Contents

Preface *xiii*

1 Introduction to Carbon Capture and Environmental Sustainability *1*
1.1 What is Carbon Capture? *1*
1.2 The Role of CO_2 in Global Climate Change *3*
1.3 Definitions and Pillars of Environmental Sustainability *3*
1.4 Historical Context and Evolution of Carbon Capture Technologies *4*
1.5 Why Carbon Capture is Needed: A Multidimensional Perspective *5*
1.5.1 Environmental Necessity: Reducing Atmospheric CO_2 *6*
1.5.2 Economic Logic: Supporting Industry Without Shutting It Down *6*
1.5.3 Political Realities: Bridging Gaps Between Nations *7*
1.5.4 Time Pressure: Acting Quickly on Multiple Fronts *7*
1.5.5 Social and Ethical Dimensions: Responsibility and Justice *8*
1.5.6 Criticism and Caution *9*
1.5.7 Conclusion *9*
1.6 Bridging Policy, Environment, and Ethics *10*
1.6.1 The Role of Policy *10*
1.6.2 Environmental Goals and Trade-Offs *10*
1.6.3 Ethics and Climate Responsibilities *11*
1.6.4 Connecting the Dots *12*
1.7 Structure and Objectives of This Book *13*
1.8 Key Highlights (Chapter Summary) *14*
References *14*

2 Climate Change, Global Emissions, and the Need for Carbon Capture *17*
2.1 Overview of Global Climate Target and Role of CCS *17*
2.2 Sources and Trends of Greenhouse Gas Emissions *19*
2.2.1 Major Sources of Emission *19*
2.2.2 Global Emission Trends *20*
2.3 Role of CO_2 and Its Global Impact *22*
2.3.1 The Role of CO_2 in the Greenhouse Effect *22*
2.3.2 Global Impacts of Elevated CO_2 Levels *24*
2.3.3 Carbon Cycle and Management *25*

2.4 The Scientific Basis: IPCC Reports and Climate Models *27*
2.5 The Paris Agreement and Global Carbon Targets *28*
2.6 Limits of Current Climate Action and the Need for Carbon Capture *29*
2.7 Key Highlights (Chapter Summary) *32*
References *33*

3 Environmental Justice and Carbon Management Policies *37*
3.1 What is Environmental Justice? *37*
3.2 Historical Examples of Environmental Inequities *39*
3.3 Justice in the Context of Carbon Capture *39*
3.4 Policy Frameworks Supporting Just Carbon Management *41*
3.4.1 Policy Tools for a Just Transition *41*
3.4.2 Participation, Inclusion, and Global Perspectives *42*
3.5 Environmental Racism and Community Resistance *44*
3.6 Ensuring Equitable Access and Participation *46*
3.7 Key Highlights (Chapter Summary) *47*
References *47*

4 Principles and Types of Carbon Capture Technologies *51*
4.1 Overview of Carbon Capture Mechanisms *51*
4.2 Post-combustion Capture *52*
4.3 Precombustion Capture *54*
4.4 Oxy-Fuel Combustion *56*
4.5 Direct Air Capture (DAC) *57*
4.6 Bioenergy with Carbon Capture and Storage (BECCS) *59*
4.7 Comparative Evaluation—Efficiency, Cost, and Feasibility *62*
4.8 Key Highlights (Chapter Summary) *63*
References *64*

5 Social Acceptance and Public Perception of Carbon Capture Projects *67*
5.1 Why Public Perception Matters? *67*
5.2 Historical Cases of Public Opposition *68*
5.3 Risk Communication and Transparency *69*
5.3.1 Understanding and Communicating Risk Perception *69*
5.3.2 Transparency, Community Engagement, and Trust Building *70*
5.4 Influence of Media and Social Networks *71*
5.4.1 Influence of Traditional and Social Media *71*
5.4.2 Strategies for Media Response and Public Trust *73*
5.5 Behavioral Psychology and Climate Technology *73*
5.6 Strategies for Building Trust and Acceptance *75*
5.7 Key Highlights (Chapter Summary) *76*
References *77*

6 Health, Safety, and Environmental (HSE) Considerations *81*
6.1 Overview of HSE in Carbon Capture Projects *81*
6.2 Occupational and Community Health Concerns *81*

6.3 Environmental Impacts and Risk Scenarios *85*
6.4 Pipeline Safety and CO_2 Transportation Hazards *86*
6.5 Safety Regulations and International Standards *89*
6.6 Emergency Response and Contingency Planning *91*
6.7 Key Highlights (Chapter Summary) *93*
References *94*

7 Carbon Capture and Sustainable Development Goals (SDGs) *99*
7.1 Overview of the SDGs and Their Relevance to Carbon Capture *99*
7.2 SDG 13 (Climate Action) *101*
7.3 SDG 7 (Clean Energy) and Renewable Integration *103*
7.4 SDG 9 (Industry, Innovation, and Infrastructure) *103*
7.5 SDG 11 (Sustainable Cities and Communities) *106*
7.6 Balancing Benefits and Challenges of CCS and SDGs *110*
7.7 Key Highlights (Chapter Summary) *110*
References *111*

