Future Energy: Opportunities and Challenges

APPENDICES

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Opportunities and Challenges

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APPENDICES

APPENDIX A: MASS AND WEIGHT

This appendix addresses the proper use of measures of mass and weight in the mathematical formulas that express the laws of physics. The proper handling of these measures is quite simple, but confusion and misuse are commonplace. The discussion begins with a discussion about mass and weight for the SI system (for Système International d'Unités) followed by a similar discussion for the U.S. Customary system. The awkward U.S. Customary system label is often shortened to the American system.

Definitions of terms for SI units involved in the following discussion appear below:

- Mass: A measure of an object's tendency to maintain its state of motion (inertia)
- Weight: The force on a body of a certain mass due to gravity
- Kilogram of mass: Declared mass of a metal block stored in Paris (approximately equal to the mass of 1,000 cubic centimeters of water)
- Meter of length: Originally defined as length of a metal rod in Paris. Currently defined as the distance travelled by light in a specific time interval
- Second of time: Declared as 1/86,400 of the mean solar day (86,400 = the number of seconds in a day)
- Newton of force: Force capable of accelerating one kilogram by one meter per second per second
- Joule of energy: One Newton-meter
- Watt of power: One Joule per second

First, let us consider potential energy. Newton's Second Law says that force is mass times acceleration:

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

The work done by the application of a force is the force times the distance moved, d:

$$W = Fd \tag{A-2}$$

Since energy is defined as the capacity to do work, the potential energy of a body experiencing a force is the work that would be done if the body were released to respond to the force. For example, an object held at some height above the surface of the earth experiences gravitational force that would accelerate the object toward the surface if the object were released. The force on the object would be:

$$F = mg \tag{A-3}$$

where:

g = the acceleration due to the gravitational force

The weight of an object is the force due to gravity.

The work done by the falling object (equal to the potential energy change of the object) would be:

$$E = mgd \tag{A-4}$$

At this point, it is necessary to define the quantities in Equation A.4. The SI system (also called the MKS system) uses meters, kilograms and seconds for units of length, mass and time. All of these quantities were arbitrarily assigned. The acceleration of gravity, g, is a measured quantity that depends on where it is measured. Values of g on the surface of the earth vary slightly with location because of small variations in the earth's diameter and com-

position. A good representative value is 9.81 meters per second per second. (An object falling under gravitational force will increase its velocity by 9.81 m/sec for every second that it falls if no other forces are present.)

Mass is an intrinsic property of an object, but the weight of the object depends on gravity where the object is located.

Example A.1

Consider a one hundred kilogram mass on the surface of the earth. It weighs 981 Newtons. On the moon, where the acceleration due to gravity is 1.62 meters per second per second, the object would still have a mass of 100 kilograms, but its weight would be 162 Newtons.

Now consider the measurement system commonly used in the U.S. It is called the U.S. Customary system or the FPS system (because of the use of feet, pounds and seconds). Here is where confusion creeps in, often baffling students of physics and engineering and occasionally causing catastrophic errors in engineering design calculations. The problem is the pound. Its definition has undergone several different incarnations in the past, but is now defined strictly as a **force**, not a mass.

We begin the discussion of the U.S. Customary system as we did previously for the SI system, with Newton's Second Law:

$$F = ma \tag{A-5}$$

If the force under consideration is gravity, then:

$$F\ (\text{pounds}) = mg \tag{A-6}$$

Since the pound has been declared a unit of force in the U.S. Customary system:

$$\text{mass} = (\text{force in pounds})/g \tag{A-7}$$

The unit of mass in the U.S. Customary system is called the slug. The acceleration due to gravity in U.S. Customary units is 32.17 feet per second per second. To illustrate, an object that weighs 100 pounds has a mass of 100/32.17 = 3.11 slugs.

The confusion arises because the difference between mass and weight is important in some applications and not important in others. A man in America might say that he weighs 220 pounds. Since weight is a force and pounds measure force, this statement is entirely correct. The same man in France would say that he weighs 99.8 kilograms. But, this statement is not really correct because kilograms measure mass, not weight. In this case, it does not matter. (In France, the man would have been correct if he had said that his weight is the force exerted by 99.8 kilograms of mass.)

In America and France, the scale would measure force, probably by stretching a calibrated spring or by balancing the man's weight against known weights. Since the acceleration due to gravity is essentially the same anywhere on the surface of the earth, all of the units of mass and weight are proportional to one another, and the scale can be calibrated in any of these units. So the 220 pound man is also a 99.8 kilogram man or a 220/32 = 6.8 slug man or a 9.81 × 99.8 = 979 Newton man. All of these measures are correct and consistent so long as the man stays on the surface of the Earth.

Americans are all familiar with pounds as a unit of weight, but few have even heard about slugs as a unit of mass. Europeans (and many Americans) are familiar with kilograms as a unit of mass, but few have even heard of Newtons as a measure of force or weight. This is not a serious problem until one embarks on assessments of physical quantities such as potential energy or kinetic energy. In evaluating potential energy and kinetic energy, it is crucial to distinguish between mass and weight.

