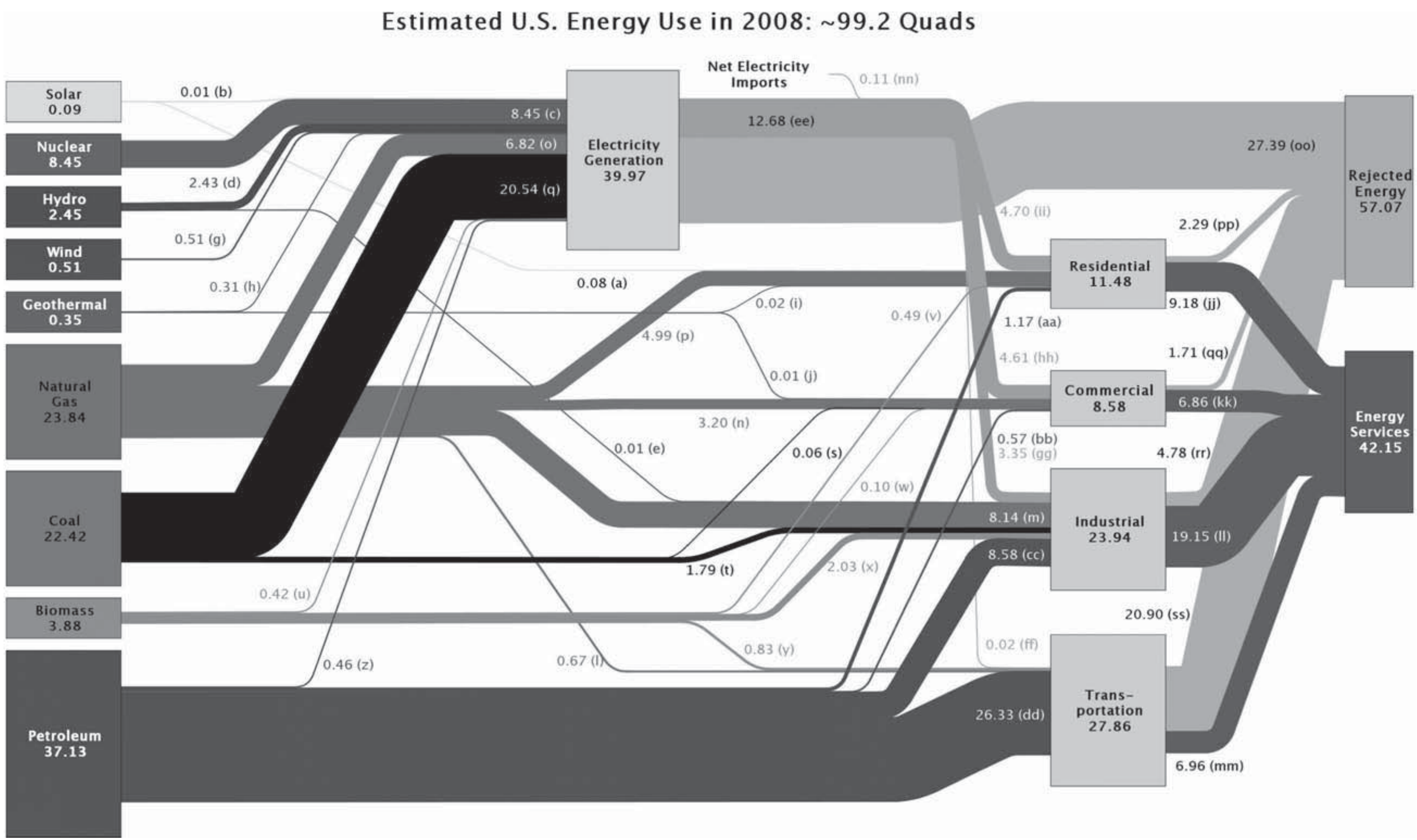
CHAPTER 14

Energy in Civilization

Energy fuels our civilization. We use it to heat our homes and our food. As mechanical energy it turns the motors in our industries and households. It is necessary for transportation and communication.



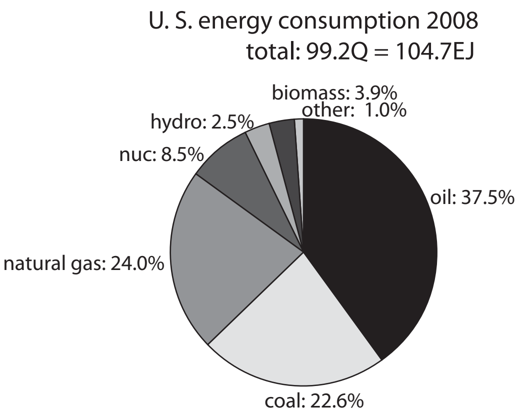
Estimated U.S. Energy Use in 2008: ~99.2 Quads
Solar 0.09
Nuclear 8.45
Hydro 2.45
Wind 0.51
Geothermal 0.35
Natural Gas 23.84
Coal 22.42
Biomass 3.88
Petroleum 37.13
0.01 (b)
2.43 (d)
0.51 (g)
0.31 (h)
8.45 (c)
6.82 (o)
20.54 (q)
Electricity Generation 39.97
Net Electricity Imports
0.11 (nn)
12.68 (ee)
0.08 (a)
0.02 (i)
4.99 (p)
0.01 (j)
3.20 (n)
0.01 (e)
0.06 (s)
0.49 (v)
0.10 (w)
8.14 (m)
1.79 (t)
2.03 (x)
0.42 (u)
0.83 (y)
0.46 (z)
0.67 (l)
4.70 (ii)
1.17 (aa)
4.61 (hh)
0.57 (bb)
3.35 (gg)
8.58 (cc)
0.02 (ff)
26.33 (dd)
Residential 11.48
Commercial 8.58
Industrial 23.94
Trans-portation 27.86
2.29 (pp)
9.18 (jj)
1.71 (qq)
6.86 (kk)
4.78 (rr)
19.15 (ll)
20.90 (ss)
6.96 (mm)
27.39 (oo)
Rejected Energy 57.07
Energy Services 42.15

We say that we *generate* energy, but we know that we can only transform it from one form to another. The *source* of our energy is overwhelmingly the internal energy of the *fossil fuels*, coal, oil, and natural gas, whose carbon content consists of the remains of living organisms built up over millions of years. There is also the internal nuclear energy of uranium in our reactors, and the energy radiated to us by the sun.

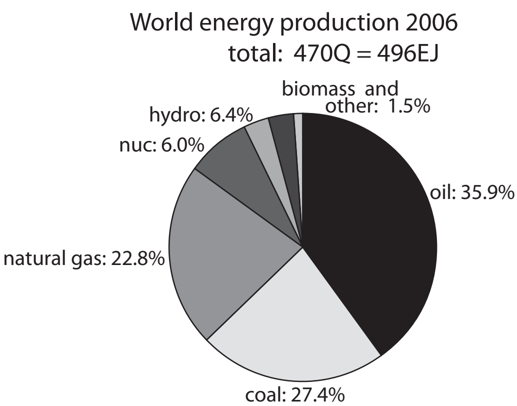
In this chapter we explore the energy transformations that underlie our civilization. We also consider the limitations described by the second law of thermodynamics, and some of the obstacles that accompany our use of energy.

