

Index

a

- active pharmaceutical ingredients (APIs)
 - 162, 510–511
 - carbon footprint 510–513
 - continuous manufacturing process 513
 - energy consumption 508–510
 - green chemistry 512–513
 - manufacturing of 507
- adiabatic system-compressed air energy
 - storage (A-CAES) 88–93
- agricultural industry 483
- aircraft grade aluminium 388
- air handling unit (AHU) 492
- air source heat pumps 143
- alkaline electrolysis cells (AEL) 207, 208, 210–213, 223, 226, 227, 249
- alkali wash 37–38
- alloy steel 326
- aluminium 387–398
 - applications 387–388
 - material specification 388–389
 - properties 387–388
- aluminium production 389–391, 394–397
 - Bayer process 391–394
 - Hall-Héroult process 394–397
 - recycling 396
- aluminosilicate glass 435–437
- amine scrubbing process 36, 37
- ammonia
 - in COGC 250
 - combustion of 249–252
 - hydrogen carrier 237–238
 - power from
 - back to hydrogen 253–255
 - electrochemical combustion 253
 - energy recovery through combustion 249–252
 - hydrogen/energy carrier 255
 - properties of 237
 - uses for 236–237
- ammonia electrolytic cell (AEC) 255
- ammonia synthesis reaction
 - alternative routes 245–246
 - CO₂ emissions 248
 - energy requirement for 248–249
 - renewable hydrogen 246–248
- catalysts for 239–240
- classical process vs. renewable hydrogen 246
- classical route 240–244
 - CO₂-emissions 244
 - gas preparation section 241
- efficiency 244–245
- thermodynamic limitations 238–239
- anaerobic digestion 486, 494, 503, 521, 524, 557
- Anderson-Schulz-Flory (ASF) distribution 279, 280
- anion exchange membrane (AEM) 207, 208, 211
- annualized furnace efficiency (AFE) 162
- annualized optical efficiency 60

Renewable Energy in the Process Industry, First Edition.

Eric van Steen, Nicholas S. Featherstone, and Linda H. Callanan.

© 2026 WILEY-VCH GmbH. All rights reserved, including rights for text and data mining and training of artificial intelligence technologies or similar technologies. Published 2026 by WILEY-VCH GmbH.

- argon oxygen decarboniser (AOD) 333, 344
- automatic generation control (AGC) 69
- autothermal methane reforming 218
- autothermal reforming (ATR) 200, 201, 203–204, 222, 224, 225, 273, 285
- Avogadro's number 96
- b**
- baking industry
 - bread production process 489, 493
 - carbon footprint of breadmaking 492–494
 - history 486–487
 - industry size 487–489
 - raw materials and process 489–492
 - renewable energy 494–495
 - research, future processes 495
- base load 70, 71, 486, 563
- basic industries 305–325, 367–369, 385, 460, 483
- cement
 - CO₂-emissions 316–317
 - CO₂ production manufacture 314–316
 - energy demand in production 313–314
 - industry size 308–310
 - material specification for 307–308
 - process description 310–313
 - research and future processes 317–318
- chloro-alkali process 358–359
- diaphragm cell 361–364
- material and industry 358–359
- membrane cell 365–366
- mercury cell 364–365
- oxygen-depolarised cathode cell 366
- process flow diagram 361
- raw materials 361
- different industries 367–368
- materials 306
- steel
 - coke production 334
 - electric arc furnace 343–344
 - emission reductions 344
 - iron and steel industry 330–333
 - iron production 334–341
 - material specification 325–330
 - oxygen steel-making 341–342
 - sub-processes 333–334
 - sulphuric acid
 - making production 354–356
 - material specifications 349
 - production process 350–354
 - size and production scale 349–350
 - spent acid waste regeneration 356–357
- basic oxygen furnace (BOF) 333, 341, 342
- battery
 - lead-acid battery 100–105
 - LiCoO₂ 105, 106, 108–110
 - lithium-ion battery 105–108
 - principle 95–100
 - solid-state battery 111
- battery energy storage system (BESS) 178, 530
- Baumann relationship 30
- Bayer process 391–394
- Becher process 414–415
- Bernoulli's equation 153
- best available technology (BAT) 245, 248
- Betz Limit 48
- beverage cans 503
- biochemical oxygen demand (BOD) 518, 520
- biofuels 8, 14, 444
- biomass 13–16, 34, 46, 70, 178, 191, 225, 284, 318, 344, 445, 458, 504, 513, 522, 524
- blast furnace 151, 332–341
 - exergy analysis of 339–341
- blister copper 401, 402
- body-centred-cubic (BCC) 325
- body-centred tetragonal (BCT) 327
- borosilicate glass 435, 436
- Boudouard reaction 277, 278, 338, 429
- Brayton cycle 31–33, 250, 251, 256
- bread
 - types of 487–489

