

Contents

- Foreword by Prof. Dr. Dr. hc. Mult. Herbert Gleiter XXXV**
Foreword by Prof. Dr. Joachim Maier XXXVII
Foreword by Prof. C.N.R. RAO, F.R.S. XXXIX
“Perspective” on the Book on Nanotechnology for Sustainable Energy by Prof. Tu Hailing XLI
A Way Forward by Baldev Raj, Marcel Van de Voorde, and Yashwant Mahajan XLV
Introduction by Baldev Raj, Marcel Van de Voorde, and Yashwant Mahajan LIII

Volume 1

Part One Energy Production 1

- 1 **Fossil Fuels: The Effect of Zeolite Catalyst Particle Morphology on Catalyst Performance in the Conversion of Methanol to Hydrocarbons 3**
 Katarzyna Anna Łukaszuk, Pablo del Campo Huertas, Andrea Molino, Malte Nielsen, Daniel Rojo-Gama, Juan Salvador Martinez-Espin, Karl Petter Lillerud, Unni Olsbye, Silvia Bordiga, Pablo Beato, and Stian Svelle
- 1.1 **Zeolites and Zeotypes as Nanocatalysts for Petroleum and Natural Gas 3**
- 1.2 **Modification of Porosity: Hierarchical Zeolites 4**
- 1.2.1 **Desilication in Alkaline Media 5**
- 1.2.2 **Carbon Templating 6**
- 1.3 **Modification of Size and Morphology 8**
- 1.3.1 **Nanozeolites 8**
- 1.3.2 **Lamellar Zeolites 9**
- 1.3.3 **Zeolite Growth Modifiers 12**
- 1.4 **Tools to Predict and Characterize Zeolite Morphology 14**
- 1.4.1 **Computationally Guided Morphology Prediction 14**
- 1.4.1.1 **Predicting Zeolite Equilibrium Morphology 15**
- 1.4.1.2 **Modifier/Template Effect on Morphology 15**
- 1.4.2 **Structural Characterization of Zeolites by Transmission Electron Microscopy (TEM) 16**

1.4.3	Powder XRD Anisotropic Peak Broadening Analysis for Morphology Investigations	17
1.5	Tailor-Made Catalysts for the Methanol-to-Hydrocarbons (MTH) Reaction	18
1.5.1	Introduction: The MTH Reaction – A Prime Example of Shape-Selective Nanocatalysis	18
1.5.2	Crystal Size Effects	20
1.5.2.1	SAPO-34 (CHA-Topology)	20
1.5.2.2	ZSM-5 (MFI Topology)	23
1.5.3	Mesoporosity as Variable Parameter	24
1.5.3.1	SAPO-34 (CHA Topology)	24
1.5.3.2	ZSM-5 (MFI Topology)	24
1.5.4	Nanostructured Materials	25
1.5.4.1	SAPO-34 (CHA Topology)	25
1.5.4.2	ZSM-5 (MFI Topology)	27
1.6	Summary and Outlook	29
	Acknowledgments	30
	References	30
2	Fossil Fuels: Nanotechnologies for Petroleum Reservoir Engineering	41
	<i>Igor N. Evdokimov</i>	
2.1	Introduction	41
2.2	Addition of Nanosized Colloidal Particles to Technological Fluids	42
2.2.1	Modification of Bulk Fluid Properties	42
2.2.1.1	Drilling Fluids	42
2.2.1.2	Fracturing Fluids	46
2.2.1.3	Nanosensors	46
2.2.2	Modification of Interfacial Properties	49
2.3	Indigenous Nanocolloidal Particles in Native Petroleum Fluids	51
2.3.1	Multiple Structural States of Asphaltene Nanocolloids	51
2.3.2	An Apparent Dependence of Technologically Important Crude Oil Properties on the Structural States of Asphaltene Nanocolloids	52
2.4	Conclusions	53
2.5	Appendix	54
	References	55
3	Fossil Fuels: Coke-Resistant Nanomaterials for Gas-to-Liquid (GTL) Fuels	59
	<i>Brian A. Rosen and Sarika Singh</i>	
3.1	Introduction to Gas-to-Liquid (GTL) Technology	59
3.2	A Thermodynamic View of Catalyst Coking	60
3.3	Tuning of Active Sites to Resist Coking	65
3.4	Methods for Characterizing Carbon Deposits	71
3.5	Summary and Outlook	79
	References	79

4	Photovoltaics: Light Energy Harvesting with Plasmonic Nanoparticle Networks	83
	<i>Jean-Paul Hugonin, Mondher Besbes, and Philippe Ben-Abdallah</i>	
4.1	Introduction	83
4.2	Light Absorption by a Single Particle	84
4.3	Light Absorption by a Collection of Particles	86
4.4	Upper Bound for Light Absorption in Nanoparticle Networks	89
4.5	Light Absorption Beyond the Dipolar Approximation	91
4.6	Design of Absorption Spectrum with Plasmonic Particles	93
4.7	Concluding Remarks	97
	Acknowledgments	97
	References	98
5	Photovoltaics: Role of Nanotechnology in Dye-Sensitized Solar Cells	101
	<i>Murugesan Janani, Shantikumar V. Nair, and A. Sreekumaran Nair</i>	
5.1	Nanotechnology and Its Relevance	101
5.2	A Brief History on Dye-Sensitized Solar Cells (DSSCs)	102
5.3	Construction and Working of DSSCs	103
5.4	Transparent Conducting Substrate	104
5.5	Semiconductor Materials	105
5.6	Nanotechnology vis-à-vis Renewable Energy Industry	105
5.7	Nanotechnology vis-à-vis Dye-Sensitized Solar Cells	105
5.7.1	Nanoparticles	107
5.7.2	One-Dimensional Nanostructures and Anisotropic Nanostructures	110
5.7.3	Vertically Aligned TiO ₂ Nanostructures	113
5.7.4	Composites with Carbon Nanostructures	115
5.8	Sensitizer	118
5.8.1	Quantum Dots as Sensitizers	120
5.9	Plasmonics	122
5.10	Counter Electrode	124
5.11	Conclusions	127
	References	128
6	Photovoltaics: Nanomaterials for Photovoltaic Conversion	133
	<i>Abdelilah Slaoui, Daniel Lincot, Jean François Guillemoles, and Ludovic Escoubas</i>	
6.1	Introduction	133
6.2	Photovoltaic Materials and Technologies: State of the Art	134
6.2.1	Principle and Limiting Factors	134
6.2.2	Present Photovoltaic Technologies	134
6.3	Nanomaterials for Photovoltaics	137
6.3.1	Quantum-Confinement Effects for Photovoltaic	138
6.3.1.1	Principle	138

