

Table of contents

| | |
|---|--------|
| About the book series | vii |
| Editorial board | ix |
| Contributors | xxvii |
| Foreword by Gustav Melin | xxix |
| Editor's Foreword | xxxii |
| About the editor | xxxiii |
| Acknowledgements | xxxv |
| Introduction <i>Erik Dahlquist</i> | 1 |
| <i>Part I Biomass resources</i> | 3 |
| 1. Introduction and context: global biomass resources – types of biomass, quantities and accessibility. Biomass from agriculture, forestry, energy crops and organic wastes <i>Erik Dahlquist & Jochen Bundschuh</i> | 5 |
| 1.1 Hard facts | 5 |
| 1.2 Crops used primarily for food | 8 |
| 1.2.1 Soybean | 8 |
| 1.2.2 Rice | 8 |
| 1.2.3 Wheat (<i>Triticum</i> spp.) | 9 |
| 1.2.4 Corn (<i>Zea mays</i>) and cassava | 9 |
| 1.2.5 Barley, rye and oats | 10 |
| 1.2.6 Oil crops | 10 |
| 1.2.7 Sugar cane | 10 |
| 1.3 Energy crops | 10 |
| 1.3.1 Switch grass | 11 |
| 1.3.2 Giant Kings Grass | 11 |
| 1.3.3 Hybrid poplar | 13 |
| 1.3.4 Other proposed energy crops | 14 |
| 1.3.5 Quorn | 14 |
| 1.4 Animalian biomass and algae | 15 |
| 1.4.1 Animalian food | 15 |
| 1.4.2 Algae | 17 |
| 1.5 Regional overviews | 18 |
| 1.5.1 EU27 – an overall energy balance | 18 |
| 1.5.2 China – today and in year 2050 | 19 |
| 1.5.3 India | 23 |
| 1.5.4 USA | 24 |
| 1.5.5 Brazil | 26 |
| 1.5.6 Africa south of the Sahara | 27 |
| 1.6 Other regions | 27 |

| | | |
|---------|---|----|
| 1.7 | Global perspective | 30 |
| 1.8 | Questions for discussion | 31 |
| 2. | Chemical composition of biomass | 35 |
| | <i>Torbjörn A. Lestander</i> | |
| 2.1 | Introduction | 35 |
| 2.1.1 | A new biocarbon era | 35 |
| 2.1.2 | The potential of biomass for energy conversion | 36 |
| 2.2 | Major components of biomass | 38 |
| 2.2.1 | Water in biomass | 39 |
| 2.2.2 | Dry matter content | 40 |
| 2.3 | Organic matter | 40 |
| 2.3.1 | Cellulose | 41 |
| 2.3.2 | Hemicellulose | 41 |
| 2.3.3 | Lignin | 42 |
| 2.3.4 | Extractives | 42 |
| 2.3.5 | Sugars | 42 |
| 2.3.6 | Starch | 43 |
| 2.3.7 | Proteins | 43 |
| 2.4 | Inorganic substances | 43 |
| 2.5 | Energy content | 46 |
| 2.6 | Chemical compounds and biomass processing | 48 |
| 2.6.1 | Drying | 48 |
| 2.6.2 | Wet processing | 49 |
| 2.6.3 | Health aspects | 49 |
| 2.6.4 | Bulk handling | 50 |
| 2.6.5 | Heat treatment of biomass | 51 |
| 2.7 | Conclusion | 53 |
| 2.8 | Questions for discussion | 54 |
| 3. | Characterization of biomass using instruments – Measurement of forest and crop residues | 57 |
| | <i>Robert Aulin</i> | |
| 3.1 | Introduction | 57 |
| 3.2 | Quality aspects and sources of variation | 57 |
| 3.2.1 | Volume, weight and moisture content | 57 |
| 3.2.2 | Calorific value | 58 |
| 3.2.3 | Other parameters | 58 |
| 3.3 | The fuel chain and its impact on the moisture content | 59 |
| 3.3.1 | The fuel chain | 59 |
| 3.3.2 | Sources of variation in moisture content | 59 |
| 3.3.2.1 | The forest | 59 |
| 3.3.2.2 | Terminal storage | 59 |
| 3.3.2.3 | Transport | 61 |
| 3.3.2.4 | Site storage and fuel handling | 61 |
| 3.4 | Moisture measurement | 61 |
| 3.4.1 | Gravimetric moisture measurement | 61 |
| 3.4.1.1 | The gravimetric method | 61 |
| 3.4.1.2 | Sampling | 62 |
| 3.4.1.3 | Practical illustration | 63 |
| 3.4.2 | Instrumental methods | 63 |
| 3.4.2.1 | Introduction | 63 |
| 3.4.2.2 | Near-infrared spectroscopy (NIR) | 64 |

