

# TABLE OF CONTENTS

---

1. Introduction .....	1
Biomass Energy in the Year 2000—The Issues .....	1
Background .....	1
The Resurgence of Biomass Energy .....	2
A Commercial Opportunity for the Agricultural Sector .....	3
Incentives for the Food-to-Biofuel Transition .....	4
The Seemingly Intractable Problem of Farm Surpluses .....	6
An Energy Policy Including Biomass .....	8
The Risks of Biomass Energy Commercialization .....	10
The Current Importance of Biomass Energy .....	12
Barriers to Biomass Energy Progress .....	14
Biofuels—A Brief History .....	19
Solid Fuels.....	19
Liquid Fuels .....	22
Gaseous Fuels .....	27
The North–South Energy Divide .....	30
Introduction to the Third World .....	30
A Daunting Prospect .....	30
The Energy Poverty of Developing Countries .....	31
Terms and Definitions .....	34
2. Photosynthesis and Biomass Yields .....	57
Solar Energy—From Sun to Earth .....	57
Mechanisms of Photosynthesis .....	60
Photosynthetic Efficiencies .....	62
Plant Biomass Productivities .....	63
Energy Farming .....	65
3. Dedicated Biomass Feedstocks .....	69
Energy Forestry and Nonwoody (Herbaceous) Crops—An Introduction .....	69
Overview .....	69

Biomass Feedstocks in the US .....	69
Woody and Herbaceous Crops—Production Technology for Improved Results .....	73
Short Rotation Woody Crops (SRWCs) .....	73
Introduction .....	73
Site Requirements .....	76
Agronomic and Cropping Strategies .....	77
Harvesting Approaches .....	79
Herbaceous Energy Crops (HECs) .....	80
Introduction .....	80
Thin-Stemmed Perennials .....	81
Thick-Stemmed Perennials .....	84
Thick-Stemmed Annuals .....	85
Other Herbaceous Crop Candidates .....	87
Strategies for Woody and Herbaceous Energy Crops .....	87
Biotechnologically Improved Energy Crops .....	89
Introduction .....	89
The Genetic Improvement of Napiergrass and Hybrids .....	90
Genetic Improvement of <i>Pennisetum</i> for Biomass Production via DNA Markers .....	92
The Genetics and Management of Sorghum Systems for Biomass Production .....	93
Oil Crops .....	95
Introduction .....	95
Crops and Yields .....	96
African Oil Palm .....	96
Coconut Palm .....	97
Babassu Palm .....	97
Chinese Tallow Tree .....	98
Physic Nut .....	98
<i>Salicornia Bigelovii</i> .....	98
Cuphea and Others .....	99
Sunflower .....	99
Groundnut .....	99
Soybean .....	99
Rapeseed .....	100
Microorganisms .....	100

## Table of Contents

---

Algae .....	100
Conclusions .....	101
Economic Factors.....	101
Overview .....	101
Feedstock Production Costs in the US .....	102
Introduction.....	102
Projected Costs Based on Past Costs.....	103
Individual Energy Crop Comparisons .....	105
European and Other Countries' Feedstock Production Costs .....	110
Overview .....	110
Implementation Barriers .....	113
 4. Biomass Residues and Wastes .....	115
Introduction .....	115
Agricultural and Forestry Residues and Wastes .....	118
The Overall UK Scene .....	118
The US Situation .....	119
Comparisons with Coal .....	120
Municipal and Industrial Wastes .....	123
The UK Scene .....	123
The US Situation .....	125
Economic, Commercial, Social, and Political Factors .....	129
 5. Conversion Technologies and Energy Products .....	135
Fermentation to Ethanol .....	135
Overview .....	135
The Fermentation and Distillation Processes .....	138
The Basic Technology .....	138
Energy Conservation .....	140
Ethanol-Gasoline Blends .....	145
Introduction.....	145
Octane Quality.....	147
Fuel Economy .....	149
Vehicle Performance .....	150
Gasoline-Engined Vehicles .....	150

