

The Physics of Energy

The Physics of Energy provides a comprehensive and systematic introduction to the scientific principles governing energy sources, uses, and systems.

This definitive textbook traces the flow of energy from sources such as solar power, nuclear power, wind power, water power, and fossil fuels through its transformation in devices such as heat engines and electrical generators, to its uses including transportation, heating, cooling, and other applications. The flow of energy through the Earth's atmosphere and oceans, and systems issues including storage, electric grids, and efficiency and conservation are presented in a scientific context along with topics such as radiation from nuclear power and climate change from the use of fossil fuels.

Students, scientists, engineers, energy industry professionals, and concerned citizens with some mathematical and scientific background who wish to understand energy systems and issues quantitatively will find this textbook of great interest.

Robert L. Jaffe holds the Morningstar Chair in the Department of Physics at MIT. He was formerly director of MIT's Center for Theoretical Physics and recently chaired the American Physical Society's Panel on Public Affairs. Jaffe is best known for his research on the quark substructure of the proton and other strongly interacting particles, on exotic states of matter, and on the quantum structure of the vacuum. He received his BA from Princeton and his PhD from Stanford. In recognition of his contributions to teaching and course development at MIT, Jaffe has received numerous awards including a prestigious MacVicar Fellowship. Jaffe is a member of the American Academy of Arts and Sciences.

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A long awaited book which comprehensively covers the fundamentals that engineers, scientists and others specializing in energy related fields need to master. Wonderfully written, it unlocks and presents the science behind energy systems in a pure yet accessible manner, while providing many real world examples to help visualize and frame this knowledge. This book would serve as an excellent text for a foundational course in energy engineering.

Khurram Afridi, Department of Electrical, Computer and Energy Engineering, University of Colorado Boulder

Finding the energy to power a civilization approaching 10 billion people without unacceptable consequences to the environment is the greatest challenge facing humanity this century. This book develops all of the fundamental concepts in physics underlying a quantitative understanding of energy sources, interconversion, and end usage, which are essential parts of meeting this challenge. It will serve as unique and authoritative textbook for the teaching of these topics. . . . Overall it is a masterful exposition of the fundamental concepts of physics and their application to the energy-environment problem.

*Michael J Aziz, Gene and Tracy Sykes Professor of Materials and Energy Technologies,
Harvard John A. Paulson School of Engineering and Applied Sciences*

The textbook by Jaffe and Taylor is an invaluable resource, for instructors and students alike, discussing the physics of energy, a subject that is most important for humankind. . . . The book has great potential as a teaching text for emerging courses on energy physics and promises to become a classic for years to come.

Katrin Becker and Melanie Becker, Texas A&M University

Jaffe and Taylor have produced in a single volume a comprehensive text on energy sources, energy conversion technologies, and energy uses from the unifying vantage of physics. Either in a course or in self-study *The Physics of Energy* can serve as the foundation for an understanding of conventional and renewable energy technologies.

Paul Debevec, Professor Emeritus, Department of Physics, University of Illinois

Jaffe and Taylor have compiled a comprehensive treatise that covers all aspects of energy: its fundamental role in physics, its sources and its uses. In addition to serving as the backbone for a variety of courses, this book should be an invaluable resource for anyone interested in the physics of energy in all of its forms.

*David Gross, Chancellor's Chair Professor of Theoretical Physics, Kavli Institute for Theoretical
Physics, University of California, Santa Barbara, Joint Winner of the Nobel Prize for Physics, 2004*

The book can be very useful as a mid-level textbook, as a survey for self-instruction for the serious-minded energy policy analyst, or as a desk reference covering the physics of the full range of energy topics – everything from the energy content of biofuels, to safe nuclear reactor design, to efficient design and placement of wind turbines, to geothermal energy flow, and dozens more topics . . . This book very effectively fills a gap between the plentiful simplistic treatments of energy issues and books for full time professionals in the various energy areas.

Rush Holt, CEO of the American Association for the Advancement of Science, former Member of Congress

We live in an age of wonders, when a designer in almost any engineering field can find a dizzying assortment of tools, materials, components, and construction technologies for building. . . . *The Physics of Energy* answers the question of where to begin. No engineer's library will be complete without a copy of this literary and intellectual masterpiece. A brilliant story of the foundations of everything.

Steven Leeb, Professor of Electrical Engineering and Computer Science, Massachusetts Institute of Technology

The book is the only comprehensive discussion of energy sources, flows, and uses that I know of. . . . It is designed as a text for a college level course, or as a refresher for those who already have the background, and is successful in achieving its goal of introducing the student to the science of energy.

