Future Energy: Opportunities and Challenges

Part I. Getting Started

Chapter 2. Fundamentals

Future Energy:
Opportunities and Challenges

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2
Fundamentals

The Main Points

- **An understanding of basic physics, chemistry, and biology permits the quantitative assessment of energy options.**
- **There are different forms of energy, but mechanical energy, thermal energy, and electrical energy are the energy forms usually desired for practical applications.**
- **Transformations from one form of energy to another are possible and are routinely performed.**
- **Energy is always conserved in transformation processes.**
- **Heat production accompanies all transformation processes, and this heat is usually viewed as waste.**
- **Plants use energy from the sun to produce biomass by photosynthesis. The captured energy is the maximum energy that can subsequently be obtained from the biomass or from biofuels produced from the biomass.**
- **Electricity and hydrogen must be manufactured. They are energy carriers rather than energy resources.**

2.1 Understanding Energy

Producing energy and transforming energy from one form to another are the stuff of physics, chemistry, and, increasingly as we develop renewable energy sources, biology. Fortunately, it is NOT necessary to be a physicist, a chemist, or a biologist to understand the important concepts. But the concepts are crucial to understanding the energy issue. If they are new to you, please pay close attention to the material in the rest of this chapter. The concepts presented below provide a brief look at the science needed for quantitative understanding of the energy story. How they relate to energy production and use appears in future chapters.

We begin with definitions of some key terms that appear in discussions of energy.

Force is that which causes a body to accelerate. The quantitative relationship, called Newton's Second Law, is

$$F = ma \tag{2-1}$$

where

F	=	force
m	=	mass
a	=	acceleration

Mechanical work is the product of a force operating on an object in some direction and the displacement of that object caused by the force. It should be noted that the word "work" has many meanings in the English language. "Work" may be a noun or a verb. One might say that solving algebra problems or holding a heavy bag of groceries is work, but these activities do not satisfy our definition of mechanical work.

Energy is the capacity to do work. If an object transfers energy to another object, it transfers the capacity to do work. For example, a stream of flowing water possesses energy. If the water stream is used to turn a paddle wheel, part of the energy in the water stream is transferred to the paddle wheel, and the rotation of the paddle wheel can be used to do work.

A study or understanding of energy involves five components: energy production, energy storage, energy transport, energy use, and energy waste. We will address all of these in later chapters.

2.2 Conservation of Energy

A simple, but very important, law of physics is called the law of conservation of energy. It states: Energy cannot be created nor destroyed. It can only change form.

> *You can change forms of energy, but you can't get more energy out of a system than was put in.*

The law of conservation of energy is also called the first law of thermodynamics.

For example, when wind turns a windmill, the windmill gains energy at the expense of the wind, so the wind must lose energy (slow down). A hybrid car may recover energy during braking, but that energy must have been produced previously by the car's engine. To use the classic expression, there is no free lunch.

2.3 Energy and Power

In evaluating the performance of energy systems, we are interested in how fast energy is flowing as well as the total amount of energy involved in some process. For this, we use the concept of power. Power is just the rate of energy flow. A low power device can deliver (or use) just as much energy as a high power device, but it will take longer.

2.4 Units of Measure

In order to be really useful, a technical concept must somehow be related to numerical values. Dollars and euros and yen were invented by man to make the concept of money meaningful and quantifiable. Similarly, it must be possible to assign numerical values to measures such as temperature, mass, length, speed, force, energy, and power. It would be nice if there were only one set of units. But just like there are different currencies with different rates of exchange with other currencies, there are different measures for physical quantities. Each of these measures can be converted into an equivalent alternate measure, just like currency. There are two different fundamental systems in use today, the SI (for Systeme International d'Unites) system and the U.S. Customary system.

2.4.1 Mass and Weight

The SI system is often called the MKS system because it is based on meters for length, kilograms for mass, and seconds for time. Similarly, the U.S. Customary system is often called the FPS system because it is based on feet for length, pounds for weight, and seconds for time. Therein lies a huge seed for confusion. One system uses kilograms for MASS, and the other uses pounds for WEIGHT. But a bunch of bananas that registers 1 kilogram on a scale in France would register 2.2 pounds on a scale in America. One might conclude that mass and weight are simply proportional measures of the same thing, but that is not true. The correct definitions are:

> Mass = a measure of an object's tendency to maintain its state of motion (inertia)
>
> Weight = the force on a body due to gravity.

One might correctly say that a mass of 1 kilogram is the same as a mass that weighs 2.2 pounds.

Appendix A addresses the mass vs. weight issue. Here it suffices to note that:

$$W = mg \tag{2-2}$$

where

W	=	weight
m	=	mass
g	=	acceleration due to gravity.

On the surface of the earth, g has a value of 9.81 meters per second per second in SI units and 32.17 feet per second per second in U.S. Customary units. Therefore, in SI units, the unit of weight is 9.81 × mass (in kilograms) and is called the Newton. In U.S. Customary units, the unit of mass is weight (in pounds)/32.17 and is called the slug.

If one is working with a formula containing mass as a variable, the kilogram is the appropriate measure in the SI system, and the slug is the appropriate measure in the U.S. Customary system.

2.4.2 Energy and Power Measures

A convenient process to use in considering energy and power units is the heating of water. The calorie (an SI unit) is defined this way:

> 1 calorie = the amount of heat energy required to raise the temperature of one gram of water by one degree Celsius.

For example, if a heater raises 100 grams of water by 2 degrees Celsius, we know that 200 calories of heat energy were added to the water.

In the U.S. Customary system, the British thermal unit (BTU) is defined as follows:

> 1 BTU = the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit.

The units of energy apply equally for all forms of energy. For example, we may speak of a BTU of thermal energy or a BTU of mechanical energy or a BTU of electromagnetic energy.

The Joule, defined in mechanical terms as the energy exerted by a force of one Newton acting to move an object through a distance of one meter, is a common energy measure in the SI system. One Joule is equal to 0.239 calories or 9.4762×10^{-4} BTU. The watt is a unit of power and is equal to one Joule per second.

Prefixes are used, especially in the SI System, to indicate multiples of basic units. For example, kilo is the prefix meaning 1,000. Therefore, a kilojoule is 1,000 Joules and is abbreviated as kjoule. The prefixes for multiples of basic units are defined as follows:

Multiplier	Prefix	Symbol
10^3	kilo	k
10^6	mega	M
10^9	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E
10^{21}	zeta	Z

Relationships between some of the most common energy and power measures are shown in Table 2-1.

Example 2.1

To illustrate the use of the energy conversion factors, consider a process involving 15,000 BTU. The corresponding number of calories is 15,000 × 252 = 3,780,000.

As will be shown in later chapters, annual U.S. and world energy production and consumption are measured in quadrillions of BTUs (Quads) primarily in U.S. publications and in Exajoules or MTOE in some other countries. It is noteworthy that energy measures in Quads or Exajoules are about equal. It should also be noted that a quadrillion is defined differently in the U.S. and many other countries. In the U.S., a quadrillion is 10^{15}, and in most of the rest of the world, a quadrillion is 10^{24}. In subsequent sections of this book, the U.S. convention is used. A more complete list of useful conversion factors is given in Appendix B.