8 Carbon Capture in Developing vs. Developed Countries *115*
8.1 Global Inequality in CCS Technology Access *115*
8.2 Infrastructure Gaps in Developing Countries *118*
8.3 Financial Barriers and the Role of Climate Finance *120*
8.4 Policy Readiness and Institutional Capacity *123*
8.5 North–South Technology Transfer and Equity *125*
8.6 Case Studies: Contrasting Regional Approaches Toward CCS *127*
8.6.1 North America (United States and Canada) *127*
8.6.2 Europe (Norway, United Kingdom, and the Netherlands) *128*
8.6.3 Middle East (UAE, Saudi Arabia, and Qatar) *129*
8.6.4 Asia-Pacific (China, Japan, and Indonesia) *129*
8.6.5 Africa and Latin America *130*
8.7 Conclusion *130*
8.8 Key Highlights (Chapter Summary) *131*
References *131*

9 Policy Mechanisms and Regulatory Frameworks *137*
9.1 Overview of Carbon Policy Mechanisms *137*
9.2 Carbon Pricing: Taxes and Emissions Trading Systems *139*
9.3 Regulatory Mandates and Technology Standards *140*
9.4 Government Subsidies and Incentives *142*
9.5 International Frameworks and Agreements *144*
9.6 Evaluating Policy Effectiveness and Gaps *147*
9.7 Key Highlights (Chapter Summary) *149*
References *150*

10 Community Engagement and Ethical Dimensions of Carbon Projects *155*
10.1 Ethics of Large-Scale Environmental Technologies *155*
10.2 Procedural Justice and Inclusive Governance *157*

10.3 Informed Consent and Community Rights *159*
10.4 Trust-Building and Long-Term Commitments *161*
10.5 Benefit-Sharing Mechanisms *163*
10.6 Avoiding Green Colonialism and Ethical Missteps *165*
10.7 Key Highlights (Chapter Summary) *167*
References *167*

11 Carbon Capture and the Water–Energy Nexus *171*
11.1 Understanding the Water–Energy Nexus *171*
11.2 Water Demands of Carbon Capture Processes *172*
11.3 Energy Requirements and Carbon Intensity *174*
11.4 Geographic and Regional Constraints *177*
11.5 Design Strategies for Resource Optimization *180*
11.6 Challenges Facing CCS Projects *182*
11.7 Key Highlights (Chapter Summary) *183*
References *184*

12 Integration of Carbon Capture with Renewable Energy Systems *189*
12.1 Why Integration with Renewables Matters *189*
12.2 Opportunities for Bioenergy with CCS (BECCS) *191*
12.3 Solar- and Wind-Powered Capture Systems *193*
12.4 Hybrid Plant Designs and Case Examples *197*
12.5 Energy Storage, Load Management, and Flexibility *199*
12.5.1 Long-Duration Energy Storage (LDES) *199*
12.5.2 Demand Response and Grid Services *201*
12.5.3 Curtailment Utilization and Power-to-X Integration *201*
12.5.4 Flexible Operation and Process Optimization *203*
12.5.5 Hybrid Operation with Industrial Processes *203*
12.6 Technical and Policy Challenges of Integration *204*
12.7 Key Highlights (Chapter Summary) *205*
References *206*

13 Carbon Capture, Circular Economy, and Resource Efficiency *211*
13.1 Circular Economy Structure *211*
13.2 From Waste to Value: CO_2 as a Resource *213*
13.3 Utilization Pathways: Fuels, Chemicals, and Building Materials *216*
13.4 Resource Efficiency in Capture Technologies *220*
13.5 Designing Closed-Loop Carbon Systems *222*
13.6 Industrial Symbiosis and Innovation *223*
13.7 Key Global CCS Initiatives and Projects *225*
References *225*

14 Economic Considerations and Financial Models *231*
14.1 Overview of Global Climate Targets and the Role of CCS *231*
14.2 Levelized Cost of CO_2 Abatement (LCCA) *233*

14.2.1 What Is LCCA and Why Is It Important? *233*
14.2.2 How LCCA Is Calculated? *233*
14.2.3 Key Factors Affecting LCCA *234*
14.2.3.1 Capital and Operating Costs *234*
14.2.3.2 Capture Efficiency *234*
14.2.3.3 Project Size (Economies of Scale) *235*
14.2.3.4 Operating Lifetime and Plant Reliability *236*
14.2.3.5 Transport and Storage Costs *237*
14.2.3.6 Energy Prices and Energy Sources *238*
14.2.4 How Stakeholders Use LCCA and Other Indicators *239*
14.2.5 Summary and Importance of LCCA *240*
14.3 Risk and Return in Low-Carbon Investment *240*
14.3.1 Investment Risks in Carbon Capture Technology *240*
14.3.2 Potential Revenue Sources in Carbon Capture Technology *242*
14.4 Carbon Credit Trading and Market Incentives *244*
14.5 Public–Private Partnerships and Financing Mechanisms *246*
14.6 Case Studies of Financially Feasible Projects *249*
14.7 Key Highlights (Chapter Summary) *251*
References *252*