In the SI system, potential energy, PE, is given by:

$$\text{PE(Joules)} = 9.81 \times \text{m(kilograms)} \times \text{h(height in meters)} \qquad \text{(A-8)}$$

In the U.S. Customary system:

$$PE(\text{foot pounds}) = w(\text{pounds}) \times h(\text{height in feet}) \quad \text{(A-9)}$$

Converting between SI and U.S. Customary units for energy is based on the relationship one foot pound = 1.356 Joules.

Example A.2

Consider the 220 pound man standing on a three meter (9.842 feet) diving board. His potential energy in SI units is:

$$E(\text{Joules}) = 9.81 \times 99.8 \times 3$$
$$= 2{,}940 \text{ Joules}$$

In U.S. Customary units:

$$PE(\text{foot pounds}) = 220 \times 9.842$$
$$= 2{,}165 \text{ foot pounds.}$$

Converting foot pounds to Joules gives:

$$PE(\text{Joules}) = 2165(\text{foot pounds}) \times 1.356(\text{Joules per foot pound})$$
$$= 2{,}940$$

This is the same as obtained in the SI evaluation.

Now consider kinetic energy, KE:

$$KE = (1/2)mv^2 \quad \text{(A-10)}$$

For kinetic energy evaluations, the mass in kilograms (SI system) or slugs (U.S. Customary system) is required.

Example A.3

Consider a 100 kilogram object traveling at 10 m/s. The kinetic energy is:

$$KE(Joules) = (1/2) \times 100 \times 10^2$$
$$= 5{,}000\ Joules.$$

The 100 kilogram mass corresponds to a weight of 220.46 pounds in the U.S. Customary system. This weight corresponds to 220.46/32.17 = 6.853 slugs. The velocity in U.S. Customary units is 32.808 feet per second. So the kinetic energy in U.S. Customary units is:

$$KE(foot\ pounds) = (1/2) \times 6.853 \times (32.808)^2$$
$$= 3{,}688\ foot\ pounds.$$

Converting from foot pounds to Joules gives:

$$KE(Joules) = 1.356\ (Joules\ per\ foot\ pound) \times 3688\ (foot\ pounds)$$
$$= 5000\ Joules.$$

APPENDIX B: CONVERSION FACTORS

Some of the conversion factors needed in energy assessments appear below.

Length

Multiply	by	To Get
Centimeters	0.01	meters
	0.03281	feet
Feet	0.3048	meters
Meters	100	centimeters
	3.281	feet
Miles	5,280	feet
	1,609	meters
	1.609	kilometers
Kilometers	1,000	meters
	0.6215	miles
	3281	feet

Area

Multiply	by	To Get
Acres	0.405	hectares
	43,560	square feet
	4,047	square meters
Hectares	10,000	square meters
	2.47	acres
Square feet	0.0929	square meters
Square meters	10.76	square feet

Mass and Weight on Earth's Surface

(Grams, kilograms and metric tons, often written as tonnes, are units of mass. Pounds and short tons are units of weight. Mass and weight are proportional on the surface of the earth. The proportionality results in the following equivalencies on the surface of the earth. To emphasize the distinction between units of mass and units of weight, units of mass are shown in italic font and units of weight are shown in regular font.)

Multiply	**by**	**To Get**
Grams	0.001	*kilograms*
	0.002205	pounds
Kilograms	1,000	*grams*
	0.205	pounds
	0.001	*metric tons*
	0.0011	short tons
Pounds	453.5	*grams*
	0.4535	*kilograms*
	0.0005	short tons
Short tons	2,000	pounds
	907	*kilograms*
	0.907	*metric tons*
Metric tons	1,000	*kilograms*
	2,205	pounds
	1.1025	short tons

Volume

Multiply	by	To Get
Gallons (U.S.)	3.79	liters
	0.1336	cubic feet
	0.003785	cubic meters
Gallons (Imperial)	1.20	gallons (U.S.)
Cubic feet	28.3	liters
	0.485	gallons (U.S.)
	0.02832	cubic meters
Cubic meters	35.31	cubic feet
	264.2	gallons (U.S.)
Liters	0.2642	gallons (U.S.)

