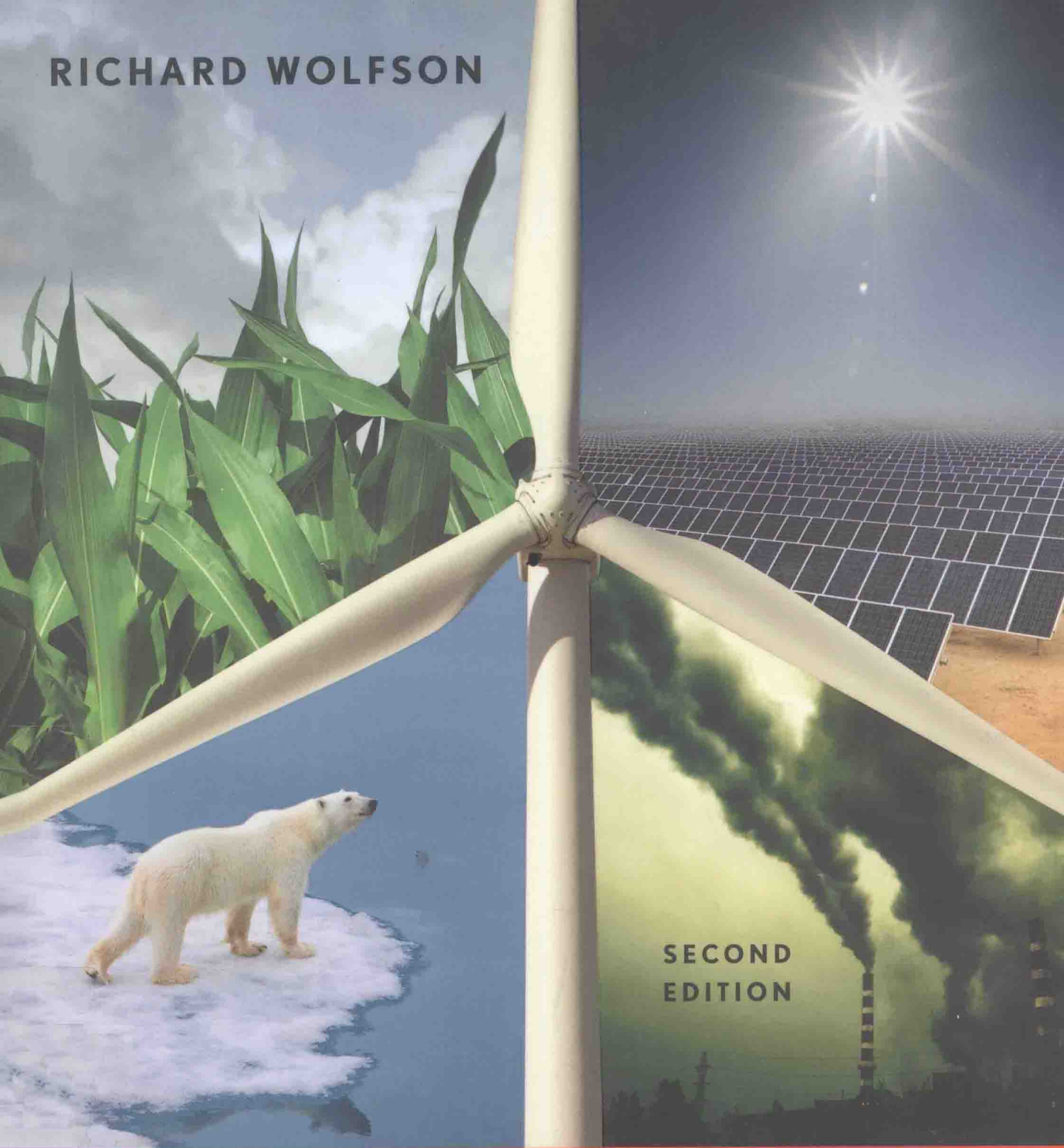


**RICHARD WOLFSON**



**SECOND  
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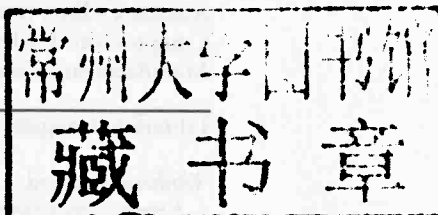
# **ENERGY, ENVIRONMENT, AND CLIMATE**

