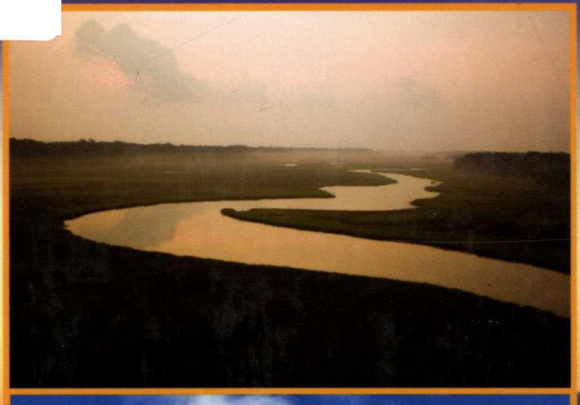
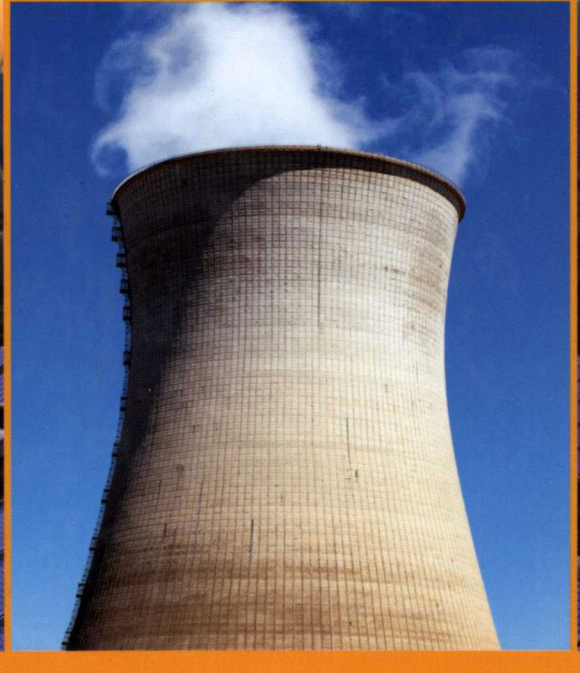
SECOND EDITION

Energy Systems ENGINEERING

Evaluation and Implementation





FRANCIS M. VANEK | LOUIS D. ALBRIGHT | LARGUS T. ANGENENT

Mc Graw Hill

Energy Systems Engineering

Evaluation and Implementation

Francis M. Vanek
Louis D. Albright
Largus T. Angenent

Second Edition

New York Chicago San Francisco
Lisbon London Madrid Mexico City
Milan New Delhi San Juan
Seoul Singapore Sydney Toronto

The McGraw-Hill Companies

Library of Congress Cataloging-in-Publication Data

Vanek, Francis M.
Energy systems engineering : evaluation and implementation / Francis M. Vanek, Louis D. Albright, Largus T. Angenent.—2nd ed.
p. cm.
ISBN 978-0-07-178778-9 (hardback)
1. Power (Mechanics) 2. Energy conservation. I. Albright, Louis D. II. Angenent, Largus T. III. Title.
TJ163.9.V36 2012
621.4—dc23

2011046163

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Energy Systems Engineering: Evaluation and Implementation, Second Edition

1 2 3 4 5 6 7 8 9 0 DOC/DOC 1 9 8 7 6 5 4 3 2

ISBN 978-0-07-178778-9
MHID 0-07-178778-X

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Largus T. Angenent, PhD, is Professor of Biological and Environmental Engineering at Cornell University, where he specializes in waste-to-energy conversion technologies. He has edited the book, *Bioelectrochemical Systems: From Extracellular Electron Transfer to Biotechnological Application*.

