Wiley Series in Environmentally Conscious Engineering

ENVIRONMENTALLY CONSCIOUS
Alternative Energy Production

MYER KUTZ

Environmentally Conscious Alternative Energy Production

Edited by
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John Wiley & Sons, Inc.

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Wiley Bicentennial Logo: Richard J. Pacifico

Library of Congress Cataloging-in-Publication Data:

Environmentally conscious alternative energy production / edited by Myer Kutz.
p. cm.
Includes index.
ISBN 978-0-471-73911-1 (cloth)
1. Electric power production. 2. Electric power production–Environmental aspects. 3. Renewable energy sources. 4. Global warming–Prevention. 5. Sustainable engineering. I. Kutz, Myer.
TK1005.E58 2007
621.31–dc22

2007006006

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Environmentally Conscious Alternative Energy Production

To Bob and Linda, to Bob and Nadine, and to Linda

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Preface

Many readers will approach the books in the **Wiley Series in Environmentally Conscious Engineering** with some degree of familiarity with, knowledge about, or even expertise in, one or more of a range of environmental issues, such as climate change, pollution, and waste. Such capabilities may be useful for readers of this series, but they aren't strictly necessary, for the purpose of this series is not to help engineering practitioners and managers deal with the *effects* of man-induced environmental change. Nor is it to argue about whether such effects degrade the environment only marginally or to such an extent that civilization, as we know it, is in peril, or that any effects are nothing more than a scientific-establishment-and-media-driven hoax and can be safely ignored. (Authors of a plethora of books, even including fiction, and an endless list of articles in scientific and technical journals, have weighed in on these matters, of course.) On the other hand, this series of engineering books does take as a given that the overwhelming majority in the scientific community is correct, and that the future of civilization depends on minimizing environmental damage from industrial, as well as personal, activities. At the same time, the series does not advocate solutions that emphasize only curtailing or cutting back on these activities. Instead, its purpose is to exhort and enable engineering practitioners and managers to reduce environmental impacts, to engage, in other words, in Environmentally Conscious Engineering, a catalog of practical technologies and techniques that can improve or modify just about anything engineers do, whether they are involved in designing something, making something, obtaining or manufacturing materials and chemicals with which to make something, generating power, or transporting people and freight.

Increasingly, engineering practitioners and managers need to know how to respond to challenges of integrating environmentally conscious technologies, techniques, strategies, and objectives into their daily work, and, thereby, find opportunities to lower costs and increase profits while managing to limit environmental impacts. Engineering practitioners and managers also increasingly face challenges in complying with changing environmental laws. So companies seeking a competitive advantage and better bottom lines are employing environmentally responsible design and production methods to meet the demands of their stakeholders, who now include not only owners and stockholders, but also customers, regulators, employees, and the larger, even worldwide community.

Engineering professionals need references that go far beyond traditional primers that cover only regulatory compliance. They need integrated approaches centered on innovative methods and trends in design and manufacturing that help them focus on using environmentally friendly processes and creating green products. They need resources that help them participate in strategies for designing environmentally responsible products and methods, resources that provide a foundation for understanding and implementing principles of environmentally conscious engineering.

To help engineering practitioners and managers meet these needs, I envisioned a flexibly connected series of edited books, each devoted to a broad topic under the umbrella of Environmentally Conscious Engineering. The series started with three volumes that are closely linked—environmentally conscious mechanical design, environmentally conscious manufacturing, and environmentally conscious materials and chemicals processing. The series continues with this fourth volume, **Environmentally Conscious Alternative Energy Production**, and thereby turns toward a subject area more commonly associated among the general public with the future of the earth's climate and ramifications of climate changes while, of course, being of intense interest to a wide variety of engineers, scientists, and public policy makers. The topic carries additional weight because of the supply of fossil fuels, which generate the bulk of the world's power needs, is limited (although there is not consensus about the extent of the future supply), because major petroleum reserves are located in countries where there is political instability or the threat of it, and where, therefore, industrial nations believe they must retain a military presence to guarantee the future availability of oil to their economies. (The series will continue with a fifth volume on **Environmentally Conscious Transportation**, a sixth on **Environmentally Conscious Materials Handling**, plus a seventh on **Environmentally Conscious Fossil Energy Production**. The fourth through seventh volumes will be loosely linked, much like the first three design–manufacturing–materials volumes are. For example, a chapter on alternative fuels will appear in the transportation volumes, although it could fit quite well in the alternative energy volume.)