Speed

Multiply	by	To Get
Feet per second	0.6818	miles per hour
	1.097	kilometers per hour
	0.3048	meters per second
Meters per second	2.237	miles per hour
	3.600	kilometers per hour
	3.2808	feet per second
Miles per hour	1.467	feet per second
	1.609	kilometers per hour
Kilometers per hour	0.6215	miles per hour

Energy

Multiply	by	To Get
BTUs	1055	Joules
	252	calories
	0.293	watt-hours
	0.000293	kilowatt-hours
Joules	0.948×10^{-3}	BTU
	0.239	calories
	2.777×10^{-7}	kilowatt-hours
	0.737	foot-pounds
Foot-pounds	1.356	Joules
Exajoules	10^{18}	Joules
	0.9479	Quads
	0.948×10^{15}	BTU
Zetajoules	10^{21}	Joules
	1,000	exajoules
Kilowatt-hours	3,413	BTU
	3.6×10^{6}	Joules
Megawatt-hours	3.412×10^{6}	BTU
Quads	10^{15}	BTU
	1.055	exajoules
	24.8	MTOE
	0.0334	terawatt-years
Million tonnes of oil equivalent (MTOE)	4.0×10^{13}	BTU
	0.04	Quads
	0.0425	exajoules
	1.18×10^{10}	kw-hours

Power

Multiply	by	To Get
Watts	1	Joules per second
	0.001	kilowatts
	3.412	BTU per hour
Kilowatts	1,000	watts
	3,412	BTU per hour
	81,888	BTU per day
	29.9×10^6	BTU per year
Megawatts	10^6	watts
	1,000	kilowatts
	3.412×10^6	BTU per hour
	81.89×10^6	BTU per day
	29.9×10^9	BTU per year
Terawatts	10^{12}	watts
	10^9	kilowatts
	10^6	megawatts
	29.9×10^{15}	BTU per year
	29.9	quads per year
BTU per hour	0.2931	watts
Horsepower	0.746	kilowatts
	2545	BTU per hour
Quads per year	0.0334	terawatts
Exajoules per year	0.9478	quads per year

APPENDIX C: FUEL HEATING VALUES

Heating values for fuels define the energy that is released upon combustion. The heating value depends on the state of the combustion products (vapor or liquid). The product of concern is water, a combustion product of fuels that contain hydrogen. Vaporization of water requires energy input, and condensation releases an amount of energy that is the same as that required for vaporization. Consequently, two different heating values are used: high heating value or HHV for combustion with liquid water as a product and low heating value or LHV for combustion in which water vapor is a product.

Coal, the predominant solid fuel, has properties that vary significantly. Consequently, ranges of heating values must be relied upon for characterizing the energy available from coal combustion. Because of the dependence of heating values on coal composition, it is meaningless to specify different values for HHV and LHV. Ranges of heating values for the three types of coal are as follows:

Sub-bituminous……..8,300 to 11,500 BTU per pound

Bituminous……..….10,500 to 14,000 BTU per pound

Anthracite…….nearly 15,000 BTU per pound

Heating values for some important liquid fuels appear in Table C-1.

Table C-1. Liquid Fuel Heating Values

FUEL	LHV		HHV	
	BTU/LB	BTU/GAL	BTU/LB	BTU/GAL
Crude Oil	18,400	129,700	19,600	138,400
Gasoline	18,700	116,000	20,150	125,000
Diesel Fuel	18,400	129,000	19,800	139,000
Propane	19,900	84,300	21,500	91,200
Ethanol	11,600	76,300	12,800	84,300
Methanol	8,600	57,300	9,800	65,200
Butanol	14,800	99,600	16,100	106,500
Source of liquid fuel data: Argonne National Laboratory at http://www.transportation.anl.gov/modeling_simulation/GREET/index.html (This URL accesses the GREET web site that contains the above data.)				

Heating values for some important gaseous fuels appear in Table C-2.

Table C-2. Gaseous Fuel Heating Values

FUEL	LHV		HHV	
	BTU/LB	BTU/CU FT	BTU/LB	BTU/CU FT
Methane	21,433	910	23,811	1,011
Ethane	20,295	1,630	22,198	1,783
Carbon Monoxide	4,368	323	4,368	323
Natural Gas	17,500-22,000	850-1,050	19,500-22,500	950-1,150
Hydrogen	51,628	275	61,084	325
Note: The volumetric heating values for gaseous fuels are evaluated at standard temperature and pressure. Note: The LHV and HHV for carbon monoxide are the same. There is no water formed in the combustion of carbon monoxide. Note: The range for natural gas is due to variations in gas composition from different sources. Source of data on gaseous fuels: The Engineering Toolbox at http://www.engineeringtoolbox.com. Note: The heating values for hydrocarbons are all around 20,000 BTU per pound.				

APPENDIX D: STIRLING ENGINES

Consider a cylinder containing a gas and a piston as shown in Figure D-1. Application of heat to the cylinder causes the gas to expand. The gas pressure increases and the piston moves up, thereby performing work. If more work is required from this system, the gas must be cooled to reduce the pressure and allow the piston to return to its initial position. Repeated heating and cooling of the cylinder could produce work continuously, but this approach would be slow and cumbersome. The Stirling engine provides a more practical way to obtain work by heating and cooling a gas. Stirling engines use a flywheel to maintain motion when the pistons are not delivering energy.

