# Handouts-4

## Chapter 4

## EFFICIENCY OF ENERGY CONVERSION

The National Energy Strategy reflects a National commitment to greater efficiency in every element of energy production and use. Greater energy efficiency can reduce energy costs to consumers, enhance environmental quality, maintain and enhance our standard of living, increase our freedom and energy security, and promote a strong economy.

(*National Energy Strategy, Executive Summary*, 1991/1992)

Increased energy efficiency has provided the Nation with significant economic, environmental, and security benefits over the past 20 years. To make further progress toward a sustainable energy future, Administration policy encourages investments in energy efficiency and fuel flexibility in key economic sectors. By focusing on market barriers that inhibit economic investments in efficient technologies and practices, these programs help market forces continually improve the efficiency of our homes, our transportation systems, our offices, and our factories.

(*Sustainable Energy Strategy*, 1995)

Our principal criterion for the selection of discussion topics in Chapter 3 was to provide the necessary and sufficient thermodynamics background to allow the reader to grasp the concept of energy efficiency. Here we first want to become familiar with energy conversion devices and heat transfer devices. Examples of the former include automobile engines, hair driers, furnaces and nuclear reactors. Examples of the latter include refrigerators, air conditioners and heat pumps. We then use the knowledge gained in Chapter 3 to show that there are natural (thermodynamic) limitations when energy is converted from one form to another. In Parts II and III of the book, we shall then see that additional technical limitations may exist as well. This is especially true for the practically important conversion of heat to work. Finally, here we quantify efficiency and show why some energy conversion devices are more efficient than others. Higher energy efficiency translates directly into lower energy cost. We shall illustrate this statement in the present chapter and then use the same type of analysis throughout the remainder of the book.

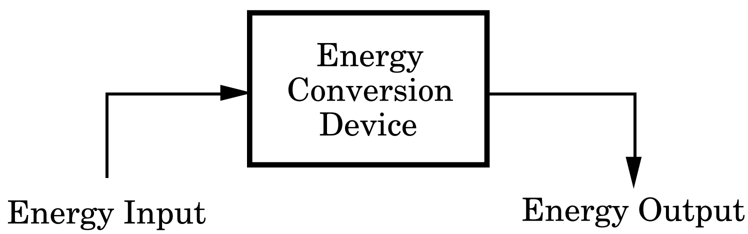
## Energy Conversion Devices and Their Efficiency

A device is a piece of equipment that serves a specific purpose. An energy conversion device converts one form of energy into another. It is an important element of progress of society. In fact, one can discuss the history of civilization in terms of landmarks in the development of energy conversion devices, as illustrated below:

| *Landmark Event* | *Approximate Date* |
|---|---|
| Emergence of man | 4,000,000 B.C. |
| Emergence of human civilization | 5000 B.C. |
| Development of the water wheel | 350 A.D. |
| Development of the windmill | 950 A.D. |
| Invention of the cannon | 1318 A.D. |
| Development of first atmospheric steam engine (Newcomen) | 1712 A.D. |
| Development of modern steam engine (Watt) | 1765 A.D. |
| Development of high-pressure steam engine (Trevithick) | 1802 A.D. |
| Development of the automobile engine (Daimler) | 1884 A.D. |
| Operation of first nuclear power plant | 1954 A.D. |

The Industrial Revolution began when James Watt invented the steam engine in 1765; today we live in the “nuclear age,” marked by the existence of devices (reactors or bombs) that convert nuclear energy into other energy forms.

An energy conversion device is represented schematically in Figure 4-1. It may be a very simple gadget, such as an electric toy automobile (which converts electricity into mechanical energy), or a very complex machine, such as an automobile engine (which converts the chemical energy of gasoline into mechanical energy). As shown in Figure 3-3 for systems in general, these devices will be pretty much black boxes for us. We shall not place undue emphasis on how they work; we shall concentrate on *what* they accomplish. In other words, energy supply (output) and demand (input), at this microscale, will be our focus. This is illustrated in Figure 4-1. Energy supply and demand at the macroscale (United States and the world), which will be the focus of our discussion in Parts II and III of the book, are very much dependent on the balance between energy input and output in the devices that we use in our homes and at work.




Energy Output = Energy Input   (1st Law)

Useful Energy Output   Energy Input   (2nd Law)

**FIGURE 4-1**. Schematic representation of an energy conversion device.

The efficiency of an energy conversion device is a quantitative expression of this balance between energy input and energy output. It is defined as follows:

$$\text{Device efficiency} = \frac{\text{Useful energy output}}{\text{Energy input}}$$

The key word in the above definition is ‘useful’. Were it not for this word, of course, the definition would be trivial, as shown in Figures 3-3 and 4-1. The First Law of Thermodynamics tells us that energy is conserved in all its transformations. So the ratio of energy output to energy input is always unity, or 100%.

The meaning of the word ‘useful’ depends on the purpose of the device. For example, if the device is an electric heater, the useful energy output is heat, and the energy input is electricity. Electricity is converted to heat. Heat is also obtained from electricity in a light bulb, as we well know. But this is *not* the useful energy obtained from a light bulb; the purpose of a light bulb is to convert electricity into light. Table 4-1 summarizes the useful energy output and energy input for some common energy conversion devices. Figures 4-2 and 4-3 are illustrations of how to use the information provided in Table 4-1 for the case of two ubiquitous devices, an electric motor and a furnace. We may know, or may be interested in knowing, how they work, but this is not necessary for our purposes. For becoming an energy-informed and (perhaps more importantly) energy-conscious member of society, all one needs is the information provided in Table 4-1.

**TABLE 4-1**
Tasks performed by common energy conversion devices

| Energy Conversion Device | Energy Input | Useful Energy Output |
|---|---|---|
| Electric heater | Electricity | Thermal energy |
| Hair drier | Electricity | Thermal energy |
| Electric generator | Mechanical energy | Electricity |
| Electric motor | Electricity | Mechanical energy |
| Battery | Chemical energy | Electricity |
| Steam boiler | Chemical energy | Thermal energy |
| Furnace | Chemical energy | Thermal energy |
| Steam turbine | Thermal energy | Mechanical energy |
| Gas turbine | Chemical energy | Mechanical energy |
| Automobile engine | Chemical energy | Mechanical energy |
| Fluorescent lamp | Electricity | Light |
| Silicon solar cell | Solar energy | Electricity |
| Steam locomotive | Chemical | Mechanical |
| Incandescent lamp | Electricity | Light |

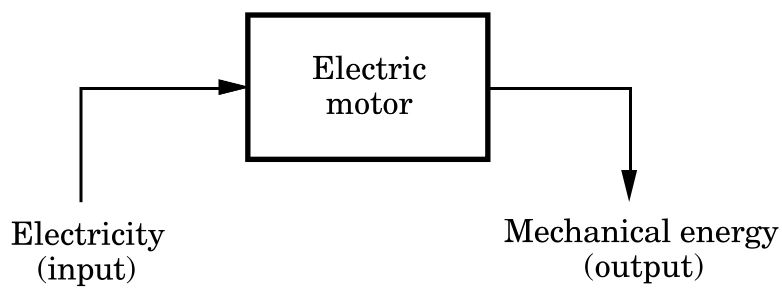



**FIGURE 4-2**. Energy conversion in an electric motor (electric-to-mechanical).

**Illustration 4-1**. An electric motor consumes 100 watts (W) of electricity to obtain 90 watts of mechanical power. Determine its efficiency (E).

