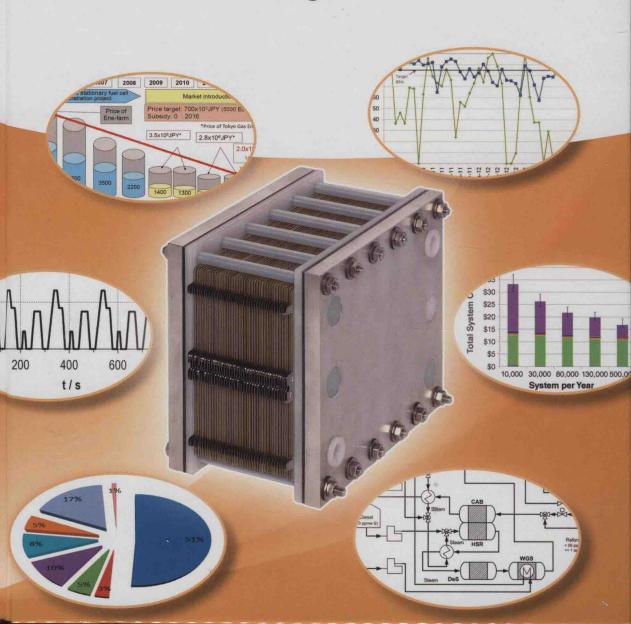
Eartea by Detret Stolten, R. Can Samsun, and Nancy Garland

Fuel Cells

Data, Facts, and Figures



Edited by Detlef Stolten, Remzi C. Samsun and Nancy Garland

Fuel Cells

Data, Facts and Figures



Editors

Prof. Detlef Stolten

Forschungszentrum Jülich GmbH IEF-3: Fuel Cells Leo-Brandt-Str. 52425 Jülich Germany

Dr. Remzi C. Samsun

Forschungszentrum Jülich Wilhelm-Johnen-Str. 52428 Aachen Germany

Dr. Nancy Garland

U.S. Department of Energy EE 32, 5G-023 1000 Independence Ave., S.W. Washington D.C., DC 20585-0121 USA All books published by **Wiley-VCH** are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the

Internet at http://dnb.d-nb.de.

© 2016 Wiley-VCH Verlag GmbH & Co. KGaA, Boschstr. 12, 69469 Weinheim, Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form — by photoprinting, microfilm, or any other means — nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Print ISBN: 978-3-527-33240-3 ePDF ISBN: 978-3-527-69389-4 ePub ISBN: 978-3-527-69391-7 Mobi ISBN: 978-3-527-69390-0 oBook ISBN: 978-3-527-69392-4

Cover Design Formgeber, Mannheim
Typesetting Thomson Digital, Noida, India
Printing and Binding Markono Print Media
Pte Ltd, Singapore

Printed on acid-free paper

Edited by Detlef Stolten Remzi C. Samsun Nancy Garland

Fuel Cells

Related Titles

Gao, F., Blunier, B., Miraoui, A. (eds.)

Proton Exchange Membrane Fuel Cells Modeling

2012

Print ISBN: 978-1-848-21339-5

Bagotsky, V.S.

Fuel Cells

Problems and Solutions, Second Edition

2 Edition

2012

Print ISBN: 978-1-118-08756-5

Jiang, S.P., Yan, Y. (eds.)

Materials for High-Temperature Fuel Cells

2013

Print ISBN: 978-3-527-33041-6

Stolten, D. (ed.)

Hydrogen and Fuel Cells

Fundamentals, Technologies and Applications

2010

Print ISBN: 978-3-527-32711-9

Stolten, D., Emonts, B. (eds.)

Fuel Cell Science and Engineering

Materials, Processes, Systems and Technology

2012

Print ISBN: 978-3-527-33012-6

Preface

Fuel cell technology made substantial progress in the last decade, although this was not always reflected in the public mind due to unrealistically high expectations and partial overselling in the previous decade. The automotive industry for one made strong and steady progress and is edging ever closer to bringing fuel cell-based vehicles to market.

Hyundai and Toyota produced cars using the world's first dedicated manufacturing lines for fuel cell vehicles. In the stationary sector, fuel cells also became more prominent through the deployment of over 100,000 residential systems in Japan, amongst other countries, as well as portable applications (the latter, however, remain focused on special market segments and niches).