6.3.1.2	Solar Cells Based on PbS or PbSe Nanoparticles	141
6.3.1.3	Solar Cells Based on Silicon Nanoparticles	142
6.3.2	Geometric-Confinement Effects for Photovoltaics	144
6.3.2.1	Principle	144
6.3.2.2	Organic and Hybrid Nanostructured Cells	145
6.3.2.3	Nanostructured Cells Based on Silicon or III-V Compounds	146
6.3.3	Optical Management Based on Nanostructures	149
6.3.3.1	Plasmonics for Photovoltaics	149
6.3.3.2	Up/Down Photon Conversion for Photovoltaics	152
6.3.3.3	Multiple Exciton Generation Solar Cells	154
6.3.3.4	Hot Carrier Solar Cells	155
6.4	Conclusion and Outlook	157
	References	158
7	Photovoltaics: Light-Trapping in Crystalline Silicon and Thin-Film Solar Cells by Nanostructured Optical Coatings	<i>163</i>
	<i>Pierpaolo Spinelli, B.K. Newman, and A. Polman</i>	
7.1	Introduction	163
7.2	Crystalline Si Solar Cells	165
7.2.1	Integration of Mie Coatings on c-Si Cell Architectures	166
7.2.2	Nanostructures for Improved Surface Passivation	168
7.2.2.1	Surface Passivation	169
7.2.2.2	Thin Devices	169
7.2.3	Properties of Nanostructured Coatings for Si Solar Cells	169
7.3	Nanostructured Coatings for Thin-Film Solar Cells	171
7.3.1	Application to High-Efficiency GaAs Solar Cells	171
7.3.2	Nanostructured Coatings for Organic Solar Cells	174
7.4	Other PV Applications of Resonant Nanostructures	176
7.5	Summary	177
	References	178
8	Photovoltaics: Nanoengineered Materials and Their Functionality in Solar Cells	<i>181</i>
	<i>Kaining Ding, Thomas Kirchartz, Karsten Bittkau, Andreas Lambertz, Vladimir Smirnov, Jürgen Hüpkes, and Uwe Rau</i>	
8.1	Introduction	181
8.2	Functional Elements of a Solar Cell	182
8.3	Transparent and Conductive Front Electrodes	185
8.4	Nanostructured Contact Material	187
8.4.1	Material Properties	188
8.4.2	Applications in Photovoltaic Devices	190
8.5	Nanostructured Absorber Materials	191
8.5.1	Nanocrystalline Silicon Absorber	192

8.5.2	Organic Bulk Heterojunction Solar Cells	193
8.6	Back Electrodes and Intermediate Layer	196
8.6.1	Back Electrodes	196
8.6.2	Intermediate Reflectors	198
8.7	Conclusions	200
	References	200

9 Nonselective Coatings for Solar Thermal Applications in CSP 207

Raj Kumar Bera, Daniel Mandler, and Shlomo Magdassi

9.1	Introduction	207
9.1.1	Absorptance and Emittance	208
9.2	Materials	210
9.2.1	Carbon-Based (Organic) Pigments	210
9.2.1.1	Carbon Black-Based Coatings	210
9.2.1.2	CNT-Based Coatings	210
9.2.2	Inorganic Pigment-Based Coatings	211
9.2.2.1	Metal Oxides	211
9.2.2.2	Mixed Metal Oxides	211
9.2.2.3	Metal Borides and Metal Silicides	212
9.2.2.4	Semiconducting Materials	212
9.2.3	Other Black Materials	212
9.3	Fabrication Methods	212
9.3.1	Wet-Chemical Method	212
9.3.1.1	Paints	213
9.3.1.2	Conversion Methods	213
9.3.1.3	Electrochemical Methods	214
9.3.2	Gas-Phase Method	214
9.3.2.1	CVD Method	214
9.3.2.2	Sputter Deposition	214
9.3.2.3	Vacuum Evaporation	215
9.4	Performance	215
9.4.1	Absorptance and Emittance	215
9.4.1.1	Factors Affecting Emittance	221
9.4.1.2	Transforming Nonselective to Selective Coating	222
9.4.2	Thermal Stability	222
9.4.3	Durability	224
9.4.3.1	Degradation Mechanisms	224
9.4.4	Corrosion Inhibition	226
9.5	Advantages and Disadvantages of Nonselective Overselective Coatings	227
9.6	Conclusions and Perspectives	227
9.7	Future Aspects	228
	References	229

