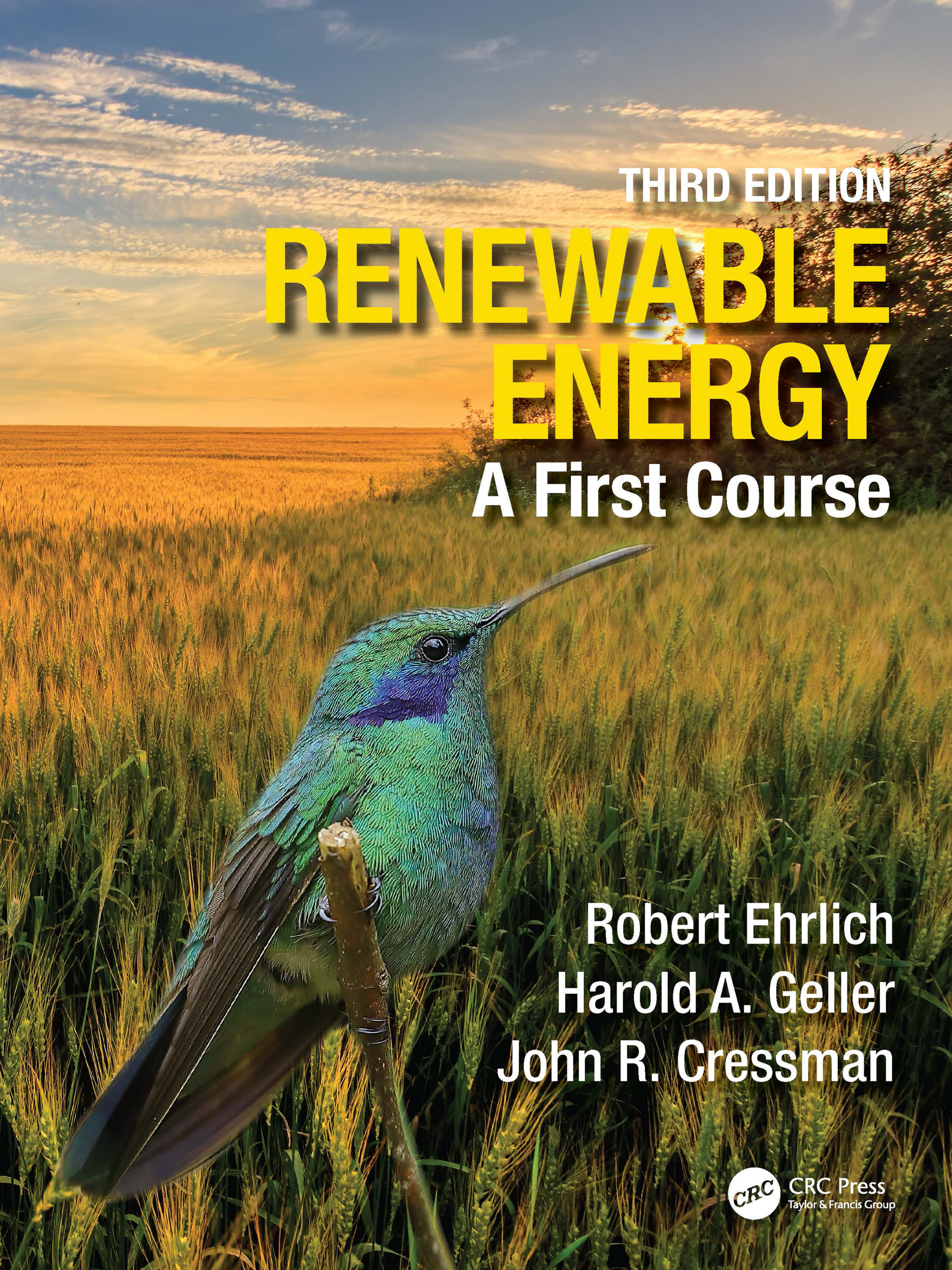

THIRD EDITION

# RENEWABLE ENERGY

## A First Course

Robert Ehrlich
Harold A. Geller
John R. Cressman

CRC Press
Taylor & Francis Group

# Renewable Energy

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*For Lochlan, Meridian, Richard, and Eugenio*

# Brief Contents

# Contents

# Preface to the First Edition

Robert Ehrlich

If you are a student in one of the sciences or engineering who has taken a few introductory courses in physics and calculus, you will find this book useful, because it covers a variety of technologies in renewable energy and explains the basic principles. It avoids, if at all possible, technical jargon and mathematically advanced approaches found in many books on the subject. It is also not overly long, unlike many other books on renewable energy, and its 14 chapters should easily fit within a standard semester, at least in most schools in the United States. I personally find the sheer weight of some textbooks intimidating, so hopefully, this book will not fall into that category. Most importantly, until about 4 years ago, I was in your shoes. No, I am not a young faculty member, but I am relatively new to the energy field. In fact, I am pretty much at the end of my teaching career. Four years ago, I wanted to find something meaningful to which I could devote the remainder of my career, and renewable energy certainly seemed a good fit for me. Until that point, my teaching and research had been entirely or almost entirely in the field of physics. Thus, 4 years ago, I was a relative "newbie" in the field of renewable energy, and I had to figure out a lot of things for myself. I thus still remember the kinds of issues that confuse students in this subject and how to explain these to them as clearly as possible.

Renewable energy assumes great significance for the future of the world, given the environmental issues that are related to the ways we generate most of our energy and the central place that energy occupies in our society. Proper energy choices need to be made in order to avoid an environmental disaster, severe energy shortages, and even social chaos or war. These proper choices are not obvious, and certainly, it is not as simple as saying "Let us stop using fossil fuels and nuclear power now in order to save the environment!" Making wise decisions involves sound consideration of all the implications and a thorough look at economic, environmental, technical, political, and other perspectives, weighing relative costs and benefits for a host of possible technologies. Thus, even if you are not planning a career in this field, this book should help you make more intelligent choices as a citizen and consumer.

This book, despite its title, does include three chapters on nonrenewable energy: one on fossil fuels and two on nuclear, the first focused on the science and the second on the technology. This is an important addition, because renewable energy needs to be compared with the other primary ways in which we now produce energy in order to better evaluate its advantages and shortcomings. Moreover, these other technologies will probably remain for some time to come, even if some nations such as Germany have opted to phase out both their nuclear- and coal-fired electricity-generating plants. Some observers believe that it is realistic to move entirely toward renewable energy (such as solar, wind, biofuels, geothermal, and hydropower) by 2030, while most would probably put the date further into the future. This book also includes four overarching topics that go beyond any specific type of energy, namely, energy conservation, energy storage, energy transmission, and energy policy. The energy field is a continually changing one, and so it is important to keep up with the latest advances. This book provides up-to-date information, although it will inevitably require some revisions in a few years. I hope you enjoy it—let me know if you do, and certainly, let me know if you find any errors or ambiguities.

# Preface to the Second Edition

**Robert Ehrlich**

**Harold A. Geller**

The first edition of any textbook is bound to include some number of typographical errors. This revision gives a full update on the original text, and it fixes any problems or mistakes of its predecessor. As before, it is intended for undergraduate students in physics or engineering who have taken an introductory course in physics and calculus. It not only mainly focuses on renewable energy, but also addresses nonrenewables such as fossil fuels and nuclear technology. We continue with a physics orientation, while also addressing important conservation, economic, and public policy issues. The emphasis is on a nontechnical presentation, avoiding advanced math while teaching fundamental analytical skills with wide application.

We have appreciated the feedback of current adopters in developing this second edition. The addition of two new chapters on population growth and energy use and probability and risk constitutes a major addition. We have tried throughout to maintain a readable, lively text with healthy use of anecdotes, history, illustrations, and sidebar topics.

Problem sets have been updated and expanded. Instructors may access some additional test bank questions and answers through the publisher's website at http://www.crcpress.com (search for the page for the book and click on Downloads/Updates).

# Preface to the Third Edition

**Robert Ehrlich**

**Harold A. Geller**

**John R. Cressman**

Much has changed in the world since the first publication of this text. On the one hand, the foreboding specter of climate change is no longer a distant boogie man, but rather a stark reality whose undeniable consequences are playing out in the form of extreme, and often catastrophic, climate-related phenomena, producing flooding, droughts, and wild-fires in just the last year in the United States, not to mention around the globe. Even in the middle of a pandemic-induced global recession, the year 2020 tied for the warmest temperature on record, which should not surprise us since the science says that not only do we have to stop increasing greenhouse gas concentrations, but most likely will need to actively reduce them to keep the earth from increasing more than 2°C from preindustrial levels.

On the other hand, as you will read in this book, the knowledge, and in large part technology, to provide the world's energy needs without producing greenhouse gas emissions already exist. We have updated this book to keep abreast of advancements in energy technologies, not just renewable sources, to provide proper context for a path forward. Humanity is at a crossroads, where we either muster our collective skills and talents, and resolve to take control of our actions, or spiral into a chaotic future. If you want someone's opinion on how things are going to play out, you are going to need to find another book. However, here you will gain an overview of current and cutting-edge energy technologies and utilization and how energy is the essential linchpin to the problem of global warming and climate change.

# Acknowledgments

We would like to thank the students in our classes for giving us useful feedback on this book and the two reviewers contacted by the publisher, Professor Michael Ogilvie (Washington University in St. Louis) and Professor John Smedley (Bates College), for their review of the entire manuscript.

