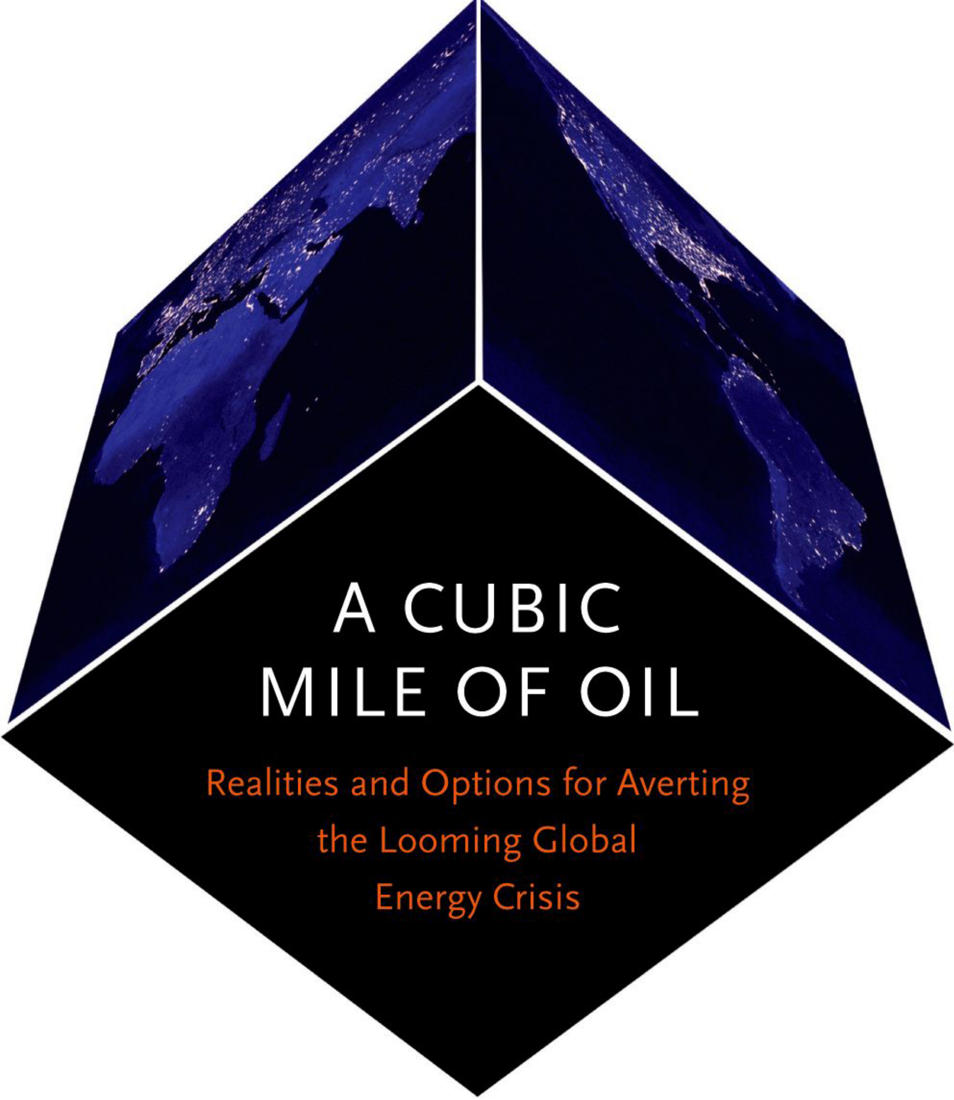

A CUBIC MILE OF OIL

Realities and Options for Averting the Looming Global Energy Crisis

Hewitt D. Crane

Edwin M. Kinderman

Ripudaman Malhotra

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Preface

History books and television series tend to give the impression that religions, emperors and kings, wars and treaties, invasions and rebellions, and pestilence and famine were the only truly important influences on the development of modern civilization. But it can also be argued that the availability of usable energy has been equally important, if not more so. Fire changed early man's life in many ways, as did the use of animals and simple mechanical devices such as the wheel, lever, and pulley. More complex mechanisms followed, including the steam and internal combustion engines and modern electrical and electronic technologies. All of these innovations have allowed humankind to continually expand its use of energy, and with it to improve living conditions and attain prosperity.

The oil shortages and price shocks of the 1970s made the industrialized countries conscious of their profligate use of energy, and individuals became aware of the benefits of conservation. Nations initiated schemes to encourage conservation in industry, residential, and commercial activities, as well as in transportation. These efforts resulted in substantial gains in energy efficiency. When we began the predecessor to this book more than a decade ago, the price of oil—the dominant source of energy—was declining in inflation-adjusted terms. Major oil producers, boasting of new oil and gas finds as well as improved extraction technologies, promised an assured supply of oil for 40 years.