To my wife, Catherine Johnson, to my parents,
Jaroslav and Wilda Vanek, and to my children,
Raymond and Mira Vanek-Johnson

—Francis M. Vanek

To my wife and partner in life, Marilyn Albright

—Louis D. Albright

To my wife and son, Ruth Ley and Miles Ley Angenent

—Largus T. Angenent

Preface

The goal of this book is to provide both professional engineers and engineering students interested in energy systems with essential knowledge of major energy technologies, including how they work, how they are quantitatively evaluated, what they cost, and what is their benefit or impact on the natural environment. A second goal is to provide the reader with an overview of the context within which these systems are being implemented and updated today and into the future. Perhaps at no time in recent history has society faced such challenges in the energy field: the yearning to provide a better quality of life to all people, especially those in the more impoverished countries, coupled with the twin challenges of a changing energy resource base and the effects of climate change due to increased concentration of CO_2 in the atmosphere. Energy systems engineers from many disciplines, as well as nonengineers in related fields, will serve at the forefront of meeting these challenges.

As we updated the book from the first edition (edited in 2007 and published in 2008) into the second, the routine process of updating figures on CO_2 emissions and on the installation of renewable energy capacity highlighted both the challenge and the opportunity for the energy field around the world. Figure 4-3 in Chap. 4 gives world emissions of carbon from fossil fuel use, which in 2004 stood at 7.6 gigatonnes of carbon equivalent. Figure 4-3 in the current version of the book gives emissions for 2008 (the most recent year available from the U.S. Carbon Dioxide Information and Analysis Center) at 8.8 gigatonnes—an increase of 1.2 gigatonnes in the annual emissions rate in just four years. Not only does this increase represent the growing challenge of meeting energy needs without increasing atmospheric CO_2, but the increased emissions also symbolize newly added energy consuming devices, ranging from large power plants to small individual private vehicles, for which populations will expect continued access to energy supplies in the years going forward. On a more positive note, we have documented the many-fold increase in the installed capacity of solar and wind photovoltaic capacity around the world in Chaps. 10 and 13—637% for solar and 231% for wind from 2005 to 2010, measured in total installed gigawatts—suggesting that individuals, businesses, and governments are beginning to embrace this challenge.

Turning from motivation to content, chapter topics are chosen in the first part of the book to provide key background for the analysis of energy systems, and in the second part to give a representative view of the energy field across a broad spectrum of possible approaches to meeting energy needs. In Chaps. 1 to 3, we present tools for understanding energy systems, including a discussion of sustainable development, a systems approach to energy, and economic tools for evaluating energy systems as investments. In

Chaps. 4 and 5, we consider climate change and fossil fuel availability, two key factors that will shape the direction of energy systems in the twenty-first century. Chapters 6 through 14 present a range of technologies for generating energy for stationary applications, including fossil fuel combustion, carbon sequestration, nuclear energy, solar energy, wind energy, and biological energy (the last of these being newly added in the second edition). Chapters 15 and 16 turn to energy conversion for use in transportation systems, and Chap. 17 provides a brief overview of some emerging technologies not previously covered, as well as the conclusions for the book.

The contents of the book assume a standard undergraduate engineering background, or equivalent, in physics, chemistry, mathematics, and thermodynamics, as well as a basic introduction to statistics, fluid mechanics, and heat transfer. Each technology area is introduced from first principles, and no previous knowledge of the specific technologies is assumed.

This book originated in two courses taught at Cornell University, one in the School of Mechanical and Aerospace Engineering entitled "Future Energy Systems," and the other in the Department of Biological and Environmental Engineering entitled "Renewable Energy Systems." In addition, a third course, "Civil Infrastructure Systems" taught in the School of Civil & Environmental Engineering, influenced the writing of passages on sustainable development and systems engineering. Energy system concepts, example problems, and end-of-chapter exercises have been developed through introduction in the classroom. In both courses, we have focused on solar and wind energy systems, so we have also placed a special emphasis on these two fields in this book. Interest in solar and wind energy is growing rapidly at the present time, but information about these fields may not be as accessible to some engineers, so we aim to provide a useful service by giving them extensive treatment in Chaps. 9 through 13.