- breadmaking, carbon footprint 492–494
 Brønsted acids 115
 Bulk Fermentation Process (BFP) 490
 Butler-Volmer equation 97
- C**
- calcium looping (CaL) technique 320, 559
 canning processes
 high-acid and low-acid foods 497
 overall process 498–499
 packaging materials recycle 503–504
 pasteurising 501–502
 retorting batch process 499–501
 thermal food processing 502–503
 thermal processes 496–498
 capacity factor 41, 45, 51–52, 60, 66, 397, 552
 carbon-based materials 94, 559
 carbon capture 34–37
 carbon capture and sequestration (CCS) 224–226
 carbon capture and storage (CCS) 204, 285, 319, 431, 557–560
 carbon capture utilisation or storage (CCUS) 325
 carbon-carbon coupling 277
 carbon emissions 73, 173, 190, 276, 289, 367, 369, 406–407, 433, 441–442, 493, 495, 544, 548
 carbon footprint 18, 20, 42, 46, 52, 88, 93, 95, 125, 173, 317, 368, 401, 406, 407, 416, 431, 442, 444, 492–494, 510, 515, 529, 530, 543, 544
 of breadmaking 492–494
 carbon pricing 18–20, 369
 carbon steel 325–330, 333, 334, 341
 carbon tax 19, 20, 495, 544–548
 carbothermal process 433
 Carnot efficiency 28, 31, 40, 56, 64, 233
 carrot method 548
 cast aluminium alloys 388–389
 cement
 CO₂ production manufacture 314–316
 CO₂-emissions 316–317
 energy demand in production 313–314
 industry size 308–310
 material specification for 307–308
 process description 310–313
 research and future processes 317–318
 alternative fuels 322–324
 calcium looping 320
 CO₂ capture 320
 making cement more sustainable 318–319
 oxy-fuel 320
 replacements 319
 chalcocite 398, 399
 chalcopyrite 398, 399, 402
 chemical energy carriers 8–11
 chemical energy storage
 ammonia 236–257
 alternative routes for 245–246
 classical route for 240–244
 efficiency of 244–245
 hydrogen carrier 237–238
 power from 249
 production process 238
 uses for 236–237
 hydrocarbons 274–285
 CO₂-hydrogenation 282–283
 Fischer-Tropsch synthesis 275–276
 FT process cost and efficiency 284–285
 hydrogen energy carrier
 efficiency of 216–223
 production 191–193
 properties 191
 transport and storage 227–229
 LOHCs 257–258
 dibenzyl toluene to
 perhydro-dibenzyl toluene 261–262
 methylcyclohexane-toluene-hydrogen 258–261
 methanol and dimethyl ether 264–265
 power to X (PtX) process 189
 chemical heat pumps 145–146

- chemical pulping process 451, 453
- chemical waste 485
- chlor-alkali process 305, 307, 359–361, 365, 366, 367, 369
- chloride process 412–418
- chloro-alkali process
 - diaphragm cell 359, 361–364
 - material and industry 358–359
 - membrane cell 365–366
 - mercury cell 364–365
 - oxygen-depolarised cathode cell 366
 - process flow diagram 361
 - raw materials 361
- chlorofluorocarbons (CFCs) 544
- Chorleywood Bread Process (CBP) 490, 494
- Claus process 350, 351, 356
- close-loop recycling 442
- coal consumption 13
- coal gas 193, 195
- coal gasification 191, 193–200, 204, 217, 218, 224, 285
 - adiabatic temperature 196–197
 - carbon with water 198
 - gasifier configurations 195
 - hydrogen yield in 197–199
 - multigeneration 218
 - NO_x formation 38, 194, 431
- coefficient of performance (C.O.P.) 47, 139, 144, 146, 147, 178, 294, 553, 563
- CO₂ emission 18, 41, 71, 200, 237, 244, 418, 483
 - cement/concrete 316–317
 - from renewable ammonia production 248–249
- CO₂ production in cement manufacture 314–316
- CO₂ removal
 - energy cost for 35
 - physical CO₂ absorption 37
 - using amine scrubbing process 37
- CO₂-hydrogenation 282–283
 - limitations 283–284
- coke production 334
- combined cycle gas turbine (CCGT) 32, 33, 36, 560
- combined heat and power (CHP)
 - engines 524
 - systems 526–529
- combined open gas cycle (COGC) 250
- combustion furnace
 - combustion characteristics 158
 - fuel nozzle 155
 - fuel types 159
 - gaseous fuels 155
 - industrial side-burner 154
 - radiative section 152–153
 - water and CO₂ emissivity 160
 - Wobbe index 156
- combustion processes 38, 560
- commercial glass 435, 436, 438, 443
- compound annual growth rate (CAGR) 399, 418, 422, 487, 489, 498, 505
- compressed air energy storage (CAES) 88–93, 121–124
 - life cycle analysis 92–93
 - principal of 88–93
 - pseudo-isothermal compressed air storage 90
 - temperature of 91–92
- concentrated solar power (CSP)
 - advantage 63
 - environmental impacts 68–69
 - with heat storage 64–66
 - installations 66–68
 - principle 60–64
 - solar light conversion efficiency 64–66
- concrete
 - CO₂-emissions 316–317
 - material specification for 307–308
- conductive heat transfer 491
- consumer goods industry
 - baking industry
 - bread production process 489, 493
 - carbon footprint of breadmaking 492–494
 - history 486–487
 - industry size 487–489
 - raw materials and process 489–492