With the decline in oil prices in the 1990s and the apparent "glut of oil," energy concerns dropped off of the radar screen for most individuals. Perusing the Web site of the U.S. Energy Information Agency for the historical prices of crude oil reveals that as recently as 2002, crude oil was selling on the spot market for less than $20 a barrel, essentially the same price, with adjustments for inflation, as that in the 1920s. Yet, the questions of where and how will we as a society obtain the energy to meet our future needs remained critical.

That fact is especially evident to those of us who engage in energy research. It takes many decades to effect changes in the pattern of energy use to bring a new technology from its first implementation to a useful scale. Even if we may have oil supplies for 40 years at our current rate of consumption, and even though we are likely to find additional sources, we will likely face the time when the projected increases in demand will outstrip our ability to produce oil at the necessary rate. At that time we will need additional resources. History has shown that obtaining energy from new sources takes a long time, particularly because the new sources often require developing a new infrastructure for their extraction, distribution, and use. That is why it is urgent to deal with the energy issue *now*: we can no longer ignore the impending energy crisis. A lack of awareness of the issues surrounding energy in the general media led us to title the predecessor to this book *Global Energy: The Ignored Crisis*.

Contrast the decline of oil prices in the 1990s with prices since 2005. Crude oil prices began a steady increase to $60 a barrel by early 2008, then soared to a high of $147 a barrel in July of that year, when just about every newspaper, magazine, or media report carried a story about energy. Although oil prices fell to around $40 a barrel by the end of 2008, energy is no longer an *ignored* topic. Energy-related greenhouse gas emissions and their effects on climate are constantly discussed and debated. World leaders propose and counterpropose new energy strategies for mitigating the impact of using coal and oil on climate. The public is being presented daily with options purported to be better for the environment. Yet, many of those options are no more than mere "greenwash." Some simply trade one problem for another, and still others do little more than make us feel good.

Renewable energy sources—which we refer to as income sources in this book—that could replace our inherited fossil fuels are being considered anew. However, can these income energy sources economically—if at all—replace the standard inherited energy sources? To make matters worse, the most abundant of the "standard" fuels are coal and heavy oils, which are by far the least desirable from an environmental point of view.

A large number of books on the subject of energy and climate change have recently appeared on the bookshelves. Only very few take a global view of energy production and consumption. Many of the books strongly advocate one technology or course of action and deride others. Some are filled with doomsday predictions resulting from global warming. Some even go on to specify 12-point plans to wean mankind off its addiction to oil and to live on renewables. On the other hand, there are books that claim that man-made global warming is the greatest fraud being perpetrated on the public, that solar energy will never scale, and that focusing on producing energy from renewable resources will have disastrous consequences for the economy and well-being of people. In this book, we have tried to stay clear both of cheer-leading slogans and of vitriolic diatribes.

Replacing one energy resource for another is a complex process, made even more complicated because it requires balancing the concerns of three E's: environment (including climate), economy, and the energy security of various nations. There is the real danger that in our effort to solve one problem, say, provide energy security, we can inadvertently create a worse problem, such as disrupting the food supply by diverting resources to produce fuel. We have made such mistakes in the past and must do everything to avoid them in the future. Exacerbating the situation is the immensity of the undertaking and the time and resources we will need to effect any substantial change.

This book's title, *A Cubic Mile of Oil*, was chosen to convey the sheer size of the challenge; a cubic mile of oil happens to be the current global annual rate of oil consumption. We have used it as a staple in this book and express the amounts of other sources of energy in equivalents of the energy contained in a cubic mile of oil (CMO). We believe that a readily comprehensible volume term—usable without exponential modifiers—helps laypersons and energy experts alike to better appreciate the scale of the problem we are facing. It is also the scale at which changes will need to happen. As we demonstrate in this book, it is very difficult to obtain energy at that scale from any of the alternative sources, so it will likely take a combination of many technologies to supply our energy needs in the future. Yet, in order to make any significant contribution, any technology will have to at least approach 1 CMO/yr, so in debating the merits of alternate energy sources, we have to consider what it would take to scale them to produce 1 CMO of energy per year and how their implementation at that level will affect us.

In 2007, we undertook a major revision of the book and updated all the statistics of energy production and consumption to reflect 2006 figures. While we were making these revisions, oil prices climbed from around $60 a barrel in early 2007 to $147 in July 2008, and then precipitously dropped to less than $40 a barrel by the end of 2008. These gyrations in oil price, and to some extent the prices of other fuels, reinforce the necessity to have a long-term energy policy spanning decades that is divorced from the prevailing price of oil.