*Solution.*
Because power is the rate of energy utilization, efficiency can also be expressed as a power ratio. The time units cancel out, and we have

$$\text{Efficiency} = \frac{\text{Useful energy output}}{\text{Energy input}} = \frac{\text{Useful power output}}{\text{Power input}}$$

Therefore, the efficiency of this electric motor is:

$$E = \frac{\text{Mechanical energy (power) output}}{\text{Electric energy (power) input}} =$$

$$= \frac{90\ \text{W}}{100\ \text{W}} = \frac{90\ \frac{\text{J}}{\text{s}}}{100\ \frac{\text{J}}{\text{s}}} = \frac{90\ \text{J}}{100\ \text{J}} = 0.9 = 90\%$$

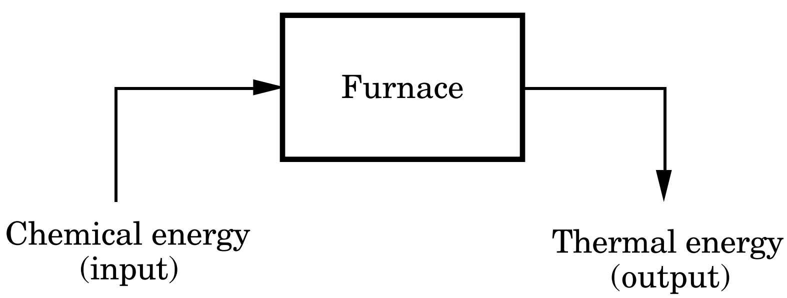



**FIGURE 4-3**. Energy conversion in a furnace (chemical-to-thermal).

Illustrations 4-1 and 4-2, while very simple, should be studied carefully. They carry two important messages. First, the efficiency of an energy conversion device is a *quantitatively* unitless (or dimensionless) number between 0 and 1 (or between 0 and 100%). Obviously, the larger this number is, the higher the efficiency of the device will be; however, a number greater than one would contradict the First Law of Thermodynamics. The second message is both formal and substantive. Its formal part has to do with the cancellation of units (see pp. 15-17). It is not sufficient to convert energy quantities into the same units, for example BTU to joules or calories to kilowatthours. The units must also be of the *same energy form*. It is not possible, for example, to cancel out chemical BTU and thermal BTU. In substantive terms, the efficiency is not a *qualitatively* unitless number. Even when its units are not explicitly stated, as in Illustration 4-1, we should remember what they are, from knowledge of the device's function (as shown in Table 4-1 and illustrated in Figures 4-1, 4-2 and 4-3).

**Illustration 4-2**. A gas furnace has an efficiency of 75%. How many BTU will it produce from 1000 BTU of natural gas.

*Solution.*
The function of a gas furnace is to convert the chemical energy of the gas into heat (thermal energy), as shown in Table 4-1 and illustrated in Figure 4-3.

Therefore, we have:

$$\text{Useful energy output} = [\text{Energy input}]\ [\text{Efficiency}]$$

$$= [1000 \text{ BTU (chemical energy)}]\ [\frac{75 \text{ BTU (thermal energy)}}{100 \text{ BTU (chemical energy)}}]$$

$$= 750 \text{ BTU (thermal energy)}$$

The concept of efficiency thus embodies both laws of thermodynamics. It reflects the quantitative equality and the qualitative difference of the various energy forms. Its understanding requires some knowledge of thermodynamics; once understood, it is only this concept – from the entire field of thermodynamics – that is necessary for understanding the principal energy issues facing society today.

Table 4-2 summarizes the energy efficiencies of a number of common energy conversion devices. They are listed in order of decreasing efficiency. The numbers shown are typical but they can be different for different models of the same type of device (depending on details of its design) or for the same device, depending on whether it is used and maintained properly. For example, your car engine will be more efficient if you change the oil regularly.

Why some numbers are high and others are low can be understood, at least in part, from the information provided in Chapter 3. The ‘easiest’ conversions are those that are in the direction of increasing entropy, and in particular those that produce heat (thermal energy). We just need to rub our hands and convert mechanical energy into heat. So the electric drier and the electric heater are very efficient. Home furnaces also produce heat, but gas furnaces are typically more efficient than oil furnaces, which in turn are often more efficient than coal furnaces. The reason for this is that it is easiest to burn the gas completely within the furnace, and it is most difficult to burn coal. In other words, the largest part of the chemical energy of the gas ends up as useful heat in our home. This is discussed in more detail in Chapters 6-9. Note also the low efficiencies of such common devices as the steam turbine and automobile engine. The reason for this is explored next.

**TABLE 4-2**
Efficiencies of common energy conversion devices

| Energy Conversion Device | Energy Conversion | Typical Efficiency, % |
|---|---|---|
| Electric heater | Electricity/Thermal | 100 |
| Hair drier | Electricity/Thermal | 100 |
| Electric generator | Mechanical/Electricity | 95 |
| Electric motor (large) | Electricity/Mechanical | 90 |
| Battery | Chemical/Electricity | 90 |
| Steam boiler (power plant) | Chemical/Thermal | 85 |
| Home gas furnace | Chemical/Thermal | 85 |
| Home oil furnace | Chemical/Thermal | 65 |
| Electric motor (small) | Electricity/Mechanical | 65 |
| Home coal furnace | Chemical/Thermal | 55 |
| Steam turbine | Thermal/Mechanical | 45 |
| Gas turbine (aircraft) | Chemical/Mechanical | 35 |
| Gas turbine (industrial) | Chemical/Mechanical | 30 |
| Automobile engine | Chemical/Mechanical | 25 |
| Fluorescent lamp | Electricity/Light | 20 |
| Silicon solar cell | Solar/Electricity | 15 |
| Steam locomotive | Chemical/Mechanical | 10 |
| Incandescent lamp | Electricity/Light | 5 |

## Heat Engines and System Efficiency

The Industrial Revolution began with the invention of a heat engine (the steam engine). We live today in the era of revolutions in electronics and communications, but the heat engine continues to play a key role in modern society. It converts heat to work. It deserves our special attention.

In Chapter 3 we explored the natural limitations in the conversion of heat to work. Simply stated, this energy conversion goes against nature and nature imposes a ‘tax’ on it. Part of the energy input is wasted. It is used to increase the entropy of the surroundings.

