Renewable Energy Resources

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Preface

Our aim

We have written this book to cover a subject of increasing technical and economic importance worldwide. It is primarily intended to support courses for undergraduates in physical science and engineering, beyond first year level. However since many practicing scientists and engineers will not have had a general training in renewable energy, the book is also intended for wider use beyond colleges and universities. Each chapter begins with fundamental theory from a physical science perspective, then considers applied examples and developments, and finally concludes with a set of problems and solutions. The whole book is structured to share common material and to relate aspects together. After each chapter, reading material is reviewed for further study.

Therefore the book is intended both for basic study and for application. Throughout the book and in the appendices, we include essential and useful reference material.

The subject

Renewable energy supplies are of steadily increasing importance in all countries. Most governments have substantial plans directed towards commercial development, and World agencies, such as the United Nations, have large programs to encourage the technology. In this book we stress the scientific understanding and analysis of renewable energy, since we believe these are distinctive and require specialist attention. The subject is not easy, mainly because of the spread of disciplines involved, and it certainly cannot be fully covered in just one book. This book is intended to bridge the gap between descriptive reviews and specialized engineering treatises on particular aspects. It centres on demonstrating how fundamental physical processes govern renewable energy resources and their application. Although the applications are being updated continually, the fundamental principles remain the same and we are confident that it will continue to provide a useful platform for those advancing the subject in the future. We have been encouraged in this approach by the rapidly increasing commercial importance of renewable energy technologies.

Readership

We expect our readers to have a basic understanding of science, especially of physical science, and of mathematics including calculus. It is not necessary to read or refer to chapters consecutively, as each aspect of the subject is treated, in the main, as independent of the other aspects. However some common elements, especially heat transfer, will have to be studied seriously if the reader is to progress to any depth of understanding. The disciplines behind a proper understanding and application of renewable energy include both biology and engineering. We are aware that our readers with a physical science background will usually be unfamiliar with life science and agricultural science, but we stress the importance of these subjects with obvious application for biofuels and for developments akin to photosynthesis.

Ourselves

We would like our readers to *enjoy* the subject of renewable energy, as we do, and to be stimulated to *apply* the energy sources for the benefit of their societies. Our own interest and commitment has evolved from work in both hemispheres and in a range of countries. Common elements have been teaching and application in the South Pacific and Scotland. We do not see the world as divided sharply between developed industrialized countries and developing countries of the Third World. Rural and remote communites of all countries share common opportunities, including opportunities associated with renewable energy. Developments from these circumstances will be of increasing industrial importance. This is meaningful to us personally, since we wish our own energies to be directed for a just and sustainable society, increasingly free of poverty and the threat of cataclysmic war. We sincerely believe the development and application of renewable energy technology will favor these aspirations, and we therefore entirely endorse the sentiments of those who have promulgated a smaller scale of resource use, such as the late E. F. Schumacher. Our readers may not share these views, and this fortunately does not affect the content of the book. One thing they will have to share, however, is contact with the outdoors. Renewable energy is drawn from the environment, and practitioners must put on their rubber boots or their sun hat and move from the closed environment of buildings to the outside. This is no great hardship however, as anyone who knows the beauties of the South Pacific and the Scottish islands will affirm.

Suggestions for using the book in teaching

How a book is used in teaching depends mainly on how much time is devoted to its subject. For example, at the University of the South Pacific, we have taught the one-semester course on'Energy Resources and Distribution' to senior undergraduates in Physics. About half this course was on energy use in society, fossil fuels and their limitations, and other similar matters adequately and accessibly covered in many existing books. The remaining lecture hours were devoted to the analysis of those renewable energy supplies that seemed most applicable in that part of the world. A similar course has been taught at the University of Strathclyde. We found no existing books covering this range of topics at a suitable level for students in science or engineering. We have also taught other lecture and laboratory courses, and have found many of the subjects in renewable energy can be incorporated with great benefit into conventional teaching.

This book deliberately contains more material than could be covered in one specialist course. This enables the instructor and reader to concentrate on those particular energy supplies of benefit in their situation. To assist in this selection, most chapters start with a preliminary estimate of each resource, and its geographical variation.