While many of the chapters in the books in the series are accessible to lay readers, the primary intended audience is practicing engineers and upper-level students in a number of areas—mechanical, chemical, industrial, manufacturing, plant, electrical, and environmental—as well as engineering managers. This audience is broad and multidisciplinary. In the case of power generation, an electrical or environmental engineer may be concerned with improving the performance of a plant that uses a particular technology, or an industrial or plant engineer may be involved in selecting a power generating technology for a new facility, and these practitioners be found in a wide a variety of organizations, including commercial facilities, institutions of higher learning, and consulting firms, as well as federal, state and local government agencies. A volume that covers a broad range of technologies is useful because every practitioner, researcher, and bureaucrat can't be an expert on every topic and may need to read an authoritative summary on a professional level of a subject that he or she is not intimately familiar with but may need to know about for a number of different reasons.

The Wiley Series in Environmentally Conscious Engineering is comprised of practical references for engineers who are seeking to answer a question, solve a problem, reduce a cost, or improve a system or facility. These books are not a research monographs. The purpose is to show readers what options are available in a particular situation and which option they might choose to solve problems at hand. I want these books to serve as a source of practical advice to readers. I would like them to be the first information resource a practicing engineer reaches for when faced with a new problem or opportunity—a place to turn to even before turning to other print sources, even any officially sanctioned ones, or to sites on the Internet. So the books have to be more than references or collections of background readings. In each chapter, readers should feel that they are in the hands of an experienced consultant who is providing sensible advice that can lead to beneficial action and results.

This fourth volume in the series, **Environmentally Conscious Alternative Energy Production**, offers technical descriptions of a number of different technologies so that readers may be able to not only evaluate them on their own merits, but also compare and contrast them, and, ultimately, choose from among them for a particular purpose. After an opening chapter that compares power generation technologies on an economic basis, the book presents chapters on the technologies, including solar, fuel cells, geothermal, wind, cogeneration, hydrogen, and coal, and closes with a chapter on using waste heat from power plants. Some experts may descry the lack of a chapter on nuclear power, but I excluded this technology because of uncertainty about environmentally friendly and politically palatable schemes for disposing of spent fuel rods, as well as the potential for mischief in diverting nuclear fuel to weaponry.

I asked the contributors, all of whom are located in North America, to provide short statements about the contents of their chapters and why the chapters are important. Here are their responses:

Todd Nemec (GE Energy, Schenectady, NY), who contributed the opening chapter on **Economic Comparisons of Power Generation Technologies**, writes, "this chapter discusses the components and applicability of Cost of Electricity models in addition to economic aspects of emissions regulation, nondispatchable (intermittent) generation, and cogeneration. From technology development to product design, applications/siting optimization, and operations, economic models are integral to environmentally friendly power-generation growth—as the basis for good decision making and increased customer value. Many environmentally friendly technologies have inherently low power density, affecting cost competitiveness, siting, and fuel availability/market viability concerns that aren't as significant in high power density thermal powerplants. On the opposite side, however, emissions control mechanisms such as cap and trade are efficient at delivering emissions control technologies to thermal plants as well as unlocking additional environmental value for emerging renewable platforms. High fidelity economic models and their effective use through technology selection, design, and applications will give newer, cleaner technologies the greatest chance to succeed.

The chapter on **Solar Energy Applications** by Jan F. Kreider (University of Colorado in Boulder, Colorado) has appeared in all three editions of the *Mechanical Engineers' Handbook*, published by Wiley. He writes, "Solar energy represents the most basic of renewable energies with its source both permanent and continuous. With terrestrial levels sufficient to supply all of the earth's energy needs, it will be the ultimate energy source after the fossil fuel era ends on earth. This chapter describes the resource and several practical methods for producing useful energy—including thermal energy and electricity—with engineering details."

