

Chapter 10: Energy Utilization

Preview

How we use energy is even more important than how we produce it. Because of inefficiencies in energy production, each kJ of energy saved is worth more than one kJ produced. Energy can be saved in many ways. Topics considered in this chapter include

- Entropy and the efficiency of heat engines
- Fuel cells
- Cogeneration
- Energy storage
- Energy and materials
- Systems efficiency

We conclude the chapter and the energy section of the book by tying atmospheric CO₂ stabilization with reduction in the rate of increase of energy-associated CO₂ emissions, through “stabilization wedges”.

10.1 Efficiency and heat

Extraction of energy from the various available sources is one side of the human energy equation; utilizing the extracted energy is the other. We need energy for myriad human activities, but the amount of energy required depends strongly on the efficiency with which it is used. The efficiency of energy utilization can vary enormously, and offers great opportunity for energy savings. It depends on technology, on the integration of energy systems, and on our patterns of living.

When energy is converted from one form to another there is always some loss of useful energy as waste heat. If you push a box across the floor, some of your muscle energy is converted to the mechanical energy needed to move the box, but some of it becomes heat because of the friction with the floor. This friction can be reduced by putting the box on wheels, but it cannot be eliminated entirely. The wheels increase the efficiency of the conversion from muscle energy to mechanical energy, but the efficiency can never be 100%. A major challenge in energy conservation is minimizing waste heat.

10S.1 Heat, Temperature and Entropy

The highest efficiency attainable in energy conversion processes is set by the second law of thermodynamics. The first law is simply a statement of energy conservation: energy is neither destroyed nor created, provided we remember that heat is a form of energy. [Strictly speaking it is the sum of matter and energy that is conserved. Energy can be converted to matter and vice versa, according to Einstein’s famous formula: $E = mc^2$, where E is energy, m is mass and c is the speed of light. Only in nuclear reactions, however, does this conversion become significant.] The second law of thermodynamics states that the *entropy* always increases in a spontaneous process, i.e. one in which there is no input of external energy.

Entropy is a measure of disorder, and the second law is a statement of the fact that disorder naturally increases. If we allow a handful of white marbles and a handful of blue marbles to roll around in a box, the two colors will mix; they become disordered. The entropy was lower before the mixing, and higher afterward. Moreover, the blue and white marbles will not unmix by themselves, no matter how long they roll around. It takes external energy – e.g. in the form of fingers picking out all the blue marbles – to unmix them, and thereby lower the entropy. This is a simple illustration of the second law.

There is a close connection between entropy and heat. Heat arises from the motion of atoms and molecules. When water feels hot on our hand, we sense the rapid motion of the water molecules, imparting their *kinetic* energy to our skin. The temperature of the water is the average kinetic energy of the molecules, while the heat itself is the total kinetic energy of all the molecules in the quantity of water we are dealing with.

One measure of entropy [S] is the heat energy [Q] divided by the temperature [T]:

$$S = Q/T \quad [10-1]$$

In this expression, T is the absolute temperature. Zero on the absolute temperature scale corresponds to zero kinetic energy, i.e. no motion of the molecules. The absolute temperature is measured in degrees Kelvin. Degrees Centigrade are the same as degrees Kelvin, but offset by 273, i.e. 0 °C = 273 K. [The degree superscript is usually omitted from the absolute temperature.]

Equation [10-1] expresses the fact that a given quantity of heat energy produces greater disorder for a cold sample [small value of T] than for a hot sample [high value of T] of matter. The second law says that Q/T increases in a spontaneous process. A familiar example is the cooling of a cup of hot tea. We know that a quantity of heat is transferred from the hot liquid to the cool surroundings. If this quantity is Q_{transf} , then clearly

$$Q_{\text{transf}} / T_{\text{hot}} < Q_{\text{transf}} / T_{\text{cool}}$$

Thus entropy has increased in the cooling process.

Equation [10-1] allows us to find the maximum efficiency of a power plant, or any other heat engine. Consider the diagram of a steam-to-electricity plant in **Figure 10.1**. Steam is generated by burning fuel in a boiler, and then turns a turbine that generates electricity. The spent steam is then condensed to liquid water and returned to the boiler. Thus the energy obtained from combustion is converted to work in the turbine. The work energy must be the difference between the quantity of heat used to boil the water, Q_h , and the quantity of heat transferred to the cooling water in the condenser, Q_c :

$$W = Q_h - Q_c \quad [10-2]$$

Equation 10-2 is just an expression of energy conservation, the first law of thermodynamics. Dividing both sides by Q_h , we obtain

$$W/Q_h = 1 - Q_c/Q_h \quad [10-3]$$

W/Q_h is the efficiency by which heat is converted to work.

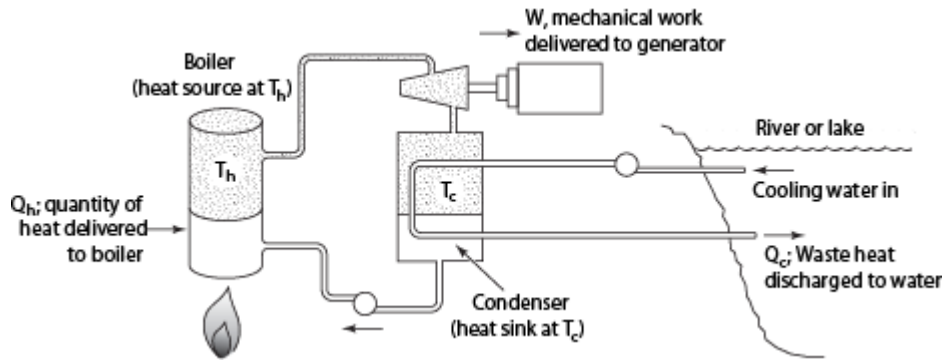


Figure 10.1 Maximum work and waste heat from a steam engine power plant.

But the second law tells us that entropy must increase, and therefore

$$Q_c/T_c > Q_h/T_h \quad [10-4]$$

where T_h is the temperature of the heat source, and T_c is the temperature of the condenser. Multiplying both sides by T_c/Q_h gives

$$Q_c/Q_h > T_c/T_h \quad [10 - 5]$$

If we now substitute [10 - 5] in [10 - 3], we see that

$$W/Q_h < 1 - T_c/T_h \quad [10 - 6]$$

Equation [10 - 6] has far-reaching implications. It means that no matter how the power plant is designed, its efficiency is constrained by T_c/T_h , the ratio of the condenser temperature to the temperature of the heat source, in this case the boiler. The lower this ratio, the closer the efficiency approaches unity. Since the condenser temperature is constrained by the available cooling water, i.e. the temperature of the environment, the ratio mainly depends on how hot the boiler can be heated.

The same equation holds for all heat engines, whether a steam plant for electricity or an internal combustion engine. It stresses the critical importance of the temperature at which the heat energy is delivered. Although energy is always conserved, the efficiency with which heat can be converted to work is fundamentally constrained by its temperature. The maximum conversion efficiency goes up with the temperature of the heat source. High-temperature heat is high-quality energy, because its entropy [per unit of energy] is low.

10.2 Heat Engine Efficiencies

An industrialized society relies on converting heat to work. Transport, manufacturing, mining and construction systems all utilize the energy of fossil fuels in internal combustion engines, while electricity is produced in power plants, where heat [from fossil fuels or from nuclear reactors] produces steam to drive turbines [Figure 10.1]. The electricity lights, and

sometimes heats, buildings and powers innumerable appliances and motors. This vast array of heat-driven processes offers many opportunities for improved energy efficiency.

The design of power plants has improved substantially, but the heat-to-electricity efficiency is still only about 40% at best. In a modern coal-fired plant the boiler temperature reaches about 550 °C [823 K]. The condenser temperature depends somewhat on the available cooling water, but cannot be far from 300 K [27 °C]. The maximum theoretical efficiency, according to equation [10 – 6], is $1 - 300 \text{ K}/823 \text{ K} = 0.64$, or 64%. However, additional heat losses from the boiler, the turbine and the electrical generator all conspire to reduce the actual efficiency well below the theoretical efficiency. Thus about 60% of the heating value of the coal is lost to waste heat. For a nuclear power plant the theoretical efficiency is lower, because the temperature of the boiler is restricted for safety reasons; the overall efficiency of a nuclear power plant is about 30%. [However, the efficiency will be higher for high-temperature gas-cooled reactors that are currently in design.]

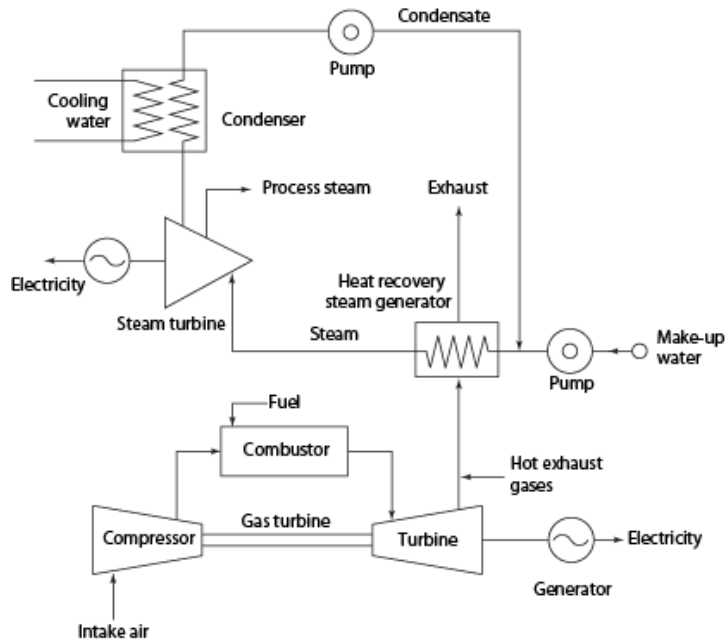


Figure 10.2 Schematic of gas/steam turbine combined-cycle power plant. *Source:* R.H. Williams and E.D. Larson (1993). *Advanced gasification-based biomass power generation. In Renewable Energy, Sources for Fuels and Electricity.* T.B. Johansson et al., eds. (Washington, DC: Island Press).

Higher efficiencies could be achieved by boosting the temperature of the heat source. A boiler cannot be heated much higher than 550 °C, but a gas turbine can be run at temperatures up to 1260 °C. Gas turbines were developed as jet engines for aircraft, but have recently been adapted to run electricity-generating turbines. Despite the high operating temperature, the efficiency of a gas turbine is modest, because the temperature at which the heat is transferred to the environment, i.e. the exhaust gas, is still quite high, typically 500 °C. These values for T_h and T_c give a maximum efficiency of 50%; the actual efficiency is only about 33%, about the same as a nuclear plant. But the hot gases can themselves be used to run a steam turbine (**Figure 10.2**). This second stage operates at about the same conversion efficiency as a regular steam plant. By combining these two stages, one can extract close to 80% of the energy in the fuel. Many coal-fired power plants have been fitted with a natural gas turbine “topping cycle”, in order to boost efficiency.

The same thermodynamic considerations apply when energy is “consumed.” The energy does not disappear; it is converted to “waste” heat, raising the entropy of the universe. En route to

this destination, the energy can be utilized more or less efficiently. Heating a house provides an illustrative example. A gas furnace is more efficient for this purpose than is electrical heating, because most of the energy in the fossil fuel can be transferred directly to the house (assuming a highly efficient furnace), whereas with electrical heating, about two-thirds of the energy has been thrown away at the power plant to produce the electricity that is then converted back to house heat.

Electricity can be converted to heat in a much more efficient way, however, by using it to run a heat pump. This device (see **Figure 10.3**) is a small version of a power plant run in reverse. Mechanical work is used to condense a working fluid at the temperature of the heat sink. The fluid is then allowed to evaporate, thereby absorbing heat from the heat source. In this way heat can be pumped from lower to higher temperatures by the expenditure of work. This is how refrigerators and air-conditioners operate. A house can be heated in cold weather by reversing the direction of the air-conditioner.

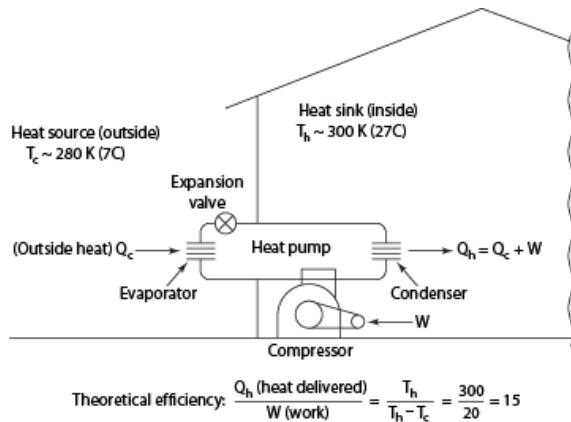


Figure 10.3 The heat pump: an efficient means of residential space heating and cooling.

The conversion of work to heat is governed by the same entropy considerations as the reverse process. The maximum degree of conversion is simply given by the inverse of equation [10-6]

$$Q / W < T_h / (T_h - T_c) \quad [10-7]$$

but T_h and T_c are reversed, since the heat source (T_c) is now colder than the heat sink (T_h). If the inside temperature is about 300 K, and the outside temperature is 20 °C colder, then the amount of pumped heat is potentially $300/20 = 15$ times greater than the amount of work. One kJ of electricity could transfer as much as 15 kJ of heat. Does this mean that we have violated the first law of thermodynamics? Not at all. It just means that we need to pay attention to the quality as well as the quantity of the energy. The higher the temperature, the higher the quality; high-grade heat can be converted to a larger quantity of low-grade heat, increasing the entropy in the process. Electricity is very high-quality energy, and this quality is largely wasted by converting it directly to heat at low temperature; the heat pump allows this quality to be more fully utilized. The high theoretical efficiency cannot be achieved in practice because of resistances to heat transfer, but a heat/work ratio of 2 is easily attainable, thereby recapturing a substantial fraction of the fossil fuel calories that are lost at the power plant.