# Energy, Environment, and Climate

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Second Edition

RICHARD WOLFSON

*Middlebury College*



W. W. NORTON & COMPANY  
NEW YORK • LONDON

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Printed in the United States of America

Editor: Erik Fahlgren

Project editor: Carla L. Talmadge

Editorial assistants: Mina Shaghaghi, Mary Lynch

Production manager: Chris Granville

Managing editor, College: Marian Johnson

Design director: Rubina Yeh

Photo editor: Stephanie Romeo

Associate editor, eMedia: Matthew A. Freeman

Composition: TexTech

Manufacturing: Courier

Library of Congress Cataloging-in-Publication Data

Wolfson, Richard.

Energy, environment, and climate / Richard Wolfson.—  
2nd ed.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-393-91274-6 (pbk.)

1. Climatic changes. 2. Energy consumption—  
Climatic factors. 3. Energy consumption—  
Environmental aspects. 4. Power resources—Climatic  
factors. I. Title.

QC981.8.C5W645 2012

551.6—dc23

2011030173

W. W. Norton & Company, Inc., 500 Fifth Avenue,  
New York, N.Y. 10110  
[www.wwnorton.com](http://www.wwnorton.com)

W. W. Norton & Company Ltd., Castle House, 75/76 Wells  
Street, London W1T 3QT

1 2 3 4 5 6 7 8 9 0

# Energy, Environment, and Climate

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Second Edition

## PREFACE

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Many behaviors distinguish the human species from our fellow inhabitants of Planet Earth. Of these, our use of energy in amounts far exceeding what our own bodies can produce affects the environment in an unprecedented way. Centuries ago, pollution from coal burning was already a serious urban problem. Despite regulatory and technological progress in pollution control, diminished air and water quality continue to be major consequences of our ever-growing energy consumption. Further environmental degradation results as we scour the planet for fuels that contain the stored energy of which we demand an unending supply. Our energy-intensive society also enables other environmentally damaging developments such as sprawl, large-scale mechanized agriculture, and massive deforestation. At the same time, energy brings us higher standards of living and allows our planet to sustain a larger population.

In recent decades, a new and truly global impact of humankind's energy consumption has overshadowed the long-standing and still significant consequences associated with traditional pollution, resource extraction, and energy-enabled development. That impact is global climate change, brought about largely by the emissions from fossil fuel combustion. Climate change is a problem that knows no national or even continental boundaries. It will affect us all—although not all equally. It won't have the civilization-ending impact of an all-out nuclear war or a major asteroid hit, but climate change will greatly stress an already overcrowded, divided, and combative world.

Achieving a healthier planet with a stable, supportive climate means either using less energy or using energy in ways that minimize adverse environmental impacts. Here we have choices: To use less energy, we can either deprive ourselves of energy's benefits or we can use energy more intelligently, getting the same benefits from less energy. To minimize environmental and especially climate impacts, we can shift from fossil fuels to energy sources that don't produce as much pollution or climate-changing emissions. Or we can learn to capture the emissions from fossil fuels and sequester them away from Earth's surface environment.

Earth's energy resources are limited to relatively few naturally occurring stores of energy—the fuels—and to energy flows such as running water, sunlight, wind, geothermal heat, and tides. A realistic grasp of our energy prospects demands that we understand these energy resources. We need to know,

first and foremost, if a given resource or combination of resources is sufficient to meet humankind's energy demand. For fuels, we need a good estimate of the remaining resource and a time frame over which we can expect supplies to last. We need to understand the technologies that deliver useful energy from fuels and flows, to assess their environmental impacts, and to recognize that none is without adverse effects. And we need to be realistic about the near-term and long-term prospects for different energy sources in the economic context.

The oil shortages of the 1970s spawned a serious exploration of energy alternatives. Governments and industries sponsored research programs, while tax credits encouraged the installation of alternative energy systems. Vehicle mileage and other measures of energy efficiency increased significantly. At the same time, colleges and universities developed specialized courses in energy issues and the relationship between energy and environment. These courses emerged in traditional departments such as physics, chemistry, and engineering; in interdisciplinary programs dealing with technology and society; and in the burgeoning new programs in environmental studies and environmental science that have sprung up with the emergence of a widespread environmental conscience in the last decades of the twentieth century. Textbooks written for such courses addressed the science and policy issues surrounding energy and the environment.