Matthew W. Mensch (The Pennsylvania State University in University Park, Pennsylvania), who contributed the chapter on **Fuel Cells** (this chapter also appears in the *Mechanical Engineers' Handbook*, Third Edition), writes, "In the coming decades, mounting pressure from environmental, security, and economic concerns will usher into the mainstream a new age of power generation from alternative sources, gradually usurping traditional sources of energy from non-renewable fossil based fuels. While the specific future outcomes of each particular possibility are impossible to predict, a global future including use of fuel cells in many applications is now all but assured. Fuel cells will almost certainly play a key role in the future energy grid, potentially ending the century long reign of the internal combustion engine in transportation applications, supplanting rechargeable batteries for many portable applications such as cell phones and laptop computers, and providing reliable electricity and heat for stationary applications. The science of fuel cells is both fascinating and highly multidisciplinary, involving nearly all fields of engineering. There are different types of fuel cell systems, which operate under a wide range of conditions with highly varied materials, myriad system configurations, and a host of technical and economic challenges. Each particular system has fundamental advantages and limitations, which must be addressed before ubiquitous implementation can be achieved. This chapter describes the basic operating principles of each of the major fuel cell systems being developed today, and addresses the fundamental advantages and challenges remaining to be overcome. I hope this introduction can serve as a valuable starting point for engineers and managers looking for a technical overview of the potential for fuel cells as serious power generation sources."

Peter Blair (The National Academy of Sciences in Washington, DC), who contributed the chapter on **Geothermal Resources and Technology: An Introduction** (this chapter also appears in the *Mechanical Engineers' Handbook*, Third Edition), writes, "Geothermal energy, or heat extracted from the earth's interior, is often included in the portfolio of renewable energy sources that are considered to be more benign environmentally than fossil and nuclear energy sources. Geothermal energy has been used for centuries for cooking and heating and since the early 1900s for producing electric power. In its most economically attractive form, in the geologically rare situation when a very hot geothermal heat source and a water aquifer coincide, the resulting dry steam can be used to run a turbine directly for electric power generation. More commonly, but still relatively unusual geologically, hot water can be drawn from a geologic formation and its heat extracted into a secondary working fluid to once again produce electric power or to provide process heat. When geothermal resources are accessible they can be very economical and environmentally attractive alternatives to conventional energy sources. This chapter surveys the types of geothermal resources present around the world and the range of energy conversion technologies that can be employed in direct use of geothermal heat, in electric power generation, and by geothermal heat pumps for utilizing low-grade geothermal heat."

Todd Nemec (GE Power Systems in Schenectady, New York), who contributed the chapter, **Wind Turbines**, writes, "Wind turbine design carries many of the fundamental complexities of designing aircraft for airline service. Like aircraft, a balanced and integrated wind turbine design requires significant understanding of markets, aerodynamics/aeroelasticity, extreme and fatigue loading, controls, weight, noise, assembly/inbound transportation, and economic efficiency. This chapter introduces readers to wind energy's recent market growth, first-principles energy formulas, and conceptual design tradeoffs. The turbine power curve and siting discussions are a starting point for effectively matching turbine and site selection. Much of wind energy's improved economics are due to advancements in system-level design, component technology, and applications understanding. Market factors, incentives, environmental regulation, along with power industry contributions—such as increased energy storage, greater thermal powerplant flexibility, growth of distributed grid systems, and improved transmission infrastructure will also enable wind energy to reach higher levels of market entitlement.

Jerald Caton (Texas A&M University in College Station, Texas), who contributed the chapter on **Cogeneration**, writes, "Cogeneration is a technology that maximizes the utilization of the available energy from the combustion of fuels. A cogeneration system produces electrical power as well as thermal energy such as heat or cooling. The major motivations for considering cogeneration systems are monetary savings, energy savings, and the potential for lower emissions. Many facilities that have a need for electrical power and thermal energy are candidates for cogeneration. The technology for cogeneration systems is available and the concept is well developed. This chapter includes detailed discussions of the overall concept, descriptions of possible systems, a summary of relevant regulations, descriptions of economic evaluations, and comments on ownership and financing."

Elias K. Stefanokos (University of South Florida in Tampa, Florida), who contributed the chapter on **Hydrogen Energy** with Yogi Goswami, S. S. Srinivasan, and John T.Wolan, writes, "Fossil fuels are not renewable, they are limited in supply, their economic cost is continuously increasing, and their use is growing exponentially. Moreover, combustion of fossil fuels is causing global climate change and harming the environment in other ways as well, which points to the urgency of developing environmentally clean alternatives. Hydrogen is a good alternative to fossil fuels for the production, distribution and storage of energy. Automobiles can run on either hydrogen used as fuel in internal combustion engines or in fuel-cell cars or in hybrid configurations. Hydrogen is not an energy source but an energy carrier that holds tremendous potential to use renewable and clean energy options. It is not available in free form and must be dissociated from other molecules containing hydrogen such as natural gas or water. Once produced in free form it must be stored in a compressed or liquefied form, or in solid state materials. It is the purpose of this chapter to bring readers up to date on the state of the art and the obstacles that must be overcome to achieve cost effective production, storage and conversion of hydrogen."