The world currently uses about 3 CMO equivalents of energy annually, in oil and other sources combined, and by 2050 we will likely consume between 6 and 9 CMO/yr. Where we are going to get that energy and what it takes to produce even 1 CMO of energy are the questions we address in this book. The task is daunting enough even for established energy industries such as coal, oil, and nuclear to increase energy production by 1 CMO; it will require an even greater effort and commitment to increase energy production from sources like wind and solar that currently provide a miniscule portion of our energy.

As will be evident from the discussion that follows, replacing one energy source with another requires more than just a few years: it is a lengthy process requiring installation of a new energy-producing system, channels for its distribution, and diffusion in the market for the devices that can use it. The process can easily take decades. In the context of human history, a few decades is a very short time. However, when many experts believe we have only a few decades left before we must find alternative sources of energy to replace dwindling oil supplies and replace the current energy sources with those that do not emit greenhouse gases, a 50- to 60-year period is too long. For example, although coal use began at the beginning of the 18th century, consumption of coal did not surpass that of wood as the world's primary fuel until the late 19th century. Oil use began about 1870 but surpassed wood use only in the 1940s and coal only in the 1960s. The use of natural gas, which began about 1900, became about equal of that of coal only in 2000.

The relatively long time required for developing alternate sources of energy to replace the energy currently obtained from oil prompts us to label our current predicament a *crisis*. Oil supplies more than 90% of the energy for our transportation systems of cars, trucks, trains, and airplanes. While we are not "running out of oil," we are certainly finding it increasingly difficult to sustain production rates. Newer oil discoveries tend to be in places that are harder to produce from, and this crude oil often requires more processing. At the same time, the global demand for oil is increasing. Switching vehicles to run on alternate fuels will require a massive retooling, not something that we can achieve in a couple of decades. We could switch cars to run on electricity, but most of the electricity is produced from coal, a resource that emits more greenhouse gases and toxic pollutants than other fuels. Hence, coal is the least desirable fuel from the environmental perspective. There are also calls for reducing greenhouse gas emissions (mainly carbon dioxide) by 20% by 2020 and by 50% by 2050. While slogans may motivate us to engage, they alone are insufficient. This book addresses what it would really take to achieve these tough targets as well as some more modest ones.

Soon, the people of the world, through their leaders, must look far ahead and make major decisions about energy resource developments and energy uses. Increasing the efficiency of our energy use and employing conservation are two approaches that could have big impacts in a relatively short time frame. Implementing these practices offers our best hope for delaying the inevitable shortages, although doing so will involve expenditures of trillions of dollars and will influence activities and relationships in every part of the globe for decades to come. Increased efficiency and greater conservation will buy us the time to fully implement technical advances. Perhaps we will make some new discoveries with the potential to radically alter the situation; even ones that seem as remote as nuclear fusion—hot or cold—or finding a way to tap into "dark" energy,[1] or engineer a new way for capturing carbon dioxide from the atmosphere.

1. We do not completely dismiss the possibility of "miracles"—we recognize the limits of our knowledge. After all, physicists tell us that dark matter and dark energy, our *terra incognita*, make up 96% of the universe, and we know absolutely nothing about them. But, while miracles may happen, counting on them is not a strategy that we advocate.

As the factors cited in this book demonstrate, technological advances alone cannot deliver us from the energy crisis. With the spectacular improvements in the performance of computers that we have witnessed of late, society has come to believe that technology can solve any problem—"Just Google it" is a common refrain. Unfortunately, the laws governing energy are markedly different from those governing information. Finding, transporting, and using energy are not the same as finding, transporting, and using information. We hasten to add, though, that the ability to quickly find and widely disseminate information is critical to the rapid development of new technologies, and in that regard, the collaborative tools made available by Google and other Internet companies are a real boon to helping avert the looming energy crisis.

> The great French marshal Lyautey once asked his gardener to plant a tree. The gardener objected that the tree was slow growing and would not reach maturity for one hundred years. The marshal replied, "In that case, there is no time to lose; plant it this afternoon!"
> —John F. Kennedy

Finally, despite the major influence that energy exerts on our lives, few truly understand its production and use. In preparing this book we have thus sought to explain energy in easy-to-understand terms to enable readers to enter more fully into the important debates and decisions that lie ahead. We believe it critical that energy debates take account of quantitative aspects—at least in an order-of-magnitude sense. To provide that information, we have mined data from numerous sources that address current energy use and future needs. We use the collected information in discussing different energy resources in terms of their total potential and also the effort required to develop them on a global scale.

