

Contents

Preface XIII

List of Contributors XV

Part 1 Introduction and Overview

1 The Case for Carbon Capture and Storage 3

Klaus S. Lackner

Abstract 3

1.1 Introduction 3

1.2 Dilution versus Treatment 4

1.3 Carbon Reservoirs 5

1.4 Excess Carbon 5

1.5 The Scale of Carbon Capture and Storage 6

1.6 Storage Capacity Requirements 7

1.7 Conclusion 8

References 9

2 Advanced Power Plant Technology 11

Hartmut Spliethoff

Abstract 11

2.1 Introduction 11

2.2 History of the Development of Power Plants –
Correlation Between Unit Size, Availability, and Efficiency 12

2.3 Possibilities for Efficiency Increases in the Development
of a Steam Power Plant 15

References 40

3	Capture Options for Coal Power Plants	45
	<i>Ernst Riensche, Jewgeni Nazarko, Sebastian Schiebahn, Michael Weber, Li Zhao, and Detlef Stolten</i>	
	Abstract	45
3.1	Introduction	45
3.2	Requirements on CO ₂ Capture and Compression	47
3.3	CO ₂ Capture Routes	53
3.4	Gas Separation Tasks and Methods	54
3.5	Plant Concepts for Carbon Capture	65
3.6	Carbon Dioxide Compression	74
3.7	Conclusion	75
	Acknowledgments	75
	References	76
4	Life Cycle Assessment for Power Plants with CCS	83
	<i>Peter Viebahn</i>	
	Abstract	83
4.1	Introduction	83
4.2	Life Cycle Assessment as an Assessment Method	84
4.3	Review of Life Cycle Assessments Along the Whole CCS Chain	85
4.4	Results	99
4.5	Constraints of LCA Regarding an Assessment of CCS	102
4.6	Comparison of Electricity from CCS and from Renewable Energies	104
4.7	Conclusion on Needs for Action	105
	Acknowledgment	107
	References	107
Part 2	CO₂ Scrubbing	
5	Physics and Chemistry of Absorption for CO₂ Capture to Coal Power Plants	113
	<i>Paul Feron and Graeme Puxty</i>	
	Abstract	113
5.1	Gas Separation for CO ₂ Capture	113
5.2	Process Engineering and Performance	120
5.3	Physical Absorption	124
5.4	Chemical Absorption	131
5.5	Physical Properties	145
5.6	Outlook	146
	Acknowledgments	147
	Symbols and Nomenclature	147
	References	149

Materials for CO₂ Scrubbing**6 Chemical Absorption Materials for CO₂ Capture 155***Kaj Thomsen*

Abstract 155

6.1 Introduction 155

6.2 Alkanolamines 157

6.3 Sodium and Potassium Carbonates 160

6.4 Ammonia 162

6.5 Amino Acid Salts 167

6.6 Ionic Liquids 168

6.7 Conclusion 168

References 169

7 Physical Absorption Materials for CO₂ Capture 175*Sebastian Schiebahn, Li Zhao and Marcus Grünewald*

Abstract 175

7.1 Introduction 175

7.2 Pre-Combustion Capture in IGCC 176

7.3 Physical Absorption Materials and Processes 179

7.4 Conclusions and Outlook 195

References 196

Processes for CO₂ Scrubbing**8 CO₂ Removal in Coal Power Plants via Post-Combustion with Absorbents 201***Hans Fahlenkamp, Bernhard Epp, Stefan Telge, Christina Stankewitz, and Martin Dittmar*

Abstract 201

8.1 Tail-End CO₂ Capture 202

8.2 Demonstration Plants and Pilot Plants 216

8.3 Conclusion 236

Symbols and Abbreviations 237

References 238

9 CO₂ Removal in Coal Power Plants via Pre-Combustion with Physical Absorption 241*Stéphane Walspurger, Eric van Dijk, and Ruud van den Brink*

Abstract 241

9.1 Introduction 242

9.2 The Sorption-Enhanced Water Gas Shift Process 250

9.3 Sorption Processes and Material Development for SEWGS 256

9.4 Conclusion and Outlook 263

Acknowledgments 264

References 264

Part 3 CO₂ Removal with Cryogenic Air Separation

10 CO₂ Capture via the Oxyfuel Process with Cryogenic Air Separation 271

Alfons Kather and Mathias Klostermann

Abstract 271

10.1 Introduction 271

10.2 Flue Gas Recycle 273

10.3 Combustion 276

10.4 CO₂ Purification and Capture 278

10.5 Efficiency 284

10.6 Current Developments 291

References 292

Part 4 Separation with Membranes

11 Physics of Membrane Separation of CO₂ 297

Matthias Wessling

Abstract 297

11.1 Introduction 297

11.2 Macroscopic Mass Transport 300

11.3 Permeation Through Materials 302

11.4 Membrane Geometries and Morphologies 309

11.5 Fluid Dynamics and Modules 310

11.6 Process Design 313

11.7 Conclusion 315

References 316

Materials for Membrane Separation of CO₂

12 Inorganic Membranes for CO₂ Separation 319

Wilhelm A. Meulenber, Ingolf Voigt, Ralf Kriegel, Stefan Baumann, Mariya Ivanova, and Tim van Gestel

