Chapter 4
Energy Conservation in Daily Life

In this chapter, we will take a look at the potential that technology offers for conserving energy use during our "daily life" activities in homes, offices and transportation. Later, in Chapter 7, we will look at these potentials again when we present the basic concepts of Vision 2050. Our proposal for Vision 2050 will take the year 1995 as our baseline year. Therefore, throughout this chapter, we will base our discussion on the state of technology in 1995. Where more recent data is available, we will examine whether we have succeeded in achieving greater efficiency in recent years.

We saw in Chapter 2 that "daily life" activities make up more than half of the total energy consumed by human activities that has been converted into useful forms such as electricity and gasoline by the energy transformation sector. In Chapter 3, we examined the theoretical minimum amount of energy required for these activities. How much energy conservation is actually possible through technology? Let's start by looking at the possibilities for energy conservation in transportation by focusing on the main user of energy, the automobile.

1 The Automobile

In the previous chapter, we saw that, in theory, the amount of energy required for transportation is zero. Thus, ideally it should be possible for passenger cars and other motor vehicles to run without consuming any fuel. But if this is true, how can we explain the fact that consumption of gasoline by motor vehicles today constitutes over 20% of the total energy use by human society? First, we will look at the mechanism by which passenger cars consume gasoline. Once we identify where the important energy losses are, we can decide which methods are most effective in achieving energy conservation in automobiles by determining the methods that can most effectively reduce these energy losses.

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Vision 2050: Roadmap for a Sustainable Earth.

How Conventional Automobiles Work

Passenger cars and other motor vehicles run by combusting fuel in the car engine. When fuel in the cylinders of the engine combusts, the resulting force is applied to the cylinder head, causing the axle to turn. Then, through a multitude of gears and other transmission parts that make adjustments for the speed and direction, the wheels are turned. In this chain of events, the chemical energy of gasoline is changed into work by the cylinder head, and that work is used to move the car.

The first step is the transformation of the chemical energy of gasoline into work and heat. The law of conservation of energy holds, so the sum of heat and work produced by the combustion of the fuel must be equal to the chemical energy of the fuel. Ideally, all of the gasoline should be transformed into work, but in passenger cars today the amount of energy that becomes work is only about 35%. The remaining 65% is lost as heat in the exhaust emissions and radiation from the engine.

To start a car moving, the driver presses the accelerator down firmly—putting the "pedal to the metal." This causes a large amount of gasoline to be combusted in the engine, producing a correspondingly large amount of work. As a result the car obtains kinetic energy, which causes it to accelerate. However, not all of the work generated in the engine is transformed into kinetic energy. Because of various forms of friction, such as the friction between the tires and the ground or the friction between the gears and the transmission, a considerable amount of the work ends up becoming – you guessed it – heat.

Once a car reaches the desired speed, the driver does not need to press the accelerator down so far because, in comparison to putting the car into motion, keeping it in motion takes less energy. However, we saw in the previous chapter that ideally no energy should be required to keep it moving at a steady velocity. So if we are traveling at a constant speed on a level road, why do we need to consume any gasoline? The culprit is friction. Once again a large part of the car's kinetic energy ends up becoming heat, through friction between the tires and the road and from the gears inside the car. Furthermore, when we are driving at faster speeds, like on a freeway, friction between the car body and the air becomes significant, producing even more heat.

Another problem is that, although the maximum efficiency for a gasoline internal combustion engine is 35%, the actual efficiency of an engine varies according to the driving conditions. Usually, a car engine is designed to have its maximum efficiency under conditions of slightly higher output, such as a moderate acceleration. When less engine power is required, such as during low-speed driving, or when maximum power is produced by pressing the accelerator to the floor, the efficiency decreases.

To stop, at a red light for example, the driver presses down on the brake. Pressing down on the brake causes a brake plate to press against the metal part of the car wheel. This results in friction between the brake and the wheel, which slows the car. As we saw in the previous chapter, the ideal way to slow a car would be to using a generator brake collect the kinetic energy of the moving car as electricity. However, in conventional cars that use brake plates, the kinetic energy of the car ends up transformed into heat through the wasteful process of friction.

What about when we are stopped at an intersection? If the engine is running, then gasoline is still being burned. At this time, all of the work created by running the engine ends up heating the engine oil, the gears and the air, and then disappearing as waste heat.

In summary, there are six factors that together explain why, even though the energy for driving a car should theoretically be zero, such a large amount of energy is consumed in reality.

1) The efficiency in transforming chemical energy to work is not 100%; some chemical energy of the fuel combusted in the engine ends up as heat that disappears into the environment.
2) Friction in the gears and moving parts of the car generate heat during the transmission of work from the engine to the tire.
3) Friction between the tires and the ground generates heat.
4) Friction between the car body and the air generates heat.
5) Friction in the brakes generates heat.
6) An idling engine results in a waste of energy.

Improving automobile technology to address these factors should be the guiding principle for improving energy conservation in cars.

High-Efficiency Engines and Hybrid Cars

One way to raise the efficiency of transforming chemical energy into work is improve the engine. In internal combustion engines, fuel is combusted in the cylinders of the engines, providing force to drive the automobile. To obtain the most force from the combustion of fuel in the engine cylinders, the gasoline needs to be vaporized and mixed with air. In gasoline engines made in the 1990's, gasoline taken into the cylinder was vaporized using the principle of "atomization." Atomization is the same process used to vaporize perfume in a perfume spray bottle. When liquid mixed with air is forced through a small opening, the liquid turns into gaseous form. Gasoline was atomized in the car engine by forcing it through a valve called a carburetor. The mixture of air and fuel was forced through the carburetor using work from the expanding cylinder; therefore that amount of work had to be subtracted from the work generated during combustion to get the net output of the engine. At low driving speeds, the amount of gasoline consumed was decreased by partially closing the carburetor, which increased the amount of work required to force the air and gasoline through. As a result, the decrease in engine efficiency was especially large at low driving speeds for engines using carburetors.

