CONTENTS

Acknowledgement of Sources *page* xiv
Preface xix

1 Energy in the Modern World 1
Introduction 1
1.1 Energy Use in the Modern World 2
Example 1.1 – Increase of Energy Use 4
1.1.1 Exponential Growth 5
Example 1.2 – Exponential Growth 6
1.2 Limiting Energy Use 7
1.2.1 Energy Efficiency 7
1.2.2 Economic Appraisal of Energy Efficiency Measures 9
Example 1.3 – Economic Appraisal of an Energy Efficiency Measure 10
1.2.3 Energy Conservation 11
1.2.4 Management of Energy Demand Only Through Price 11
1.2.5 Smart Meters 12
1.2.6 Demand Side Response and the Variable Value of Electricity 12
1.3 The Need for Renewable Energy 13
1.3.1 Reserves of Fossil Fuels 13
1.3.2 Environmental Impact of Burning Fossil Fuels 15
1.3.3 Low Carbon Electricity Generation 18
Example 1.4 – Achieving CO_2 Targets 19
Summary 20
Problems 22
Further Reading 23

2 Wind Energy 25
Introduction 25
2.1 Wind Turbines 26
2.1.1 History 26
2.1.2 Advantages and Disadvantages of Wind Energy 26
2.2 Operation of a Wind Turbine 28
2.2.1 Power Curve of a Wind Turbine 30
2.3 Energy Output of a Wind Turbine 31
2.4 Linear Momentum or Actuator Disk Theory of a Wind Turbine 33
2.4.1 The Betz Limit 35

2.4.2 Thrust Coefficient 36
2.4.3 Limitations of the Momentum Theory 37
2.4.4 Torque Coefficient 37
2.4.5 C_p/λ Curve of a Rotor 38
2.5 Fixed Speed Wind Turbines 38
2.5.1 The Generator of a Fixed Speed Wind Turbine 40
Example 2.1 – Wind Turbine Operation 40
2.6 Control of Power Above Rated Wind Speed 41
2.6.1 Pitch and Stall Regulation 44
2.7 Variable Speed Wind Turbines 46
2.7.1 Full Power Converter Variable Speed Generators 47
2.7.2 Variable Speed Wind Turbine Control 48
2.7.3 Doubly Fed Induction Generators 49
2.8 Wind Structure and Statistics 49
The Method of Bins 52
2.8.1 Weibull and Raleigh Statistics 53
2.8.2 Variations of Wind Speed with Height 54
Example 2.2 – Use of Weibull Parameters 56
2.8.3 Turbulence 57
2.8.4 Extreme Wind Speeds 58
2.9 Wind Farm Development 58
2.9.1 Wind Farm Power Output 60
2.9.2 Detailed Site Investigations and the Environmental Statement 62
2.9.3 Wind Turbine Noise 62
Example 2.3 – Estimation of Sound Pressure Level at a Dwelling 64
Example 2.4 – Estimation of Sound Power Level of a Turbine 65
Summary 66
Problems 68
Further Reading 71

3 Hydro Power 72
Introduction 72
3.1 Hydro Power 73
3.1.1 History 73
3.1.2 Advantages and Disadvantages of Hydro Power 75
3.2 Operation of a Hydro Scheme 75
Example 3.1 – Operation of a Hydro Power Scheme 77
3.3 Power Output of a Hydro Scheme 78
3.3.1 Annual Capacity Factor 82
3.4 Types of Hydro Power Scheme 82
3.5 Hydro Power Turbines 84
3.5.1 Impulse Turbines 85
3.5.2 Analysis of a Pelton Turbine 86

Example 3.2 – Operation of an Impulse Turbine 89
3.5.3 Reaction Turbines 93
3.5.4 Analysis of a Francis Turbine 95
Example 3.3 – Operation of a Francis Turbine 97
3.5.5 The Draft Tube and Cavitation 98
3.5.6 Bulb and Inclined Shaft Turbines 98
3.6 Specific Speed of a Hydro Turbine 99
Example 3.4 – Use of Specific Speed 100
3.7 Operation of a Hydro Turbine at Reduced Flows and Variable Speed 101
3.8 Net or Effective Head 104
Example 3.5 – Determination of Penstock Diameter 106
3.9 Transient Conditions 107
Example 3.6 – Load Rejection of a Turbine Generator 108
3.10 Development of Small Hydro Schemes 109
3.10.1 Environmental Impact Assessment 112
3.10.2 Generators for Small Hydro Schemes 112
3.10.3 Governors for Stand-Alone Schemes 113
3.10.4 Archimedes Screw Generators 113
Summary 115
Problems 117
Further Reading 119

