## Contents

Comp	arative Impacts of Fossil Fuels and Alternative Energy Sources	1
Klaus	S. Lackner	
1	Introduction	1
2	Climate Change	2
3	The Urgent Need for Energy	4
4	The Environmental Impact of Energy	7
5	Carbon Capture and Storage	8
6	Stabilising Atmospheric Carbon Dioxide Concentrations	10
7	Geo-Engineering as a Means of Stabilising Climate	13
8	Energy Sources, Energy Carriers and Energy Uses	15
9	A Matter of Scales	17
10	Small Carbon-Neutral Energy	19
	10.1 Ocean Tides, Waves and Currents	19
	10.2 Hydroenergy	20
	10.3 Wind	21
	10.4 Biomass	21
	10.5 Geothermal	22
11	The Three Truly Big Energy Resources	23
	11.1 Nuclear Energy	23
	11.2 Solar Energy	24
	11.3 Fossil Fuels with Carbon Dioxide Capture and Storage	25
	11.4 Summary	27
12	Capture of Carbon Dioxide Directly from Ambient Air	28
13	A Revolution in the Energy Sector	31
14	Conclusions	3.4

Issues in Environmental Science and Technology, 29

Carbon Capture: Sequestration and Storage

Edited by R.E. Hester and R.M. Harrison

Published by the Royal Society of Chemistry, www.rsc.org

<sup>©</sup> Royal Society of Chemistry 2010

viii Contents

`	ibbins and Hannah Chalmers
1	Introduction
2	Reasons for Incentivising CCS Capture Projects
2	
	and the commercial search better the commercial search between the commercial search search between the commercial search between the commercial search search between the commercial search
	Deployment  2.2 Classes of Climate Change Mitigation Banefit
	2.2 Classes of Climate Change Mitigation Benefit with CCS
3	Features of Effective Incentives for Power Plants with CCS
4	Example CCS Incentives for the Electricity Sector
4	4.1 Site and Project-Specific Funding Options for First Trans
	Plants
	4.2 Electricity Emissions Performance Standards (EPSs)
	4.3 A Sectoral CCS Standard
5	Scope for Retrofitting CCS and the Role for Carbon Captu
	Ready (CCR) Plants
6	Conclusions
	Acknowledgements
	Appendix A Carbon Dioxide Capture Technologies Closest
	Commercial Deployment
	on Capture and Storage (CCS) in Australia
	on Capture and Storage (CCS) in Australia  Lowe, Burt Beasley and Thomas Berly
len	Lowe, Burt Beasley and Thomas Berly
len 1	Lowe, Burt Beasley and Thomas Berly  Background
len	Lowe, Burt Beasley and Thomas Berly  Background CCS Programs and Strategies
len 1	Lowe, Burt Beasley and Thomas Berly  Background CCS Programs and Strategies 2.1 General Policy
len 1	Lowe, Burt Beasley and Thomas Berly  Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding
len 1 2	Lowe, Burt Beasley and Thomas Berly  Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives
len 1	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia
len 1 2	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research
len 1 2	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO)
len 1 2	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO) 3.2 Cooperative Research Centre for Greenhouse Gas
len 1 2	Lowe, Burt Beasley and Thomas Berly  Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO) 3.2 Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)
len 1 2	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO) 3.2 Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) 3.3 Centre for Low Emission Technology (cLET)
1 2 3	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO) 3.2 Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) 3.3 Centre for Low Emission Technology (cLET) 3.4 University Research Activities
len 1 2	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO) 3.2 Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) 3.3 Centre for Low Emission Technology (cLET) 3.4 University Research Activities CCS Projects in Australia
1 2 3	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO) 3.2 Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) 3.3 Centre for Low Emission Technology (cLET) 3.4 University Research Activities CCS Projects in Australia 4.1 Commercial-Scale Projects Incorporating CCS
1 2 3	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO) 3.2 Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) 3.3 Centre for Low Emission Technology (cLET) 3.4 University Research Activities CCS Projects in Australia 4.1 Commercial-Scale Projects Incorporating CCS 4.2 Large-Scale Demonstration Projects
1 2 3	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO) 3.2 Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) 3.3 Centre for Low Emission Technology (cLET) 3.4 University Research Activities CCS Projects in Australia 4.1 Commercial-Scale Projects Incorporating CCS 4.2 Large-Scale Demonstration Projects 4.3 Pilot-Scale Demonstrations
1 2 3	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO) 3.2 Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) 3.3 Centre for Low Emission Technology (cLET) 3.4 University Research Activities CCS Projects in Australia 4.1 Commercial-Scale Projects Incorporating CCS 4.2 Large-Scale Demonstration Projects 4.3 Pilot-Scale Demonstrations 4.4 Storage Projects
en 1 2 3	Background CCS Programs and Strategies 2.1 General Policy 2.2 Governmental CCS Initiatives and Funding 2.3 Black Coal Mining Industry Initiatives CCS R&D Activities in Australia 3.1 Australia's Commonwealth Scientific and Research Organisation (CSIRO) 3.2 Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) 3.3 Centre for Low Emission Technology (cLET) 3.4 University Research Activities CCS Projects in Australia 4.1 Commercial-Scale Projects Incorporating CCS 4.2 Large-Scale Demonstration Projects 4.3 Pilot-Scale Demonstrations

