CHAPTER 1
Energy and the Environment: Science, Technology, and Limits

Energy has been used by humanity ever since there have been humans. We give an indication of the way energy has been used. With use come consequences as well. Everything affects everything else. The study of energy involves scientific, economic, environmental, political, and social elements. Science works, because what we accept as a description of reality has been tested many, many times. The story of humanity's interaction with energy begins with examples of some unintended consequences of political and social decisions (both made and unmade).

KEY TERMS
energy / TANSTAAFL / falsifiability / ozone / catalyst / chlorofluorocarbon / atmospheric lifetime / "tragedy of the commons"

1.1 ENERGY IN HISTORY

Energy is what people use to exist and to grow. Energy is also what people use to make their lives easier. Energy makes our everyday lives of today possible. In this book, we will consider the benefits of energy in extending life, enhancing health, providing physical comfort, and making life more pleasant in many ways.

Energy measured in kilocalories (kcal), food "calories," may be familiar to dieters and family members. [Scientists seldom use the kcal; they usually use the joule (J) as the unit of energy. (See Chapter 3 for an explanation of energy and its units.)]

For our early ancestors, who lived by hunting, ate their kill raw, and were much smaller than we are, there was an energy budget of about 6000 to 8000 kilojoules per day. (Or, for those more familiar with food intake terms, this amounts to 1500 to 2000 kcal per day.)

When people learned how to use fire, the amount of energy used per day was probably about double or triple the former amount: about 12,500 to 17,000
TABLE 1.1

<table>
<thead>
<tr>
<th>Daily energy use per person</th>
<th>MJ per capita per day</th>
<th>kcal per capita per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hunters</td>
<td>8</td>
<td>2,000</td>
</tr>
<tr>
<td>Use of fire</td>
<td>17</td>
<td>4,000</td>
</tr>
<tr>
<td>Domestication of animals</td>
<td>40</td>
<td>10,000</td>
</tr>
<tr>
<td>Renaissance</td>
<td>100</td>
<td>25,000</td>
</tr>
<tr>
<td>1850, a U.S.</td>
<td>420</td>
<td>100,000</td>
</tr>
<tr>
<td>1900, a U.S.</td>
<td>460</td>
<td>110,000</td>
</tr>
<tr>
<td>1950, a U.S.</td>
<td>630</td>
<td>151,000</td>
</tr>
<tr>
<td>1960, b U.S.</td>
<td>705</td>
<td>168,000</td>
</tr>
<tr>
<td>1970, b U.S.</td>
<td>945</td>
<td>226,000</td>
</tr>
<tr>
<td>1980, b U.S.</td>
<td>970</td>
<td>231,000</td>
</tr>
<tr>
<td>1985, b U.S.</td>
<td>900</td>
<td>214,000</td>
</tr>
<tr>
<td>1990, b U.S.</td>
<td>945</td>
<td>226,000</td>
</tr>
<tr>
<td>2000, b U.S.</td>
<td>1,011</td>
<td>244,526</td>
</tr>
</tbody>
</table>

*a Reference 1.
*b Reference 2.

See the spreadsheet "energy converter" on the CW (companion website).

kilojoules per day. (I estimate about 20 MJ/kg heating value for wood, that is, a use of about 3 to 4 kg of wood per day.) Note that our simple definition of energy allows us to add all the contributions from all these disparate sources.

When human beings settled down to a more sedentary life of agriculture using oxen or horses, energy usage probably tripled per person; thus, a person used about 40,000 kJ per day. I obtain this by assuming that an animal uses about 100 terajoules (TJ) per year, based on an analysis(1) that estimates that 1 kg of feed must be supplied for each 50 kg of body mass and taking an average mass of 750 kg. At 16.75 MJ/kg feed, this is 250,000 kJ per day. Assuming one horse or ox to equal about 10 people, this is an additional 25,000 kJ per day per person.

In Europe during the early Renaissance, windmills and coal began to be used, and wood was used in large amounts for heating, cooking, metalworking, and

![Energy Consumption by Source, 1635–2003](image-url)

**FIGURE 1.1**


(energy Information Agency, US Department of Energy, Annual Energy Review 2003 (Washington, DC: GPO, 2003), DOE/EIA-0384(2003), August 2004, Fig. 5.)
other such tasks. Water power was also used to grind grain. Thus, energy use per capita probably doubled again, to 80,000 to 100,000 kJ per day.

