

# Contents

<b>About the editors.....</b>	xiii
<b>List of contributors .....</b>	xv
<b>Preface .....</b>	xvii
<b>Foreword .....</b>	xix
<b>Acknowledgments .....</b>	xxi
<b>1 Introduction.....</b>	1
1.1 Evolution to net-zero energy buildings .....	1
1.1.1 Net ZEB concepts .....	2
1.1.2 Design of smart Net ZEBs and modeling issues .....	4
1.2 Scope of this book.....	4
References.....	7
<b>2 Modeling and design of Net ZEBs as integrated energy systems .....</b>	9
2.1 Introduction.....	9
2.1.1 Passive design, energy efficiency, thermal dynamics, and comfort .....	10
2.1.2 Detailed frequency domain wall model and transfer functions .....	16
2.1.2.1 Distributed parameter model for multilayered wall.....	16
2.1.2.2 Admittance transfer functions for walls .....	17
2.1.3 Z-Transfer function method .....	22
2.1.4 Detailed zone model and building transfer functions .....	25
2.1.4.1 Analysis of building transfer functions .....	30
2.1.4.2 Heating/cooling load and room temperature calculation.....	32
2.1.4.3 Discrete Fourier Series (DFS) method for simulation .....	32
2.1.5 Building transient response analysis .....	33
2.1.5.1 Nomenclature.....	34
2.2 Renewable energy generation systems/technologies integrated in Net ZEBs .....	34
2.2.1 Building-integrated photovoltaics as an enabling technology for Net ZEBs .....	35
2.2.1.1 Technologies .....	36
2.2.1.2 Modeling.....	39
2.2.2 Solar thermal systems .....	45
2.2.2.1 Solar thermal collectors.....	45
2.2.2.2 Modeling of solar thermal collectors.....	49
2.2.2.3 Thermal storage tanks .....	51
2.2.2.4 Modeling of thermal storage tanks.....	52
2.2.2.5 Solar combi-systems .....	55
2.2.3 Active building-integrated thermal energy storage and panel/radiant heating/cooling systems .....	55
2.2.3.1 Radiant heating/cooling systems integrated with thermal mass .....	57
2.2.3.2 Modeling active BITES .....	58

2.2.3.3	Methods used in two mainstream building simulation software .....	62
2.2.3.4	Nomenclature .....	63
2.2.4	Heat pump systems – a promising technology for Net ZEBs.....	63
2.2.4.1	Solar air-conditioning .....	64
2.2.4.2	Solar assisted/source heat pump systems .....	64
2.2.4.3	Ground source heat pumps.....	65
2.2.5	Combined heat and power (CHP) for Net ZEBs .....	66
	References.....	67
<b>3</b>	<b>Comfort considerations in Net ZEBs: theory and design .....</b>	<b>75</b>
3.1	Introduction.....	75
3.2	Thermal comfort .....	76
3.2.1	Explicit thermal comfort objectives in Net ZEBs.....	77
3.2.2	Principles of thermal comfort.....	77
3.2.2.1	A comfort model based on the heat-balance of the human body.....	78
3.2.2.2	The adaptive comfort models.....	83
3.2.2.3	Standards regarding thermal comfort .....	85
3.2.3	Long-term evaluation of thermal discomfort in buildings.....	87
3.2.3.1	Background.....	88
3.2.3.2	The likelihood of dissatisfaction .....	89
3.2.3.3	Applications of the long-term (thermal) discomfort indices.....	91
3.3	Daylight and visual comfort.....	92
3.3.1	Introduction.....	92
3.3.2	Adaptation luminance .....	94
3.3.3	Illuminance-based performance metrics.....	95
3.3.3.1	Daylight autonomy and continuous daylight autonomy.....	95
3.3.3.2	Useful daylight illuminance .....	95
3.3.4	Luminance-based performance metrics.....	96
3.3.4.1	Daylight glare probability .....	96
3.3.5	Daylight and occupant behavior.....	97
3.4	Acoustic comfort.....	98
3.5	Indoor air quality.....	99
3.6	Conclusion .....	100
	References.....	101
<b>4</b>	<b>Net ZEB design processes and tools .....</b>	<b>107</b>
4.1	Introduction.....	107
4.2	Integrating modeling tools in the Net ZEB design process .....	108
4.2.1	Introduction.....	108
4.2.2	Overview of phases in Net ZEB realization .....	108
4.2.3	Tools .....	111
4.2.4	Concept design.....	112
4.2.4.1	Daylight .....	113
4.2.4.2	Solar protection .....	114
4.2.4.3	Building thermal inertia .....	115
4.2.4.4	Natural and hybrid ventilation .....	116