4 The Solar Energy Resource 120
Introduction 120
4.1 The Solar Resource 121
4.2 Examples of the Solar Resource 122
4.3 Sun–Earth Geometry 124
Example 4.1 – Altitude of the Sun at Solar Noon 128
Example 4.2 – Location of the Sun 129
4.4 Orientation of Solar Panels 130
4.5 Solar Spectrum and Air Mass 131
Example 4.3 – Air Mass at Solar Noon 133
4.6 Wave–Particle Duality of Light 133
Example 4.4 – Wavelength of Light to Operate a Silicon Solar Cell 134
Summary 134
Problems 136
Further Reading 137

5 Photovoltaic Systems 138
Introduction 138
5.1 Photovoltaic Energy Conversion 139
5.1.1 History 139
5.1.2 Advantages and Disadvantages of Photovoltaic Energy Conversion 139

5.2 Standard Test Conditions 141
Example 5.1 – Estimate of the Performance of a Photovoltaic System 142
5.3 Photovoltaic Technology 143
5.4 The Silicon Solar Cell 143
5.4.1 The Bond Model of the Silicon Solar Cell 144
5.4.2 The Band Model of the Silicon Solar Cell 146
5.4.3 The p-n Junction 146
Example 5.2 – Forward Voltage Drop Across a Silicon Diode 148
5.5 Operation of a Solar Cell 148
5.6 Equivalent Circuit of a Solar Cell 149
5.7 Performance of the Solar Cell with Varying Irradiance and Cell Temperature 151
Example 5.3 – Performance of a Solar Cell at Increased Cell Temperature 153
5.8 The Solar Cell as a Current Source 153
5.9 Photovoltaic Modules 154
Example 5.4 – Performance of a Photovoltaic Module 155
5.9.1 Module Bypass Diodes 156
5.9.2 Blocking Diodes 156
5.10 Performance of Photovoltaic Modules and Systems 156
5.10.1 Estimation of Cell Temperature 156
Example 5.5 – Reduction of Output with Cell Temperature 157
5.10.2 Performance Assessment of Photovoltaic Systems 157
Example 5.6 – Performance of Photovoltaic Systems 158
5.11 Stand-Alone, Off-Grid, Photovoltaic Systems 158
5.11.1 Charge Regulator and LowVoltage Disconnect 159
5.11.2 Operating Characteristics of a Stand-Alone System 160
Example 5.7 – Estimate of the Charge into the Battery of a Stand-Alone System 161
5.11.3 Self-Regulating Modules 161
5.11.4 Battery Energy Storage 162
5.12 Example of a Stand-Alone Off-Grid System 164
5.13 Grid-Connected Photovoltaic Systems 166
5.13.1 Grid Conditions for Operation 166
5.13.2 Maximum Power Point Tracking 167
5.13.3 Grid-Connected PV Inverters 168
5.14 The Technologies of Photovoltaic Cells 170
Summary 175
Problems 178
Further Reading 181

6 Solar Thermal System 182
Introduction 182
6.1 Solar Thermal Energy 183
6.1.1 Advantages and Disadvantages of Solar Thermal Energy Systems 184
6.2 Passive Solar Thermal Heating of Buildings 185