Diesel-Engined Vehicles .....	150
Commercial and Economic Factors Resulting from Vehicle Modifications .....	151
A Brief Interim Summary .....	153
Techno-Market Issues Involving Oxygenates and Octane Numbers .....	154
Commercial and Economic Aspects .....	157
Corn to Ethanol in the US .....	157
Gasoline Companies and Farmers Link Up in France .....	160
Conclusions Based on UK/European Economic Factors .....	163
Summary .....	165
Anaerobic Digestion to Methane .....	165
Overview .....	165
Technology—Digester Types .....	166
System Advances .....	167
Landfill Sites .....	168
Introduction .....	168
Landfill Technology and Management .....	169
Landfill Site Selection, Planning, and Legislation in the UK .....	171
Landfill Gas .....	183
Current Economic Status and Future Prospects .....	185
Thermochemical Conversions .....	187
Introduction .....	187
Liquefaction .....	187
Gasification .....	188
Advanced Thermal Conversion Technologies .....	189
Pyrolysis to Bio-Oil and Then Electricity Generation .....	189
Gasification .....	193
Biocrude from Wood .....	194
Rapid Thermal Processing (RTP) .....	196
The Concept .....	196
Commercialization and Economics .....	196
Catalytic Upgrading of Bio-Oils .....	197
The Utilization of HZSM-5 .....	197
The Utilization of Zeolite Catalysts .....	198
The Utilization of CoMo and NiMo Catalysts .....	199
Catalytic Conditioning of Synthesis Gas Produced by Biomass Gasification .....	200

---

Utilization of Pyrolysis Oil in a Diesel Engine and Overall Economics .....	201
Combustion of Biomass .....	202
Introduction .....	202
Electricity from Biomass in the US .....	203
The Overall Rationale .....	203
Industrial Projections .....	205
Technology Options .....	206
Introduction .....	206
Direct Combustion .....	207
Biomass-Derived Fuels for Gas Turbines .....	208
Wood Cofiring .....	209
Biomass for Electric Power—The Case of California .....	211
Overview .....	211
Operational Difficulties .....	212
Biomass-Fueled, Fluidized Bed Combustion .....	214
Technology .....	214
Emissions .....	215
Cogeneration in Finland .....	217
Biodiesel from Vegetable Oils and Animal Fats .....	220
Overview and RME (Rapeseed Oil Methyl Ester) Characteristics .....	220
RME and Animal Tallow Production and Performance .....	222
Vegetable Oils .....	222
Animal Tallow .....	223
Vehicle Modifications and Demonstrations .....	225
Modifications .....	225
Demonstrations .....	225
Commercial and Economic Factors .....	227
6. Lignocellulosic Fermentation—Panacea or Cul-de-Sac? .....	231
The Difficulties of Fermenting Cellulose-Enzymatic Hydrolysis .....	232
Lignocellulose Pretreatment .....	234
Acid Hydrolysis of Lignocellulose .....	236
Simultaneous Saccharification and Fermentation (SSF) .....	237
Overview .....	237
Clostridial Fermentations .....	238

Other Microbial Fermentations .....	240
Process Energy—Potential Reductions .....	242
Technoeconomic and Commercial Prognosis .....	243
Overview .....	243
Lignin Utilization .....	244
Cost Reductions .....	245
A Practical Example .....	246
The Future .....	247
7. Biomass: The Power Behind the Third World? .....	249
Overview .....	249
The Energy Mix as a Reflection of Natural Socioeconomic Indicators .....	250
The Case of Malaysia .....	250
Energy Overview .....	250
Oil Palm Wastes .....	251
Forest Residues .....	251
Rubber Residues .....	252
Rice Residues .....	252
Urban Waste .....	252
The Overall Picture .....	253
The Technologies .....	255
Biogas Plants .....	255
Energy Crop Plantations .....	262
Improved-Efficiency Cooking Stoves .....	264
Electric Power Generation.....	264
Gasification, Pyrolysis, and Ethanol Fermentation .....	265
Algal Cultivation.....	265
8. Energy Analysis of Biomass Systems.....	267
Concept and Methodology .....	267
The IFIAS Convention .....	267
Aims and Uses .....	269
Alternatives to Monetary Evaluation .....	269
Energy Cost Prediction .....	269
Energy Quality Assessment .....	270



