Hydrogen and Fuel Cells

Emerging technologies and applications

Other books by the author:

A History of Energy. Northern Europe from the Stone Age to the Present Day, 2011

Life-Cycle Analysis of Energy Systems: From Methodology to Applications, 2011.

Renewable Energy Reference Book Set (ed., 4 volumes of reprints), 2010

Renewable Energy –physics, engineering, environmental impacts, economics and planning, 4th edition, 2010 (Previous editions 1979, 2000 and 2004)

Renewable Energy Focus Handbook (with Breeze, Storvick, Yang, Rosa, Gupta, Doble, Maegaard, Pistoia and Kalogirou), 2009

Renewable Energy Conversion, Transmission and Storage, 2007

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Blegdamsvej 17, 1989

Superstrenge, 1987

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Fundamentals of Energy Storage (with Jensen), 1984

Energi for fremtiden (with Hvelplund, Illum, Jensen, Meyer and Nørgård), 1983

Energikriser og Udviklingsperspektiver (with Danielsen), 1983

Skitse til alternativ energiplan for Danmark (with Blegaa, Hvelplund, Jensen, Josephsen, Linderoth, Meyer and Balling), 1976

Music across times and fences–a book project in progress

More information on the author’s work is available at
http://energy.ruc.dk

Hydrogen and Fuel Cells

Emerging technologies and applications

Second Edition

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AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Academic Press is an imprint of Elsevier

Academic Press is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA

Library of Congress Cataloging-in-Publication Data
Sørensen, Bent, 1941-
Hydrogen and fuel cells: emerging technologies and applications hydrogen and fuel cells emerging technologies and applications / Bent Sørensen. -- 2nd ed.
p. cm.
ISBN: 978-0-12-387709-3
1. Hydrogen as fuel. 2. Fuel cells. I. Title.
TP359.H8S68 2011
621.31'2429--dc23
2011038769

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

For information on all Academic Press publications
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Typeset by author.

Printed in the United States of America
11 12 13 14 9 8 7 6 5 4 3 2 1

Preface

When the first edition of this book was written, there was an enthusiastic belief in the fuel cell and automobile industry that hydrogen vehicles would start to penetrate the market already in the first decade of the 21st century. This did not happen–for several reasons. The target specifications of 5-year fuel cell life and a cost under US$10 000 for an array with 1 kW average production were not too ambitious but still proved unreachable in the short term. A 5-year fuel cell lifetime is really on the low side, as cars currently approach operational lifetimes of 20 years, spurred by concerns for environmental impact during manufacture and resource stewardship. The 5-year fuel cell would have to be replaced three times during the lifetime of the vehicle, greatly augmenting the real cost, considering both equipment and replacement work. Another factor in the present market evaluation is the strength of the competition, offered by electric cars, hybrids combining batteries with oil-based fuels, and new generations of biofuels for the transportation sector. A careful appraisal of the merits of these alternatives relative to a hydrogen-fuelled transportation sector is undertaken in this new edition, along with a similar assessment of other areas of fuel cell uses.

For the researchers and manufacturers of fuel cells and related equipment, the temporal setback is not uniquely negative, as it provides an opportunity for rethinking the basic design concepts and developing several new ideas that perhaps were left unprocessed during the feverish rush to reach the early goals. Fortunately, the relative absence of hydrogen-vehicle stories from the news headlines has not slowed down the pace of science and engineering efforts, and this edition has many new, exciting advances to present and discuss. This goes both for the basic understanding of electrochemical processes inside the cell structures, and for the development of vehicle and system concepts, with a promise to overcome the many challenges posed by the introduction of new technology that in several ways is departing from the traditional operational behaviour and existing infrastructure layout.

This edition has expanded the coverage of hybrid systems, considering the advantages of combining battery and fuel cell technologies, rather than seeing them as mutually exclusive competitors. It is demonstrated that suitable combinations of either plug-in hybrids between fuel cell and advanced battery use, or stand-alone concepts, can achieve performance and economic viability not obtainable for pure fuel cell or pure battery vehicles. The fuel cell R&D community has attracted some of the most skilled scientists and engineers, and it is those people I hope to inspire further by this volume.

Bent Sørensen
Gilleleje, June 2011
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Preface to first edition

These years, many scientists and engineers move into the field of hydrogen and fuel cells because it is exciting and well funded. The aim is to transform the way energy is delivered and used over the coming years, with major changes in technologies for production, distribution and conversion, as a response to political instability of many oil-producing countries, uncertainty about resources and increasing concerns over environmental effects.

This book is written to the many newcomers to the field, to students at the increasing number of courses given in the subject and to well-established scientists and developers who already have in-depth knowledge in certain sub-fields but like to keep informed about the entire field from technology to policy considerations, economical and environmental assessment. I aim to provide an introduction to people with general science background, but no special hydrogen and fuel cell experience, and also to give an up-to-date account of the frontiers of research and development to readers who need to be able to connect the emerging terminology to the concepts of conventional fields of science.

At the end of each chapter are problems and discussion topics, several of which can be used for problem-oriented mini-projects.

In fact, the pace of knowledge development in the field of hydrogen and fuel cells is so rapid that about half the content of this book is based on material less than a year old (as of the time of writing) and often not even published or found in the "in press" basket of the scientific journal publishers. It has been a pleasure to work with this extremely fresh material from the desks of my colleagues. New techniques have enabled specific investigations to be performed along with the book writing that would have been impossible 5-10 years ago.

To achieve the aim stated above I try to avoid specialist jargon or, if it is important, to define and explain the special terminology that the reader will meet in the latest scientific journals, providing the connection back to the concepts familiar to people with a physics, chemistry or biology background. The policy planner and assessor will similarly find the newest ideas and methods in these fields linked back to conventional economy and to environmental and planning sciences.

First of all, I want to convey the richness of the hydrogen and fuel cell fields and to present the challenges calling for a dedicated effort by the cream of human ingenuity, which is you, dear reader.

Bent Sørensen
Gilleleje, October 2004
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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}

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
amount[#]	mole	mol

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	$cycle\ s^{-1}$

[¤] 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.
[#] The amount containing as many particles as there are atoms in 0.012 kg ^{12}C.

Conversion factors

Type	*Name*	*Symbol*	*Approximate value*
energy	electon 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	kg of methane		6.13×10^{7} J
energy	m^3 of biogas		2.3×10^{7} J
energy	litre of gasoline		3.29×10^{7} J
energy	kg of gasoline		4.38×10^{7} J
energy	litre of diesel oil		3.59×10^{7} J
energy	kg of diesel oil/gasoil		4.27×10^{7} J
energy	m^3 of hydrogen at 1 atm		1.0×10^{7} J
energy	kg of hydrogen		1.2×10^{8} 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	min	60 s (exact)
time	hour	h	3600 s (exact)
time	year	y	8760 h

continued next page

Type	*Name*	*Symbol*	*Approximate value*
pressure	atmosphere	atm	1.013×10^5 Pa
pressure	bar	bar	10^5 Pa
pressure	pounds per square inch	psi	6890 Pa
mass	ton (metric)	t	10^3 kg
mass	pound	lb	0.4536 kg
mass	ounce	oz	0.02835 kg
length	Ångström	Å	10^{-10} m
length	inch	in	0.0254 m
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