Table 2-1. Some Conversion Factors

To	Joule	Exajoule	Calorie	BTU	Quad	Kwhr	MTOE
From							
Joule	1	10^{-18}	0.239	$9.48x1^{4}$	$9.48x10^{-19}$	$2.78x10^{-7}$	$2.35x10^{-17}$
Exajoule	10^{18}	1	$2.39x10^{17}$	$9.48x10^{14}$	0.948	$2.78x10^{11}$	23.5
Calorie	4.184	$4.184x10^{-18}$	1	$3.97x10^{-3}$	$3.97x10^{-18}$	$1.16x10^{-6}$	$9.82x10^{-17}$
BTU	1054	$1.06x10^{-15}$	252	1	10^{-15}	$2.93x10^{-4}$	$2.48x10^{-14}$
Quad	$1.054x10^{18}$	1.055	$2.52x10^{17}$	10^{15}	1	$2.93x10^{11}$	24.8
Kwhr	$3.6x10^{6}$	$3.6x10^{-12}$	$8.6x10^{5}$	3412	$3.412x10^{-12}$	1	$8.45x10^{-11}$
MTOE	$4.25x10^{16}$	0.0425	$1.02x10^{16}$	$4.0x10^{13}$	0.040	$1.18x10^{10}$	1

where MTOE = million tonnes of oil equivalent

2.5 Forms of Energy

It is useful to categorize the different forms of energy. We will be concerned with six forms of energy: mechanical, thermal, chemical, electrical, electromagnetic, and nuclear.

2.5.1 Mechanical Energy

The forms of mechanical energy are either kinetic energy or potential energy.

Kinetic energy is energy possessed by an object because of motion. A traveling bullet, a moving bus, and a wisp of breeze all possess kinetic energy. If an object moves faster, it possesses more kinetic energy. A bus traveling at 100 miles per hour possesses more kinetic energy than a bus traveling at 10 miles per hour. A heavier object has more kinetic energy than a lighter object traveling at the same speed. A baseball traveling at 100 miles per hour possesses less kinetic energy than a bus traveling at 100 miles per hour.

In order to permit assessments of kinetic energy, it is essential to quantify the relation between kinetic energy and the mass and speed of a moving object. The formula is as follows:

$$KE = 1/2mv^2 \qquad (2\text{-}3)$$

where

KE	=	kinetic energy
m	=	mass of the moving object
v	=	speed of the moving object

In the SI system, it is common to express mass in kilograms and speed in meters per second. If this is done, then the corresponding energy is expressed in Joules.

Example 2.2
Consider a 10-kilogram mass moving at 100 meters/second. The kinetic energy possessed by the mass is given by:

$$KE = 1/2 \times 10 \times 100^2$$

$$= 500{,}000 \text{ Joules.}$$

The result for this example can be converted to BTUs using the conversion factor of 0.948×10^{-3} *BTU per Joule to obtain 474 BTU.*

Potential energy is stored energy. Gravitational potential energy is stored energy of position. As we shall see, there are various ways to store energy, and, strictly speaking, there are various forms of potential energy. However, it is common usage to refer to gravitational potential energy simply as "potential energy." Other forms of potential energy, such as chemical energy, generally omit specification of the term "potential." We will follow convention and use the term "potential energy" as uniquely equivalent to gravitational potential energy.

A stone suspended above the ground possesses potential energy. If the stone is released, its potential energy is transformed into kinetic energy as it falls. Potential energy increases as the distance through which it responds to a force (gravity in this case) increases. A stone suspended 100 feet above the ground possesses more potential energy than the same stone suspended 10 feet above the ground. Heavier objects possess more potential energy than lighter objects held at the same elevation. A one-ton stone possesses 2,000 times as much potential energy as a one-pound stone located at the same height.

The formula for potential energy is as follows:

$$PE = mgh \tag{2-4}$$

or equivalently:

$$PE = Wh \tag{2-5}$$

where

PE	=	potential energy
h	=	height above a selected reference point (such as the surface of the earth)
W	=	weight of the object

If mass is expressed in kilograms, and height is expressed in meters, the corresponding energy unit is the Joule. If weight is expressed in pounds, and height is expressed in feet, the corresponding energy unit is the foot pound. As shown in Appendix B, the conversion between Joules and foot pounds is 1.356 Joules per foot pound.

Example 2.3
A 10-kilogram object suspended 10 meters above the earth has a potential energy of 980 Joules.

Now repeat the calculation in U.S. Customary units. A mass of 10 kilograms has a weight of 22.05 pounds. A height of 10 meters is equivalent to 32.81 feet. Therefore the potential energy is 22.05 × 32.81 = 723 foot pounds.

Using the conversion from foot pounds to Joules gives 721 × 1.356 = 980 Joules, thereby demonstrating the consistency between the different units of measure.

2.5.2 Thermal Energy

Hotter objects possess more thermal energy than cold objects of the same mass. Energy production and consumption processes often involve adding thermal energy to or removing thermal energy from a system so as to raise or lower its temperature or to induce vaporization or condensation.

A crucial question is, “How much energy must be added or removed in order to achieve a desired temperature change?” The relation between energy supplied or removed and the corresponding temperature change for a material is quantified by a property of matter called the specific heat capacity, abbreviated as C. It is defined in SI units as:

> C = heat (calories) required to change the temperature of one gram of material by one degree Celsius

or in U.S. Customary units:

> C = heat (BTU) required to change the temperature of one pound of a material by one degree Fahrenheit

For liquid water, the specific heat capacity conveniently has a value of 1.0 in both measurement systems.

The specific heat capacity of compressible fluids (gases and, to a slight extent, liquids) depends on whether the temperature change occurs at constant pressure or constant volume. If the process occurs at constant pressure, the fluid volume must increase when the temperature increases, and this increases the energy needed because of work performed on the surroundings. Specification of the specific heat capacity for compressible fluids requires two quantities: C_p, the specific heat capacity at constant pressure, and C_v, the specific heat capacity at constant volume. C_p is always larger than C_v.

Energy processes often involve vaporization or condensation. Vaporization requires an input of energy, and condensation results in a release of energy. Condensation of a given mass of vapor releases exactly the same amount of energy as that required to vaporize that material. This energy input or release is quantified by a physical property called the heat of vaporization, usually defined as the number of calories required to vaporize one gram of liquid or the number of BTUs required to vaporize one pound of liquid. The vaporization and/or condensation of water are frequently-encountered processes in energy-related considerations, and water’s heat of vaporization is uniquely large, with a value of about 540 calories per gram or 970 BTU per pound.

Freezing and melting also must be considered. Melting a solid object requires input of energy to the object, and freezing requires removal of energy from the object. This input or removal of energy is quantified by a physical property called the heat of fusion, usually defined as the number of calories required to melt one gram of frozen material or the number of BTUs required to melt one pound of frozen material. The heat of fusion of water is 79.7 calories per gram or 144 BTU per pound.

Vaporization/condensation and melting/freezing are constant-temperature processes. Therefore, if heat is applied to a solid at an initial temperature below its melting temperature, the temperature will rise to the melting temperature, stay at that temperature until all of the material melts, increase (while the material remains a liquid) until the vaporization temperature, stay at that temperature until all of the material vaporizes, then increase in temperature while the material remains a vapor (see Figure 2-1). Water heated above its vaporization temperature is very important in steam power plants and is called superheated steam.

