John Twidell and Tony Weir

RENEWABLE ENERGY RESOURCES

Third Edition

Renewable Energy Resources

Renewable Energy Resources is a numerate and quantitative text covering the full range of renewable energy technologies and their implementation worldwide. Energy supplies from renewables (such as from biofuels, solar heat, photovoltaics, wind, hydro, wave, tidal, geothermal and ocean-thermal) are essential components of every nation's energy strategy, not least because of concerns for the local and global environment, for energy security and for sustainability. Thus, in the years between the first and this third edition, most renewable energy technologies have grown from fledgling impact to significant importance because they make good sense, good policy and good business.

This third edition has been extensively updated in light of these developments, while maintaining the book's emphasis on fundamentals, complemented by analysis of applications. Renewable energy helps secure national resources, mitigates pollution and climate change, and provides cost-effective services. These benefits are analyzed and illustrated with case studies and worked examples. The book recognizes the importance of cost-effectiveness and efficiency of end-use. Each chapter begins with fundamental scientific theory, and then considers applications, environmental impact and socio-economic aspects before concluding with Quick Questions for self-revision, and Set Problems. The book includes Reviews of basic theory underlying renewable energy technologies, such as electrical power, fluid dynamics, heat transfer and solid-state physics. Common symbols and cross-referencing apply throughout; essential data are tabulated in appendices.

An associated updated eResource provides supplementary material on particular topics, plus a solutions guide to Set Problems for registered instructors only.

Renewable Energy Resources supports multi-disciplinary Master's degrees in science and engineering, and specialist modules in first degrees. Practising scientists and engineers who have not had a comprehensive training in renewable energy will find it a useful introductory text and a reference book.

John Twidell has considerable experience in renewable energy as an academic professor in both the UK and abroad, teaching undergraduate and postgraduate courses and supervising research students. He has participated in the extraordinary growth of renewable energy as a research contractor, journal editor, board member of wind and solar professional associations, and company director. University positions have been in Scotland, England, Sudan and Fiji. The family home operates with solar heat and electricity, biomass heat and an all-electric car; the aim is to practice what is preached.

Tony Weir has worked on energy and environment issues in the Pacific Islands and Australia for over 30 years. He has researched and taught on renewable energy and on climate change at the University of the South Pacific and elsewhere, and was a Lead Author for the 2011 IPCC Special Report on Renewable Energy. He has also managed a large international program of renewable energy projects and been a policy advisor to the Australian government, specializing in the interface between technology and policy.

www.routledge.com/books/details/9780415584388

"Renewable energy requires an active approach, based on facts and data. Twidell and Weir, drawing on decades of experience, demonstrate this, making clear connections between basic theoretical concepts in energy and the workings of real systems. It is a delight to see the field having advanced to this level, where a book like *Renewable Energy Resources* can focus on the very real experiences of the energy systems of the coming decades."

– Professor Daniel Kammen, Director, Renewable and Appropriate Energy Laboratory, University of California, Berkeley, USA

"Solar and wind power are now proven, reliable, ever-cheaper sources of electricity that can play a major role in powering the world. Along with other long-established renewables such as hydropower, and complemented by improved energy efficiency and appropriate institutional support, they can be key to sustainable development. This book can play a vital role in educating the people who are needed to make it happen."

– Professor Martin Green, Director, Australian Centre for Advanced Photovoltaics, University of New South Wales, Australia

"The solar revolution that's been talked about for so long is with us here and now. This new edition of *Renewable Energy Resources*, like earlier editions, will undoubtedly make a significant contribution to informing both those involved with the technology and those in policy-making. This is critical if the promise of renewable energy is to be delivered as expeditiously and cost-effectively as is now needed."

– Jonathon Porritt, Founder Director, Forum for the Future

"I welcome this excellent third edition of Twidell and Weir with its comprehensive yet accessible coverage of all forms of renewable energy. The technologies and the physics behind them are explained with just the right amount of math, and they include a realistic summary of the economic and societal implications."

– Emeritus Professor William Moomaw, Tufts University, USA and Coordinating Lead Author, IPCC Special Report on Renewable Energy

"I highly recommend this book for its thorough introduction to all the important aspects of the topic of *Renewable Energy Resources*. The book is excellent in its completeness and description of the relevant different sources. Moreover it is strong in theory and applications. From a scientific and engineering point this book is a must."

– Professor Henrik Lund, Aalborg University, Denmark and Editor-in-Chief of the international journal Energy

"Over the years, I have used this excellent text for introducing Physics and Engineering students to the science and technology of renewable energy systems. The updated edition will be of immense value as sustainable energy technologies join the mainstream and there is an increasing need for human capacity at all levels. I look forward to the new edition and hope to use it extensively."

– Dr Atul Raturi, University of the South Pacific, Fiji

"Our school has used *Renewable Energy Resources* since 2005, as it was one of the few texts that covered the field with a good balance between background theory and practical applications of RE systems. The new updated edition looks great and I am looking forward to using it in my classes."

– Dr Alistair Sproul, University of New South Wales, Australia

"I have used the extremely valuable second edition of this book for our postgraduate courses on energy conversion technologies. My students and I welcome this new edition, as it has been very well updated and extended with study aids, case studies and photos which even further improve its readability as a textbook."