To overcome this problem, a new kind of engine, which compresses gasoline and injects it directly into the cylinder, has been developed and marketed in passenger cars sold today. This engine is called a Gasoline Direct injection engine, and it works in the same way as conventional diesel engines. In direct injection engines, fuel is pressurized and then injected into the cylinder. Therefore, at low speeds all we need to do is reduce the amount of fuel that is injected, so no additional work is required to supply the fuel into the engine. With this design, an improvement in efficiency of about 25% has been demonstrated over ordinary gasoline engines. In fact, as of the writing of this book, no more cars are being manufactured with carburetors.

The efficiency of internal combustion engines, both gasoline and diesel, also depends strongly on how much the gas mixture of fuel and air is compressed before it is ignited. The greater the compression, the larger the force of the explosion, and the higher the efficiency. Direct injection engines contribute to increased efficiency in this regard as well, because only the air is compressed by the engine and the fuel is just injected into the compressed air. Air is more compressible than fuel, so the compressibility ratio of the fuel/air mixture can be made higher. Furthermore, through the use of computers to precisely control the injection of air and fuel to the cylinder, it is possible to achieve ultra lean mixtures of air and fuel. Ultra lean mixtures are mixtures of fuel and air where the ratio of air to fuel is considerably more than the stoichiometric combustion ratio, as much as three times more. With so-called "lean burn" engines, even higher compression ratios are possible, making it possible to further reduce the loss of efficiency and pollutant emissions when driving at low power output levels. These are examples of the improvements in automobile technology that have occurred just in the past decade.

The maximum efficiency of diesel engines is 40–45%, which beats the 35% of gasoline engines. However, diesel engines cause environmental problems because the exhaust emissions often contain high levels of soot and nitrogen oxides. To take advantage of the higher efficiency of diesel engines, we must overcome this pollution problem. Some of the new technologies being developed to make diesel engines cleaner include the use of Common Rail Injection to increase the injection pressure of the fuel thereby producing a finer atomization of the fuel, and the improvement of catalytic converters with Diesel Particulate Reduction systems to reduce soot emission.

Although these methods for improving the engine itself are important, there is even more potential for reducing energy consumption by running the engine under the conditions that give the best possible fuel efficiency. The average fuel efficiency under the standard driving conditions in Japan, called the "10–15 mode," is around 13%, which is only about a third of the maximum efficiency of 35%. The reason for the decrease in fuel efficiency is that for much of the time that the car is driven in city traffic, the engine is required to provide power that is either above or below the optimal output level. If we could keep the engine producing power at the maximum efficiency, we could increase the overall efficiency almost three-fold. We could do this, for example, by storing the excess work that is produced during low driving speeds and using it to provide the additional work required for acceleration

Fig. 4-1: The Prius Hybrid Car (Courtesy of Toyota Motor Corporation)

and travel at high speeds. Technologies for improving the engine itself, like the use of direct-injection and lean burn technologies, can increase fuel efficiency by at most 10 to 15%. So an opportunity to triple fuel efficiency is something that we cannot ignore.

Hybrid cars, such as the Toyota Prius and the Honda Insight, attempt to increase fuel efficiency of gasoline engines in this way. A hybrid car is a combination of an electric car and a gasoline car; you can think of it as a normal car with a larger battery and an electric motor. In other words, a hybrid car has two sources of energy for driving: the gasoline engine and the electric motor. When a hybrid car is driven at speeds requiring power output that is close to the optimum output of the gasoline engine, the gasoline engine is used to drive the car. If excess work is produced, the hybrid car uses that work to generate electricity and charge the battery, and if additional work is required, some models of hybrid cars can use the electric motor to supplement the power output of the gasoline engine. When the hybrid car is being driven at low speeds that are not optimal for the gasoline engine, the gasoline engine is turned off and the electric motor powered by the battery is used to move the car. Also, the engine turns off when the car is stopped at a light, and the electric motor is used to start the car moving again. When the car reaches an appropriate drive speed, the gasoline engine is restarted.

Having a larger battery in the car gives us the opportunity to capitalize on another method for conserving energy we have seen, called regenerative braking. Remember the example in the previous chapter of the bicycle that can start and stop without pedaling? “Regenerative braking” means using the electric generator in the hybrid car to convert the kinetic energy of the car into electricity when braking. Therefore, the hybrid car is a design that can contribute significantly to the solution of three of the factors that contribute to the consumption of energy by automobiles: the transformation efficiency from gasoline to work, the friction in the brakes, and wasteful fuel use during engine idling. In locations such as central Tokyo where the driving efficiency of normal automobiles is low due to the traffic congestion, hybrid cars can operate with about half of the amount of gasoline used by conventional cars.

Fuel-Cell-Powered Electric Cars

Many other methods are being studied to increase the efficiency of transforming gasoline into work. As we saw in Chapter 3, the theoretical maximum efficiency for transforming the chemical energy of fuel into work is the same for engines, electrical cells, and thermal power plants – essentially 100%. All we need to do is turn the wheels of an automobile for it to run, and there are many ways to provide energy for doing that.

Proponents of electric vehicles argue that electric vehicles are more fuel efficient than gasoline engine vehicles because the efficiency of electric power plants is greater than the efficiency of gasoline engines. We have seen that the maximum efficiency for conventional gasoline engines is 35%, and that – even with the use of advanced technologies such as direct injection and lean burn – the most that we can hope for in the near future is an efficiency of 40%. Currently, there are thermal power plants in operation with power generation efficiencies of more than 50%. Not only does the generation efficiency of the thermal power plant greatly exceed the maximum efficiency of automobile engines, but because electric motors can be easily started and stopped, electric vehicles also have the advantage of eliminating the loss of energy caused by idling a gasoline or diesel engine when the car is stopped. From the combined effect of these two efficiencies, electric vehicles could contribute considerably to energy conservation in transportation.