14.1 The flow of energy

The flow diagram (courtesy Lawrence Livermore National Laboratory) shows the path of energy in the United States from the sources on the left, to the way we use it on the right. The numbers are estimates for 2008, in *quads (Q)*, or quadrillions ($= 10^{15}$) of british thermal units (*btu*), where $1btu = 1055J$. $1Q = 1.055EJ$ or *exajoules*, each equal to 10^{18} J.



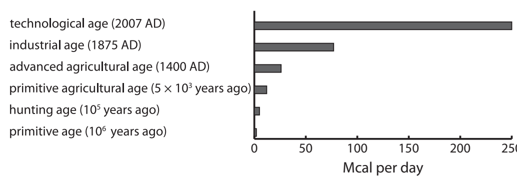
Here is a chart that shows the consumption of the various kinds of energy in the United States in 2008. The total amount is $99.2Q$ or $104.7\ EJ$.



And here is a similar chart for the energy production of the world. (The numbers for both charts are from the US Energy Information Administration.)

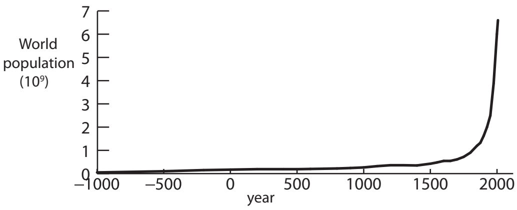
The most drastic message of these diagrams is that about 86% of the world's energy comes from fossil fuels. The other side of the message is how little of our energy comes from other sources. We will look at the alternatives, and why the patterns of energy use have been so resistant to change.

The second message is that in the United States we use about 21% of the world's energy, while our population is only 4.6% of the total.



Source: Adapted from a similar figure in *Energy and Power* (W. H. Freeman and Co., 1971).

This figure shows how our appetite for energy has changed with time. At the beginning all that was consumed was the daily food, of about 2000 food calories (or 2×10^6 cal $=$ 2 Mcal or about 8.6 MJ) per day. With hunting the amount of food increased, and wood was burned for heat and cooking. Primitive farming brought the planting of crops and the use of animal energy. In a later age animals were also used for transportation, coal was used for heating, and there were other sources of energy, including wind and water. A large increase came (in what we now call the developed world) at the time of the industrial revolution with the introduction of the steam engine and the widespread use of machinery. Finally we arrive at our own time, with modern modes of transportation and all the gadgetry of modern civilization, when we use (in the United States) about 250,000 food calories per person.



In the same period of time the number of people has increased dramatically. Already in 1798 Malthus saw that this increase could not continue indefinitely. He predicted that the population would be limited by famine, disease, war, and vice if drastic steps were not taken to limit it by other means. The world's population is now larger by a factor of about 8 than in the time of Malthus. Was he wrong? Or did he just not have the right timescale in mind when he said that disaster was then imminent? Today there are those (the neomalthusians) who believe that limiting the population is our most urgent task, while others expect that human ingenuity and technological advances will meet and resolve all challenges.

We begin with a form of energy that is not among the sources that we have listed. *Electric energy* is a *carrier* of energy. It allows us to transform energy from its primary source in one place and to use it in another.

Later we discuss another carrier of energy, one that we are not now using, but that is being considered seriously, namely hydrogen. It has to be separated from water or another substance at the cost of energy, and can then be used as fuel somewhere else.

14.2 Electric energy: what is it and what does it do for us?

Our civilization depends heavily on electric energy, on its generation, its distribution, and its eventual transformation into internal (thermal) energy, light, and mechanical energy. We also use electricity to send and receive information along wires and fibers, and through space as electromagnetic radiation.

Electric energy is often said to be *clean*. Electric motors lack the noise, the air pollution, and the waste heat of gasoline engines. Electricity is, however, not a *primary* form of energy. It has to be *generated*, i.e., transformed from some other kind of energy, today most often the internal (atomic and molecular) energy of coal, oil, or natural gas or the (also internal) nuclear energy of uranium. It is *released*, i.e., transformed to thermal energy, through the chemical reaction of burning in the first case and the nuclear reaction of fission in the second. The waste materials and unused thermal energy are still there, but they can be far from our backyards.

The question of the nature of electric energy turns out to be somewhat subtle. There is not likely to be an entry for *electric energy* in a physics textbook. We talk of *using* it, but just what are we using?

The battery stands ready to transform its internal, chemical energy to some other kind of energy, either right where it is or somewhere else. In the basic circuit the transformation is to thermal energy in the resistor. But there is an ephemeral intermediate state, before the energy is used, when it is electric *potential* energy. It is this intermediate state that allows us to transport energy from the source to the place where it is used.

We can think of a mechanical circuit with a similar sequence of energy transformations: lift some marbles in one place, transforming energy from your muscles or some device to gravitational potential energy. The marbles can now roll around at the new height, using up only the fraction of their energy necessary to overcome friction. They can drop down somewhere else and there transform their gravitational potential energy to kinetic energy. On impact there is a further transformation, ending most often in *dissipation* as thermal energy.

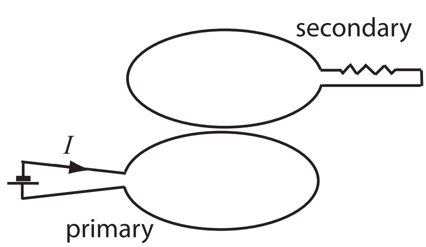
14.3 DC and AC: transformer and generator

Only a minute fraction of the electric energy that we use is transported via the direct current (DC) that we have been talking about so far. An even smaller fraction comes from batteries. The advantages of alternating current (AC) are overwhelming. Just what is *AC* and what are these advantages?

The first is the generator. Take a loop of wire with a magnetic field through it and rotate it about its diameter. For half a turn the magnetic flux through the loop is in one direction with respect to the loop. For the next half turn it is in the other direction. Imagine yourself standing on the loop and rotating with it. The direction of the field and of the flux will alternate, up toward your head, down toward your feet, up, down, and so on, and so will the emf that is induced, in accord with Faraday's law.

The rotating loop is an elementary AC generator. To make a DC generator, with an emf and a current that are always in the same direction, there has to be a switch (the *commutator*) that reverses the current direction after each half turn. Such a switch can be built in by having a split ring on the axle turning with the loop (see page 205). The current in the external circuit, on the other side of the commutator, will still vary in magnitude, but it will remain in one direction. The commutator is a weak part of any DC generator. All of the generated current has to go through the sliding contacts (the *brushes*), and the sparks there are a continuous source of deterioration.

The other great advantage of AC is that we can use *transformers*. Take two loops close to each other. A current in one will produce a magnetic field through both. But only a changing current in one will produce an emf and a current in the other loop.



Two loops in the passive *secondary* circuit will each have the same emf induced, and they can be connected so that the emfs add up. No energy is produced, but not much is lost either. The product of the emf and the current, $\mathcal{E}I$, remains almost the same, but $\mathcal{E}$ and I can be changed at will by changing the number of turns in one or the other of the two circuits.