The chapters are broadly grouped into similar areas. Chapter 1 introduces renewable energy supplies in general, and in particular the characteristics that distinguish their application from that for fossil or nuclear fuels. Chapter 2 (Fluid Mechanics) and Chapter 3 (Heat Transfer) are background material for later chapters. They contain nothing that a senior student in Mechanical Engineering will not already know, but are included for reference because much of this classical material has disappeared from Physics courses. Chapters 4–7 deal with various aspects of direct solar energy. Readers interested in this area are advised to start with the early sections of Chapter 5 (Solar Water Heating) or Chapter 7 (Photovoltaics), and review Chapters 3 and 4 as required. Chapters 8 (Hydro), 9 (Wind), 12 (Waves), 13 (Tides) present applications of fluid mechanics. Again the reader is advised to start with an applications chapter, and review the elements from Chapter 2 as required. Chapters 10, 11 deal with biomass as an energy source – respectively how the energy is stored and how it can be used. Chapters 14 (OTEC) and 15 (Geothermal) treat sources that are, like those in Chapters 12 and 13, important only in fairly limited geographical areas. Chapter 16, like Chapter 1, treats matters of importance to all renewable energy sources, namely the storage and distribution of energy and the integration of energy sources into energy systems. Appendices A (units), B (data) and C (heat transfer formulas) are referred to either implicitly or explicitly throughout the book. Suggestions for further reading and problems (mostly numerical in nature) are included with most chapters. Answers are provided.

Acknowledgments

As authors we bear responsibility for all interpretations, opinions and errors in this work. However, many have helped us, and we express our gratitude to them. Successive drafts of all, or portions of, this book have been used with undergraduate physics classes mainly at the University of the South Pacific and the University of Strathclyde, and also at a number of Universities where we have corresponded or visited. Our first debt is to these classes, whose reactions have helped shape the choice and presentation of material. We have also benefited from detailed comment from our close colleagues (Ken Taylor, Mahendra Kumar, Bob Lloyd, Surendra Prasad, Clifford Yee, Bill Grainger, Fiona Riddoch and Charles Giles) and from staff at our own and other institutions. At the University of New South Wales, these include Charles Sapsford, Graham Bowden, Hugh Outhred and Peter Barker; at the University of Queensland, Neville Jones; at the Ministry of Energy, Fiji, Peter Johnston, Jerry Ricolson; at the University of Khartoum, Farouk Habbani, Tony Egram; at the University of the South Pacific, Philip Whitney, Dick Solly; at the University of Strathclyde, Malcolm Slesser, Chris Lewis. Many others have helped us, including John Huthnance, Peter Giddens, Norman Bellamy, Norman Lipman, Jim Halliday, David Barbour, Hilary Wyper, Herick Othieno, Jerry Bass and Adam Pinney.

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List of symbols

Symbol	Main use	Other use or comment
Capitals		
A	area (m^2)	acceptor; ideality factor
A_R	Richardson's constant ($A\,m^{-3}\,K^{-2}$)	
AM	air mass ratio	
C	thermal capacitance (JK^{-1})	electrical capacitance (F); constant
C_D	drag coefficient	
C_F	thrust, force, coefficient	
C_L	lift coefficient	
C_P	power coefficient	
C_r	concentration ratio	
C_Γ	torque coefficient	
D	distance (m)	pipe or blade diameter (m); donor
E	energy (J)	
E_F	Fermi level	
E_g	band gap (eV)	
E_k	kinetic energy (J)	
E_p	potential energy (J)	
EMF	electromotive force	
F	force (N)	Faraday constant
F'_{i-j}		radiation exchange factor i to j
G	solar irradiance ($W\,m^{-2}$)	gravitational constant ($Nm^2\,kg^{-2}$); temperature gradient ($K\,m^{-1}$); Gibbs Energy
$G_{b,d,h}$	irradiance; beam, diffuse, on horizontal	
H	enthalpy (J), heat of combustion	pressure height (head) of fluids (m); wave crest/trough height (m); insolation ($J\,m^{-2}\,day^{-1}$)
I	electric current (A)	moment of inertia ($kg\,m^2$); integral
J	current density ($m^{-2}\,s^{-1}$ or $A\,m^{-2}$)	recombination current (A)
K	extinction coefficient (m^{-1})	clearness index (K_T); constant
L	distance, length (m)	diffusion length (m)
M	mass (kg)	molecular weight
M	momentum ($kg\,m\,s^{-1}$)	
N	concentration (m^{-3})	hours of daylight
N_o	Avogadro number	
P	power (W)	
P'	power per unit length ($W\,m^{-1}$)	
PS	photosystem	