In practice heat pumps work best when the weather is moderate, and may require back-up heating on cold winter days. As noted above, the use of geothermal reservoirs as the heat source can substantially improve heat pump performance.

10.3 Fuel Cells

Combustion is not the only way to extract useful energy from chemical fuels. Electricity can be obtained directly with the aid of a fuel cell. Instead of burning hydrogen to produce heat, the same reaction



can be carried out at two electrodes, with an electric current flowing between them, as illustrated in **Figure 10.4**. The electrode reactions are

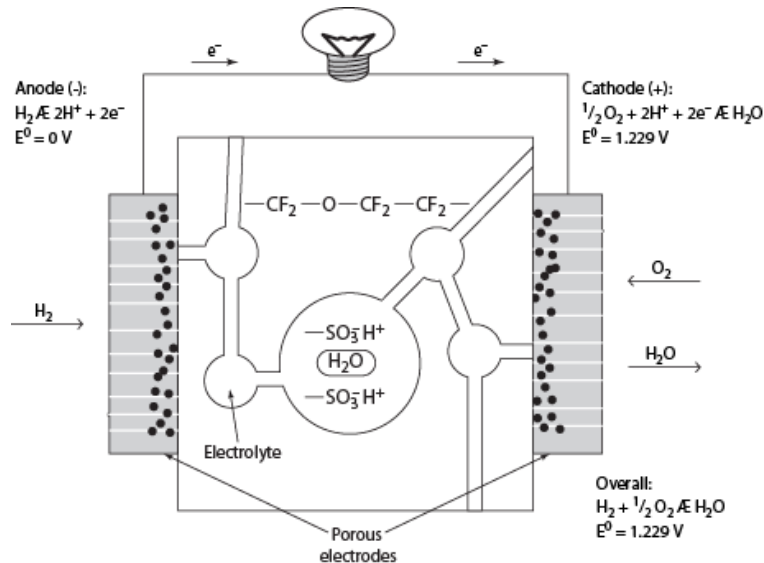
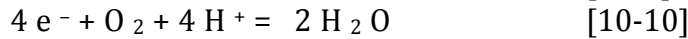


Figure 10.4 Schematic of a proton exchange membrane (PEM) fuel cell using hydrogen as a fuel.

Hydrogen is oxidized at the *anode*, where electrons are removed and passed through the external circuit to the *cathode*, where oxygen is reduced. The two electrode reactions together add up to reaction [10-8], but the energy is released mostly as electricity instead of as heat. Electricity production via the fuel cell is just the reverse of the familiar electrolysis process, in which hydrogen and oxygen are produced at a pair of electrodes immersed in water when an electric current is passed between them.

Because the reaction energy is transformed directly into electricity, the efficiency is not limited by the heat engine formula. The theoretical efficiency is given by the ratio of the free energy change to the enthalpy change, $\Delta G/\Delta H$, which is about 80%, for reaction [10-8].

However, the theoretical efficiency can only be reached if no current is actually drawn from the fuel cell. When a current does flow through the external circuit, several resistances build up that reduce the efficiency, and increase the fraction of the energy that is converted to heat (**Figure 10.5**). These include 1) the electrical resistance of moving positive ions from the region of the anode to the region of the cathode to counterbalance the electron flow (electrolyte resistance); 2) the resistance to the movement of reactant molecules to the electrodes and product molecules away from the electrodes (mass transfer resistance); and 3) the resistance to the chemical reactions themselves due to slow reaction kinetics (activation barriers). These resistances can be minimized, but not eliminated, by optimizing the fuel cell design. Thus, the reaction kinetics can be speeded up with catalysts (platinum metal is most commonly used) mass transfer can be enhanced by increasing the surface area of the electrodes, for example, by making them porous, and electrical resistance can be minimized by connecting the electrode compartments with an electrolyte having a high conductance. All three resistances are reduced at

elevated temperature, which increases rates for chemical reactions and for molecular and ion transport. Consequently, successful fuel-cell designs have tended to have elevated operating temperatures.

10.3a PEM fuel cell

However, the polymer electrolyte membrane (PEM) fuel cell, operating in a relatively low temperature range (80-100°C), has emerged as the most suitable design for transport. Characteristics of the five most prominent fuel cell technologies are listed in **Table 10.1**.

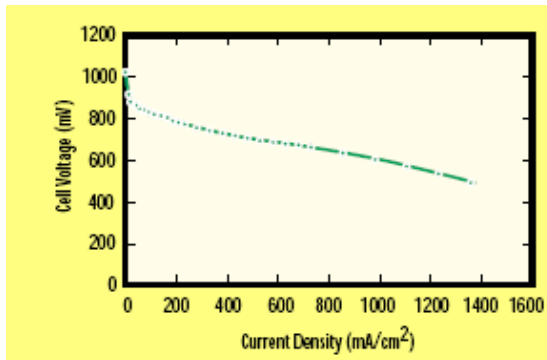


Figure 10.5 Graph of cell voltage versus current density for a hydrogen/air polymer electrolyte membrane fuel cell. *Source:* S. Thomas and M. Zalbowitz (1999) *Fuel Cells: Green Power*. Los Alamos National Laboratory: Los Alamos, NM.

Platinum is the catalyst of choice for fuel cells due to its resistance to corrosion, excellent high temperature properties, and stable electronic characteristics. All of these properties make platinum well suited for other industrial uses, in addition to the manufacture of jewelry. Because of these demands on such a limited resource, the cost of platinum exceeds that of gold. Also, platinum reserves are few and far between. The majority of platinum is mined in South Africa, while Canada, Russia, and the U.S. produce smaller quantities of the metal. Less expensive alternative catalysts are currently being studied to make fuel cells a less expensive energy option in the future. For example, recently a carbon-supported iron-based catalyst was developed that has similar performance to platinum in a PEM fuel cell.

*M. Lefevre, E. Prioretto, F. Jaouen, J.P. Dodelet (2009). Iron-Based Catalysts with Improved Oxygen Reduction Activity in Polymer Electrolyte Fuel Cells. *Science* 324: 71-74.

PEM fuel cells operate on hydrogen fuel at relatively low temperatures because proton conduction from anode to cathode is facilitated by a thin polymer electrolyte membrane. The polymer is a fluorocarbon with covalently attached sulfonate ($-\text{SO}_3^-$) groups. These sulfonate groups form a network of water-filled channels, through which protons pass easily (while anions are excluded by the negatively charged sulfonates). Because of the high proton conductivity, the PEM fuel cell starts up quickly, has a high power density, and the output can vary quickly to meet shifts in power demand. These characteristics make it suitable for automotive transport. The efficiency of PEM fuel cell engines can approach 60%, compared with 25% for an internal combustion engine (see p. ?). And, of course, there are no emissions (except water) from a hydrogen fuel cell. Thus, PEM fuel cell technology is attractive for zero-emission vehicles, and is being actively promoted by the California Fuel Cell Partnership, a state-organized coalition of automobile and oil companies, PEM fuel cell manufacturers and state and federal agencies. Currently 250 fuel cell vehicles are on the road in California as test vehicles with 25 hydrogen fueling stations around the state. Full commercialization by 2017 is forecast,

However, there are difficulties with PEM fuel cell vehicles. The lack of a hydrogen distribution system and the difficulty of on-board hydrogen storage [see p. ?] are obvious issues.

A less obvious one is that, because of the low temperatures, highly active platinum catalysts must be used. These are sensitive to poisoning by a variety of chemicals, and particularly by carbon monoxide, which binds tightly to the Pt. This would not be a problem for hydrogen generated by electrolyzing water, but this method of preparation is expensive (because of the electricity cost). For the near term, hydrogen will continue to be produced by steam reforming fossil fuels (p. ?), particularly methane. CO is an inevitable byproduct of this process, and must be extracted to very low levels if the hydrogen is to be used in PEM fuel cells. This separation step adds to the fuel cost, and the possibility of catalyst poisoning puts vehicle owners at risk of having to replace the fuel cells prematurely. Current development efforts are aimed at raising the PEM operating temperature somewhat (a challenging task, since the polymer electrolyte dehydrates at high temperatures, losing its proton conductivity) in order to make the catalyst less sensitive to poisoning.

Table 10.1 Comparison of Five Fuel-Cell Technologies

Fuel-cell type	Electrolyte	Operating temperature (°C)	Electrochemical reactions	Applications	Advantages	Disadvantages
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100	Anode: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ Cathode: $\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$ Cell: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	<ul style="list-style-type: none"> • Military • Space 	<ul style="list-style-type: none"> • Cathode reaction faster in alkaline electrolyte-so high performance 	<ul style="list-style-type: none"> • Expensive removal of CO₂ from fuel and air streams required
Polymer electrolyte membrane (PEM)	Solid organic polymer poly-perfluorosulfonic acid	60-100	Anode: $H_2 \rightarrow 2H^+ + 2e^-$ Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ Cell: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	<ul style="list-style-type: none"> • Transportation • Electric utility • Portable power 	<ul style="list-style-type: none"> • Solid electrolyte reduces corrosion & management problems • Low temperature • Quick start-up 	<ul style="list-style-type: none"> • Low temperature requires expensive catalysts • High sensitivity to fuel impurities
Phosphoric acid (PAFC)	Liquid phosphoric acid soaked in a matrix	175-200	Anode: $H_2 \rightarrow 2H^+ + 2e^-$ Cathode: $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$ Cell: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	<ul style="list-style-type: none"> • Transportation • Electric utility 	<ul style="list-style-type: none"> • Up to 85% efficient in co-generation of electricity and heat • Impure H₂ as fuel 	<ul style="list-style-type: none"> • Pt catalyst • Low current and power • Large size/weight
Molten carbonate (MSFC)	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600-1000	Anode: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ Cathode: $\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$ Cell: $H_2 + \frac{1}{2} O_2 + CO_2 \rightarrow H_2O + CO_2$	<ul style="list-style-type: none"> • Electric utility 	<ul style="list-style-type: none"> • High temperature advantages* 	<ul style="list-style-type: none"> • High temperature enhances corrosion and breakdown of cell components
Solid oxide (SOFC)	Solid zirconium oxide to which a small amount of yttrium is added	600-1000	Anode: $H_2 + O^{2-} \rightarrow H_2O + 2e^-$ Cathode: $\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$ Cell: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	<ul style="list-style-type: none"> • Electric utility 	<ul style="list-style-type: none"> • High temperature advantages* • Solid electrolyte advantages (see PEM) 	<ul style="list-style-type: none"> • High temperature enhances breakdown of cell components

*High temperature advantages include higher efficiency and the flexibility to use more types of fuels and inexpensive catalysts as the reactions involving breaking of carbon-to-carbon bonds in larger hydrocarbon fuels occur much faster as the temperature is increased.

Source: S. Thomas and M. Zalbowitz (1999) *Fuel Cells: Green Power*. Los Alamos National Laboratory: Los Alamos, NM.

10.3b Other fuel cells

The alkaline fuel cell (AFC) is another relatively low-temperature alternative to the PEM fuel cell, and was initially used in the U.S. space program to produce electricity and water in spacecraft. Instead of a polymer electrolyte, a potassium hydroxide solution provides high conductivity via the hydroxide ion. The reduction of O_2 at the cathode is faster in alkali, boosting performance. However, CO_2 must be removed from the air supply, because CO_2 reacts with hydroxide, forming carbonate. This separation step diminishes efficiency and adds to the cost. In addition, the materials in the AFCs tend to break down after shorter time periods; they need to be made more robust before they become competitive with PEM fuel cells.

Phosphoric acid fuel cells (PAFCs) use phosphoric acid for proton conduction. They operate at higher temperatures (175-200°C) and the catalyst can withstand relatively impure hydrogen streams. They are large and heavy, and are used as stationary sources for electricity generation. Fuel is provided by reforming natural gas (or even gas from landfills – see p. ?) on site. Over 200 PAFCs, each generating 200 kW, are in operation world-wide, powering hospitals, nursing homes, hotels, office buildings, schools, airport terminals, and even a municipal waste dump. Smaller PAFCs have even been used to power larger vehicles, such as municipal buses. PAFCs generate electricity at more than 40% efficiency; also the steam produced in the fuel cell reaction can be used for cogeneration (p. ?) providing up to 85% efficiency.

Fuel cells operating at still higher temperatures, 600 – 1000°C – the molten carbonate and solid oxide cells – are promising for electric utilities because of the conversion efficiencies available from the high-temperature heat, as well as the primary electrode reactions. The heat can be used to run the on-site reformer for gas-to-hydrogen conversion, and the hot exhaust gas can run a gas turbine generator, for a second stage of electricity production. As the names imply, molten carbonates or solid oxide ceramics are the fuel cell elements separating the anode from the cathode, and providing efficient ion conduction at the high operating temperatures.

All of these fuel cells operate on hydrogen, because electrode reactions of carbon fuels have been too slow to provide acceptable currents. However, researchers have recently reported direct oxidation of hydrocarbon fuels in a modified version of the solid oxide fuel cell (**Figure 10.6**). It is unclear whether this fuel cell will have improved overall performance relative to the conventional solid oxide cell with reformer.

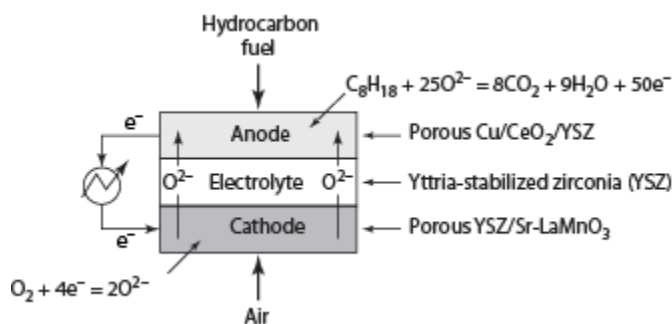
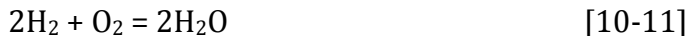


Figure 10.6 Direct oxidation of hydrocarbons in a fuel cell. *Source:* Z. Zhan and S.A. Barnett (2005). An Octane-Fueled Solid Oxide Fuel Cell. *Science* 308:844-847.