Why is this so important? A lower current means less loss of energy in the transmission. Wherever energy is transported through transmission lines there are transformers to increase the potential difference, the *voltage*, between the wires. The current decreases, and therefore also the energy (I^2R) that is lost to the surrounding atmosphere. On the other hand, more extensive and more costly insulation is then required. The balancing of the variable cost of the energy lost in transmission against the fixed cost of the installation at a certain voltage is an interesting problem in economics. The increasing cost of electric energy and the greater distances over which it is transported have pushed the voltages at which it is transmitted higher and higher, up to between 100,000 and a million volts.

14.4 Energy storage

We are really bad at storing energy in any form. It can be done with gravitational potential energy by pumping water to a greater height. It is also done in a pendulum clock. Flywheels, with stored kinetic energy, and superconducting coils, with energy stored in their magnetic field, are being considered, but storage as chemical energy in batteries is really the only method widely used.

Batteries

The cost of batteries and their poor ratio of stored energy to the mass that is required have made them a minor source of energy, used as backup for times when the transmission system fails or when portability is an overriding concern, as in cars and flashlights. There are also uses that require very little energy, as in watches, calculators, cameras, and hearing aids, and here batteries are used to great advantage.

With better batteries or other storage mechanisms the use of intermittent and unpredictable forms of energy, such as wind and solar energy, would, no doubt, be much more widespread.

Artifacts have been found that may have acted as batteries in antiquity, but modern electrochemistry began with the work of Luigi Galvani (1737–1798) and Alessandro Volta (1745–1827) near the end of the eighteenth century. Galvani was a physician and professor at the University of Bologna in Italy. The most cited story of his discovery is that he was using an iron scalpel to dissect a frog leg that was held by a brass hook when he saw the leg twitch as the muscle contracted.

He ascribed this phenomenon to "animal electricity," but Volta soon showed that the essential components of the experiment were the two different metals and an electrolyte (a liquid containing mobile ions). He constructed the first "voltaic cells," one of which had electrodes of copper and zinc separated by paper soaked in salt water. Later batteries, to this day, differ primarily in the materials that are used.

The first rechargeable cell was the lead-acid cell, invented in 1859 and now used in just about every car. Its electrodes are lead and lead oxide with sulfuric acid as the electrolyte. In a "dry cell" the liquid electrolyte is replaced by a paste. In "alkaline" batteries the electrodes are zinc and manganese dioxide and the electrolyte is potassium hydroxide, KOH.

There are two other kinds of rechargeable batteries that are widely used today. One is the nickel-metal hydride (NiMH) battery, invented in the 1980s. Its electrodes are hydrogen (as a metal hydride) and nickel hydroxide, $Ni(OH)_2$, and the electrolyte is KOH. Its stored energy per kg can be about twice that of the lead-acid battery. NiMH batteries are used in digital cameras and other small-scale applications. Large assemblies are used for short-term storage in hybrid cars.

The lithium-ion battery in one of its forms has electrodes of lithium and lithium cobalt oxide. It can store about four times the energy per kg of the lead-acid battery. It has the additional advantage that it keeps its charge better than other storage batteries. It loses only about 15% of its charge in a year, compared to 5% per month for the lead-acid battery and 20–25% per month for the NiMH battery. Its use beyond small-scale applications has been slow to develop because of its cost and because it is subject to thermal instabilities. With intensive research it is on its way to fulfill its promise.

EXAMPLE 1

(a) What is the amount of energy and the amount of energy per kg stored in a fully charged 12 V lead-acid battery with a mass of 18 kg and rated at 45 Ah?

(b) How does this compare to the kinetic energy of a 1.5-tonne car at 60 mph?

(c) What would be the cost of this amount of energy from a wall plug at 10 cents per kwh?

(d) What would be the cost of an equivalent amount of gasoline at 3 dollars per gallon, used in an engine with an efficiency of 25%?

Ans.:

(a) 45 ampere-hours at 12 V is 12×45 Wh or 540 Wh. The amount of energy per kg is $\frac{540}{18} =$ 30 Wh/kg.

(b) 60 mph = 26.8 m/s, 1 tonne = 1000 kg, $\frac{1}{2}mv^2 = \frac{1}{2}(1500)(26.8)^2 = 0.539 \times 10^6\,\text{J} = 0.15\,\text{kwh}$. The battery stores 3.6 times as much energy.

(c) The cost of the 0.54 kwh stored in the battery, if it were from a wall plug at 10 cents per kwh, would be 5.4 cents. The cost of the kinetic energy of the car would be 1.5 cents.

(d) The energy density of gasoline is about 45 MJ/kg, or, since 1 kwh = 3.6 MJ, 12.5 kwh/kg. The density of gasoline is 0.7372 kg/liter, or, since 1 gallon = 3.785 liters, it is $45\text{MJ/kg}\,\frac{0.7372\,\text{kg}}{1\,\text{liter}}\,\frac{3.785\,\text{liters}}{1\,\text{gallon}} = 125.6\,\text{MJ/gallon} =$ 34.9 kwh/gallon. With an efficiency of 25% we get 8.7 kwh from 1 gallon.

The kinetic energy of the car (0.15 kwh) uses 1.7×10^{-2} gallons, at a cost of 5.2 cents.

Supercapacitors

A recent development in energy storage is that of capacitors with a large effective area. The capacitance of a parallel-plate capacitor is $\epsilon_0 \frac{A}{d}$, so that a large area means a large capacitance. The use of porous carbon and carbon nanotubes has made it possible to increase the effective area and to achieve capacitances of thousands of farads. (A carbon nanotube is a cylinder whose diameter is about 1 nm, i.e., it is of the order of an atomic size.)

These "supercapacitors" have a number of advantages over batteries. They can be charged in seconds rather than hours. Since no chemical changes are involved they can go through millions of charging cycles without degradation, compared to perhaps hundreds for batteries. Very little of their energy is lost in a charging cycle. One of their first experimental large-scale applications has been in buses powered by supercapacitors that are recharged at every bus stop.

EXAMPLE 2

What is the amount of energy stored in a capacitor of 3000 f charged to 100 V and 200 V?

Ans.:
At 100 V it is $\frac{1}{2}CV^2 = (0.5)(3000)(100^2) = 1.5 \times 10^7$ J or 4.17 kwh. At 200 V it is four times as large, or 16.7 kwh.

Hydrogen

Hydrogen is not a primary fuel. It is the most abundant element, but it does not occur on earth as an independent substance. It combines too easily with other elements, principally with oxygen to form water. This is why it is a good fuel. For each molecule of water that is formed, 2.97 eV of energy is liberated, i.e., transformed from the internal energy of the separate atoms of hydrogen and oxygen to the energy of motion of the molecule that is formed. For a mole (18 g) of water the liberated thermal energy is 2.86×10^5 J.

The energy available from a kg of hydrogen is about 142 MJ/kg (142×10^6 J/kg.) This is greater than the value for gasoline, which is about 45 MJ/kg. The energy per unit volume is, however, smaller than that for gasoline. It is feasible to store hydrogen at a pressure of 70 MPa or about 700 atmospheres. At this pressure hydrogen takes up about eight times the volume of gasoline storing the same amount of energy.

To produce elemental hydrogen it has to be separated from the other elements with which it combines. Water can be decomposed by electrolysis, with an energy expenditure equal to that which is freed when the elements combine. This is not, however, how most hydrogen is produced today. Rather it is separated from natural gas, primarily from methane (CH_4). This is a less expensive process, but it does not take advantage of the freedom from carbon emission that hydrogen promises.

