

# Renewables-Based Technology

Sustainability Assessment



**Jo Dewulf | Herman Van Langenhove**  
Editors

 **WILEY**



# Contents

<b>Contributors</b>	<b>xv</b>
<b>Foreword</b>	<b>xvii</b>
<b>Series Preface</b>	<b>xix</b>
<b>Preface</b>	<b>xxi</b>
<b>List of Abbreviations</b>	<b>xxiii</b>
<b>Part I Renewables as a Resource and Sustainability Performance Indicators</b>	<b>1</b>
<b>1 The Contribution of Renewables to Society</b> <i>Göran Berndes</i>	<b>3</b>
1.1 Introduction	3
1.2 Historic and Present Biomass Uses for Food, Energy and Materials in the World	6
1.3 Potential Availability of Agricultural Residues and Land for Non-Food Crop Production	8
1.4 Drivers Behind Increasing Demand for Biomass for Energy and Materials	10
1.5 Land Use Competition	12
1.6 Multifunctional Biomass Production Systems	14
1.7 Summary	16
Acknowledgements	16
References	16

<b>2</b>	<b>The Potential of Renewables as a Feedstock for Chemistry and Energy</b>	<b>19</b>
	<i>Wilfried G. J. H. M. van Sark, Martin K. Patel, André P. C. Faaij and Monique M. Hoogwijk</i>	
2.1	Introduction	19
2.2	Supply of Energy and Materials Using Renewables	21
2.2.1	Solar Energy	22
2.2.2	Wind Energy	25
2.2.3	Biomass-Based Energy and Materials Supply	26
2.2.4	Resources for Materials	31
2.3	Demand for Energy and Materials	31
2.3.1	The Dynamics of Energy Use	31
2.3.2	Materials from Renewable Resources	32
2.4	Summary	34
	References	35
<b>3</b>	<b>Sustainability Performance Indicators</b>	<b>39</b>
	<i>Alexei Lapkin</i>	
3.1	Introduction	39
3.2	The Hierarchy of Sustainability Metrics	40
3.3	Aspects of Methodology	42
3.3.1	Spatial and Temporal Boundaries of Assessment	42
3.3.2	Specific Aspects of Indicator and Indices Development	45
3.4	Examples of Sustainability Metrics for Technology Assessment	46
3.4.1	Environmental Sustainability Assessment by Process-Oriented Metrics	46
3.4.2	Environmental Sustainability Assessment by Environmental Pressure-Oriented Metrics	46
3.4.3	Environmental-Economic Sustainability Assessment	49
3.5	Summary	51
	References	52
	<b>Part II Relevant Assessment Tools</b>	<b>55</b>
<b>4</b>	<b>Life Cycle Inventory Analysis Applied to Renewable Resources</b>	<b>57</b>
	<i>Niels Jungbluth and Rolf Frischknecht</i>	
4.1	Introduction	57
4.2	Conceptual Background to LCA in ISO 14040ff	58
4.3	Goal and Scope Definition	59
4.4	Inventory Analysis	59
4.4.1	Product System and Unit Process	60
4.4.2	Unit Process Inventory	60
4.4.3	Multi-Output Processes and Allocation Rules	62
4.4.4	Uncertainty Considerations in LCI	66
4.4.5	Lifecycle Inventory Analysis Result	67

4.5	LCI Data Documentation and Exchange Format	68
4.6	Consequential versus Attributional LCI	69
4.7	Summary	70
	References	71
<b>5</b>	<b>Net Energy Balancing and Fuel-Cycle Analysis</b>	<b>73</b>
	<i>Hosein Shapouri, Michael Wang and James A. Duffield</i>	
5.1	Introduction	73
5.1.1	Background	73
5.1.2	Environmental Sustainability	74
5.1.3	Domestic Energy Security	74
5.2	Methodology	75
5.2.1	Co-Product Allocation	76
5.2.2	Description of GREET Fuel-Cycle Analysis	77
5.3	Energy Balance of Fossil Fuel versus Biofuel	79
5.4	Greenhouse Gas Emissions from Corn Ethanol Production	83
5.5	Summary	84
	References	85
<b>6</b>	<b>Life Cycle Assessment as an Environmental Sustainability Tool</b>	<b>87</b>
	<i>Adisa Azapagic</i>	
6.1	Introduction	87
6.2	The LCA Methodology: A Brief Overview	88
6.2.1	Goal and Scope Definition	88
6.2.2	Inventory Analysis	90
6.2.3	Impact Assessment	91
6.2.4	Interpretation	92
6.3	LCIA Impact Categories as Indicators of Environmental Sustainability	93
6.3.1	CML 2 Baseline Method	94
6.3.2	Environmental Priority Strategies (EPS) 2000	98
6.3.3	Eco-Indicator 99	100
6.3.4	Choosing the LCIA Method and Indicators	104
6.4	Using LCA to Assess Environmental Sustainability	105
6.5	Summary	108
	References	109
<b>7</b>	<b>Exergy</b>	<b>111</b>
	<i>Jo Dewulf and Herman Van Langenhove</i>	
7.1	Introduction	111
7.2	Assessment of Sustainability of Technology: Developing Metrics	113
7.3	A Thermodynamic Basis for Developing Sustainability Assessment Metrics: Exergy	114