- renewable energy 494–495
 - research, future processes 495
 - canning processes 496–498
 - overall process 498–499
 - packaging materials recycle 503–504
 - pasteurising 501–502
 - retorting batch process 499–501
 - thermal food processing 502–503
 - energy in 529
 - overview 483–486
 - pharmaceutical drugs 504–505
 - continuous processing 513–514
 - current process 505–508
 - green chemistry 512–513
 - life cycle assessments 510–511
 - manufacture of 515–516
 - pharmaceutical industry 508–509
 - R&D process 509–510
 - recycle potential 514
 - research and future processes 515
 - solar thermal energy 515
 - wastewater treatment 516–522
 - sewage sludge 522–523
 - container glass 436, 437, 440–442
 - continuous glass fibres 441
 - conventional activated sludge wastewater treatment plant (CAS-WWTP) 527, 528
 - copper 398–410
 - hydrometallurgical processing routes 400, 403–404
 - material specification 398–399
 - pyrometallurgical processing routes 400–404
 - recycling 404–406
 - worldwide reserves, production and refining 400
 - copper production
 - carbon emissions 406–407
 - using renewable energy 407–409
 - copper slag 403
 - Coulombic efficiency 100–103, 106, 116
 - of lead-acid battery 100–105
 - COVID-19 pandemic 2, 284, 486, 505, 515
 - cryogenic separation vs. pressure swing adsorption 246–247
 - crystalline silicon (c-Si) types 420
 - crystallization 176, 361, 434, 507, 508
- d**
- daily pumped hydro-storage (DPHS) 87
 - decarbonisation 18, 71, 316, 325, 347, 357, 410, 460, 495
 - deep sea mining 385, 387
 - defossilisation 460–461
 - depth of discharge (DOD) 100, 104, 107
 - desulphurization 37–38, 192, 284, 351, 367
 - diaphragm cell 361–366
 - dibenzyl toluene 261–263
 - dichloro-diphenyl-trichloroethane (DDT) 485, 525
 - dimethyl ether (DME) 264–266, 271–273, 286
 - production 271
 - direct air capture (DAC) 35, 270, 275, 282, 289, 546
 - direct ammonia fuel cell (DAFC) 253
 - direct methanol fuel cells (DMFC) 253, 272–273
 - direct reduction of iron (DRI) 347, 562
 - discontinuous glass fibres 441
 - dispatchable power 69, 70, 72, 85
 - drug formulation 507–509, 514
 - dry steam process 40
 - duplex steel 329
- e**
- Eddy currents 166–168
 - electric arc furnace (EAF) 169, 333, 343–344
 - electric energy 14, 60, 146, 169, 348, 530, 551
 - electric furnaces
 - electric arc furnace 169
 - induction furnaces 167–169
 - microwave furnaces 163–167
 - resistive furnaces 162–163

- electrical energy distribution 313–314
 electrical power generation 135
 electric heating 138, 177–178, 444,
 553–555
 electricity generation 16, 87, 135, 226,
 281, 369, 396, 397, 409, 456
 electricity grid 69, 432, 461, 530
 electrification 18, 71, 177, 178, 385, 406,
 495, 551–555
 electrochemical combustion of ammonia
 253
 electrochemical double layer capacitors
 (EDCL) 119, 120
 electrochemical oxidation 117
 electrochemical reactions 97–100, 119,
 253, 404
 electrodes 98, 100, 102, 111, 118–117,
 120, 169, 211, 212, 213, 343, 347,
 367, 394, 397, 398, 423, 444
 electrolytes 111, 113–119, 122, 255, 408
 electrolytic refining 402
 electrolytic water splitting 213, 226
 electronic grade silicon (EG-Si)
 production 420, 422
 electro-static energy 119
 electrowinning process 401, 404, 408,
 409
 emission trading systems 18, 547, 548
 endothermic dehydrogenation 262
 energy carriers 1–12
 chemical energy carriers 8–10
 hydropower 7–8
 interconversion 14–17
 nuclear energy 11–12
 solar energy 5–6
 usage of 12–14
 wind energy 6–7
 worldwide usage 27
 energy density 9, 85, 88, 98, 109–111,
 115, 119, 121–123, 125, 174, 189,
 190, 228, 230, 237, 238, 271, 285,
 288
 for gaseous and liquid energy carriers
 10
 energy generation from sludge 526–529
 energy storage 86–93, 121–125
 battery
 lead-acid battery 100–105
 LiCoO₂ 108–109
 lithium-ion battery 105–108
 principle 95–100
 solid-state battery 111
 characteristic sizes of 122
 compressed air energy storage 88–93
 liquid air energy storage 93
 flow battery 111–113
 advantage of 118–119
 electrodes 117–118
 electrolytes 113–116
 membranes 116–117
 flywheel technology 94–95, 121
 physical and chemical principles
 85–86
 pumped hydro-energy storage 86–88
 supercapacitors 119–121
 entropic losses 49
 equilibrium quotient 96
 European Border Adjustment Mechanism
 (EBAM) 548
 European Trading System (ETS) 547,
 548
 evacuated tube collectors (ETC) 495
 excess energy 85, 86, 87, 561
 exergetic efficiency 216–220, 222, 243,
 245, 393, 394, 396, 425
 exothermic hydrogenation reaction 262
 exotic materials 147, 229
 extracting energy
 fuel cells 233–235
 hydrogen combustion 233
 extraterrestrial solar radiation spectrum
 53
- f**
- face-centred-cubic (FCC) structure 325
 Faradaic efficiency 100, 404, 416, 418
 Faraday constant 96, 101, 206, 207
 fermentation 484, 489, 490, 493–495,
 507, 562
 ferritic steel 329, 330

