Chapter

1

Introduction

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1.1 WHY ANOTHER BOOK ON ENERGY?

The idea for this book arose as a result 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. In searching for the right text I found myself disappointed at the selection of books available, which in almost all cases were either too elementary or too advanced. The handful of books at the right level seemed too focused on technicalities that obscured the basic ideas I wanted the course to cover. In addition, I prefer texts that have a relatively informal writing style, with even an occasional touch of humor that was lacking in all the texts I came across. Even though my course focused mainly on renewable energy, I believed it was important also to cover nonrenewable energy (fossil fuels and nuclear specifically), because only then could useful contrasts be drawn, and many of the books I considered omitted those topics. While the course had a physics number and was being taught by a physicist (me), its content did go well beyond physics, although it is fair to say it had a "physics orientation." Physicists do have a certain way of looking at the world that is different from other scientists and also from engineers. They (we) 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 (CT) scanner, to the atomic bomb, were invented and developed by physicists, while their refinement is often done by engineers. Thus, even though engineering is probably the discipline that makes the largest single contribution to the interdisciplinary field of renewable energy, I felt very comfortable as a physicist embarking on the task of writing this book.

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 the world's population, 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 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, as discussed in Chapter 14. The last one that was large enough to do the job apparently was 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.

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 engineering students) 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 your own power using a pedal-powered generator, since even an avid cyclist would only be able to supply at most 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 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 involves some more complicated "bookkeeping," for example, knowing how many units of heat energy (calories) are equivalent to how many units of mechanical energy (joules).

BOX 1.1 HOW MANY JOULES EQUAL ONE CALORIE?

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

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 1 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 only "conserved" 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 only 25 blocks are present, and she concludes 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 when she weighs the box that 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 mother and 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."

$$\begin{aligned}&\text{Number of visible blocks} + \text{Number hidden in box}\\&\quad + \text{Number hidden in sink} + \ldots = 28\end{aligned}$$

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, and 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 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 only found 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.

BOX 1.2 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 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 not seen in the case of the phenomenon known as beta decay—see Chapter 3.

It remains conceivable that there exists some as yet undiscovered form 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

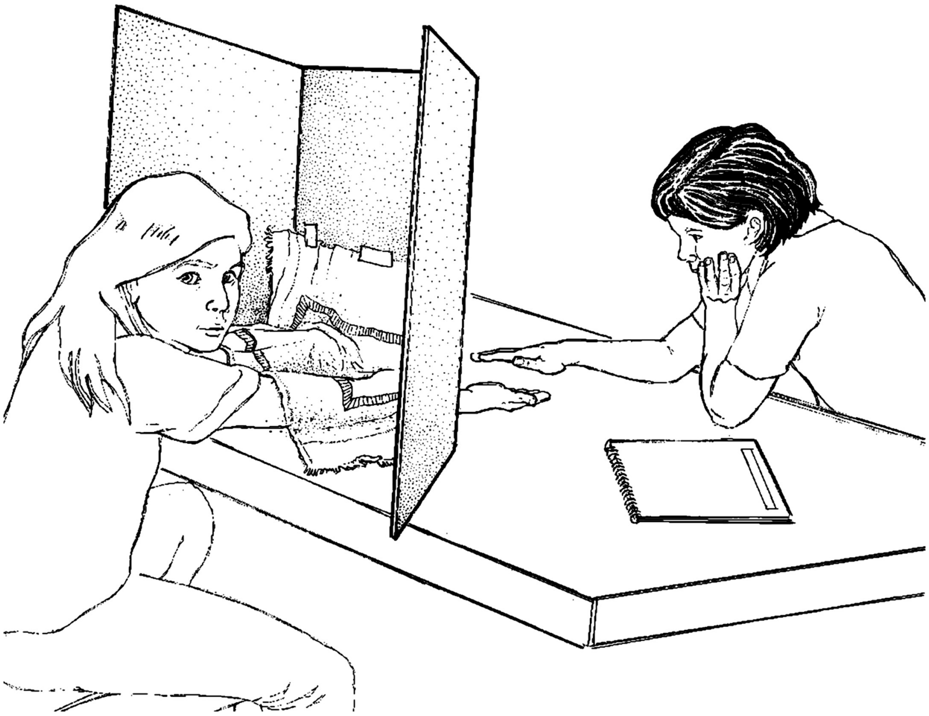

Figure 1.1 Therapeutic touch practitioner (on the left) attempting to sense which of her two hands was in the presence of the young experimenter's hand hidden from her view on the right. (Courtesy of the Skeptics Society, Altadena, CA. With permission.)