Therefore, the useful energy output is necessarily smaller than the energy input. In other words, the efficiency of a heat engine is always less than 100%.

A logical question to ask at this point is: why are heat engines so important in our society? The answer was anticipated in Figure 3-1. Even though most of the energy on our planet comes directly from the sun, we do not know how to harness solar energy directly and efficiently. (Some progress is being made, however, as we shall see in Chapter 17.) Instead we have to rely on the chemical energy of fossil fuels for most of our energy needs. The problem with chemical energy is that it is a potential energy form; so it must be converted to other forms before we can use it. The only way we know to exploit this stored solar energy is to release it by burning the fossil fuels. This process is called combustion and it is described in more detail in Chapter 6. The chemical energy of fossil fuels is thus converted to heat, and it is primarily this heat that we use in heat engines to obtain work.

Most heat engines use a fossil fuel, or a product derived from it – such as natural gas, coal or gasoline – to provide the heat, which is then converted to work. So, in essence, they consist of two sub-systems, as illustrated in Figure 4-4. We thus need to introduce the concept of *system efficiency*. By a system here we again mean a well-defined space (see p. 30) in which not one, but at least two energy conversions take place. It consists of two or more energy conversion devices.

*The efficiency of a system is equal to the product of efficiencies of the individual devices (sub-systems).*

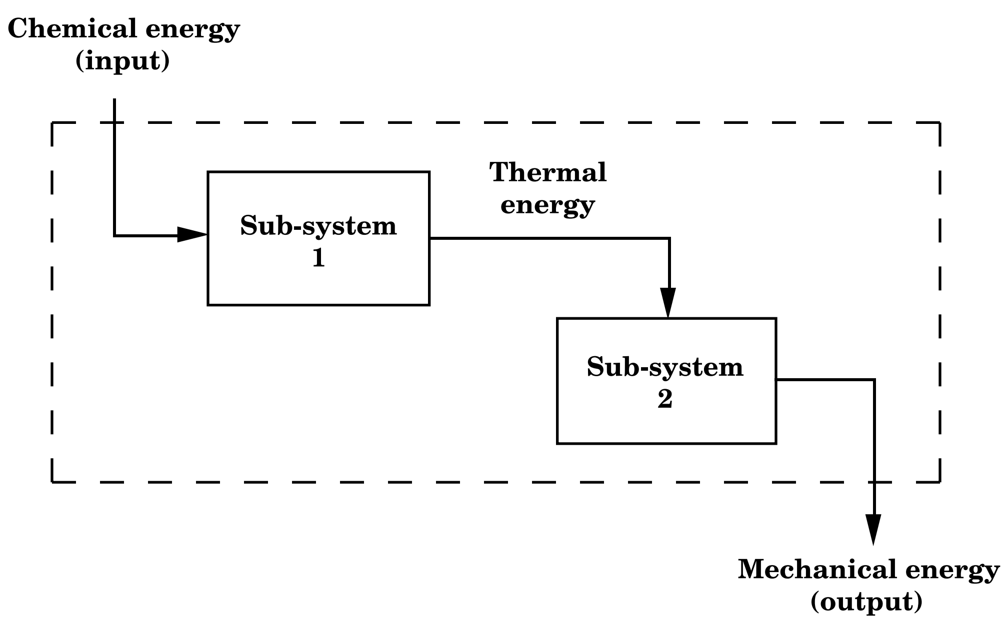



**FIGURE 4-4**. Energy conversion in a heat engine.

**Illustration 4-3**. Calculate the efficiency of a power plant if the efficiencies of the boiler, turbine and generator are 88, 40 and 98%, respectively.

*Solution.*

$E_{power\ plant} = [E_{boiler}]\ [E_{turbine}]\ [E_{generator}] =$

$= (0.88)\ (0.40)\ (0.98) = 0.35\ (35\%)$

Note that the efficiency of the system is lower than any one of the efficiencies of the individual components of the system. In the case of this electric power plant, only 35% of the chemical energy input is converted to electricity. The rest is lost to the environment, mostly as heat (to keep nature happy, by satisfying the Second Law of Thermodynamics).

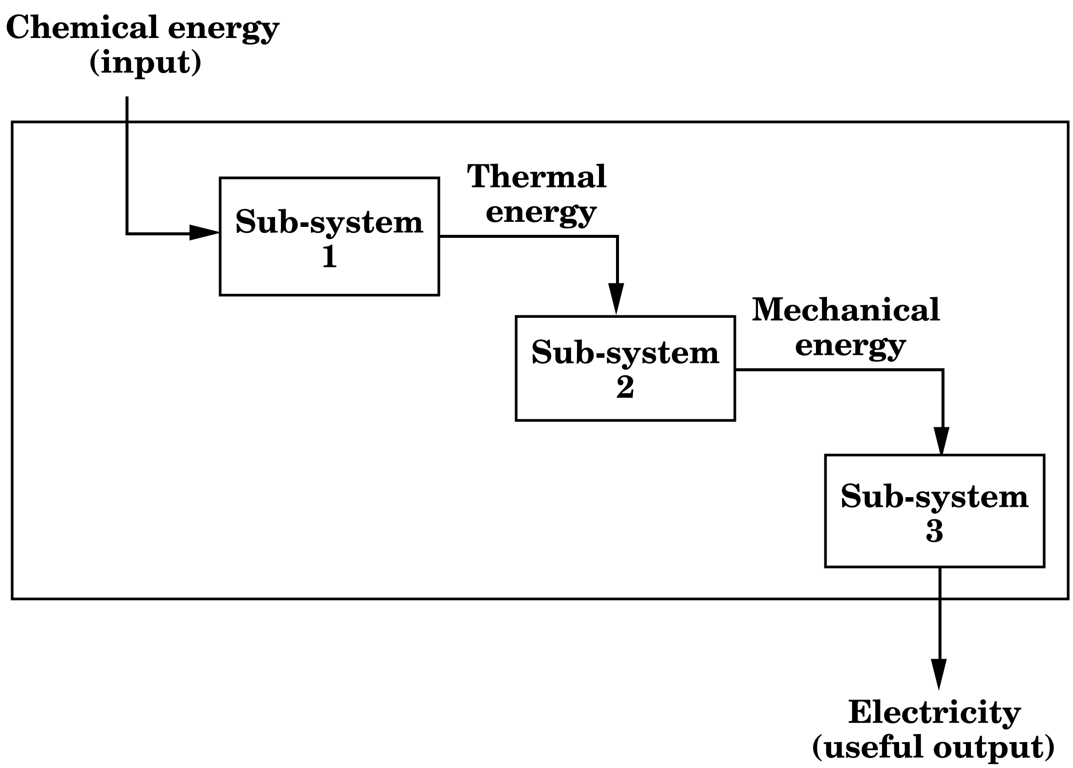



**FIGURE 4-5.** Energy conversion in an electric power plant.

One of the most important energy conversion systems in our modern society is the electric power plant. It is shown schematically in Figures 4-5 and 4-6. The chemical energy is first converted to thermal energy in the boiler; thermal energy is then converted to mechanical energy in the turbine; finally, mechanical energy is converted to electricity in the generator. System efficiency is, therefore,

$$E_{\text{power plant}} = [E_{\text{boiler}}]\,[E_{\text{turbine}}]\,[E_{\text{generator}}] =$$

$$= \left[\frac{\text{Thermal energy}}{\text{Chemical energy}}\right]\left[\frac{\text{Mechanical energy}}{\text{Thermal energy}}\right]\left[\frac{\text{Electric energy}}{\text{Mechanical energy}}\right] = \frac{\text{Electric energy}}{\text{Chemical energy}}$$