Currently, the type of electric vehicle getting the most attention is probably the fuel cell vehicle. There are many types of fuel cells, ranging from ones that operate at temperatures above 1000 °C to ones that run at close to room temperature. One of the fuel cells with the highest potential for being a power source for automobiles in the near future is the polymer electrolyte fuel cell. Polymer electrolyte fuel cells produce electricity from hydrogen fuel at close to room temperature. If hydrogen is loaded on the vehicle and electricity is generated through the reaction with oxygen in air, even now an electricity generation efficiency of 50% is possible.

The development of a commercially viable fuel cell car has yet to be achieved. Many of the problems to be solved are related to the fuel cell itself, such as lifetime, reliability, weight, capacity and cost. However, there are other problems, such as how to set up supply stations for hydrogen fuel. Furthermore, we have to figure out how to store hydrogen on the vehicle. If we store the hydrogen in a tank, the tank would have to be pressurized far higher than a propane tank. Another way is to store the hydrogen within the molecular matrix of a special metal alloy and load that metal onto the vehicle. Alternatively, configurations of fuel cell cars are being studied where methanol, which is a liquid and therefore easier to handle, is loaded onto the vehicle instead of hydrogen. In one configuration, the methanol is transformed into hydrogen for use in the fuel cell. At a large factory, it is possible to make methanol into hydrogen relatively easily and at a high-efficiency. However, in an automobile it is much more difficult. As a consequence, many automobile companies are also conducting research on fuel cells that use methanol rather than hydrogen as the fuel for generating electricity. These fuel cells are called, not surprisingly, direct methanol fuel cells.

These various configurations of fuel cells for cars are currently the subject of intense research and development. It has been estimated that if a fuel cell vehicle with high-efficiency can be developed, it could more than double the current efficiency of transformation from fuel to work.

Lowering Vehicle Weight

The most effective way to decrease friction between the tires of a vehicle and the ground is to make the body of the vehicle lighter. For example, the difference in the effort needed to pedal a high-performance racing bicycle made of light-weight alloys as compared to that needed to pedal a home-use iron clunker is unbelievable. The bicycles used in races such as the Tour de France are truly light-weight – they can be easily lifted with one hand. Using them, the competitors can pedal up and down mountains. With a typical clunker made of iron, even a superhuman competitor could not accomplish this feat. For the same reason, marathon runners are slim and lightweight, not brawny and heavy.

This point is worth emphasizing. Weight reduction is one of the most important keys to reducing the energy consumed in transportation. We can see this in the relationship between the consumption of gasoline and the weight of automobiles, which is almost linear, as shown in figure 4-2. The reason is that friction is proportional to weight. One way to reduce vehicle weight is to reduce vehicle size. However, it is also possible to maintain the size of the automobile while reducing the weight by using special materials such as an iron alloy called "high-tensile

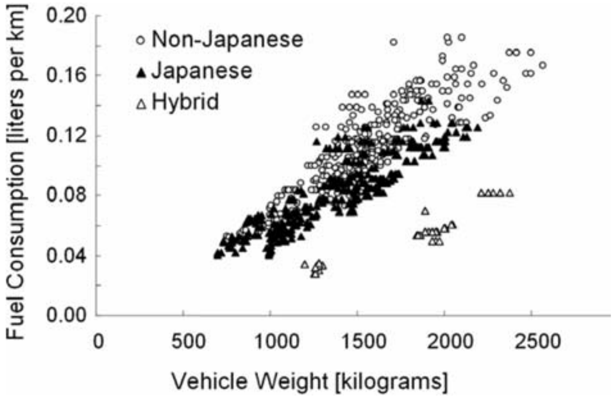

Fig. 4-2: Fuel required for a car to travel 1 km (Data from Yahoo Jidosha)

steel" that has a high strength per unit weight. The weight of vehicles can be reduced even further through the use of lightweight materials such as aluminum and plastics. Automobile manufacturers today are seeking ways to reduce automobile weight without compromising size, safety or performance. It is probably not too much to expect that the weight of passenger cars will be reduced by half in the next decade.

The Future Form of Automobiles

Because in theory automobiles can travel with zero energy, we know that there is a huge potential for reducing energy consumption in car transportation. Let us consider here some possible ways for designing automobiles that can provide the same performance as today's passenger cars while consuming considerably less energy.

First, let's think about the efficiency of a race horse. On September 30th, 2001, Trot Star ran the 1500 meter distance of the Sprinter's Stakes in a record time of 67 seconds. This corresponds to an average speed of 64 km per hour. In other words, a thorough-bred race horse, that is essentially just a single "horse-power," was able to run at a speed that matches the performance of a 100 horse-power car. Another way of saying this is that a horse can run with just 1/100th of the energy of a car. One reason is that horses have far less friction with the ground when they run than cars. A horse obtains propelling force efficiently by kicking the ground with its hooves. In the same way as we saw in the example of the iron ball hitting the ground in Chapter 2, the horse loses some of its kinetic energy as heat to the surroundings when its hooves strike the ground. However, the horse has evolved to run extremely efficiently, so this energy loss is minimal. Because the area of contact with the ground is small and the time that the horse is touching the ground is short, in essence the horse "flies" over the ground.