| | | |
|---------|---|-----|
| 3.4.2.3 | Microwave spectroscopy (RF) | 65 |
| 3.4.2.4 | X-ray spectroscopy | 65 |
| 3.4.2.5 | Method selection | 67 |
| 3.5 | Practical applications for moisture data | 67 |
| 3.5.1 | Real-time measurement | 67 |
| 3.5.2 | Price settlement | 67 |
| 3.5.3 | Logistics | 68 |
| 3.5.4 | Fuel mixing | 68 |
| 3.5.5 | Boiler control | 68 |
| 3.6 | Future perspectives | 68 |
| 4. | Bioenergy in Brazil – from traditional to modern systems <i>Semida Silveira</i> | 71 |
| 4.1 | From developing country to leading economy | 71 |
| 4.2 | From traditional fuelwood to multiple bioenergy systems | 72 |
| 4.3 | Forest-based biomass in Brazil | 74 |
| 4.3.1 | Fuel wood and charcoal – traditional uses of biomass in Brazil | 77 |
| 4.4 | Biofuels for transport | 79 |
| 4.4.1 | The development of modern bioethanol production | 79 |
| 4.4.2 | The development of biodiesel production | 81 |
| 4.5 | Bioenergy – opportunities for sustainable development | 83 |
| 5. | Biomass in different biotopes – an extensive resource <i>Erik Dahlquist & Jochen Bundschuh</i> | 87 |
| 5.1 | Bioenergy in northern Europe | 87 |
| 5.1.1 | Different biotopes | 88 |
| 5.2 | Bioenergy in southern Europe | 94 |
| 5.3 | Biomass in the tropics | 104 |
| 5.4 | Questions for discussions | 106 |
| 6. | Organic waste as a biomass resource <i>Eva Thorin, Thorsten Ahrens, Elias Hakalehto & Ari Jääskeläinen</i> | 109 |
| 6.1 | Introduction | 109 |
| 6.2 | Pre-treatment | 109 |
| 6.2.1 | Examples of pre-treatment | 111 |
| 6.3 | Biogas production | 112 |
| 6.3.1 | Basics of the biogas process | 112 |
| 6.3.2 | Technical background for waste-to-biogas utilization strategies | 113 |
| 6.3.3 | Results from waste digestion | 114 |
| 6.3.4 | Example for a local implementation strategy | 117 |
| 6.4 | Combustion of waste | 118 |
| 6.4.1 | Technical background | 118 |
| 6.4.2 | Examples of combustion of waste | 118 |
| 6.4.3 | Development considerations | 120 |
| 6.5 | Examples of use of organic waste in other conversion processes | 120 |
| 6.5.1 | Ethanol and butanol from organic waste | 120 |
| 6.5.2 | Hydrothermal carbonization of organic waste fractions | 122 |
| 6.5.2.1 | HTC reactions | 122 |
| 6.5.2.2 | Substrates | 122 |
| 6.5.2.3 | HTC of a selected biowaste substrate | 123 |
| 6.5.3 | Pyrolysis and gasification of organic waste | 127 |
| 6.6 | Questions for discussion | 129 |