ferrosilicon global production 421, 423–425
 fertiliser 236, 237, 287, 484, 495, 524, 525, 529
 fibre glass 436, 440
 fill factor (FF) 56, 58
 fire refining 402
 Fischer-Tropsch synthesis 275–280, 282–284, 347
 catalysts 276
 kinetics reactions 278–279
 process and reactor considerations 282
 product distribution 279
 products and applications 281–282
 reactions in 277–278
 flame stability 156
 flash steam process 40, 41
 flat glass 436, 440, 441, 442, 443
 flat plate collectors 408
 flow battery 112, 113, 119
 advantage of 118–119
 electrodes 117–118
 electrolytes 113–116
 membranes 116–117
 principal set-up 112
 properties of solvents employed 114
 solvents employed in 116
 flue gas composition, indication of 34
 flywheel technology 94–95, 121
 food industry, CO₂ emissions 483–486
 food processing 483, 486–487, 529
 fossil fuel reserves distribution 8
 fossil fuels 2, 9, 14, 17, 72, 139, 152, 177, 178, 191, 192, 244, 282, 286, 306, 324, 351, 357, 367, 368, 397, 402, 406, 409, 418, 431, 441, 444, 461, 495, 508, 543, 551, 552, 553, 562
 fuel cells 233–235, 253, 273, 461
 fuel-NO_x 251
 fuels, combustion characteristics 158
 furnace 151–152
 combustion furnace 152–162
 electric furnaces 162–169

g

generator-to-system area (GSR) 58, 59, 66
 geothermal energy 13–15
 geothermal power generation 39–42
 efficiency 40–41
 environmental impact 41–42
 installations 41
 principle 39–40
 Gibbs free energy 96, 101, 106, 191, 206, 216, 222, 223, 227, 234, 253, 359, 363, 415, 418, 494, 558
 glass 166, 387, 403, 434–446
 chemical composition 435
 defined 434–435
 fibres 441
 types 435–437
 glass manufacturing
 carbon emissions 441–442
 energy consumption in 440
 energy requirement 441–442
 future research process 444–445
 industry sectors 436, 437
 process stages 437–441
 recycle potential 442–443
 sustainable 443–444
 glass transition 434–435
 global copper flow model 405
 global food industry 495
 global warming potential (GWP) 4, 145, 511
 granular activated carbon (GAC) 521
 green chemistry 512–513
 greenhouse gas (GHG) 3, 4, 5, 17–20, 38, 46, 220, 251, 368, 410, 429–431, 442, 444, 445, 483, 510, 515, 526, 527, 529, 530, 544–551, 562
 emissions 529–530, 548–551, 562–563
 accounting 548–551
 reduction 544–548
 from silicon production 429–431
 green hydrogen 191, 192, 213, 227, 237, 248, 286, 289, 325, 348, 369, 410, 461, 495, 560, 563
 green liquid hydrocarbons 288