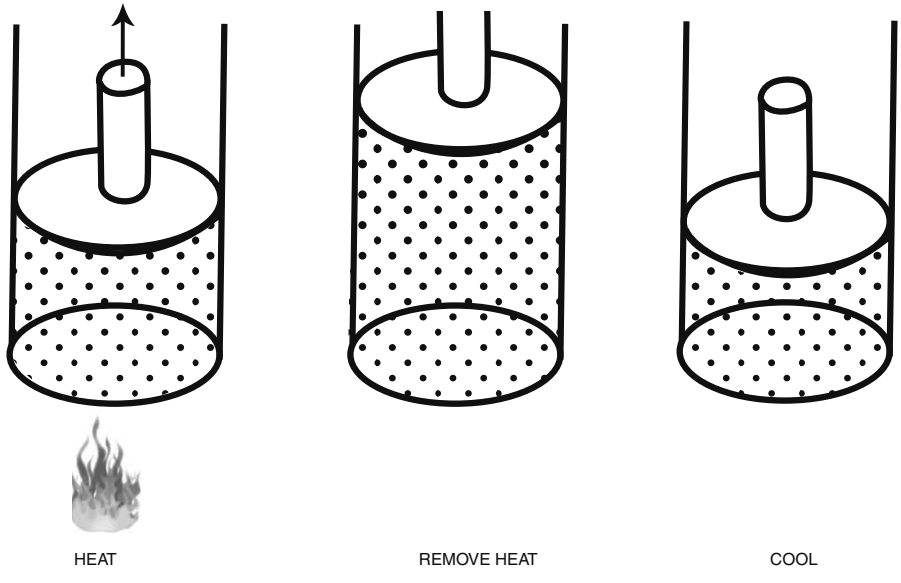

Figure D-1. Heating and Cooling a Contained Gas

The Stirling engine exists in many design variations, all of which are simple but elegantly clever. Some types have one cylinder and some have two cylinders. One type, a basic two-cylinder Stirling engine design, appears in Figure D-2. The system has four main parts:

- A heated cylinder and piston.
- A cooled cylinder and piston.
- A flywheel.
- A heat storage/transfer chamber called a regenerator, which is contained in the passage between the two cylinders. The regenerator may be a metal mesh. Its purpose is to transfer heat rapidly with hot or cold gases as they pass through, and to store heat.

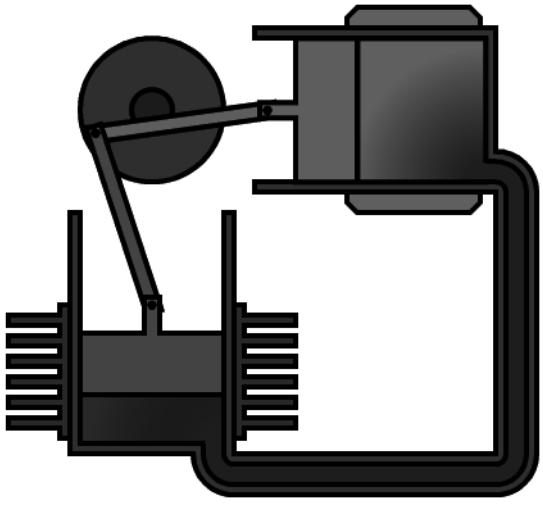

Figure D-2. A Stirling Engine (Richard Wheeler, Wikipedia, CC BY-SA 3.0 Unported)

The operation of the basic Stirling engine begins with the engine at rest and at constant temperature and pressure throughout.

To start engine operation, apply heating to one cylinder and cooling to the other. The system responds as follows:

- The gas in the heated cylinder expands.

- The gas in the cooled cylinder contracts.
- The increased gas pressure in the heated cylinder pushes the piston out and turns the flywheel clockwise to the position shown in Figure D-2.
- Flywheel motion causes the piston in the cooled cylinder to move outward.
- The piston in the heated cylinder reaches the limit of outward motion.
- The pressure difference causes gas to flow through the regenerator into the cooled cylinder. (The hot gas deposits much of its heat in the regenerator).
- The reduced pressure in the heated cylinder and the increased pressure in the cooled cylinder cause the heated piston to move inward and the cooled piston to move outward (Figure D-3).

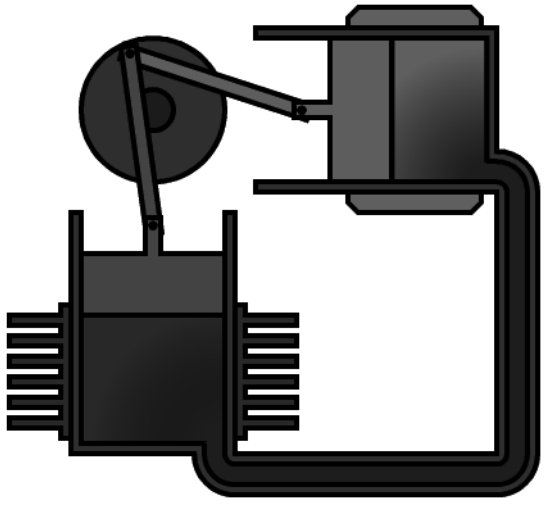

Figure D-3. Stirling Engine Operation (Richard Wheeler, Wikipedia, CC BY-SA 3.0 Unported)

- Flywheel angular momentum causes further rotation, driving the heated piston in and pulling the cooled piston out (Figure D-4).