You might think that if the friction between the tires of a car and the ground were too small, the wheels would spin freely and the car would not move. This could certainly happen in the cars that we drive today. However, a reduction in friction does not necessarily mean a reduction in the propelling force that is transmitted to the ground. One example of a mode of transportation that overcomes this problem is ice skating. In ice skating, you put your weight on the skate on one foot, which allows you to skate with just a minimum amount of friction. You use the skate on your other foot to push against the ice and gain propelling force. Another example is a method for mountain climbing where the fur of a seal, called a "climbing skin," is stretched over regular snow skis. Due to the alignment of the fur, a climbing skin makes it possible to slide forwards but not backwards. In long-distance ski competitions, the same property is achieved through a special way of applying the wax to the skis. If we could develop tires that propel a car in a similar way, we could build a car that travels with greatly reduced friction between the tires and the ground.

Here is another example that shows the importance of the weight of a car. There is a race where cars compete to have the highest fuel mileage. A slender driver operates a car with a light-weight body and thin tires. In 1998, the winning car went 1600 km on a single liter of gasoline. More recently, a fuel-cell-powered car was developed at the Swiss Federated Institute of Technology in Zurich that could go 5134 km using the equivalent of one liter of gasoline. Compared to conventional passenger cars with fuel efficiencies on the order of 10 km per liter, the winners of these fuel efficiency races can operate with 1/160th to 1/500th the amount of gasoline.

Horses run with 1/100th and a fuel-efficiency race winner runs with 1/500th the energy of a conventional passenger car. How far can we push energy conservation of cars? By doubling the transformation efficiency from fuel to work and halving the weight of the car, it should be well within the realm of possibility by the middle of the 21st century to manufacture cars that consume only one-fourth the fuel needed in 1995 models. In fact, already hybrid cars get almost twice the fuel efficiency of standard gasoline engine cars, and the introduction of Gasoline Direct injection engines has increased the fuel efficiency of conventional gasoline engines by 25%.

Here is another example. Most automobiles today have an automatic transmission. Automatic transmission engines used to consume about 10% more gasoline than a manual transmission automobile driven by an expert driver. The reason is as follows. In a manual transmission, the clutch connects without any slippage. However, in an automatic transmission, the clutch is always slightly loose, resulting in a small amount of slippage. This slippage causes friction in the car transmission, reducing the fuel efficiency of the car. But with the introduction of continuous variable transmission (CVT) engines, this problem has nearly been solved, resulting in nearly a 10% increase in fuel efficiency.

How about after that? It is probably impossible to create an automobile that runs exactly the same way as a horse. However, the development of tires that can transmit propelling force to the ground with high-efficiency and little friction should certainly be possible. By making many small technological improvements, it might be possible to achieve fuel consumption that is one tenth that of today's automobiles. However, we are unlikely to create a commercially viable passenger car having the 500-fold increase in fuel efficiency of the one-liter race winner. Still, we should not underestimate the potential of technology to make tremendous improvements in efficiency.

This discussion brings to mind the establishment of new sports records. The long believed "human barrier" of 100 meters in 10 seconds was broken in 1968. Following that, the 9.9 second barrier was broken, and in 2005, a record time of 9.77 seconds was set by Jamaica's Asafa Powell. How much further can this time be reduced? Records of 9.6 seconds or even 9.5 sections may be made, but surely no one could run the 100 meter race in 9 seconds flat. Or could they? With the development of a revolutionary training method or the appearance of a sprinter with an order-of-magnitude difference in strength, even the 9 second barrier may be broken. Technology innovation is the same. The possibility for unforeseen discoveries and inventions is ever present. Up until this point, our discussion has been limited to predictable extensions of the current state-of-the-art of technology. However, to the extent that the theoretical energy for transportation is zero, it is impossible to say what the limit of technology is.

2 Homes and Offices

In homes and offices in Japan, energy in the form of electricity, city gas, and kerosene is consumed in nearly equal amounts for three main kinds of "daily life" activities: 1) room heating and cooling, 2) cooking and heating water, and 3) lights and electric appliances. These uses account for half of the energy that is consumed in "daily life" activities, the other half being consumed by transportation. Remembering our discussion of the theoretical minimum energy needed for "daily life" activities, let's look at the difference between the reality and the ideal for room heating and cooling, water heating, and lighting.

How an Air Conditioner Works

As we saw before, a modern air conditioner provides both heating and cooling by using work created from electricity to pump heat up from the lower-temperature side to the higher-temperature side. The mechanism for heating and cooling is the same, so let's use the example of cooling shown in figure 4-3.

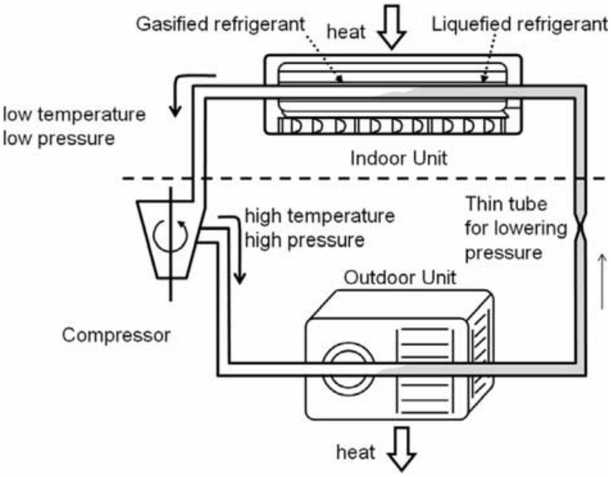

Fig. 4-3: The basic mechanism of a heat pump (example of a cooling system)

Most room air conditioners today are composed of an indoor unit and an outdoor unit. A special liquid called a refrigerant is circulated through a pipe that connects the two units. Wiping alcohol on your skin, for example before getting a flu shot, gives your skin a sudden chill. This cooling effect is caused by the removal of heat from your skin when the alcohol evaporates. In the same way, if the liquid refrigerant evaporates, it will remove heat from the surrounding air. On the other hand, if the gaseous refrigerant is cooled by the surrounding air, its heat will be transferred to the air and it will condense back to its liquid form. We can imagine this by thinking of a window pane in the winter. When it gets cold, lots of dew drops form on the window that can eventually collect to form little streams of water. The reason is that the water vapor in the room loses its heat to the cold window pane, cools, and condenses in the form of a dew drop. An air conditioner running in a cooling mode uses these vaporization and condensation mechanisms to transport heat from indoors to outdoors via the refrigerant.