| | |
|---|-----|
| <i>Part II Systems utilizing biomass – system optimization</i> | 135 |
| 7. System aspects of biomass use in complex applications: biorefineries for production of heat, electric power and chemicals <i>Erik Dahlquist & Jochen Bundschuh</i> | 137 |
| 7.1 Traditional use of wood | 137 |
| 7.2 Use of waste and wood for chemicals | 137 |
| 7.3 Use of herbs for medical and other applications | 138 |
| 8. Biorefineries using wood for production of speciality cellulose fibers, lignosulfonates, vanillin, bioethanol and biogas – the Borregaard Sarpsborg example <i>Stefan Backa, Martin Andresen & Trond Rojahn</i> | 141 |
| 8.1 Introduction | 141 |
| 8.2 The borregaard sarpsborg biorefinery of today | 144 |
| 8.2.1 Lignocellulosic crops and residues | 145 |
| 8.2.2 Biomaterials, specialty celluloses | 145 |
| 8.2.3 Bioethanol | 145 |
| 8.2.4 Biomaterials, lignosulfonates | 146 |
| 8.2.5 Food/chemicals, vanillin | 147 |
| 8.3 Energy | 147 |
| 8.4 Environment | 147 |
| 8.5 The future | 148 |
| 8.6 Conclusion | 149 |
| 9. Biorefineries using crops for production of ethanol, biogas and chemicals – a large-scale demonstration in Nanyang, Henan province, China of the bio-ethanol industry under Tianguan recycling economic mode <i>Du Feng-Guang & Feng Wensheng</i> | 151 |
| 9.1 Introduction | 151 |
| 9.2 Domestic and international background and conditions related this case study | 151 |
| 9.3 Qualitative analysis of the case study | 152 |
| 9.3.1 The scope of the case study | 152 |
| 9.3.2 Description of the basic characteristics of the case study | 152 |
| 9.3.3 The recycling economic diagram and its analysis of this case | 153 |
| 9.4 Quantitative analysis of this case study | 154 |
| 9.4.1 Changes in four major indicator systems | 154 |
| 9.5 Energy flow analysis | 155 |
| 9.5.1 The diagram of system general material flow | 156 |
| 9.6 General material flow analysis | 157 |
| 9.6.1 Analysis of systems group diversion | 158 |
| 9.7 System improvements | 160 |
| 9.8 Conclusion | 160 |
| 10. Bioenergy polygeneration, carbon capture and storage related to the pulp and paper industry and power plants <i>Jinyue Yan, Muhammad Raza Naqvi & Erik Dahlquist</i> | 163 |
| 10.1 Introduction | 163 |
| 10.2 Biorefinery systems in the pulp industry | 165 |
| 10.2.1 Black liquor gasification (BLG) based biofuel production | 165 |
| 10.2.2 Black liquor gasification-based power generation | 166 |
| 10.3 Biofuel upgrading with pellet production | 166 |
| 10.4 Performance and sustainability analysis | 168 |
| 10.4.1 Performance of BLG-based biofuel production | 168 |