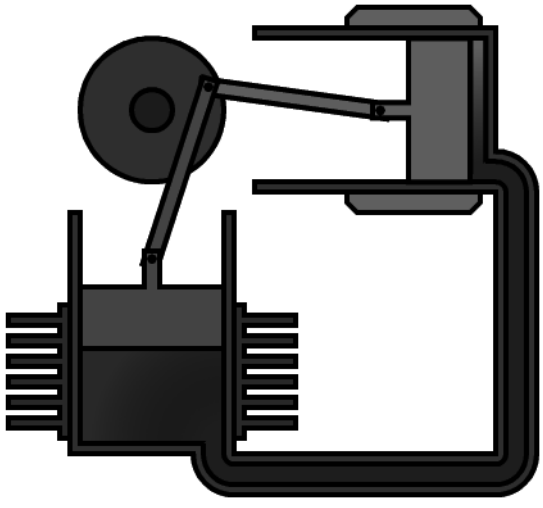

Figure D-4. Stirling Engine Operation (Richard Wheeler, Wikipedia, CC BY-SA 3.0 Unported)

- Flywheel rotation pushes the cooled piston inward, driving gas through the regenerator and back into the heated cylinder (Figure D-5).

- The gas in the heated cylinder expands because of applied heat and recaptured heat from the regenerator. This completes a cycle and the system is configured to start the next cycle.

The beauty of the Stirling engine is its simplicity and its ability to operate with any heat source, including solar heat. The Stirling engine described above is but one of many different versions. A web search on "Stirling engines" will provide information on these systems.

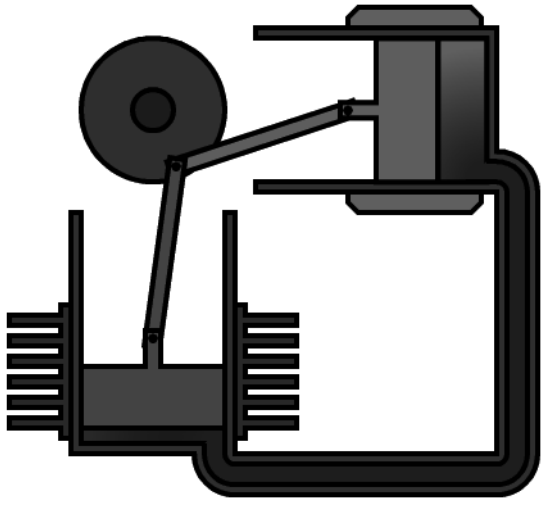

Figure D-5. Stirling Engine Operation (Richard Wheeler, Wikipedia, CC BY-SA 3.0 Unported)

APPENDIX E: ENERGY-RELATED WEBSITES

The following is a sampling of some of the more important energy-related web sites. There was no attempt at completeness in compiling this list. Most are present because they were useful to the author during the preparation of this book (primarily the period from 2005 through 2011). However, they provide an entrée into the vast web resource. Links to additional sources of energy information may be found at some of these sites.

Readers should note that web sites, and the content of web sites, are subject to change. As time passes, sites can become more or less pertinent, disappear or appear anew as time passes.

Government Agencies

Biomass Research and Development Initiative: www.bioproducts-bioenergy.gov

Argonne National Laboratory: www.anl.gov

Argonne National Laboratory Center for Transportation Research: www.transportation.anl.gov

Energy Efficiency and Renewable Energy (part of the U.S. Department of Energy): www.eere.energy.gov

Energy Information Administration (part of the U.S. Department of Energy): www.eia.doe.gov

Environmental Protection Agency: www.epa.gov

National Aeronautics and Space Administration: www.nasa.gov

National Renewable Energy Laboratory: www.nrel.gov

Oak Ridge National Laboratory: www.ornl.gov

Office of Science and Technology Information: www.osti.gov

Tennessee Valley Authority: www.tva.gov

U.S. Department of Agriculture: www.usda.gov

U.S. Department of Energy: www.doe.gov

U.S. Geologic Survey: www.usgs.gov

White House: whitehouse.gov

Research Organizations and Universities

Florida Solar Energy Center: www.fsec.edu

Geothermal Energy Association: www.geo-energy.org

Iowa State University Center for Sustainable Environmental Technology: csetweb.me.iastate.edu

Massachusetts Institute of Technology: www.mit.edu

National Transportation Research Center: www.ntrc.gov

University of California at Berkeley, Energy and Resources Group: www.socrates.berkeley.edu

University of California at Berkeley, Renewable and Appropriate Energy Group: www.rael.berkeley.edu

Princeton University, Carbon Mitigation Initiative: www.princeton.edu/~cmi

University of Tennessee, Agricultural Policy Analysis Center: www.apac.web.ag.utk.edu