There has been much speculation about the possibility of using hydrogen to replace gasoline as a fuel for cars. There are, however, formidable obstacles to the development of what has been called the *hydrogen economy*. The first is, as we have seen, that the available energy per unit volume of hydrogen is about one-eighth that of gasoline. Among the technological changes that would be required is the development of ways to store and to transport large amounts of hydrogen, to do so safely, and to provide readily available fuel through a network equivalent to that of today's filling stations.

There are also some features that favor hydrogen. One is that intermittent sources of energy, such as wind and solar energy, could be used for the electrolytic separation of hydrogen from water. Another is that it can be used in *hydrogen fuel cells* that can have efficiencies about twice as large (about 50%) as those of gasoline engines.

Fuel cells

In a hydrogen fuel cell internal energy is transformed directly into electric energy. Such a cell consists of two plates separated by a barrier through which ions can pass. Hydrogen gas flows past one of the plates and, with the help of a catalyst such as platinum, dissociates into ions and electrons. The ions move to the other plate through the barrier. The electrons move through the external circuit and their current represents the electric energy produced by the cell.

14.5 Entropy and the second law of thermodynamics: the limits of energy transformation

Thermal energy

All materials have *internal energy*. Most of the time when we say "internal energy" we mean the energy of the random motion of the atoms or molecules of which the material is composed. Part of this energy is the kinetic energy of their motion and part is their mutual electric potential energy. The sum of these two energies is the material's *thermal energy*. The thermal energy is greater when the temperature is higher. It also changes when the atoms or molecules rearrange themselves to form a different structure. This happens when there is a phase change (as from solid to liquid) or a chemical reaction.

In addition to the internal thermal energy of the motion of the atoms and molecules there is also the energy inside the atoms and molecules. Each molecule, atom, and nucleus has internal energy. The atoms in each molecule, the nuclei and electrons in each atom, the protons and neutrons in each nucleus all have kinetic and mutual potential energy.

When two objects are in contact, the greater thermal motion in one is transmitted to the other by collisions between the atoms and molecules and in metals by the free electrons. This is the process of thermal conduction. The direction is from the one at higher temperature to the one at lower temperature. When the two are at the same temperture there is no heat transfer, and the two are said to be in *thermal equilibrium*.

What happens when wood, coal, oil, or any other fuel is burned? Some of the internal energy stored inside the molecules is transformed into thermal energy, i.e., into the energy of their random motion.

Similarly, in a nuclear reactor some of the internal energy stored inside the nuclei of the nuclear fuel (most often ^{235}U) is transformed to kinetic energy of the fission products. When this kinetic energy is shared among the atoms and molecules by collisions it becomes thermal energy. The fusion reactions in stars also change some of the internal energy of nuclei to kinetic energy of the reaction products, which when shared becomes thermal energy.

In some cases (as on a stove or in a furnace) the increase in thermal energy and the accompanying rise in temperature are all we want to achieve. But we may also want to transform some of the energy to mechanical energy. A device that continuously changes thermal energy to mechanical energy is called a *heat engine*. Examples are the steam engine and the gasoline engine. They achieve the required transformation, but with a characteristically low efficiency, because of the limitations imposed by the second law of thermodynamics.

The second law of thermodynamics

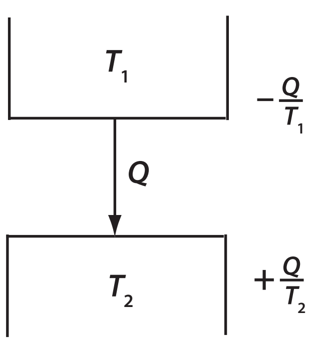
If we were limited only by the law of conservation of energy (which is also called the *first* law of thermodynamics), a ship could cross the ocean without fuel, just by cooling down the ocean and using its internal energy. That doesn't happen. Observation and experiment show that it can't be done. The generalized statement of this observation is called *the second law of thermodynamics*.

Thermal energy tranfers spontaneously from a hotter object to a cooler one, but not in the other direction. It is a process allowed by the first law of thermodynamics but not by the second.

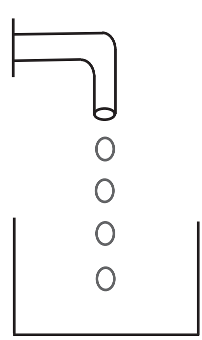
There are various versions of the second law, illustrating its immense and pervasive importance. One version is about the limitation of converting internal energy to work, usually to mechanical energy. Yes, it can happen, but only if there is a hot part of the system (the steam in a steam engine, the burnt fuel in a gasoline engine) and a cooler part, to which the condensed steam or the spent fuel can go, taking with it most of the thermal energy. A second version, which can be shown to be equivalent to the first, is about cooling an object below the temperature of its surroundings. This does not use any net energy, but requires work anyway. Only if work is done on a system can thermal energy be transferred from an object at a lower temperature to one at a higher temperature. This is what happens in a refrigerator.

Entropy

To describe the effects of the second law of thermodynamics quantitatively, there is a special



$$\Delta S = \frac{Q}{T_2} - \frac{Q}{T_1}$$



concept, the *entropy*. Unlike force, work, and energy, it has no counterpart in ordinary non-technical language.

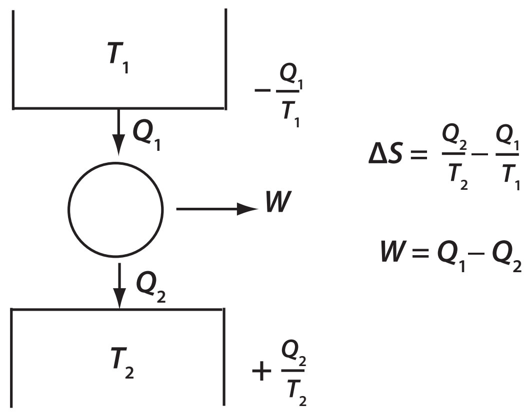
Thermal energy can transfer from an object at a higher temperature to an object at a lower temperature, but the process is *irreversible*. We can't make it go in the other direction, at least not without expending another kind of energy. Something is lost. It's a little like pure, clean water from the faucet. Once it hits the sink, or goes down the drain, we won't want to drink it. There is just as much water, but it is no longer the same.

Let's say an amount of thermal energy, Q, is taken from an object at the high (absolute) temperature, T_1, and transferred to an object at the low temperature, T_2. The hot object loses an amount of energy, Q, which is the same as the amount gained by the cold object. We need some other quantity to describe what has changed. That's where we define the *entropy*, S, to say that an amount of entropy $\frac{Q}{T_1}$ is taken from the object at high temperature and an amount of entropy $\frac{Q}{T_2}$ is given to the object at low temperature. The two are not the same. If T_1 is the higher temperature, $\frac{Q}{T_1}$ is smaller than $\frac{Q}{T_2}$, and the net entropy has increased by the amount $\Delta S = \frac{Q}{T_2} - \frac{Q}{T_1}$.

The entropy turns out to be an excellent measure of the irreversibility of the process and of the amount of energy that, although it is still there, has become unavailable. In a system that does not gain or lose energy (an *isolated* system), the entropy can only increase. At best, it can come close to the limiting "ideal" case where it remains the same.