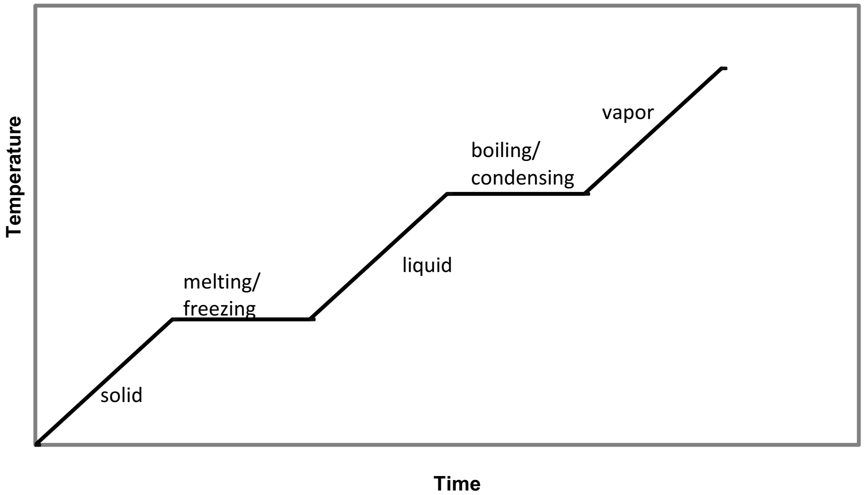


Figure 2-1. Temperature Variation of a Heated Object

Transferring heat from one material to another occurs in many energy-related processes. Heat transfer is an engineering discipline with great depth and complexity, but understanding the three mechanisms of heat transfer suffices for the development of an understanding of energy fundamentals. The three heat transfer mechanisms are conduction, convection, and radiation, defined as follows:

> Conduction: Transfer of heat through a stationary material as a result of a temperature difference within the material.
>
> Convection: Transfer of heat through a fluid as a result of internal movement of the fluid.
>
> Radiation: Transfer of heat as a result of emission, propagation, and absorption of electromagnetic radiation.

The familiar concept of temperature arises often in thermal energy considerations. The two common temperature measures are the Celsius scale and the Fahrenheit scale. The following formulas permit conversion between these scales:

$$T(^{o}F) = 1.8 \times T(^{o}C) + 32 \qquad (2\text{-}6)$$

and

$$T(^{o}C) = [T(^{o}F) - 32]/1.8 \qquad (2\text{-}7)$$

where

$T(^{o}F)$ = temperature in degrees Fahrenheit
$T(^{o}C)$ = temperature in degrees Celsius

The concept of absolute zero temperature also arises in thermal energy considerations.

Molecular motion in a material depends on temperature, with greater motion at higher temperatures. Absolute zero is the temperature at which all molecular motion stops. Temperatures below absolute zero are impossible. Absolute zero temperature occurs at approximately -459.67 degrees Fahrenheit and -273.15 degrees Celsius. Two additional temperature scales have been created to facilitate working with absolute temperatures. They are as follows:

$$\text{Kelvins} = {}^{o}\text{C}+273.15 \tag{2-8}$$

$$\text{Degrees Rankine} = {}^{o}\text{F}+459.69 \tag{2-9}$$

Note the special case of the kelvin designation instead of degrees Kelvin. This special consideration was created in honor of Lord Kelvin, a pioneer in thermal energy physics.

2.5.3 Chemical Energy

Chemical elements are held together by forces to form molecules. When a chemical reaction takes place, molecules combine and/or dissociate (split apart) to form new molecules. If the forces holding the new molecules together are smaller than the forces holding the original molecules together, energy is liberated in the form of heat. This is what happens when an object burns (combines with oxygen). There is a quantity of thermal energy released for every pound (or gram) of combustible material that burns, and it is specific for each different material.

Materials that are suitable for use as fuels or as materials that can be converted into fuels include carbon, hydrocarbons, carbohydrates, alcohols, esters, and ethers. The chemistry of these materials and the transformations that can occur in them are complex matters that have occupied chemists for many years. As noted above, when these materials burn, energy is released. Oxides of carbon (carbon dioxide in complete oxidation and carbon monoxide in incomplete oxidation) and water (in the combustion of compounds containing hydrogen) are formed.

A measure of the usefulness of a fuel is its heating value, the energy released when the fuel burns (see Appendix C). Heating value is expressed in units of energy per unit weight or mass, commonly BTU per pound or calories per gram. It is necessary to specify two different heating values for a fuel, depending on the state (liquid or vapor) of the reaction products. The burning of hydrocarbons, carbohydrates, or alcohols produces water and carbon dioxide. Carbon dioxide is a gas at the normal operating temperatures of energy processes, but water may exit the reaction as a vapor or a liquid. Since energy is required to go from a liquid to a vapor, more energy is available for release when the water produced is in the liquid state. The High Heating Value (HHV) is applicable to processes whose final temperature causes the water produced to be liquid. The Low Heating Value (LHV) applies when the water produced is a vapor. For example, gasoline has a High Heating Value of 125,071 BTU per gallon and a Low Heating Value of 115,500 BTU per gallon. Appendix C gives heating values for important fuels.

2.5.4 Electrical Energy

Electricity is the flow of an electrical current due to a voltage difference. Electricity is a convenient means for transporting energy but is not an energy source *per se*. Electricity is an energy carrier. An important and unique feature of electrical energy is there must be an exact balance between the production of electricity and the use of that electricity. Balancing production with demand is a continuous requirement in electrical grids.

Atoms have electrical charges on their nuclei, and the electrons swarming around the nucleus have electrical charges on them. The charge on the nucleus and the electron charge differ in that they attract one another. For labeling purposes, we say the nucleus is positively charged, and the electrons are negatively charged.

Electricity is simply the motion of charges. Since this charge motion can be transformed into mechanical, chemical, or heat energy, it is very important as an energy carrier.

Electrical energy is closely related to magnetism. Both produce fields. A field is a region influenced by a force. Placing a magnet beneath a sheet of paper on which iron filings are dispersed is a familiar demonstration of a magnetic field.

Electricity can be produced in a conductor by a time-varying magnetic field. As might be expected, the reverse process also occurs. Magnetism can be produced by time-varying electric charges (an electric current). An electromagnet is simply an iron rod or bar wrapped in a coil of wire through which an electrical current is flowing.

Electric generators are machines that move a conductor through a magnetic field. The principle is easily demonstrated by passing a copper wire between the poles of a horseshoe magnet (see Figure 2-2). This phenomenon is manifested in huge machines that generate millions of watts of electricity, but the basic idea is still relative motion between a conductor and a magnetic field.