At this stage, systems analysis with respect to the widespread implementation of fuel cells becomes highly important, particularly in this case. For given that fuel cells constitute a cleaner and more efficient energy conversion solution, they typically substitute existing technologies. Hence, a comparative analysis of performance, longevity and costs is paramount.

This book compiles cutting edge research to comprehensively convey the current status of the technology. It is intended as a data reference book for people familiar with energy analyses and/or fuel cells and hydrogen.

Contents

Preface XV

Part I	Transportation 1
I-1	Propulsion 1
I-1.1	Benchmarks and Definition of Criteria 1
1	Battery Electric Vehicles 3 Bruno Gnörich and Lutz Eckstein References 11
2	Passenger Car Drive Cycles 12 Thomas Grube
2.1	Introduction 12
2.2	Drive Cycles for Passenger Car Type Approval 13
2.3	Drive Cycles from Research Projects 14
2.4	Drive Cycle Characteristics 14
2.5	Graphic Representation of Selected Drive Cycles 16
2.6	Conclusion 21
	References 21
3	Hydrogen Fuel Quality 22 James M. Ohi
3.1	Introduction 22
3.2	Hydrogen Fuel 23
3.3	Fuel Quality Effects 25
3.4	Fuel Quality for Fuel Cell Vehicles 25
3.5	Single Cell Tests 26
3.6	Field Data 26
3.7	Fuel Quality Verification 27
3.8	Conclusion 28
	References 29

4	Fuel Consumption 30
	Amgad Elgowainy and Erika Sutherland
4.1	Introduction 30
4.2	Hydrogen Production 31
4.3	Hydrogen Packaging 31
4.4	Hydrogen Consumption in FCEVs 32
4.5	Conclusion 34
	References 34
I-1.2	Demonstration 37
I-1.2.1	Passenger Cars 37
5	Global Development Status of Fuel Cell Vehicles 39
	Remzi Can Samsun
5.1	Introduction 39
5.2	Update on Recent Activities of Car Manufacturers 40
5.3	Key Data and Results from Demonstration Programs 41
5.4	Technical Data of Fuel Cell Vehicles 47
5.4.1	Daimler 47
5.4.2	Ford 47
5.4.3	GM/Opel 50
5.4.4	Honda 51
5.4.5	Hyundai/Kia 51
5.4.6	Nissan 52
5.4.7	Toyota 53
5.4.8	Volkswagen 55
5.5	Conclusions 57
	References 58
6	Transportation – China – Passenger Cars 61
	Yingru Zhao
6.1	Introduction 61
6.2	National R&D Strategy (2011–2015) 62
6.3	Government Policy 63
6.4	Published Technical Standards 63
6.5	Demonstrations 65
6.6	Commercialization – Case of SAIC Motor 67
6.7	Conclusions 67
	References 68
7	Results of Country Specific Program – Korea 69
	Tae-Hoon Lim
7.1	Introduction 69
7.2	FCV Demonstration Program 70

7.2.1 7.2.2 7.3	The 2 nd Phase of the FCV Demonstration Project 70 The 2 nd Phase of the FCV Demonstration Project 70 Summary 72
3	GM HydroGen4 – A Fuel Cell Electric Vehicle based on the Chevrolet Equinox 75 Ulrich Eberle and Rittmar von Helmolt
3.1	Introduction 75
3.2 3.3	Technology 76 Conclusions 84
3.3	Acknowledgments 85
	References 86
-1.2.2	Buses 87
9	Results of Country Specific Programs – USA 89 Leslie Eudy
9.1	Introduction 89
9.2	FCEB Descriptions 90
9.3	SunLine Advanced Technology Fuel Cell Electric Bus 90
9.3.1	Fuel Economy 91
9.3.2	Availability 92
9.4	Zero Emission Bay Area Program 92
9.4.1	Fuel Economy 94
9.4.2	Availability 94
9.5	SunLine American Fuel Cell Bus 95
9.5.1	Fuel Economy 96
9.5.2	Availability 97
9.6	Conclusion 98
	References 98
-1.3	PEM fuel cells 99
10	Polymer Electrolytes 101
10.1	John Kopasz and Cortney Mittelsteadt Introduction 101
10.1	Membrane Properties 102
0.2.1	Water uptake and Swelling 102
0.2.1	Protonic Conductivity 103
0.2.3	Permeability 104
0.2.4	Membrane Mechanical Properties and Durability 107
0.3	Conclusions 108
	References 108

