

Ricardo Guerrero-Lemus
José Manuel Martínez-Duart

Renewable Energies and CO₂

Cost Analysis, Environmental Impacts
and Technological Trends- 2012 Edition



Springer

Ricardo Guerrero-Lemus
Dept. Física Básica
Universidad La Laguna
La Laguna
Spain

José Manuel Martínez-Duart
Dept. Física Aplicada
Universidad Autónoma de Madrid
Madrid
Spain

ISBN 978-1-4471-4384-0 ISBN 978-1-4471-4385-7 (eBook)
DOI 10.1007/978-1-4471-4385-7
Springer London Heidelberg New York Dordrecht

Library of Congress Control Number: 2012948399

© Springer-Verlag London 2013

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Contents

I Introduction

1 Executive Summary	3
References	7
2 Renewable Energy and CO₂: Current Status and Costs	9
2.1 The Current Use and Theoretical Potential of Conventional and Renewable Energies	9
2.2 Evolution of CO ₂ Emission Rates and Influence on Climate Change	14
2.3 Fuel and Electricity Production Costs from Renewable Energy Sources	20
2.4 Status of the Renewable Energy and Associated Technologies	25
2.5 CO ₂ Emissions, Energy Payback and Other Environmental Costs	27
References	31

II Renewable Fuels and Carriers

3 Biomass	37
3.1 Overview	37
3.2 State of the Art	41
3.2.1 Energy Crops	41
3.2.2 Cultivation Techniques	42
3.2.3 Harvesting, Storage and Transportation	42
3.2.4 Combustion	44
3.2.5 Co-firing	45
3.2.6 Gasification	45
3.2.7 Anaerobic Digestion	46
3.2.8 Stages of Development	46

3.3	Current Costs and Future Scenarios	48
3.4	Energy Payback, CO ₂ Emissions and External Costs	51
3.5	Future Technology Trends	54
3.5.1	Energy Crops	54
3.5.2	Cultivation Techniques	54
3.5.3	Harvesting, Storage and Transportation	55
3.5.4	Combustion	56
3.5.5	Co-firing	56
3.5.6	Gasification	57
3.5.7	Anaerobic Digestion	57
3.6	Pre-production Highlights 2009–2011	58
3.6.1	The World Largest Biomass Power Plant	58
3.6.2	New Strategies to Increase Biogas Production from Wastewater	58
3.7	Innovation Highlights 2009–2011	59
3.7.1	BIGCC to Produce Electricity and Heat in Ethanol Plants	59
3.7.2	Electricity Production from Anaerobic Digestion in Microbial Fuel Cells	59
3.7.3	Using Charcoal Production to Store CO ₂ and Produce Heat	59
3.8	Statistics of Publications and Patents	60
	References	62
4	Biofuels	63
4.1	Overview	63
4.2	State of the Art	65
4.2.1	First-Generation Bioethanol	65
4.2.2	First-Generation Biodiesel	66
4.2.3	Lignocellulosic Bioethanol (Second Generation)	67
4.2.4	Second-Generation Biodiesel	68
4.2.5	Hydrogen from Biomass (Third Generation)	69
4.2.6	Biodiesel from Microalgae (Third Generation)	69
4.2.7	Stages of Development	71
4.3	Current Costs and Future Scenarios	72
4.4	Energy Payback, CO ₂ Emissions and External Costs	74
4.5	Future Technology Trends	77
4.5.1	First-Generation Bioethanol	77
4.5.2	First-Generation Biodiesel	78
4.5.3	Second-Generation Bioethanol	78
4.5.4	Second-Generation Biodiesel	79
4.5.5	Hydrogen from Biomass (Third Generation)	79
4.5.6	Biodiesel from Microalgae (Third Generation)	80

