

Contents

1	Introduction	1
1.1	Overview on Global Energy Demand	1
1.2	Energy Sources	1
1.2.1	Nonrenewable Energy Sources	2
1.2.2	Renewable Energy Sources	7
1.3	Potential Global Energy Crisis	14
1.4	Climate Change and Sustainability	15
1.5	Waste Energies and Their Harvesting	15
1.6	Outline of this Book	16
	References	18
2	Waste Mechanical Energy Harvesting (I): Piezoelectric Effect	19
2.1	Introduction	19
2.2	Piezoelectricity and Piezoelectric Materials	21
2.2.1	Piezoelectricity	21
2.2.2	Brief History of Modern Piezoelectric Ceramics	24
2.2.3	Microstructures of Piezoelectric Ceramics	25
2.2.4	Typical Piezoceramics	26
2.2.5	PZT Ceramics	26
2.2.6	PZT Films	29
2.2.7	Piezoelectric Polymers	32
2.2.8	Composites	35
2.3	Principle of Piezoelectric Effect for Energy Harvesting	36
2.3.1	General Theory of Mechanical Energy Conversion	36
2.3.2	Piezoelectric Energy Harvesting Devices	39
2.3.3	Modeling of Piezoelectric Energy Harvesting Devices	43
2.4	Energy from Human Activity	44
2.4.1	Shoe-Mounted Harvesters	44
2.4.2	Energy from Human Body Motion	51
2.4.3	Energy from Joint Motion	69
2.4.4	Rotating Harvesters	87

2.5	Energy from Civil Infrastructure and Transportation.	96
2.5.1	Simulated Study of Bridge	96
2.5.2	In Situ Study of Bridge	101
2.6	Energy from Natural Sources	104
2.6.1	Wind Energy.	104
2.6.2	Wind Energy Through Tree	107
2.6.3	Water Flow.	112
2.6.4	Energy from Rain	117
2.7	Strategies to Enhance Energy Harvesting Efficiency	118
2.7.1	Brief Introduction	118
2.7.2	Frequency Tuning	118
2.7.3	Mechanical Tuning	119
2.7.4	Electrical Tuning	124
2.7.5	Bandwidth Widening	126
2.8	Summary and Perspectives	127
	References	128
3	Waste Mechanical Energy Harvesting (II):	
	Nanopiezoelectric Effect	135
3.1	Introduction.	135
3.2	Crystal Characteristics of ZnO.	136
3.3	Growth of Piezoelectric ZnO Nanostructures.	138
3.3.1	Vapor Phase Deposition	138
3.3.2	Pulse Laser Deposition.	142
3.3.3	Chemical Processes	144
3.3.4	Growth of Patterned Nanowire Arrays	147
3.4	Concept and Principle of Nanogenerators	153
3.4.1	Piezopotential	153
3.4.2	Outputs of Nanogenerators	157
3.5	Nanogenerators with Vertically Aligned ZnO Nanowires	160
3.5.1	Concept of Piezoelectric Nanogenerators	160
3.5.2	Schottky Barrier at the Electrode-Nanowire Interface.	163
3.5.3	Charge Generation and Output Processes	164
3.5.4	Principle of Nanogenerators with <i>n</i> -Type Materials	168
3.5.5	Nanogenerators with <i>p</i> -Type Materials	170
3.5.6	Strategies Toward High-Performance Nanogenerators	174
3.5.7	New Record of Power Output	187
3.6	Nanogenerators with Laterally Bonded Nanowires	192
3.6.1	Brief Introduction	192
3.6.2	Fabrication Process	192
3.6.3	Electrical Characterization	193
3.6.4	Principle of Nanogenerator	195
3.6.5	Linear Connections	196

3.6.6	Power Conversion Efficiency	197
3.6.7	Applications-Harvesting Biomechanical Energies.	197
3.6.8	High-Output Nanogenerators with Lateral Nanowire Arrays	200
3.7	Flexible Fiber Nanogenerators	210
3.7.1	Microfiber-Nanowire Hybrid Nanogenerators	211
3.7.2	Flexible Fiber Nanogenerators Driven by Pressure.	216
3.8	Multifunctional Nanogenerators	222
3.8.1	Nanogenerators with Noncontact Nanowires	222
3.8.2	Hybrid Nanogenerators.	229
3.8.3	Nanogenerators for Self-Powering	234
3.9	Nanogenerators with Other Nanowires	243
3.9.1	Wurtzite Nanowires	243
3.9.2	Ferroelectric Nanowires	243
3.9.3	Poly(Vinylidene Fluoride) (PVDF).	253
3.10	Summary and Prospects	259
	References	259
4	Waste Thermal Energy Harvesting (I): Thermoelectric Effect	263
4.1	Overview on Waste Thermal Energies: Definition, Identification, and Classification	263
4.2	Principle of Thermoelectric Effect	266
4.2.1	Thermoelectric Effect.	266
4.2.2	Seebeck Effect	266
4.2.3	Thermopower	267
4.2.4	Charge Carrier Diffusion	268
4.2.5	Phonon Drag.	269
4.2.6	Peltier Effect.	269
4.2.7	Thomson Effect.	270
4.2.8	Thomson Relations	271
4.3	Criteria of Thermoelectric Materials for High Efficiency	271
4.3.1	Figure of Merit	271
4.3.2	Device Efficiency	272
4.4	Thermoelectric Materials	273
4.4.1	Single-Phase Materials	273
4.4.2	Anisotropic Chalcogenide Compounds	281
4.4.3	Isotropic Chalcogenide Compounds	288
4.4.4	Oxide Thermoelectric Materials.	294
4.5	Physics and Strategies of Thermoelectric Materials	304
4.5.1	Electrical Transport	304
4.5.2	Higher Z Through Increasing Power Factor.	318
4.5.3	Lattice Thermal Conductivity (k_L)	326