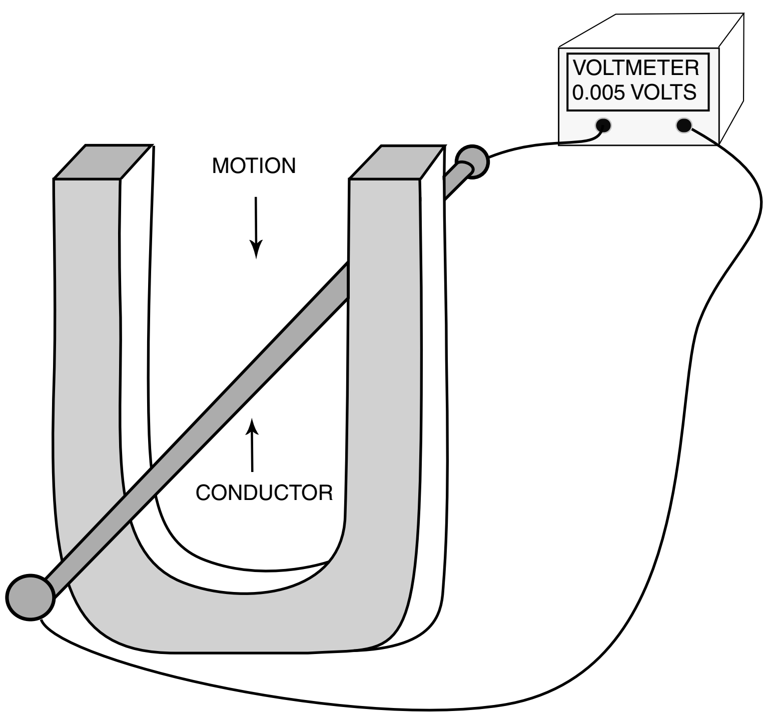


Figure 2-2. A Simple Electric Generator

Electricity is quantified by four main measures:

- Electromotive Force (EMF) is a measure of the force that causes electrical charges to flow.
- Current is a measure of the rate at which electrical charges flow.
- Resistance is a measure of a material's tendency to retard the flow of electric current.
- Electrical power is the rate at which the electrical energy flows as a result of an electrical current.

The common units of measure for these quantities are volts for EMF, amperes for current, ohms for resistance, and watts for power. Their interrelationships are given as follows:

$$I = V/R \tag{2-10}$$

$$P = V \times I \tag{2-11}$$

where

I	=	current in amperes
V	=	EMF in volts
R	=	resistance in ohms
P	=	power in watts

The way to think about this is as follows: Voltage causes current to flow. The magnitude of the current due to a voltage is determined by the resistance of the material through which the current flows. The power is the consequence of the current flow.

Example 2.4
Consider a 100-ohm resistor connected to a six-volt battery. The current flowing in the circuit is 6/100 = 0.06 amperes. The power dissipated (converted into heat) in the resistor is 6×0.06 = 0.36 watts.

Batteries and capacitors are energy storage devices. Batteries function by the conversion of stored chemical energy to electrical energy and vice versa (in the case of rechargeable batteries). Capacitors function by the storage of electrical charges on conductors separated by a non-conducting material called a dielectric. When a direct current voltage is applied to a capacitor, a positive charge builds up on one conductor, and a negative charge builds up on the other. When the voltage is removed, the charges remain. When the two sides of a charged capacitor are connected through a conductor, the stored charges flow through the conductor. Batteries and capacitors are useful for storing electrical energy when it is available and delivering the electricity when it is needed.

2.5.5 Electromagnetic Energy

Electromagnetic (EM) energy is visible light and its close relatives such as infra-red light, ultra-violet light, and x-rays. An example is the heating effect of the sun's rays. This is heating due to electromagnetic radiation that travels at very high speed (186,000 miles per second) from the sun to you. The radiation is absorbed by your skin and results in heating.

Electromagnetic energy is somewhat harder to visualize than other forms of energy, but knowledge about its characteristics is well established. Light and other forms of EM energy travel in packets of oscillating electric and magnetic fields. These energy packets, called photons, constitute the sunlight that makes life possible on earth. All other forms of EM energy also travel in photons.

Since the fields oscillate, photons may be characterized by their frequency of oscillation or, correspondingly, their wavelength. Each photon carries a fixed amount of energy that depends on its frequency. These photons travel through space (including vacuums) indefinitely until they interact with matter. Photons can interact with electrons in atoms, and, in so doing, transfer energy to the electron. An important phenomenon is the transfer of an amount of energy sufficient to cause the electron to escape from the atom. This is called the photoelectric effect, a phenomenon that is exploited in solar cells.

2.5.6 Nuclear Energy

While chemical reactions involve the electrons that swarm around atomic nuclei, nuclear reactions involve the nuclei themselves. Certain heavy nuclei (those with high atomic mass) can be made to split apart (fission), and this process releases energy. Certain light nuclei (those with a low atomic mass) can be made to join together (fusion), and this also releases energy. The energy released in a fission or fusion reaction is due to a transformation of mass into energy.

The conditions, materials, and arrangement needed to make a practical energy-producing fission reactor are well-known, practical, and in routine use. Achieving the conditions, materials, and arrangement for a practical fusion reactor is much more difficult, and a practical energy-producing fusion reactor has not yet been built.

Radioactive nuclei spontaneously undergo transformations that yield new daughter nuclei and emissions, usually alpha particles, beta particles, or gamma rays. These products of radioactive decay possess kinetic energy that degrades to thermal energy by interaction with matter. If the matter is human tissue, then ionization by the radiation can cause cell damage, and disease may result. If the matter is the material deep within the earth, then geothermal heating occurs.

2.5.7 Relationships Between Energy Forms

Practical energy processes almost always have heat and/or mechanical energy as the desired end products. There are exceptions, such as lighting, electrolysis, and electroplating, but these processes are much less significant parts of total energy use than heat and mechanical energy.

Example 2.5
Consider an elevator that is driven by a motor that is connected to an electric grid powered by coal-burning power plants. The following five transformations take place, from the chemical energy initially stored in the coal to the desired end product, raising the elevator:

1. *Chemical to thermal (burning the coal)*
2. *Thermal to kinetic (in the steam turbine)*
3. *Kinetic to electric (in the generator)*
4. *Electric to kinetic (in the elevator's motor)*
5. *Kinetic to potential (raising the elevator)*

Another important example is the hydrogen-powered car. Free hydrogen does not exist in nature. It can be made by processing hydrocarbons or carbohydrates or by processing water by electrolysis. Hydrogen from water is probably the process that will be used if hydrogen use ever becomes commonplace in energy systems. Electrical energy is used to break the chemical bonds holding hydrogen and oxygen together in water, thereby creating stored energy in the hydrogen. Hydrogen provides energy storage and energy transport capabilities. Hydrogen certainly has a potential for widespread use in the energy enterprise, but it clearly is an energy carrier, not an energy resource. (See Chapter 12.)

2.6 Energy Utilization

Obtaining energy in a useful form usually involves transforming an available form of energy into the desired form of energy.

Heat is obtained by the transformation of other forms of energy. Processes for obtaining heat range from standing in the sun (transforming electromagnetic energy into heat energy) to the combustion of hydrocarbons (transforming chemical energy into heat energy) to nuclear fission or fusion (transforming nuclear energy into heat energy). The heat may be used directly or for inducing desired changes in material properties.

Engines are devices for obtaining mechanical work from a non-mechanical energy source. For example, an electric motor is an engine for obtaining mechanical work from electric energy.

Heat engines are devices for obtaining mechanical work from heat energy. The development of heat engines made the industrial revolution possible, and they are essential for maintaining modern society. In heat engines, mechanical work is obtained by motion that is induced by a pressure difference which is, in turn, induced by appropriate heating and cooling. The main types of heat engines are internal combustion piston engines and internal and external combustion turbines (Stirling engines, a type of external combustion piston engine previously used infrequently, may yet see increased use in solar power systems).