In the mid-nineteenth century, the United States used about 400 MJ per capita per day, and today as an industrial power, it uses about 1000 MJ per capita per day (see Table 1.1). With only about a twentieth of the world population, we use about a fourth of the world's total manmade energy. Some important energy equivalents and units are listed on the inside covers and in Extension 3.7, Various Units.

In modern times, we have substituted other forms of energy for human labor, making life easier (Figure 1.1). The chemical energy of gasoline is transformed into kinetic and thermal energy. The chemical energy of wood (which is actually stored solar energy) powers boilers that generate electric energy. This electric energy can become mechanical energy (in machines), radiant energy (from light-bulbs), thermal energy (in ovens or water heaters), and so forth.

1.2 TANSTAAFL

John W. Campbell, editor of Astounding Science Fiction Magazine, formed a group of writers in the 1940s who wrote “hard science” science fiction. Some authors, such as Robert Heinlein and Eric Frank Russell, applied engineering principles to society. Many of these authors wrote stories of worlds that ran on the principle of TANSTAAFL (tan-sta-elf): “There Ain’t No Such Thing As A Free Lunch.” The stories were antutopian in that nothing in future societies was free, and everyone realized this and lived accordingly. In other words, if people want something, they have to pay for it.

We are certainly conversant with this principle in everyday life. We say: “You get what you pay for.” This fact holds for physical phenomena as well. Life on Earth would not exist if the planet’s energy deficit were not paid for by the Sun. (We will explore this dependence on solar energy later.)

Everything done by people has an effect on everything else. For example, a communications satellite (orbited with the laudable intention of allowing India to broadcast to the entire subcontinent with only one transmitter) interfered with radio astronomy. SMS-I, a synchronous meteorological satellite (synchronous means it does not move relative to one particular point on Earth), also caused problems for astronomers.

Words of Science

We live in a world in a state of flux: things are always changing. Jokes change, politics change, the definitions of words we use to express ourselves change. Which word is this year’s fashion?

Code words can be used to make complex issues seem simpler, but often they distort rather than simplify. Take “energy crisis”: Experts, newscasters, and others said in the early 1970s that the days of cheap energy were over. It may look now as if they were right before their time; but between the 1980s and the new millennium, Americans thought they didn’t need to worry. Cheap gasoline was available then, and so it always would be. We were led to that conclusion, because the 1970s energy crisis was partly to do with a temporary gasoline shortage caused by political decisions rather than a real shortage of resource. But, oil is not a resource that is increasing on Earth. This reality may take some time to
be felt, but the code words allow us to make the real, underlying difficulties seem less of a bother.

One of the purposes of this book is to dampen the rhetorical extravagance of popular "energy language" in order to examine the underlying issues. First, however, we have to agree on definitions; that is, we have to speak the same language. Science uses words that have specific meanings. It is something like a foreign language, and some words will simply have to have their definitions committed to memory. Science words allow scientists to speak precisely to one another so that meanings do not get muddled.

**What Science Is**

Many people admire the fruits of science, but few take the time to think about what science really is—a process by which fallible humans attempt to pry Nature's secrets from her grasp for the common good (through increased knowledge). Scientists have a value system that rewards those who determine that a prediction was wrong, and therefore, allows checks to be built into the structure of science. Most people do not like to hear "no." The community of science values the "no" answer, when Nature says it does not work a certain way.

Many of you reading this book will have thought of scientists as having all the answers, but real scientists value the questions over the answers. It is true that the answers to some questions spawn other questions, and that is all to the good. So, why is science so good at prediction, at answers? It's no mystery. Real science bears some relationship to the scientific method you probably learned in elementary school. It is built on guesses (usually called hypotheses) of the way the world works. If that were all, nothing would have come of it.