# Authors

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Chapter 1

# Introduction

## 1.1 WHY ANOTHER BOOK ON ENERGY?

The idea for this book arose as a result of one of the author's first time teaching a course on renewable energy. The course was not Energy 101, but it was intended for students who had completed an introductory physics sequence and taken a few courses in calculus. Most available books were either too elementary or too advanced, and the handful of books at the right level seemed too focused on technicalities that obscured the basic ideas. In addition, many of those texts lacked the desired informal writing style, with even some occasional touches of humor that can enhance readability. Moreover, any course focused on renewable energy must also cover nonrenewable energy (fossil fuels and nuclear, specifically), because only then could useful contrasts be drawn. Renewable energy is a multidisciplinary subject that goes well beyond physics, although it is fair to say that this book has a physics orientation. Physicists do have a certain way of looking at the world that is different from other scientists and from engineers. They want to understand how things work and strip things down to their fundamentals. It is no accident that many new technologies, from the laser, to the computed tomography scanner, to the atomic bomb, were invented and developed by physicists, while their refinement is often done by engineers.

## 1.2 WHY IS ENERGY SO IMPORTANT TO SOCIETY?

Those of us who are fortunate to live in the developed world often take for granted the availability of abundant sources of energy, and we do not fully appreciate the difficult life faced by half of the population of the world, who substitute their own labor or that of domestic animals for the machines and devices that are so common in the developed world. A brief taste of what life is like without access to abundant energy sources is provided at those times when the power goes out. But while survival during such brief interludes may not be in question (except in special circumstances), try to imagine what life would be like if the power were to go out for a period of, say, 6 months. Not having cell phones, television, Internet, or radio might be the least of your problems, especially if the extended power failure occurred during a cold winter when food was not available, and your "taking up farming" was a complete joke, even if you had the knowledge, tools, and land to do so. As much as some of us might imagine the pleasures of a simple preindustrial lifestyle without all the trappings of our high-technology society, the reality would likely be quite different if we were suddenly plunged into a world without electricity. It is likely that a large fraction of the population would not survive 6 months. The idea of a prolonged failure of the power

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grid in many nations simultaneously is not just some outlandish science fiction prospect and could occur as a result of a large solar flare directed at the planet. The last one that was large enough to pose a threat of catastrophic damage was apparently the Carrington event, which occurred in 1859 before our electrified civilization existed, but it did cause telegraph systems all over North America and Europe to fail. Or severe disruptions may be caused by more down-to-earth weather-related phenomena like the ice storm in February 2021 that affected a large swath of the United States from Mexico to Canada. That storm caused significant blackouts in the independent Texas Interconnection power grid for several days, in sub-zero temperatures, resulting in over 150 deaths. Perhaps the most likely cause of a wide scale power disruption would occur due to human action, either accidental, like the clogging of the Suez Canal for 6 days in April 2021, or malicious, like the cyberattack that forced the Colonial Pipeline to go offline for 6 days in May 2021. Furthermore, the prospect of competing in a global market for limited resources has become increasing difficult with the further ascension of China, dysfunctional US leadership, and a world still reeling from a pandemic.

## 1.3 EXACTLY WHAT IS ENERGY?

In elementary school, many of us learned that "energy is the ability to do work" and that "it cannot be created or destroyed" (conservation of energy). But these memorized and parroted phrases are not always easy to apply to real situations. For example, suppose you had a hand-cranked or pedal-driven electric generator that was connected to a light bulb. Do you think it would be just as hard to turn the generator if the light bulb were unscrewed from its socket or replaced by one of lower wattage? Most people (even some engineering students) who were asked this question answer yes and are often surprised to find on doing the experiment that the answer is no—the generator is easier to turn with the bulb removed or replaced by one of lower wattage. This of course must be the case by conservation of energy, since it is the mechanical energy of your turning the crank that is being converted into electrical energy, which is absent when the light bulb is unscrewed. Were the handle on the generator just as easy to turn regardless of whether a bulb is being lit or how brightly it glows, then it would be just as easy for a generator to supply electric power to a city of a million people as one having only a thousand! Incidentally, you can probably forget about supplying all your own power by using a pedal-powered generator, since even an avid cyclist would be able to supply at most only a few percent of what the average American consumes.

Aside from misunderstanding what the law of energy conservation implies about specific situations, there are also some interesting and subtle complexities to the law itself. Richard Feynman was one of the

### HOW MANY JOULES IS EQUAL TO 1 CALORIE?

The calorie is the amount of heat needed to raise 1 g of water by 1°C. But since this amount slightly depends on temperature, one sometimes sees slightly different values quoted for the conversion factor commonly taken to be 4.1868 J/cal.

great physicists of the twentieth century who made many important discoveries, including the field of quantum electrodynamics, which he coinvented with Julian Schwinger. Feynman was both a very colorful person and a gifted teacher, who came up with novel ways to look at the world. He understood that the concept of energy and its conservation was more complex and abstract than many other physical quantities such as electric charge where the conservation law involves a single number—the net amount of charge. With energy, however, we have the problem that it comes in a wide variety of forms, including kinetic, potential, heat, light, electrical, magnetic, and nuclear, which can be converted into one another. To keep track of the net amount of energy and to recognize that it is conserved involve some more complicated "bookkeeping," for example, knowing how many units of heat energy (calories) are equivalent to how many units of mechanical energy (joules).

In presenting the concept of energy and the law of its conservation, Feynman made up a story of a little boy playing with 28 indestructible blocks (Feynman, 1985). Each day, the boy's mother returns home and sees that there are in fact 28 blocks, until one day, she notices that only 27 are present. The observant mother notices one block lying in the backyard and realizes that her son must have thrown it out the window. Clearly, the number of blocks (like energy) is "conserved" only in a closed system, in which no blocks or energy enters or leaves. In the future, she is more careful not to leave the window open. Another day when the mother returns, she finds that only 25 blocks are present, and she concludes that the missing three blocks must be hidden somewhere—but where?

The boy seeking to make his mother's task harder does not allow her to open a box in which blocks might be hidden. However, the clever mother finds that when she weighs the box, it is heavier than it was when empty by exactly three times the weight of one block, and she draws the obvious conclusion. The game between the mother and the child continues day after day, with the child finding more ingenious places to hide the blocks. One day, for example, he hides several under the dirty water in the sink, but the mother notices that the level of the water has risen by an amount equivalent to the volume of two blocks. Notice that the mother never sees any hidden blocks, but can infer how many are hidden in different places by making careful observations, and now that the windows are closed, she always finds the total number to be conserved. If the mother is so inclined, she might write her finding in terms of the equation for the "conservation of blocks":

$$\text{Number of visible blocks} + \text{number hidden in box} \\ + \text{number hidden in sink} + \cdots = 28,$$

where each of the numbers of hidden blocks had to be inferred from careful measurements, and the three dots suggest any number of other possible hiding places.

Energy conservation is similar to the story with the blocks in that when you take into account all the forms of energy (all the block hiding places), the total amount works out to be a constant. But remember that in order to conclude that the number of blocks was conserved, the mother needed to know exactly how much excess weight in the box, how much rise in dishwater level, etc., corresponded to one block. Exactly the same applies to energy conservation. If we want to see if energy is conserved in some process involving motion and heat, we need to know exactly how many units of heat (calories) are equivalent to each unit of mechanical energy (joules). In fact, this was how the self-taught physicist James Prescott Joule proved that heat was a form of energy. Should we ever find a physical situation in which energy appears not to be conserved, there are only four possible conclusions. See if you can figure out what they are before reading any further.

## 1.4 MIGHT THERE BE SOME NEW FORMS OF ENERGY NOT YET KNOWN?

Feynman's story of the boy and his blocks is an appropriate analogy to humanity's discovery of new forms of energy that are often well hidden and found only when energy conservation seems to be violated. A century ago, for example, who would have dreamed that vast stores of energy exist inside the nucleus of all atoms and might actually be released? Even after the discovery of the atomic nucleus, three decades elapsed before scientists realized that the vast energy the nucleus contained might be harnessed. Finding a new form of energy is of course an exceptionally rare event, and the last time it occurred was in fact with nuclear energy.

It remains conceivable that there exists some as-yet undiscovered forms of energy, but all existing claims for it are unconvincing. The likelihood is that in any situation where energy seems not to be conserved, either the system is not closed or else we simply have not accounted for all the known forms of energy properly. Likewise, those who believe in energy fields surrounding the human body that

## FOUR POSSIBLE CONCLUSIONS IF ENERGY APPEARS NOT TO BE CONSERVED

- We are not dealing with a closed system—energy in one form or another is entering or leaving the system.
- Energy stays within the system but is in some form we neglected to consider (possibly because we did not know that it existed).
- We have made an error in our measurements.
- We have discovered an example of the violation of the law of conservation of energy.

For most physicists, the last possibility is considered sufficiently unthinkable, so that when it seems to be occurring, it prompts proposals for highly radical alternatives—the neutrino, for example, to account for the "missing" energy in the case of the phenomenon known as beta decay—see Chapter 3.

are not detectable by instruments, but which can be manipulated by skilled hand-waving "therapeutic touch" practitioners, are deluding themselves. The idea that living organisms operate based on special energy fields different from the normal electromagnetic fields measureable by instruments is essentially the discredited nineteenth-century belief known as "vitalism." This theory holds that there exists some type of energy innate in living structures or a vital force peculiar to life itself.