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 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.

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, 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;

Table 1.1 Some Units of Energy

Name	Definition
Joule (J)	Work done by a 1 N force acting through 1 m (also a watt-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 (kW-h)	Energy of 1 kW of power flowing for 1 h
Quad	A quadrillion (10^{15}) BTU
Therm	100,000 BTU
ElectronVolt (eV)	Energy gain of an electron moved through a 1 V potential difference
Megaton (Mt)	Energy released when a million tons of TNT explodes
Foot-pound	Work done by a 1 lb force acting through 1 ft

Note: A calorie associated with food is actually 1000 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.

and million electronVolts (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.,

$$p = \frac{dE}{dt} = \dot{E} \quad \text{or} \quad E = \int p\,dt \tag{1.1}$$

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 kW-h) is energy (Table 1.1).

BOX 1.3 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 kW-h, 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 1000 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 "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

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

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 only would hold 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 *d*Q 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 $dS > 0$

BOX 1.4 PERPETUAL MOTION MACHINES

Over the course of history, many inventors have come up with ideas for devices known as perpetual motion machines, which either generate energy from nothing (and violate the first law of thermodynamics or the law of conservation of energy), or 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 United States 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.

1.6.1 Example 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 1000 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.

Solution

We shall assume here that during the time which 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.

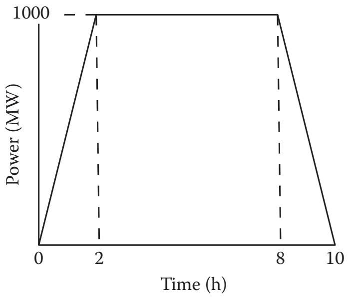

Figure 1.2 Power profile of nuclear reactor during the 10 h test.

Based on Equation 1.1, and the definition of the integral as the area under the power–time curve, the energy must equal the area of the trapezoid in Figure 1.2 or 8000 MWh (Table 1.2).

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 either 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 are 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 1000 MW nuclear reactors—more than 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 such a short time—around $30\,\mu\text{s} = 3\times10^{-5}\,\text{s}$, so by Equation 1.1, the energy contained is around $10^{12}\times3\times10^{-5} = 3\times10^{7}\,\text{J} = 30\,\text{MJ}$. Thirty million joules may sound impressive, but suppose we designed a "lightning catcher" that managed to capture say 10% of this energy. It would only be sufficient to light a 100 W light bulb for a time $t = E/p = 3\times10^{6}\,\text{J}/100\,\text{W} = 3000\,\text{s}$, 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 vary considerably. 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 rising significantly over time due to human actions, and (b) these rising emissions are responsible for some degree of climate change—which most climate scientists consider significant, perhaps even 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 Fourth Assessment Report issued in 2007) found that "human actions are 'very likely' the cause of global warming, meaning a 90% or greater probability." Moreover, a 2007 Statement signed by the national science academies of Brazil, Canada, China, France, Germany, Italy, India, Japan, Mexico, Russia, South Africa, the United Kingdom, and the United States agrees that: "It is unequivocal that the climate is changing, and it is very likely that this is predominantly caused by the increasing human interference with the atmosphere."

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). 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 contrast sharply with those of climate scientists, with far smaller percentages of scientists 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 also 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' 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 slowed significantly in recent decades, it is unclear if it has happened in time to avert catastrophe, with some observers maintaining that the Earth already has far too many humans to have a long-term future that is sustainable. Currently, half of humanity survives on less than $2.50/day, and the gap between the developed and developing world may widen rather than narrow because of demographic trends. Even though the population in many developed nations has 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.