– Dr Wilfried van Sark, Utrecht University, Netherlands

Praise for the 2nd edition

"Twidell and Weir are masters of their subject and join the ranks of acomplished authors who have made a powerful contribution to the field. Renewable Energy Resources is a superb reference work."

– Paul Gipe, www.wind-works.org

"It's ideal for student use - authoritative, compact and comprehensive, with plenty of references out to more detailed texts ... a very valuable book."

– Professor Dave Elliott of the Open University, UK, in Renew 162 2006

"What we need to combat climate change is a stream of students and graduates with the knowledge they can gain from this book ... suitable not only for engineering students but also for policy-makers and all those concerned with energy and the environment.'

– Corin Millais, CEO Climate Institute

Renewable Energy Resources

Third edition

John Twidell and Tony Weir

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This book is dedicated to our wives, Mary and Christine,
who have supported us continuously in the labor
of textbook writing.

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SUPPLEMENTARY MATERIAL

Examples of extra eResource material on the publisher's website for this book at www.routledge.com/books/details/9780415584388

PREFACE

Why a third edition?

For this third edition of *Renewable Energy Resources*, we have made significant changes in recognition of the outstanding progress of renewables worldwide. The basic principles remain the same, but feedback from earlier editions enables us to explain and analyze these more beneficially. Important aspects of new technology have been introduced and, most importantly, we have enlarged the analysis of the institutional factors enabling most countries to establish and increase renewables capacity.

When we wrote the first edition in the 1980s, modern applications of renewable energy were new and largely ignored by central planners. Renewables (apart from hydropower) were seen mainly as part of 'appropriate and intermediate technology', often for small-scale applications and rural development. In retrospect this concept was correct, but of limited vision. Yes, domestic and village application is a necessity; renewables continue to cater for such needs, now with assured experience and proven technology. However, since those early days, renewables have moved from the periphery of development towards mainstream infrastructure while incorporating significant improvements in technology. 'Small' is no longer suspect; for instance, 'microgeneration' is accepted technology throughout the developed and developing world, especially as the sum total of many installations reaches national significance. We ourselves have transformed our own homes and improved our lifestyles by incorporating renewables technology that is widely available; we are grateful for these successes. Such development is no longer unusual, with the totality of renewable energy substantial. Commercial-scale applications are common, not only for long-established hydropower but also for 'new renewables', especially the 'big three' of biomass, solar and wind. Major utilities incorporate renewables divisions, with larger and much replicated plant that can no longer be described as 'small' or 'irrelevant'. Such success implies utilizing varied and dispersed resources in an environmentally acceptable and cost-effective manner. Today, whole nations are developing their energy infrastructure with significant contributions from renewable energy for heat, fuels and electricity. This third edition reflects these welcome changes.

The rise of renewables has coincided with the rise to maturity of other 'new' technologies, including solid-state electronics, composite materials, computer-aided design, biotechnology, remotely communicated supervisory control and data acquisition, smart technology, and the internet; these have all supported the improvement and acceptance of renewable energy systems. For the environment as a whole, pollution reduction remains vital with the added concern of climate change. The cause: excessive use of fossil fuels. The obvious remedy is to replace fossil fuels by renewables and to improve efficiency of energy use. The gradual acceptance, at least partially, of this strategy has transformed the institutional framework surrounding renewable energy at all levels – international, national, regional and local.

Aim and structure of this book

The main aim of our book is unchanged: to explain renewable energy resources and technologies from fundamental scientific principles. Also largely unchanged is the basic structure of the book, although some chapters have been rearranged and renumbered. Chapter 1 introduces the features of renewable energy (RE) that distinguish it from other energy sources. Chapters 2 to 14 consider in turn the significant renewable energy technologies (solar, wind, bioenergy, etc.), the resources available and analysis of their basic operation The last three chapters consider subjects common to all energy resources: Chapter 15 – the distribution and storage of energy, Chapter 16 – the efficient use of energy, and Chapter 17 – institutional and economic factors.

As in previous editions, we expect our readers to have a basic understanding of science and technology, especially of physical science and basic mathematics. It is not necessary to read chapters consecutively, because each topic stands alone. However, certain background subjects underpin a variety of technologies; therefore, in this edition we have analyzed these subjects in a series of 'Reviews' near the end of the book (electrical power, fluid dynamics, heat transfer, solid state physics, units and conversions). Each review is a concise yet necessary explanation of standard theory and application needed in the chapters. Appendices A to D contain important background data.

What's new in the third edition?

This third edition responds to technological and socioeconomic changes occurring as renewables have become mainstream energy supplies. We have therefore improved and updated all the chapters. In particular this applies to solar photovoltaics, wind power and bioenergy; each of these subjects now has two chapters: one on the resource and the other on the technology. Chapter 16 – 'Using energy efficiently' – is new, since this is a vital subject for all forms of energy supply and presents some particular opportunities with renewables. New material has been added on the science of the greenhouse effect and projected climate change in Chapter 2, being a further reason for institutional and economic appreciation of renewables (Chapter 17).

