# Contents

List of Contributors .......................................................... xvii
Series Preface .................................................................. xxiii
Preface ........................................................................... xxv

1 The Growing Role of Biomass for Future Resource Supply—Prospects and Pitfalls .......................... 1
   Helmut Haberl
   1.1 Introduction .................................................................. 1
   1.2 Global Ecological and Socioeconomic Biomass Flows ......... 3
   1.3 Global Biomass Potentials in 2050 ................................. 5
      1.3.1 Primary Biomass Potentials .................................. 6
      1.3.2 Residue and Waste Potentials ............................... 8
   1.4 Critical Socio-Ecological Feedbacks and Sustainability Issues ...................................................... 9
      1.4.1 Land-Use Competition and Systemic Feedbacks ...... 9
      1.4.2 Carbon Cycle Feedbacks ...................................... 11
   1.5 Conclusions ................................................................ 12
Acknowledgements ................................................................. 12
References .................................................................. 13

2 The Growing Role of Photovoltaic Solar, Wind and Geothermal Energy as Renewables for Electricity Generation .................................................. 19
   Wilfried G.J.H.M. van Sark, J. Gerard Schepers, and Jan Diederik A.M. van Wees
   2.1 General Introduction .................................................... 19
   2.2 Photovoltaic Solar Energy ............................................. 21
      2.2.1 PV Technology .................................................... 22
      2.2.2 Environmental Issues ........................................... 23
      2.2.3 Outlook ............................................................ 24
2.3 Wind Energy 24
   2.3.1 Social Acceptance and the Move Toward Offshore 27
   2.3.2 Costs/kWh 27
   2.3.3 Wind Energy in the Next Decade: Prognosis 28
2.4 Geothermal Energy 28
   2.4.1 Geothermal Development 29
   2.4.2 Geothermal Technology 30
   2.4.3 Future Outlook 33
2.5 Conclusion 33
References 34

3 Assessment of Sustainability within Holistic Process Design 37
   Alexei Lapkin, Philipp-Maximilian Jacob, Polina Yaseneva,
   Charles Gordon, and Amy Peace
   3.1 Introduction: Holistic Process Design from Unit Operations
   to Systems Science Methods 37
   3.2 Use of Life Cycle Assessment in Holistic Process Design 40
   3.3 A Decision-Tree Methodology for Complex Process Design 41
   3.3.1 Identification of Key Process Drivers 42
   3.3.2 Process Decision Tree 43
   3.4 Generation of New Synthesis Routes in Bio-Based Supply Chains 45
   3.5 Conclusions 47
Acknowledgements 48
References 48

4 A Mass Balance Approach to Link Sustainable Renewable Resources
   in Chemical Synthesis with Market Demand 51
   Claudius Kormann and Andreas Kicherer
   4.1 Introduction 51
   4.2 Renewable Feedstock: Market Drivers, Political Frame 52
   4.3 Traceability of Biomass as Feedstock in the Chemical Industry 53
   4.3.1 Chain-Of-Custody Schemes 53
   4.3.2 Upstream Traceability in the Supply Chain 54
   4.3.3 Downstream Traceability in Production: Biomass for
       Dedicated and Mass Balanced Chemicals 55
   4.3.4 Certification Quality and Trust 56
   4.3.5 Conclusion 56
   4.4 Standard of Mass Balance in Chemical Synthesis 57
   4.4.1 CEN Definition of Mass Balance 57
   4.4.2 Mass Balance in the Biofuel Sector as Example 57
   4.4.3 Mass Balance Adapted to Chemistry 57
       4.4.3.1 Principle of Mass Balance in an Integrated
               Chemical Production 58
       4.4.3.2 Mass Balance Example Calculation 59
### 5 Early R&D Stage Sustainability Assessment: The 5-Pillar Method

*Akshay D. Patel, John A. Posada, Li Shen, and Martin K. Patel*

5.1 Introduction 65  
5.2 Methodology 67  
5.2.1 The 5-Pillar Method 67  
5.2.2 5-Pillars and Integration 68  
5.3 Case Study 73  
5.3.1 Case Study Results 74  
5.4 Validation Case Study 75  
5.5 Critical Review and Outlook 76  
5.6 Conclusion 79  
References 79

### 6 Assessing the Sustainability of Land Use: A Systems Approach

*Miguel Brandão*

6.1 Introduction 81  
6.2 Methodological Issue 1: Consequential Analysis of Land Use Decisions 82  
6.3 Methodological Issue 2: Land Use Impacts on Ecosystems 87  
6.4 Methodological Issue 3: Land Use Impacts on Climate 89  
6.5 Methodological Issue 4: Economic and Social Impact Assessment 90  
6.6 Methodological Issue 5: Integrating Environmental and Economic Assessments 92  
6.7 Discussion 93  
6.8 Conclusions 94  
References 94