The guesses, or models, of the way Nature works lead to predictions that can be tested and (this is crucial) be proved wrong if the model is wrong. The condition that the idea can be proven wrong is called falsifiability. If the prediction fails, the model is junked, and another is created. If the prediction succeeds, another prediction of the model is made and tested, again and again. In this way, only models that make predictions that cannot be disproved survive. False predictions doom models. After many thousands of tries at disproof by very clever people, a model that survives must have something right about it. It will be accepted provisionally as correct, until it fails to survive a test. Further, when the model is superseded by another, the part where conditions correspond to what was found to be correct before should give the same correct result as found before.

This does not mean that the experiments have proven the model. Science can never present proof that something is true, only proof that something is false. A model reigns only until dethroned. The process works to give us models that resemble reality—but they are still models, not the reality itself. And all models will fail somewhere.

Scientists have some prejudices about the way Nature works. They think that some experimental result would be equivalent to one done elsewhere or at another time (the result is independent of time or place). For example, what we learn about the Sun now should describe the Sun 1000 years ago. It should describe what would happen to an equivalent sun in another galaxy. The result is independent of the experimenter. (If it only works once, it isn't science.) Experimental scientists are also fanatic record-keepers, because they need to make sure of every effect that might affect their result.
Science is tentative, and scientists are willing to be led by the evidence to renounce what is false and use whatever hasn’t so far been proven false. We think we know a pretty good description of the way the world works, because we’ve eliminated so many ways we’ve found that the world doesn’t work. We treat all knowledge as provisional and accept the models that have not been proved wrong as tentatively correct.

What Technology Is

Technology, as expressed in engineering, is the process of developing scientific knowledge in the form of practical machines, ones that work. The wonders of modern technology include jetliners, DVDs, and personal computers. Scientists conceived of and investigated radio waves. Engineers designed and built radios and televisions. Scientists discovered x rays. Engineers designed x-ray tubes. Scientists discovered radioactivity. Engineers built machines that use radioactivity to help cure cancer. Scientists developed a theory of microwave radiation; engineers developed (microwave) radar and microwave ovens.

Without engineers, scientists would not have apparatus with which to ask questions of Nature. Without scientists, engineers would have to become scientists. Indeed, engineers sometimes act as scientists, and scientists sometimes act as engineers.

Energy and Pollution

The topic of energy and pollution is an inextricable mix of physical and social (or societal) questions. Energy is a physical entity; pollution, on the other hand, requires some value judgment to define, some recognition of the societal cost of an energy strategy. One person’s pollutant may be another’s raw material. In much of this book, we will explore the physical aspects of energy generation and the ensuing pollution. Inevitably, value judgments will be made. I will try to warn you when I make them. We will also explore how to use information without being overwhelmed by it. We must consider how to interpret data and how to judge what other people have done with these data.

To make these ideas more concrete, let us recognize two constraints that limit us in dealing with our problems. One constraint—TANSTAAFL, which we have already addressed—is basically physical; the other—the “tragedy of the commons”—is purely a social phenomenon.

The Ozone Layer

Normal oxygen (\(O_2\)) has two atoms in its molecule. Ozone is a form of oxygen in which three oxygen atoms (\(O_3\)) are bound together. As everyone probably knows, Earth possesses a layer of ozone in the stratosphere (upper atmosphere). Ozone is formed and destroyed by ultraviolet solar radiation in a cycle known as the Chapman cycle (see Extension 1.1, Earth’s Ozone Layer). Under normal conditions, ozone is created and destroyed at the same rate, maintaining a constant concentration. Earth’s ozone layer is unique, at least in our own solar system. The ozone layer, formed because plant life on Earth emitted oxygen into the atmosphere, has, in turn, molded life on Earth. Ozone concentrations change
in the atmosphere throughout the year. In local winter and spring, ozone builds up at the poles through transport from lower latitudes. In summer, ozone levels decrease.

Even large-scale meteorological features of our planet, such as the protective ozone layer, which shields Earth from the Sun's ultraviolet radiation, can be altered by people. This provides an example of TANSTAAFL at work.