The heart (and the 'bottleneck', as we shall see) of the electric power plant is the boiler. It is shown in Figure 4-7. In the boiler a fuel is burned and the heat from the hot combustion products is transferred to the water that flows through the tubes surrounding the combustion chamber. The water boils and is converted to steam. The steam reaches a high temperature and a high pressure, of the order of 1000 °F and 1000 pounds per square inch (roughly sixty times greater than atmospheric pressure); it contains a lot of thermal energy. This steam is directed to the turbine, which consists of a bladed wheel set on a shaft. The impulse of the high-velocity steam causes the rotation of the blades of the turbine, which in turn causes the rotation of the shaft. In this process, the steam becomes 'exhausted'; it loses its energy, and its temperature decreases. It is transformed back to water in the condenser and recirculated into the boiler to repeat the cycle. The rotation of the shaft of the turbine within a magnetic field of the electric generator produces electricity, according to the principles of electromagnetic induction. We need not elaborate this statement further; consider the generator to be a black box that converts mechanical energy to electricity.

The elaborate water cooling system, shown in Figure 4-6, is a necessary component of the power plant. In fact, when a cooling tower is used for this purpose, as shown in Figure 4-6, it is the most prominent part of the plant. It satisfies the Second Law of Thermodynamics, as discussed in Chapter 3. The entropy decreases within the power plant (within system limits shown in Figure 4-5). So it must increase in the surroundings; the surroundings in this case are the river and the atmosphere, as shown in Figure 4-6, whose temperature increases.

It is the temperature decrease between the steam in the boiler and the water in the condenser that provides the energy for the conversion of heat to work in the turbine. To understand how this happens, the following analogy is helpful even though it is not totally valid (p. 45).

Consider the water wheel in Figure 4-8. It converts the potential energy of the falling water into the mechanical (or kinetic) energy of the wheel shaft. On the basis of the discussion in Chapter 3, we know that the design shown in Figure 4-8a is not very efficient. Only a limited conversion of potential energy to kinetic energy occurs before the water hits the wheel. The arrangement shown in Figure 4-8b is much more efficient. It takes advantage of the conversion of most of the water's potential energy to kinetic energy. The analogy of this situation with the conversion of heat to work is illustrated in Figure 4-9. Water at high level falls to a lower level and loses some of its potential energy, which is converted to kinetic energy. In other words, the “driving force” for the conversion of potential energy to kinetic energy is the difference in height of the two water reservoirs. Water at high temperature (for example, steam) ‘falls’ to a lower temperature level (for example, liquid water) and loses some of its thermal energy, which is converted to mechanical energy. Therefore, the driving force for the conversion of heat to work is the temperature difference between the two thermal reservoirs. The larger this driving force, the greater the conversion of potential energy to kinetic energy, and of heat to work.

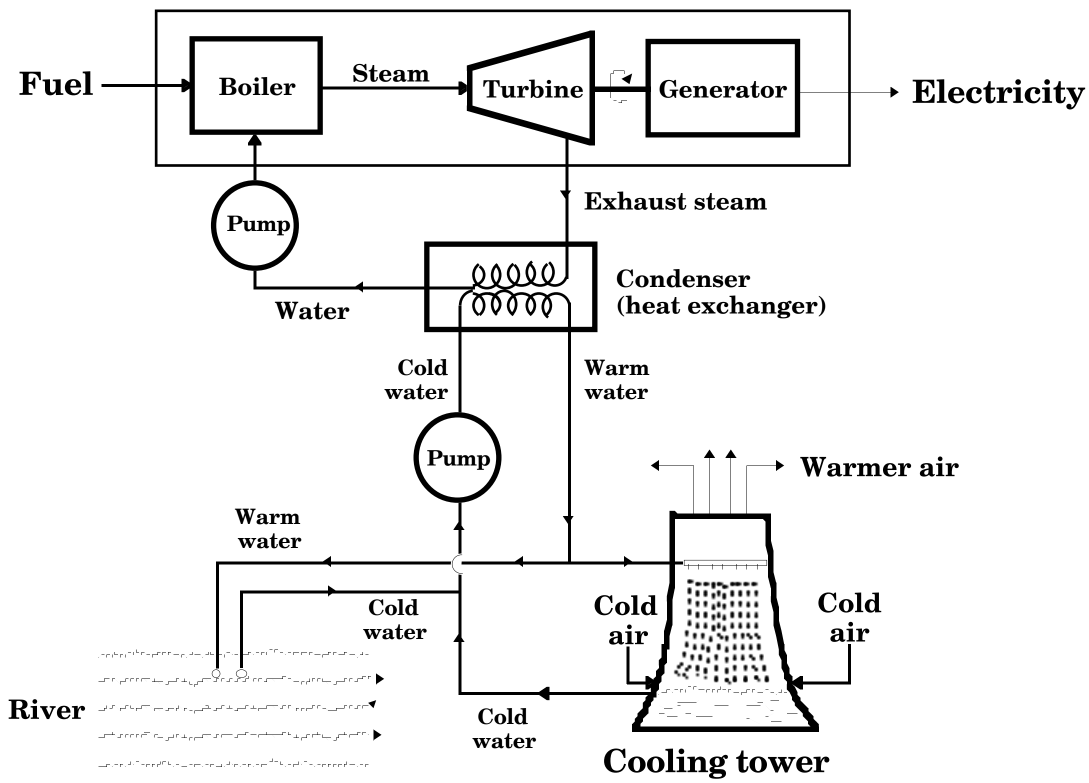



**FIGURE 4-6**
Schematic representation of an electric power plant.

**FIGURE 4-7**. Schematic representation of a steam boiler. [Source: Fowler, op. cit.]

Figure 4-10 is a schematic representation of a heat engine. Any "working fluid" can be used, not necessarily water, but water is commonly used because of its availability and convenience. All we really need to know to determine the (maximum) efficiency of the engine are the high temperature ($T_H$) and the low temperature ($T_L$) of the two reservoirs.