We can take an amount of heat Q_1 and a corresponding amount of entropy $\frac{Q_1}{T_1}$ from the hot part of the system and transfer a smaller amount of energy Q_2 and the corresponding entropy $\frac{Q_2}{T_2}$ to the cooler part of the system. The difference in energy $Q_1 - Q_2$ can be *used*, i.e., transformed to some other kind of energy, such as mechanical energy. This is what happens in a heat engine.

The best that we can imagine, the "ideal" limiting case, is that the entropy does not change, so that $\frac{Q_1}{T_1}$ is the same as $\frac{Q_2}{T_2}$. In any real situation it increases. We have seen that the entropy increases whenever there are two parts of a system at different temperatures, T_1 and T_2. Some thermal energy (Q) is then transferred from the



hotter part to the cooler one, and the entropy increases by $\frac{Q}{T_2} - \frac{Q}{T_1}$.

The process is *irreversible*, and the increase of entropy is a measure of the irreversibility. The amount of thermal energy that is transferred to the object at the lower temperature, T_2, remains thermal energy. It is "waste heat" that is unavailable, unless an object at a still lower temperature can be found, so that another heat engine can be used for a further energy transformation.

EXAMPLE 3

A pot of boiling soup at 100°C is put on the table, where it eventually cools to the room temperature of 22°C. 5×10^4 J leave it while it is still at 100°C.

(a) Describe the changes in energy.

(b) Describe the changes in entropy.

Ans.:

(a) The internal energy of the pot and the soup decreases. This is the energy of the motion of the atoms and molecules of which the pot and the soup are composed. It consists of both kinetic energy and the mutual potential energy of the atoms and molecules. The energy is transferred to the surroundings, i.e., to the table and to the air, primarily by collisions between the atoms and molecules. (There is also some electromagnetic radiation.)

(b) The entropy leaving the soup is $\frac{Q}{T_1}$, where T_1 is the absolute temperature of the soup, $100 + 273 = 373\,\text{K}$, so that it is $\frac{5\times10^4}{373} = 134\,\text{J/K}$. The entropy gained by the surroundings at $22 + 273 = 295\,\text{K}$ is $\frac{5\times10^4}{295} = 169.5\,\text{J/K}$. The net increase of entropy is 35.3 J/K.

EXAMPLE 4

A steam engine uses steam at 100°C and cools it to 25°C as it does work at the rate of 10 kW.

(a) What is the work done in one minute?

(b) What is the maximum (ideal) efficiency?

(c) How much energy (Q_1) is taken from the steam in one minute?

(d) How much energy is given to the environment as waste heat in one minute?

(e) What can be done to increase the ideal efficiency?

Ans.:

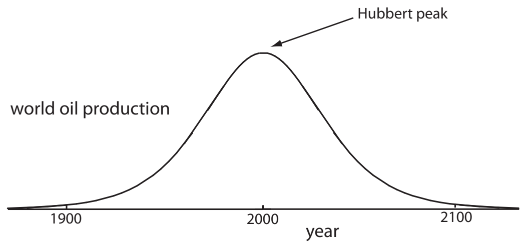
(a) $10\,\text{kW} = 10^4\,\text{J/s} = 60 \times 10^4\,\text{J/min}$.

(b) In the ideal heat engine with the maximum efficiency there is no change in entropy, and $\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$. Hence $\frac{Q_2}{Q_1} = \frac{T_2}{T_1}$, and the efficiency is $\frac{Q_1-Q_2}{Q_1} = \frac{T_1-T_2}{T_1} = 1 - \frac{T_2}{T_1}$. Here this is equal to $1 - \frac{298}{373} = 1 - 0.80 = 0.20$.

(c) Since the efficiency is $\eta = \frac{W}{Q_1}$, $Q_1 = \frac{W}{\eta} = \frac{60\times10^4}{0.20} = 3 \times 10^6\,\text{J/min}$.

(d) $Q_2 = Q_1\frac{T_2}{T_1}$, so that $Q_2 = 3 \times 10^6\,\frac{298}{373} = 2.4 \times 10^6\,\text{J/min}$.

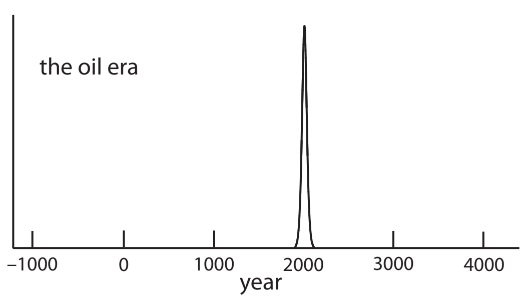
(e) Even in this unattainable best case only a fifth of the energy taken from the hot part of the system is available to be used. Four times as much is rejected to the environment as waste heat or *heat pollution*. We can do better only by making T_1 larger or by making T_2 smaller. T_2 is the lowest temperature in the environment, i.e., that of the atmosphere, or of the available cooling water. The ideal efficiency can then be increased only by raising the high temperature, T_1. The temperature of the steam can be raised above 100°C. (It is then called "superheated steam.")



In 1956 the geologist M. King Hubbert described the exploitation of a limited natural resource through a cycle of expansion followed by decline and eventual exhaustion. He developed a formula for such a cycle and applied it to oil and coal. With the data available at that time he suggested that the U.S. production of oil would reach its maximum near 1970. This is in fact what happened. (See *Energy and Power*, W. H., Freeman, and Co., 1971, first published as the September 1971 issue of *Scientific American*.)

It is more difficult to make a similar analysis for world oil production. New sources of oil continue to be discovered, and some that were previously too expensive to exploit become economically competitive.

Hubbert's analysis leads to the conclusion that after the maximum (the "Hubbert peak") is reached, on the downward part of the curve, the supply can no longer meet the demand. There are then shortages, rising prices, and disruption of activities and processes that depend on oil.



14.6 Our addiction to fossil fuels

Availability

Coal, oil, and natural gas have accumulated over millions of years. Over smaller time intervals they are a nonrenewable resource. Eventually they will be used up, but it is not clear when that will happen.

Even before the middle of the twentieth century it was widely predicted that there would be sufficient oil for only about 30 years. This prediction has derisively been called "time invariant," in that now, almost three quarters of a century later, some people think that the Hubbert peak is still 30 years away. Others suggest that the time of the peak is much closer. The figure shows a

Hubbert curve with its peak at the year 2000. Looked at from the perspective of history, over a longer time, the "petroleum era" is just a blip. The known reserves of coal will last longer, probably at least 100 to 200 years. Unfortunately, this most abundant of the fossil fuels is also the dirtiest, leading (if unchecked) to greater amounts of air pollution than oil and natural gas.

Some of the pollution comes from the part of the fuel that is not carbon. When fossil fuels burn, sulfur and nitrogen compounds are emitted, as well as small amounts of other substances, including mercury and radioactive materials. There are also solid particles, primarily of carbon, which are so small that they remain suspended in the air. Today all cars in the United States have pollution-control devices that limit the amounts of some of the combustion products that are released into the atmosphere.

It is possible to derive liquid fuel from coal. There has been exploratory research on ways to use coal cleanly, but costs have prevented the further development and use of the methods that have been found.