University of Tennessee, Bio-Based Energy Analysis Group: www.beag.utk.edu

University of Tennessee, Institute for a Secure and Sustainable Environment: isse.utk.edu

Commercial: Energy Supply Companies

British Petroleum: www.bp.com

Non-Profit Groups

Alliance to Save Energy: www.ase.org

American Coalition on Ethanol: www.ethanol.org

American Council for an Energy Efficient Economy: www.aceee.org

American Council on Renewable Energy: www.acore.org

American Solar Energy Society: www.ases.org

American Wind Energy Association: www.awea.org

Australian Institute of Energy: www.aei.org

Biomass Council: www.biomasscouncil.org

Center for American Progress: www.americanprogress.org:

Center for Resource Solutions: www.resource-solutions.org

Clean Energy Group: www.cleanegroup.org

Clean Energy States Alliance: www.cleanenergystates.org

Clear the Air: www.cleartheair.org

Climate Solutions: www.climatesolutions.org

Database of State Incentives for Renewable Energy: www.dsire-usa.org

Energy Future Coalition: www.energyfuturecoalition.org

Environmental and Energy Study Group: www.eesi.org

European Renewable Energy Council: www.erec-renewables.org

European Union, New and Renewable Energies: www.europa.eu.int/comm/energy/res/index_en.htm

Geothermal Energy Association: www.geo-energy.org

Green Building Alliance: www.gbapgh.org

Green Renewable Electricity Certification: www.green-e.org

International Energy Agency: www.iea.org

Interstate Renewable Energy Council: www.irecusa.org

National Biodiesel Board: www.biodiesel.org

National Hydropower Association: www.hydro.org

Natural Resource Defense Council: www.nrdc.org

Pew Center for Climate Change: www.pewclimate.org

Renewable Energy Policy Project: www.repp.org

Renewable Fuels Association: www.ethanolrfa.org

Rocky Mountain Institute: www.rmi.org

Solar Energy Industries Association: www.seia.org

Union of Concerned Scientists: www.ucsusa.org

U.S. Green Building Council: www.usgbc.org

Utility Wind Integration Group: www.uwig.org

Worldwatch Institute: www.worldwatch.org

World Energy Council: www.worldenergy.org

APPENDIX F: OIL DEPLETION ANALYSIS: THE HUBBERT SOLUTION

Introduction

This Appendix addresses the forecasting of future oil production by the famous Hubbert method. Because of the importance of the forecasting method and the lack of rigorous and understandable descriptions of Hubbert's method in the literature, this appendix is more detailed than most of the text.

Oil is a finite resource that is steadily being used up. There is no doubt that decreasing reserves will eventually slow production. The growth of cumulative oil produced exhibited a slow start, followed by a rapid exponential growth. This growth must taper off as total depletion is approached.

Such an epoch is called a gradient-driven process. The following example provides an illustration of the general behavior of a gradient-driven process. Heat conduction was chosen for this example because such a process relates intuitively to common experience.

Example F.1

Heat conduction in a solid is driven by temperature gradients. Initially, an interior point in a mass responds only slightly to a surface temperature change Visualize dropping a cool brick into a large tank of hot water. The center of the brick is largely "unaware" that anything has changed at the surface until heat has diffused to the center. The interior temperature then undergoes a rapid rise until the rising interior temperature reduces the temperature gradient between interior points and the surface. This gradient eventually disappears and the brick's interior stabilizes at the same temperature as the surrounding water. A plot of the center temperature versus time would be a distorted S shape.

Many processes in diverse fields such as population growth and chemical reactions follow an S-shaped response curve. The curve is called a sigmoid, and any of a number of equations that define sigmoid curves is called a sigmoid function. A sigmoid function conforms to the logical progression of oil depletion: slow initial growth, then rapid increase, then tapering off.

Logistic Function Modeling

In developing mathematical models for processes such as cumulative oil production, the analyst fits available data to an equation that is thought to represent the process. This involves assigning values for coefficients in the model that cause the model to best agree with available data. Once the model coefficients have been found, the model equation can be used to estimate results outside the region where data are available. Basically, the model equation is an extrapolation or interpolation tool.

The choice of the model to be used may be empirical, semi-empirical or theoretical. Empirical models are based on equations that have no theoretical foundation at all. Essentially, the analyst asserts no knowledge about the form of the relationships between cause and effect. Semi-empirical models are based on limited theoretical knowledge. For example, choosing a sigmoid as the model would be based on logic that indicates the general way the process will have to unfold. A purely theoretical model is based on detailed understanding of the process and the equation that describes it.

The numerical values of the coefficients in the model are obtained by fitting the model to available data.

The semi-empirical approach is the best approach possible in an effort to use available information to predict future oil production. Theoretical modeling of all possible factors related to oil production (population, economic conditions, wars, etc.) is impossible.

