Chapter 3
The Limit of Energy Efficiency

1 The Elementary Steps of Human Activities

How much conservation of energy is theoretically possible? To answer this question, we must first know the minimum energy required to perform a particular activity. The difference between this minimum and the current amount of energy consumed for the activity would be – in theory – the maximum amount of conservation possible. Applying principles of mechanics and thermodynamics, we can obtain this theoretical value for energy conservation. One way to do this would be to calculate the theoretical minimum energy for each energy-consuming human activity, such as the production of steel, the manufacture of plastics, and the use of air conditioners, refrigerators and automobiles. This approach, however, would require studying a countless number of activities. Therefore, let's take another approach here. We will break down the complex human activities into elementary steps and then study the activities where we wish to conserve energy as a sequence of those elementary steps.

As an example, let's consider the process of manufacturing plastic products from oil. The process is comprised of the following parts.

- Oil that is pumped from the oil fields is transported by pipeline to the harbor, loaded into a tanker, and shipped to the region where the plastic is manufactured, where it is transported again by pipeline to a refinery.
- At the refinery, crude oil is separated into various component materials such as gasoline, kerosene, and heavy oil. One of these components, naphtha, is the raw material for plastic.
- Naphtha is heated in a combustion furnace, where through a chemical reaction called pyrolysis, or thermal cracking, compounds such as ethylene and propylene are formed.
- The product of thermal cracking is cooled to around −100°C, compressed and liquefied, and separated by distillation into various component compounds.
- These various components are then further processed into various kinds of plastics and synthetic fibers. For example, ethylene, one of the component compounds, is placed under high pressure and converted through the chemical

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reaction of polymerization to grains of a macromolecule called polyethylene. Those grains of polyethylene are then melted and molded to create the polyethylene plastic products and containers you see in stores, such as shampoo bottles and children's toys.

Looking at the description of the process of manufacturing plastics in the previous paragraph, we see that we can break down this process into the following elementary steps: transportation, separation, combustion, heating and cooling, compressing, liquefying, melting, chemical reactions, and shaping. In fact, if we look at the various human activities of "making things" and "daily life" from the viewpoint of energy, almost all of them can be broken down into a combination of some of the elementary steps in the sequence above. We can even break down the human activity of making drip coffee this way. Making drip coffee proceeds through the following steps: coffee beans are transported from some location such as Brazil, roasted, ground up, and finally water is heated and percolated through the grind to make coffee. Therefore, making coffee can be broken down into transport, heating, shaping, heating, and separation.

If we can determine the theoretical minimum amount of energy used in each of these elementary steps, we can easily find the theoretical minimum energy consumption for any kind of human activity by considering it as a combination of the elementary steps. Next, we will estimate the theoretical minimum energy for each elementary step.

2 The Energy of Elementary Steps

The Energy of Transportation Is Zero

First let's consider how much energy is required in the ideal case to transport materials, products, people and so on. As our first example, imagine a car traveling on a level road. To start the car moving, energy is needed. This is because the law of energy conservation states that in order to give objects kinetic energy, the energy of motion, work is necessary.

However, after starting the car and reaching a constant travel speed, theoretically we do not require any more energy to keep it moving. Think back to the speed skating event at the Nagano 1998 XVIII Olympic Winter Games. The gold metal winner, Hiroyasu Shimizu, after reaching the goal, took off his goggles, took off his hat, waited anxiously for the record to appear in the display panel, checked his score, thrust out his fist in exhilaration, and finally stopped moving when he was hugged by his coach. During the whole time he was moving, he did not kick his foot once. Then in the Turin 2006 XX Olympic Winter Games, Shizuka Arakawa performed her signature "Ina Bauer" to win the gold in figure skating. Both of these movements were possible because the friction of ice is small. If there were no friction at all, it would be possible to circle a skating rink that is properly banked for all of eternity without slowing down. Telecom satellites and the moon orbit the earth without stopping, and the earth has continued to orbit around the sun since its formation because there is essentially no friction in outer space.