The greenhouse effect

Concerns about the continued availability of fossil fuels have been expressed almost since the beginning of their use. A more recent additional problem is the "greenhouse effect."

The atmosphere is transparent to electromagnetic radiation in the visible region, but absorbs radiation in the infrared portion of the spectrum. The absorption is not by the main air components, nitrogen and oxygen, but by larger molecules that have more closely spaced energy levels as a result of their rotation. The most important are CO_2, H_2O, and CH_4.

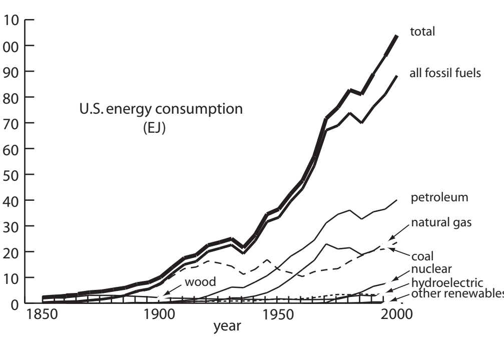
The radiation that reaches the earth from the sun in and near the visible region of the spectrum passes through the atmosphere more or less unhindered and heats the earth. The earth, in turn, radiates electromagnetic energy. The energy and frequency of the earth's radiation are determined by the earth's temperature, and are much lower than those of the radiation that comes to us. (The emitted spectrum has photon energies with a peak near kT, where k is Boltzmann's constant.) Consequently some of this radiation is absorbed by the "greenhouse gases" and transformed into internal energy of the atmosphere, which then heats the earth.

(In a real greenhouse a major fraction of the warming comes from the fact that the enclosed air is stationary, and therefore is not cooled by convection, i.e., by the movement of air.)

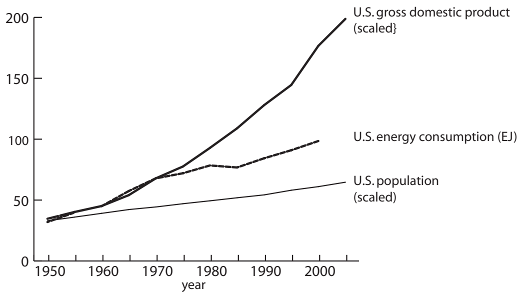
The most important greenhouse gas is CO_2, because as a result of the burning of fossil fuels its concentration in the atmosphere is increasing to the point where it can lead to major climate changes, principally the increase in the average temperature of the earth, commonly called "global warming." There may also be secondary effects, such as increasing severe storms, and more extreme temperature swings, but their connection with the increase of CO_2 is harder to establish.

Global warming through the greenhouse effect is expected to have such drastic consequences that it is now thought to impose the most severe limit on the use of fossil fuels. In other words, even though the resources, particularly of coal, are sufficient for our energy use in the near future, the threat of global warming is leading to reductions and modifications in the use of fossil fuels.

The rate of energy increase



The consumption of energy in the United States has gone from 2.5 EJ in 1850, when it came mainly from burning wood, to 104 EJ in 2000. The figure (with data from the United States Energy Information Administration) shows the rise in the use of coal to about 1920, followed by the more rapid rise of oil and gas during the rest of the twentieth century, and the resulting overwhelming dependence on fossil fuels.



The figure correlates the rise in the use of energy with that of the gross domestic product (GDP) and that of the population. The line for the GDP as a function of time is multiplied by a scaling factor so that it coincides with the energy line in 1970. That allows us to see that in the decades before then energy use and GDP rose at about the same rate. It seemed evident that to tame the rise in the consumption of energy it would be necessary to reduce the rate of increase of the GDP. As the graph shows, this prediction proved to be incorrect. What happened?

Perhaps surprisingly, it seems that we became more efficient. Although the country's output continued to rise, the amount of energy that it took to do that rose at a considerably slower rate. The graph of population against time, scaled to coincide with the others in 1950, shows that the rate of increase in energy use became closer to the rate of population change than to the rate at which the GDP changed.

14.7 Other sources of energy

Nuclear energy

A nuclear reactor provides heat for the high-temperature part of a heat engine, just as does a boiler fueled by burning coal or oil. Let's look at the process in more detail. The nuclei of uranium barely hold together. Heavier elements don't occur in nature because they are too unstable and fall apart. The net force holding the protons and neutrons together in the nucleus is the result of a delicate balance between the attractive nuclear force that acts between the nucleons (protons and neutrons) in the nucleus and the repulsive electric force that tends to drive the protons apart.

A neutron that moves toward a uranium nucleus and collides with it causes the forces to become unbalanced. Normally the nucleus is roughly spherical, but when a neutron sticks to it the uranium nucleus becomes even more unstable. It begins to vibrate so that its surface area increases. At the surface the particles are held less strongly because there are neighboring particles on only one side. The result is that as the surface area increases during the vibration, the attractive force decreases. On the other hand the repulsive force does not change much because it doesn't act just between neighboring particles. Its range is much greater (as given by Coulomb's law) and is influenced by all the protons in the nucleus.

As a consequence, the nucleus doesn't just fall apart. It flies apart, exploding into two roughly equal pieces, the *fission fragments* or *fission products*.

After the fission fragments fly apart they collide with the other atoms. They slow down as they share their kinetic energy, leading to increased thermal energy and higher temperature of the material. Some of this energy is carried to the hot part of a heat engine by the circulation of water or some other fluid.

In the reactors used for power the neutrons are slowed down by a *moderator*. The moderator decreases the speed of the neutrons, but it increases the rate at which fission occurs, because slow neutrons are more efficient in causing fission. Of course there still has to be enough energy for the reaction to take place even if the neutron does not bring any kinetic energy. There are two substances for which this is the case. Both ^{235}U and ^{239}Pu can undergo fission when they are bombarded by slow neutrons. Plutonium does not occur in nature (although trace amounts have been identified) and ^{235}U is only 0.72% of natural uranium.

The nuclear reactors that now produce energy for the generation of electricity do so with slow neutrons on ^{235}U. The number of reactors worldwide was 439 in 2007, of which 104 were in the United States. Each produces of the order of 1 GW of energy. The country that relies on them most heavily is France, where in 2004 they produced 78% of the country's electric energy. In Germany it was 32.1%, in Japan 29.3%, and in the United States 19.9%.

It is also possible to build a reactor without a moderator that slows the neutrons. This increases the number of neutrons that are absorbed by the abundant isotope ^{238}U with the production of ^{239}Pu. They are therefore called "breeder reactors." To use a resource that is 140 times as abundant as ^{235}U is tempting, especially since with the use of only slow-neutron reactors the known uranium reserves are expected to be exhausted in less than a century. Breeder reactors have been built in France, Japan, and the United States, but have been largely abandoned. They are inherently less stable and safe than slow-neutron reactors.

All reactors produce plutonium to some extent. It can be separated from uranium chemically, which is a lot easier than to separate the uranium isotopes or to "enrich" the uranium to enhance the concentration of ^{235}U. It is, however, generally not done because of the extreme hazards associated with plutonium. The lethal dose of ingested plutonium is in the microgram range. Furthermore, an amount beyond the "critical mass" of a few kilograms undergoes a spontaneous chain reaction. In other words, it explodes as an "atomic bomb."