h

- Haber-Bosch process 238, 244, 248, 249, 255, 484
- Haber-reaction 253
- Hall-Héroult process 391, 394–398
- hardwoods 446
- heating
 - energy consumption in USA 136
 - furnace 151–152
 - combustion furnace 152–162
 - electric furnaces 162–169
 - heat integration 170–174
 - future of 173–174
 - pinch analysis 171–173
 - heat pumps 139–145
 - chemical heat pump 145–146
 - heat storage 174–177
 - resistive heaters 146–151
- heat integration 170–174
 - future of 173–174
 - pinch analysis 171–173
- heat pumps 139–146, 178, 354, 357, 495, 501, 504, 530, 533, 562
 - ammonia working fluid 142
 - chemical heat pump 145–146
 - coefficient of performance 139, 141, 144, 147
 - principal operation of 140
- heat storage 74, 174–177, 347
- helium Brayton process 231, 232
- heteropolyacids (HPAs) 115
- high alloy steel 326
- hourly pumped hydro-storage (HPHS) 87
- hydrocarbons 157, 273–285, 288, 318, 356, 429, 461, 526, 544, 555, 556, 560, 561
 - CO₂-hydrogenation 282–283
 - limitations 283–284
 - Fischer-Tropsch synthesis 275–276
 - catalysts 276
 - kinetics reactions 278–279
 - process and reactor considerations 282
 - product distribution 279–282
 - reactions in 277–278
 - FT process cost and efficiency 284–285
- hydrochlorofluorocarbons (HCFCs) 544
- hydrogen-assisted magnesio-thermic reduction (HAMR) 417
- hydrogenation of dibenzyl toluene (HO DBT) 262, 263
- hydrogenation reactions 258, 361
- hydrogen-based fuel cells 253
- hydrogen combustion 233
- hydrogen economy 325, 560
- hydrogen evolution reaction (HER) 208, 210–212, 215
- hydrogen fuel cells 233
- hydrogen oxidation reaction (HOR) 233
- hydrogen pipelines 229
- hydrogen production 191–193
 - coal gasification 193–200
 - cost of 223–227
 - distribution of 192
 - efficiency 216–223
 - coal gasification 218
 - exergetic efficiency 216–220
 - methane steam reforming 221
 - extracting energy
 - fuel cells 233
 - hydrogen combustion 233–235
 - methane reforming 200–205
 - photocatalytic water splitting 214–216
 - transport and storage 227–229
 - liquefying hydrogen 230–232
 - through pipelines 229–230
 - water electrolysis 205–214
- hydrogen sulphide (H₂S) 194, 350–352
- hydrogen transport through pipelines 229–230
- hydrometallurgical processing routes 400, 403–404
- hydropower 7–8, 13–16, 25, 27, 42–46, 70, 86–88, 432, 434
- hydropower generation
 - efficiency 43–44
 - environmental impact 46
 - installations 45–46
 - principle 42–43

i

individual section machines
(IS-machines) 440
induction furnaces 167–169, 178, 347,
348, 369
industrial greenhouse gas emissions 19
industrial waste 323, 485, 516
intermediate load 70, 71
intermittent power supply 213–214
International Alloy Designation System
388
iron 109, 113, 168, 211, 227, 238–241,
276–281, 283, 307, 312, 315, 323,
325–329, 333, 341–348, 357, 369,
388, 391, 393, 397, 403, 412–414,
416, 417, 419, 423, 430, 436, 438,
454, 487, 496, 547, 548, 562
iron industry 330–333
iron production 334–341

j

Joule heating 147, 162, 166, 167, 169,
177, 347, 444
Joule's law 167
Joule-Thompson effect 231, 232
Joule-Thomson coefficient 230, 231, 242
Joule-Thomson expansion 141, 230, 231,
242
Joule-Thomson valve 93, 139, 140

k

Kraft process 451, 453–456, 458
Kroll process 415–416

l

land-use 484
lead-acid battery 100–105
characteristics of 103
Coulombic efficiency 102
number of cycles 104
temperature on voltage of 104
lead glass 435, 437
levelised cost of electricity (LCOE)
72–74, 125, 213, 226, 551–554

levelised cost of energy storage (LCOS)
118, 122–125, 555
levelised cost of hydrogen (LCOH)
223–226
life cycle analysis (LCA) 52, 92, 93, 95,
510
life cycle assessments (LCAs),
pharmaceutical industry 510
life cycle emissions 549
lignocellulosic residues (LRs) 512, 513
limestone 37, 308, 310, 312–315, 319,
323, 333, 338, 339, 368, 402, 437,
438, 445, 557
liquefied fuel gas (LFG) 288
liquefying hydrogen 230
liquid air energy storage (LAES) 93, 123
liquid electrolyte 111, 119
liquid fuels 70, 153, 156, 159, 193, 288,
322, 524
liquid organic hydrogen carriers (LOHCs)
257–258
dibenzyl toluene to perhydro-dibenzyl
toluene 261–264
methylcyclohexane-toluene-hydrogen
258–261
to transport hydrogen 257
lithium cobalt battery 106–108
lithium cobalt oxide (LCO) 108, 109
lithium-ion battery 105–108, 110, 111,
555
lithium iron phosphate (LFP) 109, 110
lithium manganese oxide (LMO) 108,
109
lithium titanate (LTO) batteries 109
logarithmic mean temperature difference
170
low alloy steel 326
lower heating value (LHV) 9, 155, 156,
159, 160, 189, 191, 264, 552, 556
Lurgi Ol-Gas-Chemie GmbH process
269