*Burton Richter, Paul Pigott Professor in the Physical Sciences, Emeritus and Director Emeritus,
Stanford Linear Accelerator Center, Joint Winner of the Nobel Prize for Physics, 1976*

This is a unique textbook: broad, deep, and crucially important for our society. . . . [Students] are also inspired by new insights into nature and everyday life: no other energy book covers heat pumps, spark ignition engines, climate change, wave/particle duality and the Big Bang.

Joshua Winn, Princeton University

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*To our parents, our teachers,
our spouses and, most of all,
to our children*

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Preface

This book provides a comprehensive introduction to energy systems for individuals interested in understanding the fundamental scientific principles underlying energy processes from sources to end uses.

Origins and Uses

The Physics of Energy emerged from a one-semester course with the same title that we developed and have taught at MIT (Massachusetts Institute of Technology) since 2008. The course serves as an introduction to energy science in a new energy curriculum at MIT and is open to students who have completed freshman calculus, a year of physics with calculus, and a term of college chemistry. Although particularly suited to students majoring in hard sciences or engineering, many students who have taken the course were interested primarily in economics and policy. The MIT course also serves as an elective for physics majors, where the concepts developed in more formal courses are brought together into a broader context and applied to real-world problems.

Finding no existing book that matched the level of our course and the approach we wished to take, we began to generate lecture notes for “The Physics of Energy” in 2007. Those lecture notes slowly expanded in scope and depth into this book, which has developed a coherent structure in its own right. Because the students in the course have a wide range of backgrounds, we do not assume an extensive amount of physics background. Our goal in the course, and in the book, is to take students from a basic freshman physics background to a qualitative and quantitative understanding of both the physical principles underlying all energy systems and an appreciation of how these ideas are interconnected and relevant for practical energy systems.

This book can be used in many ways. It can serve as a textbook for a single-semester course for undergraduates in a broad range of science and engineering fields or

as a “capstone course” for physics undergraduates; these are the audiences for the MIT course. A course using this book could also be tailored primarily to focus on various subsets of the material; depending upon the goals, one could focus for example on the basic physics underlying energy sources, on the aspects most relevant to climate and twenty-first century energy choices, on renewable energy sources, etc. Some specific one-semester paths through the material are suggested below. While we continue to teach the material from this book as a one-semester course at MIT, with roughly one lecture per chapter, this requires a rather fast pace and many topics are not treated in the full depth of the material in the book. With more careful and thorough treatment, the book can also serve as the text for a more advanced two-semester course in energy science, for example in conjunction with a graduate certificate in energy studies. The book is also designed to be self-contained and suitable for self-study. Anyone with a serious interest in energy and some background in basic mathematics and physics should hopefully find most of the book accessible.

We hope that *The Physics of Energy* also will serve as a “desk reference” for those who work in energy-related fields of science, engineering, economics, or policy, who need to be aware of the scientific foundations of technologies beyond their own field of specialization.

Scope and Focus

Providing energy for the world to use in a sustainable fashion is a major challenge for the twenty-first century. Economic considerations and policy decisions will be central to any global attempt to address this energy challenge. For individuals, organizations, and nations to make rational choices regarding energy policies, however, a clear understanding of the science of energy is essential. Decisions made in the absence of good scientific understanding have

the potential to waste vast amounts of effort and money and to adversely affect countless lives and large ecosystems.

This book aims to provide an in-depth introduction to energy systems, from basic physical principles to practical consequences in real systems. The goals of the book are to provide a clear picture of what energy is and how it flows through Earth systems (Part II), how humans use energy (Part I), and how energy systems take energy from natural sources to end uses (Part III). In each of these areas our goal is to build a basic understanding of the underlying science, develop a global picture of how the parts fit together into a coherent whole, and to develop sufficient technical understanding to assess energy systems in a quantitative fashion.

Introductory textbooks on energy issues typically mix science, economics, and policy, with the aim of presenting a unified introduction to the subject. Throughout this book, however, we focus solely on the science of energy and energy systems and refrain from addressing issues of economics and politics. This is not because we believe economics and policy are unimportant, but instead because we believe that the science is best conveyed without constant reference to the economic and political context. Those aspects of energy studies are well presented in many other books and in other courses in a typical curriculum in energy studies. Our goal is to help to provide the scientific understanding of energy systems that is a prerequisite for any informed discussion of energy choices in the economic and political realm.