We still work from first principles with unified symbolism throughout; we have tried hard to be *user friendly* by improving presentation and explanations. Each technology is introduced with fundamental analysis and details of international acceptance. Data on installed capacities and institutional acceptance have been updated to the time of publication. For updating, we list recommended websites (including that for this book), journals and other publications; internet searches are of course invaluable. This third edition has more 'boxed examples' and other such devices for focused information. We have extended the self-study material by grading the end-of-chapter problems, and by including chapter summaries and 'Quick questions' for rapid revision. Short answer guidance for problems is at the end of the book.

Detailed solutions to all the end-of-chapter problems (password protected for instructors only!) are in a new *associated website* at www.routledge.com/books/details/9780415584388. The public area of this website includes useful supplementary material, including the complete text of three chapters from the second edition: on OTEC, tidal range power and photosynthesis, which have some background material omitted from this third edition to help keep the length of the printed book manageable.

NOTE TO READERS: 'BORDERED TEXT'

To help readers we use ruled borders (e.g. as here) for:

Boxes: case studies or additional technical detail.

Worked Examples: numerical analysis usually with algebraic numbered equations.

Derivations: blocks of mathematical text, the less mathematically may omit them initially.

Acknowledgments

In earlier editions we acknowledge the support of the many people who helped in the production and content of those stages; we are of course still grateful to them. In addition, we thank all those who have provided detailed comments on earlier editions, in particular, Professor G. Farquhar and Dr Fred Chow (Australian National University), Professor J. Falnes (Norwegian University of Science and Technology), and other academics and students worldwide who have contacted us regarding their use of the book. Over the years, we have been supported by our colleagues and by undergraduate and postgraduate students at Strathclyde University, De Montfort University, Reading University, Oxford University and London City University (JT), and at the University of the South Pacific (JT and ADW); they have inspired us to continuously improve the book.

TW acknowledges financial support for his work on RE from Project DirEKT (EU) and from the Intergovernmental Panel on Climate Change (WG3), and thanks Shivneel Prasad of USP for research assistance, and Professor George Baird (Victoria University of Wellington), Dr Alistair Sproul (University of New South Wales) and Dr M.R. Ahmed (USP) for helpful advice on particular subjects. JWT acknowledges the many agencies in the EU and the UK who have funded his research projects and demonstrations in renewables, especially solar thermal and photovoltaics, wind power, solar buildings and institutional policies. We both acknowledge the importance to us of the many books, journal papers, websites and events where we have gained information about renewables; there is no way we could write this book without them and trust that we have acknowledged such help by referencing. We apologize if acknowledgment has been insufficient.

We thank a succession of editors and other staff at Taylor & Francis/Routledge/Earthscan, and last but not least our families for their patience and encouragement; we have each been blessed with an added family generation for each subsequent edition of the book. May there be a fourth.

John W. Twidell MA, DPhil, FInstP (UK)
A.D. (Tony) Weir BSc, PhD (Canberra, Australia)

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Figure and photo acknowledgments

Note: full bibliographic references for sources not fully described here are given in the Bibliography of the appropriate chapter.

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16.9 US Energy Administration, *International Energy Outlook 2011*, fig. 33.
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D5 From IRENA (2013), *Renewable Power Generation Costs in 2012: An overview*.
D6 IPCC SRREN (2011, fig. 1-20).

List of symbols

This list excludes symbols for fundamental and other units, see Appendix A2 etc.

Symbol	Main use	Other use or comment
Capitals		
A	Area (m^2)	Acceptor; ideality factor
B	Magnetic flux	Benefit
C	Thermal capacitance (J/K)	Electrical capacitance (F); constant
C_P	Power coefficient	
C_r	Concentration ratio	
C_w	Capture width (of wave device)	
C_Γ	Torque coefficient	
D	Distance (m)	Diameter; damping factor
E	Energy (J)	
E_F	Fermi level	
E_g	Band gap (eV)	
E_K	Kinetic energy (J)	
F	Force (N)	Faraday constant (C/mole); Fill factor (photovoltaics)
F_{ij}	Shape factor	
F'_{ij}	Radiation exchange factor (*i* to *j*)	
G	Solar irradiance (Wm^{-2})	Gravitational constant (Nm^2kg^{-2}); Temperature gradient (K/m); Gibbs energy (J)
G_b, G_d, G_{h*}	Solar irradiance (beam, diffuse, on horizontal)	
G_{0*}	Solar constant	

Symbol	Main use	Other use or comment
H	Enthalpy (J)	Head (pressure height) of fluid (m); wave crest height (m); insolation (J m^{-2} day^{-1}); heat of reaction (ΔH: *J per component mass or volume*)
I	Electric current (A)	Moment of inertia (kg m^2); wind turbulence intensity (m s^{-1})
J	Current density (A/m^2)	
K	Extinction coefficient (m^{-1})	Clearness index (K_T); constant
L	Distance, length (m)	Diffusion length (m)
M	Mass (m)	Molecular weight
N	Concentration (m^{-3})	Hours of daylight
N_0	Avogadro number	
P	Power (W)	
P'	Power per unit length (W/m)	
Q	Volume flow rate (m^3/s)	
R	Thermal resistance (K/W)	Radius (m); electrical resistance (Ω); reduction level; tidal range (m); gas constant (R_0); blade length (m)
R_m	Thermal resistance (*m*ass transfer; K/W)	
R_n	Thermal resistance (co*n*duction; K/W)	
R_r	Thermal resistance (*r*adiation; K/W)	
R_v	Thermal resistance (con*v*ection; K/W)	
RFD	Radiant flux density (W/m^2)	
S	Surface area (m^2)	Entropy (J/K)
S_v	Surface recombination velocity (m/s)	
T	Temperature (K)	Period (s^{-1})
U	Potential energy (J)	Heat loss coefficient ($Wm^{-2}K^{-1}$)
V	Volume (m^3)	Electrical potential (V)
W	Width (m)	Energy density (J/m^3)
X	Characteristic dimension (m)	Concentration ratio
Z	Capacity factor (dimensionless)	