VIII	Contents			
	11	MEAs for PEM Fuel Cells 110		
		Andrew J. Steinbach and Mark K. Debe		
	11.1 Introduction 110			
	11.2	MEA Basic Components (PEMs, Catalysts, GDLs and		
		Gaskets) 111		
	11.3	MEA Performance, Durability, and Cost Targets for		
		Transportation 112		
	11.4	MEA Robustness and Sensitivity to External Factors $$ 115		
	11.5	Technology Gaps 117		
	11.6	Conclusion 118		
		References 118		
	12	Gas Diffusion Layer 121		
		Sehkyu Park		
	12.1	Introduction 121		
	12.2	Macroporous Substrate 122		
	12.3	Microporous Layer 123		
	12.4	Characterization of GDL 124		
	12.5	Conclusion 126		
		References 127		
	13	Materials for PEMFC Bipolar Plates 128		
		Heli Wang and John A. Turner		
	13.1	Introduction 128		
	13.2	Composite BP Materials 130		
	13.3	Metallic BP Materials 131		
	13.3.1	Light Alloys 131		
	13.3.2	Stainless Steel Bipolar Plates 132		
	13.3.2.1	Metal-Based Coatings 132		
	13.3.2.2	Carbon/Polymer-Based Coatings 133		
	13.3.3	Remarks 133		
		Acknowledgments 133		
		References 133		

14 Single Cell for Proton Exchange Membrane Fuel Cells (PEMFCs) 135 Hyoung-Juhn Kim 14.1 Introduction 135 14.2 Main Components of a Single Cell for a PEMFC 136 14.3 Assembly of a Single Cell 137 14.4 Measurement of a Single Cell Performance 138 14.5 Conclusions 139

1-1.4	Hydrogen 141
I-1.4.1	On board storage 141
15	Pressurized System 143
	Rajesh Ahluwalia and Thanh Hua
15.1	Introduction 143
15.2	High Pressure Storage System 144
15.3	Cost 147
15.4	Conclusions 148
	References 148
16	Metal Hydrides 149
	Vitalie Stavila and Lennie Klebanoff
16.1	Metal Hydrides as Hydrogen Storage Media 149
16.2	Classes of Metal Hydrides 152
16.2.1	Interstitial Metal Hydrides 152
16.2.2	Magnesium and Magnesium-Based Alloys 153
16.2.3	Complex Metal Hydrides 154
16.2.3.1	Off-Board Reversible Metal Hydrides 157
16.3	How Metal Hydrides Could Be Improved 157
	References 160
17	Cryo-Compressed Hydrogen Storage 162
	Tobias Brunner, Markus Kampitsch, and Oliver Kircher
17.1	Introduction 162
17.2	Thermodynamic Principles 163
17.3	System Design and Operating Principles 167
17.4	Validation and Safety 169
17.5	Summary 172
	References 173
I-1.4.2	On board safety 175
18	On-Board Safety 177
0 = 0	Rajesh Ahluwalia and Thanh Hua
18.1	Introduction 177
18.2	High Pressure Fuel Container System 179
18.3	Hydrogen Refueling Requirements and Safety 180
18.4	Conclusions 182
	References 182

1-2	Auxiliary power units (APU) 183
19	Fuels for APU Applications 185
	Remzi Can Samsun
19.1	Introduction 185
19.2	Diesel Fuel 186
19.2.1	Petroleum-Based Diesel Fuels 186
19.2.2	Non-Petroleum-Based Diesel Fuels 187
19.3	Jet Fuel 189
19.3.1	Petroleum-Based Jet Fuels 189
19.3.2	Non-Petroleum-Based Jet Fuels 190
19.4	Other Fuels 190
19.4.1	Liquefied Natural Gas (LNG) 190
	Methanol 192
19.5	Conclusion 195
	References 195
20	Application Requirements/Targets for Fuel Cell APUs 197
	Jacob S. Spendelow and Dimitrios C. Papageorgopoulos
20.1	Introduction 197
20.2	DOE Technical Targets 198
20.2.2	Target Justification 198
	Electrical Efficiency at Rated Power 199
	Power Density 199
	Specific Power 199
	Factory Cost 200
	Transient Response 200
	Startup Time 200
	Degradation with Cycling 200
	Operating Lifetime 200
	System Availability 201
	References 201
21	Fuel Cells for Marine Applications 202
	Keno Leites
21.1	Introduction 202
21.2	Possible Fuel Cell Systems for Ships 204
21.3	Maritime Fuel Cell Projects 205
21.4	Development Goals for Future Systems 206
21.5	Conclusions 206
	References 207