10	Selective Surfaces for Solar Thermal Energy Conversion in CSP: From Multilayers to Nanocomposites	<i>231</i>
		<i>Audrey Soum-Glaude, Laurie Di Giacomo, Sébastien Quoizola, Thomas Laurent, and Gilles Flamant</i>
10.1	Introduction	231
10.2	State of the Art on Selective Surfaces for Solar Thermal Energy Conversion	232
10.2.1	Optical Properties of Selective Surfaces	232
10.2.2	Selective Coatings	234
10.3	W–SiC Multinanolayers as High-Temperature Solar Selective Coatings	237
10.3.1	Synthesis and Optical Characterization of W and SiC(N)H Coatings	238
10.3.2	Optical Simulation and Synthesis of W–SiC(N)H Multilayer Coatings	239
10.3.3	Thermal Stability of W–SiC(N)H Multilayer Coatings	242
10.4	Conclusions	243
	Acknowledgments	244
	References	244
11	Nanobiotechnology Augmenting Biological Gaseous Energy Recovery	<i>249</i>
		<i>Shantanu Roy and Debabrata Das</i>
11.1	Introduction	249
11.2	Dark Fermentative Hydrogen Production and Its Improvement Using Nanoparticles	250
11.2.1.1	Biochemistry of Dark Fermentative H ₂ Production	252
11.2.1.2	Role of Nanoparticles in the Improvement of H ₂ Production via Dark Fermentation	254
11.3	Gaseous Energy Extraction via Biomethanation Process and Improvement of Biomethanation Process Using Nanoparticles	256
11.3.1	Biomethane Production Using CO ₂ and H ₂ by Hydrogenotrophic Methanogens	257
11.3.1.1	CO ₂ Reduction to <i>N</i> -Formylmethanofuran with H ₂ Comprises Three-Enzyme Complexes	257
11.4	BioH ₂ Production via Photofermentation and Role of Nanoparticles in the Improvement of H ₂ Production	260
11.5	Photocatalytic Conversion of Acetate in Spent Media to H ₂	262
11.6	Conclusion	265
	Acknowledgments	266
	References	266

12	Nanotechnologies in Sodium-Cooled Fast Spectrum Reactor and Closed Fuel Cycle Sustainable Nuclear Energy System	271
	<i>Baldev Raj and U. Kamachi Mudali</i>	
12.1	Introduction	271
12.2	Nanomaterials for Nuclear Systems	273
12.2.1	Advanced Clad for Sodium-Cooled Fast Reactors: The Choice of Nanodispersed ODS Steels	276
12.3	Nanosensors, Surface Modification, and Coatings for Reactor and Reprocessing Applications	280
12.3.1	Nanoscale Sensors	280
12.3.2	SQUID Sensors	281
12.3.3	Nano Ferrofluid-Based Sensors	282
12.3.4	Sensors for Sodium Monitoring in Fast Reactors	282
12.3.5	Hydrogen Sensor	284
12.3.6	Oxygen Sensor	284
12.4	Surface Modification and Coating Technologies Based on Nanotechnology	285
12.4.1	Titanium	285
12.4.2	Stainless Steels	287
12.4.3	Nanocontainer-Based Coatings	287
12.4.4	Superhydrophobic Coatings	289
12.4.5	Nanocomposite Coatings	289
12.5	Summary	290
	Acknowledgments	291
	References	291
13	Nanotechnology and Applications for Electric Power: The Perspective of a Major Player in Electricity	295
	<i>Didier Noël</i>	
13.1	The Context and Perspective of a Global Player in Electricity	295
13.1.1	Group Presentation	295
13.1.2	Climate Change and the Energy Revolution Needed	297
13.2	The Issue of Nanotechnology for Electric Power	298
13.3	Main Subjects Studied	299
13.3.1	General Approach: Focus on the Enhancement of Materials Properties	299
13.3.2	From Physical Phenomena to the Applications for the Power Industry: Applications Relevant for EDF	301
13.3.3	The Structural Materials for Nuclear Power Generation: GEN-IV	302
13.3.4	Applications for Energy Transformation	305
13.3.4.1	Heat Transfer and Hydrophobic–Hydrophilic Surfaces	305
13.3.4.2	Energy Storage	309
13.3.4.3	High-Temperature Ceramic Oxide Cells	310
13.3.4.4	Thermoelectric Materials	311

13.3.5	Nanosensors, Autonomous and Communicating	314
13.4	Social Acceptance and Health Risk	315
13.4.1	Different Aspects of the Perception of the Nano Risk	316
13.4.2	The Limited Impact of Sociological Studies in Terms of Social Innovation	316
13.4.3	Hidden Public Opinion	317
13.4.4	Consequence: Risk of Negative Forecasts	318
13.4.5	Nanotechnologies for Energy: A Relatively Positive Context (Perceived Promise Would Appear to Be Greater than Perceived Threat)	319
13.4.6	Various Points Requiring Attention, in Parallel to Research on Technological Innovation, and Conclusion	319
13.5	Conclusions	320
	Acknowledgments	320
	References	320
14	Lightweight Nanostructured Materials and Their Certification for Wind Energy Applications	323
	<i>Bikramjit Basu, Sherine Alex, and N. Eswara Prasad</i>	
14.1	Introduction	323
14.2	Property Requirements for Wind Energy Applications	326
14.2.1	Aerodynamics Properties	326
14.2.2	Aeroacoustic Properties	327
14.2.3	Aeroelastic Properties	328
14.2.4	Fatigue Properties and Material Selection Criteria	329
14.2.5	High Strength Requirement	331
14.3	Brief Overview on Materials for Wind Energy Applications	332
14.3.1	Polymer-Based Lightweight Materials	332
14.3.2	Steels and Other Conventional Materials	335
14.3.3	Ultrafine Grained/Nanostructured Materials	336
14.3.3.1	Processing-Related Challenges	336
14.3.3.2	Challenges Faced Due to Agglomerated Powders	338
14.3.3.3	Processes Used for Developing Bulk Nanocrystalline Ceramics	338
14.4	Properties of Bulk Ceramic Nanomaterials	339
14.4.1	Mechanical Properties	339
14.4.1.1	Hardness and Yield Strength	339
14.4.1.2	Fracture Strength and Fracture Toughness	341
14.5	Certification	342
14.5.1	Certification of Nanomaterials	343
14.5.2	Certification of Nanomaterial Processing	345
14.5.3	Certification of Nanostructured Components	345
14.6	Conclusion and Outlook	346
	Acknowledgments	348
	References	348