There is a problem, though, with the mechanism described in the previous paragraph. The refrigerant evaporates at higher temperatures and condenses at lower temperatures, but in that case, heat will be transported from the high-temperature side to the low-temperature side. In the summer, that means we would be transporting heat from the hot outdoors into our home, exactly the opposite of what we want! The way room air conditioners reverse this flow is to make the pressure of the refrigerant in the outdoor unit higher than that in the indoor unit. If the pressure is high, the refrigerant will condense even at a high temperature. The reason a pressure-cooker can cook food more quickly is the same – by increasing the pressure, the boiling temperature of water becomes higher than 100 °C. To increase the pressure, an air conditioner uses a compressor, which consumes electricity. In fact, the electricity consumption of the compressor makes up almost all of the energy consumed by an air conditioner. When liquid refrigerant is returned to the indoor unit, it passes through a thin tube, called an expansion valve, which decreases the pressure. At the lower pressure, the liquid refrigerant evaporates even at the lower temperature in the room. In this way, it is possible to transport heat from the cool indoors to the hot outdoors.

Let's say that you want to use the air conditioner to keep your room at a reasonably cool 28 °C on a summer day with an outdoor temperature of 35 °C. Under these conditions, an air conditioner with ideal energy efficiency would evaporate the liquid refrigerant indoors at a temperature of 28 °C and condense the gaseous refrigerant outdoors at a temperature of 35 °C, using a compressor that requires just the theoretical minimum amount of work to compress the gaseous refrigerant. As we saw in Chapter 3, the relationship between the energy consumption of this ideal air conditioner and the amount of heat pumped out of the room is given by the temperature of the room in absolute temperature units divided by the temperature difference, which is $(273 + 28)/7$, so the amount of heat that can be pumped out of the room is 43 times the amount of work consumed. However, room air conditioners sold in 1995 could pump out an amount of heat from a room that was at most four times the amount of electricity consumed. We have seen that the value of electricity and work is equal, so those models achieved less than a tenth of the ideal efficiency.

Energy Conservation by Improving Air Conditioner Efficiency

There are two main reasons for this gap between the ideal value and the actual value for the efficiency of room air conditioners. The first is that the compressor consumes about twice the electricity theoretically required. This excess electricity is consumed because the efficiency of converting electricity into work and the amount of work used in compression are both much larger than the ideal values. We can improve the efficiency of converting electricity into work by using a high-performance permanent magnet in the motor. By improving technologies, the work used for compression in large-scale compressors, such as those in factories, has already been raised to efficiency levels as high as 90%. The efficiency of compressors in room air conditioners is only 50%, so it should be possible to improve this value. As we saw in Chapter 3, the basic principle for making compression efficient is to do the compression slowly, as reflected in the fact that if you compress the air in a syringe slowly, you can do so with a relatively small amount of work, but if you compress the air quickly, the work required increases greatly. In small-scale compressors, like those used on room air conditioners, there is often no way to avoid doing the compression quickly. However, if we include energy conservation in design goals, we can certainly improve this efficiency.

The second and more important reason that the difference between the ideal and the reality is so large is the size of the temperature difference used in room air conditioners. Although the difference between the indoor temperature of 28 °C and the outdoor temperature of 35 °C in our example is only 7 °C, room air conditioners made in 1995 were designed so that the temperature of the refrigerant was 5 °C in the indoor (cooling) unit and 40 °C in the outdoor (heating) unit – a difference of 35 °C. For this reason alone, more than five times the ideal amount of electricity is required. Combining this five-fold increase from temperature difference with the two-fold increase from compression yields the ten-fold difference we saw before between the ideal efficiency and the actual efficiency of a typical room air conditioner.

The difference between the indoor temperature and the indoor unit is 23 °C. In contrast, the difference between the outdoor temperature and the outdoor unit is just 5 °C. Why is this? Conventional air conditioners improve the heat transfer efficiency in the outdoor unit by using a powerful fan to blow air through the tubes containing the pressurized refrigerant. Because the air flow is so strong, the five degree temperature difference between the 35 °C air and the 40 °C refrigerant is enough for the air conditioner to work. However, there is a downside: when you walk close to an outdoor unit, you are hit by a blast of hot air. If we could make the flow of air in the indoor unit about the same strength as that of the outdoor unit, then a cooling refrigerant temperature of five degrees less than the indoor air temperature would be sufficient. As a result, the temperature difference between the indoor unit and the outdoor unit in our example would be reduced from 35 °C to 17 °C, so we could realize a 50% energy savings.

Recently, manufacturers have been studying ways to improve the transfer of heat in the indoor unit. If we could increase the heat transfer area between the refrigerant and the air, a smaller temperature difference would be enough to supply the required cooling without strengthening the flow of air. Various techniques are used in current air conditioners to increase the heat transfer area. One technique increases the surface area in contact with the air by attaching fins to the outside of the pipe through which the refrigerant flows. Another technique involves attaching baffles on the inside of the pipe, which causes turbulence in the flow of the refrigerant, thereby increasing the heat transfer rate. Also, new configurations such as wall heating and cooling are being tried. If we use the entire area of the wall, a far greater heat transfer area can be obtained, so a sufficient heating and cooling effect can be obtained through a smaller temperature difference. Furthermore, the variation of temperature in the room will be reduced; thus, as a side benefit, we create a more comfortable living environment.