Presentation of technical content in the book adheres to several premises for energy systems engineering that are independent of the technologies themselves. The first is that *energy systems choices should be technology-neutral.* No energy system is perfect, and every system has a range of advantages and disadvantages. Therefore, to the extent possible, the choice of any system should be based on choosing criteria first and then finding a system, or mixture of systems, that best meets those criteria, rather than preordaining that one type of system or another be chosen.

A second premise is that *there is value to a portfolio approach to energy options.* All the energy pathways described in this book are, to varying degrees, subject to uncertainty over both the short and long term, in terms of cost, availability, and reliability. There is therefore value in developing diversity in energy options so that in the future we are not vulnerable to the disadvantages of any one technology. Also, given the global demand for energy that is anticipated in the twenty-first century, having multiple sources of energy will allow us to add capacity more quickly when it is needed while still striving to meet our environmental obligations to present and future generations.

A third premise is that *where long-term technologies will take time to develop fully, there is value to developing "bridge" technologies for the short- to medium term.* Some of the technologies presented in this book eliminate harmful emissions or use only renewable resources, but are not yet reliable or cost-competitive enough to enter the market in a large-scale way. In this situation, there is value to bridge technologies that are cost-effective now and also reduce nonrenewable resource consumption or CO_2 emissions, even if they do not eliminate them entirely. Typically, these technologies consume fossil

fuels but are more efficient or have higher utilization, so that they deliver more energy service per unit of resource consumed or CO_2 emitted.

Although the book is written by American authors in the context of the U.S. energy system, we maintain an international focus. This is important because of the increasingly global nature of the energy industry, in terms of both the resource base and also the transfer of technology between countries. We hope that non-U.S. readers of the book will find the material accessible, and that U.S. readers can apply the content to energy projects in other countries, and also to understanding the energy situation around the world. For simplicity, all costs are given in dollars; however, other world currencies can of course be substituted into equations dealing with financial management.

Both a systems approach and an engineering economics approach to designing and costing projects are emphasized. The use of good systems engineering techniques, such as the systematic consideration of the project scope, evaluation of tradeoffs between competing criteria, and consideration of project life-cycle cost and energy consumption, can deliver more successful projects. Consideration of cost and revenues from a project, as well as technical efficiency, helps us to better understand the profitability of a project.

For the purposes of cost analysis, approximate prices for the cost of energy resources and the purchase of energy conversion equipment have been introduced in places at their appropriate value. These values are intended to give the reader a general sense of the financial dimensions of a technology, for example, approximately what proportion of an energy technology's life-cycle cost is spent on fuel versus capital or nonfuel operating costs. Note, however, that theses values should not be used as a basis for detailed decision making about the viability of a project, since up-to-date costs for specific regions are the required source. It is especially important to find up-to-date numbers for one's particular project of interest because of the volatility in both energy and raw material prices that has developed since 2004 or 2005. With rapid economic growth in the two largest countries by population in the world, namely China and India, there is burgeoning demand not only for energy commodities but also for materials such as steel or copper that are essential for fabricating energy conversion technologies. This affects not only operating costs of fossil-fuel-driven energy systems but also capital cost of both renewable and nonrenewable energy systems. As a result, the cost of virtually all energy system options has risen markedly in the past few years.

Earlier books on energy systems have placed an emphasis on equipment to prevent release of air pollutants such as scrubbers or catalytic converters. As presented in the body of the book, emerging technologies that use new energy resources and eliminate CO_2 emissions also tend to eliminate emissions of harmful air pollutants, so air quality as a separate objective is deemphasized in this book. In some cases, it appears instead as a constraint on energy systems development: where air quality problems may be aggravated by emerging technologies that are beneficial for other objectives but increase emissions of air pollutants, regulations or targets related to air quality may restrict our ability to use that technology.