22	Reforming Technologies for APUs 208 Ralf Peters
22.1	Introduction 208
	Guideline 208
	Chemical Reactions 208
	Aspects of System Design 210
	Catalysts in Fuel Processing 211
22.2.4	Reactor Development of Fuel Processing 213
22.2.5	Further Data Sets of Interest 219
22.2.6	Other Fuels 219
	Appendix 22.A 220
	Abbreviation 220
	List of Symbols 221
	Definitions 221
	References 222
23	PEFC Systems for APU Applications 225
23	Remzi Can Samsun
23.1	Introduction 225
23.2	PEFC Operation with Reformate 226
23.3	Application Concepts 229
23.4	System Design 230
23.5	System Efficiency 232
23.6	System Test 232
23.7	Conclusion 233
23.7	References 233
	Neiterines 200
24	High Temperature Polymer Electrolyte Fuel Cells 235
	Werner Lehnert, Lukas Lüke, and Remzi Can Samsun
24.1	Introduction 235
24.2	Operating Behavior of Cells and Stacks 236
24.3	System Level 240
	References 246
	Enterties to any core of the base of
25	Fuel Cell Systems for APU. SOFC: Cell, Stack, and Systems 248
	Niels Christiansen
	References 255
Part II	Stationary 257
26	Deployment and Capacity Trends for Stationary Fuel Cell Systems
	in the USA 259
	Max Wei, Shuk Han Chan, Ahmad Mayyas, and Tim Lipman
26.1	Fuel-Cell Backup Systems 260
26.2	Fuel-Cell Combined Heat and Power and Electricity 262
	References 269

27	Specific Country Reports: Japan 270 Tomio Omata
27.1	Introduction 270
27.2	Start of the Sales of Residential Fuel Cell Systems 271
27.3	Market Growth of the Ene-Farm 272
27.4	Technical Development of the Ene-Farm 272
27.4.1	SOFC-type Ene-Farm and Improvement of Performance 272
27.4.2	The Ene-Farm as an Emergency Electric Supply System 273
27.4.3	Ene-Farms for Nitrogen Rich City Gas 274
27.5	Sales of the Ene-Farm for Condominiums 274
27.6	Conclusions 274
	References 275
	references 275
28	Backup Power Systems 276
	Shanna Knights
28.1	Introduction 276
28.2	Application and Power Levels 277
28.3	Advantages 277
28.4	Fuel Choice 278
28.5	Product Parameters 279
28.6	Economics 280
28.7	Conclusion 280
	References 280
29	Stationary Fuel Cells – Residential Applications 282
29	Stationary Fuel Cells – Residential Applications 282 lain Staffell
29 29.1	Part Let's
	Iain Staffell
29.1	lain Staffell Introduction 282
29.1 29.2	lain Staffell Introduction 282 Key Characteristics 283
29.1 29.2 29.2.1	Introduction 282 Key Characteristics 283 Residential Energy Sector 283
29.1 29.2 29.2.1 29.2.2	Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283
29.1 29.2 29.2.1 29.2.2 29.3	lain Staffell Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1	Iain Staffell Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1 29.3.2	Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284 Degradation 285
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1 29.3.2 29.3.3	lain Staffell Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284 Degradation 285 Lifetime 286
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1 29.3.2 29.3.3 29.3.4	lain Staffell Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284 Degradation 285 Lifetime 286 Emissions 287
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1 29.3.2 29.3.3 29.3.4 29.4	lain Staffell Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284 Degradation 285 Lifetime 286 Emissions 287 Economic and Market Status 288
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1 29.3.2 29.3.3 29.3.4 29.4 29.4.1	Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284 Degradation 285 Lifetime 286 Emissions 287 Economic and Market Status 288 Capital Costs 288 Sales Volumes 290 Conclusions 290
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1 29.3.2 29.3.3 29.3.4 29.4.1 29.4.1	Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284 Degradation 285 Lifetime 286 Emissions 287 Economic and Market Status 288 Capital Costs 288 Sales Volumes 290
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1 29.3.2 29.3.3 29.3.4 29.4 29.4.1 29.4.2 29.5	Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284 Degradation 285 Lifetime 286 Emissions 287 Economic and Market Status 288 Capital Costs 288 Sales Volumes 290 Conclusions 290 References 290
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1 29.3.2 29.3.3 29.3.4 29.4.1 29.4.1	lain Staffell Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284 Degradation 285 Lifetime 286 Emissions 287 Economic and Market Status 288 Capital Costs 288 Sales Volumes 290 Conclusions 290 References 290 Fuels for Stationary Applications 293
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1 29.3.2 29.3.3 29.3.4 29.4 29.4.1 29.4.2 29.5	lain Staffell Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284 Degradation 285 Lifetime 286 Emissions 287 Economic and Market Status 288 Capital Costs 288 Sales Volumes 290 Conclusions 290 References 290 Fuels for Stationary Applications 293 Stephen J. McPhail
29.1 29.2 29.2.1 29.2.2 29.3 29.3.1 29.3.2 29.3.3 29.3.4 29.4 29.4.1 29.4.2 29.5	lain Staffell Introduction 282 Key Characteristics 283 Residential Energy Sector 283 Residential Fuel Cell Systems 283 Technical Performance 284 Efficiency 284 Degradation 285 Lifetime 286 Emissions 287 Economic and Market Status 288 Capital Costs 288 Sales Volumes 290 Conclusions 290 References 290 Fuels for Stationary Applications 293