Consider an internal combustion piston engine. It consists of one or more cylinders, each containing a piston and a means for injecting fuel and air and achieving ignition by a spark or by heating caused by vapor compression when the piston is near the closed end of the cylinder (see Figure 2-3). The resulting explosion results in high temperature gaseous combustion products. This creates high pressure on the face of the piston. Since the opposite side of the piston experiences lower pressure, the pressure difference drives the piston away from the closed end of the cylinder. The piston is connected to a crankshaft and delivers mechanical energy to it. In automobile engines, the mechanical energy propels the car, provides energy for operating accessories, and provides energy for venting combustion gases and for compressing the fuel-air mixture.

Now consider the steam or gas turbine. A turbine is essentially a set of fan blades mounted on a shaft. Shaft rotation is induced by fluid flowing through the turbine. For steady operation, a constant pressure difference must be maintained across the turbine. In a steam turbine, heat is supplied to vaporize water (and possibly further heat it into a superheated condition) on the upstream side, and cooling is supplied on the downstream side to

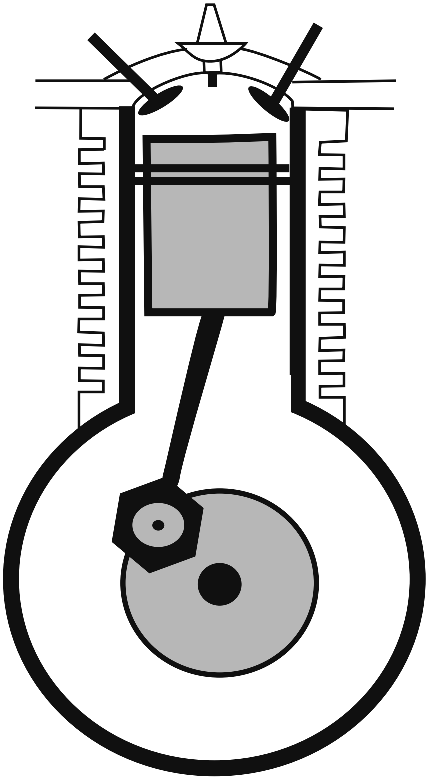


Figure 2-3. Cylinder of an Internal Combustion Engine

condense the steam that exits the turbine. This provides the pressure difference that induces steam flow through the turbine. Gas turbine operation is similar. Heat energy is supplied to a gas on the upstream side of the turbine. The downstream pressure is maintained at a lower pressure by venting to the atmosphere or by cooling the exhaust gas.

Jet engines are turbines in which fuel combustion occurs within the engine. Hot gases resulting from combustion provide thrust upon exiting the engine. In turbojet and turbofan jet engines, the exhaust gas drives a turbine that is mounted on the same shaft as a compressor at the engine entrance.

A third type of heat engine is the Stirling engine. The Stirling engine can use any high temperature heat source to power the engine. The initial invention of the Stirling engine occurred in the early nineteenth century, but its implementation has been limited. However, implementation may now increase because it is well-suited for use as a component of solar heat engines. The basic idea of a Stirling engine is to cause a contained gas to move back and forth between a heated section and a cooled section. Pistons in each section turn a flywheel whose angular momentum serves to keep the process going when energy is not being delivered by the pistons. Since Stirling engine operation is somewhat involved, a discussion of operating principles appears in Appendix D.

Heat engines that operate with the working fluid circulating in a closed loop are called closed-cycle heat engines (such as Stirling engines or steam turbines), and those that exhaust the working fluid after one pass through the system are called open-cycle heat engines (such as automobile, truck, and jet engines).

The common use of the output of a heat engine is to drive a generator. Large electric generators used in power plants are machines that create electricity by rotating conductors through a magnetic field. Figure 2-4 shows the rotating portion of a large steam turbine that is used to drive a generator in an electric power plant.

2.7 Energy Efficiency

Many processes that are essential to modern civilization involve the conversion of energy from one form to another. Kinetic energy is transformed into electrical energy by a generator, electrical energy is transformed into kinetic energy by a motor, chemical energy is transformed into electrical energy by a battery, etc. In all these transformations, the desired transformation is always accompanied by a second (usually undesired) transformation into heat, with the attendant release of this heat energy to the environment. This heat can sometimes be put to use (space heating or water heating with waste heat is sometimes done), but it is usually considered waste to be disposed of. It must be concluded that heat energy is less valuable for practical applications than the other forms of energy.

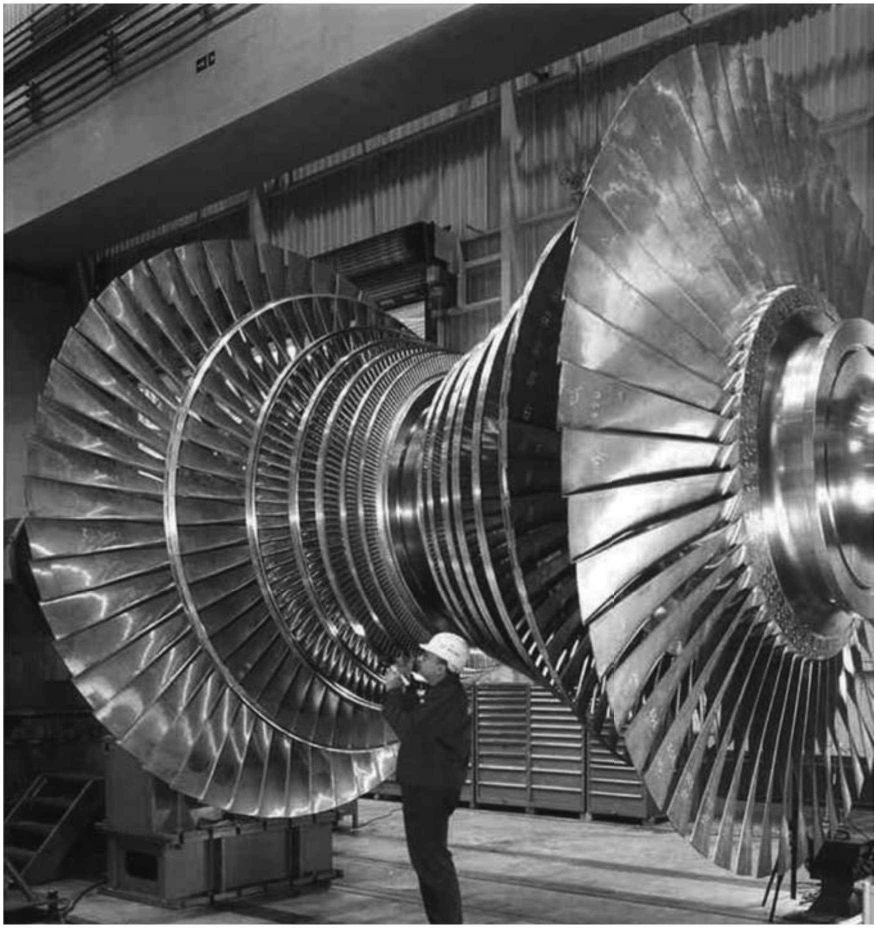


Figure 2-4. Internals of a Large Steam Turbine (courtesy of Siemens)

Furthermore, while other forms of energy can be transformed entirely into heat energy, it is not possible to transform heat energy entirely into one of the other forms of energy. In addition, the heat remaining after a partial transformation into another form of energy is less useful than was the heat initially. Operation of heat engines always results in only part of the heat energy being converted into mechanical energy, with the rest of the energy being dissipated as lower grade energy (heat). The efficiency of a heat engine is defined as the fraction of the heat energy applied that can be converted into mechanical energy. A very simple and useful principle reveals the maximum efficiency with which thermal energy can be converted into mechanical energy. The maximum possible efficiency is given by the following:

$$e = (T_h - T_c)/T_h \tag{2-12}$$

where

e	=	maximum efficiency
T_h	=	absolute temperature at which heat is added to the system
T_c	=	the absolute temperature at which heat is removed from the system

Example 2.6
Consider a heat engine in which the heat is added at 500 ^oC and heat is removed at 0 ^oC. Conversion to absolute temperatures gives $T_h = 500+273 = 773$ kelvins and $T_c = 0+273 = 273$ kelvins. The maximum achievable efficiency is given by

$$e = (773-273)/773 = 0.65$$

Practical heat engines have lower efficiencies than the maximum efficiency because of energy losses within the system.

