

Linkages of Sustainability

Edited by

Thomas E. Graedel and Ester van der Voet

Program Advisory Committee:

Thomas E. Graedel, David L. Greene, Thomas Peter Knepper,
Yuichi Moriguchi, David L. Skole, and Ester van der Voet

The MIT Press
Cambridge, Massachusetts
London, England

© 2010 Massachusetts Institute of Technology and
the Frankfurt Institute for Advanced Studies

Series Editor: J. Lupp
Assistant Editor: M. Turner
Photographs: U. Dettmar
Typeset by BerlinScienceWorks

All rights reserved. No part of this book may be reproduced in any form by electronic or mechanical means (including photocopying, recording, or information storage and retrieval) without permission in writing from the publisher.

MIT Press books may be purchased at special quantity discounts for business or sales promotional use. For information, please email special_sales@mitpress.mit.edu or write to Special Sales Department, The MIT Press, 55 Hayward Street, Cambridge, MA 02142.

The book was set in TimesNewRoman and Arial.
Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Ernst Strüngmann Forum (2008 : Frankfurt, Germany)

Linkages of sustainability / edited by Thomas E. Graedel and Ester van der Voet.

p. cm. — (Strüngmann Forum reports)

Includes bibliographical references and index.

ISBN 978-0-262-01358-1 (hardcover : alk. paper)

1. Sustainability. 2. Conservation of natural resources. 3. Sustainable development. I. Graedel, T. E. II. Voet, E. van der.

GE195.L555 2010

333.72—dc22

2009039035

10 9 8 7 6 5 4 3 2 1

Subject Index

- activated sludge treatment 236, 237
- ACT Map 406–408, 414
- agriculture 84–89, 285, 316, 422, 427–429, 463, 465
 - crop yield 11, 22, 84, 89, 426
 - environmental impacts 13, 14, 25, 30
 - greenhouse production 12, 18
 - impacts of climate change 424–427
 - water footprint 231, 264, 282, 283, 293
- agroforestry 424, 437
- Alberta Basin 330
- aligned carbon nanotubes 222
- alternative states 44–46
- aluminium 103, 112, 132, 136, 137, 143, 200
- anaerobic wastewater treatment 251, 253, 258, 259
- ANAMMOX 257, 261
- Annual Failed States Report 54
- anode slimes 473–475
- aquifers 277–283, 288
- Aral Sea 294
- arsenic 119
- Aswan Dam 287
- Australia Group 56

- backyard recycling 186, 192, 210
- balanced scorecard approach 57–61
- baseline scenarios 407, 408, 414
- BEAMR process 254
- beneficiation 107, 114, 206
- bimodal distribution 124–128, 132
- biodiversity 26, 30, 34, 35, 82, 84, 87, 379
- bioeconomy 85–87, 421, 422, 427–430, 434, 436
- biofuels 18, 86, 92, 93, 306, 364, 405, 431–433, 465, 467
 - carbon footprint 425
 - impact on land 414–416
 - payback period 426
 - water footprint 246, 247, 263, 414–416
- biomass 246, 395
 - conversion 379
 - energy 336–338, 365, 397, 405
 - production 430–432, 464
 - water footprint 246
- biorefinery 423, 429, 430
- BLUE Map 326, 406–408, 414, 415
- blue water 262, 295
- brackish water 233, 234, 241, 250
- Brazilian Cerrado 84
- by-product metals 177, 180, 189, 193

- Canadian Policy Research Initiative 63–65
- carbon dioxide, capture and storage 407, 463
- carbon markets 434–436
- carbon sequestration 25, 30, 83, 84, 94, 348, 351, 424, 434
- car catalysts 169, 170, 185, 190
- cathode ray tube recycling 156–158, 162
- certification 42, 60, 94
 - Fair Trade labeling 61–65
- climate change 306, 325, 375, 376, 421–427, 436, 463, 464
 - impact on agriculture 424–427
 - impact on water 260, 261, 284, 285, 297, 298, 310
- coal 324–327, 333, 334, 395, 404
- Colorado River 287, 295
- comminution 144–146
- consumer behavior 42, 84, 85, 310
 - demand 203–205, 211
- consumer–producer interactions 36, 37, 39, 41, 45
- copper 104, 106, 113–116, 122, 125, 126, 136–138, 142, 167, 214–216, 471–473
 - decline in ore grade 132, 133
 - recycling 160–162
 - reserve estimates 123
- Corporate Social Responsibility 58–61
- creative destruction 44
- cultural theory 49, 65–68