Another way to improve heat transfer in the indoor unit is to design a better flow path through the unit. Today, manufacturers use computer simulation models to plan the best positions for the heat exchanging units inside the air conditioner so as to maximize the transfer of heat.

As a result of these technology improvements, room air conditioners have improved remarkably over the last decade. The newest air conditioners in Japan can pump an amount of heat out of a room that is more than seven times the electricity consumed – an improvement of 40% compared to the highest-efficiency models in 1995. This increase in efficiency has been achieved in part through improvements in the efficiencies of the compressor and other components of the air conditioner. However, even more important were the improvements in air flow that made it possible to reduce the difference between the room temperature and the temperature of the refrigerant in the indoor unit by almost 30%.

However, if we raise the temperature of the indoor refrigerant for cooling in the summer too high, another problem will emerge. Cooling is actually only one of two important services provided by air conditioners. The other is the drying effect. Part of the discomfort that you feel on a hot summer day is from the high temperature, but high humidity also is an important factor. Conventional air conditioners remove not only heat from a room, but also humidity. They can do this because the humidity in the warm air condenses inside the indoor unit and is removed. But this condensation only happens when the indoor unit is sufficiently cold. If the temperature of the indoor unit gets much above 15 °C, the rate of condensation will decrease dramatically.

To answer this problem, manufacturers are designing air conditioning systems that remove heat and humidity in separate stages. Humidity is removed through the use of special materials called desiccants, so the heat pump part of the air conditioner only needs to remove the heat from the room. In this way, the temperature difference in the indoor unit can be reduced even more.

Energy Conservation Through Load Reduction

Improving the air conditioner is not the only way that we can reduce the amount of energy consumed in heating and cooling. We can also better insulate our homes. In the summer when you return home, if you have been gone for awhile and the sun has been shining brightly, you may find that your house is stiflingly hot. So you quickly turn on the air conditioner. In just two or three minutes, your house cools down. However, if you then turn off the air conditioner, heat will leak in from outside, and soon it will become hot again. Therefore, it is better to think of air conditioning not as cooling a hot room, but rather as pumping out the heat that leaks in from outside. Insulating your home reduces the amount of heat that leaks in.

The amount of heat that leaks in from the hot outdoors is called the cooling load. The energy needed for cooling is given by the ratio of the cooling load to the amount of heat that can be pumped out of the room using a given amount of energy. Increasing the efficiency of the air conditioner reduces energy consumption by increasing the heat pumped out with a given amount of energy. However, we can also reduce the energy required for cooling by reducing the cooling load.

The amount of heat that flows into a room is proportional to the indoor/outdoor temperature difference; the larger the difference, the greater the flow of heat. So one way we can reduce the cooling load is to raise the thermostat setting; in fact, we can reduce the cooling load to zero by setting the room temperature the same as that outdoors. Energy saving actions such as raising the thermostat in summer are important. However, the focus of this book is on the role technology can play in achieving a sustainable society. Deciding to raise or lower the room temperature to save energy – a problem of lifestyle – is outside the scope of this book.

The technological method for lowering the cooling load is to improve the insulation of the room being heated or cooled. This includes doing things like using high-quality materials to insulate the floors, walls, and roofs, and making windows double-paned. In houses in Northern Europe and Canada, where the winters are severe, many ingenious devices for insulation are employed. However, in the process of insulating our homes, if we end up making them too air-tight, the air inside will get stuffy and stale, so we will need to improve ventilation. Of course, if we just open the windows, the heating and cooling load will increase, defeating the purpose of insulation.

On the other hand, if we allow the outside air flowing into the house to exchange heat with the inside air flowing out through a thin plate of metal, we can use the warm inside air to heat the cold outside air as it flows into the house. Moreover, if instead of metal, we use a separator that allows water vapor as well as heat to pass through and exchange between the incoming and outgoing air, we can dry the air coming in during summer and recover the moisture of the air going out in winter. In fact, almost half of the new office buildings in Japan are equipped with such heat and humidity exchange systems. Residential buildings are also increasingly using such ventilation systems. However, much of the air that is taken out of rooms such as kitchens and bathrooms is not suitable for heat and humidity exchange.

Therefore, the efficiency is not as high in houses and apartments as it is in office buildings.

It Is Wasteful to Use Gas to Boil Water

Next, let's take a look at the consumption of energy for heating water by considering the example of preparing a bath. The process of preparing a bath involves heating 20 °C water to 40 °C, and for the same reasons as in heating a room, the minimum amount of energy required is achieved by an ideal heat pump. If the temperature difference is 20 °C, then at least in theory just 20/(40 + 273) or 1/15th of the amount of heat needs to be supplied as work. In comparison, heating the bath directly by burning some fuel such as gas means that we need to consume at least an amount of fuel energy that is the same as the amount of heat required for the bath. Therefore, we can achieve our goal with far less fuel consumption using a heat pump. This is the same as the reason we noted in the previous chapter that burning gas to boil water in making drip coffee is such a waste of fuel.

Using a heat pump to heat a bath or boil water is more difficult than to heat a room. If we were to make the temperature of the heat pump fluid 45 °C in order to obtain 40 °C water for the bath, it would take too long for the water to heat up. To heat the water fast enough, we must raise the temperature; however, as the temperature difference of the heat pump is increased, and the amount of work required increases. Ten years ago, this might have seemed to be an insurmountable problem. However, through the efforts of electric power companies and manufacturers, heat pumps are now available on the market that heat water from ambient temperature to 90 °C, which is more than enough to supply the hot water needs of homes.

