	<b>494</b>

## **Part G**

### **International Issues and the Politics of Introducing Renewable Energy Schemes**

#### **23. Energy Storage Worldwide**

*Trevor Sweetnam, Catalina Spataru*

<b>1. Introduction: The Energy Storage Challenge</b>	<b>501</b>
<b>2. Barriers to Development and Deployment</b>	<b>501</b>
<b>3. Case Studies</b>	<b>502</b>
3.1. The Situation in Japan	502
3.2. The Situation in the United States	503
3.3. The Situation in Germany	505
<b>4. Lessons for the Development of Storage</b>	<b>506</b>
4.1. Overcoming Technological Barriers	506

4.2. Market and Regulatory Developments	506
4.3. Strategic Framework	507
5. Conclusions	507
References	508
<b>24. Storing Energy in China—An Overview</b>	
<i>Haisheng Chen, Yujie Xu, Chang Liu, Fengjuan He, Shan Hu</i>	
1. Introduction	509
2. Imperativeness and Applications	510
3. Technical and Development Status	511
3.1. Pumped Hydroelectric Storage	511
3.2. Compressed Air Energy Storage	514
3.3. Flywheel Energy Storage	515
3.4. Lead–Acid Battery	518
3.5. Sodium–Sulfur Battery	519
3.6. Lithium-Ion Battery	520
3.7. Flow Battery	522
4. Summary and Prospects	524
5. Conclusions and Remarks	525
Acknowledgment	525
References	525
<b>25. The Politics of Investing in Sustainable Energy Systems</b>	
<i>Alan Owen, Leuserina Garniati</i>	
1. Introduction	529
2. Sustainable Energy Systems Policy and Politics	531
3. Implications for Investment in Sustainable Energy Systems	533
4. Technology Selection	534
5. Transition	535
6. Global Implications	535
7. The Circular Economy	536
8. Conclusions	537
References	537
Subject Index	539