Volume 2**Part Two Energy Storage and Distribution 353**

- 15 **Nanostructured Materials for Next-Generation Lithium-Ion Batteries 355**
T. Sri Devi Kumari, T. Prem Kumar, and A.K. Shukla
15.1 Introduction 355
15.1.1 Advantages and Disadvantages of Nanostructured Materials 356
15.2 Anode-Active Materials 357
15.2.1 Intermetallics 358
15.2.2 Silicon as an Anode Material 359
15.2.2.1 Thin-Film Silicon Anodes 359
15.2.2.2 Silicon Nanostructures 360
15.2.3 The “Zero Strain” Li₄Ti₅O₁₂ and GCMN 360
15.3 Cathode-Active Materials 361
15.3.1 Olivines 361
15.3.2 Other Polyanionic Cathodes 362
15.4 Electrolytes 362
15.4.1 Taming Lithium 364
15.5 New Reactions 364
15.5.1 Unusual Reactions 364
15.5.2 Conversion Electrodes 365
15.5.3 Nonconversion Reactions 366
15.5.4 A Biological Approach 367
15.6 Safety 367
15.7 Conclusions 369
References 369
- 16 **Carbon Nanotube Materials to Realize High-Performance Supercapacitors 377**
Anthony Childress, Jingyi Zhu, Mehmet Karakaya, Deepika Saini, Ramakrishna Podila, and Apparao Rao
16.1 Introduction 377
16.2 CNI’s Contributions 380
16.3 Sustainability 386
16.4 Conclusions and Future Prospects 387
Acknowledgment 387
References 387
- 17 **Recent Developments and Prospects of Nanostructured Supercapacitors 391**
Katherine L. Van Aken and Yury Gogotsi
17.1 Introduction 391

17.2	Properties of Supercapacitors	391
17.3	Terminology and Electric Double Layer	393
17.4	Nanostructured Electrode Materials for Supercapacitors	395
17.4.1	Nanostructured Porous Carbon Materials	396
17.4.2	Nanostructured Nonporous Carbon Materials	396
17.4.3	Two-Dimensional Materials	397
17.5	Electrolytes for Electrochemical Capacitors	398
17.5.1	Aqueous Electrolytes	399
17.5.2	Organic Electrolytes	399
17.5.3	Room Temperature Ionic Liquids	399
17.6	Electrode–Electrolyte Interfaces	400
17.6.1	Relationship between Pore Size and Ion Size	400
17.6.2	Effect of Surface Chemistry	401
17.6.3	Electrolyte Additives	404
17.7	Design of Capacitive Energy Storage Devices through Electrode–Electrolyte Coupling	404
17.7.1	Ionic Liquid Mixtures	405
17.7.1.1	Increasing the Operating Temperature Window	405
17.7.1.2	Increasing the Operating Potential Window	406
17.7.1.3	Optimizing the Electrode Capacitive Performance	408
17.7.2	Modeling Efforts for Supercapacitor Interfaces	409
17.8	Future Outlook and Recommendations	409
	Acknowledgments	410
	References	410
18	Nanostructured and Complex Hydrides for Hydrogen Storage	415
	<i>Lars H. Jepsen, Mark Paskevicius, and Torben R. Jensen</i>	
18.1	Introduction	415
18.2	The “Weaker” Bonds Formed by Hydrogen	417
18.2.1	Physisorption	417
18.3	The “Stronger” Bonds Formed by Hydrogen	418
18.3.1	Metallic Hydrides	418
18.3.2	Thermodynamic Consideration for Solid-State Hydrogen Storage	419
18.3.3	Ionic Hydrides	420
18.3.4	Covalent Hydrides	421
18.3.5	Reactive Hydride Composites: Tailoring Thermodynamic Properties	422
18.3.6	Nanoconfinement: Enhancement of the Kinetic Properties	423
18.3.7	New Types of Hydrides	425
18.3.7.1	Derivatives of Complex Hydrides Using Neutral Ligands	425
18.3.7.2	Metal Hydrides as Ion Conductors in Batteries	426
18.3.7.3	Porous Metal Borohydrides	426
18.3.7.4	Metal Borohydride Perovskites: Various Properties	426
18.4	Conclusion	427
	References	427

19	Nanotechnology for the Storage of Hydrogen	433
	<i>Marek Nowak and Mieczyslaw Jurczyk</i>	
19.1	Introduction	433
19.2	Nanotechnology	433
19.2.1	Mechanical Methods	434
19.2.1.1	Milling Processes	435
19.2.1.2	Mechanical Alloying	436
19.2.1.3	High-Energy Ball Milling	438
19.2.1.4	Mechanochemical Synthesis	439
19.2.1.5	Mechanochemical Activation Synthesis	439
19.2.2	Important Hydride Properties	439
19.3	Intermetallics-Based Hydrides with Nanostructure	440
19.3.1	TiFe-Type System	440
19.3.2	ZrV ₂ -Type System	444
19.3.3	LaNi ₅ -Type System	447
19.3.4	Mg ₂ Ni-Type Alloys	450
19.4	Nanocomposite-Based Hydrides	452
19.4.1	Nanoscale Mg ₂ Ni/LaNi ₅ and Mg ₂ Ni/ZrV ₂ Composites	452
19.4.2	Nanoscale Mg ₂ Ni/Tini Composites	454
19.5	Summary	456
	References	456
20	Phase Change Nanomaterials for Thermal Energy Storage	459
	<i>Kinga Pielichowska and Krzysztof Pielichowski</i>	
20.1	Introduction	459
20.2	Nanoenhanced PCMs	461
20.2.1	Carbon Nanomaterials-Enhanced PCMs	461
20.2.1.1	Salt and Salt Hydrates PCMs	461
20.2.1.2	Paraffin-Based PCMs	462
20.2.1.3	Fatty Acids-Based PCMs	466
20.2.1.4	Other Organic PCMs	468
20.2.1.5	Polymer-Based PCMs	469
20.2.2	Metal Nanoparticles-Enhanced PCMs	473
20.2.3	Inorganic Nanoparticles-Enhanced PCMs	474
20.3	Nanostructured PCMs	476
20.4	Conclusions	478
	Acknowledgment	479
	References	479
21	Carbon Nanotube Wires and Cables: Near-Term Applications and Future Perspectives	485
	<i>Jeremy Lee and Seeram Ramakrishna</i>	
21.1	Introduction	485
21.1.1	Properties of Carbon Nanotubes	486
21.1.2	Synthesis of Carbon Nanotubes	487