7.4	Technology Assessment by Exergy Analysis	116
7.5	Exergy-Based Indicators: How to Assess the Role of Renewables	117
7.5.1	The Case of Ethanol	118
7.5.2	Bio-Fuels	119
7.6	Exergy-based Indicators: Integrating the Role of Renewables in an Overall Physical Chemical Sustainability Assessment	122
7.7	Summary	123
	References	123
<b>8</b>	<b>Material Flow Analysis and the Use of Renewables from a Systems Perspective</b>	<b>127</b>
	<i>Stefan Brinquez</i>	
8.1	Introduction	127
8.2	Overview of the Methodology	128
8.3	Examples of MFA Studies in the Context of Renewables	130
8.3.1	Type Ia Studies: SFA – Agriculture, Nitrogen and Heavy Metals	130
8.3.2	Type Ib Studies: Analysis of Selected Bulk Materials – Timber Products	131
8.3.3	Type IIb Studies: Analysis of Sectors – Construction and Energy Supply	131
8.3.4	Type IIc Studies: Economy-wide MFA and Derived Indicators	132
8.4	Summary	139
	Acknowledgements	140
	References	140
<b>9</b>	<b>Ecological Footprints and Biocapacity: Essential Elements in Sustainability Assessment</b>	<b>143</b>
	<i>William E. Rees</i>	
9.1	Introduction	143
9.2	Eco-Footprint Analysis	144
9.2.1	Basic Methods	145
9.2.2	The Eco-Footprints of Nations: Measuring Relative Sustainability	147
9.3	Inherent Strengths in EFA	150
9.3.1	The Scientific Merit of EFA	150
9.3.2	Popular Acceptance of EFA	151
9.4	Answering the Critics	151
9.4.1	Conceptual and Methodological Critiques	152
9.4.2	EFA and Sustainability Policy	154
9.5	Summary	155
	References	156

<b>10 The Sustainable Process Index (SPI)</b>	<b>159</b>
<i>Michael Narodoslawsky and Anneliese Niederl</i>	
10.1 Introduction	159
10.2 Computation of the SPI	162
10.2.1 The Raw Material Area $A_R$	164
10.2.2 The Energy Supply Area $A_E$	165
10.2.3 The Area for Installation and Staff $A_I, A_S$	166
10.2.4 The Area for Dissipation of Products $A_P$	167
10.3 Case Study: Biodiesel from Used Vegetable Oil	168
10.4 Summary	170
References	171
 <b>Part III Case Studies</b>	 <b>173</b>
<b>11 Assessment of Sustainable Land Use in Producing Biomass</b>	<b>175</b>
<i>Helmut Haberl and Karl-Heinz Erb</i>	
11.1 Introduction	175
11.2 Sustainability Issues Involved in Promoting Biomass Energy	177
11.2.1 The 'Footprint' of Biomass Use	178
11.2.2 Intensity of Land Use: Human Appropriation of NPP (HANPP)	181
11.2.3 Impacts of Biomass Use on Carbon Flows	183
11.3 Recommendations	186
11.4 Summary	187
References	188
 <b>12 Assessment of the Forest Products Industries</b>	 <b>193</b>
<i>Klaus Richter, Frank Werner and Hans-Jörg Althaus</i>	
12.1 Introduction	193
12.2 Metrics and Criteria to Assess the Sustainability of Forestry	195
12.2.1 History of the Term 'Sustainability'	195
12.2.2 Existing Criteria and Indicator Systems for Forestry in Europe	195
12.2.3 Current Status of Certification	196
12.2.4 Case Study: The Swiss National Forest Inventory	197
12.3 Metrics and Criteria for Assessing the Sustainability of the Wood Industry	198
12.3.1 Company-Oriented Criteria	198
12.3.2 Product-Oriented Criteria	199
12.3.3 Wood Sector-Oriented Criteria	202
12.4 Scope for Action	205
12.5 Summary	205
References	206

<b>13</b>	<b>Assessment of the Energy Production Industry: Modern Options for Producing Secondary Energy Carriers from Biomass</b>	<b>209</b>
	<i>André Faaij</i>	
13.1	Introduction	209
13.2	Technology Overview	210
13.2.1	Combustion	211
13.2.2	Gasification	214
13.2.3	Production of Bio-Oils: Pyrolysis and Liquefaction Processes	217
13.2.4	Fermentation: Production of Ethanol	220
13.2.5	Digestion	221
13.2.6	Extraction and Production of Esters from Oilseeds	221
13.3	Economics of Biomass Energy Systems	224
13.3.1	Power Generation	224
13.3.2	Production of Liquid and Gaseous Fuels from Biomass	224
13.4	Heat, Power and Fuels from Biomass: Key Markets	225
13.5	Summary	227
	References	228
<b>14</b>	<b>Assessment of Biofuels</b>	<b>231</b>
	<i>James A. Duffield, Hosein Shapouri and Michael Wang</i>	
14.1	Introduction	231
14.2	Background	231
14.3	Biofuel Feedstocks	232
14.4	Bio-Transportation Fuels and Fuel Additives	234
14.5	Current Supply of Biofuels	235
14.6	Future Supply of Biofuels	236
14.6.1	Potential Production of Cellulosic Ethanol	238
14.7	Measuring the Sustainability of Biofuels	238
14.7.1	Environmental Benefits of Biofuels	240
14.7.2	Greenhouse Gas Reduction Effects	241
14.8	Summary	243
	References	243
<b>15</b>	<b>Assessment of Organic Waste Treatment</b>	<b>247</b>
	<i>Jan-Olov Sundqvist</i>	
15.1	Introduction	247
15.2	General Description of Options for Organic Waste Treatment	247
15.2.1	Incineration	248
15.2.2	Landfilling (of mixed waste)	248
15.2.3	Anaerobic digestion	248
15.2.4	Composting	249