30.3 30.4 30.5	Biogas, Landfill Gas, and Biomethane 296 (Bio)ethanol 298 Hydrogen 300 References 302		
31	SOFC: Cell, Stack and System Level 304 Anke Hagen		
31.1	Introduction 304		
31.2	Cell Concepts and Materials 305		
31.3	Cell Designs 307		
31.4	Stack Concepts 310		
31.5	Stationary Systems 310		
31.6	Performance and Durability Parameters 313 References 319		
Part III	Materials handling 321		
32	Fuel Cell Forklift Systems 323 Martin Müller		
32.1	Introduction 323		
32.2	Forklift Classification 324		
32.3	Load Profile of Horizontal Order Pickers 324		
32.4	Energy Supply for Forklifts 326		
32.5	Systems Setup and Hybridization 326		
32.6	Cost Comparison of Different Propulsion Systems for Forklifts 328 References 332		
33	Fuel Cell Forklift Deployment in the USA 334		
	Ahmad Mayyas, Max Wei, Shuk Han Chan, and Tim Lipman		
33.1	Fuel Cell-Powered Material Handling Equipment 334 References 340		
Part IV	Fuel provision 343		
34	Proton Exchange Membrane Water Electrolysis 345 Antonino S. Aricò, Vincenzo Baglio, Nicola Briguglio, Gaetano Maggio, and Stefania Siracusano		
34.1	Introduction 345		
34.2	Bibliographic Analysis of PEM Electrolysis versus Water Electrolysis 346		
34.3	Electrocatalysts Used in PEM Water Electrolysis 347		
34.4	Anode Supports for PEM Water Electrolysis 349		
34.5	Membranes for PEM Electrolysis 349		

XIV	Contents	
	34.6 34.7	Stack and System Costs in PEM Electrolysis 351 PEM Electrolysis Systems in Comparison with Competing Technologies 352
		References 354
	35	Power-to-Gas 357 Gerda Reiter
	35.1	Introduction 357
	35.2	Main Components and Process Steps 358
	35.2.1	Water Electrolysis 358
	35.2.2	CH ₄ Synthesis 360
	35.2.3	CO ₂ Separation 361
	35.3	Transport and Application of H ₂ and CH ₄ 363
	35.4	Current Developments: Pilot Plants 365
	35.5	Conclusion 366
		References 366
	Part V	Codes and standards 369
	36	Hydrogen Safety and RCS (Regulations, Codes, and Standards) 371 Andrei V. Tchouvelev
	36.1	Introduction 371
	36.2	Hydrogen Safety 372
	36.2.1	Flammability Limits and Ignition Energy 372
		Unique Hydrogen Flammability Limits 372
	36.2.1.2	Hydrogen Ignition Energy 372
	36.2.2	Materials Compatibility 374
		Hydrogen Embrittlement 374
		Materials Suitability for Hydrogen Service 375
	36.3	Hydrogen Regulations, Codes, and Standards (RCS) International Activities 376
	36.3.1	ISO/TC 197 Hydrogen Technologies 376
	36.3.2	CEN and European Commission 376
	36.3.3	HySafe and IEA HIA Hydrogen Safety Activities 377
	36.4	Conclusions 377
		Acknowledgments 377
		References 378

Index 379