Chapter 2
Knowing Energy

Any action that does not happen naturally or spontaneously, such as lifting something heavy from a low place to a high place or moving heat from a cold place to a hot place, requires energy. Because almost none of the human activities of "making things" and "daily life" occur spontaneously, they nearly all require energy. Therefore, energy is an essential piece of the puzzle in figuring out how to sustain the biosphere while we provide a modern standard of living for the human population of the earth. But many fundamental concepts of energy are difficult to grasp. Although a lesson on what energy is and what it means to consume energy may seem unexpected in a book about creating a sustainable society, it is important that we clarify these concepts before introducing ways in which technology can be used to make human existence on the earth sustainable.

1 Energy Is Conserved

Energy Is the Ability to Do "Work"

You have probably seen a building demolition team use a crane to lift an iron ball and drop it to break up concrete structures. When any object, not just an iron ball, is dropped from a high place, it can do "work." "Work," like energy, is a word we use in many ways in ordinary conversation; however, in the world of science and technology, "work" has a strict definition. "Work" is defined as the product of a force and the distance that an object is moved by applying that force. For example, when an iron ball is raised a certain distance, the "work" done equals the force applied to the ball times the distance the ball is raised. To raise the ball twice the distance, twice as much work is required, and if the weight of the ball is reduced to half, then half the work is enough to raise the ball. However, work can also take the form of other changes. For example, crushing concrete structures is a form of work that is done by the iron ball dropped from the crane. An iron ball flung through

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the air does work when it hits a thin sheet of iron and changes the shape of the iron sheet. A definition of energy that is appropriate for the discussion in this book is the ability of physical objects and their conditions, such as their temperatures and pressures, to do work.

Kinds of Energy

There are three basic types of energy: external energy, internal energy, and field energy. The energy contained in the iron ball that is lifted up by the crane is called potential energy, and the energy of the ball flying through the air is called kinetic energy; these are both types of external energy. Other objects that have potential energy include helicopters hovering in the air, water held up in a dam, and a car stopped at the top of a hill. Other objects having kinetic energy include a moving car, flowing air, and a spinning motor.

"External energy," such as the motion of a car or the position of a helicopter high above the ground, is apparent from outside. In contrast, "internal energy" is energy hidden in the object itself, which cannot be detected from outside appearances. Internal energy includes heat energy, chemical energy, and nuclear energy.

Although most people have a vague understanding of what "heat energy" is, the term "heat energy" is not actually correct. It is more accurate to say that objects having a high temperature have internal energy. Recall that the definition of energy is the ability to do work. If we have water with a high temperature, then we can use it to make steam and use the resulting pressure of the steam to drive a steam engine, making it possible, for example, to do the work of moving a steam locomotive. In other words, water with a high temperature has internal energy that can be used to do work in the same way as kinetic and potential energy. "Heat," on the other hand, is the transport of internal energy from an object having a high temperature to an object having a lower temperature.

Fuels such as kerosene have internal energy in the form of chemical energy. If we combine kerosene with oxygen in a chemical reaction called combustion, a hot flame will be produced, a flame we can use to turn water into steam. Nuclear energy is contained in every atom; however, there are only a few elements whose atoms can be easily used to obtain energy for doing work. One of those elements is uranium. We can use the heat generated when an atom of uranium is split into smaller atoms through the process of nuclear fission to do work, for example to make electricity. Nuclear fusion is another process that creates heat from nuclear energy. When two hydrogen nuclei are fused together to make a helium nucleus, heat is also released. This fusion is what powers the sun.

Field energy can be imagined by thinking of the inside of a microwave oven. When you turn a microwave oven on, the inside becomes filled with electromagnetic waves, which is a form of "field energy," and that energy can do the work of raising the temperature of the cup of coffee in front of you that has gotten cold as you were reading this chapter.

Energy Media and the Law of Energy Conservation

We often refer to work, heat, electricity and light as "energy;" however, strictly speaking, they are energy media, that is, ways for transporting energy from one object to another. For example, if we burn some propane to heat the water in a teapot, the chemical energy that was in the propane is changed into the internal energy of the water through the medium of heat, resulting in the rise of the water's temperature.

The energy of an object can be used to do work, and work can be used to add energy to an object. Think back to the iron ball being dropped from the crane to break up a building. When the crane lifts the iron ball, the ball will gain no more potential energy than the amount of work that is applied to it by the crane. When the iron ball is released from some height, it will fall. As it falls, it loses potential energy corresponding to the distance that it has fallen, and its kinetic energy increases by essentially the same amount. So as the ball falls, potential energy is transformed into kinetic energy. The form of the energy is transformed, but the total amount of energy – the sum of the potential energy and the kinetic energy – remains constant, as illustrated in figure 2-1. As a general principle, when energy changes from one form to another, the total amount of energy in all forms remains the same. This principle is called the law of energy conservation.

What happens when the iron ball hits the ground and stops? Both the kinetic energy and the potential energy of the ball are gone because the ball is no longer at a high location, nor is it moving. But if that is all that happens, the law of energy conservation will be abrogated. Actually, when the iron ball hits the ground, heat is generated, and the temperature of the ground and the surrounding air is raised. When we say that the temperature rises, we mean that the internal energy of the ground and air is increased, and this increase in internal energy is exactly the same as the potential energy of the iron ball before it fell. Furthermore, this amount of

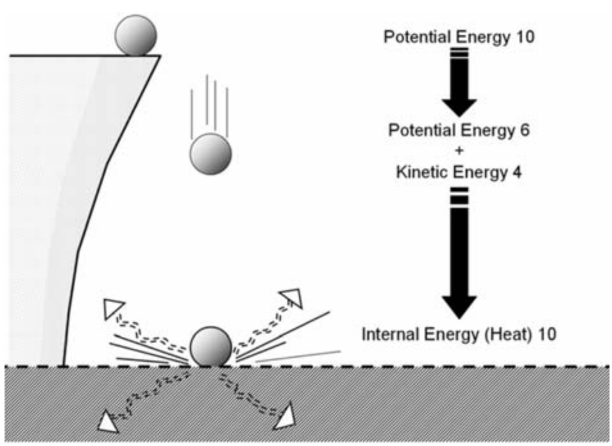

Fig. 2-1: Transformation and conservation of energy

energy is also the same as the work that is required to lift the iron ball back to its original height.