So what happens when the car stops? If we use a brake to stop the car, the kinetic energy of the moving car turns into heat and ends up warming the air just a little bit. We saw in the last chapter that kinetic energy has the same value as fuel energy, but stopping a moving car in this way causes all of its value to be lost. This is just like the "burning of oil fields" – energy is just wasted. In order to deplete the car of its kinetic energy in a less wasteful fashion, we could force the car to turn an electric generator and transform the energy into electricity. Remember the bicycle with a generator-type light that we saw in the last chapter? Pedaling the bicycle becomes harder when the generator light is turned on, and if you stop pedaling, the bicycle will quickly come to a stop. Therefore, we see that the generator light can function as a brake.

Instead of using a light, let us suppose that we store the generated electricity in a small rechargeable battery. The amount of this electricity will be the same as the kinetic energy that was lost by the bicycle, which is also the same as the amount of work needed to get the bicycle moving again. Therefore, if we use this electricity to drive a motor, we can accelerate the bicycle back to the same speed at which it was traveling before we stopped it (remember that we are considering the ideal case without any friction, but in reality some kinetic energy is always lost to heat in any transformation). Once the electricity is transformed back into kinetic energy, the bicycle will move at a constant speed without any input of energy, and when we want to stop, we can just use the generator to recapture the electricity. In other words, we can make a bicycle that can be started and stopped without having to pedal. And we can think about a car or a truck in exactly the same way. Therefore, we can see that the theoretical minimum amount of energy required for transport on a level surface is zero.

Next, as an example of vertical transportation, let us consider how much we can reduce the amount of electricity required to move an elevator up and down under ideal conditions. You might think that when an elevator goes up, a wire attached to the elevator is wound up using a motor so that electricity is required, and when an elevator goes down, it falls by its own weight, so no energy is needed. However, modern elevators do not work in such a wasteful manner. In elevators, the wire hauling the elevator car up is attached to a pulley, and the other end of the wire is attached to a block having the same weight as the elevator car. Both sides of the pulley have the same weight, and if the pulley is made using high quality bearings so that friction is nearly zero, no energy is required to move the elevator car up and down. In other words, the minimum energy to raise and lower an elevator is zero.

For the transport of oil and natural gas by pipeline, if the diameter of the pipe is increased, the transport friction will become smaller, and at the theoretical limit, the energy required is zero. Even if the pipe goes up and down mountains and valleys, as long as the starting and ending points are at the same height, no energy is required. Think of using a siphon to draw water out of a bath tub into a bucket on the bathroom floor. As long as the outlet end of the hose is lower than the inlet, no matter how high the hose must go to get over the side of the tub, water will flow out of the tub and into the bucket. Energy loss occurs during the transmission of electricity as heat generated by the resistance of the transmission wire. This is the same as the mechanism that an electric heater uses to generate heat. However, without even bringing up the example of superconducting power transmission, we can see here as well that by making the transmission wire "thicker" and the resistance smaller, less heat will be generated. At the theoretical limit, the energy lost during transmission is zero.

From materials to electricity, the theoretical minimum amount of energy consumption for transportation is zero. The main reason that energy is consumed in transportation today is friction. Therefore, the key to reducing energy consumption by transportation is seeing how far we can reduce friction. This is an important point that we will come across again in the next chapter when we consider ways for making passenger cars more energy efficient.

Energy Is Needed for Separation

We saw earlier that separation is an important elementary step in the manufacturing of plastics. In fact, separation is used in all kinds of manufacturing processes, from separating mineral ores from rock to extraction of food seasonings from fermented liquids. Concentration is one form of separation, an example of which is the production of distilled spirits by concentrating the alcohol from fermented alcohol. Also, laundering is the separation of dirt from clothing. Coffee is made from the separation of the coffee component from coffee beans, and butter is obtained by separation of fat from milk. These examples show us that separation is an important step both in "making things" and in "daily life."

In order to separate a mixture into its components, energy is always required. For example, the minimum energy to separate fresh water from sea water is the product of a pressure of 24 atmospheres and the amount of fresh water produced. Let's use this example to see how much energy is needed for separation.

If we partition sea water and fresh water in a container with a cellophane-like semi-permeable membrane that permits water to pass through but not salt, fresh water will seep into the sea water side due to osmotic pressure, and the level of the sea water side will rise above the fresh water side. Osmotic pressure depends on concentration, and in the case of sea water, it is about 24 atmospheres. This means that if we apply a pressure of 24 atmospheres on the sea water side, fresh water will stop seeping through the membrane. If we apply even more pressure, fresh water will seep through the membrane from the sea water side. This way of producing fresh water is called the reverse osmosis method for desalination of sea water.