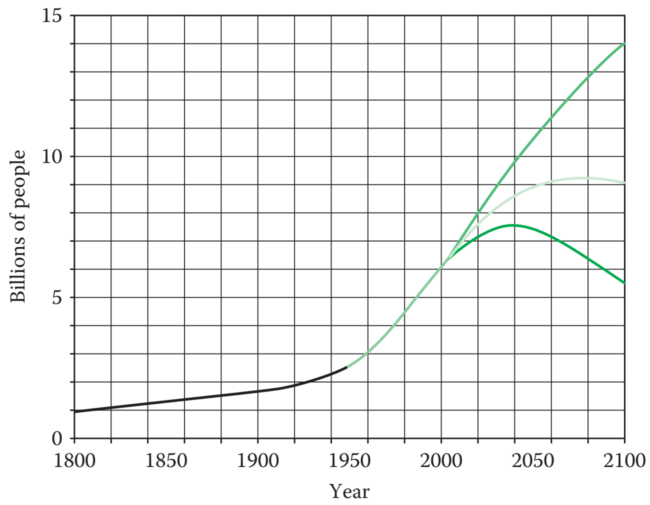

Figure 1.3 World population growth since 1800 based on UN 2004 projections and U.S. Census Bureau historical estimates. The two curves show the high and low estimates beyond 2010 for the population growth according to the UN.

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 have been on the scale and time frame suggested by Ehrlich. Yet the concern over an eventual day of reckoning continues unabated 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 as it does 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 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 40 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 like the United States and Japan that depend 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 of 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 7 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, 2.4 kW. (The figure for the United States is four times as great or about 10 kW.) As shown in Figure 1.4, the influx of solar radiation dwarfs all the other flows and it is about 5000 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 only be necessary to cover a mere 1/5000th the surface of the planet with solar collectors to generate all the energy currently used in the world.

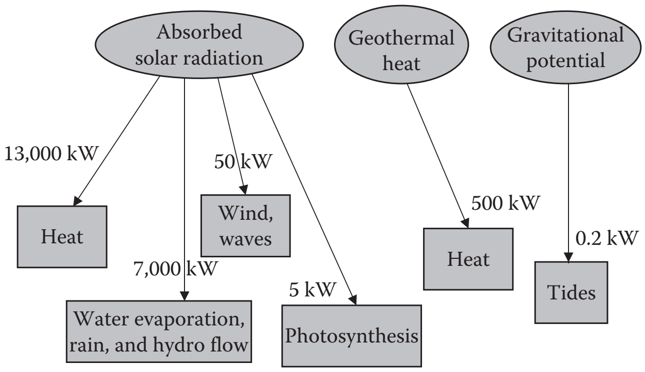

Figure 1.4 Per capita power influxes from renewable sources accessible at the Earth's surface. In the case of geothermal, however, the power would require drilling wells to be accessed.

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") May involve some degree of environmental issues

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 that use garbage to 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 leader in 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 clearly has been a relatively recent effort to move toward 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 vary considerably. 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 varies widely, 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

Figure 1.5 Solar-powered family homes (Note that the home is near Boston, MA.).

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. Cost, in fact, is perhaps the biggest problem with some renewable sources, especially upfront costs. While the fuel may be free, many renewable sources have in the past not been cost-competitive compared to fossil fuels, although this is changing rapidly, and does not apply to renewable sources across the board. As Table 1.4 shows, some of the renewable sources, including geothermal and biomass, and especially hydropower and onshore wind, compare

Table 1.4 Costs of Generating Electric Power per MW Installed as of 2011, with Renewable (Green) Sources Shown Using a Bold Font

Source	$/MWh	Capacity (%)
Gas (comb cycle)	66.1	87.0
Hydro	86.4	52.0
Coal	94.8	85.0
Wind	97.0	34.0
Geothermal	101.7	92.0
Biomass	112.5	83.0
Adv nuclear	113.9	90.0
Coal with CCS	136.2	85.0
Solar PV	210.7	25.0
Wind (offshore)	243.2	34.0
Solar thermal	311.8	18.8

Source: EIA, *Annual Energy Outlook 2011*, 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.

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.

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 if 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 like upgrading your home's insulation 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 (LEDs) or upgrading poor insulation.

1.11 DOES ENERGY EFFICIENCY REALLY MATTER?

This 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.

1.11.1 Example 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 $1000, but they had an efficiency of only 5%. Five type B panels cost $5000 but they had an efficiency of 10%, and lasted only 15 not 30 years. Which panels should you buy?

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 of time—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 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 may soon be at cost parity with conventional sources and expected to reach it around 2020 for coal-fired generating plants.

