

---

# Contents

## Part I Electrochemical Storage Systems – An Overview

<b>1 Overview of battery systems</b> .....	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

<b>2 Lithium-ion battery overview</b> .....	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
<b>3 Materials and function</b> .....	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

<b>4</b>	<b>Cathode materials for lithium-ion batteries</b> . . . . .	29
	Christian Graf	
4.1	Introduction. . . . .	29
4.2	Oxides with a layered structure (layered oxides, $\text{LiMO}_2$ ; M = Co, Ni, Mn, Al) . . . . .	30
4.3	Spinel ( $\text{LiM}_2\text{O}_4$ ; M = Mn, Ni) . . . . .	33
4.4	Phosphate ( $\text{LiMPO}_4$ ; M = Fe, Mn, Co, Ni) . . . . .	36
4.5	Comparison of cathode materials . . . . .	39
	Bibliography . . . . .	40
<b>5</b>	<b>Anode materials for lithium-ion batteries</b> . . . . .	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
<b>6</b>	<b>Electrolytes and conducting salts</b> . . . . .	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
<b>7</b>	<b>Separators</b> . . . . .	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
<b>8</b>	<b>Lithium-ion battery system design</b> . . . . .	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
<b>9</b>	<b>Lithium-ion cell . . . . .</b>	<b>101</b>
	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
<b>10</b>	<b>Sealing and elastomer components for lithium battery systems . . . . .</b>	<b>113</b>
	Peter Kritzer and Olaf Nahrwold	
10.1	Introduction . . . . .	113
10.2	Cell sealing components . . . . .	114
10.3	Battery system sealing components . . . . .	114
	Bibliography . . . . .	122
<b>11</b>	<b>Sensor and measuring technology . . . . .</b>	<b>123</b>
	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
<b>12</b>	<b>Relays, contactors, cables, and connectors . . . . .</b>	<b>133</b>
	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
<b>13</b>	<b>Battery thermal management . . . . .</b>	<b>155</b>
	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
<b>14</b>	<b>Battery management system . . . . .</b>	<b>165</b>
	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
<b>15</b>	<b>Software . . . . .</b>	<b>177</b>
	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
<b>16</b>	<b>Next generation technologies . . . . .</b>	<b>187</b>
	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**

<b>17 Lithium-ion cell and battery production processes</b> . . . . .	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
<b>18 Facilities of a lithium-ion battery production plant.</b> . . . . .	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
<b>19 Production test procedures.</b> . . . . .	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**

<b>20 Areas of activity on the fringe of lithium-ion battery development, production, and recycling.</b> . . . . .	249
Reiner Korthauer	
<b>21 Occupational health and safety during development and usage of lithium-ion batteries.</b> . . . . .	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
<b>22</b>	<b>Chemical safety . . . . .</b>	<b>263</b>
	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
<b>23</b>	<b>Electrical safety . . . . .</b>	<b>277</b>
	Heiko Sattler	
23.1	Introduction. . . . .	277
23.2	Electrical safety of lithium-ion batteries. . . . .	278
23.3	Outlook . . . . .	284
<b>24</b>	<b>Functional safety in vehicles . . . . .</b>	<b>285</b>
	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
<b>25</b>	<b>Functional and safety tests for lithium-ion batteries . . . . .</b>	<b>301</b>
	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
<b>26</b>	<b>Transportation of lithium batteries and lithium-ion batteries . . . . .</b>	<b>315</b>
	Ehsan Rahimzei	
26.1	Introduction. . . . .	315
26.2	Transportation of lithium batteries and lithium cells . . . . .	318
	Bibliography . . . . .	323
<b>27</b>	<b>Lithium-ion battery recycling . . . . .</b>	<b>325</b>
	Frank Treffer	
27.1	Introduction and overview . . . . .	325
27.2	Lithium-ion battery recycling . . . . .	326

---

27.3	Outlook .....	331
	Bibliography .....	332
<b>28</b>	<b>Vocational education and training of skilled personnel for battery system manufacturing</b> .....	<b>335</b>
	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
<b>29</b>	<b>Standards for the safety and performance of lithium-ion batteries</b> .....	<b>347</b>
	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
<b>30</b>	<b>Fields of application for lithium-ion batteries</b> .....	<b>359</b>
	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
<b>Part V Battery Applications – Sectors and Requirements</b>		
<b>31</b>	<b>Requirements for batteries used in electric mobility applications</b> ....	<b>371</b>
	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

---

<b>32 Requirements for stationary application batteries</b> .....	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
<b>Index.....</b>	<b>405</b>