*Energy, Environment, and Climate* also focuses on energy and its impact on the environment. Unlike its predecessors, it's built from the ground up on the premise that climate change is the dominant energy-related environmental issue of the twenty-first century. More traditional concerns such as pollution and energy resources remain important, and they, too, are covered here. But a full five chapters—about one-third of the book—are devoted to climate and the energy-climate link.

*Energy, Environment, and Climate* begins with a survey of Earth's history and the origin of the planet's energy resources. A quantitative look at past and present patterns of human energy consumption follows, including a discussion of the link between energy, economic development, and human well-being. Chapters 3 and 4 provide an introduction to the science of energy, including the all-important role of the second law of thermodynamics. Chapters 5 through 10 describe specific energy sources and their resource bases, the role each plays in today's global energy system, their associated technologies and prospects for future technological development, and their environmental impacts. This section of the book is organized around fundamental resources, including fossil fuels, nuclear energy, geothermal and tidal energy, and direct and indirect solar energy. Because fossil fuels dominate today's energy supply, there are two chapters dealing, first, with the fossil resource and fossil fuel technologies and, second, with the environmental impacts of fossil fuels. Whereas other textbooks have separate chapters on such energy-related issues as transportation, *Energy, Environment, and Climate* includes these topics in the appropriate energy chapters. For example, hybrid vehicles and combined-cycle power plants appear in the fossil-fuel chapters; fuel cells are discussed in the chapter that covers hydrogen as an energy carrier; and wind turbines are included in the chapter on indirect solar energy.

Completely redone in this second edition is Chapter 11, which now provides a detailed look at the energy carriers electricity and hydrogen. The electric power grid, smart-grid technology, distributed generation, AC and DC transmission, load management, integration of renewable electricity sources, energy-storage technologies, and other issues relevant to our growing use of electricity are covered, either for the first time or in much more detail than in the first edition. Material on nuclear fusion, formerly in Chapter 11, has been moved to Chapter 7 on nuclear energy. Hydrogen as an energy carrier remains, appropriately, in the revised Chapter 11.

Four chapters on climate follow the section on energy. Chapter 12 describes the scientific principles that determine planetary climates, including the natural greenhouse effect in the context of planets Venus, Earth, and Mars. The chapter ends with a discussion of the nature of scientific theories and of certainty and uncertainty in science. Chapter 13 details the so-called “forcings”—both natural and anthropogenic—that can upset the energy balance that ultimately establishes Earth’s climate. Chapter 14 documents the observations that suggest Earth is now undergoing unusually rapid climate change, and shows why scientists believe much of that change is attributable to human activities. Chapter 15 outlines projections of future climate, and includes a look at the workings of computer climate models and the role of climate feedbacks. The final chapter brings together the two main themes of the book—energy and climate—and explores how humankind might continue to enjoy the benefits of energy while minimizing climate-changing impacts.

*Energy, Environment, and Climate* is written primarily from a scientific perspective. However, questions of policy and economics are never far behind the science of energy and climate. The text therefore ventures occasionally into policy and economic considerations—although to a far lesser extent than a policy-oriented book would do. In particular, many chapters end with a section specifically dedicated to a policy-related issue that grows out of the science covered in the chapter.

Any serious study of energy and the environment has to be quantitative. We need to understand just how much energy we actually use and how much energy is available to us. It makes little sense to wax enthusiastic about your favorite renewable energy source if it can’t make a quantitatively significant contribution to humankind’s total energy supply. Assessment of environmental impacts, too, requires quantitative analysis: *How much* pollution does this energy source emit? *At what rate* are we humans increasing the atmospheric CO<sub>2</sub> concentration? *What’s the maximum* CO<sub>2</sub> concentration we can tolerate without incurring dangerous climate change? *How long* will nuclear waste remain dangerous? *How much* waste heat does this power plant dump into the river? *How much* CO<sub>2</sub> results from burning a gallon of gasoline? *What’s exponential growth* and what are its consequences for future levels of energy consumption, environmental pollution, or carbon emissions? In dealing with such questions, this book doesn’t shy away from numbers. At the same time it isn’t a heavily mathematical text with equations on every page. Rather, the text attempts to build fluency with quantitative information—a fluency that means being able to make quick order-of-magnitude estimates, work out quantitative



answers to simple “how much” questions, and to “read” numerical information from graphs. The book doesn’t require higher mathematics—there’s no calculus here—but it does demand your willingness to confront quantitative data and to work comfortably with simple equations. Anyone with a solid background in high-school algebra can handle the material here. As for a science background, the text assumes only that the reader has some familiarity with high-school level chemistry and/or physics. Despite its scientific orientation, this book is written in a lively, conversational style that students have welcomed in my other textbooks.