## Contents

4.2.4.5	Building envelope thermal resistance.....	118
4.2.4.6	Solar energy technologies integration .....	119
4.2.5	Design development.....	119
4.2.5.1	Envelope and thermal inertia.....	120
4.2.5.2	Daylight .....	120
4.2.5.3	Plug loads and electric lighting .....	122
4.2.5.4	RET and HVAC.....	123
4.2.6	Technical design .....	124
4.2.7	Integrated design process and project delivery methods .....	126
4.2.8	Conclusion .....	133
4.3	NET ZEB design tools, model resolution, and design methods .....	133
4.3.1	Introduction.....	133
4.3.2	Model resolution .....	134
4.3.3	Model resolution for specific building systems and aspects.....	141
4.3.3.1	Geometry and thermal zoning.....	141
4.3.3.2	HVAC and active renewable energy systems .....	144
4.3.3.3	Photovoltaics and building-integrated photovoltaics .....	145
4.3.3.4	Lighting and daylighting.....	147
4.3.3.5	Airflow .....	149
4.3.3.6	Occupant comfort.....	151
4.3.3.7	Occupant behavior .....	153
4.3.4	Use of tools in design.....	157
4.3.4.1	Climate analysis .....	157
4.3.4.2	Solar design days .....	159
4.3.4.3	Parametric analysis .....	160
4.3.4.4	Interactions.....	161
4.3.4.5	Multidimensional parametric analysis.....	162
4.3.4.6	Visualization .....	162
4.3.5	Future needs and conclusion .....	163
4.4	Conclusion .....	165
	References.....	166
<b>5</b>	<b>Building performance optimization of net zero-energy buildings.....</b>	175
5.1	Introduction.....	175
5.1.1	What is BPO?.....	175
5.1.2	Importance of BPO in Net ZEB design .....	176
5.2	Optimization fundamentals .....	179
5.2.1	BPO objectives (single-objective and multi-objective functions) .....	179
5.2.2	Optimization problem definition .....	180
5.2.3	Review of optimization algorithms applicable to BPS.....	180
5.2.4	Integration of optimization algorithms with BPS.....	183
5.2.5	BPO experts interview .....	184
5.3	Application of optimization: cost-optimal and nearly zero-energy building .....	186
5.3.1	Introduction.....	186

5.3.2	Case study: single-family house in Finland .....	188
5.3.3	Results.....	190
5.3.4	Final considerations about the case study .....	194
5.4	Application of optimization: a comfortable net-zero energy house....	195
5.4.1	Description of the building model.....	195
5.4.2	The adopted methodology and the statement of the optimization problem.....	196
5.4.3	Discussion of results .....	199
5.4.4	Final considerations .....	202
5.5	Conclusion .....	202
	References.....	203
<b>6</b>	<b>Load matching, grid interaction, and advanced control .....</b>	<b>207</b>
6.1	Introduction.....	207
6.1.1	Beyond annual energy balance .....	207
6.1.2	Relevance of LMGI issues .....	207
6.1.2.1	Peak demand and peak power generation .....	207
6.1.2.2	Load management in the grid and buildings .....	209
6.1.2.3	Smart grid and other technology drivers .....	211
6.2	LMGI indicators.....	212
6.2.1	Introduction.....	212
6.2.2	Categories of indicators.....	215
6.3	Strategies for predictive control and load management.....	219
6.3.1	Energy storage devices.....	219
6.3.1.1	Electric energy storage .....	219
6.3.1.2	Thermal energy storage.....	220
6.3.2	Predictive control for buildings.....	220
6.3.2.1	Preliminary steps.....	222
6.3.2.2	Requirements of building models for control applications.....	223
6.3.2.3	Modeling of noncontrollable inputs .....	225
6.3.2.4	Development of a control strategy .....	226
6.4	Development of models for controls .....	226
6.4.1	Building components: conduction heat transfer.....	227
6.4.2	Thermal modeling of an entire building.....	227
6.4.3	Linear models.....	228
6.4.3.1	Continuous-time transfer functions .....	228
6.4.3.2	Discrete-time transfer functions (z-transforms transfer functions) ....	229
6.4.3.3	Time series models.....	231
6.4.3.4	State-space representation .....	232
6.5	Conclusion .....	235
	References.....	236
<b>7</b>	<b>Net ZEB case studies .....</b>	<b>241</b>
7.1	Introduction.....	241
7.2	ÉcoTerra.....	243
7.2.1	Description of ÉcoTerra.....	243