- dashboard approach 57, 58
 decomposition 38–40, 360
 deforestation 12, 18, 28, 55, 59, 237,
 422, 424, 427
 denitrification 257, 260
 desalination 222, 223, 248–250
 direct material input 105
 dismantling 150, 153, 157, 184, 187, 195
 diversity–stability hypothesis 41
 drinking 250
 drinking water 221, 227, 231, 233–242,
 281, 311
 energy consumption 250
 dry processing 146, 147
 dual-mode transportation system
 441–445
 economics of 454–458
 environmental impacts 451–454
 road capacity 450–454
- eco-labeling. *See* certification
 ecological footprint 78
 ecological rucksack 101
 ecosystem services 34, 35, 45, 468, 469
 payments for 94
 ecosystem structure 37–39
 end-of-life (EoL) phase 115, 165, 175,
 176, 194, 195, 213
 energy 323–340, 360–365, 389–396,
 406, 413, 424, 427, 462, 465
 challenges for 376
 consumption 324, 325, 337, 347, 361,
 377–380, 383, 394, 451
 defined 391
 demand 350, 379–383
 impacts of mining 145, 207, 214
 measuring 360, 364, 367, 373, 376,
 409–413
 recovery from waste 91
 security 357, 366–368
 water footprint 244–255, 272–274,
 283–285, 314, 317, 389
 energy footprint, defined 249
 energy service 360, 392
 defined 391
 energy supply, impact matrix 414, 418
 energy sustainability 341–354
 assessing 381, 403
 defined 355, 390
 dimensions of 350, 351
 measuring 346–349, 352, 355–374,
 376, 384, 409–413
 environmental footprinting 57–61
 ethanol 86, 246, 247, 431–433
 evapotranspiration 224, 228, 270,
 276, 426
- Fair Trade label 61–65
 FAO data 15–17, 20
 fertilizer 20, 23, 89, 90, 425, 428
 firms 57–61
 floods 426, 427
 food production 13, 14, 18, 20–25, 28,
 39, 316, 436, 462
 cereal 22, 24, 84–86, 424, 426
 livestock 12, 24
 rice 20, 75, 310, 425, 426, 433
 security 421–423
 soybean 79, 84, 426, 433
 water footprint 261–263
 forests 12, 14, 25–28, 428
 land area 15–20
 rates of change 13
 recovery 26–30
 Forest Stewardship Council 60–64, 94
 forward osmosis 222
 fossil fuels 325–327, 336, 358,
 375–377, 422
 transition to nonfossil 429–434, 462
 freshwater 222, 223, 267–270, 276, 310,
 375, 463
 availability 233, 272, 463
 global estimates 309
 impact of agriculture 425
 impact of deforestation 237
 fuel cell vehicles 414, 416, 417
 full-cost accounting 57
- gallium 113, 168, 176, 471, 472
 GATT 56
 geologically based fuels 325, 393–395

- geothermal energy 338, 364, 395,
400–404, 480
- germanium 113, 168, 176, 471, 473
- gold 113, 119, 121, 122, 133, 166, 168
- Great Plains 283
- greenhouse gas emissions 91, 357,
451–452
- agricultural sources of 25, 425
- of primary metals 143, 144
- SRES 297, 299
- Green Revolution 13, 20
- green water 262, 295, 305
- groundwater 223, 224, 227–230, 269,
279–281, 285
- characteristics of 277–279
- contamination 230, 231
- decline of 294
- global estimates 226
- quantification methods 476–480
- Gulf of Mexico 89, 285
- Haber–Bosch process 39
- heavy metal contamination 102, 186
- high pressure grinding rolls 145–147
- Hubbert's curve 121
- human appropriation of NPP 73, 76, 77
- human capital 48–53, 68, 69
- defined 49, 50
- Human Development Index 51, 52,
360, 361
- human diet 261–263, 462
- meat 24, 28, 90
- human well-being 34, 44, 356, 357, 360,
410–413. *See also* quality of life
- hydrologic cycle. *See* water cycle
- hydropower 246, 248, 305, 306, 324,
336–339, 395, 398, 404, 480
- IAEA 56
- IEA scenarios 357, 383, 406, 407
- ACT Map 406–408, 414
- Baseline 406, 407, 414
- BLUE map 326, 406–408, 414, 415
- IMPACT model 24, 85
- indium 119, 127, 167–169, 473
- innovation 48, 62, 69
- input-output economic analysis 212–214
- institutional capacity 49, 54–61, 68
- integrated water resources model
300–302, 306
- intellectual capital 51, 53, 62
- International Councils of Scientific
Unions 66
- IPCC 2, 66, 365, 366, 423, 424
- iron 102, 106, 121, 125, 126, 132, 200
- irrigation 23, 237, 247, 258, 285, 425,
426, 428
- Kaya identity 381, 382
- Kimberley Process 60
- Kondratiev waves 343
- Kuznets curve, environmental 52
- Lake Baikal 222, 223
- Lake Superior 222
- land 71–96, 421, 436, 463, 465
- accounting 73–76
- cropland 16–20, 84
- defined 72–75, 79
- degradation 72, 88, 89, 101
- efficiency gains in 91–94
- impact of NRR extraction 88
- impact on mineral resources 206, 207
- link to water 261–263, 272–274,
315–317
- management 11, 22, 88, 91
- production gains 89–94
- property rights 19, 59–63
- use change 12, 15–20, 77, 78,
421–425, 436
- land resource independence 19
- lead 106, 113, 122, 136, 137, 168, 174
- life cycle assessment 38, 93, 94,
210–214
- major metals 200
- defined 205
- Marine Stewardship Council 60–64
- MARKAL model 372