10S.2 Entropy and Chemical Energy

Chemical reactions are associated with changes of entropy, as well as energy, and the entropy limits the amount of work that can be extracted, just as it does in the case of heat engines. The reaction of H_2 with O_2 :



releases 482 kJ of energy, as heat, per mole of O_2 (p. ?). This reaction also results in a decrease in entropy, because there are only two product molecules, but three reactant molecules. There are fewer ways to arrange two molecules [fewer *degrees of freedom*] than three molecules. Also if the reaction is run at a temperature below the boiling point of water, the product is a liquid while the reactants are gases. Liquids take up less space [for a given number of molecules] than do gases, and therefore have lower entropy.

The decrease in entropy limits the amount of energy that can in principle be extracted from the reaction, consistent with the second law of thermodynamics. The amount of energy available for work is the *free energy* change of the reaction, ΔG . The heat release is the *enthalpy* change of the reaction, ΔH . The free energy is related to the enthalpy by

$$\Delta G = \Delta H - T\Delta S \quad [10-12]$$

ΔS , the entropy change of the reaction, is multiplied by the absolute temperature in order to express the energy deficit that it produces. [Recall that $S = Q/T$, so that $T\Delta S = Q$, the heat value of the entropy.] Since ΔG is the maximum chemical energy that can be converted to work, the maximum efficiency for energy conversion is

$$\Delta G/\Delta H = 1 - [T\Delta S]/\Delta H \quad [10-13]$$

$T\Delta S$ increases with increasing temperature, and therefore the efficiency goes down as the temperature goes up, in contrast to the efficiency of a heat engine. However, ΔS can also change with temperature, especially when there is a phase change, as when water vaporizes. In addition ΔH is not entirely independent of temperature, so the relationship of the efficiency to the temperature depends on the particulars of the reaction.

An additional point of interest is that for some reactions, the entropy increases. In that case, the theoretical efficiency exceeds 100%.

The convention for writing energy changes is to subtract the energy of the reactants from the energy of the products. Thus if heat is released [an *exothermic* reaction], the reactants have higher energy than the products, and ΔH is negative. Likewise ΔG is negative, if the reaction proceeds spontaneously as written. And ΔS is negative if the entropy of the products is lower than the entropy of the reactants. For an exothermic reaction, a negative ΔS makes ΔG less negative [smaller] than ΔH .

For the H_2/O_2 reaction above, $\Delta H = -476$ kJ at 1000 K, while $T\Delta S = -84$ kJ, giving $\Delta G = -392$ kJ, for a theoretical efficiency of 82%. At 300 K, the entropy change is greater, because of the condensation of liquid water, and $T\Delta S = -116$ kJ, but ΔH also increases, to -590 kJ/mol. ΔG is now -474 kJ, and the theoretical efficiency remains at 80%.

10.4 Space Heating, Cogeneration

Much of our energy supply goes into direct heating of houses, offices and factories. This heat is eventually dissipated to the environment, but the longer it is held in place, the less fuel is required. There are many opportunities for energy savings from improved insulation and windows, as well as improved delivery of the heat to needed areas. “Smart” buildings are being designed to tailor heat, light and air-conditioning to the needs of the occupants through sensors and control systems.

In addition, energy savings are available through *cogeneration*, combining power and heat generation. Industrially generated heat, instead of being vented, can be used to run turbines for electricity production. Examples include exhaust heat from steel plant blast furnaces, heat from drying wood and agricultural products, heat produced at gas compressors – the list is long. Conversely, the waste heat from power plants can be put to use by piping it into the heating systems of buildings.

In district heating, heat is generated in a central location, typically from a cogeneration power plant burning fossil fuels, and distributed to nearby residential and commercial buildings for space and water heating. The heat can also be generated from biomass burning, geothermal heating, surplus heat from industry, municipal waste incinerators, and central solar heating. This centralized system allows for higher efficiencies and better pollution control than localized boilers. Although smaller systems have been implemented in the U.S., this is a technology that has been utilized in many European cities due to their compact nature. A 2003 assessment of energy use for 32 European countries by Euroheat & Power determined that Europe as a whole wastes more heat than it uses. Since three quarters of Europeans are urban dwellers, the report recommended implementation of energy efficient heating districts.

In the U.S., steam from Thomas Edison’s early power plants was once used to heat nearby buildings, but the practice was discontinued, as the plants became larger and moved away from populated areas. Reversing this process is not easy, but new and efficient small generators are becoming available to produce both heat and electricity. Since electricity travels further without serious loss than does heat, it would make sense to equip factories and buildings with these generators for their heating and electricity needs, and send any excess electricity into the grid.

10.5 Electricity Storage: The Hydrogen Economy

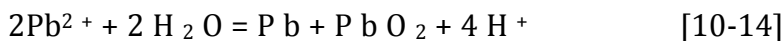
Electricity storage and conversion is a critical issue for many power systems at both large and small scales. In many cases either the source of electricity or the need for it is intermittent, producing a mismatch between supply and demand. Efficient electricity storage is then needed to optimize the system. The main drawback to the production of direct solar or wind electricity is the intermittent nature of the energy source. Electricity is produced only when the sun shines or the wind blows. On the other side of the ledger, power companies must cope with large fluctuations in the daily demand for electricity. Extra generating capacity is required to meet peak demands during daylight hours, particularly during the summer when air-conditioners draw a heavy load; the extra capacity is left idle much of the time. To some extent these fluctuations can be coordinated, since the solar flux also peaks during daylight hours and during the summer, but there is still an important need for efficient energy storage.

A few electricity companies have developed water pump storage, in which excess electricity is used to pump water uphill to reservoirs and the water running back downhill can then be used to run turbines to meet peak demands. Because of the continually fluctuating water levels, these reservoirs create ecological problems, and are especially contentious if they displace multiple-use ponds. Other energy storage schemes under consideration include storage of compressed air in caverns, mechanical energy storage in flywheels, and direct electrical storage in large superconducting magnets.

10.5a Batteries

On the small-scale end of electricity utilization, electricity storage is also a critical issue for the development of the electric car. The most highly developed and reliable storage device is

lead-acid storage battery. In this battery (**Figure 10.6**), electricity is stored in the chemical conversion of Pb^{2+} ions to metallic Pb at one electrode, and to PbO_2 at the other. The overall reaction,



is energetically uphill. When current is drawn, both electrode reactions are reversed, and the reaction is allowed to run downhill. The lead-acid battery performs these energy conversion steps very efficiently, and can be charged and discharged many times before it is worn out through competing chemical processes. It is used in all automotive vehicles as a portable store of electricity for auxiliary needs.

In electric vehicles, however, the need is not auxiliary; electricity is the source of power for locomotion itself. The lead-acid battery has two serious drawbacks as the main power source: 1) it is heavy and adds significantly to the weight of the vehicle, thereby lowering the efficiency and the driving range; 2) it takes several hours to charge, making “refueling” an inconvenient operation. Consequently, much effort has been devoted to developing alternative batteries that give more power with less weight and easier charging.

Nickel-cadmium batteries, already in use for many appliances, offer greater power, energy density, and longer life than lead-acid batteries but are substantially more expensive. In Ni-Cd batteries, metallic cadmium is oxidized to $\text{Cd}(\text{OH})_2$, while $\text{NiO}(\text{OH})$ is reduced to $\text{Ni}(\text{OH})_2$, and these reactions are run in reverse on recharge. The toxicity of cadmium (p. ?) is a concern with respect to disposal or recycling of Ni-Cd batteries.

Most of the hybrid electric vehicles in production today use nickel metal hydride batteries for electrical storage. They involve the same $\text{NiO}(\text{OH})$ reduction as in a Ni-Cd, but at the other electrode a metal hydride is converted to metal and water. Because of this replacement of a metal hydride for cadmium, nickel metal hydride batteries are lighter and cheaper than Ni-Cd batteries.

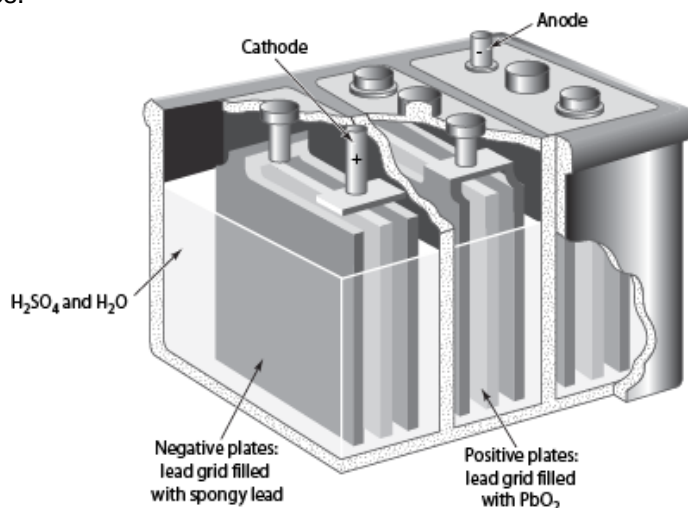


Figure 10.7 Cross-section of lead-acid battery. *Source:* P. Buell and J. Gerard (1994). *Chemistry in Environmental Perspective* (Upper Saddle River, New Jersey: Prentice Hall).

Still lighter and cheaper are lithium ion batteries, first used in laptop and cell phone batteries. They are being developed for electric vehicles because of their high energy to weight ratio and slow loss of charge when not in use. Lithium ion batteries work by moving lithium ions between the anode and cathode, depending on whether the battery is being charged or

discharged (**Figure 10.8**). Many different Li-bearing cathode and anode materials are being tested for reversibility and durability; the figure illustrates a graphite anode, where electrons are added upon charging, and a LiCoO_2 cathode, where the charging electrons are extracted.

Capacity and recharge rates remain issues for electric vehicles. Lead-acid or nickel metal hydride battery packs of practical sizes permit driving about 100 miles on a charge, while lithium ion battery packs may provide 200-300 mile ranges. Recharging times depend on available currents and the battery characteristics. They are generally one to a few hours, but new materials and charging stations are under development that may reduce the time to minutes. An option for drivers may be to lease batteries that can be swapped at 'battery stations', where they are recharged for other drivers.

The hydrogen fuel cell offers an attractive alternative to any of the storage batteries. Indeed, it can itself be thought of as a battery, in which the storage medium is hydrogen and oxygen, instead of reduced and oxidized metals. The same drive train can be utilized with a battery or a fuel cell. But the fuel cell is not required to run itself backward with external electricity in order to store its energy. A canister of hydrogen, or alternatively, a tank of methanol with an onboard reformer (see below) is all that is required. Consequently, refueling is as fast as it is for gasoline-powered cars. And since hydrogen or methanol are much lighter than lead or most other metals, more energy can be stored for the same weight, giving a fuel-cell electric car a greater driving range than one with storage batteries.

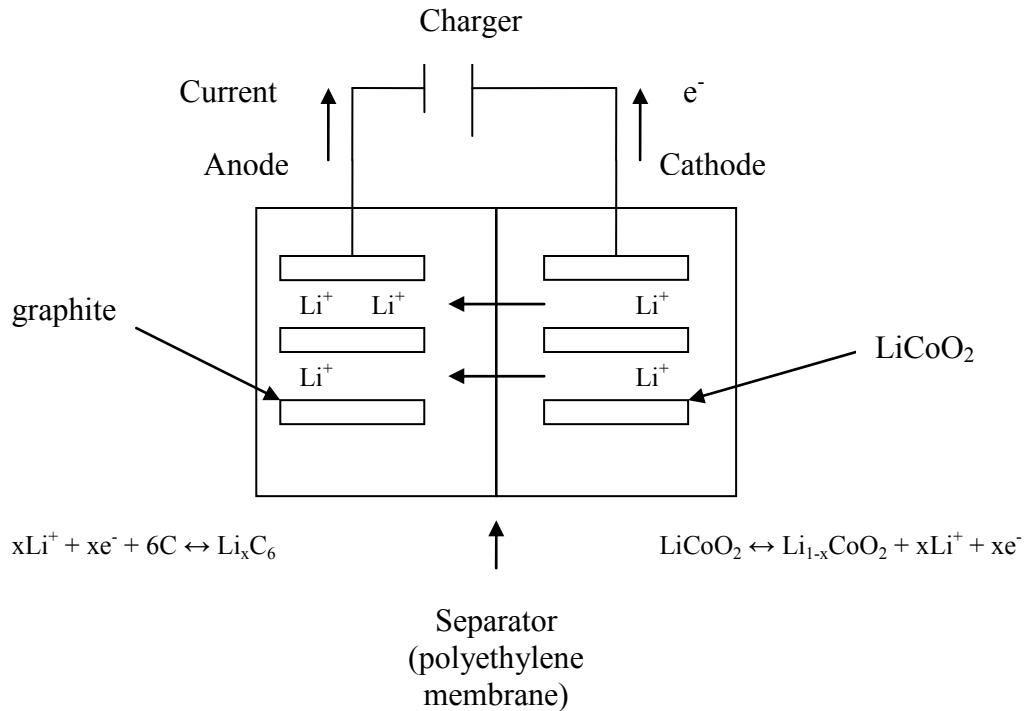


Figure 10.8 Figure of a rechargeable lithium-ion battery while charging.

10.5b Hydrogen Storage

However, hydrogen storage is a major problem for fuel cell cars. The density of H₂ is very low, even when compressed to high pressures. Currently, demonstration hydrogen cars are equipped with high pressure tanks, made of composite materials, capable of holding H₂ at up to 700 Bar (atmospheres). The tanks are expensive and bulky, taking up much of a car's trunk space. They must be filled at compressed H₂ stations, using special transfer devices. Compressing the H₂ exacts an energy and cost penalty. Alternatively, the H₂ can be liquefied cryogenically, but the required temperature is extremely low (20K), and a liquid H₂ storage tank needs specialized thermal insulation, making it impractical for transport.