Abstract 319

12.1 Introduction 320

12.2 Membranes for Gas Separation 321

12.3 Conclusion and Outlook 343

References 344

13	Polymer Membranes for CO₂ Separation	351
	<i>Sander R. Reijerkerk, Kitty Nijmeijer, Jens Potreck, Katja Simons, and Matthias Wessling</i>	
	Abstract	351
13.1	Introduction	352
13.2	Polymer Membranes for CO ₂ Capture	354
13.3	Theoretical Gas and Vapor Transport Through Dense Polymer Membranes	360
13.4	Gas and Vapor Transport Through Dense Polymer Membranes for Flue Gas Treatment	364
13.5	Conclusion	374
	References	376

Processes for Membrane Separation of CO₂

14	CO₂ Separation via the Post-Combustion Process with Membranes in Coal Power Plants	381
	<i>Peter Michael Follmann, Christoph Bayer, Matthias Wessling, and Thomas Melin</i>	
	Abstract	381
14.1	Introduction	381
14.2	Process Boundary Conditions	382
14.3	Membranes and Membrane Modeling	386
14.4	Membrane Processes	391
14.5	Economics of Membrane Processes for CO ₂ Capture	399
14.6	Summary and Conclusions	400
	Acknowledgment	400
	References	401
15	CO₂ Separation via the Oxyfuel Process with O₂-Transport Membranes in Coal Power Plants	405
	<i>Franz Beggel, Nicolas Nauels, and Michael Modigell</i>	
	Abstract	405
15.1	Introduction	405
15.2	MIEC Membrane Operating Concepts	406
15.3	Hard Coal Membrane-Based Oxyfuel Process	408
15.4	Literature Review of Membrane-Based Oxyfuel Processes	416
15.5	Towards Realization – Module Design	421
15.6	Conclusion	427
	References	428

16	CO₂ Separation via Pre-Combustion Utilizing Membranes in Coal Power Plants	431
	<i>Viktor Scherer and Johannes Franz</i>	
	Abstract	431
16.1	Introduction	431
16.2	Process Conditions, Membrane Characteristics, Classification Numbers, Permeation Laws, and Water Gas Shift	432
16.3	Pre-Combustion Concepts with Scrubbing Technologies	444
16.4	Pre-Combustion Concepts with CO ₂ -Selective Membranes	445
16.5	Pre-Combustion Concepts with H ₂ -Selective Membranes	453
16.6	Conclusion	466
	References	468
Part 5	Chemical Looping for CO₂ Separation	
17	Chemical Looping Materials for CO₂ Separation	475
	<i>Anders Lyngfelt and Tobias Mattisson</i>	
	Abstract	475
17.1	Introduction	475
17.2	Chemical Looping Combustion of Solid Fuels	478
17.3	Chemical Looping with Oxygen Uncoupling (CLOU)	478
17.4	Chemical Looping Reforming	479
17.5	Chemical Looping Gasification of Solid Fuels	480
17.6	Oxygen Carrier Development	481
17.7	Reactor Design and Operational Experience in Chemical Looping Combustors	493
17.8	Reactivity and Solids Inventory	495
17.9	Conclusion	495
	References	496
18	Chemical Looping in Power Plants	505
	<i>Bernd Eppler and Jochen Ströhle</i>	
	Abstract	505
18.1	Introduction	505
18.2	Chemical Looping Combustion	506
18.3	Carbonate Looping Process	514
18.4	Conclusion	520
	References	522

Part 6	Transportation and Storage of CO₂	
19	CO₂ Compression	527
	<i>Mark A. Gray</i>	
	Abstract	527
19.1	CO ₂ Compression and Storage – Magnitude of the Issue	527
19.2	CO ₂ Compression Energy Consumption – Heat Integration	528
19.3	Heat Recovery Opportunities	532
19.4	CO ₂ Purity and Pipeline Transport Issues	533
19.5	CO ₂ Storage Development – Prudent Practices	534
19.6	Public Policy and Long-Term Liability	537
19.7	Conclusion	539
	References	540
20	CO₂ Transport – The Missing Link for CCS	541
	<i>Chris A. Hendriks, Erika de Visser, and Joris Koornneef</i>	
	Abstract	541
20.1	Introduction	541
20.2	Experience with CO ₂ Transport	542
20.3	CO ₂ Transport by Pipeline	544
20.4	CO ₂ Transport by Ship	552
20.5	Ships Compared with Pipelines	557
20.6	CO ₂ Infrastructure Networks	558
20.7	Regulation and Investment Decisions	561
20.8	Strategic Planning for Pipelines	565
	References	568
21	Storage of Fossil Carbon	573
	<i>Klaus S. Lackner</i>	
	Abstract	573
21.1	Introduction	573
21.2	Summary of Storage Options	574
21.3	Current Activities	578
21.4	Utilization Versus Disposal	581
21.5	Different Forms of Stored Carbon	584
21.6	Storage Lifetime	591
21.7	Storage Capacity Requirements	592
21.8	Closing Natural Carbon Cycles	593
21.9	The Role of Alkalinity	593
21.10	Storage Safety	594
21.11	Storage Accountability	595
21.12	Conclusion	596
	References	598
Index		601