2.8 Energy Balances

Acquiring, processing, storing, and transporting fuels require an expenditure of energy. A measure of the value of a fuel is the energy available from using the fuel compared to the energy required to get that fuel. The "energy balance" for fuels is expressed in several different ways, reflecting the preference and purpose of the analyst involved. Here, a measure called the Energy Ratio will be used to illustrate the concept. It is defined as follows:

Energy Ratio = (Energy available in fuel)/(energy consumed in getting fuel)

Even this simple definition may have different interpretations. For example, the energy balance may or may not include factors such as energy expended to transport or store the fuel or raw material used to produce the fuel.

If the energy ratio is less than one, more energy is consumed in all of the activities required to get the fuel than can be obtained by burning the fuel. Large values of energy ratio are desirable.

A refinement of the energy ratio concept takes into account the "value" of the energy used in getting the fuel versus the "value" of the fuel. For example, liquid fuels are said to be more "valuable" than solid fuels because of their transportability and ease of use, and using domestic energy for getting fuel is said to be more "valuable" than using imported energy.

Since the concept of energy balance is most often used in assessing liquid fuels, it is informative to consider only the consumption of liquid fuels in producing liquid fuels. To maintain clarity, we define the Liquid Energy Ratio as follows:

> Liquid Energy Ratio = (Energy available in liquid fuel produced)/(energy consumed from liquid fuel in getting produced fuel)

2.9 A Little Chemistry

2.9.1 Atomic Structures

As has been mentioned, atoms consist of a central nucleus surrounded by electrons. The nucleus is composed of protons and neutrons (except in the case of hydrogen which lacks neutrons in its most common isotopic form). Protons and electrons are electrically charged, and neutrons are electrically neutral. The arbitrarily adopted convention on electrical charge is positive for protons and negative for electrons. An atom has equal numbers of protons and electrons, rendering the atom electrically neutral.

Electrons form a fast-moving cloud of negatively-charged particles around the central nucleus. The attraction of the positively-charged nucleus prevents the electrons from flying away. The electrons can possess only discrete energies, and the number of electrons in each energy state is limited. The allowable energy states are called shells. For example, the maximum number of electrons in the lowest energy shell, which is closest to the nucleus, is two. The second shell is populated after the first shell is full and contains up to eight electrons. Additional shells, each with its own maximum electron population, contain the remaining electrons in the atom. The most stable (chemically inert) atoms are those whose outer shells are filled to the maximum allowable electron population.

2.9.2 Molecular Structures

Atoms combine to form molecules. Molecules may be combinations of atoms of the same type or of dissimilar atoms. The formation of molecules depends on the outer electrons in atoms, called the valence electrons. If the number of valence electrons is less than the maximum number that the outer shell can hold, the atom can interact with other available atoms to increase or decrease the outer shell electron population to achieve a filled outer shell.

Electrons may be taken from or given to other atoms to provide filled outer shells. These bonds are called ionic bonds. Electrons may also be shared between participating atoms to provide filled outer shells. These bonds are called covalent bonds.

The chemical properties of compounds depend on the arrangement of atoms in the molecules as well as on the atomic composition of the molecules. Molecules may be linear, branched, or ring-shaped. Larger molecules have complex three-dimensional shapes. Chemists have devised diagrams for depicting molecular structures. These diagrams may simply show the connections between atoms in the molecules or they may show the three-dimensional configurations. See Figure 2-5 for some diagrams that show the connections between the atoms in selected molecules.

Molecules with the same composition but different arrangements of atoms are called isomers. For example, consider propanol, an alcohol with three carbon atoms. Figure 2-6 shows the two isomers of propanol, one with an OH group attached to an end carbon atom and the other with an OH group

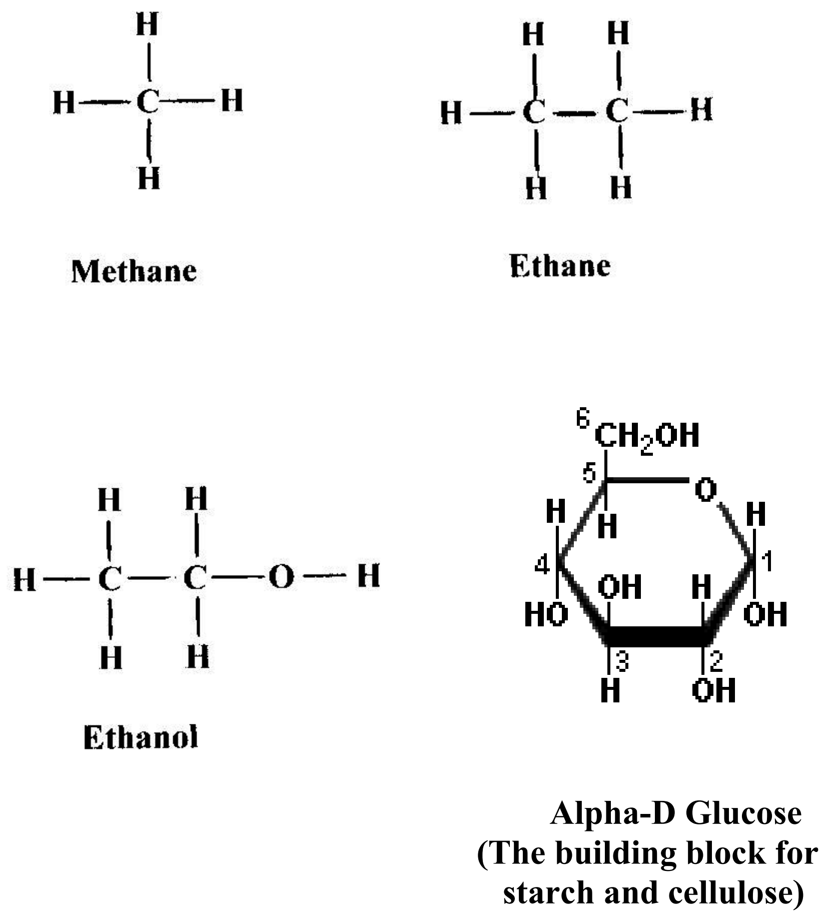


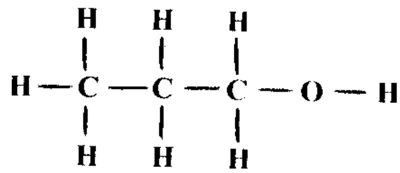
Figure 2-5. Some Molecular Structures

attached to the middle carbon atom. Larger atoms have the possibility of multiple isomers, all with the same composition but different properties.