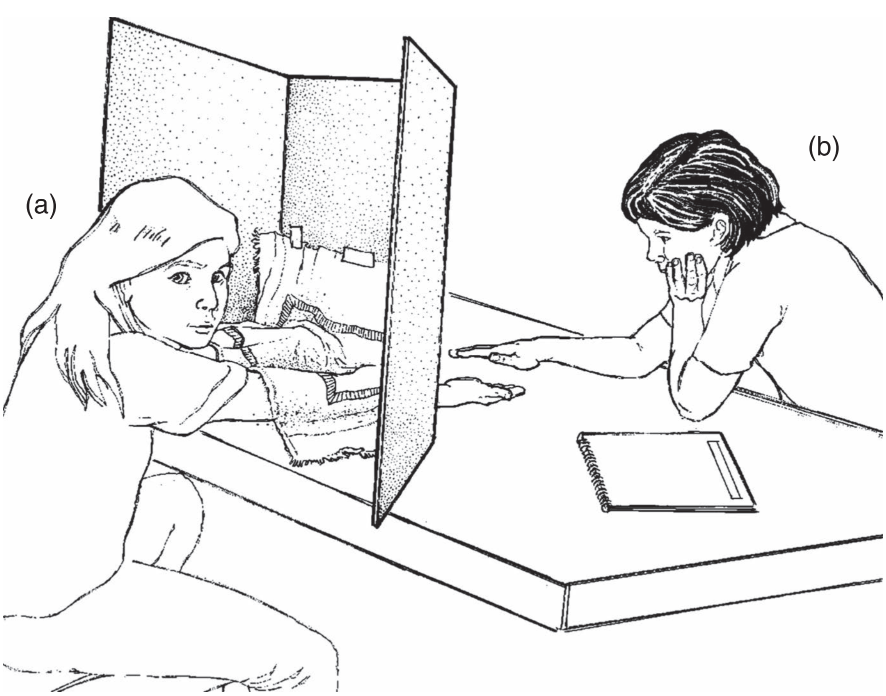


**Figure 1.1** Therapeutic touch practitioner (a) attempting to sense which of her two hands was in the presence of the young experimenter's hand hidden from her view on the right (b). (Courtesy of the Skeptics Society, Altadena, CA.)

In one clever experiment designed and conducted by a sixth-grade student, and published in a prestigious medical journal, practitioners of therapeutic touch were unable to perceive any energy fields where they should have been able to. In fact, they guessed correctly only 44% of the time, i.e., less than chance (Rosa et al., 1998). Needless to say, believers in such nonsense are unlikely to find much of interest in this book (Figure 1.1).

## 1.5 WHAT ARE THE UNITS OF ENERGY?

The fact that energy exists in many forms is part of the reason why there are so many different units for this quantity—for example, calories and British thermal units (BTUs) are typically used for heat; Joules, ergs, and foot-pounds for mechanical energy; kilowatt-hours for electrical energy; and million electron volts (MeV) for nuclear energy. However, since all these units describe the same fundamental entity, there must be conversion factors relating them all. To make matters more even confusing, there are a whole host of separate units for the quantity power, which refers to the rate at which energy is produced or consumed, i.e.,

$$p = \frac{\mathrm{d}E}{\mathrm{d}t} = \dot{E} \quad \text{or} \quad E = \int p\,\mathrm{d}t. \tag{1.1}$$

Note that a dot over any quantity is used as shorthand for its time derivative. Many power and energy units unfortunately sound similar, e.g., kilowatts are power, whereas kilowatt-hour (abbreviated kWh) is energy (Table 1.1).

**Table 1.1 Some Units of Energy**

| Name | Definition |
|---|---|
| Joule (J) | Work done by a 1 N force acting through 1 m (also 1 W s) |
| Erg | Work done by a 1 dyne force acting through 1 cm |
| Calorie (cal) | Heat needed to raise 1 g of water by 1°C |
| BTU | Heat needed to raise 1 lb of water by 1°F |
| Kilowatt-hour (kWh) | Energy of 1 kW of power flowing for 1 h |
| Quad | A quadrillion ($10^{15}$) BTU |
| Therm | 100,000 BTU |
| Electron volt (eV) | Energy gain of an electron moved through a 1 V potential difference |
| Megaton (Mt) | Energy released when a million tons of trinitrotoluene explodes |
| Foot-pound | Work done by a 1 lb force acting through 1 ft |

*Note:* A calorie associated with food is actually 1,000 cal by the aforementioned definition or a kilocalorie (kcal). Sometimes 1 kcal is written as 1 Cal (capitalized C). Readers should be familiar with some of the more important conversion factors.

### DO YOU PAY FOR POWER OR ENERGY?

Electric power plants are rated according to the electric power they produce in megawatts (MW), but for the most part, they charge residential customers merely for the total energy they consume in kilowatt-hours and not the rate at which they use it, or the time of day you use it. The situation is often very different for large consumers, where these factors are taken into account. Moreover, in order to smooth out their demand, some electric utilities actually do allow residential customers to pay a special rate if their usage tends to be very uniform, and in another plan, they bill for very different rates for on-peak and off-peak usage. These special pricing options aside, the utility company charges you the same price to supply you with 100 kWh of energy, whether you use it to light a 100 W bulb for 1,000 h or a 200 W bulb for 500 h.

## 1.6 LAWS OF THERMODYNAMICS

The law of conservation of energy is also known as the first law of thermodynamics, and as we have noted, it has never been observed to be violated. Essentially, as applied to energy, the first law says that "you cannot get something from nothing." The second law, however, is the more interesting one, and it says that "you cannot even break even." Although the second law has many forms, the most common one concerns the generation of mechanical work $W$ from heat $Q_C$, where the subscript C stands for heat of combustion. In general, we may define the energy efficiency of any process as

$$e \equiv \frac{E_{\text{useful}}}{E_{\text{input}}} = \frac{W}{Q_C} = \frac{\dot{W}}{\dot{Q}_C}. \tag{1.2}$$

The last equality in Equation 1.2 reminds us that the equation for efficiency applies equally well to power as to energy. By the first law, the maximum possible value of the efficiency would be 1.0% or 100%. However, the second law places a much more stringent limit on its value. For a process in which fuel combustion takes place at a temperature $T_C$ and heat is expelled to the environment at ambient temperature $T_a$, the efficiency in general, defined as the useful work output divided by the heat input, cannot exceed the Carnot efficiency:

$$e_C = 1 - \frac{T_a}{T_C}, \tag{1.3}$$

where both temperatures must be in kelvin. This limitation is a direct consequence of the second law of thermodynamics, which states that heat energy spontaneously always flows from high temperatures to low temperatures. The Carnot efficiency would hold only for ideal processes that can take place in either direction equally, which do not exist in the real world, except as limiting cases. For example, were you to take a movie of any real process, such as an isolated swinging pendulum slowing down gradually, there would be no doubt when the movie was run backward or forward. Time-reversible, ideal processes would require that the net entropy $S$ remain constant, where a small change in entropy can be defined in terms of the heat flow dQ at some particular temperature $T$ as

$$dS = \frac{dQ}{T}. \tag{1.4}$$

Thus, an alternative definition of the second law of thermodynamics is that for any real process, $dS>0$.

## Example 1.1: Calculating Energy When Power Varies in Time

Suppose during a test of a nuclear reactor, its power level is ramped up from zero to its rated power of 1,000 MW over a 2 h period, and then after running at full power for 6 h, it is ramped back down to zero over a 2 h period. Calculate the total energy generated by the reactor during those 10 h.

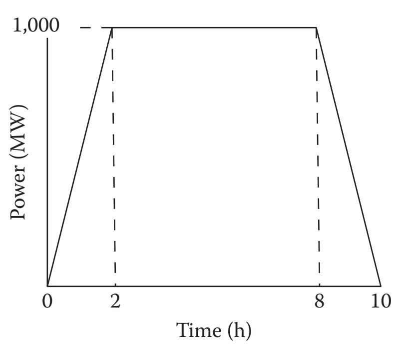


**Figure 1.2** Power profile of nuclear reactor during the 10 h test.

**Solution**

We shall assume here that during the time that the power is ramped up and down, it varies linearly, so that the power the reactor generates varies accordingly during the 10 h test as shown in Figure 1.2.

Based on Equation 1.1, and the definition of the integral as the area under the power–time curve, the energy must be equal to the area of the trapezoid in Figure 1.2 or 8,000 MWh (Table 1.2).

### PERPETUAL-MOTION MACHINES

Over the course of history, many inventors have come up with ideas for devices known as perpetual-motion machines, which generate either energy from nothing (and violate the first law of thermodynamics or the law of conservation of energy) or violate the second law of thermodynamics. In the latter case, the useful work they produce, while less than the heat they consume, exceeds the amount dictated by the Carnot limit. None of these machines have ever worked, although patent applications for them have become so common that the US Patent and Trademark Office (USPTO) has made an official policy of refusing to grant patents for perpetual-motion machines without a working model. In fact, it is interesting that the USPTO has granted quite a few patents for such devices—even some in recent years. However, it is also important to note that granting of a patent does not mean that the invention actually works, only that the patent examiner could not figure out why it would not.