In this way, the forms of energy can be changed, but the total amount is conserved. But if that is the case, how can we talk about an energy crisis or say that a form of energy is being depleted? We shall return to this question in the third section of this chapter.

Because our explanation of energy has been brief and because the concepts can be a bit tricky to grasp, let's pose a few questions here that may bring these concepts of energy closer to home.

Question 1: In a closed room, which has a larger heating effect: turning on a 1 kW electric heater, or turning on television sets, radios and lights with a total power rating of 1 kW?

Answer:

A) turning on a 1 kW electric heater
B) turning on the televisions and other appliances
C) almost the same
D) exactly the same

Question 2: If you leave the door of a refrigerator open in a closed room, what will happen to the room's temperature?

Answer:

A) the temperature will increase
B) the temperature will decrease
C) the temperature will not change much
D) the temperature will not change at all

The answer to question 1 is "almost the same." After electricity is transformed into light and sound by television sets, radios, and lights, all of the energy in the end becomes heat, so the heating effect of the appliances is almost the same as turning on a 1 kW heater. The reason that the answer is "almost the same" is that since we can see light from the television and hear sound from the radio from outside the room, we know that a small part of the energy from those appliances escapes the room through the energy media of light and sound. Therefore, there will be a very small difference in the heating effect.

The answer to question 2 is "the temperature will rise." This may seem counterintuitive to you, but if we consider the law of conservation of energy in the closed room, the internal energy of the room must increase by an amount equivalent to the electricity consumed by the refrigerator. A refrigerator is actually just a device for pumping out the heat that leaks into the space inside the refrigerator from the air in the room. In the back of a refrigerator, there is always a place that is hot, and from that place heat is released into the room. If the refrigerator door is left open, the amount of heat released from the back of the refrigerator will be more than the cooling effect coming from the open door. The difference is exactly the amount of electricity that is consumed. Recently, in places like hotels, refrigerators are often placed in a box made to look like a piece of furniture in order to keep them out of sight. However, if there are not enough openings in the box, it will get hotter and hotter until the refrigerator ceases to work. Many of you who travel a lot have probably stayed in hotel rooms having this problem.

Here is one more question (the last, I assure you!).

Question 3: In the situations described in the previous two questions, where does the heat generated from the electricity go?

If every time we use energy, that energy ends up warming the surrounding air as heat, why is it that the temperature of the earth does not rise? The reason is that in the end, energy that becomes an increase in the temperature of the air and the surrounding environment, what is called the “ambient temperature,” is finally radiated to outer space as infrared radiation. As we saw in the section describing the mechanism of global warming from the previous chapter, when the temperature of the earth’s surface starts to rise, the radiation from the earth increases, thereby keeping the temperature stable. An increase in radiation from the earth means that energy that has taken the form of an increase in ambient temperature is escaping to outer space through the medium of heat.

How a Thermal Power Plant Works

Among the many different media for energy, electricity is one of the most outstanding. Electricity can be easily changed into light, work, or heat; it can be transported using just a wire, and it can be turned on and off with a single switch. The amount of energy a nation consumes usually increases with improvement in living standards, and the increase is especially large for electricity. However, unlike forms of energy such as gasoline, which we can see, electricity is invisible, so it can be more difficult to understand. Let’s summarize the main concepts here. There are two methods for obtaining electricity. One is to use an electric generator. The other is to use an electric cell.

An electric generator works the same way as a generator-type light on a bicycle. You know those non-battery powered bicycle lights with a little wheel that is turned by the front wheel of your bicycle? These generator-type lights contain a magnet that is placed around a coil of metal wire. The coil can be turned on an axis, and when it rotates inside the magnet, electricity is generated that flows through the coil. Therefore, an electric generator is a mechanism for transforming rotational work into electricity. There are many techniques used to rotate the coil. In the case of the bicycle light, the rotation energy comes from the wheel that turns when you pedal. In wind power, wind is used to create rotation energy by turning the blades of a wind turbine. In hydropower, the force of water that flows down through a pipe turns the blades of an impeller.

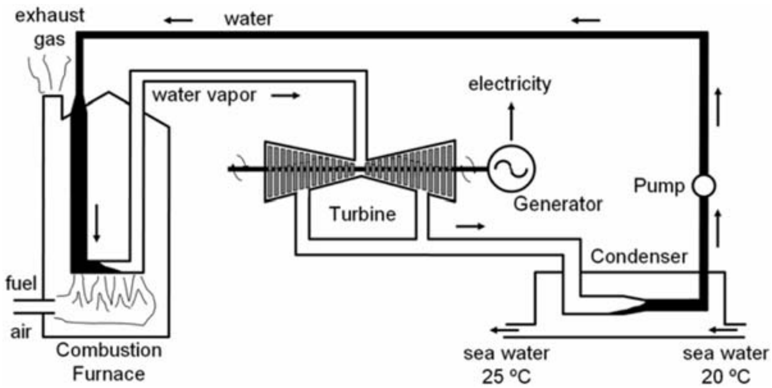

Fig. 2-2: The basic mechanism of thermal electric power generation

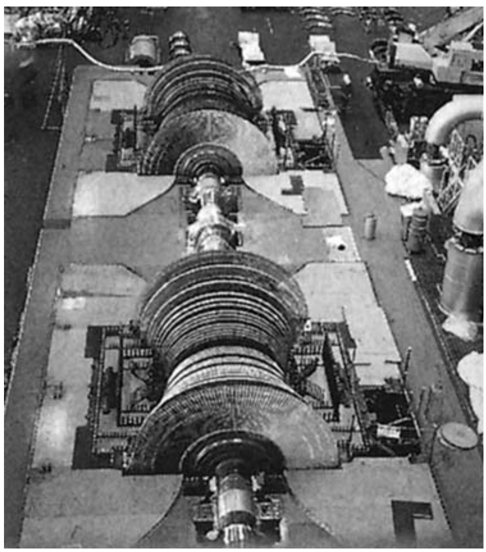

Fig. 2-3: The turbine of a thermal power plant (Courtesy of Tokyo Electric Power Company)