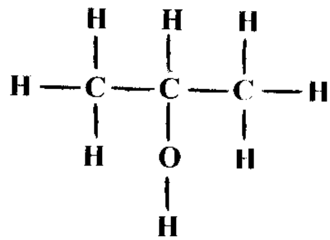
2.9.3 Chemical Separations

Processing raw materials to obtain desired liquid fuels often involves separating the components of a mixture. The most important separation technologies in producing liquid fuels are distillation and solvent extraction.

Distillation uses differences in the boiling points of the components of a mixture to separate them. Petroleum processing and alcohol production



1-Propanol



2-Propanol

Figure 2-6. Structures of Propanol Isomers

rely on distillation to yield desired products. Heating a mixture of volatile components yields a vapor that is richer in the component with the lower boiling point. Greater differences in the boiling points of the constituents result in higher concentration of the low boiling point component or components in the vapor.

Sometimes, the vapor is rich enough in the desired product that condensation of the vapor achieves the desired separation. However, the boiling point differences are often insufficient to yield a pure enough product. To obtain a pure enough product, one might consider further purification by condensing the vapor, then heating the resulting liquid to induce vaporization of the new mixture, which is already richer in the low boiling (that is, low boiling point) component. Repetition of the vaporization/condensation cycle yields greater and greater separations.

Repetitive vaporization and condensation can be accomplished in a single system, called a fractional distillation column. In such a column, there is a steady downflow of condensed liquid and an upflow of vapor in contact with one another. Separation of multiple components in a mixture may be accomplished by withdrawing material at different locations along the column.

Solvent extraction involves moving a dissolved chemical from one solvent to another. The dissolved substance will distribute itself between two solvents according to its solubility in those solvents when the two solvents are mixed. Moving the dissolved substance into a new solvent creates new opportunities for further processing.

2.9.4 Isotopes

The chemical properties of an element are determined by the number of electrons in the atom, which equals the number of protons in the nucleus. The nucleus, however, contains neutrons as well as protons. These neutrons do not have much effect on chemical properties, but they do affect nuclear properties, most notably radioactivity and the tendency to undergo nuclear reactions such as neutron absorption. Atoms with the same number of protons but differing numbers of neutrons are called isotopes. Some isotopes occur in nature, and many others are produced in nuclear reactors.

2.9.5 Catalysts

Catalysts are substances that facilitate chemical reactions without being consumed in the process. A catalyst can speed reactions that would proceed slowly or not at all in the absence of the catalyst. Specific reactions require specific catalysts. Finding effective and practical catalysts to facilitate desired chemical reactions is often the deciding factor in determining the viability of a process.

Catalysts can provide selectivity when two or more reactions are possible among the chemicals present. The physical state of the catalyst can influence selectivity. For example, pore sizes in catalysts can be controlled, and this allows smaller molecules to enter the pores and to interact with the catalyst while larger molecules are excluded.

2.9.6 Electrochemistry

Electrochemistry deals with the conversion of chemical energy into electrical energy and with chemical reactions that occur because of an electric current.

Batteries use fixed quantities of chemical reactants to produce electricity, while fuel cells use constantly replenished quantities of reactants. Fuel cells can operate with hydrogen or methane and oxygen (from air) as reactants. Fuel cells are under consideration for mobile applications in vehicles and in stationary applications for local electricity production. New systems are available that provide enough locally-produced electricity to reduce or eliminate the need for electricity from the grid. However, the fuel of choice for these systems, natural gas, still produces carbon dioxide (a greenhouse gas) when used in a fuel cell.

Application of an electric voltage across a fluid can cause compounds in the fluid to dissociate. This process is called electrolysis. The separation of the hydrogen and oxygen in water is a special case of electrolysis. The reaction may be represented as follows:

$$2H_2O + \text{energy (direct current electricity)} \rightarrow 2H_2 + O_2$$

Electrolysis is a potential method for producing large quantities of hydrogen for use in future energy systems.

Electrolysis is also important in producing certain chemicals, including sodium, potassium, chlorine, fluorine, and aluminum.

Electrolysis is the basis for electroplating, the deposition of metals on an electrode. The process usually involves the deposition of precious metals on less valuable substrates.

Electrochemical reactions also result in the corrosion of metals, as in the formation of rust on iron.

Electrolysis is a potential option for producing materials with processes that are now dependent on energy from fossil fuels. Industry may find it advantageous to switch to greater use of electrical energy in its processes. The electrification of industry will stimulate research to find new, economical ways to produce materials by electrolysis. For example, conversion of iron ore into iron metal by electrolysis has been demonstrated in laboratory work, and efforts to develop economical, large-scale processes are under way.

2.10 A Little Biology

2.10.1 Introduction

Biology is the science of living things: plants and animals. For energy considerations, plant biology is the issue of greatest interest. Plants manufacture biomass, an assortment of compounds composed mostly of carbon, hydrogen, and oxygen. Biomass can produce heat energy directly by burning, but the current main focus is on converting biomass into liquid or gaseous biofuels because of their portability.

2.10.2 Photosynthesis

Photosynthesis is the process by which plants use energy from the sun to convert water and atmospheric carbon dioxide into carbohydrates. The electromagnetic energy in sunlight is converted into chemical energy stored in the plant matter. The biochemical processes in photosynthesis are complex, but the net reaction is as follows:

$$6CO_2+6H_2O+\text{solar energy} \rightarrow C_6H_{12}O_6+6O_2$$

The product shown in this reaction is a simple sugar. Further biochemical reactions convert these simple sugars into larger organic molecules.

The continual replacement of carbon dioxide with oxygen in the atmosphere by photosynthesis is essential for animal life.

The photosynthesis reaction begins with absorption of solar photons by chlorophyll, the green pigment in plants. However, chlorophyll can use only light with certain wavelengths. Green light is reflected (that is why plants look green to us). Chlorophyll is able to use photons with wavelengths that are lower or higher than the wavelength corresponding to the color green. Plants can use only a portion of incoming solar energy because of this selectivity, because of inhibition of photosynthesis by plants in excessive sunlight, because of an inadequate or excessive water supply, because of inadequate trace minerals needed for plant growth, and because of shading from the upper parts of the plant. Typical farm plants grown in America can use one to two percent of incident solar energy, but some plants are much more efficient than others.

One of the major factors in determining plant growth rates is the concentration of carbon dioxide. Plants grow much faster in a CO_2-rich environment.

Algae, simple plants that grow in water, are also a potential source of material for energy production. Algae are fast-growing, and some produce large quantities of oils that can serve as fuel.

2.10.3 Carbohydrates and Energy Storage

When biomass burns, the carbohydrates undergo a reaction that is the reverse of the photosynthesis reaction. For example, oxidation of hexose sugar, a simple carbohydrate, proceeds as follows:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

The energy released in this reaction is equal to the energy initially received by the plant during photosynthesis to create that quantity of biomass.

2.10.4 Oils and Energy Storage

Plants also produce oils. Chemically, these oils are compounds called triglycerides (see Appendix L). Triglycerides are compounds with a three-carbon spine to which are attached long chains of fatty acids. Fatty acids are chemical structures composed of carbon chains with hydrogen attached to all of the carbon atoms except for one carbon connected to a hydroxyl radical (a hydrogen-oxygen combination). Triglycerides will burn, resulting in conversion of the carbon and hydrogen atoms into carbon dioxide and water. Some terrestrial plants and some algae produce oils that can serve as fuel.