- markets 57–61
 - carbon 434–437
- material flow analysis 105, 152, 212–214
- materials cycling 38, 42, 150–152
- Matlab/Simulink dynamic recycling model 158, 160
- meat consumption 24, 30, 90
 - projected 85
- MELiSSA 258
- membrane filtration 236, 237, 259
- metallurgical processing 151, 154–156, 206
- metals 100, 132–134
 - extraction 135, 164, 465
 - impact assessment of 103–105
 - production 163, 176, 471–475
 - recovery 163, 165, 184, 187, 200
 - refining 135, 185, 206
- methane 255, 331, 333
- Millennium Ecosystem Assessment 30, 66
- mineral processing 111, 135
 - beneficiation 107, 114, 206
 - reducing energy consumption 144, 145
 - reducing water consumption 146–148
- minerals 99–108, 110–113, 116–118, 199, 200, 201
 - conventional deposits 120–124
 - defined 100, 111, 132, 200
 - exploration for 128, 207
 - quantification of stocks and flows 104–107
 - reserve base 117–127
 - unconventional deposits 124–127
- mining 101, 102, 107, 111, 114, 135, 144–146, 164, 206
 - efficiency 127–129
 - environmental impacts 102–104, 206, 207
 - minor metals 177, 178
 - water footprint 245, 255–257, 319
- minor metals 165, 168, 176, 179–181, 200
 - defined 166, 167, 205
 - distribution of 471–475
 - recycling rates 184–188
 - scarcities in 193–195
- Mississippi River 89, 285
- molybdenum 113, 177
- Montreal Protocol 56
- MOSUS project 106
- motor vehicles 439–460
 - lifetime cost analysis 456–458
- natural environment 65–68
- natural gas 326, 331–333, 394, 395, 404
- nature, views of 65–67, 403, 406
- Neem 433
- net primary production 73, 76, 77
- network dynamics 64, 65
- nickel 106, 120, 136, 137, 142
- nonmetal minerals 100
- nonrenewable fuels 393–395
- nonrenewable resources 109–129, 164
 - recycling of 149–162
- nuclear energy 246, 306, 334–336, 362, 366, 395–397
- Nuclear Suppliers Group 56
- nutrient management 256–259
- ocean energy 248, 395, 399, 405, 480
- OECD 63, 105
- oil 326–331, 358, 364, 379, 394, 451–453
 - estimates 359, 363
 - proved reserves 404
- oil sands 379, 404
- oil shales 255, 331, 363, 379, 404
- OPEC 56
- ore grade 101, 133, 138–143, 464
- Orinoco Basin 330
- persistence 36, 39, 40, 42, 45
- pesticides 428, 433
- photovoltaics 364, 379, 402, 464
- physical separation 150–154
- platinum 120, 416, 417, 471
- platinum group metals 113, 167, 169, 176, 191, 206
- political stability 54
- population growth 21, 24, 28, 39, 87, 222, 310, 380, 424

