

Contents

Part I Electrochemical Storage Systems – An Overview

1	Overview of battery systems	3
Kai-Christian Moeller		
1.1	Introduction	3
1.2	Primary systems	4
1.3	Secondary systems	5
1.4	Outlook	8
Bibliography		9

Part II Lithium-ion Batteries – Materials and Components

2	Lithium-ion battery overview	13
Stephan Leuthner		
2.1	Introduction	13
2.2	Applications	14
2.3	Components, functions, and advantages of lithium-ion batteries	14
2.4	Charging procedures	16
2.5	Definitions (capacity, electric energy, power, and efficiency)	16
2.6	Safety of lithium-ion batteries	16
2.7	Lifetime	17
Bibliography		19
3	Materials and function	21
Kai Vuorilehto		
3.1	Introduction	21
3.2	Traditional electrode materials	21
3.3	Traditional inactive materials	23
3.4	Alternatives for standard electrode materials	24
3.5	Alternatives for standard inactive materials	26
3.6	Outlook	27
Bibliography		27

4 Cathode materials for lithium-ion batteries	29
Christian Graf	
4.1 Introduction	29
4.2 Oxides with a layered structure (layered oxides, LiMO ₂ ; M = Co, Ni, Mn, Al)	30
4.3 Spinel (LiM ₂ O ₄ ; M = Mn, Ni)	33
4.4 Phosphate (LiMPO ₄ ; M = Fe, Mn, Co, Ni)	36
4.5 Comparison of cathode materials	39
Bibliography	40
5 Anode materials for lithium-ion batteries	43
Călin Wurm, Oswin Oettinger, Stephan Wittkaemper, Robert Zauter, and Kai Vuorilehto	
5.1 Anode active materials – introduction	44
5.2 Production and structure of amorphous carbons and graphite	45
5.3 Lithium intercalation in graphite and amorphous carbons	47
5.4 Production and electrochemical characteristics of C/Si or C/Sn components	52
5.5 Lithium titanate as anode material	53
5.6 Anode active materials – outlook	54
5.7 Copper as conductor at the negative electrode	55
Bibliography	57
6 Electrolytes and conducting salts	59
Christoph Hartnig and Michael Schmidt	
6.1 Introduction	59
6.2 Electrolyte components	60
6.3 Functional electrolytes	67
6.4 Gel and polymer electrolytes	71
6.5 Electrolyte formulations – customized and distinct	73
6.6 Outlook	74
Bibliography	74
7 Separators	75
Christoph J. Weber and Michael Roth	
7.1 Introduction	75
7.2 Characteristics of separators	76
7.3 Separator technology	78
7.4 Electric mobility requirement profile of separators	81
7.5 Alternative separator technologies	82
7.6 Outlook	87
Bibliography	88
8 Lithium-ion battery system design	89
Uwe Koehler	
8.1 Introduction	89
8.2 Battery system design	90

8.3	Functional levels of battery systems	92
8.4	System architecture	93
8.5	Electrical control architecture	97
8.6	Electric vehicle geometrical installation and operation	99
	Bibliography	100
9	Lithium-ion cell	101
	Thomas Woehrle	
9.1	Introduction	101
9.2	History of battery systems	102
9.3	Active cell materials for lithium-ion cells	104
9.4	Passive cell materials for lithium-ion cells	105
9.5	Housing and types of packaging	105
9.6	Worldwide market shares of lithium-ion cell manufacturers	106
9.7	Inner structure of lithium-ion cells	108
9.8	Lithium-ion cell production	109
9.9	Requirements on lithium-ion cells	109
9.10	Outlook	110
	Bibliography	111
10	Sealing and elastomer components for lithium battery systems	113
	Peter Kritzer and Olaf Nahrwold	
10.1	Introduction	113
10.2	Cell sealing components	114
10.3	Battery system sealing components	114
	Bibliography	122
11	Sensor and measuring technology	123
	Jan Marien and Harald Staeb	
11.1	Introduction	123
11.2	Galvanically isolated current sensor technology in battery management systems	124
11.3	Outlook	130
	Bibliography	131
12	Relays, contactors, cables, and connectors	133
	Hans-Joachim Faul, Simon Ramer, and Markus Eckel	
12.1	Introduction	134
12.2	Main functions of relays and contactors in the electrical power train	134
12.3	Practical applications	136
12.4	Design examples	140
12.5	Future contactor developments	143
12.6	Lithium-ion battery wiring	144
12.7	Cable requirements	144

12.8	Wiring cables	145
12.9	Future cable developments	148
12.10	Connectors and terminals	148
12.11	Product requirements	149
12.12	High-voltage connectors and screwed-in terminals	151
12.13	Charging sockets	152
12.14	Future connector and terminal developments	152
	Bibliography	153
13	Battery thermal management	155
	Achim Wiebelt and Michael Guenther Zeyen	
13.1	Introduction	155
13.2	Requirements	156
13.3	Cell types and temperature balancing methods	157
13.4	Outlook	163
14	Battery management system	165
	Roland Dorn, Reiner Schwartz, and Bjoern Steurich	
14.1	Introduction	165
14.2	Battery management system tasks	166
14.3	Battery management system components	167
14.4	Cell supervision and charge equalization	169
14.5	Charge equalization	170
14.6	Internal battery communication bus	173
14.7	Battery control unit	174
15	Software	177
	Timo Schuff	
15.1	Introduction	177
15.2	Software development challenges	177
15.3	AUTOSAR – a standardized interface	180
15.4	Quick and cost-efficient model-based development	181
15.5	Requirements engineering	184
15.6	An example of requirements engineering	184
15.7	Outlook	185
16	Next generation technologies	187
	Juergen Janek and Philipp Adelhelm	
16.1	Introduction	187
16.2	The lithium-sulfur battery	190
16.3	The lithium-air battery	198
16.4	Challenges when using metallic lithium in the anode	201
16.5	All-solid state batteries	203
16.6	Outlook	204
	Bibliography	205