6.2.1 Solar Gain from Glazing 188
Example 6.1 – Heat Gain Through a Window 188
6.3 Circuit Representation of Heat Transfer in Low Temperature Solar Thermal Systems 189
6.4 Heat Loss of Buildings due to Ventilation 191
Example 6.2 – Estimation of the Heat Loss from a Small Building 192
6.5 Degree Days 193
6.5.1 Monitoring the Thermal Performance of Buildings Using Degree Days 194
Example 6.3(a) – Use of Degree Days to Monitor the Performance of a Building 197
Example 6.3(b) – Use of Degree Days to Predict Building Energy Consumption 198
6.6 Radiation and the Behaviour of Glass 199
6.7 Solar Water Heating 201
6.8 Performance of a Flat Plate Solar Collector 205
Example 6.4 – Performance of a Flat Plate Solar Collector 208
6.8.1 Selective Absorber Surface 209
6.9 High Temperature Concentrating Solar Thermal Systems 210
Summary 217
Problems 221
Further Reading 224

7 Marine Energy 225
Introduction 225
7.1 Tidal Range Generation 227
7.1.1 The Tidal Energy Resource 229
7.1.2 Description of the Tides Using Harmonic Constituents 232
Example 7.1 – Type of a Tide 235
7.1.3 Tidal Range Generation 235
Example 7.2 – Power Available in an Estuary 236
7.1.4 Ebb Generation 236
7.1.5 Turbine Generators for a Tidal Range Generation Scheme 238
7.1.6 Environmental Impact 240
7.1.7 Tidal Lagoons 241
7.2 Tidal Stream Generation 242
7.2.1 The Tidal Stream Resource 242
Example 7.3 – Variation of Tidal Stream with Depth 245
7.2.2 Development of a Tidal Stream Project 246
7.2.3 Tidal Stream Turbines 246
7.2.4 Comparison of a Tidal Stream Turbine with a Wind Turbine Using Linear Momentum Theory 250
Example 7.4 – Comparison of Tidal Stream and Wind Turbines 251
Example 7.5 – Performance of Tidal Stream Turbine 253
7.3 Wave Power Generation 254
7.3.1 Water Waves 256

Example 7.6 – Waves at Intermediate Depths 259
Example 7.7 – Power Monochromatic in Deep-Water Waves 262
7.3.2 The Wave Energy Resource 263
Example 7.8 – Wavelength of Deep-Water Waves 264
7.3.3 Devices for Wave Power Generation 267
Summary 272
Problems 274
Further Reading 276

8 Bioenergy 277
Introduction 277
8.1 Bioenergy: Energy from Biomass 278
8.2 Photosynthesis 280
Example 8.1 – Land Required for Bioenergy 282
8.3 Bioenergy Processes 282
8.4 Combustion of Solid Biomass 283
8.4.1 Properties of Solid Biomass 287
Example 8.2 – Moisture Content of Biomass 288
8.4.2 Combustion 291
Example 8.3 – Stoichiometric Combustion 292
8.4.3 Burning of Biomass 293
Example 8.4 – Combustion of Biomass 294
8.4.4 Analysis of the Combustion of Solid Biomass 295
Example 8.5 – Combustion of Biomass Analysed Using Ultimate Analysis 296
8.4.5 Combustion of Biomass in Large Generating Stations 298
8.5 Gasification of Biomass 299
8.5.1 Gasification 300
8.5.2 Gasifiers 302
8.6 Anaerobic Digestion 306
8.6.1 Landfill Gas 308
8.7 Conversion of Biomass into Fuel for Road Transport 309
8.7.1 Fermentation of Biomass into Ethanol 309
8.7.2 Extraction of Natural Vegetable Oil and Biodiesel 310
8.7.3 Social and Environmental Impacts of Biomass Vehicle Fuel 311
Summary 312
Problems 313
Further Reading 315

9 Development and Appraisal of Renewable Energy Projects 317
Introduction 317
9.1 Project Development 317
9.1.1 Phases of Project Development 318
9.1.2 Assessment of the Renewable Energy Resource 320

9.1.3 Aspects of Project Development 322
9.2 Economic Appraisal of Renewable Energy Schemes 324
9.2.1 Simple DCF appraisal 324
Example 9.1 – Economic Appraisal Using Discounted Cash Flow 326
9.3 Environmental Impact Assessment of Renewable Energy Projects 328
9.3.1 Uses of an Environmental Statement 329
9.3.2 Contents of a Typical Environmental Statement 329
Summary 330
Problems 331
Further Reading 332