Symbol	Main use	Other use or comment
Q	volume flow rate ($m^3 s^{-1}$)	
R	thermal resistance (KW^{-1})	radius (m); electrical resistance (Ω); reduction level; gas constant; tidal range (m)
R_n	thermal resistance (co*n*duction)	
R_r	thermal resistance (*r*adiation)	
R_v	thermal resistance (con*v*ection)	
R_m	thermal resistance (*m*ass transfer)	
RFD	radiant flux density ($W m^{-2}$) (see ϕ)	
S	surface area (m^2)	entropy
S_v	surface recombination velocity (ms^{-1})	
STP	standard temperature & pressure	
T	absolute temperature (K)	period (s)
U	potential energy (J)	
V	volume (m^3)	electrical potential (V)
W	width (m)	mass flow rate per unit area ($kg s^{-1} m^{-2}$); energy density
X	characteristic dimension (m)	concentration ratio
Script capitals	(Non dimensional)	
$\mathscr{A}$	Rayleigh number	
$\mathscr{G}$	Grashof number	
$\mathscr{N}$	Nusselt number	
$\mathscr{P}$	Prandtl number, ν/κ	
$\mathscr{R}$	Reynolds number	
$\mathscr{S}$	Shape number of turbine	
Lower case		
a	amplitude (m)	wind interference factor, area (m^2)
b	width, of channel, (m)	wind profile exponent
c	specific heat capacity ($J kg^{-1} K^{-1}$)	velocity of electromagnetic radiation in vacuum ($m s^{-1}$); phase velocity of wave ($m s^{-1}$); chord length (m); Weibull speed factor ($m s^{-1}$)
d	distance (m)	zero plane displacement (wind) (m), depth
e	electron charge (C)	base natural logarithm (2.718)
f	frequency of cycles ($Hz = s^{-1}$)	pipe friction coefficient; fraction
g	acceleration of gravity ($m s^{-2}$)	
h	heat transfer coefficient ($Wm^{-2} K^{-1}$)	vertical displacement (m); Planck constant (6.63×10^{-34} Js); hole
$\hbar$	$h/(2\pi)$ = Planck constant/(2π)	
i	$\sqrt{-1}$	integer
j		integer
k	thermal conductivity ($Wm^{-1} K^{-1}$)	wave vector, $2\pi/\lambda$, (m^{-1});
k		Boltzmann constant 1.38×10^{-23} JK^{-1}
l	distance (m)	
m	mass (kg)	air mass ratio (see AM)
n	number	number of wind turbine blades; hours of bright sunshine; concentration (m^{-3}); number of nozzles
$\hat{\mathbf{n}}$	unit vector normal to plane	
p	pressure (Nm^{-2} = Pa)	concentration (m^{-3}); (porosity p′)