Contents	xiii
4.6 Pre-Production Highlights 2009–2011	80
4.6.1 Danish Companies Novozymes and Nanisco Announce Breakthroughs in Enzymes to Produce Ethanol from Cellulose	80
4.6.2 ExxonMobil Enters the Race to Produce Biofuel from Microalgae	81
4.6.3 Genetically Modified Microbes Produce Biodiesel	81
4.6.4 Hybrid Cellulosic Ethanol Plant of Abengoa Bioenergy in Kansas, USA (2010)	81
4.6.5 Producing Biodiesel at Home	82
4.7 Innovation Highlights 2009–2011	82
4.7.1 New Procedure to Produce Jet Fuel from Waste Biomass	82
4.7.2 Direct Conversion of CO ₂ Into Biofuels	82
4.7.3 Design of an Improved Process for the Use of Pyrolysis Oils	83
4.7.4 Genetic Modification of <i>E. coli</i> Converts Seaweed into Ethanol	84
4.7.5 Discoveries on Isobutanol and on Ethanol Production in Microorganisms	84
4.8 Statistics of Publications and Patents	85
References	87
5 Hydrogen Production	89
5.1 Overview	89
5.2 State of the Art	91
5.2.1 Reforming	91
5.2.2 Gasification	92
5.2.3 Water Electrolysis	92
5.2.4 Thermolysis	93
5.2.5 Thermochemical Cycles	93
5.2.6 Biochemical Fermentation	94
5.2.7 Photocatalysis and Photoelectrolysis	94
5.2.8 Hydrogen Storage	95
5.2.9 Market Penetration	95
5.3 Current Costs and Future Scenarios	96
5.4 Energy Payback, Carbon Emissions and External Costs	100
5.5 Future Technology Trends	101
5.5.1 Reforming	101
5.5.2 Gasification	101
5.5.3 Electrolysis	102
5.5.4 Thermolysis	102
5.5.5 Biochemical Fermentation	103
5.5.6 Photocatalysis and Photoelectrolysis	103
5.5.7 Thermochemical Cycles	104
5.5.8 Hydrogen Storage	104

5.6	Pre-Production Highlights 2009–2011	105
5.6.1	First World Fuel Cell and Hydrogen Energy Station in Orange County (USA)	105
5.6.2	The Commercial Vehicle That Travels More Kilometres Driven by Hydrogen	105
5.6.3	Waste Treatment Plant Capable of Producing Energy with Hydrogen	105
5.7	Innovation Highlights 2009–2011	105
5.7.1	Thermochemical Cycles for Water Dissociation in Two Stages Using Fe_3O_4 and NiFe_2O_4 Particles on ZrO_2 Porous Ceramic Devices	105
5.7.2	Production of Hydrogen from Water by the Effect of Light on Polymeric Carbon Nitride	106
5.7.3	Production of Hydrogen from Virus	106
5.7.4	Artificial Leaves That Produce Hydrogen	106
5.7.5	Improvement of the Kinetics for the Water Electrolysis . .	107
5.8	Statistics of Publications and Patents	107
	References	109

III Power from Renewable Sources

6	Photovoltaics (PV)	115
6.1	Overview	115
6.2	State of the Art	119
6.2.1	Crystalline Silicon Cells	119
6.2.2	Thin Film Cells	119
6.2.3	Third-Generation Solar Cells	120
6.2.4	Organic Solar Cells	120
6.2.5	Efficiencies and Required Areas	121
6.2.6	Market Penetration	122
6.3	Current and Future Costs Scenarios	123
6.4	Energy Payback, Carbon Emissions and External Costs	124
6.5	Future Technology Trends	127
6.5.1	Crystalline Silicon Solar Cells	127
6.5.2	Thin Film Solar Cells	127
6.5.3	Third-Generation Solar Cells	128
6.5.4	Organic Solar Cells	128
6.5.5	Other Future Trends	128
6.6	Pre-Production Highlights (2009–2011)	129
6.6.1	Transport Driven by Photovoltaic Energy	129
6.6.2	PV Plants Without Feed-in Tariff Are Planning in Spain in 2012	129