15.3	Environmental Characteristics of Organic Waste Treatment	249
15.3.1	Incineration	249
15.3.2	Landfilling (of Mixed Waste)	249
15.3.3	Anaerobic Digestion	250
15.3.4	Composting	250
15.4	Results of a Life Cycle Assessment of Organic Waste	250
15.4.1	General	250
15.4.2	Results	255
15.5	Discussion	262
15.6	Summary	262
	References	262
<b>16</b>	<b>Oleochemical and Petrochemical Surfactants: An Overall Assessment</b>	<b>265</b>
	<i>Erwan Saouter, Gert Van Hoof, Mark Stalmans and Alan Brunskill</i>	
16.1	Introduction	265
16.2	Main Chemical and Structural Differences	267
16.3	Resource and Usage	268
16.3.1	Relative Usage	268
16.3.2	Petrochemicals	269
16.3.3	Oleochemicals	269
16.4	Environmental Profile	270
16.5	Sustainability Aspects of Oleochemical Production	276
16.6	Summary	278
	References	279
<b>17</b>	<b>Assessment of Bio-Based Packaging Materials</b>	<b>281</b>
	<i>Andreas Detzel, Martina Krüger and Axel Ostermayer</i>	
17.1	Introduction	281
17.1.1	The Packaging Market	281
17.1.2	Waste Management Framework for Biopackaging	282
17.1.3	Life Cycle Assessment of Biopolymers	282
17.1.4	Focus on Polymer Production and Waste Management	283
17.2	Environmental Aspects of Polymer Production	283
17.2.1	Ecoprofile Data for PLA and PET	283
17.2.2	PLA: Process Chain Analysis	284
17.2.3	Production of Agricultural Crops: Example Corn Growing	285
17.2.4	Other Issues Related to Environmental Assessment	286
17.3	Environmental Aspects of Packaging Disposal	287
17.3.1	Packaging Waste Disposal Pathways	287
17.3.2	Waste Scenario Description	289
17.3.3	Findings	291
17.4	Summary	295
	References	296



<b>18</b>	<b>Assessment of Biotechnology-Based Chemicals</b>	<b>299</b>
	<i>Peter Saling and Andreas Kicherer</i>	
18.1	Introduction	299
18.2	Explanation: What is Eco-Efficiency Analysis?	300
18.2.1	ISO Standards for LCA	300
18.2.2	Link between ISO and the BASF Method	301
18.2.3	Eco-Efficiency Methodology at BASF	302
18.3	Evaluation of Decision-making Processes with Eco-Efficiency Analysis	307
18.4	Case Studies	308
18.4.1	Indigo Processes	308
18.4.2	Vitamin B <sub>2</sub> Case Study	309
18.5	Summary	311
	References	312
<b>19</b>	<b>Assessment of Bio-Based Pharmaceuticals: The Cephalixin Case</b>	<b>315</b>
	<i>Alle Bruggink and Peter Nossin</i>	
19.1	Introduction	315
19.2	Assessment Methods During Process Development and Technology Transfers	316
19.2.1	History and Growth of the Need for Adequate Assessment Methods at DSM	316
19.2.2	Sustainability Assessment in the Early Phases of Development	317
19.2.3	Sustainability Assessment in the Engineering and Commercial Stages	319
19.3	Assessment of Bio-Based Routes to Cephalixin	322
19.3.1	Traditional Routes to Semi-Synthetic Antibiotics	322
19.3.2	Bio-Based Routes to Cephalixin	323
19.3.3	Sustainability Metrics Applied to the Cephalixin Processes	326
19.4	Summary	328
	References	329
<b>Part IV</b>	<b>Conclusions</b>	<b>331</b>
<b>20</b>	<b>Conclusions</b>	<b>333</b>
	<i>Jo Dewulf and Herman Van Langenhove</i>	
20.1	Introduction	333
20.2	The Available Sustainability Metrics	334
20.2.1	The Themes in Sustainability Metrics	334
20.2.2	Definition of Functional Unit and System Boundaries	335

20.2.3	The Basic Metrics	335
20.2.4	Case Studies of Assessment Metrics	336
20.3	Where Are We Going in Assessing Renewables-Based Technology?	336
	Reference	337
	<b>Index</b>	<b>339</b>