m

malachite 398
market stability reserve (MSR) 547

- martensitic steel 330
 mechanical pulping 451
 medical waste 485–486
 membrane cell 359, 361–363, 365–367
 membranes 116–117
 membrane separation 146, 222, 454, 517, 558
 mercury cell 359, 361, 364–367
 metallurgical grade silicon (MG-Si) 419, 422, 423, 425, 426, 428–434
 production 423–425
 metal-organic frameworks (MOFs) 559
 methane emissions 2
 methane reforming 193, 200–205
 CO₂-emissions, energetic efficiency 222
 methane steam reforming 191, 200–202, 218–222, 224, 225, 244, 245, 248
 exergy vs. energy analysis 220
 methanol and dimethyl ether 264–265
 back to hydrogen 273–274
 from CO₂ 269–270
 combustion of 271–272
 direct methanol fuel cell 272–273
 fuel production feedstock 273
 properties of 264
 renewable hydrogen 270
 synthesis catalyst 267–269
 synthesis reactions and equilibrium 266–267
 uses of 265
 worldwide consumption of 265
 methanol synthesis 266–267
 methanol to gasoline (MTG) 273
 methanol to olefins (MTO) 273, 461
 methyl cyclohexane (MCH) 260, 261
 methylcyclohexane-toluene-hydrogen system (MTH) 258, 260
 methyl-t-butyl ether (MTBE) 265
 microwave-assisted technology 445
 microwave furnace 163–167
 municipal waste 485, 556
- n**
 nationally determined contributions (NDCs) 17
 natural gas 8, 9, 13, 15, 16, 25, 27, 28, 31, 34, 36, 38, 52, 70, 72, 121, 123, 139, 158, 161, 191–193, 200, 203, 204, 224–226, 229, 236, 246, 266, 270, 275, 281, 284, 286, 288, 345, 347, 348, 351, 368, 401, 402, 407, 439, 441, 442, 444, 461, 492–495, 502, 515, 559, 563
 Nernst's equation 96
 net-zero scenario 17–18, 310
 NEWater 517
 non-hydraulic cements 308
 nuclear energy 11
 nuclear fission 11
 nuclear waste 11, 486
 Nusselt number 62
- o**
 open-circuit voltage 55, 102
 of PV-cell 55–56
 open-loop recycling 442
 oxy-fuel combustion 320
 oxygen-depolarised cathode cell (ODC) 366, 367
 oxygen evolution reaction (OER) 208, 210–212, 364
 oxygen reduction reaction (ORR) 233–235, 253
 oxygen steel-making 341–342
- p**
 packaging materials recycle 503–504
 paper 387, 410, 446–459
 paper and paperboard production 447, 448
 paper and pulp industry 358, 446–449, 453, 458
 emissions from 455–456
 energy usage and generation 454–455
 future research process 457–458
 objectives 457
 processes 449–454

- water usage 455
- papermaking 446, 449, 451, 453, 455, 456, 458, 462
- paper production 446, 447, 455, 456, 458
 - fresh water consumption 455
- paper testing 447
- parabolic trough collectors 408
- parabolic trough technology 66
- pasteurising 501–502
- peak load 70, 71
- PEM electrolyzers 209, 210, 213, 227, 494
- PEM-fuel cells 253
- PEM-stack 228
- perhydro-dibenzyl toluene 261–263
- Peukert's constant 100
- pharmaceutical drugs 485, 504–505
 - continuous processing 513–514
 - current process 505–508
 - green chemistry 512–513
 - life cycle assessments 510
 - pharmaceutical industry 508–509
 - recycle potential 514
 - research and development process 509–510
 - research and future processes 515
 - solar thermal energy 515
- pharmaceutical industry, energy
 - consumption 508–510
- pharmaceutical ingredients (APIs), life cycle assessments 510
- phase-change-materials (PCMs) 176
- photocatalytic water splitting 214–216
- photovoltaics
 - installations 59–60
 - principle 54–56
 - solar light conversion efficiency 56–59
- pigment-grade titania production 411, 412
 - Becher process 414
 - chloride process 414–415
 - sulphate process 412–414
- Pigouvian taxation 544, 545
- pinch analysis 171–173
- Planck's radiation law 162
- plasma heating 445
- pluri-annual pumped hydro-storage (PPHS) 87
- policy-driving carbon pricing 18
- polycrystalline silicon production 425–428, 432
- Portland cement 307, 315, 319, 368
 - Bogue's compounds in 308
 - clinkering development 312
 - CO₂ produced per tonne of 315
- power density function 113, 122
- power generation 2, 13–17, 20–28, 71–74
 - electricity grid 69–71
 - from geothermal energy 39–42
 - annualized capacity factor 41
 - efficiency 40–41
 - environmental impact 41–42
 - installations 41
 - principle 39–40
 - hydropower 42–46
 - in selected countries 26
 - solar power 53–69
 - sources 69–70
 - thermal 28–39
 - wind energy 46–52
- power to X (PtX) process 189–190, 212, 286, 555, 560
- primary energy carriers, in oil refineries 15
- primary energy consumption 3, 14–16, 135, 136
- primary energy demand 1, 2, 11, 13, 14, 17
- Process Analytical Technologies (PATs) 514
- process emissions 316, 324, 398, 416, 430, 432, 445, 557, 562
- process industry 20, 135, 146, 151, 152, 170, 178, 385, 543, 548, 549, 551, 554, 555, 560, 562–563
- process mass intensity (PMI) 510
- prompt-NO_x 38
- proton exchange membrane (PEM) 207–213, 223, 226–228, 234, 248, 249, 253, 255, 494