6.7	Innovation Highlights (2009–2011)	130
6.7.1	The New Efficiency Record for Solar Cells Reached 43.5 %	130
6.7.2	Advances in High-Efficiency GaAs Thin Films Manufacturing on Flexible Plastic Substrates	130
6.7.3	Dye-Sensitised Solar Cell Exceeds 12 % Efficiency	130
6.7.4	Peak External Photocurrent Quantum Efficiency Exceeding 100 %	130
6.8	Statistics of Publications and Patents	131
	References	133
7	Concentrated Solar Power	135
7.1	Overview	135
7.2	State of the Art	138
7.2.1	Parabolic Troughs	138
7.2.2	Tower Systems	139
7.2.3	Parabolic Dish Concentrators (“dishes”)	139
7.2.4	Linear Fresnel Systems	140
7.2.5	Thermal Storage	140
7.2.6	Water Consumption	141
7.2.7	Stages of Development	141
7.3	Current Costs and Future Scenarios	142
7.4	Energy Payback, CO ₂ Emissions and External Costs	143
7.5	Future Technology Trends	144
7.5.1	Parabolic Trough	144
7.5.2	Tower System	145
7.5.3	Parabolic Dish	145
7.5.4	Linear Fresnel Systems	145
7.5.5	Thermal Storage	146
7.5.6	General Technology Trends	147
7.6	Pre-Production Highlights 2009–2011	148
7.6.1	DESERTEC Project to Feed Europe with Electricity from Sahara Desert	148
7.7	Innovation Highlights 2009–2011	148
7.7.1	A new Computationally Efficient Model and Biomimetic Layout for Heliostat Field Optimisation	148
7.7.2	Thermochemical Dissociation of CO ₂ and H ₂ O Using non-Stoichiometric Cerium	148
7.8	Statistics of Publications and Patents	149
	References	151

8 Wind Power	153
8.1 Overview	153
8.2 State of the Art	156
8.2.1 On-Shore Turbines	156
8.2.2 Microturbines and Urban Turbines	157
8.2.3 <i>Wind Energy Storage Using Compressed Air (CAES)</i>	158
8.2.4 Off-Shore Wind Turbines	158
8.2.5 Off-Shore Foundations	158
8.2.6 Wind Resources	160
8.2.7 Off-Shore Logistics	161
8.2.8 Stages of Development	161
8.3 Current Costs and Future Scenarios	162
8.3.1 Turbine Costs and Total Costs	162
8.3.2 Operation and Maintenance Costs (O&M)	164
8.3.3 Cost of Electricity	164
8.4 Energy Payback, CO ₂ Emissions and External Costs	166
8.5 Future Technology Trends	167
8.5.1 On-Shore Turbines	167
8.5.2 Microturbines and Urban Turbines	168
8.5.3 <i>Wind Energy Storage Using Compressed Air (CAES)</i>	169
8.5.4 Off-Shore Turbines	171
8.5.5 Off-Shore Foundations	171
8.5.6 Wind Resources	172
8.5.7 Off-Shore Logistics	173
8.6 Pre-Production Highlights 2009–2011	174
8.6.1 Alpha Ventus Off-Shore Wind Farm Come Into Operation in the North Sea	174
8.6.2 The world's largest wind turbine	174
8.6.3 Sensors to Analyse the Wind Before Reaching the Turbine	175
8.6.4 Multi-Megawatts Direct-Drive Turbines	175
8.7 Innovation Highlights 2009–2011	175
8.7.1 Nacelles Located at Ground Level	175
8.7.2 Concrete-Steel Hybrid Towers of 100–150 m	175
8.7.3 World Largest Floating Wind Turbine	177
8.7.4 Global Off-Shore Wind Speed Increases	177
8.8 Statistics of Publications and Patents	177
References	180
9 Hydropower	181
9.1 Overview	181
9.2 State of the Art	184