**FIGURE 4-8**. Energy conversion (from potential to kinetic) in a water wheel.

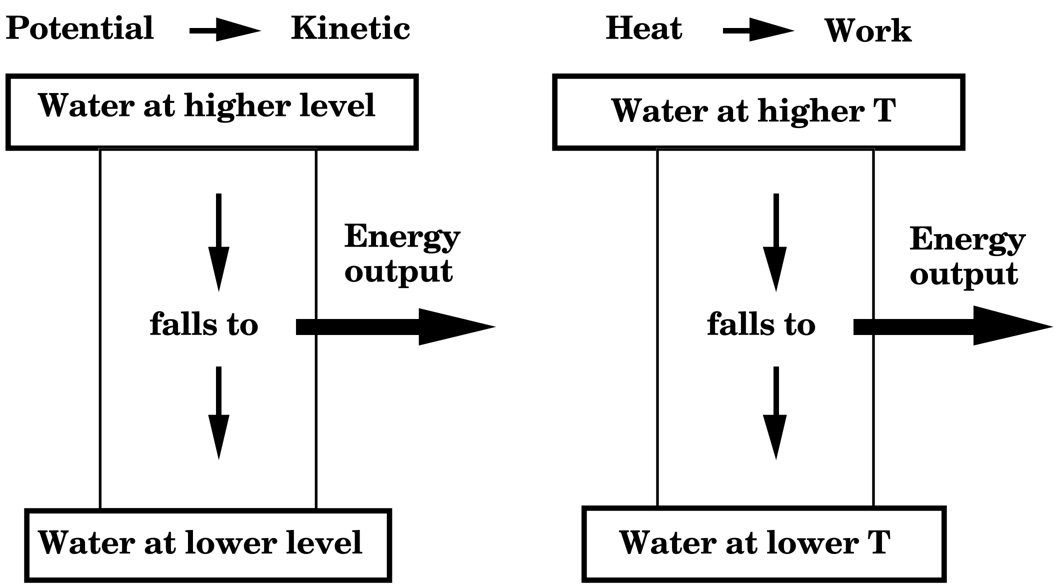



**FIGURE 4-9**. Analogy between energy conversion in a water wheel and a heat engine.

**FIGURE 4-10**. Schematic (thermodynamic) representation of a heat engine.

From thermodynamic analysis, which we do not need to go into, it is possible to define the *maximum (or ideal) heat engine efficiency* ($E_{max}$).

$$E_{max} = \frac{\text{Maximum useful work output}}{\text{Energy input}} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H}$$

**Illustration 4-4**. In a power plant, the steam from the boiler reaches the turbine at a temperature of 700 °C. The spent steam leaves the turbine at 100 °C. Calculate the maximum efficiency of the turbine. Compare it to the typical value listed in Table 4-2.

*Solution.*
From the above expression and noting that 700 °C = 973 K and 100 °C = 373 K, we have:

$$E_{max} = \frac{973\ \text{K} - 373\ \text{K}}{973\ \text{K}} = 1 - \frac{373}{973} = 0.62\ \ (62\%)$$

This is, as expected, larger than the typical efficiency of about 45% shown in Table 4-2.

Here the temperatures are expressed in absolute units. Two important consequences of this definition need to be emphasized: (1) the maximum efficiency increases with decreasing $T_L$, reaching 100% only when $T_L = 0$ K; and (2) the difference $T_H - T_L$ is in the numerator and the larger it is, the higher the efficiency will be.

**Illustration 4-5**. An automobile engine could operate between 2200 °C (the combustion temperature of gasoline) and 20 °C (ambient temperature). If it did, what would its maximum efficiency be? Compare this value to that shown in Table 4-2, for a typical car engine.

*Solution.*

$$E_{max} = \frac{2473\text{ K} - 293\text{ K}}{2473\text{ K}} = 1 - \frac{293}{2473} = 0.88 \ \ (88\%)$$

This values is much higher than that of a typical engine (25%). In Chapter 20, we shall come back to this issue.

## Heat Transfer Devices and Their Efficiency

In contrast to energy conversion devices, which convert one energy form into another, the energy transfer devices just transfer the *same* form of energy from one place to another. Here we shall only be interested in devices that transfer heat. We call them heat movers. The refrigerator, air conditioner and heat pump are familiar examples that we shall analyze in more detail here.

Let us examine the refrigerator. We know that it consumes energy, because it is plugged into the electric outlet. What does it do with the electricity? Well, we also know that it is cold inside the refrigerator, say 10 °C. In the freezer, it is even colder, say -5 °C. The air in the kitchen is at about 25 °C. Hence, the refrigerator uses energy to maintain its temperature lower than that of the surroundings. When we open the door of the refrigerator, heat flows spontaneously from the kitchen to the refrigerator. The electric energy consumed by the refrigerator is used to reverse this process, to pump heat from inside (low-temperature reservoir or ‘source’) to the outside air (high-temperature reservoir or ‘sink’). This is illustrated in Figure 4-11.

The air conditioner and the heat pump accomplish exactly the same task as the refrigerator. This is illustrated in Figure 4-12. They pump heat ‘uphill’, from $T_L$ to $T_H$. In the case of the air conditioner, the sink is the air inside the house (say, at 60 °F), and the source is the outside air (say, at 90 °F).

The heat pump is an energy transfer device that may be very convenient for residential comfort in certain geographical areas. There are two heat exchangers instead of one (a condenser and an evaporator instead of just a condenser). A special liquid (freon or antifreeze) is used as the working fluid because water would, of course, freeze in winter. In winter, its $T_L$ is the outdoor air (say, at 20 °F), and $T_H$ is the indoor air (say, at 65 °F). Electricity is used to increase the energy of this liquid, by compressing it, and the compressed liquid delivers this energy to the house by condensing in the internal heat exchanger. The external heat exchanger is necessary to bring it back into the gaseous state (by evaporation) so that it can be compressed again and the cycle repeated. In summer, the pump functions as an air conditioner, with $T_L$ being the inside air and $T_H$ the outside air. The interior heat exchanger is now the evaporator and the exterior one is the condenser. Evaporation is a process that requires energy input. So the warm inside air flows past this freon evaporator, it transfers to it some of its energy and thus becomes cooler.