There are other alternatives to reducing the large waste of energy occurring when we heat a bath directly. For example, we know from the law of energy conservation that when we combust energy resources at factories and power plants, even if along the way the energy is transformed into useful forms such as electricity, work and kinetic energy, in the end it all becomes heat. In general, useful forms of energy cannot be obtained from heat that is at a temperature of around 40 °C, so at a factory, there are countless sources of excess heat at these relatively low temperatures. We can think of this low-temperature heat as a waste product of energy resources, and in fact we often speak of waste heat being dumped into rivers by thermal power plants. If we were fortunate enough (or unfortunate enough!) to be living near a factory or power plant, we could use their low-temperature heat to heat our bath water.

How Effective Is Cogeneration?

Another possibility that has been suggested for obtaining heat with less waste is a method called cogeneration. Cogeneration, sometimes called "combined heat and power," means the simultaneous generation of both electricity and heat.

In Chapter 2, we saw that there are two ways to generate electricity – using a generator or using an electric cell. Many different techniques are used to generate electricity in both of these ways, including gas turbines or fuel cells. Each technique loses some amount of the input energy as heat. For example, in the process of generating electricity using a gas turbine, a large amount of the chemical energy of the fuel becomes heat. Cogeneration tries to put both the heat and the electricity to effective use. If the heat from the gas turbine is released at a temperature of 100 °C, that is sufficient for heating bath water, making coffee, and providing hot water for other uses in homes and offices. In this way, we could make use of heat that would otherwise have dissipated into the environment.

In reality, cogeneration has not succeeded as well as expected. The main reason is that, compared to the demand for electricity, the demand for heat is small. In cogeneration systems based on gas turbines at the turn of the century, 30% of the chemical energy of the fuel is made into electricity, 40% into heat, and the remaining 30% is lost. However, there are only a few places where more heat is used than electricity, such as hotels with heated pools. If we are not going to use the heat anyway, then it is better to use standard electric power plants, which have electricity generation efficiencies of more than 50%. Even if we include the heat from cogeneration, a cogeneration system that produces 30% electricity and 40% heat at 90 °C, is a worse deal in terms of resources consumed than an electric power plant that generates 50% electricity and throws away the rest of the heat. The reason is that even if we end up using 20% of the electricity generated by the standard power plant to produce heat, we can use heat pumps available on the market today to pump up three times as much heat from ambient temperature to 90 °C. That is equivalent to 60% of the original chemical energy, which exceeds the 40% heat produced by the cogeneration system.

Current cogeneration systems have improved so that up to 50% of heat can be recovered, which means the heat loss is just 20%. However, to encourage the use of cogeneration systems, we must develop small cogeneration systems with high electricity generation efficiency. One possibility is a cogeneration system based on a fuel cell. Fuel cells can generate electricity at an efficiency of 50%, but the rest of the chemical energy of the fuel ends up as heat. If the fuel cell operates at a temperature of 100 °C, then the excess heat is released from the fuel cell at 100 °C. From a fuel cell operating at 100 °C and generating electricity at an efficiency of 50%, we could obtain some of the chemical energy that was not converted into electricity as hot water having a temperature of 100 °C. This hot water would contain as much as 30% of the original chemical energy. Even if we were to use some of the heat released from the fuel cell to preheat the fuel and air, there would still be an excess of heat. In fact, such a fuel cell must be equipped with a cooling system because if we did not release the heat from the fuel cell, it would overheat. In other words, even if there were no demand for heat, we would have to remove the heat from the coolant before returning it to the fuel cell. If we could develop a cogeneration system based on a fuel cell, its efficiency in generating electric power would rival that of large-scale electric power facilities, so any usable heat that is cogenerated would be an added benefit.

Reduce Energy Consumed for Heating and Cooling to One Tenth

In the last few sections, we have seen that the waste of energy resources from technologies related to space heating and cooling, refrigerators, baths, and water heating is quite large. Consequently, there should be lots of room left for reducing energy consumption. Even if we only cut the temperature difference of heat pumps by a factor of three and improve the efficiency of compression pumps from their current value of about 50% to 75%, this would still reduce the electricity consumed by air conditioners for transporting a given amount of heat to about one fifth. If we cut the heating and cooling load by half through improvement of insulation, it should be possible to reduce the electricity consumed for air conditioning to one tenth of what it was in 1995.

Refrigerators are also heat pumps. So, theoretically, it should be possible to achieve energy conservation in the same way as described for air conditioners. Furthermore, in addition to improving the insulation, we could minimize the increase in the load that occurs when the refrigerator door is opened and closed by compartmenting off the space in the refrigerator.

We could devise ways to use the waste heat from refrigerators and other appliances to heat water or provide space heating, resulting in even more energy savings.

Lighting

Lighting is a “daily life” activity with particularly low energy efficiency. Incandescent light bulbs change only 2% of electricity into light, and even fluorescent light bulbs, which we consider to be energy-saving devices, have efficiencies of only about 12%. We need to improve the efficiency of lighting devices. Semi-conductors could make an important contribution here. Special semi-conductors called light-emitting diodes are starting to appear as indicator lights for televisions and stereos, lighted road signs, and the display panels in airports and train stations. Recently, these lights have started to appear in hotels. If you see a light that you think is an LED, carefully see if it is hot. Even fluorescent light bulbs get too hot to touch. So if it isn’t hot, it is probably a high-efficiency LED light. As this kind of technology develops, we should see a two to three-fold increase in efficiency in lighting, even in comparison to fluorescent light bulbs.

3 Power Plants

We have seen that technologies increasing the efficiency of electrical devices, such as air conditioners and lighting, can have a huge impact on energy use. The possibilities for conserving energy on the electricity supply side, in other words at power plants, are also great. Here, let's consider energy conservation in thermal electric power plants.

As we saw in figure 2-2, a thermal electric power plant is a mechanism to transform the chemical energy of fuel into electricity. The waste heat from a thermal power plant is the chemical energy that is not transformed into electricity. Therefore, the way to increase the efficiency of electricity generation is to minimize the part lost as heat.