The amount of energy consumed to produce some amount of fresh water using the reverse osmosis method is determined by the product of the pressure applied and the volume of water obtained. Therefore, the energy used to produce fresh water is proportional to the pressure applied to the sea water side. The theoretical minimum energy is achieved when the pressure is 24 atmospheres, but if we apply just this pressure, fresh water will not actually be produced. If we apply a little more pressure, fresh water will start to seep through the membrane. In actual applications, a pressure of about 80 atmospheres is applied in order to produce a vigorous flow of fresh water. However, to do this, energy is consumed at a rate of 80 divided by 24 or 3.3 times more than the theoretical minimum. The same amount of water is produced, so where did the extra energy consumed go? As in the examples that we have seen before, it is turned into heat and ends up radiated to outer space.

For most kinds of separation in "making things" and "daily life," as much as ten to twenty times more energy than the theoretical minimum is consumed in actual processes. And in all of these cases, the common result of attaining a sufficient rate of separation is the generation of waste heat. Many researchers are working hard to find ways to reduce the amount of excess energy required to attain sufficient rates of separation. For example, one reason that such a large excess pressure is required for desalination of sea water is that the resistance of the separation membrane is large. Therefore, the development of a strong, thin semi-permeable membrane will help us to approach the theoretical minimum of 24 atmospheres of pressure.

Various methods of separation, such as distillation, adsorption, and ion exchange, are used for a variety of purposes, but the theoretical minimum energy required is the same for all of these methods. In fact, the theoretical minimum value does not even depend much on the kind of material to be separated. The main factor affecting the theoretical minimum energy required for separation is the concentration of the different components to be separated. For example, the energy needed to separate the 3% salt content in sea water is about the same as the energy to separate a 3% mixture of CO_2 in the flue gas of a power plant. However, the energy to separate the three parts per billion of uranium in sea water is orders of magnitude greater.

The Energy of Shaping and Forming Is Zero

Putting grains of plastic into a mold to form the frame of a television and pressing a thin sheet of steel into the proper shape for the body of a car are examples of shaping and forming in manufacturing. The theoretical minimum energy required for all of these processes of shaping and forming is zero. This may be difficult to believe, but think about it in the following way. If we heat a material to close to its melting point, it will get soft and easy to shape. If we then recover the heat when we cool the material back down by using an infinitely long heat exchanger to transfer all of the heat of the material to some liquid material, the amount of heat that is recovered will be the same as the energy required for heating. Even though it is not possible to convert all of the energy of heat into electricity or work, in the ideal case it is possible to transfer all of the heat from one material to another. By using that recovered heat to heat up the next material and repeat the same process, we do not need to use any energy. Likewise, the theoretical minimum energy for other forms of shaping and forming, such as making thick plates of steel into thin sheets, cutting and sectioning, and so on, is zero.

Heating and Cooling Using an Ideal Air Conditioner

You might think that if we boil water using a gas flame, as long as the heat of the flame is completely transmitted to the water, in other words, as long as there is no heat loss, we will achieve the highest energy efficiency possible. However, remember that the chemical energy of fuel gas that can be transformed into electricity or work is considerably more valuable than heat energy in the form of water boiling at 100°C or a bath heated to 40°C. Therefore, using fuel to boil water is a huge waste of valuable chemical energy. We saw the same thing when we looked at the different ways of heating a room. The theoretical minimum energy needed for heating and cooling can be determined by considering an idealized form of the common-place air conditioner that we use to cool (and sometimes heat) our homes.

The theoretical minimum amount of energy that is required for cooling was first made clear through the principles of the reverse Carnot cycle in thermodynamics. According to those principles, the minimum amount of electricity needed to pump out a certain amount of heat is determined just by the temperature inside and outside the space to be cooled. The equation that gives this minimum amount of electricity is the temperature difference between the warmer and the cooler spaces divided by the temperature of the cooler side. This is almost the same as the equation that gave us the value of heat in the last chapter, but in this case the denominator is the cooler temperature. Like in the previous equation, all of the temperatures must be expressed in the absolute temperature scale or units of Kelvin, which means we must add 273 to the temperature in Celsius. If the room temperature is 28°C and the outside temperature is 35°C, the value given by this equation is 7/(28 + 273) or 1/43. Therefore, we only need to supply an amount of electricity equal to one forty-third the amount of heat to be pumped out. This is the theoretical minimum for cooling at this temperature.