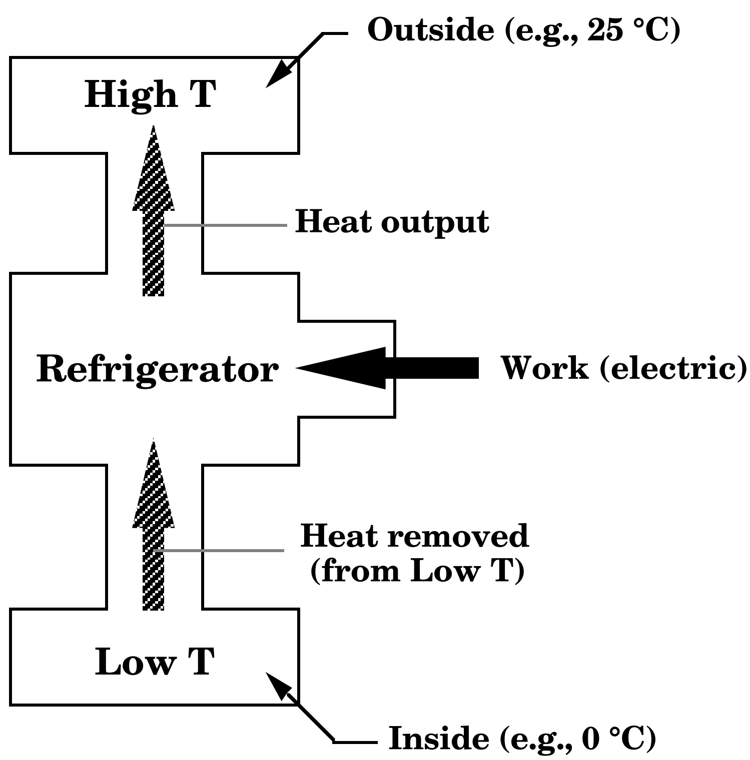



**FIGURE 4-11**. Schematic (thermodynamic) representation of a refrigerator.

**FIGURE 4-12**. Schematic (thermodynamic) representation of a heat mover.

The efficiency of a heat mover is called the *coefficient of performance,* or COP. The reason for this will be apparent soon. It is defined in the same way as the efficiency of an energy conversion device:

$$\text{COP} = \frac{\text{Useful energy output}}{\text{Energy input}}$$

There is one important difference between energy conversion devices and energy transfer devices. In a conversion device, only a portion of the energy input is obtained as useful energy output, and the efficiency is necessarily a number between zero and one. In a transfer device, the useful energy output is the quantity of heat extracted from $T_L$, and this is not a portion of the energy input. In fact, the useful energy output can exceed the energy input, and this is why heat pumps can be extremely attractive for space heating purposes. So the coefficient of performance (sometimes also called "energy efficiency ratio") can be a number larger than one and this does not violate the First Law of Thermodynamics. Obviously, the larger it is, the more efficient the heat mover will be.

From thermodynamic analysis, which again we do not need to go into, it is possible to define the *maximum (or ideal) coefficient of performance* ($COP_{max}$). The definition depends on whether the heat mover is used as a heater or as a cooler. If it is a heater, then the definition is:

**Illustration 4-6**. Determine the coefficient of performance of a refrigerator that consumes 800 watts of power to remove heat at a rate of 5 BTU per second.

*Solution.*

$$COP = \frac{\text{Useful energy output}}{\text{Energy input}} = \frac{5\ \frac{BTU}{s}}{800\ W} = \frac{5\ \frac{BTU}{s}}{800\ \frac{J}{s}}\ \frac{1055\ J}{1\ BTU} = 6.6$$

The meaning of this number is that for every watt of electric power used to drive this heat mover, 6.6 watts of heat are delivered to the high-temperature reservoir (air in the kitchen) and 5.6 watts are extracted from the low-temperature reservoir (refrigerator).

$$COP_{max} = \frac{T_H}{T_H - T_L}$$

If the mover is a cooler, then the definition is:

$$COP_{max} = \frac{T_L}{T_H - T_L}$$

As in the case of maximum efficiency, the temperature in these definitions has to be expressed in absolute units (kelvin, K).

This may sound unnecessarily complicated, but here is the "bottom line." In contrast to the maximum efficiency of a conversion device, note that the temperature difference ($\Delta T$) between the two reservoirs is in the denominator of the above expressions. This has very important practical implications. For a conversion device, the larger the $\Delta T$ is, the more efficient it will be. For a heat mover, the opposite is true: the smaller the $\Delta T$ is, the more efficient it will be. Obviously, a refrigerator 'works' more on a hot summer day when the kitchen temperature is 95 °F than on a winter day when the kitchen temperature is 65 °F.

Illustration 4-7 shows that the heat pump is a better buy in milder climates. Typical COP values of heat pumps are much lower than the ideal ones, and may be as low as 3-4.

## Comparison of Efficiencies

Now that we have introduced all the thermodynamics that we need, we can illustrate its usefulness in comparing energy alternatives. For example, let us consider the case of electric home heating using different primary energy sources. We have a common useful energy output (electric home heating), and we are evaluating the most important alternatives

**Illustration 4-7**. Compare the heating efficiencies (maximum COP) of the same heat pump installed in Miami and in Buffalo. In Miami, since the climate is milder, assume that $T_H$ is 70 °F and that $T_L$ is 40 °F. In Buffalo, assume that $T_H$ is the same, but that $T_L$ (the outside temperature) is much lower, say (on average), 15 °F.

*Solution.*
The temperatures, converted into kelvins, are the following: 70 °F = 294 K; 40 °F = 277 K; 15 °F = 263 K. Since the heat pump is used as a heater, we have the following expression for the maximum COP:

$$\text{Miami:}\quad COP_{max} = \frac{T_H}{T_H - T_L} = \frac{294}{294 - 277} = 17.3$$

$$\text{Buffalo:}\quad COP_{max} = \frac{294}{294 - 263} = 9.5$$

available as energy input (coal, petroleum and natural gas). This is illustrated in Figure 4-13. The only way to produce electricity commercially from these primary sources is to convert their chemical energy to heat, then heat to work, and finally work to electricity (see Figure 4-5). Now, before we can use these primary sources in a power plant, they need to be extracted from the earth, processed and transported. This is illustrated in Figure 4-14 and described in some detail in Chapters 7-9. The efficiencies of each one of these operations are different and their estimates are shown in Figure 4-14. Once these fuels reach the power plant, the efficiency of conversion of their chemical energy to electricity is approximately the same, if the power plant is designed to burn that particular fuel.