A sigmoid function often used in oil forecasting is the logistic function. The idea of the logistic function is to combine the exponential growth observed in early phases of resource utilization with the slowing of growth that must occur as total depletion is approached. Exponential growth occurs when the current rate of growth of cumulative production Q at any time is proportional to the cumulative production at that time. The differential equation for exponential growth is as follows:

$$dQ/dt = aQ \tag{F-1}$$

where:

a = a constant (a method for determining its value is presented below)

The growth must slow as total depletion is approached. One way to approximate this behavior is to assume that the factor, a, decreases linearly with cumulative production. That is:

$$dQ/dt = (a-bQ)Q \tag{F-2}$$

The value of the factor, b, may be determined by noting that dQ/dt must be zero when the cumulative production reaches the point of total depletion and Q is equal to Q_t, the total quantity of resource produced over all time:

$$0 = (a-bQ_t)Q_t \tag{F-3}$$

or:

$$b = a/Q_t \tag{F-4}$$

Thus, the growth model becomes:

$$dQ/dt = a(1-Q/Q_t)Q \tag{F-5}$$

or:

$$dQ/dt = aQ-(a/Q_t)Q^2 \tag{F-6}$$

Since dQ/dt is simply the annual rate of production, P, we may write:

$$P/Q = a(Q_t-Q)/Q_t \tag{F-7}$$

This equation reveals that, according to the logistic premise, a plot of P/Q versus Q should be a straight line. The intercept on the P/Q axis is the value of the constant, a. This value may be obtained from a graph of P/Q vs Q.

Equation F-6 is a nonlinear differential equation (because of the Q^2 term). Exact analytical solutions are not known for all nonlinear differential equations, but the solution for this one is known. The solution is as follows:

$$Q = Q_t/(1+\exp(-at)) \tag{F-8}$$

The validity of this solution can be verified by substituting the solution for Q in Equation F-6 and checking for equality.

The production rate, P, at any specified time is equal to dQ/dt. P may be calculated by substituting values of Q from Equation F-8 into Equation F-6.

The solution also depends on a specific initial condition (the condition when elapsed time is zero). The initial condition implicit in the solution may be identified by setting t = 0 in Equation F-8 as follows:

$$Q(0) = Q_t/2 \tag{F-9}$$

That is, time is measured from the instant when cumulative production is half of the cumulative production at the time of total resource depletion. Values of cumulative production after the half consumption point are obtained by substituting positive values of t into Equation F-8, and values before the half consumption point are obtained by substituting negative values of t.

The analysis presented above gives cumulative production and annual production for times measured relative to the time of peak production. It is necessary to convert to true calendar time. In this analysis, the curve will be normalized by forcing it to agree with known prior production in a prior year. Equation F-7 may be rewritten as follows:

$$(Q/Q_t)^2-(Q/Q_t)+(P/aQ_t) = 0 \qquad \text{(F-10)}$$

Equation F-10 is a quadratic equation with two solutions, given below:

$$(Q/Q_t) = (1+sqr(1-(4P)/(aQ_t)))/2 \qquad \text{(F-11)}$$

and:

$$(Q/Q_t) = (1-sqr(1-(4P)/(aQ_t)))/2 \qquad \text{(F-12)}$$

These solutions give the fractional cumulative production on both sides of the peak. The second solution (with the minus sign) applies for times before the peak.

The time relative to the time of peak production may be found by evaluating Q/Q_t for specified values of P, a and Q_t using Equation F-12, then solving Equation F-8 for t as follows:

$$t = -(\ln((1-Q/Q_t)/(Q/Q_t)))/a \qquad \text{(F-13)}$$

where:

ln denotes the natural logarithm.

This value of t is the time before the time of peak production. It gives the number of years by which time relative to the time of peak production must be shifted to give calendar time.

A Computer Program

A BASIC language computer code has been prepared to perform a Hubbert analysis. Users must specify the following four inputs:

1. The intercept on the P/Q axis in a plot of P/Q vs Q (the constant, a, in Equation F-7)
2. The total recoverable reserves
3. The reference year
4. The production during the reference year

The program listing appears below:

```
10 print “Hubbert Peak Solution”
20 print “Basis: solution of differential equation”
30 print “Input intercept”
40 input a
50 print “Input total recoverable reserves”
60 input Q1
70 print “Input Reference Year”
80 input y
90 print “Input Production in Reference Year”
100 input P
```

```
110 f = (1-sqr(1-(4*P/(a*Q1))))/2
120 t1 = (-1/a)*log((1-f)/f)
130 print
140 print
150 print "Year     Cumulative Production     Annual Production"
160 For t = -100 to -10 step 10
170 Q = Q1/(1+exp((-1)*a*t))
180 P = a*Q-(a/Q1)*Q*Q
190 print INT(y+t-t1),INT(Q),"     ",(INT(100*P))/100
200 next t
210 for t = -9 to 9
220 Q = Q1/(1+exp((-1)*a*t))
230 P = a*Q-(a/Q1)*Q*Q
240 print INT(y+t-t1),INT(Q),"     ",(INT(100*P))/100
250 next t
260 For t = 10 to 100 step 10
270 Q = Q1/(1+exp((-1)*a*t))
280 P = a*Q-(a/Q1)*Q*Q
290 print INT(y+t-t1),INT(Q),"     ",(INT(100*P))/100
300 next t
```

Readers can download a free Basic compiler from http://www.just basic.com.