**Table 1.2 Some Common Prefixes Used to Designate Various Powers of 10**

| Prefix | Definition |
|---|---|
| Terra (T) | $10^{12}$ |
| Giga (G) | $10^{9}$ |
| Mega (M) | $10^{6}$ |
| Kilo (k) | $10^{3}$ |
| Milli (m) | $10^{-3}$ |
| Micro (μ) | $10^{-6}$ |
| Nano (n) | $10^{-9}$ |
| Pico (p) | $10^{-12}$ |

## 1.7 WHAT IS AN ENERGY SOURCE?

Some energy sources are stores (repositories) of energy, typically chemical or nuclear, that can be liberated for useful purposes. Other energy sources are flows of energy through the natural environment that is present in varying degrees at particular times and places. An example of the first type of source might be coal, oil, or uranium, while wind or solar energy would be examples of the second type of source. Consider the question of electricity—is it an energy source or not? Electricity does exist in the natural environment in the extreme form of lightning, and therefore, it can be considered to fall into the second category. In fact, lightning could be considered an energy source, since the electric charge from a lightning strike could be captured and stored (in a capacitor) and then later released for useful purposes. Anyone watching a storm is likely to marvel at the awesome power of a lightning bolt, which is indeed prodigious—typically about 1 TW ($10^{12}$ W). This amount is equal to the power output of a thousand 1,000 MW nuclear reactors—more than what exists in the entire world! Such a comparison may prompt the thought: Great! Why not harness lightning as an energy source? The problem is not figuring out how to capture the lightning, but rather that while the power is very high, the energy lightning contains is quite small, since a lightning bolt lasts for such a short time—around 30 $\mu s = 3\times10^{-5}$ s; so by Equation 1.1, the energy contained is around $10^{12}\times3\times10^{-5}=3\times10^{7}$ J=30 MJ. Thirty million joules may sound impressive, but suppose we designed a "lightning catcher" that managed to capture say 10% of this energy. It would be sufficient to only light a 100 W light bulb for a time, $t=E/p=3\times10^{6}$ J/100 W=3,000 s, which is just under an hour—hardly a useful energy source, considering the likely expense involved.

What about electricity that humans create—can it be thought of as an energy source? Hardly! Any electricity that we create requires energy input of an amount that is greater than that of the electricity itself, since some energy will always be lost to the environment as heat. Thus, human-created electricity, whether it be from batteries, generators, or solar panels, is not an energy source itself, but merely the product of whatever energy source that created it. In the case of a generator, it would be whatever gave rise to the mechanical energy forcing it to turn, while in the case of a solar panel, it would be the energy in the sunlight incident on the panel.

## 1.8 WHAT EXACTLY IS THE WORLD'S ENERGY PROBLEM?

All sources of energy have some environmental impact, but as you are aware, the impacts of different sources considerably vary. The energy sources people worry the most about are fossil fuels (coal, oil, and gas) as well as nuclear, while the renewable ("green") energy sources are considered much more benign—even though they too have some harmful impacts. Moreover, the environmental impact of fossil fuel and nuclear energy usage has gotten worse over time, as the human population has grown and the energy usage per capita has also grown—an inevitable consequence of the rise in living standards worldwide. This is not to say that higher per capita wealth invariably requires higher per capita energy usage, but the two are strongly correlated. People are well aware of the harmful environmental impacts of fossil fuel and nuclear plants based on dramatic events, reported in the news of oil spills, coal mine disasters, and nuclear meltdowns such as that at Fukushima, Japan. Other impacts involving air, water, and land pollution may be ongoing and less dramatic but may cost many more lives over the long term.

### 1.8.1 Climate Change

The long-term environmental impact raising perhaps the greatest level of concern among many people is that of global climate change or global warming associated with the increasing level of greenhouse gases put into the Earth's atmosphere from a variety of causes, but most notably the burning of fossil fuels. The basic science behind the greenhouse effect is solid. There is no debate among scientists concerning whether (a) atmospheric greenhouse gas levels have been significantly rising over time due to human actions and (b) these rising emissions are responsible for some degree of climate change—which most climate scientists consider the predominant cause.

Periodically, the Intergovernmental Panel on Climate Change (IPCC), an international collaboration of hundreds of climate scientists, issues reports summarizing the state of the science behind climate change. The most recent comprehensive assessment *The IPCC Sixth Assessment Report* (issued in 2022) states that "it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th Century." Finally, a widely cited survey found that 97.4% of active researchers in climate science believe that "human activity is a significant contributing factor in changing mean global temperatures" (Doran and Kendall Zimmerman, 2009; Cook et al., 2016). Some have used the results of this survey to draw the conclusion that the issue of human-caused global warming is therefore entirely settled among climate scientists, which is perhaps a bit of an overstatement. Agreeing that the human-caused component of climate change is "significant," i.e., not trivial, is not at all the same as agreeing that it is the only cause. More importantly, issues in science are never decided on the basis of a majority vote, but on the merits of the arguments. Nevertheless, surveys of the general public on the issue of global warming sharply contrast with those of climate scientists, with far smaller percentages of people believing that human actions are primarily responsible. Chapter 9 discusses the topic of climate change in much greater depth, and Chapter 14 discusses why levels of climate change skepticism have risen so significantly in the United States and suggests a way forward to bridge the divide.

### 1.8.2 Is Human Population Growth the Root Cause of Our Energy and Environmental Problem?

The Reverend Thomas Robert Malthus, who lived from 1766 to 1834, was an economist noted for his highly influential writings on demography and the growth in human population. Like many other economists, he was also a pessimist about human nature. Writing at a time when the impact of the industrial revolution had begun to fuel a growth in human population that had been static for many centuries, Malthus realized that "the power of population is indefinitely greater than the power of the Earth to produce subsistence for man." Advances in technology undreamed of by Malthus have led part of humanity to live in a manner to which kings of his day might aspire, and they allowed the numbers of humans to reach levels far in excess of what then existed. Malthus, being pessimistic regarding the future progress of humanity, believed that throughout history, through wars, epidemics, or famines abetted by population, pressures would always lead to a substantial fraction of humanity to live in misery. To Malthus's list of scourges of famine, war, and disease, modern-day observers might add drastic climate change; pollution; species loss; and shortages in natural resources, energy, and water—all of which are exacerbated by overpopulation (Figure 1.3).

Although the growth in the human population has significantly slowed in recent decades, it is unclear if it has happened in time to avert catastrophe, with some observers maintaining that the Earth has already far too many humans to have a long-term future that is sustainable. Currently, half of humanity survives on <$2.50/day, and the gap between the developed and developing worlds may widen rather than narrow because of demographic trends. Even though

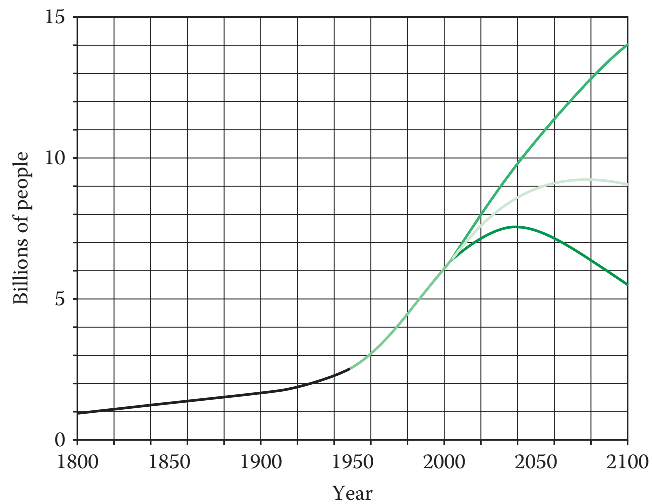


**Figure 1.3** World population growth since 1800 based on United Nations (UN) 2010 projections and US Census Bureau historical estimates. The two curves show the high and low estimates beyond 2010 for the population growth according to the UN.

the populations in many developed nations have begun to decline, demographers foresee an inevitable increase in population throughout the first half of this century given the high fertility of previous generations and the numbers of future parents who are already alive (even if their fertility is relatively lower), with the largest increases coming in regions where poverty is endemic.

One of the prominent twentieth-century environmentalists who foresaw disaster stemming from overpopulation was the biologist Paul Ehrlich (no relation), whose famous and controversial 1968 book, *The Population Bomb*, began with the dramatic and explicit statement:

> The battle to feed all of humanity is over. In the 1970s hundreds of millions of people will starve to death in spite of any crash programs embarked upon now. At this late date nothing can prevent a substantial increase in the world death rate…
>
> Ehrlich (1968)

Of course, while many drought- or war-induced famines have occurred, none has been on the scale and time frame suggested by Ehrlich. Yet the concern over an eventual day of reckoning unabatedly continues among many environmentalists who believe that the Earth is well past its carrying capacity, in terms of the maximum human population it can support.

If the Earth is indeed already 50% beyond its capacity as some environmentalists such as Paul Gilding believe, then improvements in energy efficiency might do little to solve the root cause of humanity's problem, namely, too many people. Given that demographers tell us that the population will continue to rise by roughly another 50% by around 2050, with an ever-larger percentage living in poverty, the old scourges of epidemics, famine, and war and the new ones of climate change, species loss, and resource shortages might well cause mass suffering and death on an unimaginable scale. Surprisingly, Gilding himself believes in a possible happier ending to the story. Just as the imminent prospect of a hanging does wonders to concentrate the mind, Gilding thinks that when the coming "Great Disruption" does arrive, we will finally act like grown-ups and take the concerted drastic actions required "at a scale and speed we can barely imagine today, completely transforming our economy, including our energy and transport industries in just a few short decades." Let us hope he is right and Malthus and Paul Ehrlich are wrong.