## Contents

7.2.2	Design process .....	252
7.2.2.1	Design objectives .....	252
7.2.2.2	Design team and design process .....	252
7.2.2.3	Use of design and analysis tools .....	253
7.2.2.4	Assessment of the design process .....	255
7.2.3	Measured performance.....	256
7.2.4	Redesign study .....	259
7.2.4.1	Boundary conditions .....	260
7.2.4.2	Form and fabric.....	260
7.2.4.3	Operations .....	260
7.2.4.4	Renewable energy systems .....	261
7.2.4.5	Simulation results.....	261
7.2.4.6	Implementation of redesign strategies.....	262
7.2.5	Conclusions and lessons learned .....	266
7.3	Leaf house .....	269
7.3.1	Main features of the leaf house .....	269
7.3.2	Description of the design process.....	272
7.3.3	Purposes of the building design .....	272
7.3.4	Description of the thermal system plant .....	272
7.3.5	Monitored data.....	277
7.3.6	Features and limits of the employed model.....	278
7.3.7	Calibration of the model.....	280
7.3.8	Redesign .....	284
7.3.9	Conclusions and lessons learned .....	288
7.4	NREL RSF .....	289
7.4.1	Introduction to the RSF.....	290
7.4.2	Key project design features .....	291
7.4.2.1	Design process .....	291
7.4.2.2	Envelope .....	292
7.4.2.3	Daylighting and electric lighting .....	293
7.4.2.4	Space conditioning system.....	293
7.4.2.5	Thermal storage labyrinth .....	295
7.4.2.6	Transpired solar thermal collector .....	297
7.4.2.7	Natural ventilation.....	298
7.4.2.8	Building operation, typical monitored data, and thermal performance .....	298
7.4.2.9	Photovoltaics.....	301
7.4.2.10	Building simulation software support .....	302
7.4.2.11	Software limitations .....	303
7.4.2.12	Significance of the early design stage .....	304
7.4.3	Abstraction to archetypes .....	306
7.4.3.1	Model development .....	307
7.4.3.2	Model validation and calibration.....	311
7.4.3.3	Integrating design and control for daylighting and solar heat gain – option with controlled shading .....	312

7.4.4	Alternative design and operation for consideration.....	319
7.4.4.1	Building-integrated PV: optimal use of building roof and façade .....	319
7.4.4.2	Building-integrated PV/T and transpired collector with air-source heat pump.....	319
7.4.4.3	Active building-integrated thermal energy storage .....	320
7.4.5	Conclusions.....	320
7.5	ENERPOS.....	321
7.5.1	Natural cross-ventilation and ceiling fans .....	322
7.5.2	Solar shading and daylighting.....	323
7.5.3	Microclimate measures .....	323
7.5.4	Materials .....	324
7.5.5	Ergonomics and interior design .....	324
7.5.6	Energy efficiency .....	325
7.5.6.1	Artificial lighting.....	325
7.5.6.2	Ceiling fans .....	325
7.5.6.3	Air-conditioning system.....	326
7.5.6.4	Computer network and plug loads .....	326
7.5.6.5	Building management system and individual controls.....	326
7.5.7	Integration of renewable energy technology .....	327
7.5.8	Description of the design process.....	327
7.5.8.1	Design objectives and importance of the design brief.....	328
7.5.8.2	Design team and timeline.....	328
7.5.8.3	Design tools .....	328
7.5.8.4	Human factors consideration in the design .....	330
7.5.9	Monitoring system .....	331
7.5.10	Monitored data.....	331
7.5.10.1	Measured performance.....	331
7.5.11	Comparison of model prediction with measurements for ENERPOS .....	333
7.5.11.1	Energy use.....	333
7.5.11.2	Thermal comfort .....	336
7.5.12	Thermal comfort experimental study .....	338
7.5.12.1	Purpose and methodology .....	338
7.5.12.2	Main results of the surveys .....	339
7.5.12.3	A comparison between the experimental data and the Givoni comfort zones .....	339
7.5.13	Lessons learned for future design of Net ZEBs in tropical climate ....	341
7.5.13.1	Interior lighting .....	342
7.5.13.2	Elevator energy .....	343
7.5.13.3	Air-conditioning.....	343
7.5.13.4	Occupant behavior .....	343
7.5.13.5	Use of building thermal mass and night cooling .....	343
7.6	Conclusions.....	343
	References.....	345

## Contents

<b>8</b>	<b>Conclusion, research needs, and future directions .....</b>	351
8.1	Net ZEB modeling, design, and simulation .....	351
8.2	Future directions and research needs.....	352
	<b>Glossary .....</b>	355
	<b>Index .....</b>	361