Renewable Energy

Its physics, engineering, use, environmental impacts, economy and planning aspects

Third Edition

Other books by the author:

Hydrogen and Fuel Cells. Forthcoming 2005
Life-cycle analysis of energy systems (with Kuemmel and Nielsen). 1997
Blegdamsvej 17. 1989
Superstrenge. 1987
Fred og frihed. 1985
Fundamentals of Energy Storage (with Jensen). 1984
Energi for fremtiden (with Hvelplund, Illum, Jensen, Meyer and Nørgård). 1983
Energikriser og Udviklingsperspektiver (with Danielsen). 1983
Renewable Energy. First edition, 1979; Second edition 2000
Skitse til alternativ energiplan for Danmark (with Blegaa, Hvelplund, Jensen, Josephsen, Linderoth, Meyer and Balling). 1976

- more information about the author at http://mmf.ruc.dk/energy

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ELSEVIER
ACADEMIC
PRESS

Amsterdam Boston Heidelberg London New York Oxford
Paris San Diego San Francisco Singapore Sydney Tokyo

Elsevier Academic Press

200 Wheeler Road, 6th Floor, Burlington, MA 01803, USA
525 B Street, Suite 1900, San Diego, California 92101-4495, USA
84 Theobald's Road, London WC1X 8RR, UK

This book is printed on acid-free paper. ♾

Library of Congress Cataloging-in-Publication Data

Application submitted

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN: 0-12-656153-2

For all information on all Academic Press publications
visit our Web site at www.academicpress.com

Layout and print-ready electronic-medium manuscript by author
Printed in the United States of America
04 05 06 07 08 09 9 8 7 6 5 4 3 2 1

Preface to third edition

The present edition has been updated in a number of renewable energy technology areas (Chapters 4 and 5), where progress has been made over the recent years. New solar simulation studies have been added to Chapter 6, and market considerations have been included in the overview in Chapter 1 and in discussing industry liberalisation in Chapter 7. The remarks on advanced subjects made in the preface to the second edition are still valid. A new growth area is fuel cells for stationary and mobile uses of hydrogen and other fuels. Only modest updates have been done in this area, as it is the subject of a new, companion book to be published about a year after this one (Sørensen: Hydrogen and Fuel Cells, Elsevier/Academic Press). Some older material has been omitted or tidied up, and manoeuvring through the book has been eased, both for reference and for textbook uses. The following diagrams may assist in following the tracks of interest through the book:

Topic-driven paths

Chapter	Wind	Solar power	Solar heat	Biofuels	Others
1	1.1	1.1	1.1	1.1	1.1
2	2.3.1 (end), 2.4.1, 2C	2.2.2, 2.4.1	2.2.2, 2.4.1	2.4.1	2.3.2, 2.4.1, 2B, 2D
3	3.2	3.1	3.1	3.6	3.3-3.5, 3.7
4	4.1.4, 4.3	4.1.5, 4.2.3	4.2.1-2, 4.6	4.8	4.1.3, 4.1.6, 4.4-5, 4.7, 4.8
5	5.1.2, 5.2.2	5.1.2, 5.2.2	5.1.1, 5.2.1		
6	6.2.5, 6.3.2, 6.4	6.2.4, 6.4	6.3.1, 6.4	6.2.7, 6.4	6.4
7	7.4.12-13, 7.5	7.4.12-13		7.4.12-13	
8	8	8	8	8	8

Course material uses

Chapter	Resource studies	Energy engineering	Energy planning	Energy economics	Energy & environment
1	1		1	1.1	1.2
2	2				2.4.1
3	3	as needed			3.4.2 (end)
4		4	as needed	4.8 (start)	4.5
5		5	as needed		
6			6	as needed	as needed
7			7	7	7.4
8	8	8	8	8	8

Gilleleje, October 2003, *Bent Sørensen*

Preface to second edition

When the first edition of *Renewable Energy* appeared in 1979, it was the first textbook and research monograph since the 1920s to deal with the renewable energy sources and systems at a scholarly level. Indeed, it was instrumental in establishing the now universally used term "renewable energy" for a new area of science, which emerged under names such as "regenerative energy" in Germany and "solar energy" in the United States of America. In many countries, renewable energy appeared in planning documents as "supplementary energy", based on a conviction by administrators, that this could never become a major source of energy. My suggestion in the journal *Science* (Sørensen, 1975b) that renewable energy could potentially become a hundred per cent solution was regarded as absurd by many. Things have changed today, where official energy plans of some countries call for over fifty per cent renewable energy coverage by year 2030 (Danish Department of Environment and Energy, 1996), where the best renewable energy technologies are already economically competitive relative to fossil options and where increased concern over greenhouse warming effects may well alter the perceived indirect costs of different energy solutions.