The possibility of abundant energy for thousands of years has given rise to discussions of a "plutonium economy" based on the widespread use of breeder reactors. It is evident that the dangers that would accompany large-scale use of plutonium would be great. In addition to the hazards associated with the chemical and radioactive properties, it would be necessary to store or dispose of large quantities of radioactive waste material. There would also be the problem of security, primarily to prevent the stealing of amounts sufficient for bombs. To some extent we live with these hazards now with the present use of nuclear reactors. It is doubtful that we could tolerate their magnification by several orders of magnitude.

Fusion

Nuclear fusion reactions are responsible for the radiation of energy from the sun and the stars, but it has been unexpectedly difficult to use the same kinds of processes in a controlled way on earth. The reactions have been studied by using accelerators that give the reacting positively charged nuclei the kinetic energy to come close in spite of the repulsive elecrostatic force between them. The experiments show how much energy is transformed from the internal energy of the nuclei to kinetic energy of the reaction products.

For any sustained energy release, however, it is necessary to bring a much larger number of nuclei together and to keep them close long enough for the reactions to occur. They still have to have sufficient kinetic energy to overcome the Coulomb barrier, and this is done by heating the gas containing the reacting nuclei to a high temperature.

Two methods have been explored extensively. One is to bombard pellets of material with high-power lasers This is called *inertial fusion*. The more widely used method is to produce a *plasma*, i.e., a gas of ions, and to contain it by using magnetic fields while it is being heated by high currents or other means. This is called *magnetic confinement fusion*.

The great attraction of using fusion reactions is that the raw material is essentially unlimited. The difficulty of confining the reacting material for sufficient times at a high enough temperature has, however, turned out to be great. Although the amount of material that needs to react is minute, the installation that is required is very large.

Solar energy

What about solar energy? No fuel, no pollution. Why are we not using more than the present small amount?

The energy that reaches the earth is huge, but it doesn't always get down to where we are, and the 1.3 kW/m^2 turns out to be rather dilute. In other words, it takes quite a bit of area to use solar energy on a large scale.

Direct heating is the simplest way to use the sun's radiation. In some parts of the world with a lot of sunshine, tanks on the roof are widely used to heat water. Solar radiation can also contribute to home heating, but its intermittent nature is an obvious drawback.

The simplest solar collection system consists of tubes with circulating water. The water is heated and carried to where it is needed. The efficiency can be increased by using a surface that maximizes the absorption of the solar radiation and at the same time minimizes its reemission. The absorber can also be surrounded by a reflecting surface to concentrate the radiation. At the cost of even greater complexity it can *track* the sun, i.e., it can be turned so as to remain at the best angle to the sun's rays. Quite elaborate large-scale systems have been built. One example is a "power tower" on top of which a container receives the radiation focused on it by an array of mirrors.

Conversion to electric energy is possible through a kind of photoelectric effect in semiconductors. We describe the process used in *solar cells* in the next chapter. Why they are not more widely used is a question of economics not physics. The reasons have to do partly with the expensive manufacturing processes and with the lack of good energy-storage mechanisms as well as the other difficulties that come from having an intermittent source. It would be necessary to devote large areas to the collection and conversion of the energy, and to devise systems for the maintenance of the vast arrays.

In 2009 the cost of a unit of energy from solar cells was at least three times that from fossil fuel sources. So far the relatively low cost, continued availability, and convenience of the fossil fuels have discouraged the investment required for the development of large-scale solar installations. In 2005 0.01% of the energy used in the United States was supplied by solar collectors and solar cells. The exhaustion of our oil resources, and, more slowly, of coal, has been long predicted, and is eventually inevitable. From time to time government subsidies have encouraged research and development, but most of the time the solar industry has been an orphan looking for its place.

Wind

Modern windmills are much more efficient than those used in the Netherlands and elsewhere for hundreds of years. They are also less picturesque. Opposition to their use shows that even the most benign sources of energy have drawbacks. "Wind farms" are installations of many windmills, often along mountain ridges or offshore near beaches. They tend to be opposed by the local population because they spoil the view. Their huge rotating blades are noisy and hazardous to birds.

Nevertheless wind energy is gaining ground. The cost of electric energy generated by wind is now close to that from fossil fuels.

Biomass

The word "biomass" refers to material of biological origin that can be burned as fuel. Wood has been used as a fuel since the time of the first man-made fire. It supplied 3.7% of the world's energy in 2004. Other fuels derived from biological material include household and agricultural waste such as straw and manure. Today there is increased attention to crops specifically planted as energy sources. In general they are not used directly, but are processed to produce ethanol and other petroleum substitutes.

Ethanol (C_2H_5OH) is the same alcohol as in alcoholic drinks. It is made by the fermentation of sugar or starch-containing plant material and subsequent distillation. The amount of energy released when 1 liter of ethanol is burned is 23.6 MJ, which is 65% of the amount (36.1 MJ) from 1 liter of gasoline. Up to 10% can be added to gasoline and used in conventional engines. "E85" is a mixture of 85% ethanol and 15% regular gasoline that is available in some parts of the United States for use in cars with specially modified engines.

In the United States ethanol for fuel use is derived primarily from corn kernels. The amount of energy that is gained this way is controversial. The sun's energy is used to grow the corn, but a good deal of additional energy is required for tractors, fertilizers, and the distillation process. Estimates differ depending on the kinds of energy that are considered and how they are counted. The consensus is that the energy available when the ethanol is burned is between 1.2 and 1.7 times as great as the energy that is used.

The burning of ethanol made from corn leads to only a small reduction (13% by one estimate) in the emission of greenhouse gases. Its most significant advantage is that it replaces gasoline made from domestic or imported oil. In 2004 the ethanol used in the United States represented the energy equivalent to 1.3% of the gasoline and 11% of the nation's corn harvest.

The balance of energy is quite different when ethanol is made from other plant materials. In Brazil ethanol from sugar cane provided 18% of the automobile fuel in 2004. The gain in energy is much greater than with corn, with the ethanol yielding about eight times the amount of fossil fuel energy input. One-half of all cars and 80% of new cars in Brazil are made to accept mixtures of ethanol and gasoline in any proportion.

The basic building block of plant material is *cellulose*, and when ethanol is made from whole plants, including stalks and leaves, it is called *cellulosic ethanol*. Estimates of the ratio of energy gain range from 4.4 to 6.6, representing a significant improvement over the values for ethanol derived from corn. The reason that cellulosic ethanol has not been made on a large scale is that different microorganisms are required for the fermentation, and processes that can be used for industrial-scale manufacture are still under development.

Energy from rivers, oceans, and the earth

The kinetic energy of the flowing water in rivers has long been exploited with water wheels, and more recently with more efficient turbines that drive electric generators. Even this seemingly very benign source of energy has detrimental side effects, primarily from the dams that are built to control the flow. Sometimes large areas are flooded, destroying animal and human habitat. Ancient monuments were submerged by the *Aswan Dam* project in Egypt, and whole villages disappeared as a result of the *Three Gorges* project in China.

The vast amounts of energy in the oceans have led to speculations on how they might be used. Demonstration projects are planned and some are underway to use the kinetic energy of tides and waves. The thermal energy is huge, but it is unavailable as long as the water is all at the same temperature. If there are temperature differences, however, energy can be extracted with heat engines between the hotter and the colder parts. For the relatively small temperature differences in the ocean the efficiency is very small, and attempts to use this energy have remained on a small scale.