21.1.3	Purification and Enrichment of Produced Carbon Nanotubes	489
21.2	Carbon Nanotube Wires and Cables	490
21.2.1	CNT Yarns	490
21.2.1.1	Wet Spinning of Carbon Nanotube Yarns from Dispersions	490
21.2.1.2	Dry Spinning of Carbon Nanotube Yarns from Superaligned Forests Grown on Substrates	491
21.2.1.3	Continuous Dry Spinning of Carbon Nanotube Yarns from Carbon Nanotube Aerogel	493
21.2.1.4	Wet Spinning of Carbon Nanotube Yarns from Liquid Crystalline Solutions	494
21.2.1.5	Chemical Doping of Carbon Nanotube Yarns	495
21.2.2	CNT–Metal Composites	497
21.3	Applications of CNT Wires and Cables	500
21.4	Conclusion	502
	Acknowledgments	502
	References	502

Part Three Energy Conversion and Harvesting 507

22	Nanostructured Thermoelectric Materials: Current Research and Future Challenges	509
	<i>Hilaal Alam and Seeram Ramakrishna</i>	
22.1	Introduction to Thermoelectricity	509
22.2	Challenges to Increase the Efficiency	511
22.3	Electronic and Phonon Properties	516
22.3.1	Electronic Properties	516
22.3.2	Phonon Properties	518
22.4	Current Researches: Thermoelectric Nano Materials materials and Their Performances	518
22.4.1	Bismuth-Based Materials	519
22.4.2	Lead-Based Materials	522
22.4.3	AgSbTe ₂	523
22.4.4	Silicon and Germanium	524
22.4.5	β -Zn ₄ Sb ₃	524
22.4.6	Oxides	524
22.4.7	Half Heusler Material	526
22.4.8	Skutterudites	528
22.4.9	Clathrates	530
22.5	Future Challenges	530
22.5.1	Material Level Challenges	531
22.5.2	Fabrication Level Performance	531

22.5.3	Device Level Performance	532
22.6	Roadmap for the Future Researches	533
22.7	Conclusion	535
	References	537
23	Nanostructured Cost-Effective and Energy-Efficient Thermoelectric Materials	547
	<i>Zhi-Gang Chen and Jin Zou</i>	
23.1	Introduction	547
23.2	Key Parameters for Controlling ZT	548
23.3	Material Requirements	550
23.4	Nanostructure Engineering to Lower Thermal Conductivity	551
23.5	Band Engineering to Enhance the Power Factor	554
23.6	Development of Cost-Effective and Energy-Efficient Nanostructured Thermoelectric Materials	555
23.7	Outlook and Future Challenge	559
	Acknowledgment	560
	References	560
24	Nanomaterials for Fuel Cell Technology	569
	<i>K.S. Dhathathreyan, N. Rajalakshmi, and R. Balaji</i>	
24.1	Introduction	569
24.2	Nanomaterials for Polymer Electrolyte Membrane Fuel Cell and Fuel Cells Operating on Small Organic Molecules	569
24.2.1	Porous PGM-Based Nanocatalysts: Mesoporous and Hollow Structure	570
24.2.2	Supported Electrocatalysts	571
24.2.2.1	Carbon Nanomaterials as Catalyst Support: Mesoporous, Nanoporous, Graphene, Heteroatom-Doped Carbon Structures	571
24.2.2.2	Noncarbon-Supported Electrocatalysts	573
24.2.2.3	Nonprecious Metals and Metal-Free Catalysts	573
24.2.2.4	Nanocomposite Membranes	574
24.2.2.5	Nanostructured Catalyst Layers	578
24.3	Role of Nanomaterials in Solid Oxide Fuel Cells	579
24.3.1	Nanostructured SOFC Anode Materials	580
24.3.2	Nanostructured Electrolytes in SOFC	581
24.3.3	Nanostructured SOFC Cathode Materials	584
24.4	Conclusion	585
	References	586
25	Contributions of Nanotechnology to Hydrogen Production	597
	<i>Sambandam Anandan, Femi Thomas Cheruvathoor, and Muthupandian Ashokkumar</i>	
25.1	Introduction	597
25.2	Photocatalytic Water Splitting Reaction	598

25.3	Nano Semiconductor Materials for Photocatalytic Water Splitting 600
25.3.1	Titanium Dioxide 602
25.3.2	Iron Oxide 611
25.3.3	Zinc Oxide 613
25.3.4	Carbon Nitrides 620
25.3.5	Other Materials 623
25.4	Summary 624
	Acknowledgment 624
	References 625
26	Nanoenhanced Materials for Photolytic Hydrogen Production 629
	<i>Xiuquan Gu, Shuai Yuan, Mingguo Ma, and Jiefang Zhu</i>
26.1	Introduction 629
26.2	Basic Principle and Evaluation Methods for Photolytic H ₂ Production 630
26.3	Photolytic H ₂ Evolution Based on Nanoenhanced Materials 632
26.3.1	Photolytic H ₂ Generation Using Photocatalyst Powders 633
26.3.2	Photolytic H ₂ Generation Using PEC Systems 636
26.3.3	Photolytic H ₂ Generation Using Tandem PV-electrolysis or PV–PEC Systems 642
26.4	Conclusion and Outlook 645
	Acknowledgments 646
	References 646
27	Human Vibration Energy Harvester with PZT 649
	<i>Tamil Selvan Ramadoss and Seeram Ramakrishna</i>
27.1	Introduction to Micro Energy Harvesting 649
27.2	Human Vibration Energy Harvester with PZT 655
27.3	Alternative Design of Cantilever Piezoelectric Energy Harvester 660
27.4	Stress Distribution Simulation for Different Surface Shapes 664
27.5	Variable Profile Thickness of the Metal Shim 666
27.5.1	Elliptical Profile 666
27.5.2	Parabolic Profile 668
27.5.3	Tapered Profile 669
27.6	Comparison of Stress Distribution for Various Surface Shapes and Profiles 671
27.7	Output Power Comparison of Various Profiles 672
27.8	Conclusion 673
	Acknowledgment 674
	References 674