Once produced at the power plant, electricity needs to be transported to our homes. The efficiency of this operation is relatively high, say, about 90%. When it reaches our homes, electricity is converted to heat at 100% efficiency because this is a conversion of low-entropy energy to high-entropy energy. So the overall (system) efficiencies for the three cases considered are calculated as follows:

$E_{coal}$ =

$[E_{extraction}]\ [E_{processing}]\ [E_{transport}]\ [E_{power\ plant}]\ [E_{transmission}]\ [E_{electric\ heater}]$

$= (0.66)\ (0.92)\ (0.98)\ (0.35)\ (0.90)\ (1.00) = 0.19\ \ (19\%)$

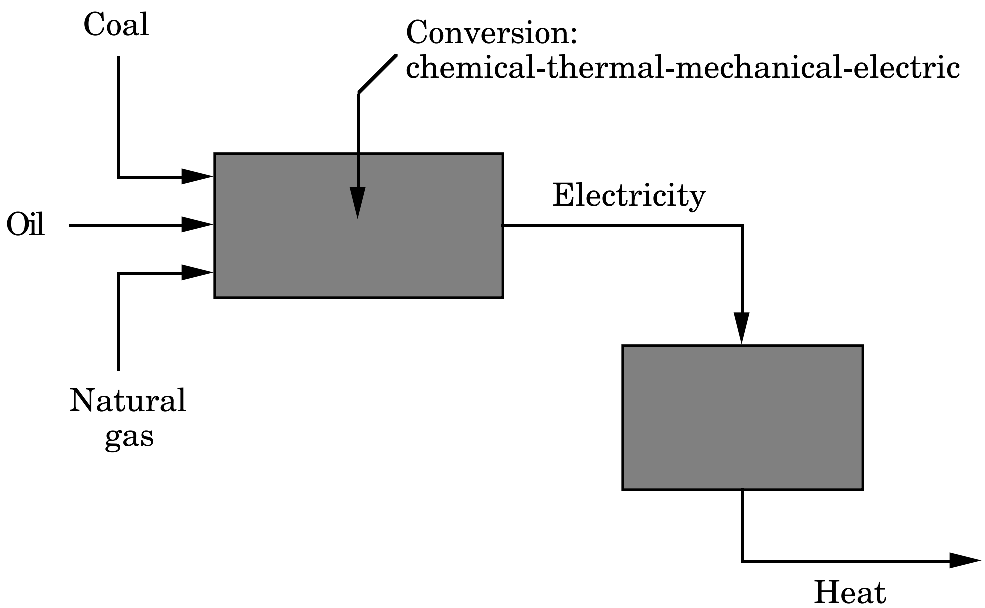



**FIGURE 4-13**
Analysis of electric home heating using different primary energy sources.

$E_{oil}$ =

= $[E_{extraction}]$ $[E_{processing}]$ $[E_{transport}]$ $[E_{power\ plant}]$ $[E_{transmission}]$ $[E_{electric\ heater}]$

= (0.35) (0.88) (0.95) (0.35) (0.90) (1.00) = 0.09 (9%)

$E_{gas}$ =

= $[E_{extraction}]$ $[E_{processing}]$ $[E_{transport}]$ $[E_{power\ plant}]$ $[E_{transmission}]$ $[E_{electric\ heater}]$

= (0.73) (0.97) (0.95) (0.35) (0.90) (1.00) = 0.21 (21%)

These results mean that in our homes we have available only 21, 19 and 9% of the chemical energy of natural gas, coal and petroleum, respectively. The rest is wasted. From this simple analysis, we can reach an important conclusion about the use of coal, oil and natural gas in power plants (if the efficiencies given in Figure 4-14 are correct). Primarily because of the low thermodynamic efficiency of oil extraction (35%, compared to 66 and 73% for extraction of coal and natural gas), it makes more (technical) sense to use coal or natural gas than to use oil. This is the conclusion that a utility executive would reach if he or she were concerned about the optimum allocation of fossil fuels.

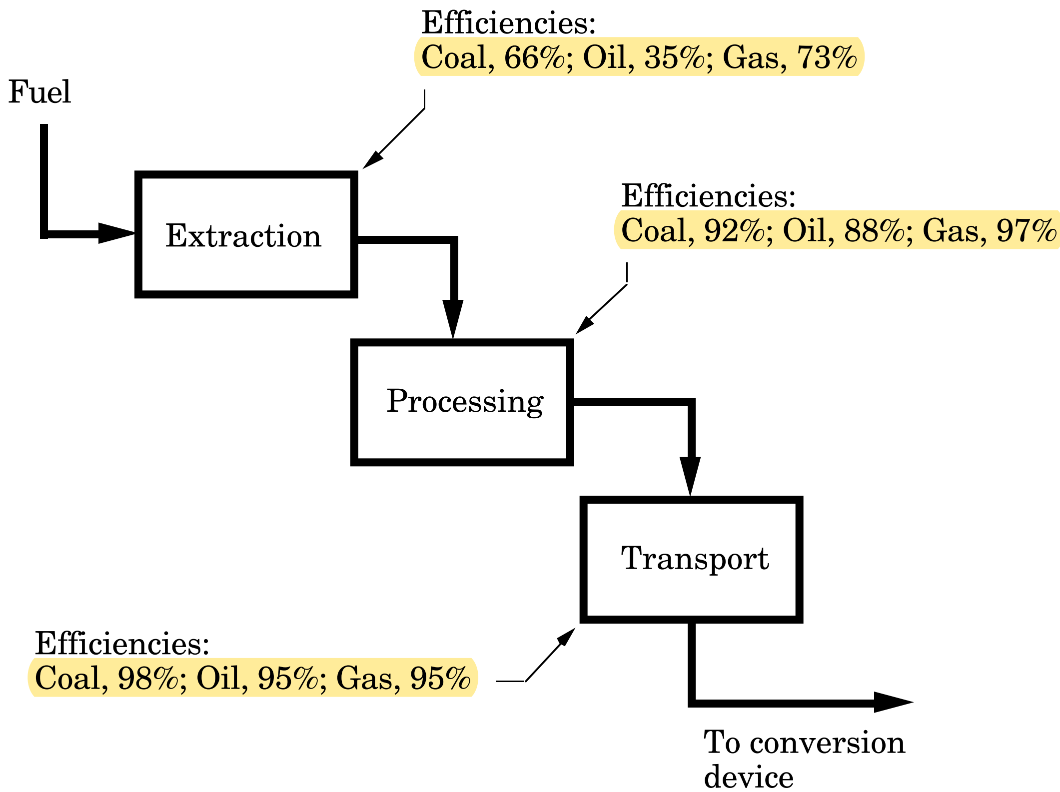



**FIGURE 4-14**. Schematic (thermodynamic) representation of fuel preparation for use in an energy conversion device. Typical efficiencies are also included.