The growth in installed photovoltaic (IPV) solar panels for electric power generation both by 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 24.7%, is described by the equation

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

where

t is the year minus 1975

IPV represents the amount of installed PV solar cells in MW

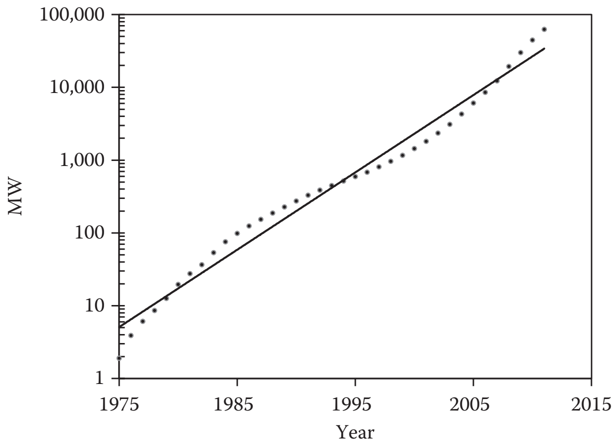

Figure 1.6 Growth in global installed PV capacity in MW. (From EPI, 2011 Data compiled by Earth Policy Institute with 1975–1979 data from Worldwatch Institute, Signposts 2004, CD-ROM, Washington, DC, 2004; 1980–2000 from Worldwatch Institute, Vital Signs 2007–2008, Washington, DC, 2008, p. 39; 2001–2006 from Prometheus Institute and Greentech Media, "25th Annual Data Collection Results: PV Production Explodes in 2008," *PVNews*, 28(4), 15, April 2009; 2007–2009 from Shyam Mehta, GTM Research, e-mail to J.M. Roney, Earth Policy Institute, June 21, 2010.)

BOX 1.5 "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 approximately $70/p$ years. You can easily verify this rule by starting with $df/dt = pf$ and integrating to find $f = f_0e^{pt}$. 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.

As of 2012, the installed PV supplies only about 0.06% of the world's total energy. As an exercise, we estimate using the "rule of 70" that with a 24.7% annual growth rate the amount of installed PV doubles every 70/24.7 ≈ 2.5 years. To increase from 0.06% to 100% requires an increase by a factor of 100/0.06 ≈ 1700, which requires between 10 and 11 doublings, or between 25 and 27.5 years. Thus, as of 2012, 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 installation has 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 of time since 1975 (Handleman, 2008):

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

where
C is the cost in dollars per watt

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, 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?

Three nations—China, the United States, and Germany—rank number 1, 2, and 3 in the world in terms of renewable energy usage. 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 half the world's CO_2 emissions, which is not too surprising as they are the two largest economies.

Germany on a per capita basis would rank far ahead of China who is number one in absolute terms, with the United States number two. There are nations that could be considered even "greener" than Germany in terms of the percentage of their energy from renewable sources—Norway and Iceland, for example. However, in such cases the extensive renewable usage is largely a fortunate accident of geography: Norway generates 99% of its electricity using hydropower, while Iceland gets 100% from renewable sources—both hydro and geothermal.

Germany. There are few nations (like Germany) whose commitment to "going green" is so strong that they made a commitment to embracing green energy long before it approached economic parity with conventional sources. The Germans have supported green energy through national policies that subsidize its deployment, and also by removing unwise subsidies for conventional sources, including coal. Germany remains the number one nation in installed PV capacity, and in 2011 following the Fukushima accident it has decided to phase out its nuclear power plants. Germany may serve as a test case for just how fast a nation can move toward renewable sources without harming its economy or paying an excessive price for its energy. Of course, when comparisons are made between the costs of various energy sources, difficult-to-quantify environmental costs are often not factored-in to the usual calculation, so the German approach may make considerable sense. However, some observers worry that if Germany abandons nuclear too quickly and is forced to import power from neighboring countries to make up for any energy shortfall the Germans are simply exporting any environmental impact, and they may even exacerbate the problem of climate change, since nuclear power has no CO_2 emissions.

China. Unlike Germany, 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. In some cases, government subsidies may be less motivated by promoting renewable energy domestically than increasing the nation's exports, since 95% of China's solar panels are made for export. 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 (96%) 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 tiny fraction of the nation's energy usage, the United States appears to be committed 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 like California are quite generous in their support, and even states such as Texas, noted for its conservative political outlook appears very receptive toward wind power. At the federal government, the political gridlock of a divided government and an uncertain economy (as of Fall 2012) has stymied any real action on advancing renewable energy. Even worse, 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). In one positive development, the federal government has committed to raising the mileage standard in new automobiles over a period of time—an important way of achieving greater energy efficiency in the transportation sector.