- proton exchange membrane electrolysis cell (PEMEL) 223, 227
- pseudo-isothermal compressed air energy storage (I-CAES) 90
- pulp 138, 358, 446–460, 547
- pulp and paper manufacturers 448, 449
- pulping process 449, 451, 453
- pulpwood 446
- pumped hydro-energy storage (PHES) 86–88
- pyrolysis 194, 195, 225, 226, 344, 425, 522–524, 557
- pyrometallurgical processing routes 400, 401, 403
- q**
- quartz 163, 164, 312, 419, 422, 423, 429, 430, 434
- quartz distribution 422–432
- quartzite 423
- r**
- radiative heat transfer 147, 158, 160, 161, 163, 169, 233, 250, 315, 461
- Rankine cycle 28–33, 36, 39, 63, 65, 68, 72, 250, 251, 425, 431, 443, 556
- rechargeable lead-acid battery 105
- recycling 319, 320, 343, 344, 356, 358, 368, 462
- aluminium 396
- copper 404–406
- recycling food packaging 504
- red mud 391, 393, 485
- relative humidity (RH) 490–492
- renewable energy 13–14, 17, 18, 20, 25–74, 85, 86, 93, 95, 105, 121, 125, 136, 143, 146, 174, 177, 178, 189–192, 213, 226, 237, 245, 246, 255, 257, 282, 285–287, 289, 316, 318, 343, 347, 356, 367–369, 387, 397–399, 409–410, 416–417, 432, 434, 444, 446, 460–462, 484, 496, 501, 504, 514, 515, 530, 543, 548, 551, 552, 557, 560–563
- breadmaking 494–495
- copper production using 407–409
- thermal food processing 502–503
- renewable hydrogen 236, 245–248, 270, 274–276, 279, 282, 286, 318, 347
- renewable reductants 344
- resistive furnaces 162, 163
- resistive heaters 146–151
- resistive heating 137, 147, 432
- Retort, canning 499
- reverse Boudouard reaction 338
- reverse water gas shift (RWGS) 204, 266, 267, 275, 283, 561
- S**
- Sankey diagram, of primary energy consumption 15
- Scope 1 type emissions 549
- Scope 2 type emissions 549
- Scope 3-type emissions 18, 485, 499, 549
- Scope A emissions 549–551
- Scope B emissions 549–551
- Scope C emissions 549–551
- Scope D emissions 550
- seasonal pumped hydro-storage (SPHS) 87
- selective catalytic reduction (SCR) reaction 39, 250, 252
- selective non-catalytic reduction (SNCR) process 39
- sensible heat storage 176
- sewage sludge 522–523
- anaerobic digestion 524
- combustion and incineration 524
- energy generation from 526–529
- fertiliser and irrigation 525–526
- pyrolysis 524
- Shockley-Queisser efficiency 57
- Shockley-Queisser limit 57
- SiemensTM process 420, 425, 427, 428, 432
- silicon 57, 58, 149, 163, 167, 342, 387, 388, 403, 418–419
- compositions 419
- as feedstock for chemical industry 428–429