The High-Temperature Limit

In the second half of the 20th century, a remarkable improvement in technologies for generating electricity in thermal power plants occurred. The electricity generation efficiency of thermal power plants, which was around 20% in the middle of the century, rose to over 40% by the end of the century. This increase in efficiency was due to technologies that made it possible to raise the temperature and pressure of the steam in the power plants. The temperature of the steam in thermal electric power plants, which was around 450 °C initially, is now over 600 °C. At the same time, the pressure of the steam, which was around 40 atmospheres initially, has increased to more than 300 atmospheres. As a result of these advances in technology, the efficiency of electricity generation could be increased to more than 42%. And currently the makers of thermal power plants are trying to push the temperature limit to 700 °C, thereby increasing the efficiency even further. However, the current temperature and pressure of the steam are close to the limits for the materials of the power plant. If we were to increase them much more, the steam would melt or corrode the iron-based materials of the turbine.

There are actually two ways to consider the efficiency of a thermal power plant. Heat is required to change water into steam, even if the temperature does not change, and when steam is changed into water, heat energy can be obtained. To calculate the efficiency of a thermal power plant, we divide the electricity obtained by the heat required to produce that electricity. However, the amount of heat available from steam depends on whether we consider the heat that is obtained when the steam providing the heat is changed into water. The amount of heat including the heat obtained when steam is changed to water is called the higher-heating value (HHV). The amount of heat obtained just when steam is lowered from the initial to final temperature is called the lower-heating value (LHV). The HHV is larger than the LHV, so the efficiency of a thermal power plant calculated in terms of the HHV will be lower than the efficiency given by the LHV. In fact, fossil fuel energy must be provided to convert water to steam in addition to raising the temperature of the steam, so the efficiency based on the HHV is probably more accurate. We will use the HHV based efficiency in this book.

Even an efficiency of 42% means that during the process of generating electricity in a thermal power plant, 58% of the chemical energy of the fuel is lost to the environment, mainly in the condenser. To make this efficiency higher, we must find a way to increase the input temperature of the turbine. The reason is that, as we saw in Chapter 2, high-temperature heat has a greater value than low-temperature heat because a larger fraction of the heat can be transformed into electricity.

Combined Cycle Electric Power Generation

The technological innovation that broke through this efficiency barrier was combining a steam turbine and a gas turbine to produce a combined cycle (figure 4-4). A gas turbine works in essentially the same way as a jet engine. In a combined cycle, first the combustion gas of the fuel is used to turn the gas turbine, and as much electricity is obtained as possible. The exhaust gas from the gas turbine still has a temperature as high as 1000 °C, so this exhaust gas is used to generate steam, and additional electricity is obtained from a normal steam turbine. The efficiency can be increased in the combined cycle because the maximum temperature at which electricity is generated is higher. Instead of being used to produce 600 °C steam, a combustion gas with a temperature as high as 1500 °C is used by the gas turbine to produce electricity directly. A commercially operated combined cycle plant with an electricity generation efficiency of 53% has been in operation since June 2007 at the Kawasaki thermal power station in Japan. Another example is GE’s H system power plant in operation in Baglan Bay, Wales.

Theoretically the efficiency can be raised even further if the temperature is increased, so efforts are being made to find ways to raise the temperature of the gas turbine even higher. One problem is that the materials of gas turbines used in power plants today cannot handle temperatures much higher than 1500 °C. However, with the development of new materials and the improvement of the structural

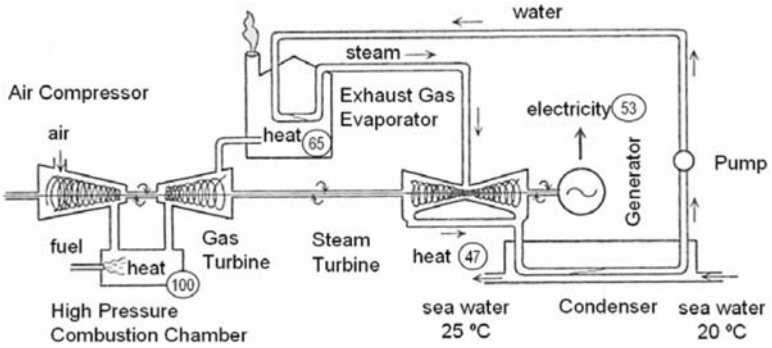

Fig. 4-4: The basic mechanism of a combined cycle gas turbine power plant
Note: The air compressor, gas turbine, and steam turbine are installed on the same axis. The system is essentially the same as the system shown in figure 2-2 with a gas turbine added. The numbers in circles are energy amounts in each of the parts when the fuel energy is 100.

design of the gas turbine, prospects look good for reaching a temperature of 1700 °C. As a result of these efforts together with advances in cooling technologies that are necessary to keep the turbine blades from deteriorating, it is thought that an electric generation efficiency of more than 55% should be possible in the near future.

Is this the limit? Not at all. The theoretical limit of electric generation efficiency is 100%. Various ways to approach this efficiency level are being studied. We just saw some ways that are being explored to make the temperature of the gas turbine even higher. Other research aimed at increasing the electric generation efficiency include devising better ways for combining the gas turbine and the steam turbine. There is even work to develop a triple stage combined cycle where before delivering the fuel to the gas turbine, electricity is first obtained from a fuel cell. Fuel cells do not consume all of the fuel that is input to the cell. The fuel that remains in the gas emitted by the fuel cell can be combusted in the gas turbine to generate more electricity. Finally, the hot exhaust gas is used to generate steam for use in the steam turbine.

In summary, the efficiencies of electricity generation using either generators or electric cells vary widely based on the methods and technologies that are used. By realizing better efficiencies, we can reduce the amount of fossil fuel we consume. This is an important part of the potential for conserving energy through technological advances.