| | | |
|--------|--|-----|
| 10.4.2 | Performance of BLG-based electricity generation | 171 |
| 10.4.3 | Performance of pellet production system | 171 |
| 10.5 | Bioenergy systems and CCS potential | 172 |
| 10.5.1 | BLG systems with CCS | 173 |
| 10.6 | Conclusions | 174 |
| 11. | Biofuels and green aviation | 177 |
| | <i>Emily Nelson</i> | |
| 11.1 | Introduction | 177 |
| 11.2 | Aviation fuel requirements | 180 |
| 11.2.1 | Jet fuel specifications | 180 |
| 11.2.2 | Alternative jet fuel specifications | 188 |
| 11.3 | Fuel properties | 190 |
| 11.3.1 | Effect of composition on fuel properties | 190 |
| 11.3.2 | Emissions | 200 |
| 11.4 | Biofuel feedstocks for aviation fuels | 201 |
| 11.4.1 | Crop production for oil from seeds | 201 |
| 11.4.2 | Crop production for oil from algae | 204 |
| 11.5 | Manufacturing stages | 208 |
| 11.5.1 | Dewatering, crude oil extraction and pre-processing | 209 |
| 11.5.2 | Transesterification | 210 |
| 11.5.3 | Hydroprocessing | 212 |
| 11.5.4 | Other strategies | 213 |
| 11.5.5 | Co-products | 213 |
| 11.6 | Life cycle assessment | 214 |
| 11.7 | Conclusions | 218 |
| 12. | Pulp and paper industry – trends for the future | 229 |
| | <i>Erik Dahlquist & Jochen Bundschuh</i> | |
| 13. | Biorefineries using waste – production of energy and chemicals from biomasses by micro-organisms | 235 |
| | <i>Elias Hakalehto, Ari Jääskeläinen, Tarmo Humpi & Lauri Heitto</i> | |
| 13.1 | Introduction | 235 |
| 13.2 | Sustainable production of fuels and chemicals from wastes and other biomasses | 236 |
| 13.2.1 | Circulation of matter and chemical energy in microbiological processes | 236 |
| 13.3 | Replacing fossil fuels by the biomasses as raw materials | 236 |
| 13.4 | Microbes carry out the reactions with energetically feasible biocatalysis | 238 |
| 13.4.1 | Ecological thinking based on understanding microscopic interactions | 238 |
| 13.4.2 | Air and water pollution diminished by natural processes | 239 |
| 13.5 | Transport of fuels and chemicals less abundant and risky when local sources are exploited | 239 |
| 13.6 | Beneficial impact on the socio-economic structures of the new, small or medium sized bioindustries | 240 |
| 13.7 | Biomass and raw materials | 241 |
| 13.7.1 | Enzymatic hydrolysis of macromolecules | 242 |
| 13.7.2 | Hemicellulose, cellulose and lignin | 242 |
| 13.7.3 | Starch and other saccharides from food industry by-streams and agriculture | 243 |
| 13.7.4 | Industrial waste biomasses | 243 |
| 13.7.5 | Municipal waste and waste water utilization | 245 |
| 13.7.6 | Removal of harmful substances | 247 |

| | | |
|---------|---|-----|
| 13.8 | Fermentation processes and bioreactor design revolutionized | 248 |
| 13.8.1 | Increased productivity lowers the cost of bioreactor construction and downstream processes | 248 |
| 13.8.2 | PMEU (Portable Microbe Enrichment Unit) used for process simulation | 248 |
| 13.8.3 | Anaerobiosis made efficient | 249 |
| 13.8.4 | Some exploitable biochemical pathways of bacteria and other microbes | 250 |
| 13.8.5 | Mixed cultures in bioengineering | 251 |
| 13.8.6 | Novel principles for the planning of unit operations for bulk production | 251 |
| 13.9 | Thermophilic processes | 253 |
| 13.10 | Volatile products | 254 |
| 13.11 | Differences between chemical technologies and biotechnical process solutions | 255 |
| 13.12 | Biorefinery concept evaluation | 255 |
| 13.12.1 | New ideas on materials: all process wastes serve as raw materials in nature | 255 |
| 13.12.2 | Multiple uses of the production equipment | 256 |
| 13.12.3 | Plant nutrition and agriculture connected with bioindustries | 256 |
| 13.12.4 | Local products of microbial metabolism with global impacts | 257 |
| 13.13 | Conclusions | 258 |
| 14. | Concluding remarks and perspectives on the future of energy systems using biomass <i>Erik Dahlquist, Elias Hakalehto & Semida Silveira</i> | 263 |
| | Subject index | 267 |