The ozone layer protects living things. If the ozone layer is damaged, our eyes and skin get more ultraviolet (UV) radiation, which causes sunburn and leads to increases in skin cancer and blindness. Skin cancer affects fair-skinned people the most. Even now, there are around 400,000 cases of skin cancer in the United States each year. A 1% ozone decrease causes roughly a 2% increase in UV radiation at Earth's surface. A 5% ozone decrease would lead to more than 8000 additional cases of cancer yearly among U.S. whites. If the ozone concentration in the ozone layer decreased greatly, even people with the darkest of skins would suffer. Increased UV (of the type designated UV-B, wavelength 280 to 320 nm) has been shown to affect plants and animals adversely, and the increase in UV-B in temperate zones has been documented.

The Sun emits enormous amounts of radiant energy, which is spread over a very wide band (spectrum) of energies. Most radiant energy reaches Earth in the form of light. This energy can break apart oxygen molecules into atomic oxygen (O), which combines with normal oxygen molecule (O₂) to form ozone (O₃). Ozone absorbs certain bundles of energy from the Sun's UV radiation. This breaks ozone into an oxygen atom and a normal oxygen molecule. The oxygen atom then combines with another O₂ to reform ozone while re-emitting the energy in smaller bundles. The smaller bundles of light that get into the atmosphere below the ozone layer can no longer escape into space. The absorption of radiant energy by the ozone layer heats the atmosphere.

Naturally occurring chemicals can hasten the rate of ozone breakup. Three major atmospheric cycles can reduce ozone. These cycles involve nitrogen oxide (NO), bromine (Br), and chlorine (Cl). These chemicals interact with ozone to produce the normal molecular oxygen, destroying the ozone. In the absence of human intervention, small numbers of these molecules (as well as hydrogen) destroy ozone at the same rate it is created by radiant energy from molecular oxygen. If human actions add chlorine, nitrogen oxide, bromine, or hydrogen to the stratosphere, the equilibrium concentration of ozone decreases. See the section "Sources of methyl halides" in Extension 1.1.

Nitrogen Oxides and TANSTAAFL

When an NO molecule interacts with an ozone molecule, it forms nitrogen dioxide (NO₂) and a normal oxygen molecule (O₂). If NO₂ encounters a single oxygen atom (O), it forms NO and O₂. The whole cycle can then begin again. The NO acts as a catalyst — although it allows the reaction to occur, the NO remains unchanged at the end of a cycle and can repeat its performance. Nitrogen oxide gets into the atmosphere naturally when lightning breaks up molecular oxygen (O₂) and molecular nitrogen (N₂) into single atoms. Sometimes, a nitrogen atom and an oxygen atom get together. In fact, this process is responsible for the major part of all the nitrogen fertilizer applied each year to the world's soil. Very little of the lightning-formed NO gets into the ozone layer and so is little threat. Application of ever-increasing amounts of nitrogen fertilizer, however, is a threat.
Supersonic transport (SST) airplanes, such as the Concorde, burn kerosene in the upper atmosphere, thereby producing carbon dioxide (CO₂), nitrogen oxides, and water. The nitrogen oxides are created in the combustion chamber, where some atmospheric nitrogen is broken up into atoms that combine with oxygen.⁶[30] In addition, when the plane flies faster than the speed of sound (supersonic speeds), the shock wave causes most normal nitrogen molecules (N₂) and normal oxygen molecules (O₂) to break up; many do not recombine but form nitrogen oxides instead. Ozone is eaten up by nitrogen oxides from SSTs. Because SST exhaust is emitted in or near the ozone layer, SSTs pose an immediate threat to the integrity of the ozone layer.

There are few civilian supersonic planes now flying. In 1974, an estimate was made that a fleet of 500 continuously operating supersonic transports would result in a permanent reduction of ozone by 16% in the Northern Hemisphere and 8% in the Southern Hemisphere.⁷[30] This estimate as well as concerns about sonic booms convinced the U.S. Congress that it was unwise to subsidize American civilian SSTs, thereby preventing major SST production. Another disincentive is that the Concorde, an SST subsidized by the British and French governments, has never been a commercial success, and stopped flying in 2003. Even the newest, fastest commercial planes planned are not supersonic.⁸[31]

Nuclear weapons tests have provided information on this ozone-depleting effect, because explosion plumes from atmospheric tests raise huge amounts of nitrogen oxides into the stratosphere. The extensive testing of U.S. and Soviet bombs between 1948 and 1961 resulted in a 4% ozone depletion that took 2.5 years to regenerate.⁹[30] The maximum effect of bomb tests on the ozone layer occurred several months after detonation. (It is possible that high-level nuclear explosions could cause nitrogen oxide to be fed into the stratosphere over a period as long as 10 years.)