On January 1, 2008, the *New York Times* carried a story about a Dutch company's plans to make use of hot asphalt on roads by laying down PVC pipes and flowing water through them to heat up homes. This sounds like a good plan, and it may indeed be one. We do not expect all the critical details to be present in a newspaper article. However, our hope is that after reading this book, such articles will immediately prompt questions like how much energy savings are we really talking about? The roads are going to be hot during the summer months, when the need for home heating is not as great. Roads often develop ruts and potholes; what is going to happen to the PVC pipes and the water flowing through them? Take another story. A company recently announced it has engineered a bug to convert waste into gasoline. That's an incredible feat and in no way are we discounting the accomplishment. However, if the bug relies on cellulosic or sugary waste, the question to be asking is whether there's enough waste. As we shall see in the chapters that follow, even in our highly wasteful society, the waste we produce contains very little usable energy—perhaps a few percent of the energy we use. If questions like these arise in the minds of our readers, we will feel that our book has served a key purpose.

There are no easy answers, which basically means that everyone will find some elements of every solution to be objectionable. There are trade-offs to be made at every step of the way. The democratic way to resolve such issues is through an open and informed debate based on facts without resorting to disdaining those with different viewpoints. Our hope is that this book provides the facts about the various competing technologies that are necessary for making informed choices and for stimulating a rational debate. We doubt that an immediate and international consensus will emerge out of such a debate but sincerely hope that sufficient numbers of people find common ground to work with and enlist ever larger numbers of people to join them in addressing this crucial issue. Our book is intended to provide the seeds for informed discussion and decision making as communities and nations align themselves to address the future.

For access to supplemental material, including a Q+A with the authors and full-color images of the exhibits, visit www.oup.com/us/CubicMile.

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We thank Dr. Curt Carlson, CEO of SRI International, for his encouragement, enthusiastic support of this project, and spirited discussions in developing many of the ideas expressed in this book. He, and his predecessors, aided us in writing this book by making many of the resources of SRI available to us. We are indebted to many of our colleagues and clients with whom we have worked over the years and who helped shape our thoughts. In particular, we thank Roger Sherman for assistance with library research, Julie Kirkpatrick for ably typing the draft manuscript, Michael Smith for insightfully editing it, Scott Bramwell for his assistance with the graphic arts, and Rajan Narang for his help in the preparation of the final manuscript. We are grateful to Jeremy Lewis, Edward Sears, Brian Desmond, and Mary Kaufman of Oxford University Press during the various steps of publication of this book, and to Trish Watson for her thoughtful and thorough copyediting.

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On a personal note, Hew thanks his wife, Sue, and his sons, particularly Doug, who provided encouragement at every step of the way. Ed acknowledges the moral and physical support from his many progeny, especially his son Albert, who provided help with several mathematical constructs. Ripudaman thanks his wife, Ellen, for supporting this project and not only giving him the time to work on the book but also serving as a sounding board, critiquing many of the earlier versions of the book, pointing to where the discussion was bogging down in details or was rife with jargon. Ripudaman also thanks the community of Hyde School in Woodstock, Connecticut. In a profound way, they influenced him to join Ed and Hew to complete their book.

Contents

The Authors

The three coauthors of this book are, or have been, employees of SRI International, an independent nonprofit research institute in Menlo Park, California, that conducts client-sponsored research and development for government agencies, commercial businesses, foundations, and other organizations. While all three authors are interested in energy matters, they came to that interest from distinctly different backgrounds and from different divisions of SRI, and before writing this book had never worked together. It was their passion for the role of energy in our and our children's lives that brought them together to write this book.

Hewitt Crane (Ph.D., electronics, Stanford University, 1960) came from the world of electronics and computers, starting in the late 1940s with work on an early IBM vacuum tube and relay machine, followed by involvement with the first all-electronic computer at the Institute for Advanced Study in Princeton, and then the first computer for banking built at SRI (known then as Stanford Research Institute). His highly acclaimed works on digital-logic technologies, multiaperture magnetic devices, and a noninvasive eye-movement tracking instrument earned him a fellowship of the Institute of Electrical and Electronic Engineers. Since that time, his interests turned toward the fields of neurophysiology, human sensory systems, and more recently cosmology—none of which has the slightest connection with the world of energy. However, Hew did have two rather remote links. The first was an infatuation with large numbers, such as those involved in biological systems, and in finding ways to express them so that their true magnitude could be more easily visualized. That love was put to the test during the early 1970s while he, like many in the

United States, sat in long gas lines. "How much oil is used annually?" suddenly became a challenging question. When he found that the global number at that time was beginning to approach a scale of a trillion (1,000,000,000,000 or 10^{12}) gallons per year, he searched for ways to convey the true magnitude of that quantity. He found that a cubic mile contains almost exactly one trillion U.S. gallons; out of this coincidence evolved the "cubic mile of oil," or CMO unit, that is used throughout the book; for all practical purposes, 1 CMO/yr accurately the current annual global consumption of oil, and 3 CMO/yr represents the world's total annual energy use.