- precious metals 164, 166
 defined 165
 life cycles of 163–198
 price development of 171–173
 role in sustainability 167–175
- precipitation 224, 228, 270–273, 427
- pressure-retarded osmosis 248
- PRI approach 64–66
- primary production 136–138, 166, 176,
 183, 193, 201–203
 challenges to 205–208
 defined 200
 losses during 178–180
- product design 38, 40, 127, 149–152,
 156, 175, 176, 182, 211
- product life cycle 163–165, 175,
 189–191, 208–210
 closed loop systems 191–193
 open loop systems 192
 role of recycling 182–184
- purchasing power parity 391, 409
- quality of life 287, 376, 461. *See*
also human well-being
 index 51, 52
- recycling 38, 116, 127, 144, 152, 163,
 176, 188, 204, 209, 211
 economic factors 188, 205
 end-of-life 115, 165, 175, 176, 194,
 195, 213
 legislation 189–191
 material liberation 152–155
 Matlab/Simulink model 158, 160
 nonrenewable resources 149–162
 opportunities and limits 182–191
 principles of 150–155
 printed wiring boards 157, 159, 185
 productions scraps 181–183
 sorting 153–155
 water 286, 311
- reliability 36, 40–43, 46
- renewable resources 92, 336–340, 365,
 395–403
- research agenda 216–218, 347, 348, 352,
 353, 468–470
- resilience 33, 36, 43–46
- reverse electro dialysis 248, 249
- reverse osmosis 235, 236, 250, 315
- runoff 226, 227, 270, 271, 276, 285, 428
 global estimates 224–226
- Sainsbury Report 50
- salinity gradient energy 248, 249, 399
- schistosomiasis 287
- seawater 230, 234, 238, 241, 248–250
- secondary production 202, 208–211
- Sewage⁺ project 255
- shredding 150, 153, 154, 187
- silver 106, 119, 122, 168, 174, 177
- smelting 103, 107, 135, 178, 185, 206
- social capital 49, 61–65, 68
- solar energy 92, 246–249, 336, 337, 365,
 379, 401–405, 464, 465, 480
- special metals 164, 169, 188
 defined 165
 life cycles of 163–198
 role in sustainability 167–175
- steel production 107, 136, 137, 143
- stirred mills 145, 146
- strong sustainability 48
- strontium 113, 119
- Sub-Saharan Africa 21–25, 84, 90
- sustainability
 assessment model 57–61
 challenges 1, 3, 6
 defined 33, 36, 342, 355
 framework for analysis 12–15
 problem of definition 417
- tailings 114, 115
- tantalum 113, 168, 177, 180, 185
- tar sands 255, 313, 376, 462
- technology metals 166–169, 176
 defined 167
- tectonic diffusion 122, 123
- tellurium 113, 120, 127, 167–169, 471
- tertiary stocks 200, 202, 209
- Three Gorges Dam 287

- tidal power 248, 336, 399
- total material requirement 102, 105
- transportation system 439, 440, 452
 - dual-mode 441–445
 - efficiency in 92, 93
 - new design 441–447
 - road capacity 450–454
- triple bottom line 57, 58

- Umicore 183, 185, 188
- uranium 334, 335, 360, 362, 375, 395–397, 404
- urban design 439–460
- urbanization 87, 88, 263, 310, 316, 439, 463

- virtual water 262, 263, 295, 312, 313

- Wassenaar Arrangement 56
- waste export regulation 55
- wastewater treatment 234–241, 249, 250, 252
 - anaerobic 251, 253, 258, 259
 - industrial 259–265
 - nutrient removal 256–258
- water 227–229, 281–284, 298–300, 304, 313, 465. *See also* drinking water; freshwater; groundwater; virtual water
 - availability 284, 293, 296–298, 476–478
 - budget 269–275, 289, 295
 - consumption 143, 247, 294
 - contamination 239, 285, 453
 - demand 309–312
 - filtration 227, 235, 236, 240
 - for metal production 136–138
 - global estimates 222, 224–227, 276
 - impact of mining 207–209, 214
 - industrial 231, 240, 293
 - link to energy 249–255, 305, 314
 - management 238, 310–313, 426
 - quality 90, 229, 233–242, 248, 277, 310, 311, 315, 463
 - stress 233, 293–299, 310, 312
 - sustainability of 276–278, 300–302
- water cycle 222, 234–237, 243–266, 268–276, 292, 311, 427
 - human impact on 226–228, 234
 - impact of climate change 260, 261, 284, 285, 297, 298
 - impact of land use 261–263, 305, 315–317
 - uncertainties in 288, 296
- water footprint 147, 244, 295
 - defined 246, 262, 296
- WaterGAP Global Hydrology Model 476–478
- wave energy 336, 339
- wind energy 246, 247, 336, 338, 364, 365, 395–397, 404, 480
- World Bank 63–65
- WPA-2000 329, 330, 364

- Yellow River 295

- zinc 106, 122, 136, 137, 176, 180