### Chlorofluorocarbons and TANSTAAFL

Just as with nitrogen oxide, if a free chlorine or bromine atom is loose in the ozone layer, it can act as a catalyst. Natural chlorine and bromine come into the atmosphere from sea salt. Chlorine and bromine atoms can destroy two ozone molecules and reconstitute themselves afterward, and do this thousands of times before being cleaned from the stratosphere.

The next illustration of TANSTAAFL concerns the effects of compounds containing carbon and fluorine, chlorofluorocarbons (mainly Freon, CF₃Cl₂, a common refrigerant once used widely in aerosol sprays; see Table 1.2), known as CFCs for short. Chlorofluorocarbons are a problem, because as they rise into or through the ozone layer, they break up, liberating atomic chlorine. Below the ozone layer, they are inert. (They were chosen as propellants in spray cans because they did not react with the contents.) Above the ozone layer, these gases encounter UV radiation, which results in their breakup. The chlorine is then free to destroy ozone.

By 1974, more than a million tonnes (metric tons) of CFCs per year were being released. That was the year that Molina and Rowland informed the world of the possible destructive effects of chlorofluorocarbons on the ozone layer.¹⁰[33] There were fears at that time of an eventual 20% depletion in ozone, but little was known about the chemistry of the atmosphere. The atmospheric lifetimes (mean time before removal) of many CFCs are long, as shown in Table 1.2. Because it takes about 15 years for the material now entering the lower atmosphere...
TABLE 1.2
Ozone-destroying chemicals

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Symbolic representation</th>
<th>In atm.</th>
<th>% Cl (yr)</th>
<th>Lifetime concentration ($\times 10^{-12}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC-11</td>
<td>CFCl₃</td>
<td>22%</td>
<td>60</td>
<td>220</td>
</tr>
<tr>
<td>CFC-12</td>
<td>CF₂Cl₂</td>
<td>25%</td>
<td>130</td>
<td>375</td>
</tr>
<tr>
<td>CFC-113</td>
<td>C₂F₅Cl</td>
<td>3%</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>CFC-114</td>
<td>C₂F₆Cl₂</td>
<td>&lt;1%</td>
<td>200</td>
<td>5</td>
</tr>
<tr>
<td>CFC-115</td>
<td>C₂F₇Cl</td>
<td>&lt;1%</td>
<td>400</td>
<td>4</td>
</tr>
<tr>
<td>HCFC-22</td>
<td>CHF₂Cl</td>
<td>3%</td>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>CCl₄</td>
<td>13%</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Methyl chloroform</td>
<td>CH₃CCl₃</td>
<td>13%</td>
<td>7</td>
<td>130</td>
</tr>
<tr>
<td>Methyl chlorideᵇ</td>
<td>CH₃Cl</td>
<td>20%</td>
<td>1.5</td>
<td>600</td>
</tr>
<tr>
<td>Halon-1211</td>
<td>CF₂BrCl</td>
<td>Coolant, foam</td>
<td>15</td>
<td>1.5</td>
</tr>
<tr>
<td>Halon-1301</td>
<td>CF₂Br</td>
<td>Fire extinguisher</td>
<td>110</td>
<td>1.7</td>
</tr>
<tr>
<td>Methyl bromideᵇ</td>
<td>CH₃Br</td>
<td>Pesticide</td>
<td>1.5</td>
<td>15</td>
</tr>
</tbody>
</table>

ᵃPicomoles per molecule, or parts per trillion.
ᵇNaturally occurring compound.

Source: Office of Technology Assessment; 1985 values given; M. J. Prather and R. T. Watson, Reference 32.