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.

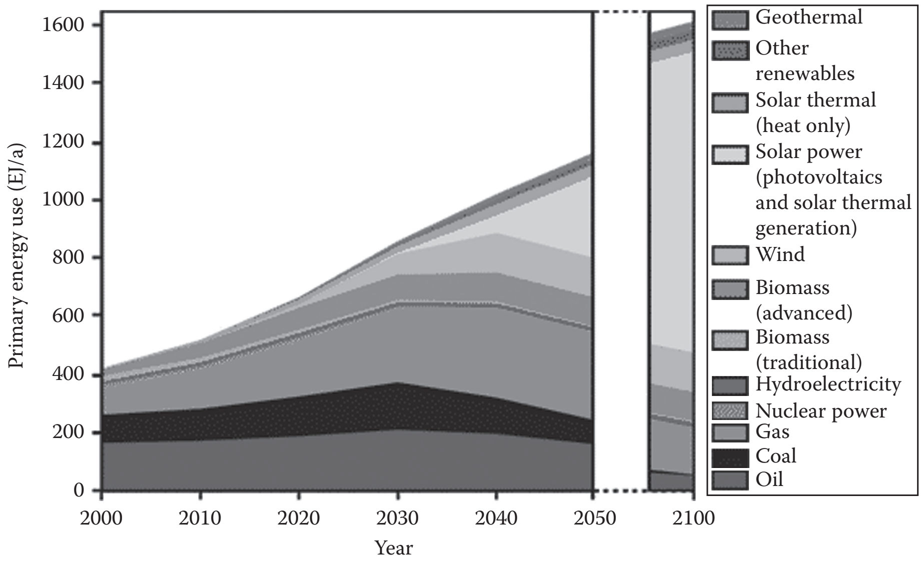

Figure 1.7 **(See color insert.)** Transforming the global energy mix: The exemplary path until 2050/2100. (From WBGU, *World in Transition: Towards Sustainable Energy Systems. Summary for Policy-Makers*, WBGU, Berlin, Germany, 2003, included with permission, http://www.rtcc.org/2009/html/renew-solar-1.html)

BOX 1.6 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."

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—cuts back the most. The most interesting projection, however, is that by far, the dominant renewable source, especially after 2050 will be solar. 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 depend greatly on human actions and the global economy! Nevertheless, given the very strong past growth in both solar and wind power, 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.

A recent report funded by the United Nations' Environment Programme making global solar PV employment projections had among its conclusions that by 2030 there are expected to be 6.3 million solar PV (photovoltaic) jobs worldwide, up from 170,000 in 2006 (UNEP, 2006). Another study by the American Solar Energy Society looking at the entire field of renewable energy concluded that by 2030 in the United States alone, some 1.3 million direct and indirect jobs could be created under a "business-as-usual" scenario, and 7.9 million under a scenario with strong national policies favoring renewable energy, including targets, standards, and invigorated R&D (ASES, 2006).

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

Table 1.6 **Number of Job Openings Listed by www.careerbuilder.com in Renewable Energy in the United States on August 1, 2011**

Engineering (232)	Installation-maintenance (31)
Management (121)	Accounting (29)
Sales (105)	Finance (29)
Skilled labor-trades (68)	Quality control (27)
Information technology (65)	Administration (23)
Marketing (61)	Consultant (23)
Manufacturing (51)	General business (21)
Design (46)	Professional services (19)
Construction (43)	Science (17)
Business development (39)	Human resources (15)
Strategy-planning (35)	

Note: No listings with fewer than 15 openings are included, and a few vague titles have been omitted.

of education is needed to best prepare for them. A search on a website advertising current openings in U.S. 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 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:

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. A reasonably comprehensive list of academic energy programs in the United States can be found at http://rev-up.org. I hope that readers who are aware of any programs not in the database will add them. The rev-up website, incidentally, has a lot of other resources you may find useful relating to renewable energy education at the college and university levels.

1.15 COMPLEXITIES IN CHARTING THE BEST COURSE FOR THE FUTURE

As noted earlier, it is imperative that over time the world 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 ever 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:

- Phase out use of natural gas as well as all other fossil fuels as quickly as possible.
- Pursue new natural gas discoveries, and use it for power generation instead of coal.
- Pursue new natural gas discoveries, and use it for transportation instead of petroleum.
- Pursue new natural gas discoveries, and use it for both transportation and power generation.

