

TABLE OF CONTENTS

PREFACE	v
ACKNOWLEDGMENTS	vii
ABOUT THE AUTHORS	viii
1. THERMODYNAMIC FUNDAMENTALS	1
1.1. Introduction	1
1.2. Energy	1
1.2.1. Applications of energy	1
1.2.2. Concept of energy	2
1.2.3. Forms of energy	2
1.2.4. The first law of thermodynamics	3
1.2.5. Energy and the FLT	4
1.2.6. Economic aspects of energy	4
1.2.7. Energy audit methods	5
1.2.8. Energy management	5
1.3. Entropy	6
1.3.1. Order and disorder and reversibility and irreversibility	6
1.3.2. Characteristics of entropy	7
1.3.3. Significance of entropy	8
1.3.4. Carnot's contribution	9
1.3.5. The second law of thermodynamics	9
1.3.6. SLT statements	10
1.3.7. The Clausius inequality	10
1.3.8. Useful relationships	11
1.4. Exergy	11
1.4.1. The quantity exergy	11
1.4.2. Exergy analysis	11
1.4.3. Characteristics of exergy	12
1.4.4. The reference environment	12
1.4.5. Exergy vs. energy	13
1.4.6. Exergy efficiencies	14
1.4.7. Solar exergy and the earth	14
1.5. Illustrative examples	15
1.5.1. Illustrative example 1	15
1.5.2. Illustrative example 2	16
1.5.3. Illustrative example 3	17
1.5.4. Illustrative example 4	19
1.6. Closing remarks	21
Problems	21
2. EXERGY AND ENERGY ANALYSES	23
2.1. Introduction	23
2.2. Why energy and exergy analyses?	23

2.3.	Nomenclature	24
2.4.	Balances for mass, energy and entropy	24
2.4.1.	Conceptual balances	24
2.4.2.	Detailed balances	24
2.5.	Exergy of systems and flows	26
2.5.1.	Exergy of a closed system	26
2.5.2.	Exergy of flows	27
2.6.	Exergy consumption	28
2.7.	Exergy balance	28
2.8.	Reference environment	29
2.8.1.	Theoretical characteristics of the reference environment	29
2.8.2.	Models for the reference environment	29
2.9.	Efficiencies and other measures of merit	31
2.10.	Procedure for energy and exergy analyses	32
2.11.	Energy and exergy properties	32
2.12.	Implications of results of exergy analyses	33
2.13.	Closing remarks	34
	Problems	34
3.	EXERGY, ENVIRONMENT AND SUSTAINABLE DEVELOPMENT	36
3.1.	Introduction	36
3.2.	Exergy and environmental problems	37
3.2.1.	Environmental concerns	37
3.2.2.	Potential solutions to environmental problems	40
3.2.3.	Energy and environmental impact	42
3.2.4.	Thermodynamics and the environment	42
3.3.	Exergy and sustainable development	45
3.3.1.	Sustainable development	45
3.3.2.	Sustainability and its need	45
3.3.3.	Dimensions of sustainability	46
3.3.4.	Environmental limits and geographic scope	47
3.3.5.	Environmental, social and economic components of sustainability	47
3.3.6.	Industrial ecology and resource conservation	47
3.3.7.	Energy and sustainable development	49
3.3.8.	Energy and environmental sustainability	49
3.3.9.	Exergy and sustainability	49
3.3.10.	Exergetic aspects of sustainable processes	51
3.3.11.	Renewables and tools for sustainable development	51
3.3.12.	Exergy as a common sustainability quantifier for process factors	55
3.4.	Illustrative example	56
3.4.1.	Implications regarding exergy and energy	57
3.4.2.	Implications regarding exergy and the environment	58
3.4.3.	Implications regarding exergy and sustainable development	58
3.5.	Closing remarks	58
	Problems	59
4.	APPLICATIONS OF EXERGY IN INDUSTRY	60
4.1.	Introduction	60
4.2.	Questions surrounding industry's use of exergy	61
4.3.	Advantages and benefits of using exergy	61
4.3.1.	Understanding thermodynamic efficiencies and losses through exergy	62
4.3.2.	Efficiency	62
4.3.3.	Loss	63