Figure 2-2 shows a conceptual image of the mechanism of a thermal power plant. First, fuel is combusted in a furnace and used to boil water in steel pipes, producing steam. Then, the steam is channeled to a turbine, causing it to turn and thus producing rotational energy that is transformed into electricity using a generator. Figure 2-3 is a picture of a turbine with its outer cover removed. A turbine is basically a huge high-precision wind mill made of a special kind of steel that is rotated using the force of steam. However, if the exit of the turbine is not at a low pressure, the steam will not flow through the turbine. Therefore, the exit is connected to a steam condenser made of numerous thin pipes through which water or some other coolant flows. By changing the steam to water in the condenser, the pressure is reduced causing more steam to flow through the turbine. The condensed water is returned to the furnace using a pump. In short, water is circulated from the combustion furnace, and during that circulation it turns the turbine which drives the electric generator. In this way, we are able to extract electricity from the chemical energy of fuel. However, less than half of the chemical energy of the fuel can actually be transformed into electricity. Most of the heat produced by combustion of fuel is lost when the steam is condensed in the condenser. As a result, more than half of the chemical energy of the fuel used in a thermal power plant is released as waste heat into the environment.

The mechanism of a nuclear power plant is essentially the same as that of a thermal power plant. The main difference is that in place of the furnace where fuel is combusted in a thermal power plant, a nuclear power plant uses a nuclear reactor, which produces heat from nuclear fission.

How Electric Cells Work

There are many kinds of electric cells. Chemical electric cells change chemical energy into electricity. Solar electric cells, which are usually just called solar cells, change sunlight into electricity. We will see how solar cells work in Chapter 6. Currently, most of the widely used chemical electric cells work by separating two chemicals with a fluid or some kind of separating membrane that is porous only to ions, placing electrodes in each chemical, and allowing the two chemicals to react.

You may recall from high school chemistry experiments that water molecules can be separated into hydrogen and oxygen by applying electricity. This is called the electrolysis of water. As shown in figure 2-4, a hydrogen-oxygen chemical electric cell uses the same mechanism, except that at the places where hydrogen and oxygen are produced in electrolysis of water, hydrogen and oxygen are supplied in a chemical electric cell, and at the place where electricity is provided in electrolysis of water, electricity is extracted in a chemical electric cell. Here is how the chemical electric cell in figure 2-4 works. The membrane of the cell is made of a material that allows only hydrogen ions to pass through. Thus, the only way for hydrogen on the left side of the membrane to get over to the right side so that it can react with oxygen to produce water is for the molecules of hydrogen to give up electrons and change into hydrogen ions. Once the atoms in the hydrogen molecules are changed into ions, they can pass through the membrane to the right side of the cell, but the electrons cannot. The electrons are needed to complete the reaction of oxygen and hydrogen to water, so they must find another way to get to the right side of the cell. This way is provided by an external circuit that connects electrodes on each side of the cell. The electrons travel via the external circuit to reach the right side of the cell, where they change the oxygen molecules into oxygen ions. The oxygen ions then react with the hydrogen ions that passed through the membrane, thereby forming water. In this process of making water from hydrogen

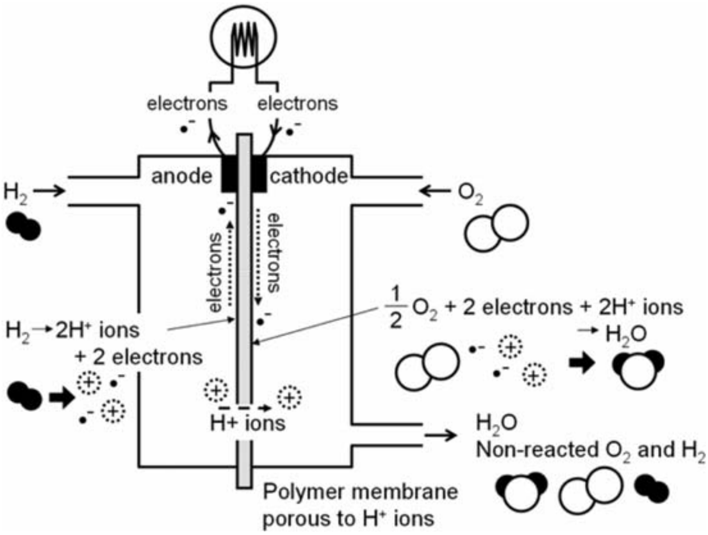

Fig. 2-4: The basic mechanism of an electric cell
Note: Ions are formed on both sides of a membrane that prevents the passage of electrons. The ions on one side pass through the membrane to react with the ions on the other side. The electrons travel through an external circuit and become electricity. The example in the figure using hydrogen and oxygen is called a fuel cell.

and oxygen, electricity can be extracted in the form of the flow of electrons through the external circuit.

In essence, hydrogen and oxygen have a natural tendency to combine spontaneously and form water, and that natural tendency can be harnessed to produce electricity. This is a specific example of the general rule that any chemical process that proceeds spontaneously can produce work.

There are many kinds of chemical electric cells. Each kind of cell has a different combination of the reacting chemicals involved and the membrane or other separator used to separate the chemicals. The most common chemical electric cell, the dry cell, uses magnesium dioxide and zinc. Lithium batteries use magnesium dioxide and lithium separated by a thin sheet of plastic, mercury batteries use mercury oxide and zinc, and car batteries use lead oxide and lead separated by sulfuric acid. The electric cell in figure 2-4, which uses hydrogen and oxygen, is called a fuel cell.

Energy Resources

When experts talk about energy crises, they are referring to the problem of a depletion or inadequate distribution of energy resources. So what is an energy resource? Basically, an energy resource is a source from which or a method by which energy can be obtained. However, when we speak of energy resources in the context of the sustainability of the earth, what we usually mean is "natural energy resources," or sources of energy obtained directly from nature. Natural energy resources may be buried in the earth, growing on the earth's surface, or falling from the sky. However, no artificial processes are necessary to create these resources.