As the title indicates, our starting point for viewing energy sources and uses is primarily through the lens of physics. Indeed, a secondary goal of the book is to illustrate how the concept of energy unifies virtually all of modern physics into a coherent conceptual framework. It is not possible, however, to provide a comprehensive overview of energy science and systems without widening the discussion to include areas that are traditionally considered the domain of chemistry, biology, earth science, and many fields of engineering. Energy science is, in fact, an excellent example of a subject where traditional academic boundaries are blurred in nearly every application. Rather than limit our perspective and therefore the usefulness of this book, we have chosen to include a significant amount of material that might not ordinarily be construed as “physics.” Overlap with other fields of science is particularly significant in chapters on energy in matter, fossil fuels, geothermal energy, energy and climate, and biological energy, while chapters on engines, heat extraction devices, nuclear reactors, wind turbines, and photovoltaic solar cells contain some material usually found in engineering courses. Some topics such as biofuels and fuel

cells, at the edges of the conceptual framework of the book and at the limit of our own expertise, receive only limited discussion. We have, however, included a more extensive discussion of some aspects of earth science particularly as it relates to issues of present and future climate, since this topic is of central importance to the future trajectory of human energy use.

Throughout the book, we strive to emphasize the underlying physical principles that govern different energy systems. In particular, we develop the basic ideas of quantum mechanics, thermodynamics, fluid mechanics, the physics of oceans and of the atmosphere, and other basic physical frameworks in enough technical detail that their application to various energy systems can be understood quantitatively as well as qualitatively. We also strive, in so far as possible, to provide explanations of phenomena in relatively simple terms from first principles and to maintain a consistent introductory level throughout the book. A reader interested in any specific topic can gain some initial understanding from the treatment here of the underlying principles and learn how the topic connects with the rest of the energy landscape, but will have to go elsewhere for a more advanced and more detailed treatment of the subject; we have attempted to give a sampling of references that can lead the interested reader further into any particular topic.

Confronting such a wide range of topics, one possibility would have been to invite other authors, experts in those areas farthest from our own expertise, to write about those topics. Instead, we have chosen to try to educate ourselves sufficiently to cover the subject in its entirety. This approach has the advantages that the level and “feel” of the book is more coherent and uniform, that the pedagogical progression is orderly, and that the unity of energy science is more apparent. The disadvantage, of course, is that we have written extensively about areas in which neither of us is an expert. We have had the help of many colleagues, who have helped us grasp the subtleties of their fields and corrected many of our misconceptions. Along the way we have come to appreciate more deeply the wisdom captured by the basic paradigms in many fields of engineering and physical science and to recognize the role that fundamental physics plays in those paradigms.

Prerequisites

As mentioned at the outset, we assume that readers have, at some point in their lives, had a two-semester course in calculus at the college level or the equivalent. We also assume that students have encountered the elementary concepts of probability theory. Some of the more advanced areas of a first-year calculus course, such as elementary

vector calculus, differential operators, line and surface integrals, and series expansions, are reviewed in Appendix B, as are the basic notions of complex numbers. We try to avoid all but the most elementary differential equations. Some simple aspects of linear vector spaces, Fourier series, and tensor analysis are used in isolated chapters and are summarized briefly in Appendix B.

We also assume that the reader has been exposed to mechanics and electrodynamics from a calculus-based perspective, and has had some introductory chemistry. Recognizing that some readers may have studied introductory physics long ago and that not all physics courses cover the same syllabus, we have organized the book to provide self-contained introductory reviews of the basics of mechanics, electromagnetism, heat, heat transfer, and chemical reactions early in the book as we describe their energy-related applications.

We *do not* assume that readers have any previous exposure to the concept of entropy, or to quantum mechanics or fluid dynamics.

Structure and Outline

This book is organized into three parts, addressing energy *uses*, *sources*, and *systems*. The first part plays a dual role of introducing many of the basic physics principles used throughout the text. Within this global framework, the book has a structure somewhat like a tree; the first ten chapters form the trunk of the tree on which the remaining material is supported. Many of the subsequent chapters branch off in different directions, and within chapters specialized topics and particular examples of energy technologies form the twigs and leaves of the tree. The dependence of each chapter on previous chapters is indicated in the *Reader's guide* at the beginning of each chapter. This enables a somewhat modular structure for the book, so that readers and instructors can follow a variety of paths and select a sequence of material based on their interest.