- future research process 432–433
- material specification 419–420
- recycle potential 431
- silicon production 420–422
 - direct greenhouse gas emissions 429–431
 - global 433–434
 - global production 421
 - sustainable 431–432
- sin tax 19, 544
- sludge-to-energy 527, 529
- sludge treatment technologies 521
- smelting process 167, 400, 402, 408–410, 414, 417
- Soave-Redlich-Kwong equation 228, 231, 237, 251, 264
- social license to operate (SLO) concept 20
- soda ash 437–439, 445, 460, 549
- soda-lime glass 435
- softwoods 446
- solar energy 5–6, 8, 13–17, 25, 27, 54, 57, 59, 64–66, 68–69, 72, 74, 85, 216, 408, 409, 436, 494, 495
- solar grade silicon (SG-Si) 420, 425, 427, 428, 431, 433, 460
- solar power generation
 - concentrated solar power 60–68
 - photo-voltaics
 - installations 59–60
 - principle 54–56
 - solar light conversion efficiency 56–59
- solar projects, in copper mining industry 408
- solar thermal energy 515
- solid oxide electrolysis (SOE) 207, 208, 211–213, 223, 226, 248, 249
- solid oxide electrolysis cell (SOEL) 223
- solid-state batteries 111
- Solvay process 438, 445
- speciality glass 436
- specific energy 9–11, 13, 85, 94, 102, 106, 108–110, 120, 189–191, 227, 228, 232, 237, 264, 271, 285, 287, 407
- consumption 460
 - for gaseous and liquid energy carriers 10
- spider plots, lithium-ion batteries 109, 110
- stainless steel 94, 326, 328–330, 333, 334, 344, 352, 388, 508
- state of charge (SOC) 100
- steam 1, 11, 29–33, 39–42, 62–63, 135–137, 139, 144, 150, 151, 165, 170, 194, 197, 200–204, 207, 212, 218–226, 233, 242, 244, 285, 349, 350, 352–354, 356, 357, 363, 366, 425, 443, 453, 455, 458, 461, 487, 491, 492, 494, 497–504, 508, 549, 556, 557
 - heat transfer 139
- steam methane reforming (SMR) 191, 200–204, 218–222, 224–226, 240, 241, 244, 245, 248, 273
- steam reforming reaction 200, 203, 204, 222, 226, 245, 273
- steel
 - coke production 334
 - electric arc furnace 343–344
 - emission reductions
 - alternative reductants 344–346
 - carbon capture and utilisation 347
 - high-temperature heat 346–347
 - recycling potential 344
 - iron production, blast furnace 334–341
 - material specification 325–330
 - oxygen steel-making 341–342
 - production of 1980 and 2024 332
 - sub-processes 333
- steel industry 3, 151, 169, 307, 330–333, 344, 346, 368, 369, 420
- Stefan-Boltzmann constant 62, 147
- sterilisation 136, 137, 485, 497, 499, 511, 530
- stick methods 548
- stock preparation 451, 456
- submerged-electrode arc furnace (SAF) 423, 424, 425, 430

sulphate process 412, 413, 418
sulphur-burning plants 356
sulphuric acid
 material specifications 349
 production process 350–354
 size and production scale 349–350
 spent acid waste regeneration
 356–357
supercapacitors 85, 119–121, 124
supplementary cementitious materials
 (SCMs) 309, 368
Sustainable Development Goal (SDG)
 516
synergistic copper process concept 409

t

tertiary amyl methyl ether (TAME) 265
tetrafluoroethylene-based
 fluoropolymer-copolymer 116,
 117
thermal energy storage (TES) 63, 64, 66,
 69, 70, 90, 91, 93, 515
thermal food processing 502–503
thermal oil 61, 137, 139
thermal power generation process
 28–39
 Brayton cycle 31–33
 environmental impacts 33–34
 carbon capture 34–37
 DeNO_x 38–39
 desulphurization 37–38
 Rankine cycle 28–31
thermo-catalytic conversion of ammonia
 253
thermo-catalytic decomposition 255
tinplate cans 503
titanium 362, 387, 410–418
 limitations 418
 phases 410
 recycle 416
titanium alloys 410
titanium-bearing ores 411
titanium production 411
 future processes 417–418

Kroll process 415–416
 renewable energy implementation
 416–417
titanium/titania 306, 387, 410–411
toluene (Tol) 159, 258–264
tool steel 326, 328
transport chain efficiency 288
trinitrotoluene (TNT) 236
tunnel ovens 491, 493, 495
turnover frequency (TOF) 239, 240

u

uninterrupted power supplies (UPS) 99
Uranium reserves across the world 12
US department of energy (DOE) 225,
 227

v

vacuum arc remelting 416
vacuum distillation 415, 416, 417
value-adjusted LCOE (VALCOE) 73
vanadium flow redox batteries (VFRB)
 115
variable power 69, 70, 72, 213
voltage-capacity behaviour of battery 98

w

warm air 138
waste generation 33, 485, 529, 543
wastewater treatment 486, 516–529
 sewage sludge 522–523
 anaerobic digestion 524
 combustion and incineration 524
 energy generation from 526–529
 pyrolysis 524
wastewater treatment plants (WWTPs)
 516, 518, 520, 521, 522, 526, 527,
 529
 energy consumption on 521
 energy demand of 522
wastewater treatment process 519
water electrolysis 191, 192, 205–214
 electrolysers technology 207–212

- intermittent power supply and electrolytic water splitting 213–214
 - water gas 190, 193, 195, 200, 201, 204, 205, 218, 241, 277, 283, 561
 - water gas shift (WGS) 193, 200, 201, 218, 241, 277, 561
 - reaction 278–279
 - reactors 204, 240, 241
 - water reuse 516
 - weekly pumped hydro-storage (WPHS) 87
 - Wien's displacement law 162
 - wind energy 6–7, 14, 16, 27, 46–53
 - efficiency 47–51
 - environmental impact 52
 - installations 51–52
 - principle 47
 - Wobbe index 156
 - woodchip utilisation 432
 - worldwide emission trading systems 547
 - wrought aluminium alloys 388
- Z**
- zeolites 37, 39, 145, 273, 283, 559