James Butler (Dalhousie University in Halifax, Nova Scotia), who contributed the chapter on **Clean Power Generation from Coal** with Prabir Basu, writes, "Coal accounts for roughly 40% of the world's total electricity generating capacity and shows no signs of decreasing as emerging economies such as China and India, are fueling their rapid economic expansion with coal. With increased concern over global warming caused carbon dioxide and other harmful emissions of sulphur dioxide, nitrogen oxides and mercury from coal, there is a great deal of research and development taking place into new technologies that reduce the environmental impact of electricity generation from coal."

Herbert A. Hingley, III (University of Florida in Gainesville, Florida), who contributed the chapter on **Using Waste Heat from Power Plants**, writes, "This chapter discusses several examples of integrating power production with the utilization of the associated waste heat to accomplish some other function, such as space heating, domestic water heating, cooling, steam production or process heating. In addition to several domestic applications of combined heat and power, two new innovative systems for water purification and improved thermoelectric power production are reviewed. This chapter should be of importance to engineers and policy makers seeking innovative methods to better utilize our energy resources."

That ends the contributors' comments. I would like to express my heartfelt thanks to all of them for having taken the opportunity to work on this book. Their lives are terribly busy, and it is wonderful that they found the time to write thoughtful and complex chapters. I developed the book because I believed it could have a meaningful impact on the way many engineers approach their daily work, and I am gratified that the contributors thought enough of the idea that they were willing to participate in the project. Thanks also to my editor, Bob Argentieri, for his faith in the project from the outset. And a special note of thanks to my wife Arlene, whose constant support keeps me going.

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Contents

CHAPTER 1

ECONOMIC COMPARISONS OF POWER GENERATION TECHNOLOGIES

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1 INTRODUCTION

Like power generation engineering calculations, power generation economic comparisons rely heavily on mathematical models. When only one or two major plant characteristics are being compared, a simple two-or three-term equation may be enough to reasonably predict their economic differences. Comparing all plant characteristics effectively across multiple generation platforms, and within different power markets/utility networks, may require thousands of inputs using high-frequency data.

Real energy environments include diversity and interactions of many variables, including sources of revenue, fuel cost and availability, emissions requirements, economic incentives, risk, and both initial and recurring costs—including logistics, labor rates, and investor return, among others. System designers and purchasers have different data requirements with respect to building appropriate design or applications economic models. Most system designers, however, begin their calculations by looking at variables from the owners' perspective—either by comparing revenue-requirements for a given profit, or by using market revenue rates to calculate profit.

This chapter will also look at calculations from an owners' outlook—using both revenue requirements also called *levelized cost of electricity* (COE), and projected power sale prices—when calculating cogeneration economics.

2 MARKET GROWTH AND EMISSIONS

Worldwide, electricity demand is projected to grow at 2.7 percent per year between 2003 and 2030,[1] India and China are at the high end of projections, 4.6 percent and 4.8 percent annual growth rates, respectively, while Japan's demand is projected to grow the slowest, at 0.7 percent.[1] Share projections for the types of fuels are listed in Figure 1.

Within the thermal power-plant sector, emissions have improved significantly during the last few decades due to both increased technology and tighter regulations. Market-driven regulations, such as cap and trade systems, are a cost-effective means to reduce emissions on a total system basis, and are often used in conjunction with individual power-plant limits. As an example, the 1990 U.S. Clean Air Act's Acid Rain Program uses cap and trade to reduce 2010 sulfur dioxide (SO_2, a precursor to acid rain) emissions from electric plants to 50 percent of 1980 levels.[2] Emissions reductions are achieved through overall cap levels—limits set by a central authority to meet health and/or environmental standards—broken into smaller, tradable, allowances. Companies or governments that produce above their allowance must buy credits to offset their emissions, while those that produce less than their allowance can sell them as credits.