9.2.1	Turbines	184
9.2.2	Large Hydropower Systems	185
9.2.3	Small Hydropower Systems	186
9.2.4	Run-of-River Systems	186
9.2.5	Systems with Reduced Environmental Footprint	187
9.2.6	Water Management Systems	188
9.2.7	Stages of Development	188
9.3	Current Costs and Future Scenarios	189
9.4	Energy Payback, CO ₂ Emissions and External Costs	190
9.5	Future Technology Trends	191
9.5.1	Turbines	191
9.5.2	Large Hydropower Systems	191
9.5.3	Small Hydropower Systems	192
9.5.4	Run-of-River Systems	192
9.5.5	Systems with Reduced Environmental Footprint	192
9.5.6	Water Management Systems	192
9.6	Pre-Production Highlights 2009–2011	193
9.6.1	The Three Gorges Dam Starts Operating at Full Capacity But Problems Arise	193
9.6.2	Superconductors Applied to a Run-of-River System	193
9.6.3	New Tunnel to Increase Power Capacity in Niagara Falls	193
9.7	Innovation Highlights 2009–2011	194
9.7.1	Superconducting Technology for Hydropower Generators	194
9.7.2	Hydropower Sustainability Assessment Protocol Presented	194
9.8	Statistics of Publications and Patents	195
	References	197
10	Geothermal Energy	199
10.1	Overview	199
10.2	State of the Art	201
10.2.1	Flash Technology	201
10.2.2	Enhanced Geothermal Systems	203
10.2.3	Low Temperature Resources Via Binary Plant Technology	204
10.2.4	Geothermal Heat Pumps	204
10.2.5	Stages of Development	205
10.3	Current Costs and Future Scenarios	206
10.4	Energy Payback, CO ₂ Emissions and External Costs	208
10.5	Future Technology Trends	209
10.5.1	Flash Technology	209
10.5.2	Enhanced Geothermal Systems	209

10.5.3	Low Temperature Resources Via Binary Plant Technology	210
10.5.4	Geothermal Heat Pumps	210
10.6	Pre-Production Highlights 2009–2011	211
10.6.1	EGS Promoting Projects in Australia	211
10.6.2	Protocol for Addressing Induced Seismicity Associated with EGS	211
10.7	Innovation Highlights 2009–2011	211
10.7.1	First Steps to Use CO ₂ to Improve the Extraction of Geothermal Heat	211
10.7.2	Use of Spallation Systems	212
10.8	Statistics of Publications and Patents	212
	References	214
11	Ocean Energy	215
11.1	Overview	215
11.2	State of the Art	216
11.2.1	Waves	216
11.2.2	Currents	225
11.2.3	Tidal Range	226
11.2.4	Salinity Gradients	228
11.2.5	Temperature Gradients	229
11.2.6	Stages of Development	229
11.3	Current Costs and Future Scenarios	230
11.4	Energy Payback, CO ₂ Emissions and External Costs	231
11.5	Future Technology Trends	233
11.5.1	Waves	235
11.5.2	Currents	236
11.5.3	Tidal Range	236
11.5.4	Salinity Gradients	237
11.5.5	Temperature Gradients	238
11.6	Pre-Production Highlights 2009–2011	238
11.6.1	Waves: Starting the Oyster Device for Harnessing Wave Energy	238
11.6.2	Tidal Currents: The First Commercial Device That Exploits Tidal Currents in Open Sea Comes Into Operation	238
11.6.3	Tidal Range: Sihwa Tidal Range Plant Starts Into Operation	239
11.7	Innovation Highlights 2009–2011	240
11.7.1	Tidal Range: Feasibility Studies to Exploit the Range of Tides in the Severn Estuary	240
11.7.2	Salinity Gradients: The First Power Plant Based on Osmosis Begins to Operate in Norway	240
11.8	Publications and Patents Statistics	240
	References	242

12 Nuclear Fusion	245
12.1 Overview	245
12.2 State of the Art	247
12.2.1 Magnetic Confinement Fusion	247
12.2.2 Inertial Confinement Fusion	249
12.2.3 Stages of Development	251
12.3 Current Costs and Future Scenarios	251
12.4 Energy Payback, CO ₂ Emissions and External Costs	252
12.5 Future Technology Trends	252
12.5.1 Magnetic Confinement Fusion	252
12.5.2 Inertial Confinement Fusion	253
12.6 Pre-Production Highlights 2009–2011	254
12.6.1 First Tests at NIF	254
12.6.2 Uncertainty in the Financing of ITER	255
12.6.3 Different Circumstances for ITER Facilities in Japan	256
12.7 Innovation Highlights 2009–2011	256
12.7.1 Some Scientists Still Insist on Cold and Bubble Fusion	256
12.7.2 NIF Researchers and Ignition	257
12.7.3 A Team of Researchers Reignite the JET Reactor	257
12.7.4 The Last of the Five Field-Period Module of the W7-X Stellarator Assembled	257
12.8 Publications and Patents Analysis	258
References	260
IV Storage and Management	
13 Solar Heating and Cooling	263
13.1 Overview	263
13.2 State of the Art	266
13.2.1 Materials	267
13.2.2 Cooling and Air Conditioning	268
13.2.3 Long-Term Storage	269
13.2.4 Solar Thermal Collectors	271
13.2.5 Control Systems	272
13.2.6 Stages of Development	272
13.3 Current Costs and Future Scenarios	274
13.4 Energy Payback, CO ₂ Emissions and External Costs	278
13.5 Future Technology Trends	278
13.5.1 Materials	278
13.5.2 Cooling and Air Conditioning	279
13.5.3 Long-Term Storage	280