*Energy, Environment, and Climate* helps reinforce qualitative and quantitative understandings with its end-of-chapter activities. **Chapter Reviews** summarize the big ideas presented in each chapter, invite the student to consider the meaning of new terms introduced in the chapter, and recap important quantitative information and equations. **Questions** probe the concepts behind energy sources, environmental impacts, and climate issues. **Exercises** involve calculations based on the material introduced in each chapter. Answers to the odd-numbered exercises are provided at the back of the book. **Research Problems** send the student to sources of contemporary data—usually Web-based—and allow for more detailed exploration of questions that may be related to energy and environmental issues in the student’s home state or country. Given the discoveries quickly unfolding in this growing field, research problems may also ask the student to update data presented in the book or to look more deeply into quantitative data on global energy use and its impacts. **Argue Your Case** questions ask you to formulate an authoritative argument for or against propositions relevant to each chapter’s topics.

*Energy, Environment, and Climate* is illustrated with photos, line drawings, and graphs. Line drawings describe the workings of energy technologies, the flows of energy and material throughout the Earth system, climate models and feedback effects, pollution control and waste storage systems, and a host of other content that’s best seen to be understood. Photos are largely of actual energy systems, presented to give a sense of the technologies and their scales. Graphs quantitatively describe everything from the breakdown of our energy use by source or by economic sector to projections of future global temperatures. Every graph is traceable to an authoritative source, and a list of credits and data sources documents these sources.

*Energy, Environment, and Climate* deals with rapidly changing fields, and this second edition is as up-to-date as possible. Nearly every graph and item of numerical data have been updated through 2010 or later. Wind and solar energy have seen great advances since the first edition was published in 2008, including much expanded deployment of large-scale grid-connected systems, and these developments are reflected here. New understandings of climate change have advanced beyond the 2007 Intergovernmental Panel on Climate Change Fourth Assessment Report, and the climate chapters have been appropriately updated—including the first results from the new Representative Concentration Pathway approach to future climate projections that will feature in the 2014 IPCC Fifth Assessment Report. Energy and climate legislation, both national



and international, have been thoroughly updated; an example is an expanded discussion of renewable portfolio standards.

Other improvements in the second edition include a thorough rewrite for clarity and brevity, and the addition of 12 new focus boxes with titles that include “350: The Science behind the Number,” “End-use and Primary Energy,” “The Warmest Year?,” “Being Graphically Literate,” and “Converting Units.” The second edition also has a more international emphasis, while remaining particularly relevant to students in the United States. The end-of-chapter questions and exercises have been revised in light of instructor and student experience, and the number of exercises has increased significantly. Finally, the second edition incorporates recent environmental incidents relevant to the text; these include such events as the *Deepwater Horizon* oil spill; the natural gas explosion in San Bruno, California; and the Fukushima nuclear accident.

Also complementing the main text are tables displaying important energy- and climate-related quantities; some of the most useful also appear on the inside covers. An appendix tabulates relevant properties of materials, ranging from insulation  $R$  values of building materials to half-lives of radioactive isotopes to global warming potentials of greenhouse gases. A glossary defines all key terms that appear in the book, and includes acronyms as well as symbols for physical units and mathematical quantities. A list of suggested readings and authoritative websites is also provided. In addition, instructors teaching from *Energy, Environment, and Climate* will find supplementary resources at [www.norton.com/instructors](http://www.norton.com/instructors), a password-protected website including images of the figures appearing throughout the text.

*Energy, Environment, and Climate* is not a book of environmental advocacy or activism; it's much more objective than that. I have my own opinions, and I acknowledge that many—although not all—are in line with the views of the broader environmental movement. But I pride myself on independent thinking based on my own study of others' writings and research, and I'd like to encourage you to do the same. I'm also keenly aware that there is a stronger scientific consensus on some issues, particularly climate change, than either the popular media or the general public may realize. I've been careful to base my scientific statements on the consensus of respected scientists and on peer-reviewed literature that's available to you and everyone else for direct examination. At the same time, I understand the uncertainties inherent in science, especially in an area as complex as the interconnected workings of the global environment. I openly state those uncertainties and quantify them whenever possible. That being said, I would be pleased if the knowledge you gain from this book inspires you to work toward change in our collective patterns of energy consumption. I and the majority of my fellow scientists believe such actions are essential in the coming decades if we're to avoid disruptively harmful environmental impacts.