Another alternative is to store the H₂ in a solid matrix. Many metals form hydrides (examples under study include NaAlH₄, LiNi₅H₆, TiFeH₂), which can regenerate H₂ upon heating, provided the hydride bonds are not too strong. However, the metals add much weight to the storage tank (which becomes roughly three times larger and four times heavier than a gasoline tank storing the same energy), reducing the vehicle efficiency. Also the relatively high regeneration temperatures necessitate a further loss of efficiency. Much research is currently directed at the development of high surface area solid materials that can physically absorb H₂. These include metal-organic framework solids (MOFs), which have voids built into their structure that can accommodate small molecules like H₂. Substantial loading of H₂ has been reported, up to 10 % of the weight of the solid, but so far only at liquid nitrogen temperatures.

Still another alternative is to store the H₂ as an aqueous solution of sodium borohydride, NaBH₄. The energy density of such a solution can exceed that of gasoline, providing efficient storage. A catalyst allows release of H₂ via hydrolysis BH₄⁻ to borate, BO₃²⁻. This is a facile process, but the energy cost of producing borohydride from borate is very high.

A further option for fuel cell vehicles is to generate the hydrogen fuel from methanol, via steam reforming (p. ?). Methanol is more easily reformed than are hydrocarbons, and the reaction can be run at sufficiently low temperature, that it is possible to design cars and trucks with a compact, onboard reforming unit in order to run a fuel cell with methanol. This option would have the considerable near-term advantage that it would eliminate the need to transport and store hydrogen. A number of car manufacturers are touting methanol as the fuel of choice for fuel cell vehicles. However, on-board reformers add complexity and cost to the vehicle, and it is unclear whether they can deal with the catalyst poisoning problem. Also methanol has only half the energy density of gasoline, and the fuel tank would have to be doubled for the same driving range.

While there are many options for H₂ storage, all of them have significant drawbacks for vehicles. Storage and utilization in stationary fuel cell power plants obviates many of these difficulties. A better strategy for vehicles may be to use electric drives and batteries that can be switched out and replaced at fueling stations that are connected to the electric grid. Hydrogen, produced by electrolysis of water, could become the storage medium of choice for electricity storage.

Hydrogen can be transported more efficiently than electricity. The cost of electrical transmission over large distances is high. Hydrogen transport by pipeline could be more efficient and less expensive. The areas with the greatest amount of sunlight, where solar plants would be most efficient, are often far from centers of population. Transmission problems for ocean-based generating plants are even more severe. Instead of electricity, remote plants could generate hydrogen, which could be shipped or piped to urban centers.

10.5c Hydrogen economy

These considerations have led to the concept of the hydrogen economy (**Figure 10.9**) in which hydrogen gas would become the main energy currency. It would be consumed directly for electrical generation and heating, either by combustion or by fuel cells. For transportation, it could also be used directly, via fuel-cell electric vehicles, or it could be used to synthesize liquid fuels by chemistry similar to that applied for coal conversion to methanol and liquid hydrocarbons (p. ?).

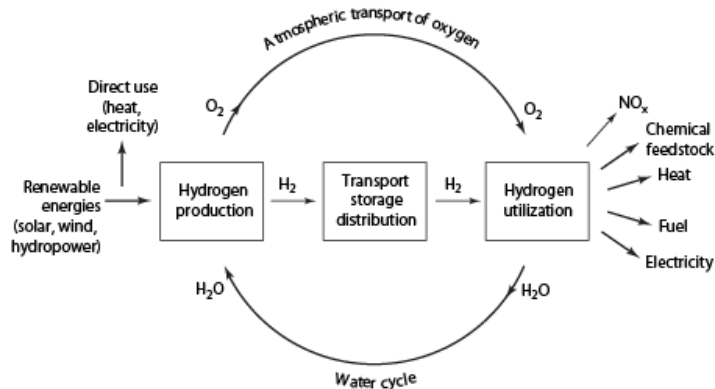


Figure 10.9 A solar-based hydrogen economy. *Source:* J.M. Ogden and J. Nitsch (1993). Solar hydrogen. In *Renewable Energy, Sources for Fuels and Electricity*. T.B. Johansson et al., eds. (Washington, DC: Island Press).

The first country to test the concept is Iceland, where 90% of all housing is heated with geothermal energy and 80% of the electricity is generated using hydropower. Over 70% of Iceland's energy portfolio derives from renewable resources. Furthermore, the country has pledged to wean itself from fossil fuels by converting to a full hydrogen economy by 2030. The first step was to replace the Reykjavik city bus fleet (100 buses) with hydrogen fuel cell buses, serviced by a hydrogen filling station. This was followed by converting other city bus fleets, and introducing hydrogen-based fuel cell cars for private transport. In parallel, the government is supporting the development of hydrogen fuel cells for powering fishing vessels, with the goal of fitting the entire fishing fleet with fuel cell engines. Large international companies have invested in the Icelandic program in order to test the feasibility of fuel cell transport.

Hydrogen is often thought to be a particularly hazardous substance. Ever since the Hindenburg disaster of 1937, when a dirigible filled with hydrogen caught fire and crashed, killing half the people on board, hydrogen has haunted the popular imagination. But hydrogen is not particularly more dangerous than natural gas or gasoline. The percentage of fuel in air that can sustain a fire [*lower flammability limit*] is only a little lower for hydrogen, 4%, than it is for methane, 5%, and is substantially higher than for gasoline, 1%. Since hydrogen is much lighter than air, it disperses rapidly if there is a leak. Methane does also, but gasoline fumes, being heavier than air, tend to accumulate in the vicinity of a leak and are more likely to catch fire. There is actually a history of hydrogen use in home heating, because, before the widespread availability of natural gas, many utilities supplied "town-gas," manufactured from coal or wastes, which was rich in hydrogen. Process industries have long used hydrogen, and hydrogen pipelines several hundred kilometers long have operated safely in Germany, England and the United States.

Despite this experience in industrial settings, the widespread availability of hydrogen will no doubt be some time in coming, and the introduction of transfer facilities at vehicle filling stations will take much longer. One can imagine intermediate stages in the development of the hydrogen economy that would smooth the transition. There might initially be increased utilization of natural gas, as petroleum stocks dwindle and the demand for clean fuels increases. The methane could be burned directly, in homes, power plants, and in new gas-powered vehicles, or it could be converted to methanol, which could serve as an intermediate fuel in fuel-cell vehicles with onboard reformers. Methanol from coal and from biomass could add to the liquid fuel supply. Eventually, the pipelines used for natural gas could be converted to hydrogen transport, as solar hydrogen becomes more feasible and demand for hydrogen increases.

10.6 The Materials Connection

The development of stronger, lighter, more durable materials has an enormous impact on the efficiency of energy utilization. In the case of cars, the substitution of strong but lightweight plastics and composites (mixtures of different structural elements such as glass or carbon fibers with resins, to increase strength) for metal body parts has decreased the weight required for the same carrying capacity. New materials have decreased the weight of many consumer and industrial products, thereby decreasing the energy costs for their transportation, and frequently for their manufacture as well. This trend is augmented by miniaturization of many products, also made possible by advanced materials. More durable materials also mean longer life for the products and a lower production rate. These trends are sometimes called the “dematerialization” of industrial societies, as advanced materials and better information make it possible to make do with less stuff.

In addition, materials able to withstand high temperatures have a direct impact on energy efficiency by improving the performance of heat engines. The most notable example is the steady improvement of jet engines for aircraft, through the development of alloys and ceramics that permit the engines to operate at higher temperatures. These engines have improved aircraft fuel economy substantially. The same technology, in the form of gas turbines, is now being used to improve power plant efficiencies (pp. ?).

10.6a Materials Properties: Paper vs Plastics

The choice of materials can also affect energy efficiency in more mundane ways. Many communities have banned disposable styrofoam containers or plastic bags because of concerns that, being non-biodegradable, plastics leave unsightly trash and fills up overburdened landfills. Whether plastics are actually inferior to other disposable materials, principally paper, is a matter of debate, since biodegradation of paper can be quite slow, especially in sanitary landfills, and since plastics are probably more amenable to recycling, although not much of it is actually being recycled at the moment. But an important consideration is frequently left out in the debates on paper versus plastics, namely the environmental costs of producing the two materials. **Table 10.2** compares energy and water use as well as emissions for manufacturing paper and styrofoam cups. When the values are compared on a *per cup* basis, styrofoam is found to have considerably lower environmental impacts (see problem ?). The main reason for the difference is that a styrofoam cup of a given capacity weighs less than a sixth as much, on average, as a paper cup. Styrofoam is stronger than paper, especially because, being a hydrocarbon material, it is not wet by aqueous liquids. In contrast, paper, which is made of cellulose, a molecule covered with hydroxyl groups (**Figure 9.11**), interacts with water via hydrogen bonds, and is gradually dissolved (see discussion of water and hydrogen bonding, pp. ?). Consequently, the paper cup requires more material to maintain its integrity while in use, and its production has a much larger impact on energy use and the environment.

Table 10.2 Raw Materials, Utility, and Environmental Summary for Hot Drink Containers

Item	Paper cup*	Polyfoam cup†
Per cup		
Raw materials		
Wood & bark	25 to 27 g	0 g
Petroleum fractions	1.5 to 2.9 g	3.4 g
Other chemicals	1.1 to 1.7 g	0.07 to 0.12 g
Finished Weight	10.1 g	1.5 g
Per metric ton of material		
Utilities		

Steam	9,000 to 12,000 kg	5,500 to 7,000 kg
Power	980 kWh	260 to 300 kWh
Cooling water	50 m ³	130 to 140 m ³
Water effluent		
Volume	50 to 190 m ³	1 to 4 m ³
Suspended solids	4 to 16 kg	0.4 to 0.6 kg
BOD	2 to 20 kg	0.2 kg
Organochlorines	2 to 4 kg	0 kg
Metal salts	40 to 80 kg	10 to 20 kg
Air emissions		
Chlorine	0.2 kg	0 kg
Chlorine dioxide	0.2 kg	0 kg
Reduced sulfides	1 to 2 kg	0 kg
Particulates	2 to 3 kg	0.3 to 0.5 kg
Chlorofluorocarbons	0 kg	0 kg [‡]
Pentane	0 kg	35 to 50 kg
Sulfur dioxide	~ 10 kg	3 to 4 kg
<i>Recycle potential</i>		
To primary user	Possible, Washing can destroy.	Easy. Negligible water uptake.
After use	Possible. Hot melt adhesive or coating difficulties.	Good. Resin reuse in other applications.
<i>Ultimate disposal</i>		
Proper incineration	Clean	Clean
Heat recovery	20 MJ/kg	40 MJ/kg
Mass to landfill	10.1 g/cup	1.5 g/cup
Biodegradable	Yes, BOD to leachate, methane to air.	No. Essentially inert.

*Uncoated fully bleached kraft paper cup.

†Molded polystyrene foam bead (seamless) cup.

‡Many producers of foamable beads have never used CFCs.

Source: Updated and adapted by M.B. Hocking, from original article in M.B. Hocking (1991). Paper versus polystyrene: A complex choice. *Science* 251:504-505.

Similar considerations apply to plastic versus paper bags. Compared to paper grocery bags, the manufacture of plastic bags uses 40% less energy, and produces 80% less solid waste, 94% less waterborne waste and produce 70 percent fewer atmospheric emissions. Plastic bags also cost less, 1 cent/bag vs 4 cents/bag for paper. They are so cheap that about a trillion plastic bags are produced annually world-wide. Many are re-used, but most end up in the trash, although there is an active market in recycled plastic bags, which end up in building material.

About 1-3% of plastic bags end up littering the landscape or washed out to sea where they can choke or starve wildlife. They do not biodegrade, but are slowly broken down into smaller pieces. It is this environmental contamination that has created a backlash against plastic

grocery bags. They are now banned or taxed in Bangladesh, Taiwan, South Africa, Australia, and Ireland. Bangladesh banned them because they were blocking drainage systems, contributing to severe flooding. Ireland levied a tax of 15 cents/bag, and saw a 95% reduction in their use. Other countries, and a number of municipalities in the U.S. are considering similar measures. However, if they are aimed at plastic bags alone, the result can be to shift use to paper bags, a net loss for the environment. If fees are applied to all disposal bags, they provide an incentive for shoppers to carry reusable shopping bags instead.

10.6b Recycling

The recyclability of paper versus polystyrene is just one of the many complex issues around recycling. For most people, recycling arises in the context of solid waste disposal. The more the trash is recycled, the less there is to dump in landfills, which are rapidly being filled, and the less pressure there is to build incinerators as an alternative disposal method. In fact, there have been significant gains in recycling in the U.S. over the last 50 years, but this positive trend has been more than offset by the increase in trash generated. In 1960, per capita trash generation was 444 kg, of which 416 kg was landfilled or incinerated, corresponding to a recycling rate of 6.3%. By 2007, the recycling rate had increased to 33%, but per capita trash generation had also increased, to 763 kg, leaving 508 kg as municipal waste. It is unclear whether increased rates of recycling in the future can catch up with the ever-increasing amounts of trash generated, for there are many barriers to recycling—political, economic, and technical.

The technical barriers can be thought of in terms of the second law of thermodynamics. When materials are mixed together in products, and then mixed again when discarded products are mingled in trash, entropy is increased. Un-mixing the materials requires a decrease in the entropy of the materials, and this requires the input of energy. The trash has to be collected and sorted (the degree of cooperation of the populace in presorting the trash is a key variable), and the materials in the sorted products may have to be separated mechanically or chemically. The difficulty depends on the product and on the material. For example, lead-acid batteries are recycled at a high rate. They are easy to collect, and the lead is readily extracted. Aluminum cans are also recycled at a high rate. They are easily separated from trash and contain little except aluminum; they can be said to have relatively low entropy.

Industries generate large quantities of processing wastes containing metals in dilute concentrations. Often these wastes are classified as “hazardous”, and disposed of at high costs under stringent prescribed protocols. In a detailed analysis of industrial hazardous waste streams, researchers compared concentrations of the metals in the waste to those found in the ores from which they are derived (**Figure 10.10**), and concluded that large amounts of metal resources that are currently discarded could be recycled at a profit.