28	Energy Consumption in Information and Communication Technology: Role of Semiconductor Nanotechnology	679
	<i>Victor V. Zhirnov and Kota V.R.M. Murali</i>	
28.1	Introduction	679
28.2	Elements of Information Processing	681
28.2.1	Bits: Realization of Binary Elements	681
28.2.2	A Basic Computing System	682
28.2.3	Performance Metrics for Computing Systems	682
28.3	Energy Consumption in Computing: From Bits to Millions of Instructions per Second (MIPS)	687
28.3.1	The Field Effect Transistor : A Basic Logic Element	687
28.3.2	Energy Consumption in Computing	688
28.4	Fundamental Physics of Binary Operations	690
28.4.1	Energy Consumption for a Basic Logic Operation	691
28.4.2	Connected Binary Switches: Energy Associated with Fan Out	693
28.4.3	Energy for Communication	695
28.4.4	Essential Physics of Charge-Based Memory	695
28.4.5	Energetics of Computing: A Summary	697
28.5	Opportunities for Beyond the Current Information and Communication Technology Paradigm	701
	References	704

Volume 3

Part Four Nanoenabled Materials and Coatings for Energy Applications 707

29	Nanocrystalline Bainitic Steels for Industrial Applications	709
	<i>C. Garcia-Mateo and F.G. Caballero</i>	
29.1	Introduction	709
29.2	Design of Nanocrystalline Steel Grades: Scientific Concepts	709
29.3	Microstructure and Properties	712
29.3.1	Bainitic Transformation and Microstructure	712
29.3.2	Tensile Properties: Strength and Ductility	714
29.3.3	Toughness	716
29.3.4	Wear	717
29.3.5	Fatigue	719
29.4	Summary	721
	Acknowledgments	721
	References	722
30	Graphene and Graphene Oxide for Energy Storage	725
	<i>Edward P. Randviir and Craig E. Banks</i>	
30.1	Graphene Hits the Headlines	725

30.2	Graphene: Why All the Fuss? 726
30.3	Graphene and Graphene Oxide in Energy Storage Devices 727
30.3.1	Supercapacitors 728
30.3.2	Batteries 730
30.3.3	Solar Energy 733
30.4	Graphene and Graphene Oxide in Energy Generation Devices 734
30.4.1	Fuel Cells 735
30.4.2	Electrolyzers 738
30.4.3	Outlook 740
	References 741
31	Inorganic Nanotubes and Fullerene-Like Nanoparticles at the Crossroad between Materials Science and Nanotechnology and Their Applications with Regard to Sustainability 745
	<i>Leela S. Panchakarla and Reshef Tenne</i>
31.1	Introduction 745
31.2	Synthesis and Structural Characterization 746
31.3	Doping Inorganic Fullerenes/Nanotubes 757
31.4	Applications 758
31.4.1	Tribological Properties 758
31.4.2	Nanocomposites 762
31.5	Fullerenes and Nanotubular Structures from Misfit Layered Compounds 764
31.6	Conclusions 776
	References 776
32	Nanotechnology, Energy, and Fractals Nature 781
	<i>Vojislav V. Mitić, Ljubiša M. Kocić, Steven Tidrow, and Hans-Jörg Fecht</i>
32.1	Introduction 781
32.2	Short Introduction to Fractals 782
32.3	Nanosizes and Fractals 784
32.4	Energy and Fractals 788
32.5	Toward Fractal Nanoelectronics 793
32.6	The Goldschmidt's Tolerance Factor, Clausius–Mossotti Relation, Curie, and Curie–Weiss Law Bridge to Fractal Nanoelectronics Contribution 797
32.7	Summary 803
	Acknowledgment 805
	References 805
33	Magnesium Based Nanocomposites for Cleaner Transport 809
	<i>Manoj Gupta and Sankaranarayanan Seetharaman</i>
33.1	Introduction 809
33.2	Fabrication of Magnesium-based Nanocomposites 811
33.3	Mechanical Properties and Corrosion 814

33.3.1	Tensile and Compressive Properties	814
33.3.2	Dynamic Mechanical Properties	818
33.3.3	Creep Properties	818
33.3.4	Fatigue Properties	820
33.3.5	Corrosion Properties	820
33.4	Engineering Properties	822
33.4.1	Wear	822
33.4.2	Machinability	823
33.5	Potential Applications in Transport Industries	824
33.6	Challenges	825
33.7	Conclusions	825
	References	826
34	Nanocomposites: A Gaze through Their Applications in Transport Industry	<i>831</i>
	<i>Kottan Renganayagalu Ravi, Jayakrishnan Nampoothiri, and Baldev Raj</i>	
34.1	Introduction	831
34.2	Polymer Matrix Nanocomposites in Transport Sector	832
34.2.1	Common Matrices and Reinforcement Materials Used in PMNCs	833
34.2.2	Manufacturing Methods for PMNCs	834
34.2.3	Potential Applications of PMNCs in Transport Industry	834
34.3	Lightweight High-strength Metal Matrix Nanocomposites	838
34.3.1	Manufacturing of Metal Matrix Nanocomposites	838
34.3.2	Mechanical Property of MMNCs	842
34.3.3	Potential Applications of MMNCs in Automobile Sector	843
34.3.4	Metal Matrix Nanocomposites for Aerospace Applications	843
34.3.5	Metallic Foam-based Lightweight Structure	844
34.4	Ceramic Matrix Nanocomposites in Transport Industry	845
34.4.1	Manufacturing Methods for CMNCs	845
34.4.2	Mechanical Properties of CMNCs	846
34.4.3	Potential CMNC Entrants in Transport Industry	846
34.5	Nanocomposite Coating	849
34.6	Challenges and Opportunities for Nanocomposites	849
	References	851
35	Semiconducting Nanowires in Photovoltaic and Thermoelectric Energy Generation	<i>857</i>
	<i>Guglielmo Vastola and Gang Zhang</i>	
35.1	Introduction	857
35.2	Fabrication of Silicon and Silicon–Germanium Nanowires	858
35.2.1	Vapor–Liquid–Solid Synthesis of Silicon Nanowires	858
35.2.2	Synthesis of Silicon–Germanium Superlattice Nanowires	862
35.2.3	Top-down Approaches	863
35.3	Nanowire-based Photovoltaics	865