Hydrogen and electricity are not energy resources. The reason is that, for all practical purposes, these sources of energy cannot be obtained directly from nature. There are few people who consider electricity to be an energy resource; however, strangely, many people misunderstand hydrogen. It is often said that "hydrogen can solve the energy problem" or that "we can create a country based on hydrogen." The gist of these claims is that, because it is possible to make hydrogen from the electrolysis of water, and there is an abundant supply of water, if we were to use hydrogen to meet our energy needs, we could solve the energy problem and simultaneously end the emission of toxic materials. But this is not correct. Even if there were an inexhaustible supply of water, electricity is required to obtain hydrogen from water, which puts us back in the position of needing an energy resource to produce the electricity. To use hydrogen as a source of energy, we still must draw on some energy resource to obtain the hydrogen.

Therefore, in addition to fossil fuels and nuclear energy, the energy resources that we know about consist of geothermal energy (which is the energy of the earth's core), the rise and fall of the tides (which are pulled by the moon), and solar energy, including all of the energy resources powered by the sun, such as wind, rain, and biomass. Currently, almost 80% of the energy used worldwide is supplied by fossil fuels, including oil, coal and natural gas. Solar energy in the form of biomass and hydropower supplies about 15%, and nuclear energy supplies about 5%. Geothermal energy, tidal power, and forms of solar energy other than biomass or hydropower together make up less than 1%. The role of oil refineries and power plants is to transform energy resources into forms that are easy to transport and easy to use, such as gasoline, compressed or liquefied natural gas, and electricity. The role of engines, motors, appliances, and lighting fixtures is to transform these forms of energy into the work, heat, and light that we use directly in "making things" and "daily life."

Expressions for Energy

There are several methods to express measures of energy resources. "Coal conversion" and "oil conversion" are methods whereby a form of coal or oil is chosen, and its heating value per unit mass is taken as a standard unit. Then quantities of other energy resources needed to do a given amount of work are converted into those standard units. The numbers in figure 2-5, which we will see in the next section, use a form of oil conversion called TOE, for ton-oil-equivalent. There are methods for expressing nuclear energy and hydro energy in the same way. Because most energy resources are used as electricity, we need a way to express how many

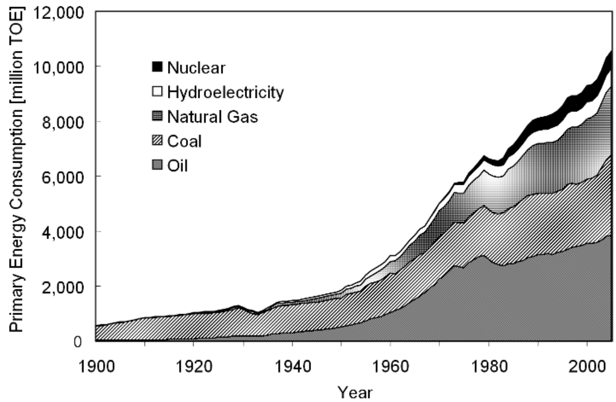

Fig. 2-5: Global consumption of energy from 1900 to 2008 (Data from the BP Statistical Review of World Energy 2007)

standard "oil conversion" or "coal conversion" units a given amount of electricity corresponds to.

There are two ways to do this. One way is to calculate the amount of heat that can be produced by using the electricity in an electric heater. Then, this amount of electricity is expressed in terms of the amount of fossil fuel needed to provide the same amount of heat. The other way is to calculate the amount of heat needed to produce a given amount of electricity in a thermal power plant. Earlier, we saw that less than half the heat energy of the fossil fuel consumed is actually transformed into electricity. The amount of fossil fuel needed to produce some amount of electricity is that amount of electricity divided by the generation efficiency of the power plant. If the generation efficiency is 33%, then three times as much fossil fuel energy is required. Using this second method gives a more accurate assessment of how much fossil fuel would be required to meet some energy demand if all of the energy were provided by fossil fuels. But if we convert the electricity produced by nuclear power and hydro power into standard units using the first method, we will underestimate the amount of nuclear and hydropower energy used. The amount of primary energy consumption provided by nuclear power plants and hydropower plants in figure 2-5 is obtained by dividing the electricity provided by the plants by a power generation efficiency of 0.33, the global average for thermal power plants.

Another way to express the measure of an energy resource is by converting to units of carbon. In this method, each energy resource is expressed as the amount of carbon contained in the resource. Therefore, this method is applicable only to carbon-based fuels and cannot be used for energy resources such as nuclear and hydropower. And this method cannot accurately compare energy resources that yield large heating values per unit of carbon, resources like natural gas, with energy resources like coal that are highly carbon intensive. Nevertheless, because the global warming is basically caused by CO_2, we can, by converting fossil fuel resources into carbon units, directly express the effect of burning those resources on global warming. In this book, when referring to precise values of energy amounts, we will use oil conversion units; and in all other cases, we will use carbon conversion units.

2 What Is Energy Used for?

World Energy Consumption Is One Ton per Person per Year

In figure 2-5, we see how dramatic the rise in energy consumption has been in the 20^{th} century, an increase of approximately 20-fold. Today, the amount of fossil fuel consumed annually (about 80% of the total energy consumption) is about 7.5 billion tons when converted to carbon units. Because the current world population is more than 6.5 billion people, the average consumption of fossil fuel energy by the people of the world at the turn of the century was just a little more than one ton per person per year.

So how do the numbers look in Japan? Japan has a population about 125 million and consumes about 350 million tons of fossil fuels, so it has a per capita fossil fuel consumption of 2.7 tons. Almost all of the fossil fuels imported to Japan each year are first sent to oil refineries, electric power plants, and gas companies. Currently, the distribution is 60% for oil refineries, 25% for power plants, and 5% for gas companies. The remainder of the fossil fuel is coal used for making iron and steel. The oil refineries, power plants and gas companies do not use the energy themselves but instead deliver it to places where it is needed in the activities of "daily life" and "making things."

So how is all of this energy used? To answer this question, we would need data on the distribution of energy use for all of the countries in the world. Unfortunately, such information is not generally available, even in many developed countries. Japan is one of the few countries that has data on the distributions of energy use, so we will illustrate the concepts of energy use for "daily life" activities with data from Japan.

The distribution of energy use in Japan is shown in figure 2-6. The places where "daily life" activities occur are homes, offices and transportation, accounting for 9.5%, 13.0% and 16.5%, or a total of 39% of the energy consumption. Industry, that is "making things," consumes 31%, and 30% is consumed in transforming various forms of energy into electricity and oil refinery products. Next, let us examine how energy is used in each of these activities.

