Solar Hydrogen Generation

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Toward a Renewable Energy Future

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Dedication

Krishnan Rajeshwar

To the three girls in my life, Rohini, Reena, and Rebecca: I could not have done this without your love and support

Robert McConnell

To my wife Suzie Star whose love and support made this possible. To my children and especially my grandson Tharyn. My hope for them is to live in a cleaner world powered by renewable energy and hydrogen.

Stuart Licht

To my children: Reeva, Gadi, Ariel, Jacob and Dov; I hope to open a path to a sustainable energy future for them. To my wife Bregt, this is here because you are here.

Preface

This book examines ways to generate hydrogen from sunlight and water. It largely arose out of a desire to bring all the disparate ways to accomplish this goal within the confines of a single edited volume. Thus we are aware of many books and reports discussing the pros and cons of a hydrogen economy but none, that we are aware of, that focus on the science and technology of generating hydrogen from sunlight and water. While renewable hydrogen currently remains an elusive goal, at least from a cost perspective, the *scientific* principles behind its generation are well understood. Thus over and above reviewing this substantial fundamental database, part of the incentive for creating this book was to hopefully inspire future generations of scientists and engineers to respond to the grand challenge of translating the impressive laboratory advances and prototype demonstrations to a practical renewable energy economy. Much of this daunting hurdle has to do with optimizing the efficiency and hence the cost-effectiveness of hydrogen producing solar energy systems.

History certainly is on our side in meeting this challenge. Many early civilizations used the sun, water, and the wind to meet basic needs. Even geothermal heat was used by North American Indians some 10,000 years ago for cooking. The ancient Greeks used hydro power to grind flour and the Persians used windmills to pump water in the first millennium. The human race is very good at solving technological problems and we can certainly wean ourselves from fossil fuels if we collectively put our minds to it. But cost is certainly going to be a driver and no amount of civic sense is going to render the hydrogen economy practically realizable if a gallon of gasoline continues to be substantially cheaper than a kilogram of hydrogen. Unfortunately however we can only give short shrift to the issue of economics in this book because of the rapidly shifting landscape of assumptions that an evolving technology brings with it. Nonetheless, the concluding chapter of this book examines investments, levelized hydrogen prices, and fuel cycle greenhouse gas emissions of a centralized electrolytic hydrogen production and distribution system powered by photovoltaic electricity.

Another important and related topic, not specifically addressed in this book, concerns the issue of how to store hydrogen, especially in a mobile transportation application. We felt that this topic was specialized and wide ranging enough to warrant a separate volume to be created by scientists and engineers far more qualified and knowledgeable than us. While fuel cells are briefly introduced in Chapter 1, how hydrogen is to be utilized to generate power is again left to many other excellent treatises in the literature; some of these are cited in what follows.

Every effort was made to remove redundancy and add homogeneity to the material in this multi-author volume. Indeed, the more authoritative level of discussion afforded by having specialists write each chapter will have hopefully overridden any "rough edges" that remain from chapter to chapter. Undoubtedly, many flaws remain for which we as editors are wholly responsible; we would welcome feedback on these.

A project of this magnitude could not have been completed without the collective contributions of many people, some of whom we wish to acknowledge at this juncture. First, Ken Howell deserves special thanks for his many useful suggestions. His patience as this book production went through countless delays is also much appreciated. Don Gwinner, Al Hicks and their production team at NREL managed to create quality illustrations from the drawings and graphs (many in primitive form) that were furnished to them. Maria Gamboa is thanked for very capably doing the pre-print lay-out of the various manuscripts. Finally we offer simple thanks to our families for their love and support and for putting up with the many weekends away spent in putting this volume together.

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Maria L. Ghirardi is a Senior Scientist at NREL and a Research Associate Professor at the Colorado School of Mines. She has a B.S., an M.S. and a Ph.D degree in Comparative Biochemistry from the University of California at Berkeley and has extensive experience working with photosynthetic organisms. Her research at NREL involves photobiological H_2 production and covers metabolic, biochemical and genetic aspects of algal metabolism, generating over 60 articles and several patents.

Kevin W. Harrison is a Senior Engineer in the Electrical Systems Center at NREL. He received his Ph.D. at the University of North Dakota and leveraging management, automated equipment design and quality control experience, gained while working for Xerox Corporation, he joined NREL in 2006. At NREL he leads all aspects of the renewable hydrogen production task whose objective is to improve the efficiency and reduce the capital costs of a closely coupled wind to hydrogen demonstration project. Generally speaking his research interests are in reducing the environmental impact of the world's energy use by integrating and utilizing renewable energy for electricity and transportation fuels.

Johanna Ivy Levene is a Senior Chemical Applications Engineer at NREL. She specializes in the technical and economic analysis of electrolysis systems, and her current focus is the production of fuels from renewable resources. Prior to her work at NREL, Johanna has worked as a process control engineer, a database administrator, a systems administrator and a programmer. Results from her work have been published in Solar Today and Science.