35.3.1	Single-Nanowire Solar Cells	867
35.3.2	Silicon Nanowire Bundle Solar Cells	868
35.4	Introduction of Thermoelectric Effects	871
35.5	Thermal Conductivity of Silicon Nanowires	874
35.6	Thermoelectric Property of Silicon Nanowires	876
35.7	Thermoelectric Property of Silicon–Germanium Nanowires	877
35.8	Thermoelectric Property of Other Nanowires	879
	References	881
36	Nanoliquid Metal Technology Toward High-Performance Energy Management, Conversion, and Storage	887
	<i>Jing Liu</i>	
36.1	Introduction	887
36.2	Typical Properties of Nanoliquid Metal	889
36.3	Emerging Applications of Nanoliquid Metal in Energy Areas	892
36.3.1	Energy Management	892
36.3.2	Energy Conversion	898
36.3.3	Energy Storage	901
36.4	Challenging Scientific and Technological Issues	904
36.5	Summary	906
	Acknowledgment	907
	References	907
37	IoNanofluids: Innovative Agents for Sustainable Development	911
	<i>Carlos Nieto de Castro, Xavier Paredes, Salomé Vieira, Sohel Murshed, Maria José Lourenço, and Fernando Santos</i>	
37.1	Introduction	911
37.2	IoNanofluids: Nature, Definitions, Preparation, and Structure Characterization	912
37.2.1	The Nanomaterial Problem	913
37.2.2	The Nanofluid Preparation	914
37.2.3	Nanofluid Stability	917
37.2.4	Methods to Improve Nanofluids Stability	919
37.2.5	Structural Characterization of Nanofluids	920
37.3	IoNanofluids Properties	920
37.4	Applications of IoNanofluids	926
37.4.1	IoNanofluids as New Engineering Fluids	926
37.4.2	IoNanofluids as Nano-Driven Catalysts	928
37.4.3	Development of New Paints for Solar-Absorbing Panels Based on Natural Nanomaterials	929
37.5	Challenges in IoNanofluids Research	930
37.6	Challenges to Industrial Applications	931
	Acknowledgments	932
	References	932

Part Five Energy Conservation and Management 937

38	Silica Aerogels for Energy Conservation and Saving 939
	<i>Yamini Ananthan, K. Keerthi Sanghamitra, and Neha Hebalkar</i>
38.1	Introduction 939
38.2	Thermal Insulation Materials 940
38.3	Aerogels 940
38.3.1	What Are Aerogels? 940
38.3.2	General Properties 942
38.3.3	General Applications 942
38.3.4	Thermal Insulation in Aerogels 944
38.4	Preparation 944
38.4.1	Gel Formation 944
38.4.2	Drying of Gel 945
38.5	Aerogels in Various Forms: Monoliths, Granules, and Sheets 945
38.6	Thermal Insulation Applications 954
38.6.1	Industrial 954
38.6.2	Architectural 955
38.6.3	Automotive 957
38.6.4	Cold Storages and Cryogenic Insulation 957
38.6.5	Aerospace 958
38.6.6	Defense 958
38.6.7	Textiles 959
38.7	Energy Saving and Conservation Using Aerogel Products 960
38.8	Challenges and Future Perspectives 961
38.9	Safety and Hazard Measures 962
38.10	Summary 962
	Acknowledgments 963
	References 963
39	Nanotechnology in Architecture 967
	<i>George Elvin</i>
39.1	Nanotechnology and Green Building 967
39.1.1	Green Building 967
39.1.2	The Role of Nanotechnology 967
39.2	Energy 969
39.2.1	Energy Conservation 969
39.2.1.1	Insulation 969
39.2.2	Aerogel 970
39.2.3	Insulating Coatings 971
39.2.4	Thin-Film Insulation 971
39.2.5	Emerging Insulation Technologies 972
39.2.6	Future Market for Nanoinsulation 972
39.2.7	On-Site Renewable Energy 973
39.2.7.1	Solar 973

39.2.8	Energy Storage	975
39.2.9	Lighting	977
39.3	Air and Water	978
39.3.1	Air Purification	978
39.3.2	Depolluting Surfaces	979
39.3.3	Water Conservation and Purification	979
39.4	Materials	980
39.4.1	Concrete	981
39.4.2	Steel	984
39.4.3	Wood	984
39.4.4	Glass	985
39.4.5	Plastics	986
39.4.6	Gypsum	988
39.4.7	Roofing	988
39.4.8	New Structural Materials	989
39.5	Nanosensors	990
39.6	Environmental and Health Concerns	991
	References	992
40	Nanofluids for Efficient Heat Transfer Applications	997
	<i>Baldev Raj, S.A. Angayarkanni, and John Philip</i>	
40.1	Introduction	997
40.2	Traditional Nanofluids	999
40.3	CNT-Based Nanofluids	1008
40.4	Magnetic Nanofluids	1009
40.5	Graphene Nanofluids	1012
40.6	Hybrid Nanofluid	1013
40.7	Thermal Conductivity of Phase Change Material	1015
40.8	Conclusions	1018
	Acknowledgment	1019
	References	1019
Part Six	Technologies, Intellectual Property, and Markets	1029
41	Nanomaterials for Li-Ion Batteries: Patents Landscape and Product Scenario	1031
	<i>Md Shakeel Iqbal, Nisha C. Kalarickal, Vivek Patel, and Ratnesh Kumar Gaur</i>	
41.1	Introduction	1031
41.2	Lithium-Ion Battery: Basic Concepts	1031
41.3	Advantages of Nanostructured Materials	1034
41.4	Patent Analysis	1035
41.4.1	Methodology	1035
41.4.2	Year-Wise Patent Publication Trend	1035