Hew put this fact aside until Iraq invaded Kuwait in 1990, when his interest in energy was rekindled and a host of new questions arose with a similar link to energy. How much oil is left? How many of the other fossil resources are being consumed, and how many are left? What is the status of alternative energy? What lies ahead?

Hew was appalled at energy waste in living and working environments and at the necessity of reliance on military force to assure the U.S. oil supply. He suggested a vigorous energy conservation program at SRI in the wake of the first Gulf War, and in short order SRI's annual \$3.5 million electricity bill was reduced by more than \$1 million, to say nothing of the energy conserved. In 1994, about a year into the program, he mentioned to SRI's president his interest in preparing a series of notes on energy to distribute to the staff to help maintain the conservation momentum, and that he intended to use the CMO unit as a simple way to answer some of the questions noted above. Little did he know at the time that he would join forces with another SRI researcher, Edwin Kinderman, who had worked in the energy field since the early 1940s, had a great deal of first-hand knowledge of many aspects of the field, and could thus provide in-depth perspective and informed analysis. That is how this book was conceived. Hew was one of SRI's most prolific inventors and visionaries and was named an SRI Fellow in 1985. He authored *The New Social Marketplace: Notes on Effecting Social Change in America's Third Century* and coauthored *Digital Magnetic Logic* with David Bennion and David Nitzan. He retired from SRI in 2001 and passed away in 2008 before he could see this book in print.

Edwin Kinderman (Ph.D., physical chemistry, University of Notre Dame, 1941) comes from the world of physics and chemistry. He began work at SRI in 1956, just two weeks before Hew Crane. By then, Ed already had an extensive background in energy, starting with isotope separation and uranium processing research at the Radiation Laboratory of the University of California in the early 1940s, followed by seven years of research related to nuclear reactor operation and nuclear fuel separation at the Richland, Washington, plutonium production plant. Following that, he was engaged in a diverse set of projects on special nuclear material control, chemical processing, and reactor operations at the General Electric Company. At SRI, while directing the diverse energy-related, laboratory-based programs of the Applied Physics Laboratory, he personally conducted research dealing with applications of ionizing radiation and reactor safety issues, as well as nuclear materials control, terrorist and rogue nation nuclear threats, and proliferation issues. The groups under his direction dealt with subjects as diverse as lasers, energy exchange between atoms, radiation emitted by nuclear explosions, superconductor-based measuring devices, magnetic train levitation, and the transfer of government-developed technology to industry.

In the early 1970s, Ed changed his focus to studies of energy end uses and conservation, and by 1980 he was fully occupied with technoeconomic and market analyses for government and industrial clients concerned with the broader spectrum of alternative energy sources. While much of his work dealt with industry confidential and government classified matters, he has published a number of research articles in peer-reviewed journals and contributed chapters to two books on nuclear proliferation. He also presented two invited papers on proliferation issues at the first International Conference on Nuclear Material Safeguards in Vienna in 1965. Although formally retired since 1994, Ed is still actively investigating alternative energy resources and technologies and environmental control policies, while devoting time to the analysis of the broader energy issues addressed in this book.

Ripudaman Malhotra (Ph.D., chemistry, University of Southern California, 1979) is associate director of the Chemical Science and Technology Laboratory in SRI's Physical Sciences Division. He is an organic chemist, and during his tenure at SRI he has worked extensively, though not exclusively, in the area of energy. Most of his studies have focused on the chemistry of processing fossil fuels. His detailed mechanistic studies of these systems have resulted in innovative processes that achieve desired product selectivity and increased efficiency. As someone deeply engaged in energy research, he was acutely aware of the looming energy crisis, which was being exacerbated by the potential of global climate change. He broadened his research interests into studying alternate resources such as biomass and application of biotechnology in the areas of energy, chemicals, and the environment. He recognized the value of the CMO unit and had been citing the unpublished work of Crane and Kinderman for about a decade. In 2005 he joined Hew and Ed to help finish their book. Among his published works are more than 90 papers in archival literature, coauthorship of a book on nitration, editorship of a book on combinatorial materials development, and coeditorship of a book on advanced materials. He is also the section editor for a multi-volume Encyclopedia of Sustainability Science and Technology, responsible for the chapters on the production, uses, and environmental impacts of fossil resources. The encyclopedia is scheduled for publication in 2011. He is an active member of the Petroleum and Fuels Chemistry divisions of the American Chemical Society. In 2005, he was named an SRI Fellow.