When we cool a room with an air conditioner, hot air is produced at the outdoor unit. From the point of view of the outside air, this is a heating effect. In other words, we can think of an air conditioner as consuming electricity to take away heat from the air in the room and use it to warm the outside air. The theoretical minimum amount of electricity that must be consumed to heat the outside air a certain amount is also determined by the inside and outside temperatures through the ratio of the temperature difference and the temperature of the hotter side. Therefore, an amount of electricity equal to 7/(35 + 273) or one forty-fourth the required heat is sufficient theoretically to heat the outside air.

Do Compression and Expansion Slowly

It is easy to see that energy is needed in order to compress air. However, the amount of energy depends on the way that the air is compressed. For example, imagine compressing air inside a syringe by covering the tip with your finger. If you press the plunger slowly, the repelling force will gradually get stronger. The energy needed to press down the plunger in this way is close to the minimum. If you press the plunger quickly, from the start, you will feel a strong repelling force, and consequentially the energy consumption will be larger.

The theoretical minimum energy does not depend much on the kind of gas to be compressed, but rather on the ratio of the pressure before and after the compression. Furthermore, the theoretical minimum energy required for compression is exactly equal to the maximum energy that can be obtained during expansion. This is another example of the law of energy conservation.

In summary, we see that the theoretical minimum energy for heating and cooling is determined by the temperature difference, for separation by the concentration of the components, and for compression and expansion by the pressure ratio.

Measuring Chemical Reactions Through an Ideal Electric Cell

We saw in Chapter 2 that all actions can be divided into actions that occur naturally or spontaneously and actions that do not occur naturally but rather require energy to proceed. A stone falls spontaneously if we drop it, but it will not rise unless we provide energy to lift it. Furthermore, we saw that while energy is required to make non-spontaneous processes occur, spontaneous processes can be used to generate energy. Chemical reactions can also be divided into spontaneous reactions such as polymerization and non-spontaneous reactions like the pyrolysis of naphtha. Like all spontaneous processes, spontaneous reactions can produce useful energy such as work or electricity when they occur, and like all non-spontaneous processes, non-spontaneous reactions require energy to occur.

The theoretical value corresponding to the maximum efficiency for chemical reactions depends on the kind of reaction. In spontaneously occurring reactions, those that produce energy, maximum efficiency means getting the maximum amount of energy from the reaction. In non-spontaneous reactions, those that require energy, maximum efficiency means using the minimum amount of energy needed to drive the reaction. Combustion is one kind of spontaneous chemical reaction. By including the reverse non-spontaneous reaction, called reduction, we can discuss the efficiency of combustion as a chemical reaction.

The electrolysis of water to produce hydrogen that we saw in the previous chapter is an example of a non-spontaneous reaction that does not proceed without the addition of energy. The electrical energy that is used during electrolysis can be calculated by multiplying the voltage, the current, and the time. The product of the current and the time of the electrolysis is the amount of electrons used, which determines the amount of water that is split. Therefore, the electrical energy that must be consumed to split a certain amount of water through electrolysis is determined entirely by the voltage, just the same as heating and cooling are determined by temperature, separation is determined by concentration, and compression is determined by pressure.

There is a certain minimum voltage that must be applied for the electrolysis of a particular chemical compound to occur. At any lower voltage, electrolysis does not occur. For water, this voltage is 1.23 volts. The electrical energy consumed at this voltage is then 1.23 volts times the amount of electrons used, and because the voltage is the lowest possible value, this is the theoretical minimum energy consumption for electrolysis of water. However, at this voltage, hydrogen is not actually produced. In order to get hydrogen to form, a little more voltage must be applied. Just as we needed to increase the pressure for the desalination of water, to obtain a sufficient rate of hydrogen production, we need to apply a voltage of about 1.5 volts. However, if we carry out the electrolysis process at 1.5 volts, an amount of electricity equal to $(1.5 - 1.23) \times$ (amount of electrons) is wasted. As before, this electricity turns into heat through the "friction" in the process and ends up disappearing into outer space.