Plastic consumer products are another matter. Although pure plastics can be readily recycled, many different plastics are mixed in trash; often a given product contains more than one plastic. Separating them completely may be prohibitively costly, and often they cannot be processed together. For example, a little polyvinylchloride, the ingredient of plastic films, can ruin the recyclability of polyesters, the ingredient of soft-drink bottles. Another recycling issue is the quality of the recycled product. Paper is recycled in substantial quantities, but the cellulose fibers are degraded in the process and lose strength; they can be recycled no more than four times, before dissolving completely.

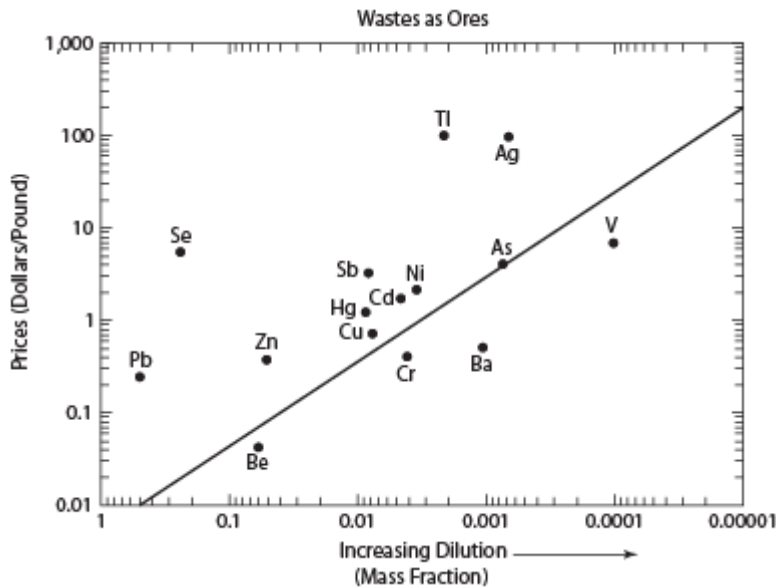


Figure 10.10 T.K. Sherwood empirically identified a relationship between the selling prices of materials and their dilution (or degree of distribution in the initial matrix from which they are separated). The diagonal line denotes this empirically observed linear relationship. The data points indicate the minimum concentrations of metal wastes typically recycled as a function of metal price. Points lying above the line indicate the existence of metals in wastes typically not recycled, even though their concentration exceeds those found in virgin ores. *Source:* D.T. Allen and N. Behamanesh (1994). *Wastes as raw materials*. In *The Greening of Industrial Ecosystems*. B.R. Allenby and D.J. Richards, eds. (Washington, DC: National Academy Press).

Despite these problems, recycling has a significant impact on energy efficiency. Although energy is required to restore materials that have been dispersed, this energy is likely to be substantially less than the energy required to produce the materials in the first place. The bar graph in **Figure 10.11** shows the amount of energy required to produce a metric ton of steel, paper, and aluminum from primary materials, compared with the energy required for production from recycled materials. We see that aluminum production from ore is particularly energy-intensive. Recycled aluminum requires only 5% as much energy to process as primary aluminum ore. Even so, enough aluminum is thrown away in the United States to rebuild its commercial aircraft fleet every three months. The savings from using steel scrap and paper waste are not as high—52% and 70%, respectively. Nevertheless, the potential for energy conservation is substantial when we consider the volume of these materials produced annually. The production of steel, aluminum, and paper consumes more than 20% of the total industrial energy.

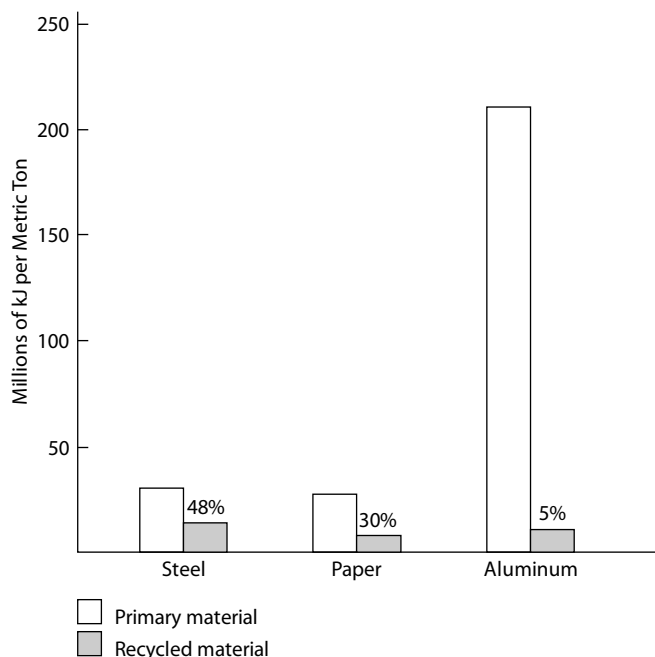
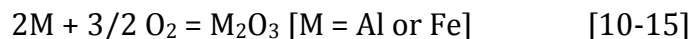


Figure 10.11 Comparison of energy requirements for production of steel, paper, and aluminum from primary and recycled materials.

10S.3 Energy Cost of Extraction: Al vs Fe

Why are the energy savings from recycling so much greater for aluminum than for steel (**Figure 10.11**)?

Many factors go into the energy accounting for recycled versus primary materials, but in this case the outstanding difference is the much greater energy requirement for refining aluminum versus iron ore. Both metals occur in the earth's crust as the oxides, Al_2O_3 and Fe_2O_3 , which must be reduced in order to recover the elemental metal. The energy required for this step is much higher for Al_2O_3 and Fe_2O_3 . This can be seen from a comparison of the *enthalpies of formation*, which are -1670 and -822 kJ/mol. The enthalpy of formation is minus the heat released when the elements combine to form a compound, in this case



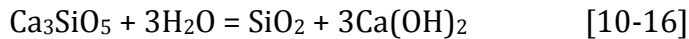
Almost twice as much heat is released by Al than by Fe in forming the oxide. A correspondingly larger amount of energy is required to reduce the oxide to the metal. This prodigious energy requirement is why aluminum refineries are generally located close to a plentiful source of energy, such as a hydroelectric power plant. It is also why the energy savings are so large in recycling aluminum.

Why is Al_2O_3 so much more stable than Fe_2O_3 , relative to the metals? The principal reason is simply that the Al^{3+} ion is much smaller than the Fe^{3+} ion [0.45 vs 0.64 Å], and has a larger electrostatic attraction to the oxide ions. Al is in the second row of the periodic table, whereas Fe is in the third row. Fe has an extra shell of electrons to shield its valence electrons from the nucleus.

10.6c Concrete

Used in myriad construction projects, concrete is produced in larger amounts than any other man-made material – about 7.5 km³ annually, more than one cubic meter for every person on earth. Concrete is the hardened product of mixing cement with water and ‘aggregate’ – bulky material made up of sand gravel and crushed stone. The aggregate can also include slag from blast furnaces and fly ash from power plants, helping to solve a serious disposal problem (p. ?).

Cement is what holds concrete together, but it also contributes about 5% of human carbon emissions. Cement is made by roasting limestone and clay, then grinding the product with gypsum, CaSO₄. Heating limestone, CaCO₃, drives off CO₂, leaving lime, CaO. The fuel for heating and the CO₂ released directly from the limestone are together the main contributors to the carbon emissions from cement production. The CaO produced on heating reacts with the silicates in clay to form a solid with the average composition Ca₃SiO₅. Adding water liberates silica and calcium hydroxide:



The resulting mixture forms a gel that binds the aggregate together. Enough water is added to allow the slurry to flow into the required space, where it dries and hardens. The hydration reaction releases heat, which aids in the bonding and hardening process.

Efforts are underway to reduce the carbon footprint of concrete. One company is trying to capture CO₂ at the start of cement manufacture by reacting it with the Ca²⁺ in seawater to precipitate the CaCO₃ starting material, instead of mining limestone.

The Ca(OH)₂ in the cement can react back with CO₂ in the atmosphere, producing CaCO₃, essentially the reverse of the lime-forming reaction. This process, called carbonation, diminishes the net carbon emission from cement production, but is limited by very slow diffusion of the CO₂ into the interior of the concrete. Experiments are underway to enhance this process by bubbling CO₂ through wet concrete. Carbonation actually enhances the hardness of concrete. However, it also enhances corrosion of steel bars that are inserted into reinforced concrete to increase its tensile strength, because the passivating oxide layer of the steel is disrupted by the reduced alkalinity of CaCO₃ relative to Ca(OH)₂ (p. ?). Chemicals that inhibit corrosion are usually added to reinforced concrete. Adding a small amount of silica fume can decrease the permeability to road salt, which enhances corrosion of steel.

Other chemicals can be added which improve the flow of concrete, or which reduce the amount of water needed to keep the cement particles dispersed. These additives can reduce the amount of cement needed, thereby also lowering the carbon footprint.

10.6d Dematerialization

The development of new materials, better suited to their task, means that less material needs to be produced in the first place. The example of paper versus plastics, above, is an illustration, but the trend is pervasive throughout the world of industrial products. Stronger light-weight materials are evident everywhere. At the same time many items are getting smaller. Computers are the most dramatic example. Currently available laptop computers have much more computing power than a roomful of computing machinery did not many years ago. These trends mean that less material needs to be extracted from the earth, and less of it goes into manufacturing, with concomitant savings in energy.

Countering these trends, however, is the desire of consumers to have more things, many of them bigger than before. Particularly in the United States, new houses have steadily become bigger, which leads to more furnishings and appliances. Cars are more numerous, and are also getting bigger, especially with the popularity of sports utility vehicles.

It appears that these countervailing trends have left overall materials use at a high level. Inventorying materials is difficult because of the complexities of the world economy and the inadequacy of data, but an analysis of the materials flows in four industrial countries (**Figure 10.12**) suggests that the totals have not changed much over the 1975 – 1994 period. However, the totals tend to be dominated by the large quantities of earth materials that are moved about.

For example, the decline in U.S. flows are attributed largely to reductions in soil erosion and to the completion of the federal interstate highway system. Nevertheless, it is encouraging that total materials use does not increase in proportion to economic growth in these countries. When the flows are divided by gross domestic product, the ratio is seen to decline steadily over time (**Figure 10.13**). [The upturn for Germany and the Netherlands in the 1990' results from the impact on Western Europe of German reunification].

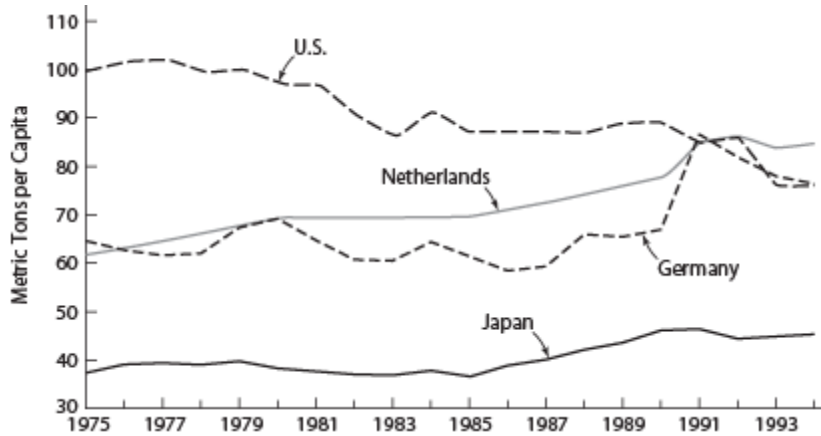


Figure 10.12 Annual flow of material requirement per capita in the U.S., The Netherlands, Germany, and Japan over the period from 1975 to 1994. *Source:* A. Adriaanse et al. (1997). *Resource Flows: The Material Basis of Industrial Economies*. (Washington DC: World Resources Institute).

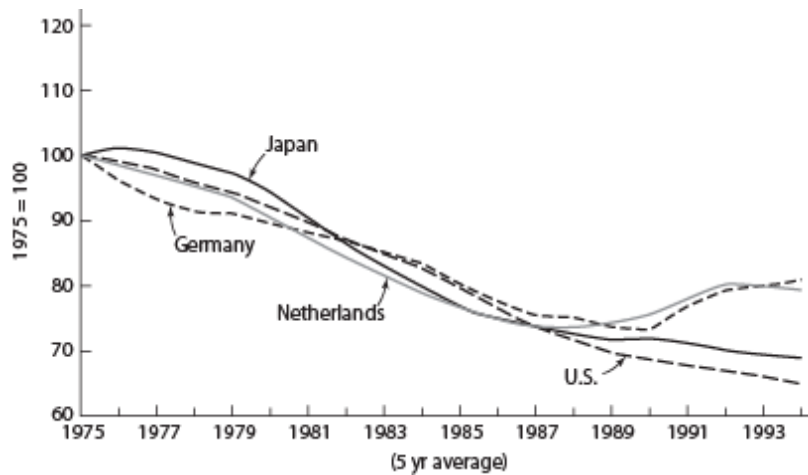
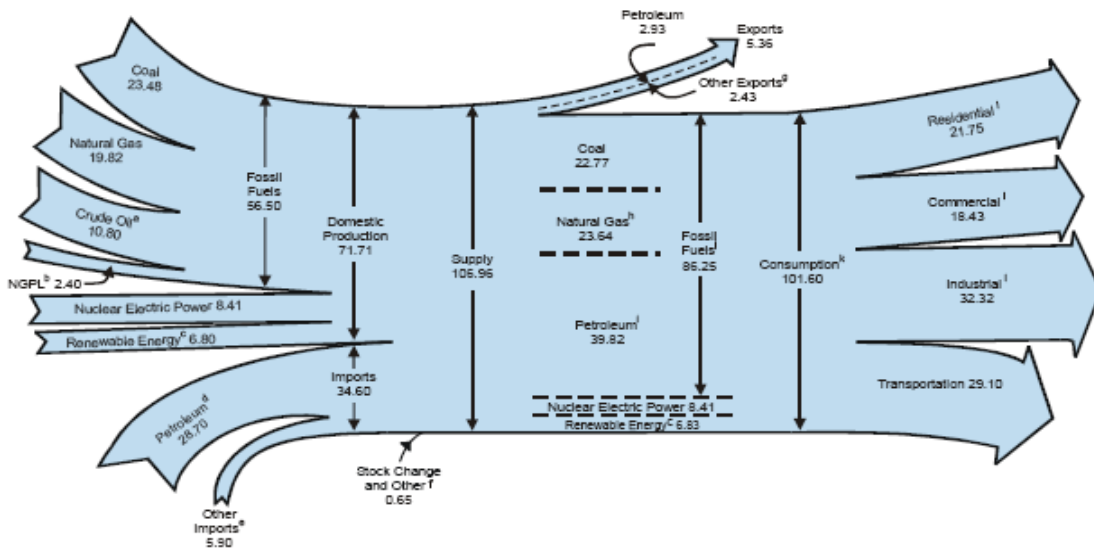


Figure 10.13 Materials intensity as measured by total materials use divided by gross domestic product for the U.S., The Netherlands, Germany, and Japan over the period from 1975 to 1994. *Source:* A. Adriaanse et al. (1997). *Resource Flows: The Material Basis of Industrial Economies*. (Washington DC: World Resources Institute).