## Table of Contents

---

Energy Analysis of Biofuel Production Systems .....	271
Energy Inputs to Feedstock Production.....	271
Biodiesel Energy .....	273
Energy Inputs to Ethanol Bioconversion Plants .....	274
Overall Ethanol Production Systems—In Temperate and Tropical Climates .....	275
A Definitive Ethanol Production Energy Analysis at Triangle, Zimbabwe .....	277
History .....	277
Process Improvements .....	278
Potential Improvements .....	279
Energy Analysis .....	279
Ethanol from Lignocellulose .....	281
Biogas Production .....	282
Thermochemical Biomass Conversion .....	283
System Comparisons .....	285
 9. Biofuels and the Environment .....	287
Perspectives on Energy Crop Plantations and International Pollution .....	287
Overview .....	287
Carbon Storage Versus Fossil Fuel Substitution .....	289
Environmental Considerations.....	292
Short Rotation Forests—An Integrated Environmental Analysis .....	294
Environmental Effects of Biomass Conversion to Energy .....	296
The Effect of Biomass Energy Crops on the Habitats of Local Organisms .....	297
Nutrient Cycling in Energy Forest Plantations .....	300
Environmental Impacts of Biomass.....	304
Bioethanol Emissions from Vehicle Exhausts .....	306
As Gasoline Substitute .....	306
As Diesel Substitute .....	306
Secondary Pollutants.....	307
Life Cycle Emissions .....	308
Conclusions .....	308
Biodiesel and Vegetable Oil Vehicle Exhaust Emissions .....	309
Methyl Esters .....	309
Unmodified Vegetable Oils .....	312
Life Cycle Emissions .....	313

10. 2000 and Beyond .....	315
Biomass—The Flexible Fuel .....	315
Overview .....	315
Plans for UK and EU Bioenergy .....	315
Electricity Generation from Biomass .....	315
Bioenergy for Heat and Combined Heat and Power (CHP) in the UK .....	316
The Future .....	316
Alternative Liquid Transport Fuels—The Future of Biofuels .....	318
Overview—Ethanol and Methanol .....	318
Alcohols for Spark-Ignition Engines .....	319
Triglycerides for Compression-Ignition Engines .....	323
Tallow Esters in Diesel Engines .....	323
Biodiesel Initiatives in the US .....	324
Hydrogen as an Energy Carrier .....	328
Genetic and Enzyme Engineering .....	330
Biomass Fuels to Offset US Fossil Fuel Dependency .....	331
Biofuel Cell Technology .....	334
Biodiesel from Vegetable Oils—The Fuel to Develop Third World Economies? .....	336
Introduction .....	336
Conversions .....	337
Possibilities .....	337
Thermal Cracking .....	337
Catalytic Cracking .....	338
Kolbe Electrolysis .....	338
Transesterification .....	339
Performance .....	340
Economics .....	344
Overview .....	344
Fuel Producers .....	345
Other Products from Vegetable Oils .....	347
Environmental Considerations .....	347
Conclusions .....	348
Introduction .....	348
Crops and Yields .....	349
Highlights for the New Millennium .....	351

## Table of Contents

---

Introduction .....	351
The Kyoto Protocol .....	352
EU Goals for Renewable Energy by 2010 .....	352
The MTBE Debate .....	353
Energy from Waste in the US .....	356
Biofuels Increase Significantly in the UK .....	357
 11. Resources .....	359
Additional Reading .....	363
Books .....	364
Journals .....	364

## FIGURES

2.1 Electromagnetic Radiation Spectrum .....	58
2.2 Annual Mean Global Irradiance ( $\text{W}/\text{m}^2$ averaged over 24 hours) .....	59
2.3 The Basic Photosynthetic Process .....	61

## TABLES

1.1 Risk Types and Underlying Issues .....	11
1.2 Reported Environmental Impacts of Biomass Co-Combusted with Coal .....	16
1.3 Environmental Impact of Coal and Biomass Co-Combustion on Land Management and Water Quality .....	18
1.4 Bioalcohol Fuels, 1830–1980 .....	27
1.5 Domestic Sector Energy Sources in the Third World .....	33
1.6 Indian Domestic Commercial Energy Consumption, 1960–2000 (Mtoe) .....	33
1.7 Energy Densities of Various Energy Sources .....	40
2.1 Insolation in Selected Countries on Horizontal Surfaces ( $\text{MJ}/\text{m}^2$ per day) .....	60
2.2 Maximum Theoretical Efficiency of Land Plants .....	63
2.3 Breakdown of Global Primary Productivity .....	64
2.4 High Short-Term Productivities and Photosynthetic Efficiencies .....	64
2.5 Annual Productivities and Photosynthetic Efficiencies .....	65
3.1 Desirable Energy Crop Species .....	70
3.2 Factors Influencing the Applicability of Energy Crop Systems .....	72
3.3 Status of Development of SRWC Species as High-Yield Energy Crops .....	75
3.4 Short-Rotation Woody Crop-Handling Assumptions .....	80