Energy Use in "Daily Life"

Energy is consumed through "daily life" activities in homes, work places, and transportation. The energy consumed in homes consists almost entirely of electricity,

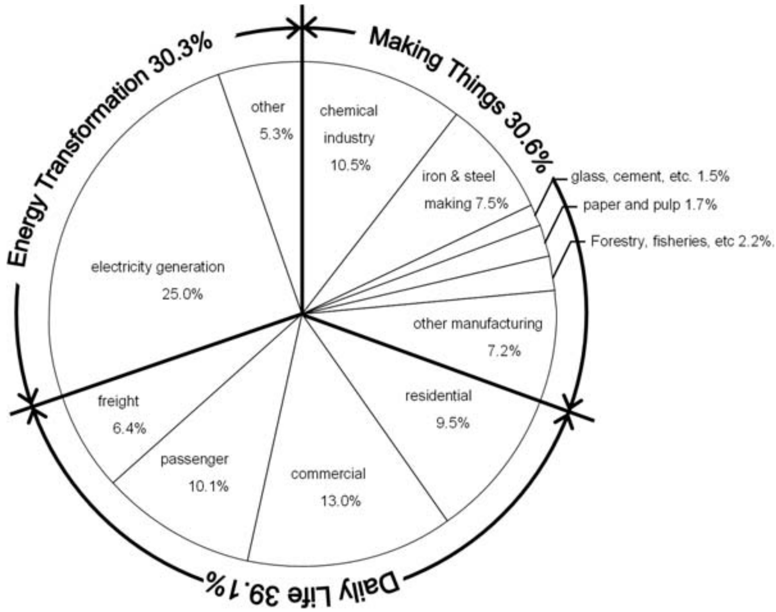

Fig. 2-6: Distribution of energy consumption in Japan (Data from Sogo Enerugi Tokei 2005, Japan Agency for National Resources and Energy)
Notes: Data is from 2007. The energy consumed in "energy transformation" is mostly energy in power plants that does not become electricity or that is used internally in the plant.

gas, and kerosene. This energy is used to cook, heat water, run electrical appliances, and heat or cool the home. Energy consumption in offices and other work places is not much different, although there is some variation in the way energy use is distributed, with a greater consumption of electricity in the work place by computers and copy machines.

Refrigerators, washing machines, and vacuum cleaners all work by using electricity to drive a motor. These uses of energy, together with lighting and televisions, make up about one third of the total consumption of energy from "daily life" activities in homes. Roughly speaking, another third is used for heating and cooling, and the last third is used for hot water and food preparation. Of the total household use of electricity, refrigerators, air conditioners, and lights each consumes about 20%.

Forms of transportation that use energy include passenger cars, trucks, buses, trains, airplanes, ships and so on. In Japan, gasoline for passenger cars accounts for more than 50% of the total energy consumption for transportation, both personal and business related. The next largest contribution is the 35% used by freight vehicles for business and personal transport, mainly trucks. Other forms of transport, such as planes, ships, taxis, buses, and trains, constitute less than 15%. Therefore, even if we assume the energy used in transportation to be just the amount used in cars and trucks, our error will not be so great.

The Production of Basic Materials Is the Core of Manufacturing

We can readily picture how energy is consumed in “daily life;” however, the consumption of energy in manufacturing may be somewhat more difficult to imagine. The manufacturing process that consumes the most energy is the making of iron and steel, followed in order by the production of chemical materials like plastics, non-metal minerals like glass and cement, and paper and pulp. In Japan, these industries alone account for more than 60% of the energy consumed in manufacturing. That is, most of the energy consumption in manufacturing is used to change natural resources into basic manufacturing materials such as iron, cement, glass, paper, plastic, synthetic fibers and rubber. As we saw before, the quantity of fossil fuels needed to make one ton of material is 600 kg for iron, one ton for plastic, 100 kg for cement, 200 kg for glass, and 300 kg for paper. This is the nature of energy consumption in manufacturing. The combustion of fossil fuels in the global flow of basic materials, the flow we looked at in the previous chapter, accounts for nearly all the energy consumed in “making things.”

You may have noticed that in the list of industries consuming the most energy, the manufacturers of cars, heavy equipment, and home appliances are not included. Construction and urban engineering companies are also missing. The reason is that, in comparison to the energy used in producing basic materials, very little energy is consumed at assembly plants and construction sites.

Consider the example of a car. The largest energy consumption in a car’s lifetime is the gasoline used to drive it. The next largest is the energy used to produce the basic materials of the car, such as iron and plastic. These materials are purchased by automobile companies and assembled into cars; however, the energy consumed by shaping the materials and assembling them is surprisingly small. According to one estimate, of the total energy consumed by a car – from production to disposal – 79% goes to the gasoline use to drive it and 14.5% to basic materials used to make it. Only 4.5% goes to the process of assembling it, with the remaining 2% used for maintenance, repair, and disposal.

We often see giant cranes at construction sites with sparks flying as workers solder parts together, and on the television, we see video footage of factories using robots and conveyer belts in assembly lines. But the amount of energy consumed at these stages of “making things” is surprisingly small. In fact, to determine which products consume the most energy in their manufacture, instead laboriously totaling the amounts of energy that different industries use to operate their machines and facilities, it is easier and almost as accurate to compare the energy consumed to produce the basic materials used to make the products. For example, in Japan about 50% of the iron produced is used in the construction of buildings and bridges, and 16%, in making automobiles. Thus, we can estimate that constructing buildings and bridges consumes about three times as much energy as manufacturing automobiles. Basic materials are produced to make the things that we consumers use, and it is in producing basic materials that the bulk of fossil fuels in manufacturing are consumed.

Energy Loss in the Energy Conversion Sector

Power plants, oil refineries, and gas companies are the main players in the energy conversion sector. The purpose of this sector is to change energy into forms that are easy for consumers to use. But it is never possible to convert 100% of one form of useful energy such as work into another such as electricity. During any transformation of energy from one useful form to another, some energy will always be transformed into heat at ambient temperature, which cannot be used. As a result, some part of the energy resources is consumed in the energy conversion sector. We saw earlier how thermal power plants fired by fossil fuels release over half of the fuel's chemical energy into the sea or atmosphere. In addition to that, a percentage of the generated electricity is consumed in operating the electric power plant itself. In the case of nuclear power plants, the power generation efficiency is lower, resulting in an energy loss of about 70%.