Symbol	Main use	Other use or comment
Script capitals (non-dimensional numbers characterizing fluid flow; all dimensionless)		
$\mathscr{A}$	Rayleigh number	
$\mathscr{G}$	Grashof number	Graetz number
$\mathscr{N}$	Nusselt number	
$\mathscr{P}$	Prandtl number	
$\mathscr{R}$	Reynolds number	
$\mathscr{S}$	Shape number (of turbine)	
Lower case		
a	amplitude (m)	wind interference factor; radius (m)
b	wind profile exponent	width (m)
c	specific heat capacity (J kg^{-1} K^{-1})	speed of light (m/s); phase velocity of wave (m/s); chord length (m); Weibull speed factor (m/s)
d	distance (m)	diameter (m); depth (m); zero plane displacement (wind) (m)
e	elementary charge (C)	base of natural logarithms (2.718); ellipticity; external
f	frequency of cycles (Hz = s^{-1})	pipe friction coefficient; fraction; force per unit length (N m^{-1})
g	acceleration due to gravity (m/s^2)	
h	heat transfer coefficient (Wm^{-2}K^{-1})	vertical displacement (m); Planck constant (Js)
i	$\sqrt{-1}$	internal
k	thermal conductivity (Wm^{-1}K^{-1})	wave vector ($=2\pi/\lambda$); Boltzmann constant ($=1.38 \times 10^{-23}$ J/K)
l	distance (m)	
m	mass (kg)	air mass ratio
n	number	number of nozzles, of hours of bright sunshine, of wind turbine blades; electron concentration (m^{-3})
p	pressure (Nm^{-2} = Pa)	hole concentration (m^{-3})
q	power per unit area (W/m^2)	
r	thermal resistivity of unit area (often called 'r-value'; r = RA) (m^{2}K/W)	radius (m); distance (m)
s	angle of slope (degrees)	
t	time (s)	thickness (m)

Symbol	Main use	Other use or comment
u	velocity along stream (m/s)	group velocity (m/s)
v	velocity (not along stream) (m/s)	
w	distance (m)	moisture content (dry basis%); moisture content (wet basis%) (w')
x	coordinate (along stream) (m)	
y	coordinate (across stream) (m)	
z	coordinate (vertical) (m)	
Greek capitals		
Γ Gamma	Torque (Nm)	Gamma function
Δ Delta	Increment of […] (other symbol)	
Λ Lambda	Latent heat (J/kg)	
Σ Epsilon	Summation sign	
Φ Phi	Radiant flux (W)	Probability function, magnetic flux
Φ_u	Probability distribution of wind speed $((m.s^{-1}))^{-1}$	
Ω Omega	Angular velocity of blade (rad/s)	Phonon frequency (s^{-1});
Greek (lower case)		
α alpha	absorptance (dimensionless)	angle of attack (deg)
α_λ	monochromatic absorptance (dimensionless)	
β beta	angle (deg)	volumetric expansion coefficient (K^{-1})
γ gamma	angle (deg)	blade setting angle (deg)
δ delta	boundary layer thickness (m)	angle of declination (deg)
ε epsilon	emittance (dimensionless)	wave 'spectral width'; permittivity; dielectric constant
ε_λ	monochromatic emittance	
η eta	efficiency (dimensionless)	
θ theta	angle of incidence (deg)	temperature difference (^oC)
κ kappa	thermal diffusivity (m^2/s)	
λ lambda	wavelength (m)	tip speed ratio of wind turbine
μ mu	dynamic viscosity ($N\ m^{-2}s$)	

Symbol	Main use	Other use or comment
ν nu	kinematic viscosity (m^2/s)	
ξ xi	electrode potential (V)	roughness height (m)
π pi	3.1416	
ρ rho	density (kg/m^3)	reflectance (albedo); electrical resistivity (m)
ρ_λ	monochromatic reflectance (dimensionless)	
σ sigma	Stefan-Boltzmann constant	
τ tau	transmittance (dimensionless)	relaxation time (s); duration (s); shear stress (N/m^2)
τ_λ	monochromatic transmittance (dimensionless)	
ϕ phi	radiant flux density (RFD) (W/m^2)	wind blade angle (deg); potential difference (V); latitude (deg); phase angle
ϕ_λ	spectral distribution of RFD (W/m^3)	
χ chi	absolute humidity (kg/m^3)	
ψ psi	longitude (deg)	angle (deg)
ω omega	angular frequency ($=2\pi f$) (rad/s)	hour angle (deg); solid angle (steradian)