Contents	ix
----------	----

	5.2 Commonwealth Offshore Petroleum and Greenhouse Gas Storage Act 2006 (OPA)	92
	5.3 State CCS Legislation	94
6	CCS Challenges in Australia	96
		70
	erground Coal Gasification (UCG) with Carbon Capture and Storage	
(CCS		102
Dern	not Roddy and Gerardo González	
1	Introduction	102
2	A Brief History of UCG	103
3	The Economic Case for UCG	105
4	An Introduction to UCG Technology	107
	4.1 Gasification Configuration and Control	108
	4.2 Directional Drilling	108
5	Current Status of UCG Deployment Worldwide	110
	5.1 UK and Europe	110
	5.2 North America	110
	5.3 Asia	111
	5.4 Australia	111
	5.5 Africa	111
6	Mechanism for Carbon Dioxide Storage in Gasified Coal Seam	
	Voids	111
7	Approaches to Environmental Risk Assessment	115
8	Linking UCG to CCS	118
9	North East England Case Study	121
10	Concluding Remarks on Scale of Opportunity and Challenges	123
Т	and 7 Edd Bullet Bullet Charlet	
	ards Zero Emission Production – Potential of Carbon Capture in	127
	gy Intensive Industry	126
David	d Pocklington and Richard Leese	
1	Overview	126
	1.1 Greenhouse Gas Reduction/Issues for Energy Intensive	
	Industry	126
2	Carbon Dioxide Emissions in Cement Manufacture	129
	2.1 Cement Manufacture	129
	2.2 Incentives for Carbon Reduction	131
	2.3 Costs Associated with Carbon Emissions	135
3	Options for Mitigation	138
	3.1 Mitigation in Cement Manufacture	138
	3.2 Carbon Capture and Cement Manufacture	140
	3.3 Removing Barriers to Development	145
4		150

	ogical Storage of Carbon Dioxide	155
Nick	Riley	
1	Introduction	155
2	Geology and CO <sub>2</sub> Storage	156
	2.1 Rock Characteristics	156
	2.2 CO <sub>2</sub> Properties and Geological Storage	158
	2.3 Pressure	162
3	CO <sub>2</sub> Storage through Enhanced Hydrocarbon	
	Recovery	165
	3.1 Enhanced Oil Recovery (EOR)	165
	3.2 Enhanced Gas Recovery (EGS)	166
	3.3 Enhanced Coal Bed Methane Recovery (ECBM)	167
	3.4 Shale Gas	167
4	Storage Options	168
	4.1 CO <sub>2</sub> Storage in Salt Caverns	168
	4.2 Underground Coal Gasification Cavities	168
	4.3 CO <sub>2</sub> Storage as CO <sub>2</sub> Hydrates	169
	4.4 CO <sub>2</sub> Storage in Igneous/Metamorphic Rocks	169
5	Storage Capacity	169
	5.1 The Resource Pyramid	169
,	5.2 Estimating Storage Capacity	170
6	Storage Site Operation	171
	6.1 Geological Characterisation	171
	6.2 Risk Assessment	172 172
	6.3 Measurement, Monitoring and Verification (MMV)	172
7	6.4 Leakage	173
7 8	Public Awareness of CO <sub>2</sub> Storage Conclusions	174
0		174
	Acknowledgements	173
Carb	on Sequestration in Soils	179
Step	hen J. Chapman	
1	Introduction to the Carbon Cycle in Soil	179
	1.1 Plant Production	180
	1.2 Decomposition	180
	1.3 Soil Organic Matter	182
	1.4 Characteristics and Age of Soil Carbon	183
_	1.5 Losses to Water	183
2	Factors Influencing Carbon Accumulation	184
	2.1 Climate	185
	2.2 Plant Inputs	185
	2.3 Other Organic Inputs	186
	2.4 Tillage	187