Symbol	Main use	Other use or comment
q	power per unit area (Wm^{-2})	
r	thermal resistivity of unit area ($m^2\,K\,W^{-1}$) ($r = h^{-1} = RA$)	radius (m); distance (m)
s	angle of slope (of a collector) (deg)	
t	time (s)	thickness (m)
u	velocity along stream ($m\,s^{-1}$)	group velocity ($m\,s^{-1}$)
v	velocity (not along stream) ($m\,s^{-1}$)	
w	distance (m)	moisture content, w dry basis, w' wet basis.
x	coordinate (along stream) (m)	
y	coordinate (across stream) (m)	
z	coordinate (upwards) (m)	z (downwards) depth (m)
Greek symbol		
Γ gamma	torque (Nm)	gamma function
Δ delta	increment of ... (other symbol)	
Λ lambda	latent heat ($J\,kg^{-1}$)	
Σ sigma	summation sign	
Φ phi	radiant flux W	probability function
Φ_u	probability distribution of wind speed ($(m\,s^{-1})^{-1}$)	
Ω omega	solid angle (deg)	phonon frequency (s^{-1}) angular velocity of blade ($rad\,s^{-1}$)
α alpha	absorptance	angle of attack, (deg)
α_λ	monochromatic absorptance	
β beta	angle (deg)	expansion coefficient (K^{-1})
γ gamma	angle (deg)	blade setting angle of wind turbine (deg)
δ delta	boundary layer thickness (m)	angle of declination (deg)
ϵ epsilon	emittance	wave 'spectral' width; permittivity; dielectric constant
ϵ_λ	monochromatic emittance	
ζ zeta	angle (deg)	
η eta	efficiency	
θ theta	temperature difference (°C)	angle of incidence (deg)
κ kappa	thermal diffusivity ($m^2\,s^{-1}$)	angle (deg)
λ lambda	wavelength (m)	tip speed ratio of wind turbine
μ mu	dynamic viscosity ($N\,m^{-2}\,s$)	
ν nu	kinematic viscosity ($m^2\,s^{-1}$) (NB $\nu = \mu/\rho$)	
π pi	3.1416	
ξ xi	electric potential (V)	roughness height (m); angle (deg)
ρ rho	density ($kg\,m^{-3}$)	reflectance; electrical resistivity (Ω m)
ρ_λ	monochromatic reflectance	
σ sigma	Stefan constant ($= 5.67 \times 10^{-8}\,Wm^{-2}K^{-4}$)	
τ tau	transmittance	relaxation time (s); duration (s); sheer stress ($N\,m^{-2}$)
τ_λ	monochromatic transmittance	
ϕ phi	radiant flux density RFD ($W\,m^{-2}$)	wind/blade relative velocity angle (deg) potential difference (V), latitude (deg)
ϕ_λ	spectral distribution of RFD ($W\,m^{-3}$)	
χ chi	absolute humidity ($kg\,m^{-3}$)	
ψ psi	angle (deg)	longitude (deg)
ω omega	frequency ($= 2\pi f$) ($radian\,s^{-1}$)	solid angle (steradian); hour angle (deg)

Symbol	Main use	Other use or comment
Subscript		
B	black body	band
D	drag	dark
E	earth	
F	force	
G	generator	
L	lift	load, loss
M	Moon	
P	power	
R	rated	
S	Sun	
T	tangential	turbine
a	ambient	aperture, available head, aquifer
abs	absorbed	
b	beam	blade, bottom, base, biogas
c	collector	cell (photoelectric), cold
ci	cut in	
co	cut out	
cov	cover	
d	diffuse	dopant, digester
e	electrical	equilibrium, energy
f	fluid	forced, friction, flow
g	glass	generation current, band gap
h	horizontal	hot
i	integer	intrinsic
in	incident	
int	internal	
j	integer	
m	*m*ass transfer	mean (average), methane
max	maximum	
n	co*n*duction	negative charge carriers (electrons)
net	heat flow across surface	
o	(see numeral zero)	free space, dry
oc	open circuit	
p	plate	peak, positive charge carriers (holes)
r	*r*adiation	relative, recombination current, room, resonant, rock
rad	radiated	
refl	reflected	
rms	root mean square	
oc	open circuit	
s	surface	significant, saturated, sun
sc	short circuit	
t	tip	total
th	thermal	
trans	transmitted	
u	useful	
v	con*v*ection	va*p*or
w	wind	water
z	zenith	
λ	monochromatic e.g. α_λ, spectral distribution w.r.t. wavelength, ϕ_λ.	
0	distant approach	ambient, extra terrestrial, dry matter, saturated, ground level
1	entry to device	first

Symbol	Main use	Other use or comment
2	exit from device	second
3	output	third
Superscript		
m or max	maximum	
*	measured perpendicular to direction of propagation, e.g. G_b^*	sidereal day
· (dot)	rate of . . . , e.g. m (kg s^{-1})	
Other Symbols		
bold face	vector	
$\hat{\mathbf{x}}$	unit vector	Same symbol in ordinary type indicates the magnitude of the vector) e.g. $\lvert\mathbf{u}\rvert = u$
=	mathematical equality	
≈	approximate equality (within a few %)	
~	equality in 'order of magnitude' (with a factor of 2 to 10)	
≡	mathematical identity (or definition), equivalent	

Contents