4.3.4. Examples	63
4.3.5. Discussion	64
4.4. Understanding energy conservation through exergy	64
4.4.1. What do we mean by energy conservation?	64
4.4.2. Exergy conservation	65
4.4.3. Examples	65
4.5. Disadvantages and drawbacks of using exergy	66
4.6. Possible measures to increase applications of exergy in industry	66
4.7. Closing remarks	67
Problems	67
5. EXERGY IN POLICY DEVELOPMENT AND EDUCATION	68
5.1. Introduction	68
5.2. Exergy methods for analysis and design	68
5.3. The role and place for exergy in energy-related education and awareness policies	70
5.3.1. Public understanding and awareness of energy	70
5.3.2. Public understanding and awareness of exergy	70
5.3.3. Extending the public's need to understand and be aware of exergy to government and the media	71
5.4. The role and place for exergy in education policies	71
5.4.1. Education about exergy	71
5.4.2. The need for exergy literacy in scientists and engineers	72
5.4.3. Understanding the second law through exergy	72
5.4.4. Exergy's place in a curriculum	73
5.5. Closing remarks	74
Problems	75
6. EXERGY ANALYSIS OF PSYCHROMETRIC PROCESSES	76
6.1. Basic psychrometric concepts	76
6.2. Balance equations for air-conditioning processes	78
6.3. Case study: exergy analysis of an open-cycle desiccant cooling system	82
6.3.1. Introduction	82
6.3.2. Operation and design of experimental system	82
6.3.3. Energy analysis	84
6.3.4. Exergy analysis	84
6.3.5. Results and discussion	87
6.4. Closing remarks	89
Problems	89
7. EXERGY ANALYSIS OF HEAT PUMP SYSTEMS	91
7.1. Introduction	91
7.2. System description	93
7.3. General analysis	94
7.4. System exergy analysis	95
7.5. Results and discussion	98
7.6. Concluding remarks	98
Problems	102
8. EXERGY ANALYSIS OF DRYING PROCESSES AND SYSTEMS	103
8.1. Introduction	103
8.2. Exergy losses associated with drying	104
8.3. Analysis	105

8.3.1.	Balances	105
8.3.2.	Exergy efficiency	106
8.4.	Importance of matching supply and end-use heat for drying	107
8.5.	Illustrative example	107
8.5.1.	Approach	107
8.5.2.	Results	107
8.5.3.	Discussion	110
8.6.	Energy analysis of fluidized bed drying of moist particles	112
8.6.1.	Fluidized bed drying	112
8.6.2.	Thermodynamic model and balances	114
8.6.3.	Efficiencies for fluidized bed drying	116
8.6.4.	Effects of varying process parameters	117
8.6.5.	Example	117
8.7.	Concluding remarks	126
	Problems	126
9.	EXERGY ANALYSIS OF THERMAL ENERGY STORAGE SYSTEMS	127
9.1.	Introduction	127
9.2.	Principal thermodynamic considerations in TES	128
9.3.	Exergy evaluation of a closed TES system	129
9.3.1.	Analysis of the overall processes	129
9.3.2.	Analysis of subprocesses	131
9.3.3.	Implications for subprocesses and overall process	133
9.4.	Relations between temperature and efficiency for sensible TES	134
9.4.1.	Model and analysis	134
9.4.2.	Efficiencies and their dependence on temperature	135
9.5.	Exergy analysis of thermally stratified storages	137
9.5.1.	General stratified TES energy and exergy expressions	137
9.5.2.	Temperature-distribution models and relevant expressions	139
9.5.3.	Increasing TES exergy storage capacity using stratification	142
9.6.	Energy and exergy analyses of cold TES systems	145
9.6.1.	Energy balances	146
9.6.2.	Exergy balances	148
9.6.3.	Efficiencies	148
9.7.	Exergy analysis of aquifer TES systems	149
9.7.1.	ATES model	149
9.7.2.	Energy and exergy analyses	150
9.8.	Examples and case studies	152
9.8.1.	Inappropriateness of energy efficiency for TES evaluation	152
9.8.2.	Comparing thermal storages	152
9.8.3.	Thermally stratified TES	155
9.8.4.	Cold TES	156
9.8.5.	Aquifer TES	159
9.9.	Concluding remarks	162
	Problems	162
10.	EXERGY ANALYSIS OF RENEWABLE ENERGY SYSTEMS	163
10.1.	Exergy analysis of solar photovoltaic systems	163
10.1.1.	PV performance and efficiencies	164
10.1.2.	Physical exergy	164
10.1.3.	Chemical exergy	165
10.1.4.	Illustrative example	167
10.1.5.	Closure	167
10.2.	Exergy analysis of solar ponds	167