### 1.8.3 How Much Time Do We Have?

The question of how quickly the world needs to move away from fossil fuels is, of course, a matter of considerable debate, depending on how serious the threat of climate change is viewed. If it is likely to be as catastrophic as some citizens and scientists believe, with the possibility of a "tipping point" if the global average temperature should rise by 2°C, then we would have almost no margin for error and need to take urgent action. As noted earlier, some environmentalists believe that it is already too late to forestall disaster.

Quite apart from climate change and the other environmental issues connected with fossil fuels, there are many other reasons the world needs to transition away from these energy sources, most importantly, that we do not have a choice. None of them can be considered renewable, and all will gradually be running out—some sooner than others. It is believed, for example, the world has perhaps a 20-year supply of oil left, and that "peak oil" production is probably occurring about the time you are reading this, meaning that depending on economic conditions, oil should become increasingly scarce in years to come. Thus, shifting away from fossil fuels (oil in particular) is a matter of assuring an adequate energy supply, as well as promoting national (and global security) and economic well-being—especially for nations such as Japan that depends so heavily on foreign sources.

## 1.9 HOW IS GREEN OR RENEWABLE ENERGY DEFINED?

We have already used the term *renewable energy*, so it might be worthwhile to define it and delineate its properties. One definition is that energy is considered renewable if it comes from natural resources. Many of these renewable sources are driven by the sun, including wind, hydropower, ocean waves, biomass from photosynthesis, and, of course, direct solar energy. Hydropower is solar driven because solar heating is what drives the planet's water cycle. Several other types of renewable energy are the tides (mainly due to the moon, not the sun) and geothermal power from the Earth's hot interior. The magnitude

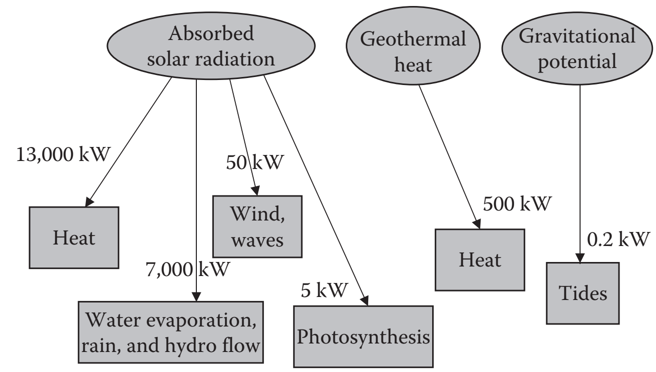


**Figure 1.4** Per capita power influxes from renewable sources accessible at the Earth's surface. In the case of geothermal, however, the power would require drilling wells to be accessed.

**Table 1.3 Desirable Properties and Drawbacks of Renewable Energy Sources**

| Desirable Properties | Drawbacks |
|---|---|
| Virtually inexhaustible | Some highly intermittent in time |
| Intrinsically nonpolluting | May be distant from populations |
| Sustainable | Very dilute (large footprint) |
| Fuel is free | Upfront costs involved |
| Ideal for off-grid use and distributed power | May be more costly (ignoring extrinsic costs)<br>May involve some degree of environmental issues |

of the amount of renewable energy sources available at the surface of the Earth is in total truly astounding. The numbers given in Figure 1.4 are on a per capita basis, so if you wanted to find the actual totals for the planet, just multiply by the world's population—about 8 billion. They have been expressed on a per capita basis because they can then be easily compared to the per capita power used on a worldwide basis, 35 kW. (The figure for the United States is four times as great or about 1.4 kW.) As shown in Figure 1.4, the influx of solar radiation dwarfs all the other flows, and it is about 5,000 times the power now used by humans worldwide. One consequence of this fact is that if we could collect solar energy with 100% efficiency, it would be necessary to cover only a mere 1/5,000 of the surface of the planet with solar collectors to generate all the energy currently used in the world.

One further type of renewable energy not derived from natural resources involves converting the wastes of human civilization into energy—which is done at some landfills or wastewater treatment plants that create methane gas from which they then create electricity. There are five key properties that renewable energy sources share that make them very desirable, and there are also some drawbacks to some of them (Table 1.3).

The concept of sustainability essentially means that their usage in no way compromises the needs of future generations' need for energy, since nothing is being "used up." Some of the renewable sources satisfy these conditions better than others. For example, geothermal energy, while it is present everywhere, is much more accessible in some places than others, depending on how deep underground you need to go to access high temperatures, but it is also much less intermittent in time than most of the others. Wind (much more than solar) is highly dependent on location, since in many areas, the wind speed is insufficient to make it a viable alternative. Thus, in some sense, we can talk about "prospecting" for renewable sources (finding the best places for particular ones), just as we talk about prospecting for mineral resources. It is interesting, however, that a nation's policies may count for more than the amount of the resource available. Germany, for example, the world's second largest per capita user of solar energy, is not noted for many sunny days!

## 1.10 WHY HAS RENEWABLE ENERGY AND CONSERVATION BEEN NEGLECTED UNTIL FAIRLY RECENTLY?

It is a bit misleading to think of humans' use of renewable energy being especially recent, since some renewable sources have been with us for millennia, including wind (to propel sailing ships and windmills), biomass/solar (growing food and lumber), and hydropower. Nevertheless, there has clearly been a relatively recent effort to move toward the greater usage of renewable sources, which currently account for a very small fraction of society's total energy use, at least in most nations. There are many reasons aside from simple inertia why moving away from fossil fuels and toward renewable energy has and will continue to be a challenge. First, the awareness of the environmental problems associated with fossil fuels has come very gradually, and views on the seriousness of the threat posed by climate change considerably vary. Moreover, in times of economic uncertainty, long-term environmental issues can easily take a backseat to more immediate concerns, especially for homeowners (Figure 1.5).

Second, compared to fossil fuels, there are problems with renewable sources, which may be very dispersed, intermittent, and expensive—although the cost differential widely varies and often fails to take into account what economists refer to as *externalities*, i.e., costs incurred by society as a whole or the environment. The intermittency poses special problems if the renewable source is used to generate electricity at large central power plants connected to the grid. One can cope with this problem using various energy storage methods and upgrades to the electric power grid, but, of course, both have costs. Many renewable sources have in the past not been cost-competitive compared to fossil fuels, although this is rapidly changing and as Table 1.4 shows, most renewable sources compare quite favorably in terms of cost of electric power generation. The low values of the capacity for some renewable sources (especially wind and solar), attributable to their intermittent nature, do however represent a serious drawback and require other dispatchable, and generally less green, power sources.

**Figure 1.5** Solar panels installed on the roof of a home. (Image from Shutterstock.)

**Table 1.4 Costs of Generating Electric Power in Dollars per Megawatt Installed**

| Source | $/MWh | Capacity (%) |
|---|---|---|
| *Geothermal* | 35.13 | 90 |
| Gas (comb cycle) | 37.11 | 87 |
| *Wind (onshore/offshore)* | 36.93 | 41 |
| *Hydro (2020)* | 39.54 | 73 |
| Coal (2015) | 95.1 | 85 |
| Adv nuclear (2018) | 90.1 | 90 |
| *Biomass (2019)* | 92.1 | 83 |
| *Solar PV* | 29.04 | 30 |
| Coal with CCS (2015) | 144.4 | 85 |
| *Wind (offshore)* | 120.52 | 45 |
| *Solar thermal (2015)* | 220.6 | 20 |

*Source:* EIA (Energy Information Administration), *Annual Energy Outlook 2021* (If not 2021, dates indicate the last time each type of power plant was constructed in the United States), Energy Information Administration, Washington, DC, 2011.

*Note:* The *capacity* refers to the average power actually generated as a percentage of the maximum rated power for that source. Renewable (green) sources are shown as italicized. CCS, carbon capture and storage.

*Energy conservation* in this section title is, of course, being used in a sense other than the law of energy conservation. Here, it refers to using less of energy and using it more efficiently. Conservation can be thought of as an *energy source* in a sense that it lessens the need for more generating capacity. There is considerable opportunity for energy conservation to make a major difference given the amount of energy wasted in various sectors of the economy, especially in the United States. Some types of energy conservation such as upgrading the insulation of your home do involve upfront costs, but many do not and instead involve simple behavioral changes, such as carpooling or turning down your home thermostat. As we shall see in Chapter 12, even when upfront costs are involved, the payback on the initial investment can be enormous, for example, in the case of replacing incandescent light bulbs with light-emitting diodes or upgrading poor insulation.

## 1.11 DOES ENERGY EFFICIENCY REALLY MATTER?

The question posed in the section title is not intended to be provocative, because there are situations where energy efficiency (usually very worthwhile) does not matter. It is always important, for example, to look at overall efficiencies and not merely the efficiency of one part of a process. Thus, the process of heating water using an electric hot water heater is 100% efficient ($e=1.0$), because all the electrical energy is used to produce heat, but this fact is irrelevant since it ignores the energy inefficiency inherent in producing electricity at the power plant and delivering it to your home. In fact, for this reason gas-fired hot water heaters are a significant improvement over electric ones on an overall efficiency basis. Another case where energy efficiency may be irrelevant involves any renewable energy source (where the fuel is free and abundant). The following example will clarify this point.