Subscripts

B	Black body	Band
D	Drag	Dark; device
E	Earth	
F	Force	
G	Generator	
L	Lift	Light
M	Moon	
P	Power	
R	Rated	
S	Sun	
T	Tangential	Turbine
a	ambient	aperture; available (head); aquifer; area
abs	absorbed	
b	beam	blade; bottom; base; biogas
c	collector	cold
ci	cut-in	

Symbol	Main use	Other use or comment
co	cut-out	
cov	cover	
d	diffuse	dopant; digester
e	electrical	equilibrium; energy
f	fluid	forced; friction; flow; flux
g	glass	generation current; band gap
h	horizontal	hot
i	integer	intrinsic
in	incident (incoming)	
int	internal	
j	integer	
m	*m*ass transfer	mean (average); methane
max	maximum	
maxp	maximum power	
n	co*n*duction	
net	heat flow across surface	
o	(read as numeral zero)	
oc	open circuit	
p	plate	peak; positive charge carriers (holes); performance
r	radiation	relative; recombination; room; resonant; rock; relative
rad	radiated	
refl	reflected	
rms	root mean square	
s	surface	significant; saturated; Sun; sky
sc	short circuit	
t	tip	total
th	thermal	
trans	transmitted	
u	useful	
v	con*v*ection	vapor
w	wind	water; width
z	zenith	
λ	monochromatic (e.g. $\alpha\lambda$)	
0	distant approach	ambient; extra-terrestrial; dry matter; saturated; ground-level
1	entry to device	first
2	exit from device	second

Symbol	Main use	Other use or comment
3	output	third
Superscript		
m or *max*	maximum	
*	measured perpendicular to direction of propagation (e.g. G_b*)	
· (dot)	rate of , e.g. $\dot{m}$	
Other symbols and abbreviations		
Bold face	vector, e.g. ***F***	
ch.	chapter	
§	section (within chapters)	
=	mathematical equality	
≈	approximate equality (within about 20%)	
~	equality in order of magnitude (within a factor of 2 to 10)	
≡	mathematical identity (or definition), equivalent	

List of abbreviations (acronyms)

This list excludes most chemical symbols and abbreviations of standard units; see also the Index, and Appendix A for units.

AC	Alternating current
AM	Air–mass ratio
BoS	Balance of system
CCS	Carbon capture and storage
CFL	Compact fluorescent light
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2eq	CO_2 equivalent for other climate-change-forcing gases
COP	Coefficient of Performance
CSP	Concentrated solar power (= CSTP)
CSTP	Concentrated solar thermal power
DC	Direct current
DCF	Discounted cash flow
DNI	Direct normal insolation (= irradiance)
DOWA	Deep ocean water applications
EC	Electrochemical capacitor
EGS	Enhanced geothermal system[s]
EIA	Environmental Impact Assessment
EMF	Electromotive force (equivalent to Voltage)
EU	European Union
EV	Electric vehicle
FF	Fossil fuel
GCV	Gross calorific value
GDP	Gross domestic product
GER	Gross energy requirement
GHG	Greenhouse gas
GHP	Geothermal heat pump (= GSHP)
GMST	Global mean surface temperature
GOES	Geostationary Operational Environmental Satellite

GPP	Gross primary production
GSHP	Ground-source heat pump
GWP	Global warming potential
HANPP	Human appropriated net primary productivity
HAWT	Horizontal axis wind turbine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle analysis
LCV	Lower calorific value
LED	Light emitting diode
LH	Light harvesting
LiDAR	Light detection and ranging
MPPT	Maximum power tracker
MSW	Municipal solid waste
NB	*Nota bene* (= note well)
NPP	Net primary production
NPV	Net present value
O&M	Operation and maintenance
OECD	Organisation for Economic Cooperation and Development
ONEL	Oakridge National Laboratory
OPEC	Organisation of Petroleum Exporting Countries
OPV	Organic photovoltaic
OTEC	Ocean thermal energy conversion
OWC	Oscillating water column
PS	Photosystem
PV	Photovoltaic
P2G	Power to grid
R&D	Research and development
R, D & D	Research, development and demonstration
RE	Renewable energy
RES	Renewable energy system
RET	Renewable energy technology
RFD	Radiant flux density (W/m^2)
SCADA	Supervisory control and data aquisition
SHS	Solar home system
SONAR	Sonic detection and ranging
SRREN	Special Report on Renewable Energy (published by IPCC)
STP	Standard temperature and pressure
TPES	Total primary energy supply
UK	United Kingdom
US[A]	United States [of America]
WMO	World Meteorological Organisation

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CHAPTER

1

Principles of renewable energy

CONTENTS

LEARNING AIMS

- Define renewable energy (RE).
- Appreciate the scientific, technical, and social implications of the difference between renewable and non-renewable energy resources.
- Consider sustainability and energy supply.
- Know the key parameters affecting individual RE supplies.
- Appreciate the variability of different RE supplies.

- Consider methods and controls to optimize the use of renewable energy.
- Relate energy supplies to environmental impact.