The fraction of electricity consumed in the operation of electric power plants around the world varies according to a number of factors, including the efficiency of the plant's operation and the technologies used to control pollution. For example, in Japanese fossil-fuel fired power plants, the ratio of electricity consumed by the plant itself is relatively high because almost all Japanese power plants use energy-consuming processes to remove sulfur oxides, nitrogen oxides, and fly ash from the combustion gas. As of 1990, world-wide there were about 2360 plants operating desulfurization equipment and 490 plants with denitrification, of which 1800 of the desulfurization plants and 350 of the denitrification plants were in Japan. Japan, a country that accounts for no more than 5% of the world's energy consumption and has no more of 5% of the world's power plants, operates more than 70% of the world's power plants with facilities for treating combustion gas. Thus it seems fair to say that in 1990 the only country doing a substantial amount of desulfurization and denitrification at power plants is Japan.

Obviously, by removing all of the desulfurization and denitrification equipment, we could increase the efficiency of fossil-fuel fired power plants. But it is hardly a reasonable solution. We must be vigilant to avoid approaches that increase efficiency only by creating other kinds of problems.

Since the 1990's, how much have other countries cleaned up their power plants? Figure 2-7 shows how much sulfur oxides were emitted on average per unit of electricity generated in 1999 and 2002 from thermal power plants using fossil fuels in several different countries. Most of the countries shown have decreased their sulfuric oxide emissions, and Germany now emits less than one gram of sulfuric oxides per kilowatt hour of electricity. However, even in Germany, fossil-fuel fired plants still emit more than three times the pollution of Japanese plants. When sulfuric oxides and nitrogen oxides dissolve in water, they become sulfuric acid and nitric acid, the precursors of acid rain. So it should be no surprise that the effects of acid rain on ecosystems are more serious in America and Europe than in Japan, although recently acid rain from China and other rapidly industrializing countries in East Asia is becoming a serious problem in Japan.

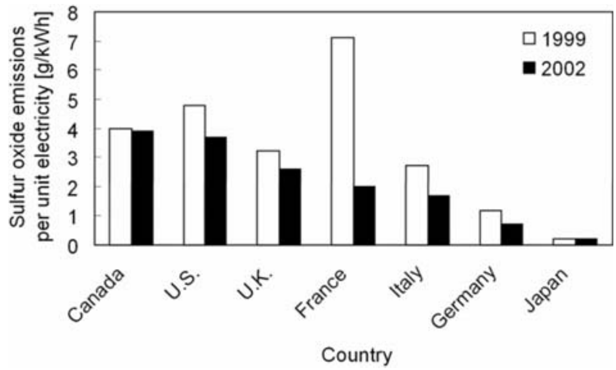

Fig. 2-7: Comparison of sulfur oxide emissions from thermal power plants (Data from Tokyo Electric Power Company)

The role of oil refineries is to separate oil into products such as gasoline, kerosene, light oil, and heavy oil, and then distribute those products to the places where they are used. The proportion of demand for the different component products of oil has varied by era as well as by country. For example, in Japan, during the era of fast economic growth following the Second World War, which centered on heavy industry and chemical plants, there was a large demand for heavy oil. At that time, about half of oil imports were refined into heavy oil. However, following that era, as a result of industrial advances in energy conservation and the increased use of automobiles, the relative demand for gasoline has increased. And now over 25% percent of imported oil is made into gasoline.

Oil refineries accommodate these changes in demand by adjusting the proportion of components in the final product. Like all other fossil fuels, oil consists mainly of carbon and hydrogen. Different refinery products have different ratios of carbon and hydrogen. Heavy oil, for example, has more carbon whereas gasoline has more hydrogen. As a result of the shift in demand from heavy oil to gasoline, most refinery products now contain more hydrogen than crude oil does. To increase the proportion of hydrogen, part of the oil is combusted, and with the energy produced, hydrogen is extracted from water and added to the oil. Using the added hydrogen, the amount of gasoline can be increased. Oil refineries must consume energy to carry out this process. This consumption rate is generally expressed as the fraction of the chemical energy of the crude oil entering the refinery that is retained in the chemical energy of the products. For modern day refineries, this fraction is about 95%. In other words, about 5% of the oil that passes through an oil refinery is consumed in the refinery process. This loss is much smaller than the loss of fuel energy in electric power plants, so making fuels like gasoline and kerosene is much less energy-intensive than making electricity.

The current role of gas companies is simply to distribute natural gas to consumers. However, if cogeneration systems can be made more efficient, for example through the application of fuel cells, gas companies could play an important role in spreading this technology by providing the necessary fuel supply networks.

Figure 2-6 shows the energy consumed for "daily life" and "making things" in Japan together with the amount consumed during energy conversion as described above. Nearly all of the energy consumed in energy conversion is the heat lost to the environment during the generation of electricity. The energy that has been converted into easy-to-use forms such as electricity, gasoline, kerosene and city gas is used for "daily life" and "making things," each of which consumes approximately half of that energy. Hence, we see the many ways in which energy is consumed in human activities leading to the supply of the products and services we use each day.

3 Energy Degrades

What Is the Value of Energy?

According to the law of energy conservation, energy is conserved. That is, the amount of energy before and after a change is always the same. However, the value of electricity, which can be used to turn on a television or run a vacuum cleaner, is totally different from the value of ambient heat, which is heat at the temperature of the environment, even if the amount of energy is the same. In other words, the value of energy is determined not only by its amount but also by its usefulness.

Under ideal conditions, a high quality motor can convert almost 100% of energy in the form of electricity into work. Similarly, a high quality electric generator can convert almost 100% of energy in the form of work into electricity. So intuitively it is clear that electricity and work have the same value. Furthermore, it is possible to convert nearly 100% of kinetic energy and potential energy into work. In short, work, kinetic energy, potential energy, electricity and all other kinds of energy except heat can be considered to have the same value.