### Example 1.2: Which Solar Panels Are Superior?

Suppose that ten type A solar panels produced enough power for your electricity needs, had a lifetime of 30 years, cost only $1,000, but had an efficiency of only 5%. Five type B panels cost $5,000, but they had an efficiency of 10%, and lasted only 15 not 30 years. Which panels should you buy assuming the installation costs were the same for both types of panels?

**Solution**

Obviously, the more efficient panels would take up only half the area on your roof than the type A panels, but who cares if they both met your needs. The cost over a 30-year period would be \$1,000 for the type A panels, but \$10,000 for the more efficient type B panels that produced the same amount of power (since they last only half as long), so clearly you would opt for the less efficient choice in this case. As a general rule, as long as the fuel is free, and there are no differences in labor or maintenance costs, your primary consideration would almost always be based on cost per unit energy generated over some fixed period—usually the lifetime of the longer-lived alternative.

## 1.12 WHICH RENEWABLE ENERGY SOURCES HOLD THE GREATEST PROMISE?

Each of the renewable energy sources is best for a given location depending on its availability. It is difficult to say which renewable energy source is likely to hold the greatest promise in the future, since a technological breakthrough could elevate one of the sources considered to have limited application, e.g., geothermal, to the first tier. In the past, two sources have generated the greatest amounts of power, namely, hydropower (3.4%) and biomass (10%), mainly used for heating, with all the other renewable sources constituting about 3% of the final energy consumed. Although there is considerable room for expansion of hydropower in the developing nations, its expansion in the developed world will probably be less significant, given that the best sites have already been used. Biofuels will likely continue to be important, especially as a transportation fuel as an alternative to electric vehicles. On a worldwide (average) basis, however, the two sources likely to have the greatest impact in the future are wind and solar power. Wind power is already economically viable for centralized power generation, and photovoltaic (PV) solar cells are below cost parity with conventional sources like coal-fired generating plants in parts of the United States.

The growth in installed photovoltaic (IPV) solar panels for electric power generation by both central power plants and individuals has been phenomenal, increasing 1 million percent since 1975. As shown in Figure 1.6, due to their declining cost as a result of technological improvements, the growth has been roughly consistent with being an exponential function—the trend line in Figure 1.6, indicating a constant percentage annual growth of 25.8%, is described by

$$\mathrm{IPV} = 4.92\exp(0.247t), \tag{1.5}$$

where $t$ is the year minus 1975 and IPV represents the amount of IPV solar cells in megawatts.

### THE RULE OF 70

According to this rule, the doubling time in years for any quantity that grows by a fixed percentage $p$ each year can be found to be ~$70/p$ years. You can easily verify this rule by starting with $df/dt = pf$ and integrating to find $f = f_0 e^{pt}$. Finally, just solve for $t$ that gives $f = 0.5f_0$ and you obtain $t = 69.3/p \approx 70/p$. The rule of 70 works equally well for a quantity that decreases at a fixed percentage each year if we wish to estimate the halving time.

In 2017, the IPV supplied about 8% of the world's total energy. As an exercise, we estimate using the "rule of 70" that with a 25.8% annual growth rate, the amount of IPV doubles every $70/25.8 \approx 2.5$ years. To increase from 0.8% to 100% requires an increase by a factor of $100/0.8 \approx 125$, which is about seven doublings, or 17.5 years. Thus, solar PV would be a major proportion of the world's energy mix by the year 2040, if its exponential growth were to continue.

At the same time that solar panel installations have been exponentially growing, their costs have been steadily declining. In fact, an interesting empirical relation has also been discovered between the cost of PV power and the cumulative amount deployed that holds true over the entire time period since 1975 (Handleman, 2008):

$$\mathrm{IPV} \approx \frac{31{,}900}{C^3}, \tag{1.6}$$

where C is the cost in dollars per watt.

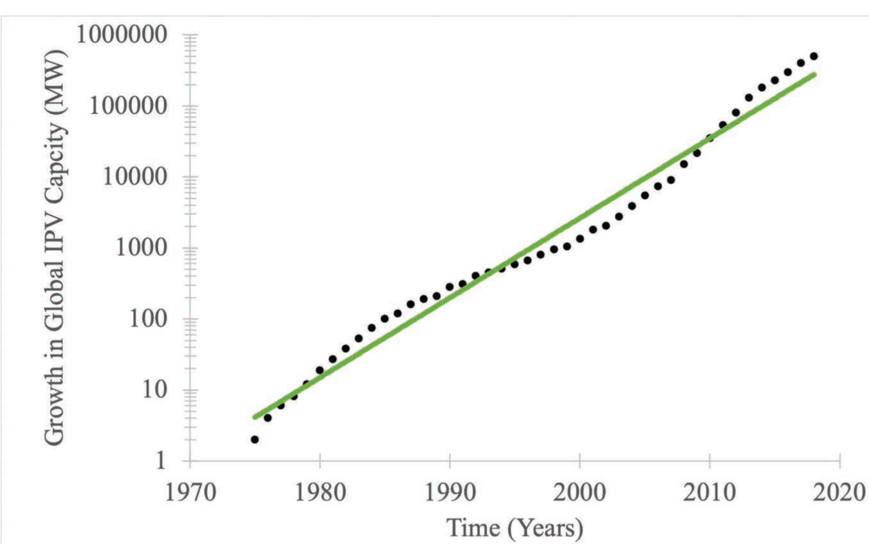


**Figure 1.6** Growth in global IPV capacity in megawatts. (Courtesy of Earth Policy Institute, Washington, DC. Data compiled by Earth Policy Institute, with 1975–1979 data from Worldwatch Institute, *Signposts 2004*, CD-ROM, Worldwatch Institute, Washington, DC, 2004; 1980–2000 from Worldwatch Institute, *Vital Signs 2007–2008*, Worldwatch Institute, Washington, DC, 2008, p. 39; 2001–2006 from Prometheus Institute and Greentech Media, 25th annual data collection results: PV production explodes in 2008, *PVNews*, 28(4), 15–18, April 2009. As well as data compiled by British Petroleum's Statistical Review of World Energy, 1996–2020.)

| Table 1.5 Advantages of Solar over Wind Power |
|---|
| *Potential*: Solar is suited to a much greater range of geographic locations than wind. |
| *Expense*: The best location for wind is offshore, which is very expensive to exploit. |
| *Maintenance*: Solar requires less maintenance than wind and is easier to install. |
| *Distributed power*: Solar is usually more suited to distributed power usage by individuals. |
| *Diversity*: Solar has three different ways it can be pursued, including PV, solar thermal, and solar chimneys, which are discussed in various subsequent chapters. |

Thus, according to this relation, exponentially declining costs are associated with exponentially rising cumulative PV deployment (Figure 1.6).

Although wind and solar may each be the better choice for a particular location, there is some basis for considering solar to be the better source on an overall average basis (Table 1.5).

## 1.13 WHO ARE THE WORLD LEADERS IN RENEWABLE ENERGY?

China is, in most regards, the leader in renewable energy. They produce nearly three times the renewable energy as the United States, which is second. Renewable sources accounts for over 24.35% of China's total electricity capacity compared to 14.7% for the United States. Together, China and the United States have invested half the world's total toward developing renewable energy, but it also needs to be said that they account for nearly half of the world's $CO_2$ emissions, which is not too surprising as they are the two largest economies.

- *China*: Unlike the West, whose leaders could possibly be accused of putting emotion ahead of reasoned analysis and paying too much attention to public opinion, China's leadership certainly falls at the other end of the spectrum. Of course, having an authoritarian system does make it easier to engage in long-term planning and execution, unhindered by serious opposition from either the public or an opposition political party—a case in point being the Three Gorges Dam and power plant that displaced over a million people from their homes and did considerable environmental damage. China's ability to forge ahead in the renewable energy area has also been greatly assisted by the government subsidies, which include tax breaks, low interest loans, and free land for factories, which has led to some American solar manufacturers to relocate there. The Chinese have several other advantages allowing them to become the world leaders in renewable energy, including an abundant pool of scientific and engineering talent, an immense pool of relatively cheap labor, and a near monopoly (90%) on the world supply of rare earth elements. These elements, such as dysprosium, neodymium, terbium, europium, yttrium, and indium, are considered to be of critical importance to clean energy technologies. Despite China's commitment to renewable energy it is even more strongly committed to increasing its energy-generating capacity generally, including fossil fuel and nuclear power, and it has been building several new coal-fired generating plant each week with plans to do so for years to come. While China's new coal plants may incorporate pollution abatement technology, on average, its plants are more polluting than those in the West, and air pollution (as well as coal miner deaths) represents serious problems—much as it did in Western nations in years past. The Chinese government very likely cares about the environment, but it probably cares more for building its economy, increasing its citizens' living standards, and, more importantly, becoming a leading power on the world scene.