In conclusion, we offer a word of "truth in advertising" about the contents of the book: it provides some answers, and also many unanswered questions. It is humbling to write a book about energy systems, just as it is to teach a course or give a presentation about them: one ends up realizing that it is a very challenging area, and that many aspects of future solutions remain hidden from us at present. We hope that in publishing this book we have helped to answer some of the questions about energy systems where possible, and, where not, posed them in such a way that the act of exploring them will

move the field forward. The extent and complexity of the challenge may seem daunting at times, yet there are and will be great opportunities for energy professionals, both now and in the future. We wish each of you success in your part of this great endeavor.

Note to Instructors

If you are an instructor of an energy systems course using this book as a textbook, please be aware that the end-of-chapter exercises included in the book are a subset of a larger collection of homework and exam problems, instructor's manual, spreadsheet solutions, PowerPoint slides, and computer scripts. Please visit www.mhprofessional.com/energysystemsengineering for information about how you can download these materials to assist your teaching.

Acknowledgments

There were many, many people whose support made such a difference in the writing of this book. I would first like to thank my family, including my wife Catherine Johnson, my parents Jaroslav and Wilda Vanek, and my children Ray and Mira, for their patience as I spent so many hours on the book, for their encouragement, and for their curiosity about the topic, which affects both young and old alike.

Within the Sibley School of Mechanical and Aerospace Engineering at Cornell, I would like to thank Prof. Zellman Warhaft who taught MAE 501 "Future Energy Systems" before I did, and who helped me to establish my teaching the course the first year and more recently with various questions about the textbook. I would also like to thank Profs. Juan Abello, Michel Louge, Betta Fisher, Sid Leibovich, Lance Collins, and other members of the Sibley School faculty for their support for my teaching the course between 2004 and 2006, and to June Meyermann and Bev Gedvillas for clerical support. Thanks also to several students who worked with me on the course as graders and proofreaders, including Tim Fu, Adam Fox, Julia Sohnen, Rob Young, and Cory Emil, and an additional thank-you to all the rest of the students whose input and discussion made teaching the course so interesting and rewarding. We had the good fortune of hosting a number of excellent guest speakers during the course whose input benefited the book as well, including Dr. Jim Lyons, PhD, from the General Electric wind energy program in Niskayuna, NY; Dr. Gay Cannough, PhD, from ETM Solar Works of Endicott, NY; Sandy Butterfield, PE, from the National Renewable Energy Laboratories in Golden, CO; and Tom Ruscitti from General Motors' Honeoye Falls, NY, fuel cell R&D facility. My thanks to all of these individuals as well.

Outside of the Sibley School, I would like to thank Profs. Mark Turnquist and Linda Nozick of the School of Civil & Environmental Engineering at Cornell for input on various issues related to transportation, nuclear energy, and systems engineering. From the Department of Biological and Environmental Engineering, I would also like to thank Profs. Norm Scott and my coauthor, Prof. Louis Albright, for their input into the "Future Energy Systems" course which helped to guide the development of the curriculum.

Many thanks are due to the various colleagues who helped with the production of the book, especially to Ellie Weyer who worked closely with me on proofreading many of the chapters and providing technical input and feedback. Additional thanks to Greg Pitts, Carol Henderson, Rob Young, Phil Glaser, my mother Wilda Vanek (PhD in history from Harvard University, 1961), and my wife Catherine Johnson (MFA in film and media studies from Temple University, 1999) for proofreading help and production assistance. Thanks also to everyone at McGraw-Hill who collaborated with me during

this project, especially Larry Hager, David Zielonka, and Rick Ruzycka for the first edition, as well as Mike Penn and David Fogarty for the second edition, all of whom worked tirelessly to answer questions, provide information, and in general, help the writing process to go smoothly. Thanks as well to Rohini Deb and everyone at Cenveo Publisher Services for their efforts. A general thank-you as well to all the individuals who provided images and figures for reprinting, as credited throughout the book.