Characteristics of several U.S. emissions programs are as follows:

- *U.S. Acid Rain NO_x Reduction Program.* Emissions are not capped, nor are trade allowances like the SO_2 program, but still overall goals are set by specifying maximum NO_x output levels relative to fuel energy input, based on boiler technology.[3]

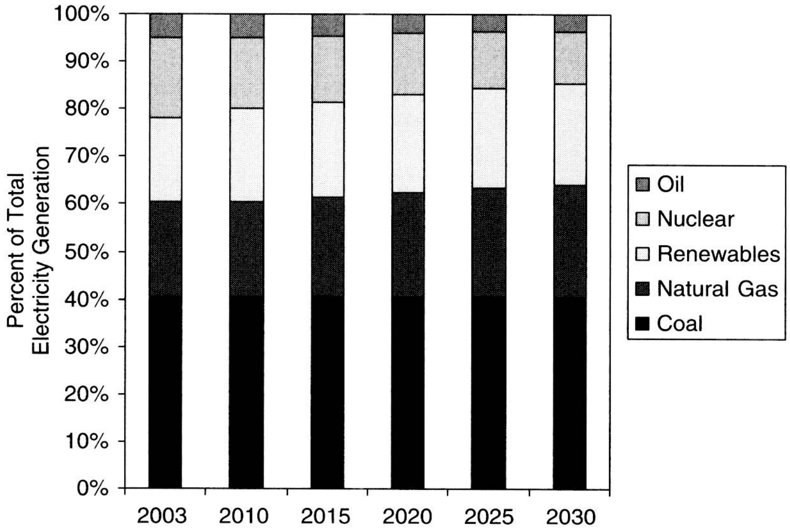

Figure 1 World electricity share projections by fuel source. (From Ref. 1.)

- *NO_x Budget Trading Program (NBP).* This is a cap and trade program involving eastern U.S. states, reducing NO_x during the summer ground-level ozone (smog) season. It is used to help States meet their EPA NOx State Implementation Plan (SIP) call.[3]
- *Clean Air Interstate Rule.* In 2005 the EPA established new or increased SIP requirements for 28 "upwind" states to reduce SO_2 and/or NO_x emissions.[4]
- *Clean Air Mercury Rule.* This cap and trade system was signed in 2005 and based on the Acid Rain Program. It will reduce 2018 coal-fired steam generating unit mercury emissions by approximately 70 percent over 1999 levels. Phase 1 of the plan, through 2017, takes advantage of mercury reduction through SO_2 and NO_x reductions in the Clean Air Interstate Rule.[5]

Although cap and trade policies promote innovative and cost-effective solutions, the increased compliance will eventually impact economics through one or more of the following factors: reduced net plant performance, increased capital cost, and/or increased operating cost. Within the Clean Air Act, economic choices for pulverized coal operators may include switching to a lower-sulfur coal and/or investing in more capable clean-up and control systems. Estimates for a typical flue gas desulfurization system, for example, which reduces SO_2 emissions of coal plants, are 0.14 cents/kWh operations cost and $144/kW in installed capital cost.[6] Gas turbine nitric oxide emissions reductions are achieved through one or more precombustion, combustion, and postcombustion technologies. As technology improves, however, peak cycle temperatures are raised to increase thermal efficiency (reducing fuel burn and CO_2), which is in direct conflict with achieving lower NO_x. Higher thermal efficiency, combustor NO_x, cost of increased technology, and pre/post combustion treatment are all evaluated during design to find the lowest lifecycle cost while meeting emissions requirements.

Where traditional thermal generation is faced with capital and operating cost challenges for emissions avoidance and/or clean-up, nonthermal generation usually has a much better emissions entitlement, but must overcome the economics of a fundamentally lower power density (power per unit weight, or airflow). High pressures and temperatures in steam and gas turbine cycles enable high power density. Renewable generators such as wind and solar-photovoltaic have limited options to increase pressure and temperature, and must increase blade length, collector surface area, and/or efficiency to increase power. Low power density generally translates into greater land use/siting challenges, higher operations costs, and higher transportation costs per kWh. On the positive side, a failure or outage involving one wind turbine or solar panel within a farm means only a small-reduction total system output, allowing high overall system reliability.

Environmentally friendly sources of power will continue to be influenced by the following factors:

- Technology improvements
- Energy independence/security/diversity