10.7 Systems Efficiency

To better understand the possibilities for increased energy efficiency, we need a more comprehensive view of the way energy is utilized in society. **Figure 10.14** is a diagram of how energy actually flowed through the U.S. economy in 2007. On the left side are the inputs from

coal, petroleum, natural gas, nuclear, and renewables, while on the right side, the end uses are broken down into residential, commercial, industrial, and transportation categories. The units are Quadrillion Btu. In 2007 the United States consumed 107.0 Quadrillion Btu's but produced only 71.7 Quadrillion Btu's from its own resources; the balance was made up mainly of petroleum imports, which accounted for 73% of the petroleum used (up from 46% in 1990). Electric utilities used 42.1 Quadrillion Btu's (**Figure 10.15**), over one-third of total consumption, supplying 14.2 Quadrillion Btu's of electricity, which was split nearly equally among industrial, residential and commercial uses.



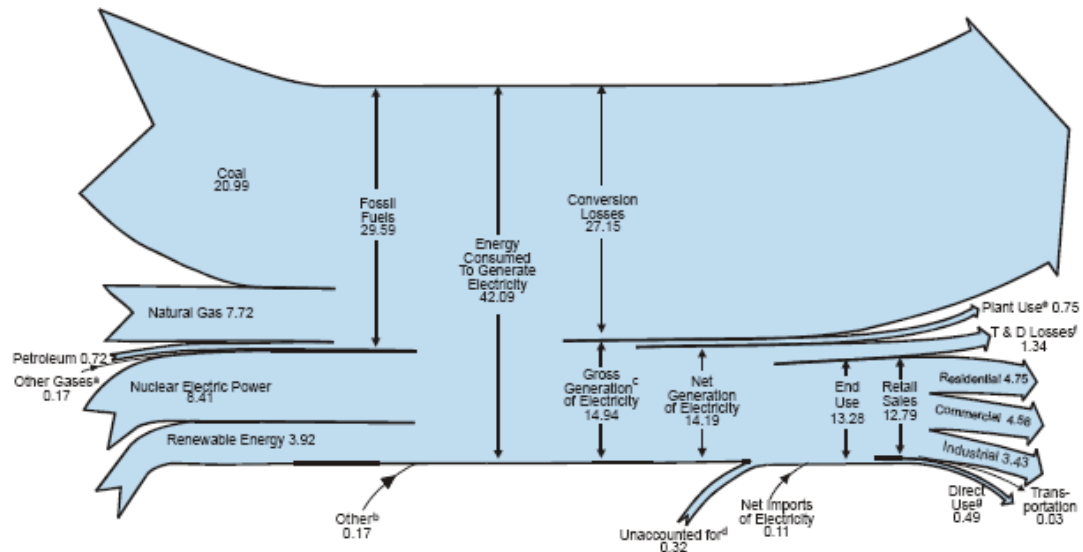
- b= Natural gas plant liquids.
- c= Conventional hydroelectric power, biomass, geothermal, solar/photovoltaic, and wind.
- e= Natural gas, coal, coal coke, fuel ethanol, and electricity.
- g= Coal, natural gas, coal coke, and electricity.

Figure 10.14 Flow of energy through the U.S. economy in 2007 (in units of Quadrillion Btu). *Source: Energy Information Administration (2008). Annual Energy Review 2007.* (Washington, DC: U.S. Department of Energy).

About 65% of the energy consumed by the electric utilities are “lost” as waste heat, due in part to the inherent inefficiency of heat engines, as discussed above. But this is far from the only loss in the system. Much of the end-use energy is also lost, in the sense that it does not accomplish its intended use before ending up as waste heat. A liter of heating oil, for example, produces exactly its heating value, wherever it is burned, but the effect on the house being heated depends on the efficiency of the furnace and heating system, on the size of the house, and on how well it is insulated. Two houses of similar size, side by side, can require quite different amounts of oil or gas to achieve the same indoor temperature. Likewise, the amount of electricity used for heat, light, and appliances depends on the efficiency of electricity conversion to the intended use. For example, compact fluorescent light bulbs provide light equivalent to a traditional tungsten bulb with 25% of the electric current requirement, and sensors are available that turn lights off when no one is in a room. Clearly, the magnitude of the end-use energy requirement for residential purposes could be less than it now appears to be, if the residents adopted energy-saving measures. Much has, in fact, been accomplished in this direction, with improved building codes and enhanced efficiencies in appliance designs, for example, but there

is still considerable room for improvement. Likewise, there are many opportunities in the industrial and transportation sectors to improve energy efficiency and reduce the energy utilization rate.

All of the energy flowing through the economy eventually ends up as waste heat. The question is what fraction of it actually accomplishes human ends on its way to its entropic destination. This fraction determines just how much energy we actually need.



b= Batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, miscellaneous technologies, and non-renewable waste (municipal solid waste from non-biogenic sources, and tire-derived fuels).

e= Electric energy used in the operation of power plants, estimated as 5 percent of gross generation.

f= Transmission and distribution losses (electricity losses that occur between the point of generation and delivery to the customer) are estimated as 9 percent of gross generation.

g= Use of electricity that is self-generated, produced by either the same entity that consumes the power or an affiliate, and used in direct support of a service or industrial process located within the same facility or group of facilities that house the generating equipment.

Figure 10.15 Flow of energy from electricity through the U.S. economy in 2007 (in units of Quadrillion Btu). *Source:* Energy Information Administration (2008). *Annual Energy Review 2007.* (Washington, DC: U.S. Department of Energy).

10.7a The 'smart grid'

The electricity sector is a collection of power plants, feeding current to buildings and factories through a network of wires, the 'grid'. The grid is required to deliver electricity as needed to millions of users, with continually shifting demand. Because overloading leads to power failures, utilities must build excess generating capacity to meet peak demand, and must then 'shed load', when demand diminishes, thus decreasing energy efficiency. A 'smart grid' can level the load by adjusting the price of electricity to demand, and providing consumers with real-time information on costs. 'Smart meters' can provide moment-to-moment readings on electricity usage and costs, allowing consumers to adjust the timing of postponable usage – laundry, for example – or the comfort level of living space (heating and air-conditioning) to minimize costs.

Controls can be included to vary lighting and thermostats automatically. Smart metering and variable pricing is already widespread in the Netherlands, and is being tried in several cities around the world.

In addition, smart grid plans for the US and many other countries, include extra-high-voltage transmission lines, capable of carrying electricity efficiently over long distances. As noted above, a major barrier to the widespread use of renewable energy is the location of especially windy and sunny sites, far from major markets for electricity. More efficient long-distance transmission will ameliorate this problem.

Conversely, smart grids are also expected to facilitate efficient two-way flow of electricity, so that excess electricity from local generators – solar panels, small-scale wind and hydro generators, and fossil fuel heat and power cogenerators – can be fed into the grid. This development would allow harvesting of decentralized energy sources, and would increase reliability, protecting against failure of large centralized sources.

10.7b Transportation

Transportation is an especially important energy sector, not only because of its high rate of energy consumption (as seen in **Figure 10.14**, it accounts for more than one-fourth of total energy consumption), but also because of the international economics and politics of oil. About half of the world's oil production goes into transportation, while about 40% is used in space heating and industrial processing (including production of petrochemicals), and about 10% in electricity production.

Table 10.3 lists the common forms of transport in the U.S., and their energy intensities (the amount of energy required to transport a passenger or a ton of freight, for a given distance). For freight, there are large disparities in the energy intensity. Transport by ship or rail takes far less energy per ton of material per kilometer of travel than does transport by truck, which in turn takes far less energy than transport by airplane. Of course, these different transport modes are appropriate to different kinds of goods of different value and perishability; they are not freely interchangeable. Nevertheless, the growth of trucking, and especially of air freight, is a significant factor in the transportation energy demand.

The data for passenger transport reveal important variations. Vanpools and intercity trains are the most efficient people movers, because they have high load factor (passengers per vehicle) about 15 and 19, respectively. City buses suffer in comparison because of low load factors (about 9). Commuter trains also have high load factors (about 35), but efficiency is lowered because of higher energy requirements, due mainly to electric propulsion, especially for commuter trains. Airplanes require even more energy, of course, but because of high load factors, their average energy intensity is not much higher than commuter trains.

Automobiles in city driving have higher energy intensity than that of airplanes, because most of them carry a single passenger. The average gasoline efficiency of new U.S. cars is 28.4 miles per gallon (mpg) (12.1 km/L) on the highway and 20.1 mpg in the city (8.5 km/L), about the same as it was in 1988 (28.2 mpg). Efficiency improved in the 1970's (**Figure 10.16**), but then leveled off. The same is true of light trucks, a category that includes vans and sports utility vehicles [SUVs]. Their mileage remains about a third less than that of cars, and their energy intensity is about 50 % higher (Table 5.3). Because of the popularity of SUVs, the average mileage of the U.S. automotive passenger fleet actually declined after 1985. This popularity is reflected in the dramatic increase in light truck passenger miles. The total miles traveled per capita increased from 11,200 (18,000 km) in 1970 to 14,900 miles (23,900 km) in 2006, and the share belonging to light trucks increased by almost a factor of three, from 14.8 to 43.4%. This increase was at the expense of cars, whose share fell from 85.7% to 55.8%. Mass transit, meanwhile, hovered around 3% for the entire period. However, in 2009 the new US administration announced substantially higher mileage targets for the US automotive fleet.

Table 10.3 Efficiencies of Freight and Passenger Transport in the U.S.

Mode	Passenger (2006)	
	PmiT(PkmT) [*] (millions)	Energy intensity kJ/PmiT (kJ/PkmT)
City bus	21,998 (35,402)	4,468 (2,776)
Commuter train	9,473 (15,245)	3,161 (1,964)
Intercity rail [†]	5,410 (8,707)	2,796 (1,737)
Auto	2,641,793 (4,251,554)	3,705 (2,302)
Light truck	1,565,595 (2,519,581)	4,161 (2,585)
Vanpool	605 (974)	1,395 (867)
Airplane	577,620 (929,589)	3,440 (2,138)

Mode	Freight (2006)	
	T-mi (T-km) [*] (millions)	Energy intensity kJ/T-mi (kJ/T-km)
Truck	1,255,900 (2,021,175)	24,751 (15,380)
Rail	1,771,897 (2,851,592)	348 (216)
Ship	591,000 (951,122)	543 (338)
Airplane	5,800 (9,334)	NA [§]

^{*} PmiT signifies “passenger miles traveled.” PkmT signifies “passenger kilometers traveled.” T-km signifies “metric ton-kilometers.”

[†] Amtrak only

[§] Data not available

Source: S.C. Davis, S.W. Diegel, and R.B. Boundy (2008) *Transportation Energy Data Book*, ORNL-6981, Edition 27 of ORNL-5198. Oak Ridge National Laboratory: Oak Ridge, Tennessee.

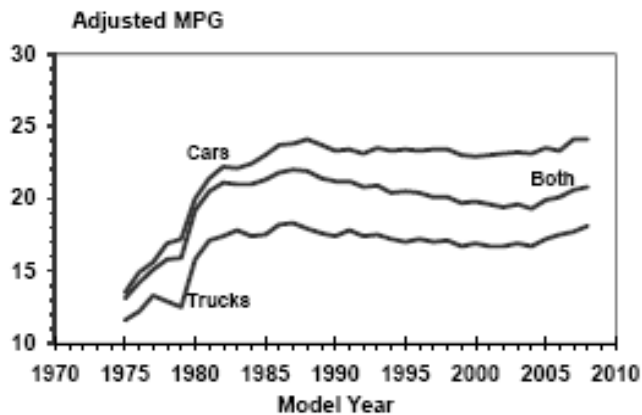


Figure 10.16 Trends in fuel economy of light-duty vehicle transportation in the U.S., 1975-2008. Source: U.S. Environmental Protection Agency (2008). *Light-Duty Automotive Technology and Fuel Economy Trends Through 2008*. EPA420-R-08-015. (<http://www.epa.gov/otaq/fetrends.htm#report>)

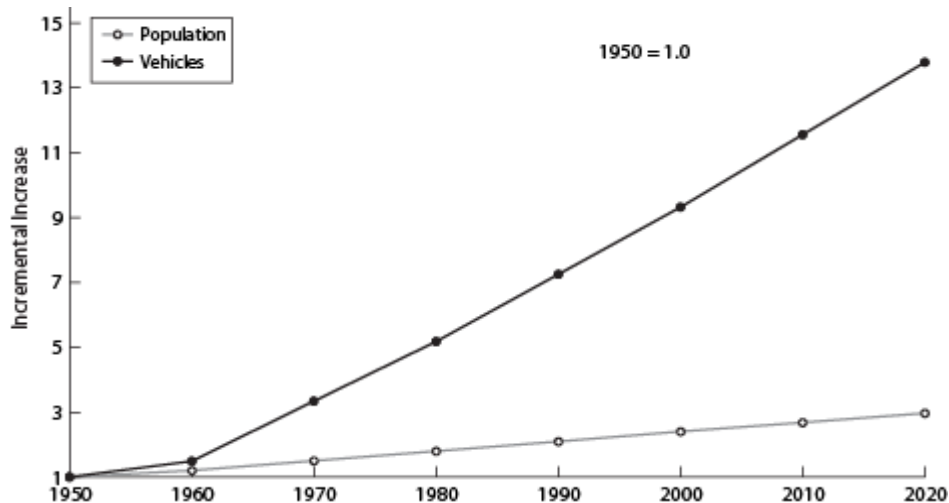


Figure 10.17 Comparison between population growth and passenger car growth globally. *Sources:* Population data are from Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2007). *World Population Prospects: The 2006 Revision*. United Nations: New York, NY. Vehicle data are from U.S. Department of Energy (2000) *World Vehicle Population, 1950-2020*, Fact of the Week, Fact #146, October, 2000.