As we can see from our discussion of fuel cells in Chapter 2, a fuel cell works in the reverse of the electrolysis of water. Therefore, once we pool up some hydrogen and oxygen by electrolysis, if we just connect a light bulb in place of the electric power source for the electrolysis, the mechanism of the apparatus will be changed such that the hydrogen and oxygen will be consumed, and electricity will be produced to light up the light bulb. Electrolysis is a process that changes water into hydrogen and oxygen against the natural flow, a non-spontaneous reaction, so energy is required. However, the reaction of hydrogen and oxygen in a fuel cell proceeds without input of energy and can be used to generate electricity, so the fuel cell reaction is a spontaneous reaction. Furthermore, the theoretical maximum energy that can be generated from some amount of hydrogen and oxygen by the spontaneous reaction in the fuel cell is equivalent to the theoretical minimum energy for the non-spontaneous reaction of electrolysis required to produce the same amount of hydrogen and oxygen.

We can obtain the theoretical maximum energy efficiency for any chemical reaction in the same way as for hydrogen and oxygen in the previous paragraph. The amount of energy that must be applied to the form of the reaction that goes against the natural flow (which is the same as the maximum amount of energy that can be extracted from the form of the reaction that goes with the natural flow) can be calculated from the voltage of an ideal electric cell using that reaction. For example, the theoretical minimum energy to make iron from iron oxide is equivalent to the energy to electrolyze the iron oxide with the minimum required voltage. Similarly, the theoretical maximum energy that can be obtained from the combustion of methane is equivalent to the amount of electrical energy can be generated at the maximum voltage of a fuel cell that uses methane in place of hydrogen.

The Theoretical Efficiencies of Energy Devices Are All the Same

A point to stress here is that the theoretical maximum efficiency of these different processes does not depend on the actual method used. For example, once we decide to use methane to produce energy, whether we do so using a fuel cell, a thermal power plant, or a methane engine, the maximum efficiency is the same. Electricity and work have the same value because theoretically one can be converted into the other 100%, so the theoretical maximum amount of electricity that can be produced by a fuel cell or a thermal power plant and the work that can be done using an engine are the same. In concrete terms, the amount is equal to the chemical energy of the methane. In other words, theoretically there is no difference in efficiency between generation of electricity by a fuel cell and by a thermal power plant. So the important question is which technology can come close to this theoretical ideal value the most easily?

The combustion of methane is an example of energy production, but we can think in the same way about the case where energy is consumed. We have seen how we can desalinate sea water using reverse osmosis, but we can also desalinate sea water by evaporating it and then condensing the fresh water. If we carry out this method ideally, the energy required will be exactly the same as using 24 atmospheres of pressure in reverse osmosis. Of course, if we were to simply burn oil and use the heat to evaporate the sea water, and then cool the water vapor until it condensed into water, this would be like warming ourselves with an oil stove in an open field. A thorough effort to make the process consume as little energy as possible is a necessary precondition for approaching its theoretical maximum efficiency.

To summarize, whether we generate energy or use it, if we carry out the process ideally, the amount of energy will be the same whatever mechanism we use. Theoretically, the efficiency of a process involving the transformation of energy does not depend on the actual mechanism of the energy transformation.

Comparing the Energy Consumption of the Elementary Steps

When we burn carbon with the oxygen in air, energy is produced, and in order to remove the oxygen from the CO_2 that is created, energy is needed. These energies are called the energy of combustion and the energy of reduction, respectively, and as explained above, they are theoretically the same. So which is larger,

Table 3-1: The size of theoretical values for energy inputs and outputs in units of kJ/mol

	chemical energy	rxn	evaporation	compression	melt	heating/ cooling	separation	transport/ shaping
Ethyl Alcohol	1278	69	38.6		5.0	2.1–10.0	0.13–1.7	0
Ethylene	1324	136	13.5	5.7–11	3.4	0.9–3.9	0.13–1.7	0
Benzene	3267	208	31.7	5.7–11	9.8	2.5–12.0	0.13–1.7	0
Hydrogen	242	84	0.9	5.7–11	0.1	0.4–1.9	0.13–1.7	0
Iron	412		354		15.1	0.5–22.0	0.13–1.7	0
Aluminum	838		291		10.7	0.5–22.0	0.13–1.7	0

Note: "rxn" is reaction energy and "melt" is melting energy. Reactions are dewatering of ethyl alcohol, hydrogenation of ethylene, hydrogenation of benzene and reduction of copper oxide with hydrogen; compressions are for pressure ratios of 10 and 100; heating is from 25°C to 100°C using 100°C heat; cooling is from 25°C to −100°C using −100°C coolant; separation is for mixtures of 1%/99% and 50%/50%.

the combustion energy of a material or the energy of separation that is required to remove impurities contained in the material? You might think that this kind of comparison is impossible to generalize, but in fact the combustion energy is almost always larger.