Here, for example, is the argument for option three. 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 new discoveries of natural gas its price has dropped considerably, and the amount available in the United States has roughly doubled in the last decade. Currently, even though natural gas is the least expensive way to generate electricity, it has in the past tended to be used mostly for power plants to supply extra power during periods of peak demand, because such plants can be ramped up or down in power much faster than coal or nuclear plants.

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 could face an uncertain market acceptance, unless their range (on a full charge) significantly improves.

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.

BOX 1.7 HOW CAN LESS BE MORE?

One illustration of the counterintuitive consequences that can occur when fossil fuel sources are replaced by renewable 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.

1.15.1 Example 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 that when it needs to be ramped up and down to compensate for the wind power variations its efficiency is reduced by according to $e = 0.35 - 0.00001p^2$, where p is the amount of wind power. Find the percentage increase in emissions that results 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 = 1429 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) = 1524 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, and 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. The 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, Mathematica, or MATLAB®, 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 the odd-numbered problems are provided in the back of the 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 1000 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 kWh would a 1000 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 1000 MW and then back down to zero over a 10 h period of time. 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 installed PV 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 approximately 1000 W.
11. Using the data in Example 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 kW-h 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/kW-h under their standard plan, but under a special "time-of-use" plan it charges 3 cents/kW-h for off-peak times (between 10 p.m. and 11 a.m. on weekdays), and 16 cents/kW-h 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 installed before 2050. Quantitatively compare that projection with the historical trend illustrated in Figure 1.5—note the different units.

REFERENCES

ASES (2006) *Green Jobs: Towards Decent Work in a Sustainable, Low-Carbon World*, a 2008 report by the United Nations http://www.everblue.edu/renewable-energy-training/solar-and-wind-energy-jobs (Accessed on Fall, 2011).

Bentek (2010) How less became more: Wind, power and unintended consequences in the Colorado energy market, http://www.bentekenergy.com/WindCoalandGasStudy.aspx (Accessed on Fall, 2011).

Doran, P.T. and M. Kendall Zimmerman (2009) Direct examination of the scientific consensus on climate change, *EOS*, 90(3), 22.

Ehrlich, P.R. (1968) *The Population Bomb*, Ballantine Books, NY.

EIA (2011) *Annual Energy Outlook 2011*, Energy Information Administration, Washington, DC.

EPI (2011) Data compiled by Earth Policy Institute with 1975–1979 data from Worldwatch Institute, Signposts 2004, CD-ROM, Washington, DC, 2004; 1980–2000 from Worldwatch Institute, Vital Signs 2007–2008, 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; 2007–2009 from Shyam Mehta, GTM Research, e-mail to J.M. Roney, Earth Policy Institute, June 21, 2010.

Feynman, R. (1985) *The Character of Physical Law*, MIT Press, Cambridge, MA. http://www.scribd.com/doc/32653291/The-Character-of-Physical-Law-Richard-Feynman (Accessed on Fall, 2011).

Handleman, C. (2008) An experience curve based model for the projection of PV module costs and its policy implications, Heliotronic. Available at: http://www.heliotronics.com/papers/PV-Breakeven.pdf (Retrieved on May 29, 2008).

Rosa, L., E. Rosa, L. Sarner, and S. Barrett (1998) A close look at therapeutic touch, *JAMA*, 279, 1005–1010.

Sanders (2011) *Sanders The Sole Vote Against Small Modular Reactor Research* http://theenergycollective.com/meredith-angwin/63331/sanders-sole-vote-against-small-modular-reactor-research (Accessed on Fall, 2011).

Shahan, Z. (2011) *Wind Power Subsidies Don't Compare to Fossil Fuel & Nuclear Subsidies* http://cleantechnica.com/2011/06/20/wind-power-subsidies-dont-compare-to-fossil-fuel-nuclear-subsidies/?utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+IM-cleantechnica+%28CleanTechnica%29 (Accessed on Fall, 2011).

UNEP (2006) *Green Jobs: Towards Decent Work in a Sustainable, Low-Carbon World* http://www.everblue.edu/renewable-energy-training/solar-and-wind-energy-jobs

WBGU (2003) *World in Transition: Towards Sustainable Energy Systems. Summary for Policy-Makers*, WBGU, Berlin, Germany.