On a global basis the automobile dominates all other sources of transport. The global car fleet has increased nearly 10-fold over the period from 1950 (when about 55 million cars were in use) to 2008, and it has outstripped the growth in global population by a factor of four (**Figure 10.17**). The relatively immature transportation sectors in much of the developing world are expected to expand rapidly as development proceeds. The U.S. Department of Energy projects that energy use for transportation will more than double in the developing world between 1997 and 2020, resulting in global transport energy to increase about 14-fold compared to 1950.

Consequently, the energy efficiency of the automobile is a critical issue of global dimensions. In addition, system-wide effects on energy consumption are important. For example, an effective mass-transport system might significantly reduce traffic congestion, thereby improving the energy efficiency of all forms of transport in the region.

10.7c Energy Efficiency in Automobiles

In the conventional automobile, only a small percentage of the energy present in the gasoline actually serves to move the car (**Figure 10.18**). The fraction of fuel energy delivered to the driveline is only 25% on highways, and 18% in urban driving, while the energy delivered to the wheels is even lower, 20% and 13% respectively. The rest of the energy either becomes waste heat (from the thermodynamic cycle of the engine), is used to overcome frictional losses (such as aerodynamic drag or rolling resistance), or powers auxiliary equipment. Somewhat higher thermal efficiencies (40 % vs 25 %) are achieved in modern diesel engines, which are popular in Europe.

Substantially improved fuel efficiency is achieved in the hybrid electric vehicle (HEV). It combines the internal combustion engine with the electric motor and battery storage of an electric vehicle. This combination offers extended range and rapid refueling with a significant fraction of the energy and environmental benefits of an electric vehicle. HEVs use regenerative braking, strong light-weight materials, and aerodynamic body shapes to minimize energy losses. The HEV is about twice as efficient as a conventional gasoline vehicle.

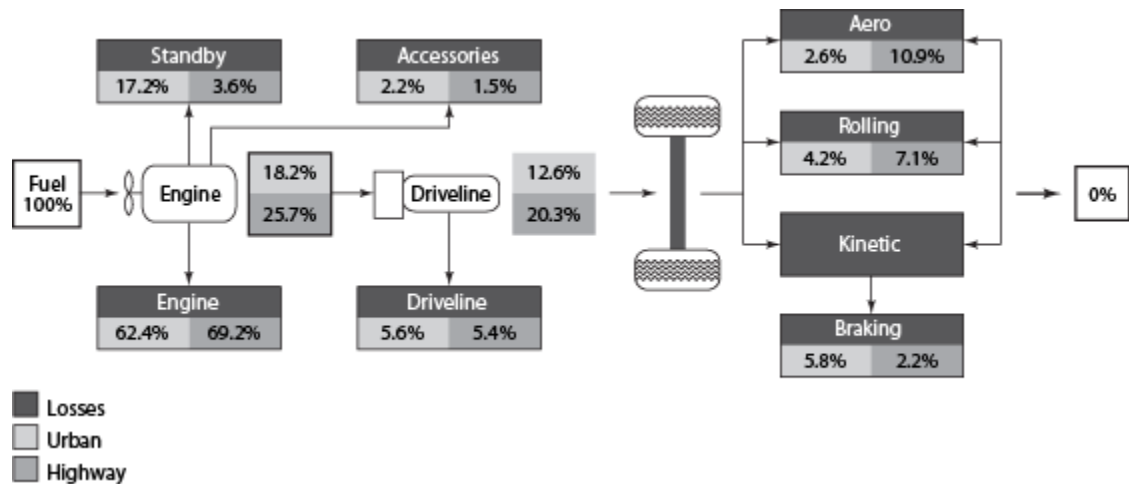


Figure 10.18 Energy losses in automobile transport point to strategies for improving fuel efficiencies in automobiles. *Source:* D.L. Illman (1994). Auto-makers move toward new generation of “greener” vehicles. *Chemical & Engineering News* 72(31):8-16.

An all-electric vehicle (EV) has the highest energy conversion efficiency. Energy from the battery is transmitted to the drive train at efficiencies of 70-85%. However, since electricity is generated from power plants at an average efficiency of 33%, and transmission losses are about 10%, the overall ‘fuel efficiency’ is 20-25%, comparable to cars in urban driving. Because the power plant fuel is much cheaper than gasoline, the cost per mile is substantially lower for an electric than a gasoline car.

While EV’s have no emissions, they are responsible for part of the emissions from power plants. The amount of CO₂ accounted to an EV depends on the mix of fuels for the grid. Coal-derived electricity would actually produce more CO₂ per EV mile than per gasoline mile, on average, but methane-derived electricity would produce less. Electricity from renewable fuels emits no net CO₂ in principle. It has been pointed out that converting biomass to electricity (‘bioelectricity’) for use in EV’s is considerably cleaner and more efficient than converting it to biofuels for transport.

As noted in the discussion of batteries, above, the main limitation of EVs is their limited range and the slowness of recharging. Most current EVs are small commuter cars, which are plugged in for recharge at home overnight, or at workplace recharge stations. However, Israeli entrepreneur Shai Agassi is promoting the use of switchable batteries. He has reached agreement with Renault-Nissan corporation and the Israeli government to establish a national network of battery switching stations and put 100,000 EVs on the road, beginning in 2011. The project is facilitated by Israel’s geography since its major cities are less than 150 km apart, and 90% of car owners drive less than 70 km/day.

The fuel cell vehicle is an alternative to the EV. As discussed on pp. ?, a PEM fuel cell engine can approach a thermal efficiency of 60%, corresponding to a fuel efficiency of 90 mpg (38.3 km/L). The emission product is H₂O when operating on pure hydrogen. However the production of H₂ from fossil fuels generates CO₂, as does electricity generation, and byproduct CO must be stringently removed to avoid poisoning the PEM catalysts (p. ?). The problem of on-board H₂ storage or generation is a stumbling block (p. ?), as is the task of establishing a H₂ infrastructure.

10.7d Industrial ecology

A systematic way of tracking and controlling energy and materials flows is emerging through the new discipline of Industrial Ecology (IE). IE strives for integrated assessment of the

connections among these flows and impacts on the environment. **Figure 10.19** provides a diagram of these connections. The assessment includes “life cycle” analysis of the full impact of various products, from extraction of raw materials, through transport and manufacture to use and disposal. It also looks for possibilities to recycle materials, turning wastes into raw materials and thereby closing ecological loops.

One application of this approach is the concept ‘industrial symbiosis’ in which industrial outputs and inputs are linked in order to minimize energy and material wastes. An often cited example is the ‘ecopark’ in Kalundborg, Denmark, which houses a large power station (1,500 MW, coal-fired), an oil refinery, the Gyproc gypsum wallboard factory (14 million m²/yr of), and a major pharmaceuticals plant (Novo Nordisk) (**Figure 10.20**).

Waste heat from the power station generates steam for district heating in Kalundborg (replacing 3,500 home furnaces), and to supply the oil refinery and pharmaceutical plant with process steam. The power plant is cooled with salt water from a nearby fiord (reducing withdrawals of fresh water from Lake Tisso), and the warmed salt water is sent to a fish farm where it provides heat and water to 57 ponds. The oil refinery, which had previously flared most of its gaseous by-product, now desulfurizes the gas and sends it as fuel to Gyproc and to the power station (reducing its coal consumption), while the byproduct sulfur is sent to a sulfuric acid producer. Fly ash from the power plant’s coal is used by a cement factory, while the calcium sulfate from its SO₂ scrubber provides raw material to the wallboard plant. Meanwhile, sludge from the pharmaceutical company and from the fish farm’s water treatment plant provides fertilizer to nearby farms. And surplus yeast from insulin production at the pharmaceutical company goes to farmers to feed hogs.

The Kalunborg ecopark saves energy and minimizes waste, generating cost savings that far exceed the original \$60 million investment in infrastructure to transport energy and materials. Other examples of industrial symbiosis have evolved through cooperative action of industries already located near one another that discover ways of recycling byproducts and waste.

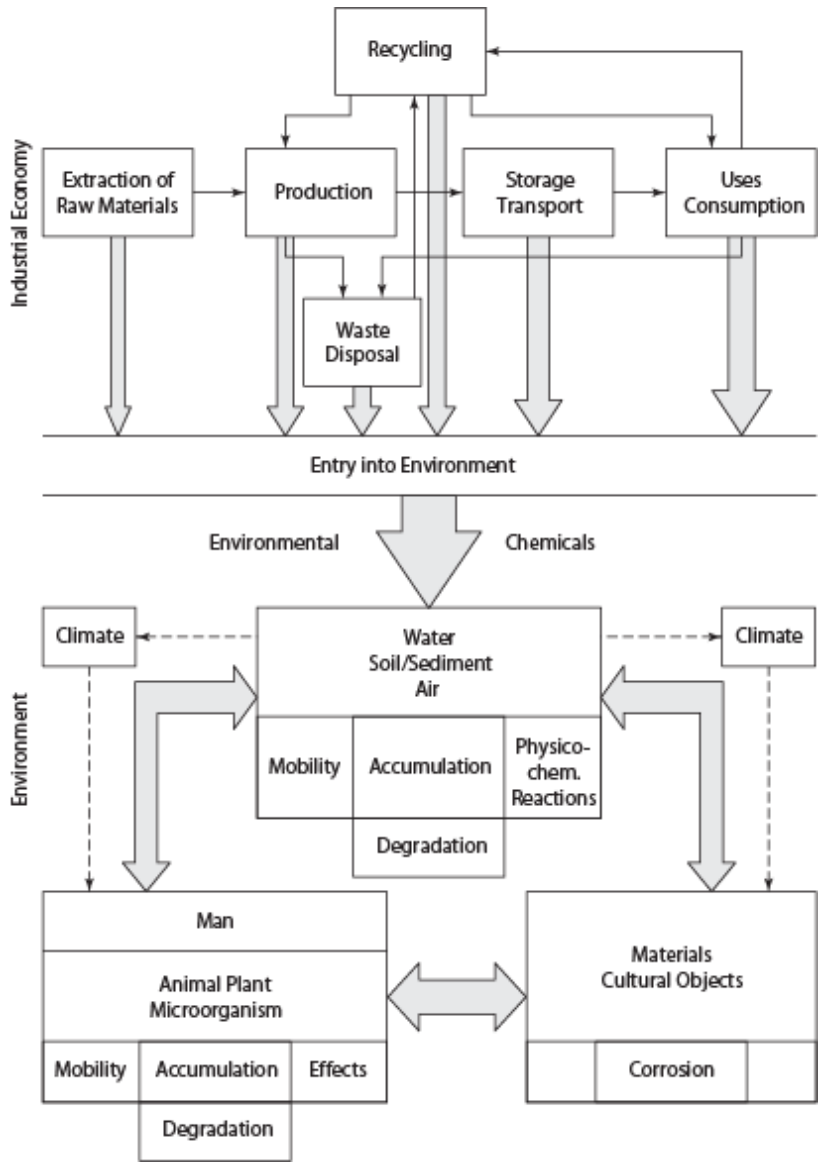


Figure 10.19 Interactions between the industrial economy and the environment. *Source: W.M. Stigliani (1993). The integral river basin approach to assess the impact of multiple contamination sources exemplified by the River Rhine. In Integrated Soil and Sediment Research: A Basis for Proper Protection. H.J.P. Eijsackers and T. Hamers, eds. (Dordrecht, The Netherlands: Kluwer Academic Publishers).*

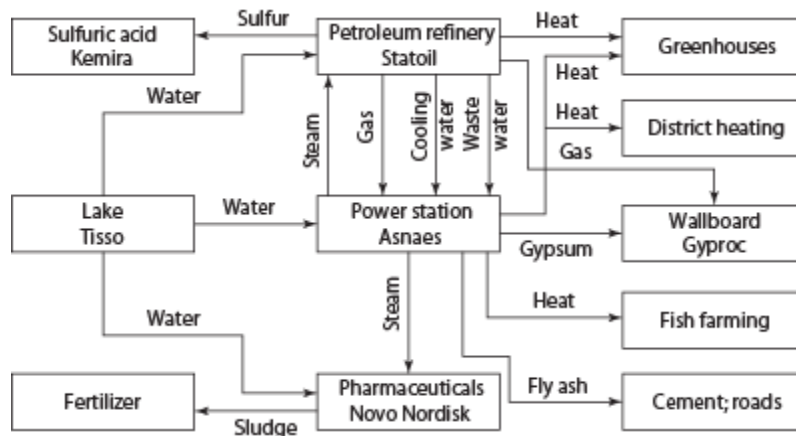


Figure 10.20 A schematic diagram of the industrial ecopark located in Kalundborg, Denmark. The figure shows the industrial firms that occupy the park, the material, and energy flows between them, and the nature and fate of outgoing material and energy streams. Adapted from B.R. Allenby and T.E. Graedel (1994). *Defining the Environmentally Responsible Facility* (Murray Hill, New Jersey: AT&T).