13.5.4	Solar Thermal Collectors	280
13.5.5	Control Systems	280
13.6	Pre-Production Highlights 2009–2011	281
13.6.1	Thermotropic Polyamide Protection Against Overheating	281
13.6.2	Gasification of Biomass Energy from the Sun	281
13.6.3	The World’s Largest Solar District Heating System	281
13.6.4	Database of Architecturally Appealing Solar Thermal Systems Integrated Into Buildings	282
13.6.5	Solar Thermal Energy for Enhanced Oil Recovery	282
13.7	Innovation Highlights 2009–2011	282
13.7.1	Solar Thermal Heat Storage in NaOH	282
13.7.2	Non-Rectangular Collector Design	282
13.7.3	Thermionic-Based Solar Energy Converter	283
13.7.4	A New Binderless Sorption Material for Thermochemical Storage	284
13.8	Statistics of Publications and Patents	284
	References	287
14	Fuel Cells	289
14.1	Overview	289
14.2	State of the Art	290
14.2.1	Proton Exchange Membrane Fuel Cell	290
14.2.2	Phosphoric Acid Fuel Cells	293
14.2.3	Molten Carbonate Fuel Cells	293
14.2.4	Solid Oxide Fuel Cells	294
14.2.5	Alkaline Electrolyte Fuel Cells	294
14.2.6	Stages of Development	294
14.3	Current and Future Costs Scenarios	296
14.4	Energy Payback, CO ₂ Emissions and External Costs	298
14.5	Future Technology Trends	299
14.5.1	Proton Exchange Membrane Fuel Cell	299
14.5.2	Phosphoric Acid Fuel Cells	300
14.5.3	Molten Carbonate Fuel Cells	300
14.5.4	Solid Oxide Fuel Cells	300
14.5.5	Alkaline Electrolyte Fuel Cells	301
14.5.6	Other Future Aspects	301
14.6	Pre-Production Highlights 2009–2011	301
14.6.1	Fuel Cell Fed with Blood Sugar	301
14.6.2	World’s First Fuel Cell and Hydrogen Energy Station Commissioned	302

14.7	Innovation Highlights 2009–2011	302
14.7.1	Advances in the Substitution or Optimisation of Pt-Based Catalysts for Fuel Cells	302
14.7.2	The Impact of Anode Microstructure on the Properties of the Solid-State Fuel Cell	303
14.7.3	High-Performance Electrocatalysts for Oxygen Reduction Derived from Polyaniline, Iron and Cobalt	303
14.7.4	Water and Air Produce Energy	303
14.8	Statistics of Publications and Patents	304
	References	306
15	Electricity Storage	307
15.1	Overview	307
15.2	Current Technology	308
15.2.1	Batteries Technology (Lead–Acid, Metal–Air, Sodium–Sulphur, Redox Flow, Li-Ion, ZnBr and NiMH)	309
15.2.2	Compressed Air Storage	312
15.2.3	Flywheels	313
15.2.4	Storage in Superconductors	314
15.2.5	Electrochemical Capacitors	315
15.2.6	Pumped Hydropower Systems	316
15.2.7	Stages of Development	316
15.3	Current Costs and Future Scenarios	318
15.4	Payback Energy, CO ₂ Emissions and External Costs	320
15.5	Future Technology Trends	322
15.5.1	Batteries	322
15.5.2	Compressed Air Storage	323
15.5.3	Flywheels	323
15.5.4	Storage in Superconductors	324
15.5.5	Electrochemical Capacitors	324
15.5.6	Pumped Hydropower Systems	324
15.6	Pre-Production Highlights 2009–2011	325
15.6.1	Three New World Records for the PV and Li-Ion Batteries Powered Aircraft	325
15.6.2	Batteries Also for Building Cars	325
15.6.3	Production of Planar Li-Ion Batteries with Durable Nanostructured Films	326
15.6.4	Off-Shore Energy Bags	326
15.7	Innovation Highlights 2009–2011	327
15.7.1	Record with Supercapacitor Energy Storage	327
15.7.2	New Material for Ultrafast Discharge Batteries	327
15.7.3	Concrete Storage Spheres on the Seafloor	327