15 Case Studies in Carbon Capture and Environmental Impact *257*
15.1 Case Study 1: Large-Scale CCS in the Power Sector *257*
15.2 Case Study 2: Industrial Capture and CO_2 Utilization *260*
15.3 Case Study 3: BECCS Pilot Projects *263*
15.4 Case Study 4: Community-Led Environmental Monitoring *266*
15.5 Comparative Analysis of Environmental Outcomes *269*
15.6 Key Takeaways and Lessons Learned *270*
15.7 Key Highlights (Chapter Summary) *272*
References *273*

16 Future Perspectives: Justice, Sustainability, and System Redesign *277*
16.1 Summary of Crosscutting Themes *277*
16.2 Rethinking Carbon Capture Beyond Technology *279*
16.3 Long-Term Justice and Global Equity *282*
16.4 Regenerative Environmental Governance *285*
16.5 Innovations on the Horizon *287*
16.6 Strategic Recommendations and Calls to Action *292*
16.7 Key Highlights (Chapter Summary) *293*
References *294*

17 Artificial Intelligence, Digitalization, and Smart Carbon Capture Systems *299*
17.1 Role of Digitalization in Carbon Capture *299*
17.1.1 Digitalization in CCS: Concept and Data Infrastructure *299*
17.1.2 Artificial Intelligence, Optimization, and Predictive Maintenance *300*
17.1.3 Digital Safety, Compliance, and Sustainability in CCS *300*

17.2 Foundations of AI and Machine Learning in Carbon Capture and Storage *302*
17.2.1 Artificial Intelligence and Data Foundations for CCS *302*
17.2.2 Machine Learning Methodologies and Training *303*
17.2.3 AI for Process Optimization and Predictive Maintenance *305*
17.3 Digital Twins for Process Optimization *306*
17.3.1 Digital-Twin Architecture and Data Integration *307*
17.3.2 Simulation, Anomaly Detection, and Process Optimization *307*
17.3.3 Operational Applications, Safety, and Sustainability *308*
17.4 Predictive Maintenance and Leak Detection Systems *310*
17.4.1 Predictive Maintenance Fundamentals and Equipment Health Monitoring *310*
17.4.2 Leak Detection, Robotic Inspection, and Safety Compliance *311*
17.5 Automation and Smart Safety Systems *313*
17.5.1 Operational Automation and Robotic Inspection *313*
17.5.2 Smart Safety Systems, Environmental Monitoring, and Cybersecurity *314*
17.6 Ethical, Workforce, and Cybersecurity Considerations *316*
17.7 Key Highlights (Chapter Summary) *318*
References *319*

18 Nature-Based Carbon Capture and Ecological Solutions *325*
18.1 Introduction to Nature-Based Carbon Removal *325*
18.1.1 Fundamentals and Benefits of Nature-Based Carbon Removal *325*
18.1.2 Limitations, Measurement Challenges, Social and Policy *326*
18.2 Forest-Based Carbon Capture Systems *328*
18.2.1 Principles and Benefits of Forest-Based Carbon Capture *328*
18.2.2 Challenges, Monitoring, and Governance *329*
18.3 Wetlands, Mangroves, and Blue Carbon Ecosystems *331*
18.4 Ocean Alkalinity and Marine-Based Approaches *333*
18.5 Soil-Carbon Sequestration in Agriculture *335*
18.5.1 Mechanisms, Practices, Benefits, and Measurement *335*
18.5.2 Policy, Socioeconomic Factors, and Integration with CCS *337*
18.6 Synergy Between Nature-Based and Engineered CCS Solutions *337*
18.7 Key Highlights (Chapter Summary) *340*
References *341*

19 Education, Skills Development, and Public Capacity-Building for Carbon Capture *345*
19.1 Importance of Knowledge and Skills in CCS Expansion *345*
19.2 University Programs and Technical Training Pathways *347*
19.3 Interdisciplinary Competencies for Future Workforce *349*
19.4 Public Awareness and Climate Education Programs *352*
19.5 International Collaboration and Knowledge Transfer *354*
19.6 Strategies for Long-Term Capacity-Building *356*
19.6.1 Strengthening Educational Infrastructure *356*
19.6.2 Promoting Long-Term Learning and Workforce Reskilling *357*
19.6.3 Building Strong Institutional Organs *357*

19.6.4 Enhancing Community Understanding and Participation *357*
19.6.5 Strengthening International Knowledge Exchange *357*
19.6.6 Supporting Innovation and Research Capacity *357*
19.7 Key Highlights (Chapter Summary) *358*
References *358*

20 Ethics, Governance, and Long-Term Stewardship of Carbon Storage *363*
20.1 Ethical Considerations in Long-Term Carbon Storage *363*
20.2 Governance Models and Institutional Responsibilities *365*
20.3 Long-Term Monitoring and Liability Frameworks *368*
20.4 Transparency and Community Accountability *371*
20.5 International Legal and Regulatory Perspectives *373*
20.6 Designing Durable Stewardship Frameworks *374*
20.7 Key Highlights (Chapter Summary) *376*
References *377*

Index *383*