Note also that all the efficiencies are relatively low. It is convenient to use electric heating in our homes, but we see that it is thermodynamically inefficient. We shall see later that it is also quite expensive. And if we stop to think about it for a minute, it really makes sense that it should be inefficient. What are we doing in the scheme shown in Figure 4-13? First we burn the fuels to obtain heat, which is what we want in the first place, and then we convert that heat to electricity and finally electricity back to heat. If we remove this convenient but inefficient constraint, the situation changes. This is illustrated in Figure 4-15. Now we are interested in using the various fossil fuels to heat our homes directly. The conversion of chemical energy to thermal energy is accomplished in a furnace. Typical efficiencies of coal, oil and gas furnaces are given in Table 4-2. So, the system efficiencies are now obtained as follows:

$E_{coal}$ =

= $[E_{extraction}]\ [E_{processing}]\ [E_{transport}]\ [E_{furnace}]$ =

= (0.66) (0.92) (0.98) (0.55) = 0.33 (33%)

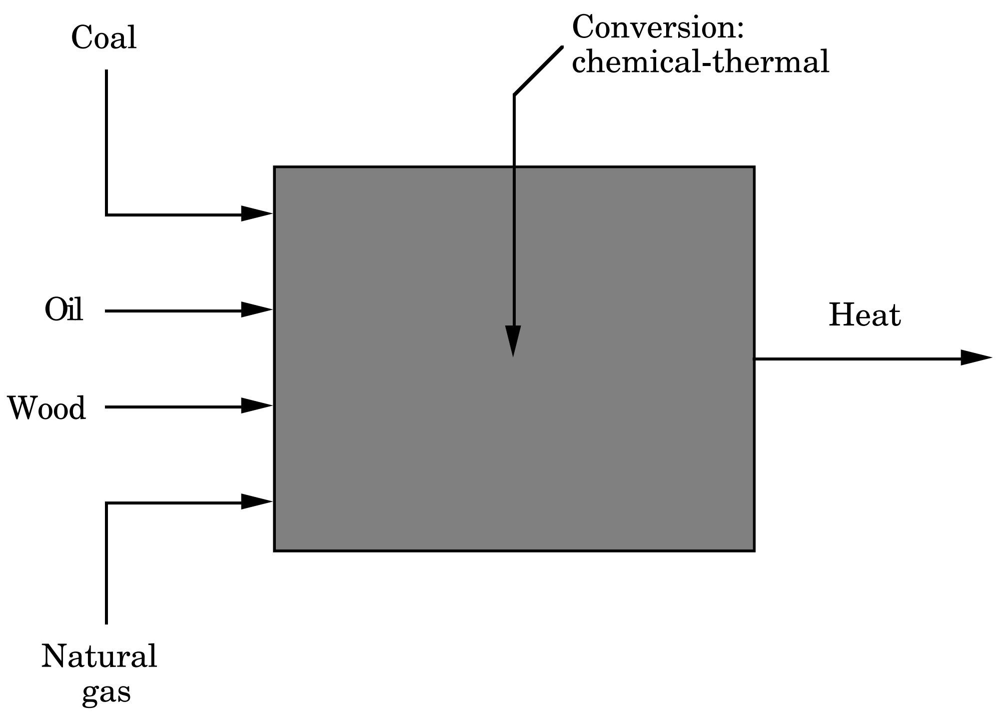



**FIGURE 4-16**. Analysis of home heating using different primary energy sources. (Wood is also included, mostly as an aesthetic complementary fuel, but not a major source of energy in modern society.)

$E_{oil}$ =

= $[E_{extraction}]\ [E_{processing}]\ [E_{transport}]\ [E_{furnace}]$ =

= (0.35) (0.88) (0.95) (0.65) = 0.19 (19%)

$E_{gas}$ =

$$= [E_{extraction}]\ [E_{processing}]\ [E_{transport}]\ [E_{furnace}] =$$

$$= (0.73)\ (0.97)\ (0.95)\ (0.85) = 0.57\ \ (57\%)$$

Now, natural gas turns out to be a clear (thermodynamic) winner, with by far the highest efficiency.

The calculations shown above are meant to accomplish two objectives. First, they illustrate an important fact: among the fossil fuels, natural gas is the most attractive one for home heating purposes. Second, they illustrate the usefulness and power of the concept of efficiency. We do not need to know any details of the technology used to bring energy to our homes; if we know the various efficiencies, we can assess the relative technical merits of the different methods available. And what is more important, as we shall see later, we can also assess their relative economic merits. Therefore, the theoretical development that we conclude here (at last, the reader may say!) was not an academic exercise. Now we are ready to make *practical use* of this simple thermodynamic tool.

## ***REVIEW QUESTIONS***

4-1. The energy input into a hair drier is 1000 watts of electricity. The output is 3400 BTU per hour of heat. Determine the efficiency of the hair drier.

4-2. The energy input into a 40-watt light bulb is 40 watts. The output is 950 lumens Determine the efficiency of the light bulb. (Note: One lumen is equivalent to 0.001496 watts.)

4-3. General Electric provides the following information on its EnergyChoice™ light bulbs: Compared to the regular (soft white) light bulb, which has a rating of 1170 lumens and 75 watts, the bulb that GE wants you to buy has a rating of 1080 lumens and 67 watts. Are the efficiencies of the two light bulbs different?

4-4. By how much does the efficiency of a turbine have to increase in order to raise the efficiency of a power plant from 35 to 40%. The efficiencies of the boiler and generator are 90 and 95%.

4-5. In order to achieve the efficiency increase in Problem 4-4, by how much does the inlet steam temperature have to increase? Assume that the efficiency is proportional to the temperature difference between hot and cold steam and that the cold steam is in both cases at 100 °C.

4-6. You are shopping for an air conditioner and the salesman tells you that the more expensive model ($800) is a “much better buy” than the less expensive model ($500). Both remove heat at a rate of 6000 BTU/hour but the former does it with a COP of 6. The COP of the latter is only 4. Is the salesman right? (How long will it take you to recover the investment in the more expensive model if electricity costs $0.10/kWh?)

4-7. Are the following statements true or false?
(a) The efficiency of a refrigerator is inversely proportional to the temperature difference between indoors and outdoors.
(b) The efficiency of an automobile is inversely proportional to the temperature difference between the engine and the outside air.
(c) The efficiency of a heat pump is directly proportional to the temperature difference between indoors and outdoors.
(d) One of the key energy conversion devices in an electric power plant converts work to heat.
(e) One of the key energy conversion devices in an automobile converts heat to work.
(f) The efficiency of conversion of heat to work is typically higher than the efficiency of conversion of work to heat.

## *INVESTIGATIONS*

4-1. James Watt is a ‘household’ name. Collect some basic facts about his life.

4-2. The development of the high-pressure steam engine was mentioned on p. 54. Find out some basic facts about the life of its inventor, who is not as well known as James Watt. Try the Internet first, at http://www.eb.com.

4-3. Find out more about the heat pump. For example, pick up a heat pump brochure at Sears. See also *Consumer Reports* of October 1985. How is it different from an air conditioner or a refrigerator? Draw its schematic representation, analogous to that shown in the upper part of Figure 4-6. (Check also whether *Consumer Reports* has any more recent articles on heat pumps.) Finally, surf the Internet by typing “heat pump” in the search field of a search engine such as Lycos and Yahoo. An interesting (and reliable!) site is at http://www.heatpumpcentre.org.

4-4. Compare the furnace efficiency information provided here with the information provided in a *Consumer Reports* article of January 1987 (“High-efficiency furnaces”).