No individual can be an expert on all the topics covered in a book like this one, and during the writing process I've been fortunate to be able to call on specialists in many fields. They've contributed to making this book more authoritative and timely than I, working alone, could have done. With appreciation, I acknowledge the individuals who have given their expert opinion, read drafts

of individual chapters, or otherwise contributed advice and encouragement to this project:

Climate experts Gavin Schmidt (NASA Goddard Institute for Space Studies) and Michael Mastrandrea (Stanford University) reviewed the climate chapters and made many helpful suggestions. Dr. William Glassley (Lawrence Livermore National Laboratory and California Energy Commission) reviewed the sections on geothermal energy in Chapter 8; Dr. JoAnn Milliken (Acting Program Manager, U.S. Department of Energy Hydrogen Program) reviewed Chapter 11; Roger Wallace (Vermont Wood Energy) and Greg Pahl (Vermont Biofuels Association) reviewed sections of Chapter 10 on biomass. Others who offered advice include Dr. William Ruddiman (University of Virginia), Dr. Irina Marinov (University of Pennsylvania), the late Dr. Stephen Schneider (Stanford University), Dr. Michael Mann (Pennsylvania State University), Dr. Peter Vitousek (Stanford University), Dr. Robert Romer (Amherst College), Dr. Mark Heald (Swarthmore College), Dr. Gary Brouhard (McGill University), Elizabeth Rosenberg (Argus Media), and George Caplan (Wellesley College). For this second edition, Dr. James Williams of the Monterey Institute provided a thorough review of Chapter 11's new material on electricity. My Middlebury colleagues Sallie Sheldon (biology), Steve Sontum (chemistry) Jon Isham (economics), Jeffrey Munroe (geology), Chris Watters (biology), Bill McKibben (environmental studies), and Grace Spatafora (biology) were kind enough to share their expertise and encouragement. Finally, I thank my former student Peter Mullen for a thorough reading of the manuscript, and I thank both Peter and Wendy Mullen for their support of this and other projects.

In addition to those acknowledged above, I am grateful to the following instructors of energy and/or climate courses who contributed reviews at the request of W. W. Norton. Their comments, many based on instructor and student experiences with the first edition, offered a blend of pedagogical and scientific expertise that has enhanced the readability, teachability, and authority of this textbook.

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 Scott Wissink (Indiana University Bloomington)  
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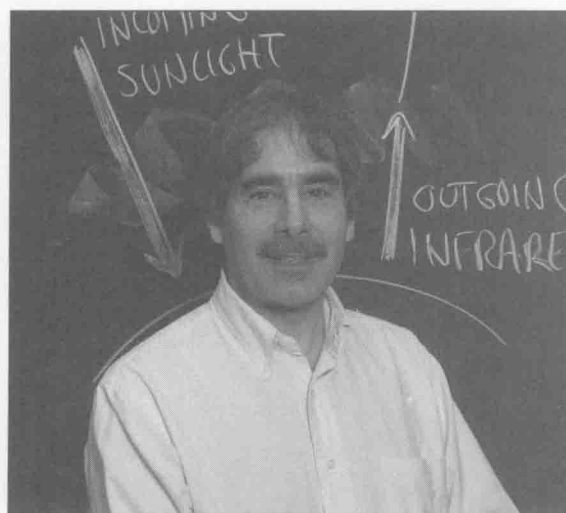
Finally, special thanks to E. J. Zita (Evergreen State College) for her efforts in checking answers to the end-of-chapter exercises and preparing the online Solutions Manual for this text.

I'm honored to be publishing this book with W. W. Norton, and I am indebted to former Norton editor Leo Wiegman for inviting me to write the first book in what we hope will become a substantial Norton list in environmental studies. Inspired in part by this project, Leo left publishing to start his own environmental work; this second edition was then in the able hands of editor Erik Fahlgren and his assistants Mary Lynch and Mina Shaghaghi. Project editor Carla Talmadge and copyeditor Philippa Solomon spearheaded an efficient and successful production process. I am grateful for all their efforts, and it has been a pleasure to work with all of them.

Finally, I thank my family for their support and patience through the long process of bringing this project to fruition.