Contents	xi

	2.5 Grazing	187
	2.6 Drainage/Irrigation	187
	2.7 Erosion	188
	2.8 Fire Cycles	188
3	Land-Cover Classes and their Carbon-Sequestration	
	Characteristics	189
	3.1 Arable	189
	3.2 Grassland	190
	3.3 Forest/Woodland	190
	3.4 Semi-Natural	190
	3.5 Land-Use Change	190
4	Climatic Zones other than Cool Temperate	191
	4.1 Warm Temperate	191
	4.2 Tropical	191
5	The Quantification of Carbon-Sequestration Strategies	191
	5.1 Worldwide Soil Carbon Sequestration Potential	192
	5.2 Soil Carbon Sequestration Potential for Europe	193
	5.3 Soil Carbon Sequestration Potential for the UK	195
	5.4 Biochar Additions	195
	5.5 Other Greenhouse Gases and Carbon Equivalents	197
	5.6 Whole Cycle Analysis	198
6	Limitations and Challenges	198
	6.1 Realistic Goals	198
	6.2 Upper Limits and Timescales	200
	6.3 Competing Processes	200
Carb	on Capture and Storage in Forests	203
	ia Nijnik	200
1	Introduction: The Role of Forestry in Climate Change	
	Mitigation	203
2	Carbon Pools and Flows in Forests	206
3	Carbon Sink and Storage in Forests: Several Implications from	
	Europe	211
	3.1 A Focus on the United Kingdom	212
	3.2 A Focus on Transitional Countries of Ukraine and Slovakia	214
	3.3 A Focus on The Netherlands	217
4	A Focus on Tropical Forests	219
5	Economic Considerations of Carbon Sink and Storage in	
	Forests	221
6	Uncertainties Pertaining to Carbon Sink and Storage in	1
v	Forests	226
7	Social Considerations of Carbon Sink and Storage in Forests	229
8	Conclusions	232

xii Contents

Carbon Uptake, Transport and Storage by Oceans and the Consequences of Change		240
	urley, J. Blackford, N. Hardman-Mountford, E. Litt, C. Llewellyn,	
	owe, P. Miller, P. Nightingale, A. Rees, T. Smyth, G. Tilstone and	
	iddicombe	
1	Summary	240
2	Carbon Uptake by Oceans	241
	2.1 Air-Sea Exchange of Carbon Dioxide and the Chemistry of	
	Carbon in Seawater	241
	2.2 Carbon Fixation and Controlling Factors	243
3	Carbon Transport and Storage by Oceans	250
	3.1 The Solubility Pump	250
	3.2 The Biological Pumps	255
4	Consequences of Too Little Uptake	256
	4.1 Slow Down of the Physical Ocean Sink and Feedbacks to	
	Climate	256
	4.2 Changes in Net Primary Productivity	257
5	Consequences of Too Much Uptake	260
	5.1 Ocean Acidification	260
	5.2 Oxygen Depletion and Harmful Algal Blooms (HABs)	269
Math	nane Biogeochemistry and Carbon Stores in the Arctic Ocean:	
	rates and Permafrost	285
•	ilis Kitidis	-00
russ	ms Krims	
1	Introduction	285
	1.1 Methane: Marine Sources and Sinks	286
	1.2 Arctic Ocean Methane and Global Warming	286
2	Methane Hydrates	287
	2.1 Methane Hydrates and Hydrate Stability	287
	2.2 The 'Clathrate Gun' Hypothesis	289
	2.3 Methane Hydrates - Arctic Ocean	289
	2.4 Methane Hydrate Exploitation in the Arctic	290
3	Permafrost	291
	3.1 Permafrost Relevance to Methane	291
	3.2 Permafrost and Global Warming	292
4	Methane in the Arctic Ocean	292
	4.1 Distribution, Sources and Sinks	292
	4.2 Methane and Sea-Ice	294
5	Conclusions	295
Subi	ect Index	301