### 7 Water Use Analysis

*Francesca Verones, Stephan Pfister, and Markus Berger*

7.1 Introduction 97  
7.2 Methods and Tools for Assessing the Sustainable Use of Water 98  
7.2.1 Water in Life Cycle Assessment 98  
7.2.2 Water Footprinting as Stand-Alone Method 100  
7.2.3 Water Risk Tools 101  
7.3 Case Study: Water Consumption Analysis of Biofuels and Fossil Fuels 102  
7.4 Discussion and Conclusion 105  
References 106
8 Material Intensity of Food Production and Consumption 109
   Lucia Mancini and Michael Lettenmeier
     8.1 Introduction 109
     8.2 Material Flow Based Approaches for Assessing Sustainable
        Production and Consumption Systems 110
     8.3 MIPS Concept and Methodology 111
        8.3.1 Concept 111
        8.3.2 Methodology 112
        8.3.3 Performing a Material Intensity Analysis 112
     8.4 Material Intensity of Food Systems 113
        8.4.1 Analysis of Production Systems 114
           8.4.1.1 Data Acquisition 116
           8.4.1.2 Assumptions, Sources of Uncertainty and
              Allocation Rules 116
        8.4.2 Analysis of Consumption Habits and Impacts of Diets 117
     8.5 Results of MIPS for Agricultural Products and Foodstuffs 118
        8.5.1 Discussion on Results 121
     8.6 Conclusions 121
     References 122

9 Material and Energy Flow Analysis 125
   Goto Naohiro, Nova Ulhasanah, Hirotsugu Kamahara, Udin Hasanudin,
   Ryuichi Tachibana, and Koichi Fujie
     9.1 Background 125
     9.2 Methodology 128
        9.2.1 Material and Energy Flow Analysis 128
        9.2.2 Data Collection 129
        9.2.3 Method of Analysis 130
     9.3 Case Study 131
        9.3.1 Palm Oil 131
        9.3.2 Cassava 134
        9.3.3 Other (Case Study of the Cement Industry) 135
     9.4 Conclusion 139
     Acknowledgements 139
     References 139

10 Exergy and Cumulative Exergy Use Analysis 141
   Sofie Huysman, Thomas Schaubroeck, and Jo Dewulf
     10.1 What Is Exergy? 141
     10.2 Calculation of Exergy 142
     10.3 Applications of Exergy 144
        10.3.1 Use in Industrial System Analysis 144
        10.3.2 Use in Sustainability Analysis 145
11 Carbon and Environmental Footprint Methods for
Renewables-based Products and Transition Pathways to 2050
Geoffrey P. Hammond

11.1 Introduction
11.1.1 Transition Pathways Towards a Low Carbon Future 155
11.1.2 The Sustainability Assessment Context 157
11.1.3 The Issues Considered 158

11.2 Carbon and Environmental (or Eco) Footprinting 159
11.2.1 Carbon and Environmental Footprinting – The Basics 159
11.2.2 The Carbon Footprint Component 161
11.2.3 Other Components of the Environmental Footprint 161
11.2.4 Determination of the Biofuel Footprint Components
11.2.4.1 Bioreproductive and Built Land 162
11.2.4.2 Carbon Emissions 163
11.2.4.3 Embodied Energy 164
11.2.4.4 Transport 164
11.2.4.5 Waste Arisings 165
11.2.4.6 Water Usage 166

11.3 The Relationship between Environmental Footprint Analysis (EFA) and Environmental Life-Cycle Assessment (LCA) 166

11.4 Carbon and Environmental Footprints Associated with Global Biofuel Production 167
11.4.1 Global Projections of Biofuel Production 167
11.4.2 Carbon Footprint of Biofuels 168
11.4.3 Environmental Footprint of Biofuels 168
11.4.4 The Implications for the ‘Energy-Land-Water Nexus’ 169

11.5 Carbon and Environmental Footprints of Low Carbon Transition Pathways 171
11.5.1 Selecting Low Carbon Transition Pathways or Scenarios to 2050 171
11.5.2 Realising Transition Pathways: Insights from Footprint Analysis 171
11.5.3 Power Sector Environmental Footprints per GWh 172

11.6 Concluding Remarks 174
Acknowledgements 175
References 176
12 Tracking Supply and Demand of Biocapacity through Ecological Footprint Accounting
David Lin, Alessandro Galli, Michael Borucke, Elias Lazarus,
Nicole Grunewald, Jon Martindill, David Zimmerman, Serena Mancini,
Katsunori Iha, and Mathis Wackernagel

12.1 Summary and Rationale 179
  12.1.1 Summary and Purpose of the Chapter 179
  12.1.2 Information Needs for Sustainability 180
  12.1.3 Scale As a Core Principle of Sustainability 181
  12.1.4 Research Question/Framing the Ecological Footprint 181