Part III Battery Production – Resources and Processes

17 Lithium-ion cell and battery production processes	211
Karl-Heinz Pettinger, Achim Kampker, Claus-Rupert Hohenthanner, Christoph Deutskens, Heiner Heimes, and Ansgar vom Hemdt	
17.1 Introduction	212
17.2 Battery cell production processes and design rules	212
17.3 Advantages and disadvantages of different cell designs	220
17.4 Battery pack assembly	223
17.5 Technological challenges of the production process	224
Bibliography	225
18 Facilities of a lithium-ion battery production plant	227
Rudolf Simon	
18.1 Introduction	227
18.2 Manufacturing process and requirements	227
18.3 Environmental conditions in the production area	228
18.4 Dry room technology	229
18.5 Media supply and energy management	232
18.6 Area planning and building logistics	233
18.7 Outlook and challenges	235
Bibliography	235
19 Production test procedures	237
Karl-Heinz Pettinger	
19.1 Introduction	237
19.2 Test procedures during coating	239
19.3 Test procedures during cell assembly	239
19.4 Electrolyte dosing	243
19.5 Forming	244
19.6 Final inspection after ripening	245
19.7 Reference sample monitoring	245
Bibliography	246

Part IV Interdisciplinary Subjects – From Safety to Recycling

20 Areas of activity on the fringe of lithium-ion battery development, production, and recycling	249
Reiner Korthauer	
21 Occupational health and safety during development and usage of lithium-ion batteries	253
Frank Edler	
21.1 Introduction	253
21.2 Occupational health and safety during the battery life cycle	255

21.3	Company-specific occupational health and safety	260
21.4	Outlook	262
	Bibliography	262
22	Chemical safety	263
	Meike Fleischhammer and Harry Doering	
22.1	Introduction	263
22.2	Electrolyte	264
22.3	Anode	267
22.4	Cathode	267
22.5	Other components	270
	Bibliography	275
23	Electrical safety	277
	Heiko Sattler	
23.1	Introduction	277
23.2	Electrical safety of lithium-ion batteries	278
23.3	Outlook	284
24	Functional safety in vehicles	285
	Michael Vogt	
24.1	Introduction	285
24.2	Functional safety overview	286
24.3	Functional safety management	287
24.4	Safety of electric mobility	290
24.5	Practical application	297
24.6	Outlook	299
	Bibliography	299
25	Functional and safety tests for lithium-ion batteries	301
	Frank Dallinger, Peter Schmid, and Ralf Bindel	
25.1	Introduction	301
25.2	Using EUCAR hazard levels for the test facility	302
25.3	Functions and modules for battery testing	306
25.4	Battery testing system examples	310
25.5	Outlook	313
	Bibliography	313
26	Transportation of lithium batteries and lithium-ion batteries	315
	Ehsan Rahimzei	
26.1	Introduction	315
26.2	Transportation of lithium batteries and lithium cells	318
	Bibliography	323
27	Lithium-ion battery recycling	325
	Frank Treffer	
27.1	Introduction and overview	325
27.2	Lithium-ion battery recycling	326

27.3	Outlook	331
	Bibliography	332
28	Vocational education and training of skilled personnel for battery system manufacturing	335
	Karlheinz Mueller	
28.1	Introduction	335
28.2	Qualified staff – versatile production	336
28.3	Innovative recruitment of new employees and skilled workers in the metal-working and electrical industry	336
28.4	Integrated production technology qualification concept	341
28.5	Process-oriented qualification	344
28.6	On-the-job learning	345
	Bibliography	345
29	Standards for the safety and performance of lithium-ion batteries	347
	Hermann von Schoenau and Kerstin Sann-Ferro	
29.1	Introduction	347
29.2	Standards organizations	348
29.3	Standardization process	349
29.4	Battery standards application	351
29.5	Current standardization projects and proposals for lithium-ion batteries	353
29.6	Standards list	354
29.7	Outlook	354
30	Fields of application for lithium-ion batteries	359
	Klaus Brandt	
30.1	Stationary applications	360
30.2	Technical requirements for stationary systems	362
30.3	Automotive applications	363
30.4	Technical requirements for automotive applications	365
30.5	Further applications	366
	Bibliography	367
Part V Battery Applications – Sectors and Requirements		
31	Requirements for batteries used in electric mobility applications	371
	Peter Lamp	
31.1	Introduction	371
31.2	Requirements for vehicle and drive concepts	372
31.3	Vehicle and battery concept applications	375
31.4	Battery requirements	377
31.5	Outlook	391

32 Requirements for stationary application batteries	393
Bernhard Riegel	
32.1 Introduction	393
32.2 Requirements for industrial energy storage systems	395
32.3 Lithium-ion cells for stationary storage	396
32.4 Cathode materials for stationary lithium energy storage systems	397
32.5 Trends in cathode material technology	397
32.6 Trends in anode material technology	398
32.7 The system lithium iron phosphate (LFP)/lithium titanate (LTO)	398
32.8 The complete energy storage system	399
32.9 Examples of new applications	400
32.10 Stationary industrial storage systems	401
32.11 Existing industrial storage systems	402
32.12 Outlook	403
Bibliography	403
Index	405