Table 3-1 summarizes the theoretical minimums for the amounts of energy consumption required for the elementary processes of several different materials. Based on a consideration of these examples, we will be able to establish rough measures of the size of energy required for each of the elementary processes.

The chemical energy contained in a certain amount of ethanol called a "mole," which is about 60 ml, is 1278 kJ. The energy to separate a mixture of 1% water in a mole of ethanol is 0.13 kJ, which is just one ten-thousandth of the chemical energy. For a 50% mixture of water and ethanol, the separation energy is 1.7 kJ, or 1/705. For normal concentrations of impurities like these, the energy of separation is generally hundreds to thousands of times smaller than the chemical energy.

Furthermore, if we look at the ratio between the chemical energy and the heat of melting for ethanol, aluminum and iron, the values are 256, 78, and 27, respectively. Therefore, the chemical energy is several dozen to several hundred times larger than the energy needed to melt even metals such as iron.

Providing a rough measure of the size of energy going in or out of a particular process is helpful when considering complex energy problems. Of course the chemical energy depends on the molecular composition, and the reaction heat depends on the kind of reaction. The heats of vaporization and melting change according to the type of material. The energies of separation and compression do not depend much on the kind of material, but they are conditional on the concentrations and pressure ratios. However, we can still provide a clear measure of the approximate amounts of energy for each elementary process. By assigning a scale of 1000 to the chemical energy of a material, we can estimate that the approximate order of the theoretical energy consumption is 1000 for combustion and reduction, 100 for other chemical reactions, 10 for evaporation, condensation, compression and expansion, 1 for melting, solidification, heating, cooling, and separation, and 0 for transportation and shaping.

3 The Energy of Human Activities

In the previous section, we have determined the approximate size of the minimum amount of energy theoretically required for each of the elementary steps of human activities. Now let's use these measures to study the activity of making plastic that we looked at in the beginning of the chapter. By doing this, we can determine the theoretical minimum energy consumption needed for the manufacture of plastic by considering it as a combination of the elementary steps above.

First, the energy for transport from the oil field to the refinery is zero. Currently, oil extraction in the Middle East is conducted using a method whereby sea water is injected as oil is pumped up. This is the same principle as attaching a weight to the other side of an elevator car and moving it up and down, so the theoretical minimum energy is zero. The energy for transport by pipeline and tanker is also zero.

Energy is consumed at the refinery during the separation of the crude oil and the pyrolysis reaction of naphtha. The mixture produced by the reaction is compressed and condensed, ethylene is separated, and finally the ethylene is compressed in preparation for the polymerization reaction – all of these steps require energy. During the polymerization of ethylene, reaction energy can be obtained. Finally, the energy for forming the grains of polyethylene that are produced into various products is zero.

We can break down the process of manufacturing plastic into separation, reaction, compression, condensation, separation, reaction and shaping. The approximate measures for these elementary steps are 1, 100, 10, 10, 1, 100, and 0 respectively. Therefore, we see that the largest inputs and outputs of energy are both 100 for the pyrolysis reaction of naphtha and the polymerization reaction of ethylene. When we do the actual calculations, we find that the heat of reaction for polymerization and pyrolysis are almost the same and end up canceling each other out. Therefore, the process of making polyethylene from oil does not contain any elementary steps that require a large amount of energy. Theoretically, it should be possible to reduce the additional ton of oil that is consumed in making a ton of plastic to almost zero.

How about the activity of making drip coffee that we saw at the beginning of this chapter? This process consists of the elementary steps of transport, heating, shaping, heating and separation. The size of energy for each of these steps is 0, 1, 0, 1 and 1, respectively. None of the elementary steps that require large amounts of energy such as combustion and chemical reactions are present. Therefore, we can see that theoretically making drip coffee is an activity that should not need to consume much energy at all. When we consider how we burn gas to boil water and use gasoline to transport the beans, it is clear that we are wasting a large amount of energy. We will see why this and other kinds of energy waste happen in the next chapter.