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List of Exhibits

Some Common Energy Conversion Factors

To convert values expressed in CMOs to any of the units shown on the left, multiply the number of CMOs by the multiplier shown on the right. To convert values in those units into CMO, divide by the multiplier shown.

Unit of Measurement and its Abbreviation	Field of Use	Multiplier[a]
Barrel (bbl)	Oil	26.2×10^9
British thermal unit (Btu)	General	153×10^{15}
Calorie (cal)	General	38.7×10^{18}
Cubic meter (m^3)	Oil[b]	4.35×10^9
Gallon (gal)	General	1.10×10^{12}
Joule (J)	General	162×10^{18}
	Electricity	
Kilowatt-hour (kWh)	• End-use energy	15.3×10^{12}
	• Primary energy equivalent	45.0×10^{12}
Quad	General	153
Standard cubic foot (scf)[c]	Natural gas	153×10^{12}
Terawatt-hour (TWh)	End-use electricity	15.3×10^3
Terawatt-year (TWy)	End-use electricity	1.75
	Primary energy equivalent	5.13
	Coal[d]	
Ton (t)	• Hard coal (12,000 Btu/lb)	5.10×10^9
	• Brown coal (6,000 Btu/lb)	9.56×10^9
	Coal[d]	
Tonne (metric ton; te)	• Hard coal (12,000 Btu/lb)	4.64×10^9
	• Brown coal (6,000 Btu/lb)	8.69×10^9
	Oil	3.84×10^9
Trillion cubic feet	Natural gas	153

[a]Legend for exponents: 10^9 = 1 billion (1,000,000,000); 10^{12} = 1 trillion (1,000,000,000,000); 10^{15} = 1 quadrillion (1,000,000,000,000,000); 10^{18} = 1 quintillion (1,000,000,000,000,000,000).

[b]Oil energy values vary somewhat with the quality of the oil. We have used 40.0 MBtu/tonne as the heating value of oil, which is the same as that used by BP (formerly British Petroleum).

[c]"Standard" refers to conditions of pressure (1 atmosphere) and temperature (60°F).

[d]Coal values are approximate because coals vary substantially in their heat content.

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Symbols and Abbreviations

ABWR	Advanced Boiling Water Reactor
AC	alternating current
ANWR	Arctic National Wildlife Refuge in Alaska
bbl	barrel
bpd	barrels per day
Btu	British thermal unit
BWR	boiling water reactor
CAFE	Corporate Average Fuel Economy
cal	calorie (thermal)
Cal	food calorie (= 1 kilocalorie, or 1,000 calories)
CFL	compact fluorescent lamps
CO	carbon monoxide
CO_2	carbon dioxide
CSP	concentrating solar power
CTL	coal to liquids
DARPA	U.S. Defense Advanced Research Projects Agency
DC	direct current
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Agency
EPA	U.S. Environmental Protection Agency
eV	electron volts
FAME	fatty acid methyl ester
FBR	fast breeder reactor
ft^3	cubic foot

gal	gallon
GDP	gross domestic product
GHG	greenhouse gas
GO	gallon of oil equivalent
GTL	gas to liquids
GW	gigawatt
GWP	gross world product
HDR	(geothermally) heated dry rock
HVAC	heating, ventilating, and air conditioning
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGCC	integrated gasification combined-cycle
IPCC	Intergovernmental Panel on Climate Change
J	joule
kcal	kilocalorie = 1,000 thermal calories = 1 food calorie
kWh	kilowatt-hour
LED	light-emitting diode
lm	lumen
LPG	liquefied petroleum gas
LWR	light water reactor
m^3	cubic meter
Mbpd	million barrels per day
MBtu	million Btu
mi^3	cubic mile
MJ	megajoule
mpg	miles per gallon
MW	megawatt
MW_e	megawatt electric; specifies electricity generation capacity
MWh	megawatt-hour
NEA	Nuclear Energy Agency
NHTSA	National Highway Traffic Safety Administration
NiMH	nickel-metal hydride
NRC	U.S. Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
OTEC	ocean thermal electric conversion
ppm	parts per million
psi	pounds per square inch
PV	photovoltaic
PWR	pressurized water reactor
quad	10^{15} Btu
R&D	research and development
RAR	reasonably assured resources
scf	standard cubic feet
SNG	substitute natural gas