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§1.1 INTRODUCTION

This textbook analyzes the full range of renewable energy supplies available to modern economies worldwide. It is widely recognized that these are necessary for sustainability, security, and standard of living. The renewable energy systems covered include power from solar radiation (sunshine), wind, biomass (plant crops), rivers (hydropower), ocean waves, tides, geothermal heat, and other such continuing resources. All of these systems are included within the following general definition:

> *Renewable energy is energy obtained from naturally repetitive and persistent flows of energy occurring in the local environment.*

An obvious example is solar (sunshine) energy that 'persists' and 'repeats' day after day, but is obviously not constant but variable. Similarly, plants have an annual growing season, which stores energy from sunshine in their structure that is released in combustion and metabolism. With a renewable energy resource, the energy is already passing through the environment as a *current* or *flow,* irrespective of there being a device to intercept and harness this power. The phrase 'local environment' refers to the location of such a device to intercept the flow. The natural energy flows that are commonly harnessed for energy purposes are indicated in §1.3. Such energy may also be referred to as *green energy* or *sustainable energy*.

In contrast,

> *Non-renewable energy is energy obtained from static stores of energy that remain underground unless released by human interaction.*

Examples are nuclear fuels and the fossil fuels of coal, oil, and natural gas. With these sources, the energy is initially an isolated energy *potential,* and external action is required to initiate the supply of energy for practical purposes. To avoid using the ungainly word 'non-renewable', such energy supplies are called *finite supplies* or *brown energy*.

It is also possible to include energy from society's wastes in the definition of renewables, since in practice they are unstoppable; but are they 'natural'? Such finer points of discussion concerning resources are implicit in the detail of later chapters.

For renewable energy the scale of practical application ranges from tens to many millions of watts, and the totality is a global resource. However, for each application, five questions should be asked:

1. How much energy is available in the immediate environment; what are the resources?
2. What technologies can harness these resources?
3. How can the energy be used efficiently; what is the end-use?

4 What is the environmental impact of the technology, including its implications for climate change?
5 What is the cost-effectiveness of the energy supply as compared with other supplies?

The first three are technical questions considered in the central chapters of this book by type of renewables technology. The fourth question relates to broad issues of planning, social responsibility, sustainable development, and global impact; these are considered in the concluding section of each technology chapter and in Chapter 17. The fifth and final question is a dominant question for consumers, but is greatly influenced by government and other policies, considered as 'institutional factors' in Chapter 17. The evaluation of 'cost-effectiveness' depends significantly upon the following factors:

a Appreciating the *distinctive scientific principles* of renewable energy (§1.4).
b the *efficiency* of each stage of the energy supply in terms of both minimizing losses and maximizing economic and social benefits (§16.2).
c Considering externalities and social costs (Box 17.2).
d Considering both costs and benefits over the lifetime of a project (which may be > ~30 years).

In this book we analyze (a) and (b) in detail, since they apply universally. The second two, (c) and (d) have aspects that depend on particular economies, and so we only explain the principles involved.

§1.2 ENERGY AND SUSTAINABLE DEVELOPMENT

§1.2.1 Principles and major issues

Sustainable development may be broadly defined as living, producing, and consuming in a manner that meets the needs of the present without compromising the ability of future generations to meet their own needs. It has become one of the key guiding principles for policy in the 21st century. The principle is affirmed worldwide by politicians, industrialists, environmentalists, economists, and theologians as they seek international, national, and local cooperation. However, reaching specific agreed policies and actions is proving much harder!

In the international context, the word 'development' refers to improvement in quality of life, including improving standards of living in less developed countries. The aim of *sustainable* development is to achieve this aim while safeguarding the ecological processes upon which life depends. Locally, progressive businesses seek a positive *triple bottom line* (i.e. a positive contribution to the *economic, social, and environmental* well-being of the community in which they operate).

The concept of sustainable development first reached global importance in the seminal report of the UN World Commission on Environment and Development (1987); since then this theme has percolated slowly and erratically into most national economies. The need is to recognize the scale and unevenness of economic development and population growth, which place unprecedented pressures on our planet's lands, waters, and other natural resources. Some of these pressures are severe enough to threaten the very survival of some regional populations and in the longer term to lead to disruptive global change. The way people live, especially regarding production and consumption, will have to adapt due to ecological and economic pressures. Nevertheless, the economic and social pain of such changes can be eased by foresight, planning, and political and community will.

Energy resources exemplify these issues. Reliable energy supply is essential in all economies for lighting, heating, communications, computers, industrial equipment, transport, etc. Purchases of energy account for 5 to10% of gross national product in developed economies. However, in some developing countries, fossil fuel imports (i.e. coal, oil, and gas) may cost over half the value of total exports; such economies are unsustainable, and an economic challenge for sustainable development. World energy use increased more than ten-fold during the 20th century, predominantly from fossil fuels and with the addition of electricity from nuclear power. In the 21st century, further increases in world energy consumption may be expected, largely due to rising industrialization and demand in previously less developed countries, aggravated by gross inefficiencies in all countries. Whatever the energy source, there is an overriding need for efficient transformation, distribution, and use of energy.