10 Electrical Energy Systems 333
Introduction 333
10.1 Energy Systems 334
10.2 Ac Power Systems 336
10.3 Real and Reactive Power 338
10.4 Voltage of the Power System 340
10.4.1 Transformer Tap Changing 341
10.4.2 Voltage Drop and Power Flows 341
10.4.3 Changes of Local Voltage with P and Q Flows 342
10.4.4 Voltage Control by Reactive Power 344
Example 10.1 – Voltage Rise at the Connection of a Renewable Generator 345
10.5 Frequency 347
Example 10.2 – Effect of PV Generation on System Inertia 350
10.6 Operating the Power System 351
10.6.1 Generation Scheduling 351
Example 10.3 – Cost Function 352
Example 10.4 – Generator Scheduling 354
Example 10.5 – Generator Scheduling with CO_2 Cost 356
10.6.2 Mismatches Between the Generation and Load 357
10.6.3 Reserve Generation Requirements 358
Example 10.6 – Reserve Requirement 359
10.6.4 Stability 359
10.7 Demand Side Participation 360
10.8 Energy Storage 362
10.8.1 Battery Energy Storage 363
10.8.2 Fuel Cells 364
10.9 Renewable Energy Connections 365
10.9.1 Onshore Wind Farm Connections 365
10.9.2 Offshore Wind Farm Connections 365
10.9.3 PV Connection 367
Summary 369
Problems 371
Further Reading 374

Tutorial I Electrical Engineering 375
I.1 Direct Current (dc) 375
I.2 Alternating Current (ac) 376
Example I.1 – Instantaneous Value of a Sinusoidal Signal 377
I.2.1 Resistors 378
I.2.2 Inductors 379
I.2.3 Capacitors 381
I.2.4 Phasor Representation of Ac Quantities 381
I.2.5 Inductive Loads 383
I.2.6 Capacitive Loads 384
Example I.2 – *R*, *L* and *C* circuit 385
I.3 Power System Components 386
I.3.1 Generators 386
I.3.2 Transformers 389
Example I.3 – Ideal Transformer 390
I.3.3 Connection of Generator and Transformer Windings 390
I.3.4 Transmission Lines 392
I.3.5 Three-Phase Loads 393
I.4 Power in Three-Phase System 394
Example I.4 – Three-Phase Loads 395
I.5 Power Electronics 395
Summary 396
Problems 399
Further Reading 400

Tutorial II Heat Transfer 401
II.1 Heat Transfer 401
II.2 Conduction 402
Example II.1 – Thermal Loss by Conduction 403
Example II.2 – Heat Lost Through an Insulated Surface 404
II.3 Convection 405
Example II.3 – Thermal Resistance of Convection 406
II.4 Radiation 408
Example II.4 – Temperature of a Flat Metal Plate in Bright Sunlight 411
Example II.5 – Heat Transfer Through Radiation and Convection 412
Example II.6 – Thermal Resistance of Radiation 414
II.5 Heat Transfer Through Mass Flow of Fluid 415
Example II.7 – Heat Transfer in an Unglazed Flat Plate Solar Water Heater 415
II.6 Example of One-Dimensional Heat Transfer 416
Example II.8 – A Steam Pipe 417
Summary 418
Problems 420
Further Reading 421

Tutorial III Simple Behaviour of Fluids 422
III.1 Types of Flow 422
III.1.1 Steady Flow 422
III.1.2 Compressible and Incompressible Fluids 422
III.1.3 Laminar and Turbulent Flow 422
III.2 Viscosity and Ideal Flow 423
III.3 Mass Continuity Equation 424
Example III.1 – Continuity of Mass Flow 424
III.4 Energy Balance: Bernoulli's Equation 425
Example III.2 – Application of the Bernoulli Equation 426
Example III.3 – A Large Water Tank with Discharge 427
Example III.4 – Turbine Operation 428
III.5 Angular Momentum 429
III.6 Flow Through Pipe Systems and the Moody Chart 430
Example III.5 – Laminar Flow in a Pipe 432
Summary 432
Problems 435
Further Reading 436

Index 437

Colour plates are to be found between pp. 244 and 245.