The structure of the first edition was determined by the aim of placing renewable energy on the academic agenda. It was my goal to show young scientists, engineers and future planners that renewable energy was at least as interesting and challenging as nuclear energy, and I tried to do this by showing the depth of problems to be solved using advanced techniques, shying no complication of quantum mechanics or non-linear mathematics. This was seen as positive by reviewers and colleagues, but may have limited the sales figures for the book! Today, the requirements are quite different: now many universities and polytechnic institutes have renewable energy courses in their curriculum, and the task at hand is to provide good teaching materials for the relevant levels of courses. Therefore, I have thoroughly revised the content and presentation in the second edition. The main sections of each chapter are now suited for introductory level study, with only very general prerequisites. Any topic requiring more background is deferred to special sections marked as ADVANCED topics at the top corner of each page. They can be added individually at the choice of the teacher, or they can be left for further study by the user of the book. My reflections on whether to separate elementary and advanced topics in two volumes or keep them together are as follows. Needing to go back to a topic for more detailed study, it is very convenient to be able to find it in a book that you have already worked with. The style and assumptions are known to you, and first of all, the book is on your shelf and need not be retrieved from somewhere

else. Against the single volume solution speaks the book price for those who find it unlikely that they shall need more than the elementary sections. However, we are all surprised by the growth of our needs, and the price of this second edition is even below that of the first edition, thanks to modern preparation and printing methods.

Another issue is the arrangement of material, which I have basically kept as in the first edition: first describing the origin of renewable energy, then its disposition and availability at different geographical locations on Earth, then the techniques of energy conversion systems and systems suitable for each type of renewable energy, and finally the evaluation of the total system, in terms of economic and environmental impacts. The logic of this sequence is evident, but it means that someone wanting to know only about wind power will have to jump from chapter to chapter. This is made much easier in this edition, by the addition on each bottom left page references to previous and following sections dealing with the same form of renewable energy. As in the first edition, extensive references and an index are found at the end. The index also serves as a pointer to specialist words and concepts by giving the page where they are first explained. After the table of contents, a list of units and abbreviations is given.

The content has been revised in those areas where new advances have been made, notably in the sections on energy from biomass and on photovoltaic energy conversion, and in the economic chapter on life-cycle analysis. As in the first edition, emphasis is on basic principles. Fortunately, they do not wear much with time, and several sections needed only a light brush-up, sometimes with some tidying effort to keep the size down. However, new data available today has made it possible to improve many of the illustrations, notably in the area of global energy flows. At the end of each chapter, there are topics for discussion, including new ones. They are basically of two kinds: simple topics for classroom discussion and mini-project ideas that can serve as a basis for problem-oriented work extending from a few days to several months in duration. This is a reflection of the different style of teaching at different institutions, where small projects are often offered to individuals or groups of students for credit, with the indicated range of time devoted to each problem (and a corresponding difference in depth of investigation).

The Danish Energy Agency supported part of the work upon which the second edition updates are based. The author welcomes comments and suggestions, which may be addressed as indicated below.

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Preface to first edition

Renewable energy is the collective name for a number of energy resources available to man on Earth. Their conversion has always played an important role for the inhabitants of the planet, and apart from a period of negligible length – relative to evolutionary and historical time scales – the renewable energy sources have been the only ones accessible to mankind.

Yet the study of renewable energy resources, their origin and conversion, may at present be characterised as an emerging science. During the past fifty years of scientific and technological revolution, much more effort has been devoted to the extraction and utilisation of non-renewable energy resources (fuels), than to the renewable ones. Only very recently have funds been made available to re-establish renewable energy research and development, and it is still unclear whether the technologies based on renewable energy sources will become able to constitute the backbone of future energy supply systems.

The purpose of the present book is to provide an incentive as well as a basis of reference for those working within the field of renewable energy. The discontinuity between earlier and present work on renewable energy, and the broadness of disciplines required for assessing many questions related to the use of renewable energy, have created a need for a comprehensive reference book, covering methods and principles, rather than specific engineering prescriptions of passing interest in a rapidly developing field.

A survey of renewable energy has to draw upon a large number of individual scientific disciplines, ranging from astrophysics and upper atmospheric science over meteorology and geology to thermodynamics, fluid mechanics, solid state physics, etc. Specialists in each discipline often use a vocabulary recognised only by insiders, and they rarely emphasise the aspects pertinent to renewable energy. I have attempted to use a common language throughout, and to restrict the prerequisites for understanding to a fairly elementary level (e.g. basic physics). However, this does not mean that I have avoided any degree of complication considered relevant, and the reader must be prepared to face a number of challenges.

I envisage my reader as a research worker or student working somewhere within the field of renewable energy. Such work is currently undertaken at universities, engineering schools and various offices and laboratories in the public or private sectors. However, since a substantial part of the book deals with *energy systems* comprising renewable energy elements, and with the management and economy of such systems, including environmental and social aspects, then I sincerely hope to attract also readers in the energy planning and management sectors, whether their concern is the physical

planning and operation of energy supply systems, or the socio-economic assessment of such systems.

When used as a textbook, particular chapters may be more relevant than others. Cross-references are included in most cases where definitions or basic concepts have to be taken from a different chapter. Courses in engineering may place the emphasis around Chapter 4 (e.g. including Chapters 3 – 6), courses in "energy physics" or on energy in general may place more emphasis on Chapters 2 and 3, while courses on energy planning, systems aspects, and technological or economic assessments may find it natural to shift the emphasis to Chapters 6 and 7.