2.10.5 Enzymes

An enzyme is a specialized protein molecule that enables or hastens a biochemical reaction without being consumed in the process. In chemical terms, an enzyme is a form of catalyst.

2.10.6 Biofuels from Biomass

As we shall see in Chapter 7, the carbon and hydrogen (and sometimes the oxygen) in biomass can be converted into other compounds, mainly hydrocarbons and alcohols. Oxidizing these compounds releases chemical energy in the form of heat energy (and, of course, a small amount of electromagnetic energy in the form of light). However, it is very important to remember these compounds can release no more energy than was initially absorbed from sunlight.

2.11 Linear vs. Exponential Growth

An intuitive feel for the impact of exponential, rather than linear, change is important in assessing future energy requirements and the adequacy of various energy resources.

Many people tend to think that changes occur in a linear fashion. In linear growth, the rate of growth is proportional to the *initial* value of whatever is being considered. It is natural to think that an increase in some quantity that is observed in one year will repeat in the following year. In exponential growth, the rate of growth is proportional to the *current* value of whatever is being considered. That is:

$$dQ/dt = aQ \tag{2-13}$$

where

Q	=	the quantity under consideration
dQ/dt	=	the rate of change of the quantity under consideration
a	=	a constant

The solution of this differential equation is:

$$Q = Q_0 e^{at} \tag{2-14}$$

where

Q_0	=	initial value of the quantity under consideration

It can be shown that the time required to double the quantity under consideration is given by

$$t_d = 0.693/a \tag{2-15}$$

where

t_d	=	doubling time

Note that the rate of increase also doubles when the quantity under consideration doubles.

Intuition often fails in assessing changes in processes that grow exponentially. Consider the following examples:

Example 2.7
A city with a population of 1 million had a population growth of two percent or 20,000 people in the first year of our accounting. If the subsequent growth were linear, the population would double in 50 years. On the other hand, exponential growth would result in a doubling of population in 35 years, and the rate of increase would be 40,000 per year at that time. Exponential growth usually applies to populations

because birth rates are proportional to the current population, not some previous population.

Population, oil consumption, computer speed, and U.S. automobile production are examples of quantities that grew exponentially during at least part of their histories. Many people fail to appreciate how much faster things change in exponential growth compared to linear growth. One important case is assessing oil consumption. We will see in Chapter 4 that 1/3 to 1/2 of the oil originally in the ground has been used in the last hundred years, and that growth in consumption has been exponential. If the exponential growth continues, the remaining oil will be consumed much faster.

2.12 Energy Information on the Internet

Internet sources include a wealth of information on energy and its use. In fact, the quantity of information is a bit overwhelming. This book is an attempt to collect and organize energy information in a way that facilitates an efficient journey to an understanding of the subject. Nevertheless, it is anticipated that many readers will want to dig deeper. Some of the most important energy-related websites are listed below. They contain useful information and provide Internet links to the rest of this huge resource. The energy-related websites include official government-sponsored sites, sites sponsored by non-profit interest groups such as technical societies and universities, sites operated by advocates of various energy technologies and policies, and sites operated by energy-related businesses. A few of the most important websites are shown below. A more complete list of energy-related websites appears in Appendix E.

http://www.whitehouse.gov/energy is the website for the National Energy Policy.

http://www.energy.gov is the U.S. Department of Energy website. This site contains links to a wealth of energy-related sites, for DOE facilities and for external links. Key DOE sites are for the Energy Information Administration at http://www.eia.doe.gov and for the Office of Scientific and Technical Information at http://www.osti.gov. The USDOE also supports energy centers in the national laboratories and some universities, each with their own websites, which can be found through the main DOE website. One such laboratory is the National Renewable Energy Laboratory: http://www.nrel.gov.

http://www.usda.gov is the U.S. Department of Agriculture website. This site contains links to sites with information about biofuels.

The U.S. Geological Survey, a branch of the U.S. Department of the Interior, maintains a website at http://www.usgs.gov. It contains information about energy resources.

http://www.worldwatch.org is the website for the Worldwatch Institute, an organization that assesses worldwide challenges, including energy availability.

The World Energy Council (WEC) is an organization concerned with energy issues throughout the world. The WEC is said to be UN-accredited, non-government, non-commercial, and non-aligned. Its website is http://www.worldenergy.org.

British Petroleum compiles and disseminates a wealth of useful energy statistics. The BP website is http://www.bp.com.

http://www.newamericancentury.org is the website for a conservative organization that takes a stand on various issues. One such issue is U.S. military strategy. This pertains to energy policy in that use of U.S. military power to ensure the continued availability of foreign oil is not inconceivable to some who possess political power.

http://www.nrdc.org is the website for the Natural Resources Defense Council, an environmental group whose agenda includes energy issues.

2.13 Energy Facts vs. Energy Fiction

There is a large body of useful and valid information about energy production and consumption available to the interested reader. But there are also sources that provide misinformation. One must exercise caution in accepting "facts" presented in the literature or on the Internet.

Exercises

2-1. A force of 10 Newtons is applied to a mass of 10 grams. What would be the acceleration of the mass? (Express results in meters/sec^2 and in ft/sec^2.)

2-2. A 3,000-pound car is brought to a stop from 40 miles per hour by regenerative braking. How much energy is transferred to the braking system? (Express results in foot pounds, BTUs, and Joules.)

2-3. A man has a mass of seven slugs. What does he weigh on the surface of the earth (in pounds and in Newtons)?

2-4. How many BTU per hour of electricity are delivered by a power plant that delivers 1,000 megawatts of electricity?

2-5. How much energy (in BTUs and kilowatt hours) is required to increase the speed of a 100-pound object from 10 feet per second to 20 feet per second?

2-6. A 100-pound object is dropped from a height of 10 feet. How fast is it traveling when it hits the earth? (Ignore air resistance.)

2-7. 100 pounds of 70°F water and 100 pounds of ice are each heated to produce 100 pounds of steam. Compare the energy required for each process.

2-8. How much current is used to power a 1-watt light bulb with a 9-volt battery?

2-9. A radioactive material decays exponentially. The radiation drops to half of its initial value in one week. What fraction of the initial radioactivity will remain after eight weeks?

2-10. All heat engines rely on pressure differences to achieve gas flows. Discuss the relation between this fact and the efficiency of converting heat energy to mechanical energy.

2-11. A coal-fueled power plant produces 1,000 megawatts of electricity in winter when the cooling water fed to the condenser is at 50°F. Estimate the power production in summer when the cooling water temperature is at 80°F.

2-12. A rectangular bathtub is four feet long and two feet wide. Water is heated from 60°F to 120°F in an electric water heater. How much energy (in BTUs and in kw-hours) is required if the tub is filled to a depth of six inches? What is the cost for energy to fill the tub if electricity costs 11 cents per kilowatt hour? Assume no energy loss within the system.

2-13. A thermal power plant operates at 35 percent efficiency and produces 1,000 megawatts of electricity. The waste heat is dumped into a river flowing at 50,000 cubic feet per second. Estimate the temperature rise in the river.

2-14. An inventor submits a proposal to a government agency for funding to develop a car that uses water as a fuel. He proposes using a hydrogen fuel cell to produce electricity to be used both for propulsion and for producing the hydrogen used in the fuel cell. Should he receive the funding? Why or why not?