- *United States*: Although renewable energy still constitutes a small fraction of the nation's energy usage, the United States appears to be back on track to expanding it, and it is second only to China in the magnitude of its investment. Additionally, according to public opinion polls, many citizens support renewable energy, even if they may be skeptical about human-caused climate change. Unfortunately, many policies that could lead to greater usage of renewable energy, such as a "renewable energy standard (RES)" requiring utilities to generate a certain fraction of their power from renewable sources, exist only at the state and not the federal level, although some states such as California are quite generous in their support, and even states such as Texas, noted for its conservative political outlook, are very receptive toward wind power. At the federal government, the political gridlock of a divided government had stymied actions on advancing renewable energy, apart from those mandated by the executive branch during previous democratic administrations. The last republican administration openly supported fossil fuel exploration and exploitation, and attempted to undermine renewable energy, nonetheless the United States has continued to see some dramatic increases in renewables, particularly wind, and more recently solar, and has been able to reduce carbon emissions nearly 25% over the last decade. And even though continuing subsidies for energy from fossil fuel and nuclear energy continue to be significantly greater in the United States than those for renewable energy, with the bulk of the subsidies being in the form of tax breaks (Shahan, 2011; Timperley, 2021) renewable energy is continuing to become more competitive. The current democratic administration has announced that they intend for the country to be carbon neutral by 2035, which is most likely overly ambitious considering it would require the rate of reduction in the percentage of fossil fuels to double for the next decade and a half. However, it is not unreasonable to consider a drastic increase in solar and wind power, join existing hydrothermal, hydroelectric, along with a shoring up of the nuclear fleet to provide low-carbon electrical power that can be complemented by near carbon neutral biofuels to provide the majority of electrical power. These increases along with the elimination of coal for power, a waning reliance on oil, and relegating natural gas as a dispatchable source alongside nuclear and biofuels to compliment intermittent renewables, could see the United States at a very low level of carbon emission by the middle of the next decade. One key aspect of this reduction will be the reduction of emissions from transportation. The federal government has committed to raising the mileage standard in new automobiles over a period—an important way of achieving greater energy efficiency in the transportation sector. Perhaps the advancements in range and acceptance of electric vehicles will enable the most dramatic improvements in carbon reduction.

## 1.14 WHAT IS OUR LIKELY ENERGY FUTURE?

Given that the world population continues to grow, and many developing nations have a growing appetite for a better living standard, it is virtually inevitable that the demand for energy will grow during the coming decades. The mix of energy sources contributing to that growth is much less certain—especially if it is long term. One such projection is shown in Figure 1.7 made by the German Advisory Council on Global Change through the year 2300.

There are several interesting aspects to the projections in Figure 1.7. The first is that even though renewable sources are expected to provide a greater share of the world's energy, the council foresees little major redistribution of the mix through 2030 and some presence of the three fossil fuels through the entire coming century, with coal—the most environmentally harmful source—cutting back the most. The most interesting projection, however, is that by far, the dominant renewable source, especially after 2050, will be solar.

### AN INAPPROPRIATE TOPIC?

Some instructors may believe that it is inappropriate to have a section dealing with jobs and careers in a textbook. If you happen to be one of them, please be sure to tell your students that they "are not responsible for the material in this next section, and that it will not be covered on any exams."

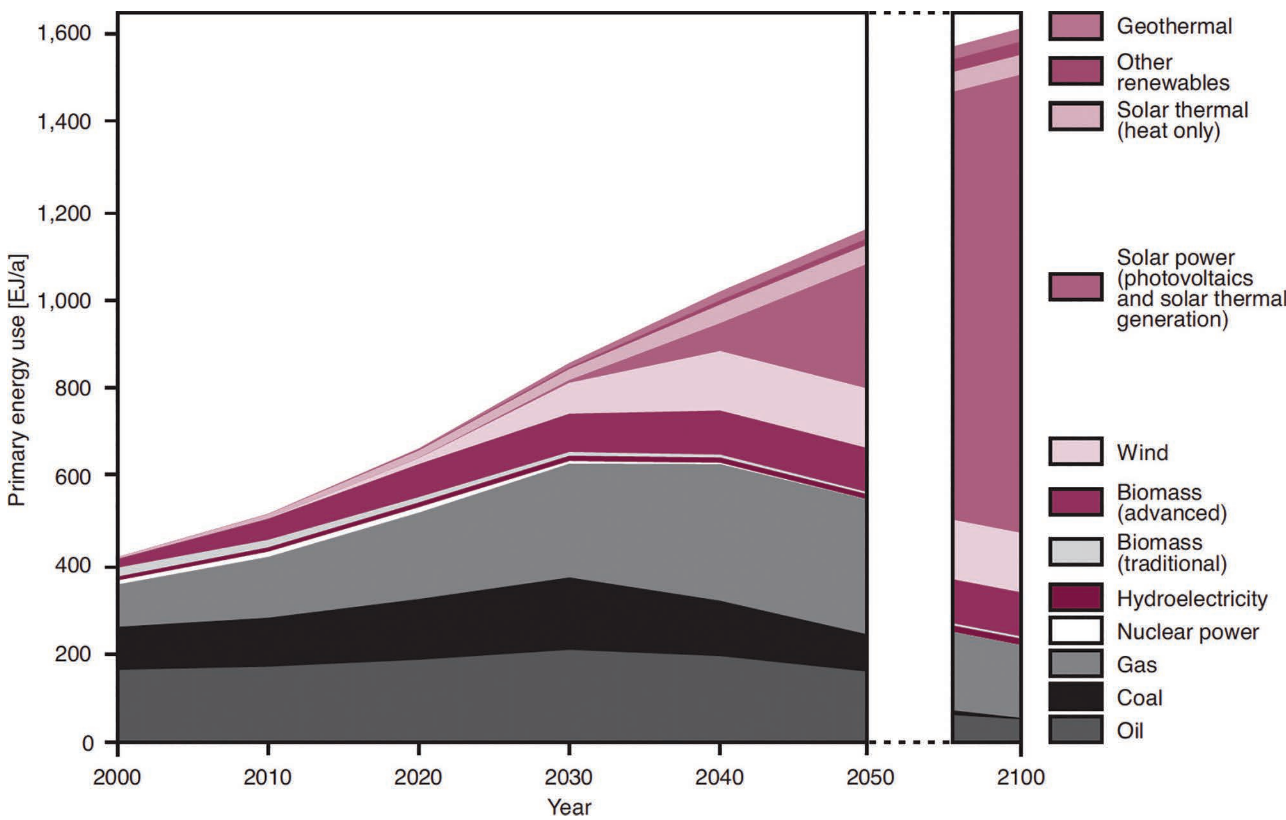


**Figure 1.7** Transforming the global energy mix: The exemplary path until 2050/2100. (From WBGU (German Advisory Council on Global Change), *World in Transition: Towards Sustainable Energy Systems. Summary for Policy-Makers*, WBGU, Berlin, 2003. With permission.)

Are these projections realistic? Lacking a crystal ball, no one can say, but the existing exponential growth of solar (starting from a very tiny base) offers some justification.

### 1.14.1 What Is Projected for Future Employment in the Renewable Energy Field?

Making projections for future employment can be very hazardous, depending as it does on future human actions and the unknown evolution of the global economy. In fact, projecting the likely employment needs 20 years in the future may have almost as much uncertainty as projecting the likely mean global temperatures a century from now, which of course also greatly depend on human actions and the global economy! Nevertheless, given the very strong past growth in both solar and wind powers, which is likely to continue if costs continue to fall, it is reasonable to imagine that the growth might continue on its present trajectory for the next decade or two.

In 2020, the International Renewable Energy Agency (IRENA) reported 756,000 direct and indirect jobs in renewable energy in the United States. According to the US Energy Employment Report (USEER, 2020), all, renewable and nonrenewable, energy source jobs in electrical power generation saw a nearly 1% decline in 2018, and the pandemic of 2020, saw the industry shed more jobs from a high of 855,000 in 2018. According to firms surveyed for the USEER, finding skilled labor to fill positions has been a barrier to increasing employment in renewable energy. A general global increase in renewable jobs, the emergence from a global pandemic, and a democratic administration focused on renewable energy should help to reestablish jobs in renewable energy over the next decade. It should be noted however that many renewable sources require a wave of jobs at the outset, in say manufacturing, sales, and installation, and that an inevitable contraction in renewable jobs will occur as it has in Germany through the last decade.

It is natural for any student thinking about going into the field of renewable energy to wonder what kinds of jobs might be available and what sort of education is needed to best prepare for them. A search on a website advertising current openings in US companies in the renewable energy field came up with the results shown in Table 1.6, with the numbers in parenthesis being the numbers of jobs listed.

Clearly, many of the kinds of jobs listed would require a 4-year degree, and most are in specific areas of study with engineering clearly topping the list, but the various subfields of business also being very important. Although *science* is far down on the list, it must be noted that the website advertises corporate opportunities and would not include opportunities in basic research available at universities, colleges, research institutes, and national laboratories in the renewable energy field. These are not only certainly less numerous, but also have fewer people seeking them. The categories listed in Table 1.6 might apply equally well to work in just about any field, so it might be more relevant to list the kinds of work areas specifically related to renewable energy that one might want to seek to work in. Here is a very partial list in alphabetic order:

**Table 1.6 Number of Job Openings Listed by http://www.careerbuilder.com in Renewable Energy in the United States on May 17, 2021**

| | |
|---|---|
| Management (1278) | Accounting (446) |
| Marketing (1024) | Finance (415) |
| Engineering (859) | Science (314) |
| Customer service (808) | Entry level (307) |
| Design (756) | General business (281) |
| Business development (677) | Quality control (274) |
| Information technology (613) | Manufacturing (234) |
| Sales (524) | Installation maintenance (148) |
| Construction (552) | Administration (144) |
| Professional services (456) | Strategy planning (135) |

*Note:* No listings with fewer than 100 openings are included, and a few vague titles have been omitted.