12.2 Methodology 182
  12.2.1 Conceptual Framework 182
  12.2.2 Implementation: The National Footprint Accounts 182
    12.2.2.1 National Biocapacity and Ecological Footprint Calculation 182
    12.2.2.2 Normalization Factors 187
    12.2.2.3 Specific Land-Use Classes 188
    12.2.2.4 Derived Products 191
  12.2.3 Ecological Footprint Applications 191
    12.2.3.1 Ecological Footprint of Products 191
    12.2.3.2 Environmental Extended Multi-Region Input Output Analysis 192

12.3 Usage Recommendations 193
  12.3.1 Key Strengths and Limitations 193

12.4 Future Developments 195

References 195

13 Life Cycle Assessment and Sustainability Supporting Decision Making by Business and Policy
Sala Serenella, Fabrice Mathieux, and Rana Pant

13.1 Life Cycle Assessment: A Systemic Approach to Evaluate Impacts 201
  13.1.1 What Is LCA? 202
  13.1.2 Procedural Steps 203

13.2 LCA: Supporting Sustainability Assessment 205
  13.2.1 Strengths and Peculiarities of LCA 205

13.3 Role of LCA in Supporting Decisions in Business and Policy Context 206
  13.3.1 Role of LCA in Supporting Business Decisions 207
    13.3.1.1 The Example of Ecodesign of Industrial Products 207
  13.3.2 Role of LCA in Policy Making 208
    13.3.2.1 Examples of LCA in Current EU Product Policies 208
    13.3.2.2 Ecodesign Directive 209
    13.3.2.3 Single Market for Green Products Initiative 209

References 209
## Contents

- **13.4 Tools and Support to Put LCA into Practice**
  - 13.4.1 The Umbrella: The European Platform on Life Cycle Assessment (EPLCA) 210
  - 13.4.1.1 How to Perform an LCA: Databases and Software 210
  - 13.4.1.2 Where to Find Data?—ELCD and Life Cycle Data Network (LCDN) 210
- 13.5 Conclusion and the Way Forward 211
- Acknowledgements 211
- References 212

### 14 Life Cycle Costing

*Andreas Ciroth, Jutta Hildenbrand, and Bengt Steen*

- 14.1 Life Cycle Costing – Definition and Principles 215
- 14.2 Environmental LCC 216
  - 14.2.1 Key Elements of an Environmental LCC Model in Common with LCA 217
  - 14.2.2 Time and Discounting 219
  - 14.2.3 Perspectives 220
- 14.3 Societal LCC 220
- 14.4 LCC and Renewables 221
- 14.5 Example Case 222
  - 14.5.1 Outline and Calculation of the Case Study 222
  - 14.5.2 Discussion of Case Study Results, and Setting Them in Perspective to Environmental LCC 223
- References 228

### 15 Social Life Cycle Assessment: Methodologies and Practice

*Alessandra Zamagni, Pauline Feschet, Anna Irene De Luca, Nathalie Iofrida, and Patrizia Buttol*

- 15.1 Introduction 229
- 15.2 Social Life Cycle Assessment: Scientific Background 230
- 15.3 Social Life Cycle Assessment in Practice 232
- 15.4 SLCA and Life Cycle Sustainability Assessment: Methodological Challenges 234
- 15.5 Conclusions and Outlook 236
- References 237

### 16 Life Cycle Assessment of Solar Technologies

*Fulvio Ardente, Maurizio Cellura, Sonia Longo, and Marina Mistretta*

- 16.1 Introduction 241
- 16.2 Solar Technologies 242
  - 16.2.1 Solar Thermal Collectors 242
  - 16.2.2 Photovoltaic Technologies 242
16.2.3 Solar Cooling Technologies 244
16.2.4 Other Solar Technologies 244

16.3 Life Cycle Assessment (LCA) and Solar Technologies 245
16.3.1 Solar Thermal Plants 246
16.3.2 Photovoltaic Plants 246
16.3.3 Concentrating Solar Power (CSP) Plants and Solar Heating/Cooling Plants 249

16.4 Assessment of Solar Technologies 249
16.4.1 Variability of the Results and Methodological Issues 254

16.5 Conclusions 256
References 256

17 Assessing the Sustainability of Geothermal Utilization 259
Ruth Shortall, Gudni Axelsson, and Brynhildur Davidsdottir

17.1 Introduction 259

17.2 Sustainable Geothermal Utilization 260
17.2.1 Nature and Production Capacity of Geothermal Resources 260
17.2.2 Sustainable Geothermal Production – Definition and Time-Scale 261
17.2.3 Long Utilization Case Histories and Modelling 263
17.2.3.1 Long Utilization Case Histories 263
17.2.3.2 Sustainability Modelling 264