Fossil fuels are not being newly formed at any significant rate, and thus current stocks are ultimately finite. The location and amount of such stocks depend on the latest surveys. Clearly the dominant fossil fuel by mass is coal. The reserve lifetime of a resource may be defined as the known accessible amount divided by the rate of present use. By this definition, the lifetime of oil and gas resources is usually only a few decades, whereas the lifetime for coal is a few centuries. Economics predicts that as the lifetime of a fuel reserve shortens, so the fuel price increases; subsequently, therefore, demand falls and previously more expensive sources and alternatives enter the market. This process tends to make the original source last longer than an immediate calculation indicates. In practice, many other factors are involved, especially government policy and international relations. Nevertheless, the basic geological fact remains: fossil fuel reserves are limited and so the current patterns of energy consumption and growth are not sustainable in the longer term.

Moreover, the *emissions* from fossil fuel use (and indeed nuclear power) increasingly determine another fundamental limitation on their continued use. These emissions bring substances derived from underground materials (e.g. carbon dioxide) into the Earth's atmosphere and oceans that were not present before. In particular, emissions of carbon dioxide (CO_2) from the combustion of fossil fuels have significantly raised the concentration of CO_2 in the global atmosphere. Authoritative scientific opinion is in agreement that if this continues, the *greenhouse effect* will be enhanced and so lead to significant *climate change* within a century or sooner, which could have a major adverse impact upon food production, water supply, and society (e.g. through increased floods and storms (IPCC 2007, 2013/2014)); see also §2.9. Sadly, concrete action is slow, not least owing to the reluctance of governments in industrialized countries to disturb the lifestyle of their voters. However, potential climate change, and related sustainability issues, is now established as one of the major drivers of energy policy.

In contrast to fossil and nuclear fuels, renewable energy (RE) supply in operation does not add to elements in the atmosphere and hydrosphere. In particular, there is no additional input of greenhouse gases (GHGs). Although there are normally such emissions from the manufacture of all types of energy equipment, these are always considerably less per unit of energy generated than emitted over the lifetime of fossil fuel plant (see data in Appendix D). Therefore, both nuclear power and renewables significantly reduce GHG emissions if replacing fossil fuels. Moreover, since RE supplies are obtained from ongoing flows of energy in the natural environment, all renewable energy sources should be sustainable. Nevertheless, great care is needed to consider actual situations, as noted in the following quotation:

> *For a renewable energy resource to be sustainable, it must be inexhaustible and not damage the delivery of environmental goods and services including the climate system. For example, to be sustainable, biofuel production should not increase net CO_2 emissions, should not adversely affect food security, nor require excessive use of water and chemicals, nor threaten biodiversity. To be sustainable, energy must also be economically affordable over the long term; it must meet societal needs and be compatible with social norms now and in the future. Indeed, as use of RE technologies accelerates, a balance will have to be struck among the several dimensions of sustainable development. It is important to assess the entire lifecycle of each energy source to ensure that all of the dimensions of sustainability are met.*
>
> *(IPCC 2011, § 1.1.5)*

In analyzing harm and benefit, the full external costs of obtaining materials and fuels, and of paying for damage from emissions, should be internalized in costs, as discussed in Chapter 17. Doing so takes into account: (i) the finite nature of fossil and nuclear fuel materials; (ii) the harm of emissions; and (iii) ecological sustainability. Such fundamental analyses usually conclude that combining renewable energy with the efficient use of energy is more cost-effective than the traditional use of fossil and nuclear fuels, which are unsustainable in the longer term. In short, renewable energy supplies are much more compatible with sustainable development than are fossil and nuclear fuels in regard to both resource limitations and environmental impacts (see Table 1.1).

Consequently, almost all national energy plans include four vital factors for improving or maintaining benefit from energy:

1 increased harnessing of renewable supplies;
2 increased efficiency of supply and end-use;
3 reduction in pollution;
4 consideration of employment, security, and lifestyle.

§1.2.2 Energy security

Nations, and indeed individuals, need *secure* energy supplies; they need to know that sufficient and appropriate energy will reach them in the future. Being in control of independent and assured supplies is therefore important – renewables offer this so long as the technologies function and are affordable.

§1.2.3 A simple numerical model for sustainability

Consider the following simple model describing the need for commercial and non-commercial energy resources:

$$R = E\,N \tag{1.1}$$

Here R *is* the total yearly energy consumption for a population of N people. E is the per capita use of energy averaged over one year, related closely to the provision of food and manufactured goods. On a world scale, the dominant supply of energy is from commercial sources, especially fossil fuels; however, significant use of non-commercial energy may occur (e.g. fuel-wood, passive solar heating) which is often absent from most official and company statistics. In terms of total commercial energy use, E on a world per capita level is about 2.1 kW, but regional average values range widely, with North America 9.3 kW, Europe 4.6 kW, and several regions of Central Africa 0.2 kW. The inclusion of non-commercial energy increases all these figures, especially in countries with low values of E.