3.5 Thin-Stemmed Perennials Tested for Energy Crop Potential .....	82
3.6 Oil Yields from Selected Oilseed Crops .....	96
3.7 Characteristics of Selected Energy Crop Selection.....	103
3.8 Cost of Supplying Energy Crops in the US Midwest and Southeast .....	104
3.9 Sorghum Production Costs in the Midwest .....	106
3.10 Switchgrass Production Costs in the Midwest .....	106
3.11 Energy Cane Production Costs in the Southeast .....	107
3.12 Switchgrass Production Costs in the Southeast .....	107
3.13 Annualized Hybrid Poplar Supply Costs with Chipping and Storage in the Midwest (18-year stand life) .....	108
3.14 Operational Cost Comparisons of Willow Coppice Production in the UK, Canada, and Finland .....	110
3.15 Mean Productivities of Main Genera Grown .....	112
4.1 Estimated Global Availability of Specific Nonwoody, Fibrous Raw Materials and Estimated Annual Collectable Yields per Hectare .....	116
4.2 Approximate Annual Biomass “Waste” in the UK.....	117
4.3 Heating Values and Chemical Characteristics of Coal and Biomass .....	121
4.4 Typical Bulk Volume of Biomass and Coal .....	122
4.5 Composition Profile of UK Domestic Refuse .....	125
4.6 Selected Technology Performance and Cost Estimates for Biomass and Waste Fuel Power Technologies .....	130
4.7 Critical Design and Economic Assumptions for Cofiring Analysis .....	131
5.1 Energy (MJ/L of pure ethanol) Requirements for Producing Absolute Alcohol .....	141
5.2 Energy Requirements for Ethanol Separation Processes .....	142
5.3 Properties of Oxygenates and Gasoline .....	147
5.4 Octane Values of Oxygenates .....	148
5.5 EC Directive on the Protection of Groundwater Against Pollution Caused by Certain Dangerous Substances .....	178
5.6 Information Sources for Preliminary Reconnaissance .....	183
5.7 Comparison of Bio-Oil and Conventional Fuel Oils .....	195
5.8 Biomass Consumption in IEA Countries.....	203
6.1 Energy Requirements for the Enzymatic Conversion of Lignocellulose to Ethanol .....	231
6.2 Some Pertinent Characteristics of <i>C. thermocellum</i> .....	239

## Table of Contents

---

6.3 Economics of the Scholler-Tornesch Process .....	244
7.1 Biofuels in the Economies of 25 Low-Income Developing Countries (1998) .....	253
7.2 Causes of Rural Digester Failure .....	255
8.1 Gross Energy Requirements for Agricultural Inputs .....	268
8.2 The Energy Costs of Intensive Forestry .....	272
8.3 Agricultural Energy Inputs for Beet and Wheat Feedstock Production .....	273
8.4 Energy Content per Unit Mass of Liquid Fuels and Bio-Oil Products .....	274
8.5 Process Energy Requirements for Ethanol Manufacture from Wheat and Beet .....	275
8.6 Overall Energy Balances of Ethanol Production in Brazil .....	276
8.7 Energy Analysis of Ethanol Production at Triangle, Zimbabwe .....	279
8.8 Energy Contents of Bioconversion Products .....	285
8.9 Bioconversion Efficiencies Using Appropriate Biomass Inputs .....	286
9.1 Deforestation, "Commercial" Energy Use, and CO <sub>2</sub> Emissions in Some Countries .....	287
9.2 Elemented Content in Mixed Wood Ashes—Output from a Short Rotation Forest with a Production of 15 t/y and the Ash Amount Needed for Compensation .....	297
9.3 Calculated Growth and Nutrient Accumulation in Roots, Stems, and Leaves During the First Rotation of a <i>Salix viminalis</i> Plantation .....	302
9.4 Calculated Growth and Nutrient Accumulation in Roots, Stems, and Leaves During the Second Rotation in a <i>Salix viminalis</i> Plantation .....	302
9.5 New Source Performance Standards .....	304
9.6 Comparison of Current Biomass Combustion Technology Emissions Guarantees .....	304
9.7 EPA Standards Emissions Performance—DDC GV-92TA Ethanol-Fueled Engine .....	307
9.8 Exhaust Emission Results from US EPA Heavy-Duty Transient Testing of Rapeseed and Soybean Methyl Esters .....	310
9.9 Exhaust Emission Results from IFP and UTAC Testing of Heavy- and Light-Duty Diesel Engines Fueled with RME .....	311
10.1 Selected Properties of Liquid Fuels .....	327
10.2 Characteristics of Thermally Cracked Soybean Oil .....	338
10.3 The Cetane Number of Methyl Esters .....	342
10.4 Palm Oil Price Versus Production Cost of Palm Oil Methyl Esters (\$/t) .....	346
10.5 Renewable Energy Use in the UK .....	357