10.8 Connecting Energy Use and Climate Change: Stabilization Wedges

In Chapter 3 we saw that rising greenhouse gas emissions are connected to global warming, and that very large reductions in the emission rates will be required to stabilize the atmospheric concentrations of these gases, even at twice the pre-industrial levels. Concentrations greater than that are likely to have dire consequences for humans and for Earth's ecosystems.

To keep the gas concentrations stable, the emission rates will have to be reduced close to zero. Eventually, the concentration of CO₂ is drawn down by ocean circulation and by weathering (p ?), but only on the geological time scale. Arriving at a carbon-neutral will energy system will require revolutionary changes in technology, and is the goal of a great deal of current research. However, there is much that can be done in the interim, as discussed in the preceding chapters.

To bring the matter into sharper focus, Stephen Pacala and Robert Socolow introduced the concept of 'stabilization wedges', measures to reduce carbon emissions by specific amounts using methods that are already available. Noting that stabilizing the CO₂ concentration at 550 ppm requires leveling off emissions over the next 50 years, and then lowering them (see Figure 2.25), they plotted an emission graph (Figure 10.22) showing how much carbon limitation this path requires. A 'flat path' requires capping emissions at the current rate of 8 Gt/yr, whereas continuation of the current trend of 1.5 % annual growth (approximated as a straight line) would lead to 16 Gt/yr 50 years hence. (Corrected upward from 14 Gt/yr since the article was published.)

The difference between these outcomes, 8 Gt/yr, is the carbon savings to be accomplished over 50 years, and was labeled the 'stabilization triangle'. Pacala and Socolow reasoned that the emissions reductions required after 50 years would be accomplished with transformative technologies (e.g. fusion energy, or artificial photosynthesis), currently in the research phase, which may then be ready for implementation. The immediate task is to set us on the flat path.

How can 8 Gt/yr of carbon emissions be avoided? Pacala and Socolow catalogued a series of measures, the 'stabilization wedges', which could each be scaled up to reduce emissions by 1 Gt/yr. Fifteen of these were identified (Table 10.4), any eight of which would place the globe on a flat path, if they were implemented over the next 50 years.

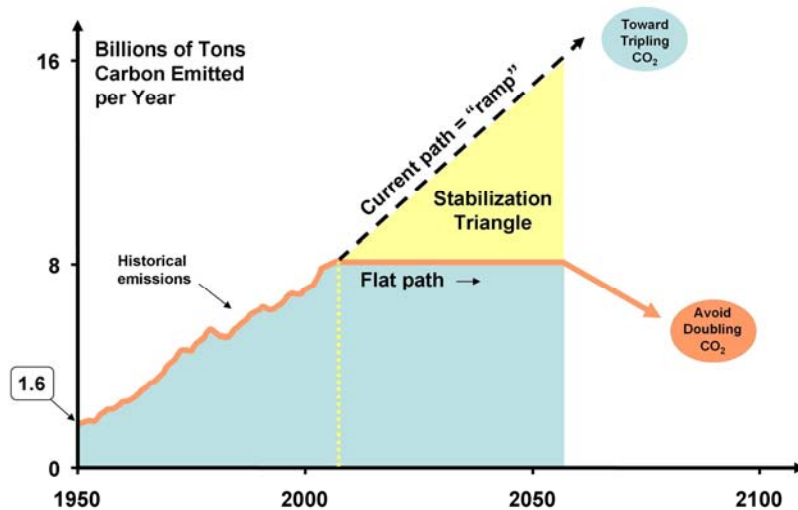


Figure 10.22 Stabilization triangle – avoided emissions required over the next 50 years to prevent atmospheric CO₂ from exceeding 550 ppm*

*Pacala, S, and Socolow, R. “Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies” *Science* (2004) 305 968-972.

Four of them could be obtained from efficiency and conservation measures, all of which could be implemented with today’s technology:

1] Double fuel economy, from 30 to 60 miles/gal, for 2 billion cars, travelling 10,000 miles/yr (the current average). Today’s global fleet of roughly 500 million cars is expected to quadruple in the next 50 years. 60 miles/gal is achievable with current technology, though average car size and power would be lowered.

2] Reduce the distance travelled by these cars, from 5,000 to 10,000 miles/yr. This might happen through enhanced mass transit and enhanced telecommuting, clustering of housing closer to workplaces, and shorter leisure trips.

3] Implement improvements in buildings, cutting their carbon emissions by one-fourth. This could be accomplished with available technology for energy-efficient space heating and cooling, water heating, refrigeration and lighting. The savings stem from avoided power plant expansion; In the U.S. buildings use 70 % of electricity production.

4] Increase the efficiency of coal power plants, assumed to double in capacity over the next 50 years, to 60 % from the expected average of 40% (currently 32%). This could involve installing boilers capable of operating at very high temperatures (p ?), or high temperature fuel cells (p ?), and also capturing heat for other uses (co-generation, p ?).

5] Another wedge could be obtained by substituting natural gas for coal in power plants, increasing gas-based power by a factor of four from current levels. Coal emits twice as much carbon as gas per unit of energy produced (p ?). However, the supply of natural gas is limited, and there are competing demands.

Three more wedges might be obtained with carbon capture and storage (CCS - pp.??):

6] Capture CO₂ at all major coal and gas power plants. If CCS is applied to biomass conversion, there is net withdrawal of CO₂ from the atmosphere, making this wedge easier to achieve

7] Capture CO₂ at plants producing H₂ from fossil fuels. Current H₂ production is 40 Mt/yr, mostly from natural gas, and mostly in oil refining and fertilizer production. The production rate can be expected to increase greatly, if elements of the hydrogen economy are put in place. CCS

would produce a wedge from 500 Mt/yr if H₂ if produced from gas, or 250 Mt/yr if produced from coal.

8] Capture CO₂ at synfuels plant. As oil reserves run low, there will be economic pressure to produce synfuels from coal (p. ?). This processes is highly carbon emitting. CCS in such plants would yield a wedge at a production rate of 30 million barrels a day, which is 200 times the production rate of the largest synfuels plant currently operating (Sasol in South Africa).

9] Another wedge would be obtained by tripling the currently installed nuclear fission capacity, if the new capacity displaces coal. The exacerbation of nuclear waste and proliferation hazards (p. ?) would need to be addressed.

Four wedges could reasonable be expected from renewable energy over 50 years.

10] Increase wind power (p. ?) by a factor of twenty.

11] Increase photovoltaic (p. ?) capacity by a factor of 700.

12] Produce H₂ from wind power for fuel cell cars, displacing gasoline from half the projected 2 billion car global fleet. A 30-fold increase in current windmill capacity would be needed.

13] Substitute biomass fuels for fossil fuels. A wedge could be achieved by increasing ethanol production to 100 times the current level of US or Brazilian production, using high-yield energy crops; an area equal to one-sixth of the world's cropland would be required. However, this calculation does not include carbon emissions from fossil fuel inputs to ethanol production. The ratio of these inputs to ethanol outputs ranges from 10% for Brazilian sugar to near unity for U.S. corn.

Finally two wedges might be achieved from forests and agricultural soils:

14] Eliminate tropical deforestation (currently producing 0.5 Gt/yr of carbon emissions) and establish new tree plantations at twice the current rate.

15] Apply conservation tillage (techniques like no-till that reduce aeration of the sol, plus reducing the period of bare fallow and planting cover crops) to all cropland (ten times the current rate).

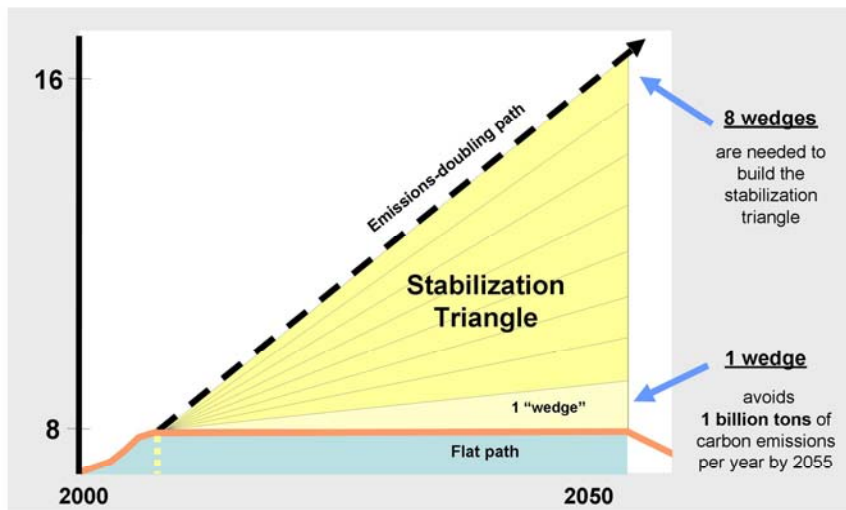


Figure 10.23 Eight 50 yr -1 billion ton wedges are required for stabilization

There are other factors that may contribute to lowering greenhouse gas emissions. Economic growth is the driver of increasing energy utilization, but the rate of carbon emissions depends on the kind of economic activity. For example, a shift from manufacturing to service industries, a characteristic of developed economies, lowers the *carbon intensity*, the ratio of carbon emissions to economic product. While global carbon emissions are growing at an annual rate of 1.5%, the growth in the gross world product is roughly 3%, so that the carbon intensity is actually falling by 1.5%. The flat path of carbon emissions (**Figure 10.23**) requires that carbon intensity decrease by 3% annually, to offset the effect of economic growth. Some of this additional decrease may occur naturally, as the developing societies become richer.

However, the flat path will clearly require carbon reduction policies as well. Pacala and Socolow's wedges give a sense of the scale of the task, and the availability of many approaches, which, if followed with determination, could keep the concentration of greenhouse gases at levels that avoid catastrophic effects on the habitability of the planet.

Problems:

1. Assume that due to dwindling supplies of crude oil and natural gas, the United States embarks on a plan to implement the "hydrogen economy," for which hydrogen will be generated by electrolysis of water. The source of electricity is from photovoltaic conversion of sunlight in the southwestern United States.

(a) Assume that a fixed, flat-plate PV system is used, with a solar conversion efficiency of 15%, and a hydrogen-production efficiency of 80%. Assume that the average annual insolation in the southwest is 270 watts per m². Calculate the annual electrical energy produced per m² in kWh and in kJ. Calculate the energy content of the H₂ produced per m², as well as the number of moles, and the weight of H₂.

(b) The United States consumed 39.8 EJ of petroleum in 1999. How many square meters of PV collectors would be needed to supply the equivalent amount of energy? The area of the southwest (the states of New Mexico, Arizona, Colorado, Utah, and Nevada) is 1,386,370 km². What percent of the land area would be covered by PV collectors?

(c) How much water per year would be required to produce the hydrogen? Assume a conversion efficiency of 80%. What percentage of total national water use would this correspond to, considering that water use in the United States is about 4.7×10^{14} liters.

2. An electric hot-water heater has a standard efficiency rating of 90% (that is, for every 10 kJ of electricity consumed, 9 go into heating the water). If the heater normally heats the water from the ambient temperature, 20°C (68°F), to 80°C (176°F), what is the *second law* efficiency (that is, what is the ratio of the amount of energy that an ideal heat pump would use to do the same job, to the amount of energy actually consumed)?

3. Calculate the theoretical efficiency of a heat pump when the room temperature is 20°C (68°F) and the outside temperature is -20°C (-4°F). If the heat pump were drawing heat from a water tank at 5°C (41°F), what would be the

theoretical efficiency? Describe how solar energy in conjunction with a heat pump can provide an efficient means of heating a house.

4. Petroleum consumption in the United States in 1999 was 39.8 EJ. Of this quantity, 23.8 EJ (60%) was supplied by foreign sources. The transportation sector accounted for 26.2 EJ (66%) of total petroleum use. The passenger car fleet, numbering 132 million, consumed 9.6 EJ, and light trucks (including vans, pickup trucks and sport utility vehicles), numbering 72 million, consumed 6.7 EJ. The average fuel efficiency of the passenger car fleet in 1999 was 21.4 miles per gallon (mpg), and for light trucks it was 17.1 mpg. Calculate how much less petroleum would have to be imported if the national stock of cars were replaced by hybrid vehicles, in which passenger car efficiency would be 60 mpg and light truck efficiency would be 40 mpg.

5. A large power plant is being constructed that will produce $6.7 \cdot 10^{10}$ kJ/day of electrical energy. For every kJ of energy produced, 2 kJ of waste heat is discharged. If a plant draws $2 \cdot 10^9$ liters/day of river water at 20°C into its cooling condensers, calculate the rise in temperature of the cooling water. If the river has a flow rate of 10^{10} liters/day, estimate the rise in temperature of the water downstream from the plant.

6. (a) As presented in Table 1.15, making a metric ton of paper requires 980 kWh of energy, whereas making a metric ton of polystyrene requires about 300 kWh. Given that an average 8 oz. paper cup weighs 10.1 g and an average polystyrene cup weighs 1.5 g, what is the ratio of the power requirements on a per-cup basis?

(b) The table also lists the amount of heat recovered from incinerating each type of cup; 20 MJ/kg (megajoule per kilogram) for paper; 40 MJ/kg for polystyrene. The heat could be converted to electricity at a power plant with an efficiency of about 30%. Compare the amount of electrical power available from incinerating discarded paper and polystyrene cups with the amount of energy needed to produce them. (1 kWh = 3.6×10^6 joules; 1 MJ = 10^6 joules.)

(c) A fast-food restaurant on a busy street uses polystyrene cups to serve coffee at a rate of 2.5 gross/day (1 gross = 12 dozen = 144). Reacting to pressure from an environmental advocacy group, the restaurant switches over to using paper cups. What is the effect of this decision in terms of kWh of power per week, if the town has no incinerator? What is the effect if the town sorts and incinerates paper and plastic for electricity production?

(d) Write a paragraph explaining to the proprietors of the restaurant in question (c) what they might do if they want to be as environmentally responsible as possible.

7. Consider the stabilization wedges listed in the text, and rank them in the order of difficulty that you anticipate for their implementation. Give you reasons.