To get into the ozone layer, CFCs stay around long enough to get their chances to wreak havoc with the ozone. Chlorine chemistry in the atmosphere is now much better understood.⁵⁴ Ozone is increasing near the ground (some is generated by internal combustion at ground level, where—as a strong oxidant—it acts as a pollutant that causes plants to sicken and die)⁵⁵ but is decreasing in the stratosphere.⁶⁴-⁶⁸ A decrease of 3% in stratospheric ozone has already been observed relative to the 1950s; the projected 20% decrease if no action on CFCs had been taken would have caused thousands of new skin cancer cases and as many as 30,000 extra deaths annually.⁶⁹ This is TANSTAAFL with a vengeance. Scientists and technologists involved in the development of spray cans never conceived that a danger to the entire human race could follow from their contributions to convenience and progress.

The Ozone Hole

Vivid evidence of ozone layer depletion was seen in measurements made by the Nimbus 7 satellite,⁶⁸ as shown in Figure 1.2. The South Pole has a visible decrease in ozone concentration (popularly dubbed an ozone "hole"). The decrease is represented in "Dobson units." One Dobson unit represents a 10 μm thickness of the ozone at standard pressure and temperature in a column of air that runs between Earth's surface and the edge of the atmosphere (many kilometers up); a "normal" reading should be around 400 to 500 Dobson units, corresponding to an equivalent thickness of 4 to 5 millimeters of pure ozone.

This Antarctic ozone deficiency was first brought to public attention in 1986 by Farman, Gardiner, and Shanklin⁶⁸ and has been shown to occur at heights between 10 and 20 km.⁶⁸ After discovery of the Antarctic ozone depletion, scientists checked and reanalyzed the data from the solar backscatter ultraviolet detector aboard Nimbus 7.⁶⁸ Thinning of the ozone has occurred each year since 1979 from September to November, during the Antarctic late winter.⁶⁸ The data
verified the decrease. It had been thought that there was a decline on the basis of
the *Nimbus 7* data. It turned out on reanalysis to be much larger than the first
analysis had shown, which agree with model calculations. The severity of the
effect in the Antarctic has been increasing virtually every year since the early
1970s, when it began (see Figure 1.2 for Spring ozone levels from 1970 through
1998). By 1981, the hole was 1.5 million km², and in 2000, it registered a record
area of over 28 million km². Now, the Arctic also experiences a severe ozone
hole, although over a smaller area.

The Arctic has a smaller polar vortex (closed swirl of air circulation) than the
Antarctic and a less extensive area of extreme cold, because it is ice-covered
water rather than an ice-covered continent. Thus, depletion is lower in the Arctic
than in the Antarctic, so the observed “hole” in the Arctic, which hadn’t existed
until recently, is less stark than that in the Antarctic. In both hemispheres, the
ozone depletion occurs in spring, as the cold temperatures coexist with light from
the Sun that can break chlorine-bearing molecules apart. See the section “How ozone is destroyed at the poles” in Extension 1.1.

Stratospheric chlorine has gone from one part per billion in 1950 to about
two parts per billion now, in eerie parallel with the ozone decrease. Three
pieces of evidence indicate clearly that CFCs, found in the stratosphere, are the
cause of ozone depletion:

1. Chlorine oxide (ClO) concentrations at the poles are 50 times greater than
   “normal.”
2. Ozone concentration decreases as ClO concentration increases.
3. Observed and predicted loss rates agree closely.

See Extension 1.2, *Why Volcanic Eruptions can't be the Cause of Ozone
Depletion.*
The Montreal Protocol

Fears of ozone loss led the United States to ban CFCs from spray cans unilaterally in 1978. Carbon dioxide is now used as the propellant in spray cans. Europe hesitated in 1978 and did nothing. By 1985, the relentless pace of new discoveries of the fatal consequences of CFC emission had finally attracted world attention. As a result, conditions for survival of the ozone layer have improved radically. An international agreement sponsored by the United Nations Environment Program, known as the Montreal Protocol, was signed by major producers in 1987. The original Montreal Protocol would have reduced CFC emissions by 50% by the year 2000; the agreement has been amended twice, in London in 1990, to eliminate CFCs altogether by 2000, and in Copenhagen in 1991, to quicken the timetable for eliminating CFCs to 1996 and to ban halons starting in 1994 and freeze methyl bromide emissions at 1991 levels. In Vienna, in 1995, it was further agreed that methyl bromide use would end by 2010, and HCFCs would be phased out by 2040. Both revisions took place because of increased knowledge of ozone destruction, including measurement of higher UV levels in both Northern and Southern Hemisphere mid-latitudes as well as at the poles.