SUV	sport utility vehicle
SVO	straight vegetable oil
t	ton (0.91 tonnes)
te	tonne (metric ton)
TWh	terawatt-hour
TWyr	terawatt-year
UNSCEAR	U.N. Scientific Committee on the Effects of Atomic Radiation
USGS	U.S. Geological Survey
USMMS	U.S. Minerals Management Service
WEC	World Energy Council
Wh	watt-hours
WIPP	Waste Isolation Pilot Plant
WNA	World Nuclear Association
yr	year

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A Cubic Mile of Oil

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1

Introduction

Energy is central to our existence and our way of life. We use it in virtually all aspects of life: manufacturing the myriads of goods that we have come to depend on, growing our food, transporting goods and people, controlling our environment, communicating with one another, entertaining ourselves, and the list goes on. By and large, the standard of living of a society is directly linked to its energy consumption. Indeed, today's technological society can be described, quite literally, as "turning oil into everything else that we eat or use." Energy use is so pervasive that we often fail to recognize its role and are only reminded of our dependence on it when for some reason or another there is a shortage. To be sure, such reminders have occurred and will occur every so often. However, the shortages we have overcome thus far are very minor compared with what may lie ahead. With ever increasing numbers of people and nations striving to improve their standard of living, the demand for energy is soaring. At the same time, traditional sources of energy are being depleted, and even their current level of use poses a serious threat of global climate change. How are we going to provide the vast amounts of energy that we will need or desire in the future? That is the central question that this book addresses.

Effective resolution of any major societal issue requires easy access to reliable and relevant information. When an issue is not only complex and multifaceted but also essential to maintaining the very fabric of the society, a lack of comprehensible information makes the public's role and government leadership less effective, and appropriate solutions become more difficult to implement. This is the situation today with global energy—arguably the world's largest industry and one central to all our lives. On the one hand, the public is generally unaware that a pervasive, long-term problem exists and that the world is facing a complex and potentially perilous, perhaps even revolutionary, future. On the other hand, experts and representatives of different segments of the vast energy enterprise have different and frequently conflicting solutions for solving the energy dilemma, and vastly differing motivations for deemphasizing one aspect or another of the problem. Moreover, commentaries in the mainstream media are often highly polarized and politicized, leaving readers or listeners bewildered about whom or what to believe.

The complexity of the energy world, the urgent need to take action, and the difficulties involved in understanding both the current and potential needs for energy and the technologies (and their potential for development) led to the writing of this book. We have sought to provide basic information about the technologies and the technical advances needed to produce future energy supplies. We believe it is important that this information be available not just to the scientists and engineers who specialize in energy issues but to people from all walks of life: a student of literature concerned about the human condition; the city planner deciding how best to provide a greener environment with limited resources; the senator (and her staffers) debating the policy options for securing our energy supplies; the venture capitalist looking to invest in clean technologies. As already mentioned, making substantial changes to the global energy supply presents a challenge of gigantic proportions, and it will affect the lives of all people—some more so than others. It will require many creative and innovative ways of overcoming those challenges. It will require fresh thinking and input from people from different backgrounds.

Scientists and engineers may come up with some solutions, but it will require business leaders and entrepreneurs to bring those ideas and solutions into the market and into the hands of the customers. There is also a critical role for government. Many of the products and solutions probably do not have ready access to the energy market, and in some instances those markets may not even exist today. By exercising certain policies, governments can create those markets. Another important role for the government is setting a level of tax on the different sources of energy that is most appropriate for its circumstance. Keeping fuel prices low may help the local economy, but it could also lead to wasteful practices. Government representatives, in turn, respond best to public demand, and because any policy actions (or inactions) are likely to affect the lives and livelihoods of millions of people, the public at large must enter into an informed debate. Accordingly, in writing this book we have attempted to present the information needed for engaging in an informed debate accessible to a broad readership by explaining basic elements of different technologies. Although specialists may find our explanations overly simple, we have sought to provide enough depth and detail so all readers can appreciate the pros and cons associated with the different choices about future sources of energy. After all, the decisions about energy choices affect the public at large, and therefore the public has to engage in the deliberations.

A Veritable Tower of Babel

As we began preparing this book, we found it frustrating that each source of energy is described with a different set of units. Production and use of coal are expressed in tons (or tonnes [metric tons]); oil in tonnes, barrels, or gallons; natural gas in standard cubic feet (scf), and so on. Although many books and articles discuss energy sources in terms of their energy content in a common unit, whether in British thermal units (Btu), joules, calories, or watt-hours (Wh), each of these units represents a relatively small amount of energy, and mind-numbing multipliers such as billions, trillions, or even quadrillions must be applied when discussing their use in the global context. A veritable tower of Babel results. Besides being unable to relate to those units (how much is a Btu, a joule, or a quad?), we found it very hard to keep those large numbers straight in our heads.