Electric utilities exploit this property of energy by pumping water upstream of a hydropower dam to store electricity. In most developed countries, the demand for electricity is greater during the day than at night. However, for many forms of power generation such as nuclear power, it is not possible to stop plant operation at night and restart it in the morning, so a surplus of electricity is produced at night. At that time, water downstream of the dam of a hydropower plant is pumped up and stored in the upstream reservoir. The next day, when the demand for electricity is large, that water is let through the dam to generate electricity. The water is pumped up using a motor driven by the excess electricity generated by the nuclear power plant at night, which adds potential energy to the water. That potential energy is converted back to electricity when the water is released through the dam again. The ideal transformation efficiencies for these processes are all 100%, so it should be possible to retrieve 100% of the nighttime electricity produced by the nuclear power plant for supplying electricity in the daytime from the hydropower plant. But in reality 70% is the best that can be achieved today.

A 100% conversion between different forms of energy, which would be possible under ideal conditions, cannot be achieved in reality because every time energy is transformed, a part of the energy becomes heat. The reason electrical appliances – such as televisions, vacuum cleaners and light bulbs – become hot when we use them is that during the process by which electricity is transformed into light, sound, kinetic energy and so on, a part of the electricity is converted to heat. This occurs regardless of whether the device is used to produce light, sound, motion, or any other useful service. However, the fraction of electricity that becomes heat in different devices varies dramatically. In a hydropower electric plant, which is an example of a highly efficient system, about 85% of the potential energy of the water behind the dam is converted into electricity. Therefore, the remaining 15% becomes heat. On the other hand, the fraction of electricity transformed into light by incandescent light bulbs is only about 2%, so 98% ends up becoming heat.

The Value of Energy as Heat

Is it impossible for us to use energy once it has turned into heat? In a thermal power plant, fuel is changed into heat, and that heat is transformed into electricity. So clearly heat can be and is used as a source of energy. However, there is probably no easy way to use the heat energy in the air warmed by an incandescent bulb to just a little higher than the ambient temperature. In other words, there is heat that can be used and heat that cannot.

The value of energy as heat is rather difficult to understand, and for a long time scientists puzzled over it. The conclusion finally reached forms one of the basic principles of thermodynamics. That principle is: “heat with a sufficiently high temperature has value comparable to work, electricity and other forms of energy, but as the temperature of the heat gets lower, the value decreases, and heat at the same temperature as the surrounding environment cannot be used at all and therefore has no value.” To boil water at 100°C, we want the stove to be at a temperature of at least 150°C, and to melt glass with a melting point of 500°C, we need a furnace with a temperature of 600°C or more. In these cases, the higher the temperature, the better.

Strictly speaking, the value of heat can be described as follows: the fraction of work that can be obtained from an amount heat at a given temperature T is the difference between T and the ambient temperature of the environment divided by T. In other words, the value of heat is the amount of heat multiplied by $(T - T_0)/T$, where T_0 is the ambient temperature. All of these temperatures must be expressed in absolute units. The most commonly used absolute temperature scale is the Kelvin scale. To convert a temperature in degrees Celsius to Kelvin, we just add 273.

For heat at a temperature that is the same as the surroundings, T is equal to T_0, so the value is zero. This means for example that it is not possible to generate electricity using sea water and air at the same temperature. The higher the temperature of the heat, the greater its value, and if the temperature is infinitely high, the ratio becomes one. For example, the sun – one of the hottest things we can imagine – has a surface temperature of about 6000°C or 6273 Kelvin. Using the equation above, we can calculate that more than 95% of heat at the temperature of the sun's surface used in room temperature surroundings could be converted to work.

Let's summarize the main points above. Energy resources from nature are transformed into electricity, gasoline, kerosene, and so on, and those forms of energy are consumed through human activities of "daily life" and "making things." Although saying that energy is consumed appears to contradict the principle of energy conservation, what we mean is that every time energy is transformed, some part becomes heat. And as the temperature of the heat is gradually reduced, its value decreases until finally it reaches the ambient temperature of the environment and loses all its value. You saw in question 3 how heat that becomes the temperature of the environment is radiated to outer space. Therefore, the real nature of energy resource consumption by humans is that through human activities, the chemical energy contained in energy resources such as fossil fuels is transformed, perhaps many times, and each time it is transformed, some part of the energy becomes ambient heat, which is eventually radiated to outer space.

Thinking about energy in this way, we see that the important thing about energy use is not that the quantity of energy is conserved, but rather that energy deteriorates until it can no longer be used. Even though the increase in the amount of energy in the air around an incandescent light bulb is basically the same as the amount of energy in the electricity used by the light bulb, the electricity can be used for many different purposes besides lighting a room, but the energy in the form of slightly heated air cannot be used for anything. This is why humanity is in constant need of new energy resources. However, as we saw in Chapter 1, the fossil fuels upon which we are dependent for almost 80% of our current total energy resources are becoming depleted. Furthermore, the burning of fossil fuels releases CO_2 which brings about global warming.

One solution might be to shift our dependency on fossil fuels to renewable energy or nuclear energy. However, there are also problems associated with using those energy resources. Developing alternative energy resources is certainly important, but completely replacing fossil fuels with renewable energy by the middle of the 21st century is probably not technologically possible, not to mention economically possible. On the other hand, from a safety point of view, it would be best to keep our dependence on nuclear power at a minimum.

So what are the possible roads left to us? This book will suggest the following mid-term and long-term goals. For the mid-term, the goals are 1) to chart a plan for extending the lifetime of fossil fuel resources by limiting the amount of energy used through improved efficiency and 2) to lay out the foundations for constructing renewable energy systems. Once we have achieved these mid-term goals, we must aim for a complete conversion to renewable energy in the long term. In the next section, we will see in concrete terms what it means to improve energy efficiency.

4 Improving Efficiency

Burning Oil Fields Versus Heating Houses

Imagine that an oil field in a desert catches fire and the oil is burned up. The oil turns into CO_2 and water, and at the same time an intense heat is generated. That heat initially raises the temperature of the surrounding air, but in the end the heat spreads out until it is no longer perceptible. Oil turns into heat, and the heat warms the ambient air just the tiniest amount. Thus energy is conserved, but that energy cannot be used to heat a building or drive a car. From the viewpoint of human activities, the energy of that oil has been completely wasted.