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**Richard Wolfson** is Benjamin F. Wissler Professor of Physics at Middlebury College, where he also teaches environmental studies. He holds a BA from Swarthmore, an MS in environmental studies from the University of Michigan, and a PhD in physics from Dartmouth. His research involves solar astrophysics and terrestrial climate, and he has published nearly 100 papers in the scientific literature. Wolfson's other books include several introductory physics texts as well as *Nuclear Choices: A Citizen's Guide to Nuclear Technology* (1993) and *Simply Einstein: Relativity Demystified* (2003). He has produced four video courses for The Teaching Company's Great Courses series: *Einstein's Relativity and the Quantum Revolution: Modern Physics for Nonscientists* (1999); *Physics in Your Life* (2004); *Earth's Changing Climate* (2007); and *Physics and Our Universe: How It All Works* (2011).



# BRIEF CONTENTS

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	<i>Contents</i>	<i>vii</i>
	<i>List of Focus Boxes</i>	<i>xi</i>
	<i>Preface</i>	<i>xiii</i>
CHAPTER 1	A Changing Planet	1
CHAPTER 2	High-Energy Society	20
CHAPTER 3	Energy: A Closer Look	35
CHAPTER 4	Energy and Heat	62
CHAPTER 5	Fossil Energy	94
CHAPTER 6	Environmental Impacts of Fossil Fuels	127
CHAPTER 7	Nuclear Energy	158
CHAPTER 8	Energy from Earth and Moon	204
CHAPTER 9	Direct from the Sun: Solar Energy	225
CHAPTER 10	Indirect from the Sun: Water, Wind, Biomass	260
CHAPTER 11	Energy Carriers: Electricity and Hydrogen	292
CHAPTER 12	The Science of Climate	319
CHAPTER 13	Forcing the Climate	341
CHAPTER 14	Is Earth Warming?	365
CHAPTER 15	Future Climates	385
CHAPTER 16	Energy and Climate: Breaking the Link	410
	<i>Appendix</i>	<i>APP-1</i>
	<i>Glossary</i>	<i>G-1</i>
	<i>Suggested Readings</i>	<i>SR-1</i>
	<i>Answers to Odd-Numbered Questions and Exercises</i>	<i>ANS-1</i>
	<i>Credits and Data Sources</i>	<i>CDS-1</i>
	<i>Index</i>	<i>I-1</i>



**CHAPTER 6****ENVIRONMENTAL IMPACTS OF  
FOSSIL FUELS**

	<b>127</b>
6.1 What's Pollution?	128
6.2 Air Pollution	129
6.3 Other Environmental Impacts of Fossil Fuels	143
6.4 Policy Issue: The Clean Air Act	150
Chapter Review	154

**CHAPTER 7****NUCLEAR ENERGY**

	<b>158</b>
7.1 The Atomic Nucleus	160
7.2 Radioactivity	163
7.3 Energy from the Nucleus	167
7.4 Nuclear Fission	169
7.5 Nuclear Reactors	174
7.6 The Nuclear Fuel Cycle and Uranium Reserves	179
7.7 Environmental and Health Impacts of Nuclear Energy	185
7.8 Policy: A Nuclear Renaissance?	192
7.9 Nuclear Fusion	193
Chapter Review	199

**CHAPTER 8****ENERGY FROM EARTH AND MOON**

	<b>204</b>
8.1 The Geothermal Resource	204
8.2 Geothermal Energy Technology	208
8.3 Environmental Impacts of Geothermal Energy	213
8.4 Geothermal Heat Pumps	214
8.5 Tidal and Ocean Energy	218
Chapter Review	222

**CHAPTER 9****DIRECT FROM THE SUN: SOLAR ENERGY**

	<b>225</b>
9.1 The Solar Resource	226
9.2 Passive Solar Heating	231
9.3 Active Solar Heating	235
9.4 Solar Thermal Power Systems	241
9.5 Photovoltaic Solar Energy	244
9.6 Other Solar Applications	252
9.7 Environmental Impacts of Solar Energy	253

9.8 Policy Issue: Solar Economics	254
Chapter Review	256

**CHAPTER 10****INDIRECT FROM THE SUN: WATER,  
WIND, BIOMASS**

	<b>260</b>
10.1 Hydropower	260
10.2 Wind	268
10.3 Biomass	275
10.4 Other Indirect Solar Energy	286
Chapter Review	288