After an introduction (§1), *Part I: Basic energy physics and uses* describes the uses of mechanical (§2), electromagnetic (§3, §4), and thermal energy (§5, §6), reviewing and introducing concepts from these subjects as needed. To proceed further it is necessary to introduce basic notions of quantum mechanics (§7) and explain the concepts of entropy and thermodynamics in depth (§8). These chapters are intended to be self-contained introductions to these subjects for students with no previous exposure. Readers with some familiarity with these subjects may find the chapters useful reviews. With these concepts in hand we describe the flow of energy in chemical processes (§9),

and the interconversion of work and thermal energy in engines and heat extraction devices (§10–§13). Although fundamental concepts such as the second law of thermodynamics and the quantization of energy are used throughout the book, we recognize that these are conceptually difficult ideas. We have endeavored to structure the book so that a reader who reads §7 and §8 lightly and is willing to accept those concepts as given will find almost all of the material in the book accessible and useful.

Part II: Energy sources focuses on the sources of primary energy. The most extensive sections are devoted to nuclear energy (§16–§19), solar energy (§22–§25), and wind energy (§28–§30). Part II begins with an interlude (§14) in which the four forces that govern all known natural processes are described and with a closer look (§15) at some aspects of quantum mechanics such as tunneling that are necessary in order to understand aspects of both nuclear and solar energy. The study of nuclear power is followed by an introduction to the nature and effects of ionizing radiation (§20).

Before delving into solar power, we pause to consider the nature of energy and its role in our universe at a fundamental level (§21). Much of Part II is devoted to following the flow of solar energy as it enters other natural systems from which energy can be extracted. Solar energy (§22–§25) is the primary source of energy that is stored in biological systems (§26) and drives oceanic (§27) and atmospheric (§28) circulations. After introducing elementary concepts from fluid dynamics (§29), we describe the harvesting of wind power by wind turbines (§30) and the utilization of water power from rivers, waves, ocean currents, and the tides (§31). We then review Earth's internal structure and the origins of geothermal power (§32). Part II ends with an introduction (§33) to the nature, occurrence, characteristics, and uses of the primary fossil fuels: coal, oil, and natural gas.

In *Part III: Energy system issues and externalities* we turn to some of the complex issues associated with energy systems. First we describe the way the flow of energy on Earth's surface affects our climate (§34), the evidence for past climate change, and prospects for future climate change (§35). Next we turn to a quantitative discussion of energy efficiency, some case studies of conservation, and an overview of possible energy sources that may replace fossil fuels and how energy systems may evolve in the coming centuries (§36). We then turn to energy storage (§37) and in the final chapter (§38), we analyze the production and transmission of electrical energy and the structure of electric grids.

In addition to the mathematical appendix, other appendices include a list of symbols used in the book (Appendix

A), and tables of units, conversion factors, and fundamental constants (Appendix C). Various data including global and national energy and carbon dioxide information are summarized in Appendix D.

Each chapter (except the introduction) begins with a *Reader's guide* that previews the content of the chapter so that readers can decide where to concentrate their efforts. Throughout each chapter, *Key concept boxes* provide a concise summary of the major points as they arise. The key concept boxes not only identify essential points for the careful reader but also provide a gloss of the chapter for a reader seeking an overview of the subject. In each chapter we include sample calculations or analyses set off as *Examples* and we present some further explanations or specialized material in *Boxes*.

Questions and Problems

We have included questions for discussion/investigation and problems at the end of each chapter. Many of these questions and problems were developed for the course taught at MIT. The questions for discussion and investigation may be suitable for discussion groups or recitation sections associated with the course or they may form the topics for term papers. The problems serve a variety of purposes: some fill in details left unstated in the text, some are designed to deepen theoretical understanding, and many are useful as applications of the ideas developed in the text. The problems can be used for homework, evaluations, or self-study. We have used labels to indicate the character of some of the problems: [T] for more *theoretically* oriented problems; [H] for more challenging (*hard*) problems; and [C] for occasional problems that require extensive analytic or computer-based *computation*. Some problems require students to find and use data about specific systems that are readily available on the web but are not provided in the text. Solutions to the problems are available for teachers upon request.

Paths Through This Book

The flexible and modular structure of *The Physics of Energy* makes it possible to use this book in many ways. As an alternative to proceeding linearly through the book, the reader interested in a particular area of energy science can focus on a given chapter or set of chapters in the later part of the book, guided by the interdependencies outlined in the *Reader's guides*. Teachers interested in structuring a course can choose a variety of paths through the material based on the background and interest of the students. And the reader interested in attaining a global understanding of energy science and systems can proceed linearly

through the book, skimming any initial chapters that contain familiar material, delving as deeply or as lightly as they are interested into the technical aspects of the material, and focusing attention on later chapters of particular interest. For a worker in one field of energy research, policy, or business, the book can be used to gain an overview of the fundamental concepts of other energy related fields. Thus, for example, §32 (Geothermal energy) provides a relatively self-contained summary of the origins, harvesting, and scope of geothermal energy, and §38 (Electricity generation and transmission) gives an introduction to the basic principles of electric grids. Larger sections of the book form comprehensive, stand-alone treatments of major fields of energy science. Thus §22 (Solar energy) through §25 (Photovoltaics) and §14 (Forces of nature) through §20 (Radiation) provide introductions to the physics of solar and nuclear energy accessible to scientists and engineers with an elementary knowledge of quantum and thermal physics.