It has been difficult to halt production entirely, because CFCs have been the predominant refrigerants used in air conditioners, the primary solvents used to clean circuitry in computer and appliance manufacture, and the foaming agent used to produce millions of rigid foam products each year. Manufacturers, however, have shown great ingenuity in designing replacements. The amount of CFCs released by the United States, the European Union, and Japan has fallen from 725,000 tonnes pre-Protocol to 6800 tonnes currently.

The Montreal Protocol succeeded. As of 2000, evidence shows that concentrations of some CFCs have peaked and have begun to decline (CFC-11 peaked in 1994–1995). Despite this progress, the long lifetimes mean that the ozone layer will continue to degrade for some time (the recovery process is made even longer by global warming). The prognosis for various replacements is good, although even with the replacements, models show continuing increase in ozone-destroying chemicals until about 2005, before eventual decline to pre-CFC levels by 2190.

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1.3 THE TRAGEDY OF THE COMMONS

Twentieth century socioeconomist Garrett Hardin has brought the concept of the "tragedy of the commons" to public attention through his investigations of the world population problem. In contrast to the views of the laissez-faire economist Adam Smith, who argued that an individual intent on personal gain would be led to benefit the public interest by an "invisible hand," Hardin holds that individuals behave in a selfish fashion that ultimately leads to societal destruction.

To illustrate his ideas, Hardin uses a village commons—a field open to all inhabitants of a village for use as pasture, park, or whatever they please. Each herdsman of the village is entitled to use the commons. Of course, each herdsman tries to keep as many cattle (or other domestic animals) on that commons as possible. This method might work well for a time, because war, famine, and disease hold both human and animal populations in check. Nevertheless, the day would eventually come when carrying capacity—the maximum number of cattle that could be supported on the commons indefinitely—would be reached.
Let us suppose that 10 villagers each had 20 cattle on the commons. In this case, there would be 200 cattle, which we take to be the carrying capacity. If another cow were added, each of the 201 cattle would get 200/201 of its requirements. The herdsman who owns the extra cow would see new assets: an additional cow; but he also would see new debits: each of his 21 cattle gets only 200/201 of its requirements, and consequently, each one is a little more bony, produces slightly less milk, and so on.

We might call his original assets $+1$, and his debits $-21/201 \approx 1/10$, giving net assets of $+9/10$. Figure 1.3 shows how the situation appears to the herdsman. The rational herdsman, seeing he is getting $9/10$ the benefit for only $1/10$ the cost, would then add another animal, and another, and another. When carrying capacity is exceeded, the entire herd is more poorly fed. Eventually, the limit of permanent damage is attained, and all cattle (not just the added one) starve, become sickly, or die. The entire herd (and its economic benefit) is lost. “Each man is locked into a system that compels him to increase his herd without limit—in a world that is limited. . . . Freedom in a commons brings ruin to all.”

There is some possibility that humanity could ruin large parts of their environment through concentration on individual gain at societal cost, the tragedy of the commons. Ecologists Daily and Ehrlich believe that “the human enterprise has not only exceeded its current social carrying capacity, but it is actually reducing future potential biophysical carrying capacities by depleting essential agricultural capital stocks.” They point to the case of deer introduced to St. Matthew Island: their numbers grew from 29 to 6000. The great numbers destroyed vegetation; the carrying capacity was so damaged that the population of deer crashed to around 50. Similarly, deer introduced on the Kaibab Plateau exploded in population and wreaked havoc on the vegetation.

Air is known in economics as a “free good.” It is breathed by everyone; everyone uses it. If an industry used air and polluted it without cost, all people would suffer, because the air would be polluted, but the industry’s owner would reap economic gains. Such a case is also an example of the tragedy of the commons.