4.6	Nanostructured Thermoelectric Materials	346
4.6.1	Heterogeneous Nanocomposite.	346
4.6.2	Polycrystalline Nanocomposites.	357
4.6.3	Superlattice Nanostructures.	358
4.6.4	Bi Nanowires	364
4.6.5	Si Nanowires.	367
4.6.6	Nanocarbon Thermoelectric Materials	368
4.7	Processing of Bulk Nanocomposites	371
4.7.1	Synthesis of Nanoparticles	372
4.7.2	Consolidation Technologies	372
4.8	Thermoelectric Effect for Waste Energy Harvesting.	373
4.8.1	Principle	373
4.8.2	Examples of Applications	376
4.9	Challenge in Thermoelectric Nanocomposites	380
4.9.1	Phonon Transport	381
4.9.2	Electronic Transport.	383
4.10	Concluding Remarks	384
	References	385
5	Waste Thermal Energy Harvesting (II):	
	Pyroelectric Effect and Others	405
5.1	Introduction.	405
5.2	Principle of Pyroelectric Effect	407
5.2.1	Definition	407
5.2.2	Pyroelectric Coefficient and Electrocaloric Coefficient	409
5.2.3	Primary and Secondary Pyroelectric Coefficient	411
5.2.4	Tertiary Pyroelectric Coefficient and Other Aspects.	412
5.2.5	Pyroelectric Effect Versus Phase Transition	415
5.2.6	Measurement of Pyroelectric Coefficient	417
5.2.7	Pyroelectric Figure of Merit	425
5.3	Pyroelectric Materials.	427
5.3.1	Triglycine Sulfate (TGS)	427
5.3.2	Polyvinylidene Fluoride	429
5.3.3	Lithium Tantalate	430
5.3.4	Strontium Barium Niobate	430
5.3.5	Perovskite Structure	431
5.3.6	Lead Germanate	432
5.3.7	Improper Ferroelectrics.	433
5.3.8	Materials Optimization.	433
5.4	Olsen Cycle and Pyroelectric Energy Harvesting	438
5.5	Pyroelectric Thermal Energy Harvesters with Olsen Cycle	439
5.5.1	Thermal Subsystem	439
5.5.2	Electrical Subsystem	441

5.5.3	Assumptions for Numerical Study	441
5.5.4	Governing Equations	442
5.5.5	Initial and Boundary Conditions	442
5.5.6	Material Properties.	444
5.5.7	Solution Method	445
5.5.8	Performance Analysis.	445
5.6	Olsen Harvesters with Pyroelectric Polymers.	446
5.6.1	Device Assembly and Characterization.	446
5.6.2	Performance	450
5.6.3	Heat Conduction	455
5.7	Olsen Harvesters with Perovskite Ceramics and Single Crystals	459
5.7.1	Relaxor–Ferroelectric PLZT Ceramics	459
5.7.2	Relaxor–Ferroelectric Single Crystals.	465
5.8	Other Types of Pyroelectric Harvesters.	472
5.9	Concluding Remarks	474
	References	475
6	Waste Thermal Energy Harvesting (III): Storage with Phase Change Materials	481
6.1	Introduction.	481
6.2	Thermal Energy Storage	482
6.3	PCMs for Thermal Storage	484
6.3.1	Organic PCMs.	485
6.3.2	Inorganic PCMs.	486
6.3.3	Eutectic PCMs	488
6.4	Design of TES Systems with PCMs	489
6.4.1	Design Criteria	489
6.4.2	Storage Systems	490
6.4.3	Heat Transfer in PCMs and Storage Systems	491
6.4.4	Exergy	506
6.5	Application Examples.	520
6.5.1	Solar Water-Heating Systems	520
6.5.2	Solar Air Heating Systems	527
6.5.3	Solar Cookers	531
6.5.4	Solar Greenhouses	534
6.5.5	Solar Buildings	539
6.5.6	Off-Peak Electricity Storage	545
6.6	Strategies to Improve PCM Storage Efficiency	547
6.6.1	Principles	547
6.6.2	Increasing Heat Transfer Surfaces	548
6.6.3	Multiple PCMs	558
6.6.4	Increasing Thermal Conductivity	562

6.7 Use of High Conductivity and Low Density Materials 569

6.7.1 Effect of Heat Exchanger 575

6.7.2 Corrosion Aspects 580

6.8 Concluding Remarks 581

References 582

Waste Energy Harvesting

Mechanical and Thermal Energies

Kong, L.B.; Li, T.; Hng, H.H.; Boey, F.; Zhang, T.; Li, S.

2014, XII, 592 p. 331 illus., 64 illus. in color., Hardcover

ISBN: 978-3-642-54633-4