10.2.1. Solar ponds	169
10.2.2. Experimental data for a solar pond	170
10.2.3. Energy analysis	172
10.2.4. Exergy analysis	180
10.2.5. Closure	185
10.3. Exergy analysis of wind energy systems	187
10.3.1. Wind energy systems	188
10.3.2. Energy and exergy analyses of wind energy aspects	189
10.3.3. Case study	192
10.3.4. Spatio-temporal wind exergy maps	196
10.3.5. Closure	204
10.4. Exergy analysis of geothermal energy systems	205
10.4.1. Case study 1: energy and exergy analyses of a geothermal district heating system	207
10.4.2. Case study 2: exergy analysis of a dual-level binary geothermal power plant	217
10.5. Closing remarks	226
Problems	227
11. EXERGY ANALYSIS OF STEAM POWER PLANTS	229
11.1. Introduction	229
11.2. Analysis	230
11.2.1. Balances	230
11.2.2. Overall efficiencies	231
11.2.3. Material energy and exergy values	231
11.3. Spreadsheet calculation approaches	233
11.4. Example: analysis of a coal steam power plant	235
11.5. Example: impact on power plant efficiencies of varying boiler temperature and pressure	235
11.6. Case study: energy and exergy analyses of coal-fired and nuclear steam power plants	238
11.6.1. Process descriptions	239
11.6.2. Approach	245
11.6.3. Analysis	245
11.6.4. Results	246
11.6.5. Discussion	248
11.7. Improving steam power plant efficiency	252
11.7.1. Exergy-related techniques	252
11.7.2. Computer-aided design, analysis and optimization	253
11.7.3. Maintenance and control	253
11.7.4. Steam generator improvements	253
11.7.5. Condenser improvements	254
11.7.6. Reheating improvements	254
11.7.7. Regenerative feedwater heating improvements	255
11.7.8. Improving other plant components	255
11.8. Closing remarks	256
Problems	256
12. EXERGY ANALYSIS OF COGENERATION AND DISTRICT ENERGY SYSTEMS	257
12.1. Introduction	257
12.2. Cogeneration	258
12.3. District energy	259
12.4. Integrated systems for cogeneration and district energy	260
12.5. Simplified illustrations of the benefits of cogeneration	261
12.5.1. Energy impacts	261
12.5.2. Energy and exergy efficiencies	263
12.5.3. Impact of cogeneration on environmental emissions	264
12.5.4. Further discussion	265

12.6. Case study for cogeneration-based district energy	265
12.6.1. System description	265
12.6.2. Approach and data	267
12.6.3. Preliminary analysis	267
12.6.4. Analysis of components	268
12.6.5. Analysis of overall system	272
12.6.6. Effect of inefficiencies in thermal transport	272
12.6.7. Analyses of multi-component subsystems	272
12.6.8. Results	272
12.6.9. Discussion	274
12.7. Closing remarks	275
Problems	276
 13. EXERGY ANALYSIS OF CRYOGENIC SYSTEMS	 277
13.1. Introduction	277
13.2. Energy and exergy analyses of gas liquefaction systems	277
13.3. Exergy analysis of a multistage cascade refrigeration cycle for natural gas liquefaction	281
13.3.1. Background	281
13.3.2. Description of the cycle	281
13.3.3. Exergy analysis	282
13.3.4. Minimum work for the liquefaction process	285
13.3.5. Discussion	288
13.4. Closing remarks	288
Problems	288
 14. EXERGY ANALYSIS OF CRUDE OIL DISTILLATION SYSTEMS	 290
14.1. Introduction	290
14.2. Analysis approach and assumptions	291
14.3. Description of crude oil distillation system analyzed	291
14.3.1. Overall system	291
14.3.2. System components	292
14.4. System simulation	294
14.5. Energy and exergy analyses	294
14.5.1. Crude heating furnace	294
14.5.2. Atmospheric distillation unit	295
14.5.3. Overall exergy efficiency	296
14.6. Results and discussion	296
14.6.1. Simulation results	296
14.6.2. Energy and exergy results	296
14.6.3. Impact of operating parameter variations	298
14.6.4. Result limitations	300
14.7. Closing remarks	301
Problems	302
 15. EXERGY ANALYSIS OF FUEL CELL SYSTEMS	 303
15.1. Introduction	303
15.2. Background	304
15.2.1. PEM fuel cells	304
15.2.2. Solid oxide fuel cells	304
15.3. Exergy analysis of a PEM fuel cell power system	305
15.3.1. System description	305
15.3.2. PEM fuel cell performance model	306
15.3.3. Analysis	307