Hardin believes that tragedy of the commons will operate in every case in which personal gain is attained by distribution of losses to others, even if the losses may seem negligible to the losers. The wealth (or other advantage) of the gainers will lead them to destroy what all possess in common. If all possess something (the air, for example), the thing is perceived as having no individual economic value.

Earth is finite and thus can support only a finite population. Certain groups see advantages in increasing their numbers and so encourage people to have many children. Earth, in this case, is similar to an English commons, where people have use of common goods: air, water, land, and resources. If population grows without restraint, Earth may not be able to support that increased population. Hardin would coerce countries with exploding populations to limit the number of children born in each family, based on the reasoning that “injustice is preferable to total ruin.”

We are led to the conclusion that if we exploit resources in a laissez-faire manner, we favor people or institutions who focus narrowly on profits and distribute losses as widely as possible. We are practically forced to foul our own nest. The cost of dumping waste, as far as a profit-oriented company is concerned, is less than the cost of cleaning up. When the waste is discovered in the environment, the companies are no longer identifiable, and the public must pay for any cleanup.

See Extension 1.3, Coal Mining as an Example of Tragedy of the Commons.

We must know the ultimate gains and costs, as well as who wins or loses, to make informed decisions about energy strategy for the future. (When speaking of costs and benefits, we must quantify. Appendix 1 presents some of the background
information needed for this book: powers of ten and scientific notation. We will use this material to practice the art of estimation in Chapter 2.) Our analysis will, of necessity, be incomplete. Society must make the best of a situation and make decisions from the best presently available knowledge. Decisions have to be made—even doing nothing involves making a decision.

Fortunately, society can intervene to ameliorate the consequences of such local blindness—this is partly why humans have governments and social norms. Researchers have observed such effects in action through what they call “indirect reciprocity.” By this is meant that individuals who observe others “cheat” with no consequences will do so themselves, but when provided with the social opportunity, instead, those individuals will discipline the cheater and insure gain for society, even if the individuals must pay a personal price. In addition, there may be a common “social capital,” a recognition of the local social interactions with the environment, that can help people manage the environment collectively and effectively. It is clear that Hardin oversimplified the situation, and that humans can overcome the challenges of managing a commons, but only if they are aware of the problems.

SUMMARY

Energy use involves gains in human comfort and ease. Energy is useful for many things and makes modern life possible. As a result, energy use has skyrocketed. Everything is connected to everything else, and everything we do exacts a price. One aim of this book is to explain both the gains and the physical and social costs associated with each strategy for generating energy. No choice connected with energy use is free of cost. Do without energy—there is a cost. Use energy—there is a cost. There is no such thing as a free lunch (TANSTAAFL).

When people exploit resources held in common, “free goods” in economic parlance, they are usually aware only of their own immediate gain or loss. This was the case for the production of CFCs, which led to ozone depletion. It seemed like a great idea to produce CFCs for propellants or coolants, because they were not reactive—they couldn’t possibly become a problem. Often, the people using “free goods” are not aware of (or ignore) the costs to everyone (the discovery of the CFC ozone problem occurred long after their development). The inexcusability of the consequences of such actions constitutes the tragic character of the tragedy of the commons, illustrated in the extensions by the effects on the ozone layer and in coal mining. However, by their actions, human beings can overcome these natural tendencies. The Montreal Protocol, an international treaty that has greatly reduced use of CFCs, is an example.

Most choices involve benefits to some people and costs to others. Because of the costs associated with every action, and because the tragedy of the commons illustrates a way in which organizations or individuals avoid paying for the social costs inflicted by their actions (leaving others to bear that burden), society at large has a legitimate interest in regulation of these actions. Such regulation is best pursued when the citizenry is aware of the costs and benefits associated with some particular action, and a general framework equitable for all is set up.

PROBLEMS AND QUESTIONS

MULTIPLE CHOICE REVIEW

1. Which gas is not involved in ozone depletion?
   a. chlorine
   b. nitric oxide
   c. neon
   d. bromine
   e. hydrogen

2. The greatest cost per ton involved in buying coal for use in power plants is most likely for
   a. the mineral rights for the land on which the mine is built.
   b. transportation of the coal to the power plant from the mine.
   c. strip mining coal from the surface.