Stuart Licht is a Program Director in the Chemistry Division of the National Science Foundation (NSF) and Professor of Chemistry at the University of Massachusetts, Boston. His research interests include solar and hydrogen energy, energy storage, unusual analytical methodologies, and fundamental physical chemistry. Prof. Licht received his doctorate in 1986 from the Weizmann Institute of Science, followed by a Postdoctoral Fellowship at MIT. In 1988 he became the first Carlson Professor of Chemistry at Clark University, and in 1995 a Gustella

Professor at the Technion Israel Institute of Science, in 2003 became Chair of the Department of Chemistry at the University of Massachusetts Boston, and in 2007 a Program Director at the NSF. He has contributed 270 peer reviewed papers and patents ranging from novel efficient solar semiconductor/electrochemical processes, to unusual batteries, to elucidation of complex equilibria and quantum electron correlation theory.

F. M. MacDonnell is Professor of Inorganic Chemistry at the University of Texas at Arlington (UTA). He received his PhD at Northwestern University in 1993. After a postdoctoral stint at the Chemistry Department of Harvard University, he joined the Chemistry and Biochemistry Department at UTA in 1995. His research interests are in the design of photocatalysts for light harvesting and energy conversion and has published over 100 articles in these areas.

Pin Ching Maness is a Senior Scientist at NREL. She received her Masters Degree in 1976 at Indiana State University, Terre Haute, IN. She worked as a Research Specialist at the University of California, Berkeley, CA from 1976 to 1980, before joining NREL in 1981. Her research interests are in studies of the physiology, biochemistry, and molecular biology of various biological H_2-production reactions in cyanobacteria, photosynthetic bacteria, and cellulolytic fermentative bacteria.

James M. Mason is Director of the Hydrogen Research Institute in Farmingdale, New York. He received his PhD at Cornell University in 1996. His research interests are the economic modelling of centralized hydrogen production and distribution systems using renewable energy sources.

Robert D. McConnell recently joined Amonix, Inc., a concentrator photovolatics (PV) company located in Torrance, CA as Director of Government Affairs and Contracts. He earned his PhD at Rutgers University in Solid State Physics following a Bachelor's degree in Physics at Reed College in Portland, Oregon. After a postdoctoral stint at the University of Montreal and employment at the research institute of the electric utility, Hydro Quebec, he joined NREL in 1978. He has authored numerous papers and edited or co-edited five books and chaired four international conferences on centrator PV. His technology interests include concentrator PV, future generation PV concepts, hydrogen, superconductivity, and wind energy. He has served as Chairman of the Energy Technology Division of the Electrochemical Society and is presently Convener of the international working group developing concentrator PV standards under the aegis of the International Electrotechnical Commission located in Geneva, Switzerland.

Daryl R. Myers is a Senior Scientist at NREl. In 1970 He received a Bachelor of Science in Applied Mathematics from the University of Colorado, Boulder, School of Engineering. Prior to joining NREL in 1978, he worked for four years at the Smithsonian Institution Radiation Biology Laboratory in Rockville Maryland, and is a Cold War veteran, serving as a Russian linguist in the United States Army from 1970 to 1974. He has over 32 years of experience in terrestrial broadband and spectral solar radiation physics, measurement instrumentation, metrology (calibration), and modelling radiative transfer through the atmosphere. Daryl is active in International Lighting Commission (CIE) Division 2 on Physical Measurement of Light and Radiation, the American Society for Testing and Materials (ASTM) committees E44 on Solar, Geothermal, and Other Alternative Energy Sources and G03 on Weathering and Durability, and the Council for Optical Radiation Measurements (CORM).

Krishnan Rajeshwar is a Distinguished Professor in the Department of Chemistry and Biochemistry and Associate Dean in the College of Science at the University of Texas at Arlington. He is the author of over 450 refereed publications, several invited reviews, book chapters, a monograph, and has edited books, special issues of journals, and conference proceedings in the areas of materials chemistry, solar energy conversion, and environmental electrochemistry. Dr. Rajeshwar is the Editor of the Electrochemical Society Interface magazine and is on the Editorial Advisory Board of the Journal of Applied Electrochemistry. Dr. Rajeshwar has won many Society and University awards and is a Fellow of the Electrochemical Society.

Michael Seibert is a Fellow at the National Renewable Energy Laboratory in Golden, CO, USA. He received his Ph.D. in the Johnson Research Foundation at the University of Pennsylvania and then worked at GTE Laboratories before joining NREL (formerly the Solar Energy Research Institute) in 1977. His research has resulted in over 180 publications and several patents in the areas of materials development for electronic microcircuits, primary processes of bacterial and plant photosynthesis, cryopreservation and photomorphogenesis of plant tissue culture, water oxidation by photosystem II in plants and algae, microbial H_2 production, hydrogenase structure and function, genomics of Chlamydomonas, and computational approaches for improving H_2 metabolism in algae. He also holds a concurrent position as Research Professor at the Colorado School of Mines and is a Fellow of the AAAS.

Ken Zweibel is President of PrimeStar Solar, a CdTe PV company located in Colorado, USA. He graduated in Physics from the University of Chicago in 1970. He was employed for 27 years at SERI and then NREL in Golden, CO, where he worked on the development of CdTe, copper indium diselenide, and amorphous and thin film silicon. When he left in December 2006, he was manager of the Thin Film PV Partnership Program. He has published numerous papers and articles, and two books on PV, the most recent being, “Harnessing Solar Power: The PV Challenge.” Besides the success of PrimeStar Solar, he is interested in solar policy and solutions to climate change and rising energy prices.