**CHAPTER 11****ENERGY CARRIERS:****ELECTRICITY AND HYDROGEN**

	<b>292</b>
11.1 Electricity	293
11.2 Toward a Hydrogen Economy?	307
Chapter Review	315

**CHAPTER 12****THE SCIENCE OF CLIMATE**

	<b>319</b>
12.1 Keeping a House Warm	319
12.2 Keeping a Planet Warm	320
12.3 In the Greenhouse	323
12.4 Earth's Energy Balance	330
12.5 A Tale of Three Planets	335
Chapter Review	338

**CHAPTER 13****FORCING THE CLIMATE**

	<b>341</b>
13.1 Climate Forcing	341
13.2 Climate Sensitivity	344
13.3 Feedback Effects	345
13.4 Natural and Anthropogenic Forcings	348
13.5 Carbon: A Closer Look	357
Chapter Review	361

**CHAPTER 14****IS EARTH WARMING?**

	<b>365</b>
14.1 Taking Earth's Temperature	365
14.2 Other Climatic Changes	376
14.3 Are We to Blame?	380
Chapter Review	383

**CHAPTER 15****FUTURE CLIMATES**

15.1 Modeling Climate	385
15.2 Climate Projections	386
15.3 Consequences of Global Climate Change	392
15.4 Climate Change and Society	397
Chapter Review	404

**CHAPTER 16****ENERGY AND CLIMATE:  
BREAKING THE LINK**

16.1 Carbon Emissions: Where We're Going and Where We Need to Be	410
	411

16.2 Geoengineering	415
16.3 Carbon Capture and Sequestration	418
16.4 Alternative Energy Sources	420
16.5 Using Less Energy	423
16.6 Strategy for a Sustainable Future	430
Chapter Review	433

<i>Appendix</i>	<i>APP-1</i>
<i>Glossary</i>	<i>G-1</i>
<i>Suggested Readings</i>	<i>SR-1</i>
<i>Answers to Odd-Numbered Questions and Exercises</i>	<i>ANS-1</i>
<i>Credits and Data Sources</i>	<i>CDS-1</i>
<i>Index</i>	<i>I-1</i>



## FOCUS BOXES

////////////////////////////////////

BOX 1.1	Being Graphically Literate	16
BOX 2.1	End-use and Primary Energy	26
BOX 3.1	Converting Units	48
BOX 3.2	SI Prefixes	49
BOX 4.1	Higher and Lower Heating Values	79
BOX 4.2	Cogeneration at Middlebury College	86
BOX 5.1	Carbon versus Carbon Dioxide	102
BOX 5.2	Exponential Growth	117
BOX 6.1	Gas or Diesel?	129
BOX 7.1	$E = mc^2$	170
BOX 8.1	The Geysers Geothermal Power Plants	210
BOX 12.1	A Greenhouse Complication	330
BOX 12.2	A Banking Analogy	332
BOX 13.1	The Intergovernmental Panel on Climate Change	349
BOX 14.1	The Warmest Year?	368
BOX 14.2	Isotopic Temperature Reconstruction	372
BOX 15.1	An Earth System Model	389
BOX 15.2	Means and Extremes	398
BOX 16.1	350: The Science behind the Number	413
BOX 16.2	Negawatts: The Rocky Mountain Institute	428

# Chapter 1

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## A CHANGING PLANET

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Earth was born some 4.6 billion years ago, and our planet has been changing ever since. Earth's evolution is driven by an interplay between **matter**—the physical “stuff” that makes up the universe—and **energy**, an equally important universal “stuff” associated with motion, heat, and the fundamental forces of nature. It's energy that makes everything happen; without energy, the universe would be a static, unchanging, lifeless place. In Earth's case, agents of change are astrophysical, geological, chemical, and biological. Astrophysical events formed our planet, and occasionally alter its history. Geological events build mountains and wear them down, move continents, shake the solid Earth, and spew gases into the atmosphere. Chemical reactions change the composition of rocks, soils, atmosphere, and oceans. Life appeared on Earth billions of years ago, and soon biological processes were radically altering the planet's atmosphere and chemistry. Hundreds of millions of years ago, life emerged from the oceans to colonize the land. Just a few million years ago, our human species evolved and began the process of **anthropogenic** (i.e., human-caused) environmental change. We've since become sufficiently plentiful and technologically advanced that we're now having a global impact on Planet Earth.