17.3 Broader Sustainability Assessment of Energy Developments 266
17.3.1 Sustainable Energy Development 266
17.3.2 Sustainability Assessment and Energy Development 266

17.4 Sustainability Assessment Framework for Geothermal Power 266
17.4.1 Framework Development 266
17.4.2 Stakeholder Engagement 267
17.4.3 Iterative Development Process 267
17.4.4 Final Set of Sustainability Goals and Sustainability Indicators 268

17.5 Conclusion 271
References 271

18 Biofuels from Terrestrial Biomass: Sustainability Assessment of Sugarcane Biorefineries in Brazil 275
Otavio Cavalett, Marcos D.B. Watanabe, Alexandre Souza, Mateus F. Chagas, Tassia L. Junqueira, and Antonio Bonomi

18.1 Introduction 275

18.2 The Virtual Sugarcane Biorefinery (VSB) 276

18.3 Methods Used in the VSB 277
18.4 Biorefinery Scenarios Case Study 279
18.4.1 Life Cycle Assessment 279
18.4.2 Hybrid Input-Output Analysis 281
18.4.3 Financial Analysis 283
18.4.4 Uncertainties on the Life-Cycle GHG Emissions 284
18.4.5 Sugarcane Biorefineries versus Fossil-Based Refineries 285
18.5 Final Remarks 286
Acknowledgements 286
References 287

19 Algae as Promising Biofeedstock; Searching for Sustainable Production Processes and Market Applications 289
Sue Ellen Taelman, Steven De Meester, and Jo Dewulf
19.1 Introduction 289
19.2 Algae Background 290
19.2.1 The Habitats and Biology of Algae 290
19.2.2 Aquatic Algae versus Terrestrial Plants 290
19.3 Algal Cultivation and Processing Methods 292
19.3.1 Cultivation Systems 292
19.3.1.1 Microalgae 292
19.3.1.2 Macroalgae 292
19.3.2 Harvesting and Processing of Algal Biomass 293
19.4 Algae: Production and Potential Applications 294
19.4.1 Pollution Treatment 294
19.4.2 Algal-Based Bioenergy 295
19.4.2.1 Biodiesel 295
19.4.2.2 Bioethanol 296
19.4.2.3 Biogas 296
19.4.2.4 Other Energy Applications 296
19.4.3 Algal-Based Bioproducts 297
19.4.4 Biorefinery 298
19.5 Environmental Sustainability of Algae Production 298
19.5.1 Non-Renewable Energy Consumption 299
19.5.2 Fresh Water Use 300
19.5.3 Atmospheric Emissions 301
19.6 Conclusions 302
References 303

20 Life Cycle Assessment of Biobased and Fossil-Based Succinic Acid 307
Marieke Smidt, Jeroen den Hollander, Henk Bosch, Yang Xiang, Maarten van der Graaf, Anne Lambin, and Jean-Pierre Duda
20.1 Production of Succinic Acid 307
20.1.1 Succinic Acid, A Key Biobased Building Block 307
22.2 Environmental Assessment of Wood Cascading by LCA 338
   22.2.1 Equality-Of-Benefits of Multi-Output Systems 338
   22.2.2 Recovered Wood Cascading in Comparison to Direct Incineration – System Description and Data 339
   22.2.3 Choice of LCA Impact Categories for Assessing Wood Products 341
   22.2.4 Results of Comparing Cascading Use to Direct Incineration 341
22.3 Discussion and Conclusion 343
   22.3.1 Assessing Resource Efficiency of Wood in LCA 343
   22.3.2 Effects of Choices of System Expansion 344
   22.3.3 Consideration of Time in LCA 344
   22.3.4 Modelling Carbon Storage 345
   22.3.5 Outlook 345
Acknowledgements 345
References 345

23 Time-Dependent Life-Cycle Assessment of Bio-Based Packaging Materials 347
Maartje N. Sevenster

23.1 Introduction 347
   23.1.1 Dynamic Modelling of Climate Change 348
   23.1.2 Recent Packaging LCA 350
   23.1.3 Outline of This Chapter 350

23.2 Methodology 351
   23.2.1 Decay in Landfill 351
      23.2.1.1 Case Study A 352
      23.2.1.2 Case Study B 352
   23.3 Results 353
      23.3.1 Case Study A 353
      23.3.1.1 Recycling of Cardboard 354
      23.3.2 Case Study B 355
         23.3.2.1 Effective GWP100 for Landfilled Materials 356

23.4 Discussion 357
23.5 Conclusions 358
References 358

24 Conclusions 361
Jo Dewulf

24.1 The Importance of Renewables-Based Products and Services 361
24.2 The Need for Sustainability Assessment for Renewables: Even More Than in the Past 362
24.3 The Growing Sustainability Assessment Toolbox 363
24.4 Outlook: Pending Challenges 364

Index 365