The use of power units such as gigawatts (GW) or terawatts (TW) in the context of energy is another source of confusion. Power is the *rate* at which energy is produced or consumed, although in common parlance power is also used to refer to electricity. It is true that we can describe annual global energy consumption in power units and therefore state the challenge for the future in terms of requiring, say, an additional 20 TW of power. However, production capacity alone does not tell the whole story. The energy produced in one year by a 1-GW coal plant is much different from a seemingly equivalent 1-GW wind installation, because a coal plant typically operates at its rated capacity about 85% of the time, while a wind farm installation does so for only around 25–30% of the time. The net result is that it takes about three times as much installed power capacity for a wind power system as for a coal power system to produce the same amount of electrical energy. Likewise, the capacity factor for solar power systems is generally less than 20%, so if we decide to go exclusively solar, our need for the additional 20 TW-year of energy will translate into a need to install about 100 TW of capacity.

In discussions of global energy and resources with our friends and colleagues, we found that many of them shared our frustration with all of the different units being used to describe energy. What we needed was a large unit of energy that could be visualized and would also evoke a visceral reaction. It is perhaps ironic that while we bemoaned the fact that we already had too many units for energy, we have ended up introducing yet another.

Cubic Mile Oil Equivalent

We turned to a unit that one of the authors, Hew Crane,[1] had devised as he sat in the long gasoline lines that typified the energy crisis of 1974. He had heard

1. We sadly mourn the passing of our friend and coauthor, Hew Crane. It is unfortunate that he did not get to hold the finished book in his hand.

that the world was using oil at the rate of about 23,000 gallons a second and began wondering how much would it be in a year. A few multiplications later, he calculated it to be approaching a trillion gallons; 724 billion gallons, to be more precise. Hew was always fascinated by large numbers, whether they be the number of cells in our central nervous system or the number of ants on Earth. He also had a passion for devising ways to communicate their magnitude. Unable to picture the trillion gallons, he began calculating how large a pool could contain that amount. A few more arithmetic steps later, he realized that if those 724 billion gallons of oil were to be poured into a pool a mile wide, a mile across, and a mile deep, the pool would be about three-quarters full.

That was the genesis of a cubic mile of oil, or CMO, as our new unit and the staple measure used in this book. Incidentally, a CMO is the amount of oil the world used in 2000; in 2006, use had increased to 1.06 CMO. A cubic mile is the same as 1.10 trillion gallons or 26.2 billion barrels. However, the unit allows us to dispense with modifiers such as billions and trillions when talking about global oil and other major resources. Whereas in the United States we take billion to mean a thousand million (10^9), and trillion to mean a million million (10^{12}), such is not the case throughout the world. In some parts of Europe, a billion is a million million. And thus, avoiding the use of these terms removes one source of confusion. We have often encountered articles in print that mistakenly refer to a billion when they meant a million, and so on. A case in point is an editorial describing that the potential savings in oil from increasing the efficiency of cars and trucks in the United States from a fleetwide average of 25 mpg (miles per gallon) to 35 mpg would amount to a *billion barrels per day*.[2] Now, the total U.S. oil consumption is only 20 million barrels a day, so immediately we realize that something is amiss: how could you save a billion barrels when the total consumption is only 20 million? An increase in fleetwide efficiency from 25 to 35 mpg could easily lead to savings of a *million barrels a day,* and perhaps even 3 million barrels a day, for a total of a *billion* barrels a *year*. So perhaps the editorial was referring to annual savings. The point is not to pick on this piece or its writer, but to illustrate how easy it is to get lost when the numbers are large and hard to comprehend.

A volumetric unit also makes it possible for us to form a mental picture: a cubic mile is a pool a mile wide, a mile long, and mile deep! If that is hard to comprehend, try picturing a large sports arena, say, 700 feet in diameter and 250 feet high (about 25 stories). The volume of this cylindrical arena would correspond to 96.2 million cubic feet, and it would take about 1,500 of these arenas to equal the volume expressed in a cubic mile. The Bird's Nest Stadium, where the opening ceremony of the 2008 Olympics in Beijing was held, was the world's largest sports facility at the time, with an official volume of about 4.9 million cubic meters. A cubic mile of oil (or any liquid, for that matter)

2. "Time, finally, for real fuel economy," *New York Times,* August 2, 2008.