The book's modularity suggests ways that sections might be organized as a text for a course focusing on a particular speciality within energy studies. Teachers or readers primarily interested in electrical engineering, for example, would find that

- §3 (Electromagnetism)
- §4 (Waves and light)
- §7 (Quantum mechanics)
- §21 (Energy in the universe)
- §22 (Solar energy)
- §23 (Insolation)
- §24 (Solar thermal energy)
- §25 (Photovoltaics)
- §36 (Systems)
- §37 (Energy storage), and
- §38 (Electricity generation and transmission)

form a relatively self-contained sequence focused on electromagnetic physics with energy applications.

Similarly, those interested primarily in earth sciences could use

- §5 (Thermal energy)
- §6 (Heat transfer)
- §8 (Entropy and temperature)
- §22 (Solar energy)
- §23 (Insolation)
- §27 (Ocean energy)

- §28 (Wind energy)
- §31 (Water energy)
- §32 (Geothermal energy)
- §33 (Fossil fuels)
- §34 (Energy and climate), and
- §35 (Climate change)

to provide an earth-science focused introduction to energy physics. Variants focused on nuclear, mechanical, chemical, and environmental engineering are also possible.

It is also possible to follow a path through the book that introduces new physics concepts in conjunction with related systems and uses. Such a course might begin with a review of mechanics (§2 and §4) followed by chapters on wind and water energy (§27, §28, §29, §30, and §31), which require only basic mechanics as a prerequisite. Next, after introducing basic thermal and quantum physics (§5–§8), the focus would shift to chemical energy (§9), engines and thermal energy transfer (§10–§13), geothermal and fossil fuel energy (§32, §33), climate (§34, §35), and efficiency and conservation (§36). Depending on the time available and the interests of the instructor and class, the focus could then turn to electromagnetic and solar energy (§3, §21–§25, and §38) or nuclear energy and radiation (§14–§20) or both.

A “capstone” course for physics majors could go over §1–§7 fairly quickly, emphasizing the energy applications, and then delve more deeply into the nuclear, solar, wind, and climate sections, adding in other chapters according to the interest of the instructor and students.

A course aimed at a broad range of students with a greater interest in implications for economics and policy could skip some of the more technical subjects of Part I, focus in Part II on material focused on giving the bottom line and overview of each energy source, such as §16, §23, §28 and the corresponding overview sections of the chapters on other resources. The course could then cover much of the material from Part III on climate and systems issues, referring back to the earlier part of the book for technical background as needed.

Units

Throughout this book we use SI units, which are introduced in §1. Each specialized area of energy studies has its own colloquial units, be they *billion barrels of oil equivalent*, or $ft^2 \text{ }^\circ F \text{ hr}/BTU$ (a unit of thermal resistance used in the US), or any others from a long list. These units have often evolved because they enhance communication within a specific community of energy practice. In a book that seeks a unified overview of energy science, there is great virtue, however, in having a single system of units. Familiarity with a single universal system of units also has the benefit of facilitating communication among specialists in different disciplines. In keeping with our interdisciplinary emphasis, with rare exceptions, we therefore keep to the SI system. Conversion tables from many colloquial units to SI units are given in Appendix C.

Further Reading

There exists a huge range of other books that cover various aspects of energy science and related issues. For each of the specific subjects covered in the individual chapters of this book, we have given a handful of references for readers interested in further study. Some more general references that cover a variety of energy science issues from a technical perspective compatible with this book, some of which we found very helpful in learning about these subjects ourselves, include [1, 2]. A good introduction to energy issues at a significantly less technical level is given by MacKay in [3]. For further reading on energy issues as connected to policy and economics, the MIT text [4] is a good starting point, as well as any of the many excellent books by Smil, such as [5]. The text by Vanek, Albright, and Angenent [6] provides an engineering perspective on energy issues, and the text by Andrews and Jelley [7] provides another perspective on energy science from a physicist’s point of view. Finally, thanks to the efforts of innumerable unnamed individuals, Wikipedia is perhaps the best starting point for investigation of specific aspects of energy systems and technologies. In particular, for most topics in this book, Wikipedia provides excellent references for further reading.

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