15.3.4. Results and discussion	308
15.3.5. Closure	312
15.4. Energy and exergy analyses of combined SOFC–gas turbine systems	313
15.4.1. Description of systems	313
15.4.2. Analysis	315
15.4.3. Thermodynamic model of the SOFC stack	318
15.4.4. Exergy balances for the overall systems	319
15.4.5. Results and discussion	320
15.4.6. Closure	323
15.5. Closing remarks	323
Problems	323
16. EXERGY ANALYSIS OF AIRCRAFT FLIGHT SYSTEMS	325
16.1. Introduction	325
16.2. Exergy analysis of a turbojet	326
16.2.1. Exergy flows through a turbojet	326
16.2.2. Exergy efficiencies for a turbojet	328
16.2.3. Impact of environment on turbojet assessment	328
16.3. Flight characteristics	329
16.4. Cumulative rational efficiency	329
16.4.1. Variable reference environment	329
16.4.2. Constant reference environment	331
16.5. Cumulative exergy loss	332
16.6. Contribution of exhaust gas emission to cumulative exergy loss	332
16.6.1. Variable reference environment	332
16.6.2. Constant reference environment	333
16.7. Closing remarks	334
Problems	334
17. EXERGoeCONOMIC ANALYSIS OF THERMAL SYSTEMS	335
17.1. Introduction	335
17.2. Economic aspects of exergy	336
17.2.1. Exergy and economics	336
17.2.2. Energy and exergy prices	337
17.3. Modeling and analysis	338
17.3.1. Fundamental relationships	338
17.3.2. Definition of key terms	340
17.3.3. Ratio of thermodynamic loss rate to capital cost	341
17.4. Key difference between economic and thermodynamic balances	341
17.5. Example: coal-fired electricity generation	342
17.5.1. Plant description and data	343
17.5.2. Data categorization	345
17.5.3. Results and discussion	347
17.6. Case study: electricity generation from various sources	349
17.6.1. Results and discussion	350
17.6.2. Relations for devices in a single generating station	350
17.6.3. Generalization of results	356
17.7. Exergoeconomics extended: EXCEM analysis	357
17.7.1. The EXCEM analysis concept	357
17.7.2. Development of a code for EXCEM analysis	357
17.7.3. Illustrative examples of EXCEM analysis	358
17.7.4. Exergy loss and cost generation	359
17.8. Closing remarks	361
Problems	361

18. EXERGY ANALYSIS OF COUNTRIES, REGIONS AND ECONOMIC SECTORS	363
18.1. Introduction	363
18.2. Background and benefits	364
18.3. Applying exergy to macrosystems	364
18.3.1. Energy and exergy values for commodities in macrosystems	364
18.3.2. The reference environment for macrosystems	365
18.3.3. Efficiencies for devices in macrosystems	366
18.4. Case study: energy and exergy utilization in Saudi Arabia	367
18.4.1. Analysis of the residential sector	368
18.4.2. Analysis of the public and private sector	371
18.4.3. Analysis of the industrial sector	377
18.4.4. Analysis of the transportation sector	380
18.4.5. Analysis of the agricultural sector	386
18.4.6. Analysis of the utility sector	388
18.4.7. Energy and exergy efficiencies and flows for the sectors and country	390
18.4.8. Discussion	393
18.4.9. Summary of key findings	394
18.5. Comparison of different countries	394
18.6. Closing remarks	394
Problems	395
19. EXERGETIC LIFE CYCLE ASSESSMENT	397
19.1. Introduction	397
19.2. Life cycle assessment	397
19.3. Exergetic LCA	398
19.4. Case study: exergetic life cycle analysis	399
19.4.1. Natural gas and crude oil transport	400
19.4.2. Natural gas reforming and crude oil distillation	400
19.4.3. Hydrogen production from renewable energy	402
19.4.4. Hydrogen compression	403
19.4.5. Hydrogen and gasoline distribution	404
19.4.6. Life cycle exergy efficiencies	405
19.5. Economic implications of ExLCA	406
19.6. LCA and environmental impact	407
19.6.1. Power generation and transportation	407
19.6.2. Environmental-impact reduction by substitution of renewables for fossil fuels	409
19.6.3. Main findings and extensions	415
19.7. Closing remarks	415
Problems	415
20. EXERGY AND INDUSTRIAL ECOLOGY	417
20.1. Introduction	417
20.2. Industrial ecology	417
20.3. Linkage between exergy and industrial ecology	418
20.3.1. Depletion number	418
20.3.2. Integrated systems	418
20.4. Illustrative example	419
20.4.1. The considered gas-turbine combined cycle with hydrogen generation	419
20.4.2. Exergy analysis of the gas-turbine combined cycle with hydrogen generation	421
20.4.3. Results	421
20.5. Closing remarks	423
Problems	423
21. CLOSING REMARKS AND FUTURE EXPECTATIONS	424

NOMENCLATURE	426
REFERENCES	429
APPENDIX A GLOSSARY OF SELECTED TERMINOLOGY	440
APPENDIX B CONVERSION FACTORS	443
APPENDIX C THERMOPHYSICAL PROPERTIES	445
INDEX	451