15.7.4	Hopes from Aluminium to Replace Lithium as Core Raw Material in Batteries	328
15.7.5	Ultra-Thin Flexible Battery With the Highest Charge Capacity Reported for Thin Film Batteries	328
15.7.6	A New Battery That Can Be Fully Recharged in Minutes	329
15.7.7	Laser Scribing of High-Performance and Flexible Graphene-Based Electrochemical Capacitors	330
15.8	Statistics of Publications and Patents	331
	References	333
16	Smart Grids and Supergrids	335
16.1	Overview	335
16.2	State of the Art	338
16.2.1	Smart Grid Components	338
16.2.2	Smart Grid Control Systems	339
16.2.3	Smart Grid Communications	339
16.2.4	Supergrids	340
16.2.5	Stages of Development	341
16.3	Current Costs and Future Scenarios	341
16.4	Energy Payback, CO ₂ Emissions and External Costs	342
16.5	Future Technology Trends	342
16.5.1	Smart Grid Components	342
16.5.2	Smart Grid Control Systems	344
16.5.3	Smart Grid Communications	346
16.5.4	Supergrids	346
16.6	Pre-Production Highlights 2009–2011	346
16.6.1	Instant Record in Wind Power, Hourly and Daily	346
16.6.2	ENTSO-E Electrical Systems Bordering Increase Electrical Exchange in 2011	347
16.6.3	SuperPower, Inc. Breaks Records in High-Temperature Superconducting Transmission of Power	347
16.7	Innovation Highlights 2009–2011	348
16.7.1	Agreement Signed Between Nine European Countries to Build the First Supergrid	348
16.7.2	DESERTEC Project Begins	348
16.7.3	Project TWENTIES Starts	349
16.7.4	Record Super-Thin Superconducting Cable	349
16.8	Publications and Patents Statistics	350
	References	352

17 Carbon Capture and Storage	353
17.1 Overview	353
17.2 The State of the Art	355
17.2.1 Post-Combustion Capture	356
17.2.2 Pre-Combustion Capture	356
17.2.3 Oxy-Fuelling	357
17.2.4 Chemical Looping Combustion	357
17.2.5 Transport of CO ₂	358
17.2.6 CO ₂ Storage	358
17.2.7 Stages of Development	359
17.3 Current Costs and Future Scenarios	361
17.3.1 Capture and Storage Costs	361
17.4 CO ₂ Emissions and External Costs	364
17.5 Future Technology Trends	365
17.5.1 Pre-Combustion Capture	365
17.5.2 Post-Combustion Capture	365
17.5.3 Oxy-Fuelling	366
17.5.4 Chemical Looping	366
17.5.5 Transport of CO ₂	366
17.5.6 CO ₂ Storage	367
17.6 Pre-Production Highlights 2009–2011	367
17.6.1 Entry Into Operation of the First CCS System Integrated in a Power Plant	367
17.6.2 Entry Into Operation of the First China's CCS Facility	368
17.6.3 Huaneng Group Opened a CCS Facility That Claims a USD 30–35/t CO ₂	369
17.7 Innovation Highlights 2009–2011	369
17.7.1 CCS Through Nanotubes	369
17.7.2 Metal-Organic Frameworks as New Materials for the Capture of CO ₂	369
17.7.3 FutureGen Project: Final Adoption in June 2009	370
17.8 Statistics of Publications and Patents	370
References	372
Index	375