Now, consider what happens if we try to warm ourselves using an oil-fired stove in an open field on a winter's night. The oil is burned, becomes heat and warms the surrounding air just a bit, which is the same as what happens in a burning oil field. However, to the extent that we can warm ourselves with the heat from the stove, we derive some benefit from the chemical energy of the oil that is consumed. Of course, if possible, we should put up a tent or some other structure to make it more difficult for the heat to escape, thereby reducing the amount of oil we must burn to stay warm.

When we heat our home with an oil stove, to the extent that we are just burning oil, the situation is the same as a burning oil field or an oil-stove in an open field. However, by burning the oil in a stove in a well-insulated home, we can achieve the goal of warming ourselves with much less oil. This is the essential point of using energy efficiently: we should use the minimum possible amount of an energy resource to achieve a certain goal.

A Vast Range of Efficiencies

Based on the ideas above, let's consider what kind of room heating system has the highest energy efficiency.

We can heat a room using an electric heater, and in that case the heater will produce heat in the same amount as the electricity consumed. So which is more efficient – an electric heater or an oil stove? To answer this, we must determine which option consumes the least energy resources. The oil stove consumes oil to produce heat, and the electric heater consumes electricity. But as we saw earlier, electricity is not an energy resource. To produce the electricity used in the electric heater, fossil fuels must be burned at the power plant. Therefore, we must compare the amount of oil consumed at the power plant to produce the electricity used by the electric heater with the amount of oil burned in the oil stove. Even state-of-the-art oil-fired power plants convert only about 40% of the chemical energy in oil into electricity, and that electricity must then be delivered to your home, which results in an additional loss. Therefore, an electric heater has only 40% of the efficiency of an oil stove.

Recently, air conditioning units that can heat as well as cool a room with electricity are becoming widespread. You might have thought that there is an electric heater in the air conditioning unit, but that is not the case. We will look at the mechanism in detail in Chapter 5, but basically a motor is used to transform the electricity into work, and the work is used to pump heat up to the room from the outside. To "pump up" heat means that even though the outdoor temperature is lower than inside, heat can be moved from outdoors to indoors. Because this is similar to the way that water is pumped up from a low place to a high place, this system is called a "heat pump." In summer, an air conditioning unit uses a heat pump to move heat from the cool indoors to the hot outdoors. In winter, the direction of the heat pump is reversed, so a single air conditioning unit can be used for both heating and cooling.

A heat pump can transport an amount of heat from a low-temperature place to a high-temperature place, an amount of heat several times more than the amount of electricity consumed. Among newer high-efficiency air conditioning units, there are models for home use that can supply an amount of heat to a room that is more than seven times greater than the amount of electricity consumed. The efficiency of transforming oil into electricity is 40%, so an electric heat pump can supply almost three times the heat of an oil-burning stove using the same amount of fossil fuel. The capacity to supply three times as much heat using the same amount of an energy resource may seem like magic, but it is just basic thermodynamics. And more and more of us are doing this when we purchase combination heating and cooling air conditioning units.

If we compare the efficiency of heaters from the point of view of fossil fuel consumption, electric heaters have the lowest efficiency, heat pumps in air conditioning units have the highest efficiency, and oil-stoves are in between. In the case of electric heaters, at even state-of-the-art oil-fired power plants already 60% of the chemical energy of the oil is lost as heat, so only the remaining 40% can be used to heat the room through direct conversion of electricity to heat. Compared to this, an oil-stove that transforms the fossil fuel resources directly into heat is the better choice. Alternatively, since all we are doing is converting electricity into heat, if we consume the same amount of electricity operating televisions, radios, lights and other appliances, we saw in question 1 that we will get almost the same heating effect. And this option gives us more benefits from energy than just running an electric heater.

A heat pump also turns the electricity consumed into heat, but at the same time it pumps several times more heat from outdoors to indoors, so the efficiency is even higher. This example illustrates how, through improved technology, we can reduce the energy resources required to achieve a given goal. With just a tiny fraction of the oil consumed when we try to warm ourselves with an oil stove in a snowy winter field, we can operate a heating system that could comfortably warm a room using a heat pump.

In fact, we can use technology to reduce the energy used for heating and cooling even more. One way is to improve the insulation of our homes by using high-performance insulation in the walls, floors, and roofs and by installing double-paned windows. By improving the insulation of our homes, we reduce the energy demand for heating and cooling. In the Rocky Mountains, at an altitude of 1500 meters, a well-insulated house was constructed in which people lived without consuming any fossil fuel resources for heating and cooling.

Other ways to reduce energy used for heating and cooling include innovative placement of windows under long, sloping roofs, such that in winter when the sun is low in the horizon, sunlight shines into the home and heats it, but in summer, when the sun is higher, the rooms are shaded by the overhanging roof. Planting deciduous trees on the south side of a home is another way to save energy because in summer the leaves block the sunlight while in winter, when the leaves have fallen, sunlight shines into the home. Using fans to circulate air in a building can reduce the cooling load tremendously in summer. And in fact by designing a building in the right way, a natural circulation can be induced so that it is not even necessary to use fans.

Even though the example of "burning oil fields" is rather extreme, in the sense that a fossil fuel resource is burned and ends up only heating the environment an imperceptible amount, there is no difference in principle between burning oil in an open field and heating a well-insulated home. However, the amount of energy resources consumed to gain the same amount of benefit is dramatically different depending on the method used. From the discussion above, we can see that there are three methods for increasing energy efficiency to reduce the amount of resources consumed. First, by using devices such as the heat pump, we can reduce the amount of energy resources consumed to provide some service such as heating, resources that are eventually lost as ambient heat. Second, we can try to do as many things as possible with the energy before it becomes ambient heat, such as turning on televisions and lights to heat a room. Third, we can reduce the amount of energy required to fulfill our needs, for example by insulating our homes and designing homes to get optimal use of sunlight to reduce the energy needed to heat our home. By such methods, we can chart out a plan for increasing energy efficiency to save fossil fuel resources through technology.

From the point of view of efficiency, there is plenty of room for improving the ways in which energy is used. In Chapters 3 and 4, we will see just how large the potential for conservation of energy by increasing efficiency is.