It should be stressed that the main purpose of the book is to provide general tools for treating problems relating to renewable energy. This is evident from the approach to energy conversion in Chapter 4 (stressing principles rather than describing individual pieces of equipment in detail), and from the treatment of supply systems in Chapter 6 (which contains no exhaustive reviews of possible system combinations, but illustrates basic modelling and simulation techniques by use of just a few, selected system examples). Energy storage and transmission (Chapter 5) are described in a highly condensed form, with the sole purpose of introducing the components for use in energy systems such as those discussed in Chapter 6.

I have been motivated to engage in work on renewable energy and to see the possibility of an increasingly important role played by the associated technologies by reflections which are largely summarised in Chapter 1, and which to some extent lie behind those amendments to conventional economic theory for application to long-term energy planning, proposed in Chapter 7. The subjective nature of a number of interpretations made in these two chapters is recognised, and an effort has been made to ban such interpretations from the remaining five chapters, so that readers disagreeing with my interpretations may still find the bulk of the book useful and stimulating.

I thank the following for reading and commenting on portions of the draft version of the manuscript: Niels Balling, Henning Frost Christensen, E. Eliasen, Frede Hvelplund, Johannes Jensen, Marshal Merriam, B. Maribo Petersen and Ole Ulfbeck.

Bent Sørensen, Allerød, January 1979

Contents

Units and conversion factors

Powers of 10

Prefix	*Symbol*	*Value*	*Prefix*	*Symbol*	*Value*
atto	a	10^{-18}	kilo	k	10^{3}
femto	f	10^{-15}	mega	M	10^{6}
pico	p	10^{-12}	giga	G	10^{9}
nano	n	10^{-9}	tera	T	10^{12}
micro	μ	10^{-6}	peta	P	10^{15}
milli	m	10^{-3}	exa	E	10^{18}

G, T, P, E are called milliard, billion, billiard, trillion in Europe, but billion, trillion, quadrillion, quintillion in the USA. M as million is universal.

SI units

Basic unit	*Name*	*Symbol*
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	Kelvin	K
luminous intensity	candela	cd
plane angle	radian	rad
solid angle	steradian	sr

Derived unit	*Name*	*Symbol*	*Definition*
energy	joule	J	$kg\ m^2\ s^{-2}$
power	watt	W	$J\ s^{-1}$
force	newton	N	$J\ m^{-1}$
electric charge	coulomb	C	$A\ s$
potential difference	volt	V	$J\ A^{-1}\ s^{-1}$
pressure	pascal	Pa	$N\ m^{-2}$
electric resistance	ohm	Ω	$V\ A^{-1}$
electric capacitance	farad	F	$A\ s\ V^{-1}$
magnetic flux	weber	Wb	$V\ s$
inductance	henry	H	$V\ s\ A^{-1}$
magnetic flux density	tesla	T	$V\ s\ m^{-2}$
luminous flux	lumen	lm	$cd\ sr$
illumination	lux	lx	$cd\ sr\ m^{-2}$
frequency	hertz	Hz	$cycle\ s^{-1}$

Conversion factors

Type	*Name*	*Symbol*	*Approximate value*
energy	electron volt	eV	1.6021×10^{-19} J
energy	erg	erg	10^{-7} J (exact)
energy	calorie (thermochemical)	cal	4.184 J
energy	British thermal unit	Btu	1055.06 J
energy	Q	Q	10^{18} Btu (exact)
energy	quad	q	10^{15} Btu (exact)
energy	tons oil equivalent	toe	4.19×10^{10} J
energy	barrels oil equivalent	bbl	5.74×10^{9} J
energy	tons coal equivalent	tce	2.93×10^{10} J
energy	m^3 of natural gas		3.4×10^{7} J
energy	litre of gasoline		3.2×10^{7} J
energy	kilowatthour	kWh	3.6×10^{6} J
power	horsepower	hp	745.7 W
power	kWh per year	kWh/y	0.114 W
radioactivity	curie	Ci	3.7×10^{8} s^{-1}
radioactivity	becqerel	Bq	1 s^{-1}
radiation dose	rad	rad	10^{-2} J kg^{-1}
radiation dose	gray	Gy	J kg^{-1}
dose equivalent	rem	rem	10^{-2} J kg^{-1}
dose equivalent	sievert	Sv	J kg^{-1}
temperature	degree Celsius	°C	K – 273.15
temperature	degree Fahrenheit	°F	9/5 C+ 32
time	minute	m	60 s (exact)
time	hour	h	3600 s (exact)
time	year	y	8760 h
pressure	atmosphere	atm	1.013×10^{5} Pa
pressure	bar	bar	10^{5} Pa
mass	pound	lb	0.4536 kg
mass	ounce	oz	0.02835 kg
length	foot	ft	0.3048 m
length	mile (statute)	mi	1609 m
volume	litre	l	10^{-3} m^3
volume	gallon (US)		3.785×10^{-3} m^3