- Basic research, consulting, consumer education, designing new materials
- Designing smart grid, energy auditing, energy education, environmental impacts
- Environmental abatement, green buildings, solar panel design, and calibration
- Wind turbine design, testing and maintenance, fluid dynamics simulations
- Wind farm management, wind resource assessment, windsmith

How might one prepare for a career in the renewable energy field? It would be useful to have a few courses in renewable energy or perhaps a minor in the subject, such as the one at George Mason University. A minor is perhaps a better preparation than a degree specifically focusing on energy, since many job listings tend to seek people having conventional academic backgrounds with degrees in engineering, business, or science.

## 1.15 COMPLEXITIES IN CHARTING THE BEST COURSE FOR THE FUTURE

As noted earlier, it is imperative that over time, the world will move away from fossil fuels, but the degree of urgency for doing so depends on one's views with regard to the possibility of a catastrophic climate change and, in particular, the need to avoid a tipping point in the climate system. Even if one is committed to moving toward renewable on a long-term basis, there remains the serious question of what to do in the interim, bearing in mind that some fossil fuels are more environmentally harmful than others and that in an era of economic uncertainty, we need to be cognizant of economic costs as well as environmental benefits. Other controversial matters include the long-term role of nuclear power and whether carbon sequestration could enable coal to become a clean energy source. Perhaps most controversial is the notion as to whether some form of geoengineering, i.e., manipulating the Earth's climate to counteract rising $CO_2$ levels, might be worthwhile or whether the dangers are simply unacceptable. These issues will be fully explored in subsequent chapters, especially Chapters 4 and 14.

As one example of the complexities facing us in trying to plan the best way forward, consider our continued reliance on natural gas. There are many possible positions one might take on this issue, and four of them are sketched out in the following; which of them is the best course depends to a large extent on your assumptions and a mix of environmental and economic issues and the weight you assign to each:

1. Phase out use of natural gas as well as all other fossil fuels as quickly as possible
2. Pursue new natural gas discoveries and use it for power generation instead of coal

3. Pursue new natural gas discoveries and use it for transportation instead of petroleum
4. Pursue new natural gas discoveries and use it for both transportation and power generation

Here, for example, is the argument for option 3. Natural gas emits significantly less pollutants as well as greenhouse gases than coal. Even though there are environmental problems with natural gas extraction involving fracking, they should be manageable if adequate precautions are taken, and its overall environmental impact is significantly less than coal. Due to recent discoveries of natural gas, its price has considerably dropped, and the amount available in the United States has more than doubled over the last two decades. Currently it provides 40% of all electrical power generation and two-thirds of power from fossil fuels. At its current usage the United States has supplies that should extend over 80 years; however, if gas were resigned to its historical role of highly dispatchable supplemental power, this horizon could be extended. It is also interesting to note that methane, the main constituent of natural gas, can be produced from hydrogen and carbon dioxide making it a potentially carbon neutral fuel.

This property will become increasingly important as more intermittent renewable sources such as wind and solar are used. In fact, few other energy sources besides natural gas have this desirable property, so a plausible argument can be made for not extending its power generation usage beyond supplying power at times of greatest demand, lest the natural gas reserves be used up too quickly. In contrast, the transportation usage of natural gas (as a replacement of petroleum) may be more crucial, because the alternatives are less clear. It may be true that alternatives to petroleum exist in the transportation sector, including all electric vehicles, but they face a competitive market place, though they have begun to find traction climbing past 2% market share in the United States and nearly 5% in China. Technological

## HOW CAN LESS BE MORE?

One illustration of the counterintuitive consequences that can occur when fossil fuel sources are replaced by renewables was done in a test conducted by the Bentek Energy Company (Bentek, 2010). In the test, wind turbines offset a certain fraction of the power supplied by a coal plant, and the coal plant needed to have its power output changed to compensate for the variability of the wind generators. One might imagine the use of wind to replace some of the power from the coal plant would have resulted in a reduction of $CO_2$ emissions (for the same total power output), but exactly the opposite occurred since coal plants that are cycled up and down on a short timescale are much less efficient. As we have seen, natural gas plants do not suffer from this drawback, and had they been used instead in conjunction with the wind turbine emissions would have been reduced.

advancements and over a decade of reliable and safe performance have made consumers less concerned about range, recharging, and safety.

Notice how in making the argument to use natural gas mainly for a transportation fuel rather than increasing its use in power generation, we have discussed a mix of environmental and economic concerns and, most importantly, a weighing of the alternatives in both the power generation and transportation sectors. It might be worthwhile for you to reflect on what a similar argument might consist of for some other alternative.

### Example 1.3: How the Usage of Wind Power to Offset Coal-Fired Plants Can Generate More Emissions, Not Less

Suppose that a certain fraction of the power produced by a 500 MW coal plant is offset by wind power. Assume that when the coal plant runs at its constant rated power, it has an efficiency of 35%, but when it needs to be ramped up and down to compensate for the wind power variations, its efficiency is reduced according to $e = 0.35 - 0.00001\ p^2$, where $p$ is the amount of wind power. Find the percentage increase in emissions that result when 90 MW of the 500 MW is generated by wind power instead of coal.

**Solution**

In order to generate the full 500 MW by itself, the coal plant requires $500/0.35 = 1{,}429$ MW of heat flow from the coal. If the wind power is 90 MW, the efficiency of the coal plant is reduced to $e = 0.35 - 0.00001\ (90)^3 = 0.269$, and the heat flow required to generate $(500 - 90) = 410$ MW is therefore $410/(0.269) = 1{,}524$ MW. The percentage increase in emissions is the same as the percentage increase in the heat flow to the coal plant, i.e., 6.7%.

## 1.16 SUMMARY

This chapter discusses some background topics on energy. It goes on to discuss the nature of renewable energy, the world's energy–environment problem, and the need to transition away from fossil fuel energy sources with their finite supply and harmful environmental impact—climate change being just one of many. This chapter concludes with a section on employment in the renewable energy field.

## PROBLEMS

*General comments on problems:* The following comments refer to the problems that follow each chapter, including this one. Some of the problems in this book may require your ability to make rough estimates, while in other cases, it is expected that you will be able to locate missing data on the web. However, do not use the web as a substitute to doing calculations, although it is fine to perhaps use it to confirm your answers. Be sure to check that the results of all calculations are reasonable. A number of problems mention using Excel to do a calculation. However, if you are more familiar with other tools such as Basic or Mathematica, feel free to use those instead. In a number of problems, hints are given. Be sure to try to figure out the relevance of any hints. The answers to selected problems are provided at the back of this book.

1. Compare the direct costs to the consumer of using a succession of ten 100 W incandescent light bulbs with an efficiency to visible light of 5%, a lifetime of 1,000 h, and a price of 50 cents with one compact fluorescent lamp giving the same illumination at 22% efficiency, a lifetime of 10,000 h, and a price of $3. Assume a price of electricity of 10 cents per kWh.
2. How many kilowatt-hours would a 1,000 MW nuclear power plant generate in a year?
3. Consider a nuclear power plant whose power level is ramped up from zero to a maximum 1,000 MW and then back down to zero over a 10 h period. Assume that the power level varies as a quadratic function of time during those 10 h. Write an expression for the power as a function of time, and then find the total energy generated by the plant during the 10 h period.
4. The United States generates and uses about 71 quads of energy each year, and its renewable sources generate about 40 GW. If the renewable sources are generating power about a third of the time, what fraction of its energy usage is based on renewable sources?
5. Based on Equation 1.6, by what factor would the total amount of PV solar panels increase if their costs decreased by 30%?
6. Prove that Equation 1.5 implies a 24.7% annual growth rate.
7. If Equations 1.5 and 1.6 continue to hold, at what date would the cost of IPV reach 50 cents/W?
8. Do you think the trend described by Equation 1.5 is the cause or the effect of that suggested by Equation 1.6? Discuss.
9. If the trend illustrated in Figure 1.6 were continued in the future, when would solar cells be able to meet humanity's present energy needs by itself?
10. How large would a square of side $L$ need to be so that if it were covered by 10% efficient solar cells in the middle of the Sahara desert, the power generated would be enough to satisfy the world's present energy needs? Assume that the incident solar radiation striking each square meter of the Earth's surface is ~1,000 W.
11. Using the data in Example 1.3, find the amount of wind power that could be used with a 500 MW coal-fired plant that would result in the least amount of emissions.

12. Although typically electricity customers are charged based merely on the total number of kilowatt-hours they consume, some utilities have payment plans designed to encourage customers to shift their energy use to off-peak times. Suppose that a utility charges most customers a flat 7.9 cents/kWh under their standard plan, but under a special time-of-use plan, it charges 3 cents/kWh for off-peak times (between 10 p.m. and 11 a.m. on weekdays) and 16 cents/kWh at other times. If a customer consumes electricity at the same rate at all times, which plan should he or she sign up for?
13. Figure 1.7 shows solar PV reaching 200 EJ/year that was installed before 2050. Quantitatively compare that projection with the historical trend illustrated in Figure 1.6—note the different units.
14. What is the efficiency of a Carnot engine if the $T_c = T_h$?
15. What must the $T_c$ temperature be in order to obtain a 100% efficient Carnot engine?

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