41.4.3	Geographical Region-Wise Distribution of Patenting Activity	1036
41.4.4	Patenting Activity by Assignees	1036
41.5	Technology Analysis	1038
41.5.1	Classification of Li-Ion Batteries	1038
41.5.2	Application of Nanomaterials in Li-Ion Batteries	1040
41.5.3	Distribution of Patents by Application Sector	1045
41.5.4	Top-20 Assignees versus Publication Year	1046
41.5.5	Correlation of Top Assignees versus Nanomaterial Usage	1047
41.6	Commercial Status of Nano-Enabled Li-Ion Batteries	1050
41.7	Market	1051
41.8	Conclusions and Future Perspectives	1051
	References	1053
42	Nanotechnology in Fuel Cells: A Bibliometric Analysis	1057
	<i>Manish Sinha, Ratnesh Kumar Gaur, and Harshad Karmarkar</i>	
42.1	Introduction	1057
42.2	Literature Analysis	1058
42.2.1	Literature Publication Trend	1059
42.2.2	Literature Publications by Geographical Region	1059
42.2.3	Publication Trend by Institutes and Organizations	1060
42.3	Patent Landscaping	1061
42.3.1	Publication Trend	1061
42.3.2	Top Assignees	1062
42.3.3	Patents by Geographical Region	1063
42.3.4	Classification of Fuel Cells	1064
42.3.4.1	Classification Based on the Type of Electrolyte	1064
42.3.4.2	Classification Based on Types of Fuel and Oxidant	1064
42.3.5	Publication Trend for Fuel Cell Types	1065
42.4	Proton Exchange Membrane Fuel Cells Patent Analysis	1067
42.4.1	Geographical Distribution of Patents for Nanotechnology in PEMFCs	1067
42.4.2	Top Assignees for Nanotechnology in PEMFCs	1069
42.4.3	Organization-Wise Distribution of Applications	1069
42.5	Technology Analysis	1070
42.5.1	Assignee Activity across Components of Fuel Cells	1071
42.5.2	Nanomaterials for Fuel Cell Catalyst Support/Active Materials	1071
42.5.2.1	Fuel Cell: Types versus Catalysts-Active Materials	1073
42.5.3	Nano-Enabled Membranes	1074
42.5.4	Nanomaterials in PEMFCs Gas Diffusion Layer	1074
42.6	Scenario of Commercial Products Can Be Moved after Future Perspectives	1075
42.7	Future Perspectives	1077
42.8	Conclusion	1077
	Acknowledgments	1078

43	Techno-Commercial Opportunities of Nanotechnology in Wind Energy 1079
	<i>Vivek Patel and Y.R. Mahajan</i>
43.1	Introduction 1079
43.2	Wind Energy Industry Requirements 1080
43.3	Growth Drivers 1081
43.4	Challenges 1081
43.5	Applications 1083
43.5.1	Structural Applications 1083
43.5.1.1	Blades 1083
43.5.1.2	Other Applications 1088
43.5.2	Functional Applications 1088
43.5.2.1	Nanocoatings 1088
43.5.2.2	Nanolubricants 1089
43.5.2.3	Nanofluids 1091
43.5.2.4	Ultracapacitors 1092
43.5.2.5	Nanosensors 1092
43.5.2.6	Structural Adhesives 1093
43.5.2.7	Other Applications 1094
43.6	Intellectual Property Scenario 1094
43.7	Products Outlook 1098
43.8	Future Development and Directions 1100
43.9	Conclusion 1102
	Acknowledgment 1103
	References 1103

Part Seven Environmental Remediation 1107

44	Nanomaterials for the Conversion of Carbon Dioxide into Renewable Fuels and Value-Added Products 1109
	<i>Ibram Ganesh</i>
44.1	Introduction: Dealing with the Waste Stream Greenhouse CO ₂ Gas 1109
44.2	Theoretical Potentials for Electrochemical Reduction of CO ₂ 1112
44.3	CO ₂ Speciation versus Electrolyte pH 1120
44.4	Effect of Particle Size on Electrode Performance in Electrochemical CO ₂ Reduction Reaction 1125
44.5	Effect of Particle Size on the Efficiency of Aqueous-Based CO ₂ Reduction Reactions 1126
44.6	Effect of Particle Size on the Efficiency of Nonaqueous-Based CO ₂ Reduction Reactions 1129
44.7	Reverse Microbial Fuel Cells: The Practical Artificial Leaves 1133
44.8	Concluding Remarks and Future Perspectives 1136

Acknowledgments	1136
References	1136
45	Nanomaterial-Based Methods for Cleaning Contaminated Water in Oil Spill Sites 1139
	<i>Boris I. Kharisov, H.V. Rasika Dias, Oxana V. Kharissova, and Yolanda Peña Méndez</i>
45.1	Introduction 1139
45.2	Inorganic Nanomaterials and Composites 1141
45.3	Nanosized Natural and Synthetic Polymers 1151
45.4	Nanomaterials-Based Membranes 1153
45.5	Aerogels 1153
45.6	Toxicity, Cost, and Selection of Nanomaterials for Water Cleanup from Oil 1154
45.7	Conclusions and Further Outlook 1155
	References 1156
46	Nanomaterials and Direct Air Capture of CO₂ 1161
	<i>Dirk Fransaer</i>
46.1	Introduction 1161
46.2	CO ₂ as a Resource 1163
46.3	Circular CO ₂ Economy 1165
46.4	CO ₂ Capture or Separation Technologies 1165
46.5	New Roads into CO ₂ Capture: Direct Air Capture and Nanomaterials 1168
46.6	Nanomaterials 1169
46.6.1	Metal–Organic Frameworks (MOF) 1170
46.6.2	Gas Separation 1171
46.7	Carbon Nanotubes 1171
46.7.1	Nanoporous Membranes 1172
46.7.2	Nanocrystals for Carbon Capture 1172
46.7.3	Nanoparticle Ionic Materials for Carbon Capture 1172
46.7.4	CuO Nanoparticle-Loaded Porous Carbons 1173
46.7.5	Selectively Permeable Membranes 1173
46.7.6	Cellulose-Based Porous Nanomaterials 1173
46.7.7	Nanocomposites for Carbon Capture 1173
46.8	Conclusion 1174
	References 1174
	Index 1179