The contents of this book benefited in a number of places from research collaboration with a number of colleagues. I would like to especially thank Prof. Emeritus Edward Morlok for his collaboration with me on the study of freight transportation energy use presented in Chap. 14, and moreover for giving my start in the area of sustainable energy systems during the time that he was my dissertation supervisor in Systems Engineering at the University of Pennsylvania from 1993 to 1998. I would also like to thank my colleagues at Taitem Engineering (Technology as if the Earth Mattered) of Ithaca, especially Ian Shapiro, PE, Lou Vogel, PE, and Susan Galbraith, for their work with me on combined heat and power systems, and on alternative fuel vehicles. Thanks are due to James Campbell and Prof. Alan McKinnon of the Logistics Research Centre at Heriot-Watt University, Edinburgh, Scotland for their collaboration on the study of energy use in freight and logistics in the United Kingdom. Thanks to the students who worked on the hydrogen feasibility M.Eng project from 2003 to 2005, especially Julien Pestiaux, Audun Ingvarsson, and Jon Leisner. Thanks also to the students who worked on the wind energy feasibility M.Eng project in 2009 and 2010, especially Christine Acker, Kim Campbell, Stephen Clark, Jesse Negherbon, Alex Hernandez, Christina Hoerig, Happiness Munedzimwe, Reginald Preston, Karl Smolenski, and Jun Wan. Lastly, thanks to students who worked on the alternative fuel vehicle M.Eng projects in 2009 and 2010, including Auret Basson, Mert Berberoglu, Ryan Cummiskey, Gurkan Gunay, Sara Lachapelle, Torsten Steinbach, Jackson Wang, Alice Yu, and Naji Zogaib.

Special thanks to reviewers of specific chapters in the book as follows: Prof. Emeritus Jaroslav Vanek, Department of Economics in the College of Arts and Sciences, Cornell University for reviewing Chap. 3 on economic tools (thanks dad!); Dr. Rajesh Bhaskaran of the Sibley School for reviewing Chap. 4 on climate change; Prof. Dave Hammer, School of Electrical and Computer Engineering at Cornell for reviewing Chap. 8 on nuclear energy systems; Paul Lyons, PE, of Zapotec Energy, Cambridge, MA, for reviewing Chap. 10 on photovoltaics; Howard Harrison, President of GTR Energy Ltd. of Oakville, Ontario, Canada and also Sandy Butterfield (introduced above) for reviewing Chap. 13 on wind energy systems; and Dr. John DeCicco of Environmental Defense in Dexter, MI, for reviewing Chap. 15 on transportation energy technologies. Thanks also to Rob Garrity, Principle of Finlo Energy Systems, for input on current conditions in the solar PV marketplace, Prof. Beth Clark, Department of Physics, Ithaca College, for providing information about the Ithaca College wind energy feasibility study referenced in Chap. 13, and to John Manning, PE, Principal of Earth Sensitive Solutions, LLC, for background on ground source heat pumps used in Chap. 17.

While revising the book into a second edition, we had the benefit of input from a number of faculty members from other universities and colleges who offered feedback from their experience with using the book in the classroom. This list includes Prof. Matthew Barth from U.C. Riverside, Prof. C.S. Chen from Miami University Ohio, Prof. David Dillard from Virginia Tech, Prof. Kerry Patterson from Lipscomb University, and Prof. Mark Schumack from University of Detroit Mercy. While contributions to the book in terms of chapter reviews, technical input to chapter content, and feedback from

instructors are gratefully acknowledged, responsibility for any and all errors rests with the authors.

Lastly, thanks to all faculty, students, and friends who expressed support and encouragement during the project—it has always been appreciated—and thanks to anyone else who deserves mention but whom I may have overlooked.

—Francis M. Vanek

No book such as this should be attempted without the benefit of first teaching the material to interested and interactive students. The students over the years who questioned, contributed, and succeeded (yes, especially those in the earlier days of my renewable energy systems course when it met, for a decade, three times a week at 8 a.m.) have helped me immeasurably in understanding the material of this book and how it can be presented. Without you, my part of this book would never have been possible and life would have been much less enjoyable.

—Louis D. Albright

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