There is also the thermal energy of the earth, its *geothermal* energy. The temperature gets higher as we go further down into the interior of the earth. Eventually it gets so large that the core of the earth is molten. (This is the *outer* core. The inner core is under such pressure that it is solid.) The origin of the energy is believed to be the radioactivity of the materials that are part of the composition of the earth.

We become aware of the thermal energy through the rising temperature as we drill down, and more spectacularly through volcanoes and geysers. In some regions the energy is being used in geothermal power plants.

The sustainability transition

The earth, as our habitat, faces a number of obstacles, and is often said to be *in crisis*, as at the turning point of a disease, from which the path is either toward recovery or toward death. Are the natural resources on which we have come to depend being depleted to the point where they are no longer adequate for our needs? Are we polluting the air, the water, and the ground with waste material to the extent that they can no longer sustain us? Is our use of fossil fuels producing greenhouse gases in amounts that will produce disastrous climate changes? Each one of us contributes to these effects, and their damage grows as the population of the earth increases. Was Malthus right when he said that the number of people was reaching the limit beyond which the earth cannot support it?

We are engaged in a grand experiment of which we are the subject. In time we will find out whether we are demanding more of the earth than it is able to give. But we are also in a position to influence the outcome. We can use our knowledge and ingenuity to bring about new ways to use the materials that are available to us. Our record of scientific discoveries and accomplishments is great and we may be able to push back the apparent limits to our resources and to the earth's population.

As time goes on we are, however, getting closer and closer to the limits set by nature. It is becoming more and more urgent that we limit what we use and what we waste. To avoid the catastrophe predicted by Malthus we must eventually approach a state of equilibrium, where we use only what can be renewed or replaced, and keep the population to a size that can be fed and housed and that can live with what we are given.

Will we be intelligent and resourceful enough to find new ways to use the materials at our disposal and so extend the limits to our growth? Will we be sufficiently intelligent to understand and to act on the fact that the earth's size and its resources are fixed, and that we must restore what we use?

In sum, will we humans be able to make the transition to an existence that can be sustained over time? At present we are using resources that are not replaced. We are disposing of waste in the atmosphere, in the rivers and oceans, and in the soil in ways that cannot continue indefinitely. Our sources of energy will need to change as fossil fuels are depleted. Pollution with toxic substances and greenhouse gases is increasing. The population of the earth is twice what it was 25 years ago.

The grand experiment in which we are engaged will show whether we can make the transition to sustainability, and so continue to exist. Malthus thought the time of crisis was at hand 200 years ago. Are we there now?

The search for new sources of energy and new methods of pollution control and waste disposal shows that the success of any new process depends on four different kinds or stages of support. The fundamental idea and scientific research come first, with observations and with experiments and tests in the laboratory. But it is not enough to have a good idea. It has to be followed by technological development, i.e., by finding ways to use it on a large scale. Solar energy, for example, continues to be the subject of search both for new scientific ideas and for improvements in technology. The reason why it and other alternatives are not more widely in use can be found as we look at the two other necessary pillars of support. One of these is economic competitiveness. As long as energy from solar cells is more than three times as expensive as that from other available sources, there is little chance that it will become more widespread. Finally, there must be the political will and popular support to bring about a change. This is true whether we talk about obstacles to the use of nuclear reactors or about the environmental damage that has led to opposition to the further large-scale development of other new and old sources of energy.

14.8 Summary

In spite of their drawbacks the *fossil fuels*, coal, natural gas, and oil, are the predominant sources of the energy we use.

Electric energy is a *carrier* of energy. It allows us to use energy more conveniently and in a place different from where it is generated. Another possible carrier is hydrogen.

Most electric energy is transported as *alternating current (*AC*)*. One advantage of AC is that it is more easily generated than DC (direct current). A second is that transformers can be used to change the voltage and current so as to reduce the loss of energy during transmission.

Batteries are used to store energy. Their use is largely restricted to applications where portability is a main consideration.

The internal energy of the fossil fuels is liberated by burning, and transformed to mechanical energy in a *heat engine*. In addition to being limited by the law of conservation of energy, the transformation is limited by the *second law of thermodynamics*, which requires that the *entropy* not decrease. It normally increases, and remains unchanged only in the limiting ideal case.

When energy ΔQ is transferred to an object at an absolute temperature T, its entropy, S, increases by $\Delta S = \frac{\Delta Q}{T}$.

The efficiency of a heat engine is $\frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$. Its maximum (ideal) value, without an entropy change, is $\frac{T_1 - T_2}{T_1}$.

Another statement of the second law of thermodynamics is that energy transfers spontaneously from a hotter object to a cooler one, but a transfer in the opposite direction can happen only if work is done on the system. Similarly an object can be cooled below the temperature of its surroundings only by doing work.

All bodies radiate. The spectrum of the radiation depends on the body's temperature. The sun's high temperature causes its radiation to be strong in the visible range, and we see it as white. Except for the effect of clouds, it passes easily through the earth's atmosphere. The earth radiates also, but because of its lower temperature the radiation is not visible. It is at a lower energy and frequency and longer wavelength, in the infrared region. The atmosphere absorbs some of this radiation as a result of the presence of molecules other than nitrogen and oxygen. These more complicated molecules can absorb infrared radiation, ususally because they can rotate. The energy that gets absorbed and does not escape is trapped and leads to warming of the earth. This is called the *greenhouse effect*.

Energy is increasingly used from sources other than fossil fuels. These sources include nuclear reactors and energy from the sun. Solar energy can be used directly to produce thermal energy, and through solar cells to produce electric energy. Other sources are wind, rivers and oceans, and geothermal energy.

The fossil fuels are resources that cannot be replaced, so that their use cannot continue indefinitely. Ultimately we must make the transition to sustainable use, that is, to sources that can continue to be available, such as wind and solar energy.

14.9 Review activities and problems

Guided review

1. The battery pack of a hybrid car consists of 38 modules, each of six nickel-metal hydride (NiMH) cells, all connected in series. Each module is rated at 6.5 Ah and has a mass of 1.04 kg.

(a) What is the energy in kwh that can be stored in this battery pack?

(b) What is the energy density in watt-hours per kilogram?

(c) How many gallons of gasoline would deliver the same energy to the car?

2. How large a capacitor, charged to 150 V, is necessary to store an amount of energy equivalent to that delivered to a car by a gallon of gasoline?

3. Energy is transferred from a hot object to one that is cooler. Show that the net entropy increases.

4. Why can the ideal efficiency of a heat engine never be attained?

Problems and reasoning skill building

1. An alkaline AA 1.5-V battery is rated at 3000 mAh. What would be the cost of this amount of energy from an electric outlet at ten cents per kwh?

Synthesis problems and projects

1. A hybrid car cannot run on electric energy alone for more than a small distance. Design an NiMH battery pack for a "plug-in" hybrid car whose batteries are to be recharged overnight from a household electric outlet. Use the given and calculated information of the first Guided review question.

Consider how many miles you expect the car to travel on one charge, the mass of the battery pack, the cost of the battery pack compared to that of the one in Example 1, and the cost of the overnight charge.

Based on your results, discuss some of the obstacles facing the design of fully electric cars.