Standard of living relates in a complex and an ill-defined way to E. Thus, per capita gross national product S (a crude measure of standard of living) may be related to E by:

$$S = f\,E \tag{1.2}$$

Here f is a complex and nonlinear coefficient that is itself a function of many factors. It may be considered an efficiency for transforming energy into wealth and, by traditional economics, is expected to be as large as possible. However, S does not increase uniformly as *E* increases. Indeed, *S* may even decrease for large *E* (e.g. due to pollution or technical inefficiency). Obviously, unnecessary waste of energy leads to smaller values of *f* than would otherwise be possible. Substituting for *E* in (1.1), the national requirement for energy becomes:

$$R = (S\,N)/f \qquad (1.3)$$

so

$$\Delta R/R = \Delta S/S + \Delta N/N - \Delta f/f \qquad (1.4)$$

Now consider substituting global values for the parameters in (1.4). In 50 years the world population *N* increased from 2.5 billion in 1950 to over 7.2 billion in 2013. It is now increasing at approximately 2 to 3% per year so as to double every 20 to 30 years. Tragically high infant mortality and low life expectancy tend to hide the intrinsic pressures of population growth in many countries. Conventional economists seek exponential growth of *S* at 2 to 5% per year. Thus, in (1.4), at constant efficiency parameter *f*, the growth of total world energy supply is effectively the sum of population and economic growth (i.e. 4 to 8% per year). Without new supplies, such growth cannot be maintained. Yet, at the same time as more energy is required, fossil and nuclear fuels are being depleted, and debilitating pollution and climate change increase.

An obvious way to overcome such constraints is to increase renewable energy supplies. Most importantly, from (1.3) and (1.4), it is vital to increase the efficiency parameter *f* (i.e. to have a positive value of Δf). Consequently, if there is a growth rate in the efficient use and generation of energy, then *S* (standard of living) increases while *R* (resource use) decreases.

§1.2.4 Global resources

With the most energy-efficient modern equipment, buildings, and transportation, a justifiable target for energy use in a modern society is $E = 2$ kW per person (i.e. approximately the current global average usage, yet with a far higher standard of living). Is this possible, even in principle, from renewable energy? Each square metre of the Earth's habitable surface is crossed by or accessible to an average energy flux of about 500 W (see Problem 1.1). This includes solar, wind, or other renewable energy forms in an overall estimate. If this flux is harnessed at just 4% efficiency, 2 kW of power can be drawn from an area of 10m × 10m, assuming suitable methods. Suburban areas of residential towns have population densities of about 500 people km^{-2}. At 2 kW per person, the total energy demand of l000 kW/km^{2} could be obtained in this way by using just 5% of the local land area for energy production, thus allowing for the 'technical potential' of RE being less than the 'theoretical potential', as indicated in Fig.1.2 and §1.5.4. Thus, renewable energy supplies may, in principle, provide a satisfactory standard of living worldwide, but only if methods exist to extract, use, and store the energy satisfactorily at realistic costs. This book will consider both the technical background of a great variety of possible methods and a summary of the institutional factors involved.

§1.3 FUNDAMENTALS

§1.3.1 Energy sources

The definitions of renewable energy and of fossil and nuclear energy given at the start of this chapter are portrayed in Fig. 1.1. Table 1.1 provides a comparison of renewable and conventional energy systems.

There are five ultimate *primary* sources of useful energy:

1. The Sun.
2. The motion and gravitational potential of the Sun, Moon, and Earth.
3. Geothermal energy from cooling, chemical reactions, and natural radioactive decay.
4. Nuclear reactions on the Earth.
5. Chemical reactions from mineral sources.

Renewable energy derives continuously from sources 1, 2, and 3. Note that biomass and ocean heat are ultimately derived from solar energy, as

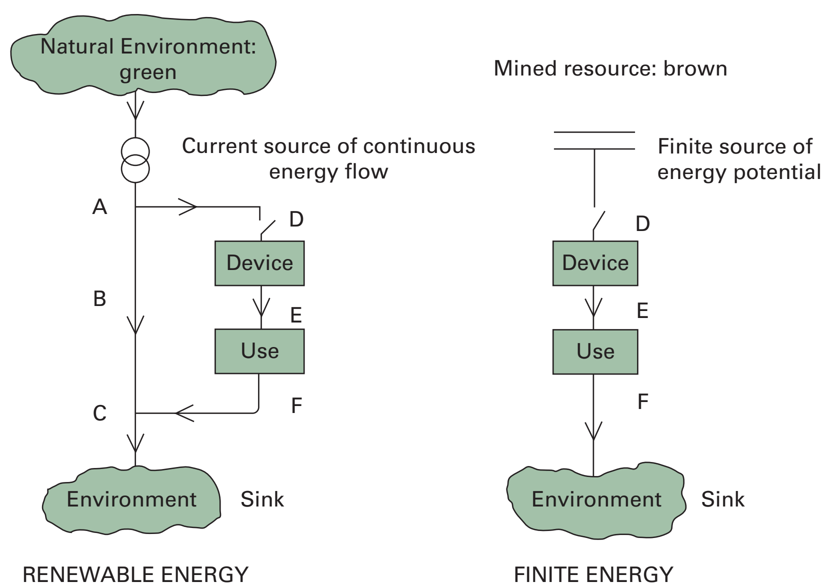

Fig. 1.1

Contrast between renewable (green) and finite (brown) energy supplies. Environmental energy flow ABC, harnessed energy flow DEF.