Analysis of U.S. Oil Depletion

The computer program was used to perform a Hubbert analysis for the lower 48 states. Using Deffeyes' (Ref. 1) values of 0.0536 for the intercept, a, and 228 billion barrels for total recoverable reserves, Q_t, a reference year of 1958 and a 1958 production value of 2.45 billion barrels, gives the following results:

Hubbert Peak Solution

Basis: solution of differential equation

Input intercept

?.0536

Input total recoverable reserves

?228

Input Reference Year

?1958

Input Production in Reference Year

?2.45

Year	Cumulative Production	Annual Production
1875	1	0.05
1885	1	0.09
1895	3	0.16
1905	5	0.27
1915	8	0.45
1925	14	0.73
1935	23	1.14
1945	38	1.69
1955	58	2.32
1965	84	2.84
1966	87	2.88
1967	89	2.91
1968	92	2.95
1969	95	2.97
1970	98	3.00
1971	101	3.02
1972	104	3.03
1973	107	3.04
1974	110	3.05
1975	114	3.05
1976	117	3.05
1977	120	3.04
1978	123	3.03
1979	126	3.02
1980	129	3.00
1981	132	2.97
1982	135	2.95
1983	138	2.91
1984	140	2.88
1985	143	2.84
1995	169	2.32
2005	189	1.69
2015	204	1.14
2025	213	0.73
2035	219	0.45
2045	222	0.27
2055	224	0.16
2065	226	0.09
2075	226	0.05

Annual U.S. production predicted by the above Hubbert analysis appears in Figure F-1 along with actual data.

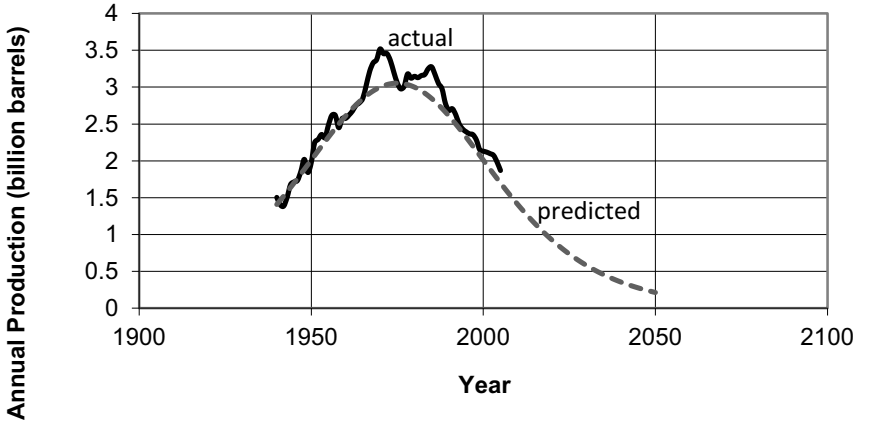

Figure F-1. Hubbert Prediction of Annual Production and Actual Production

For those who wish to work with historical U.S. production statistics for the lower 48 states to draw their own conclusions about trends and future production, data are available from the U.S. Energy Information Agency (http://www.eia.gov).

References

1. Deffeyes, K. S. *Beyond Oil* New York: Hill and Wang, 2005.

APPENDIX G: SOLAR RADIATION

Introduction

This Appendix provides a derivation of a simple model for solar radiation absorption at the earth's surface. This derivation shows the dependence on geometrical factors that vary with season, latitude and time of day. This simple model does not account for all of the factors that determine local solar radiation absorption, but it does illustrate the relation between geometric factors and solar radiation absorption.

The solar constant (the solar energy flux through space at the earth's outer atmosphere) is well known, with a value of 1370 watts per square meter[1], or 435 BTU per hour per square foot, or 10,434 BTU per day per square foot. For evaluation of the use of this energy for human purposes, the issue is determining the fraction of the solar energy stream that can be captured and used.

The intensity (power per unit of area) of the radiation reaching the earth's surface depends on two factors:

- The angle between the incoming beam and the surface at a location of interest

- The absorption and reflection of radiation by the atmosphere

The photons in the solar radiation beam emitted from the sun have a distribution of wavelengths that are determined by the sun's surface temperature. As the radiation passes through the earth's atmosphere, the spectrum is altered by atmospheric chemicals that selectively absorb photons of certain wavelengths. Since some energy-collection processes of interest (photosynthesis and the photovoltaic effect) require certain wavelengths, the spectrum of radiation reaching the surface is important in renewable energy considerations. Figure G-1 shows the spectrum of radiation reaching the earth's surface after experiencing atmospheric absorptions and scatterings[1].

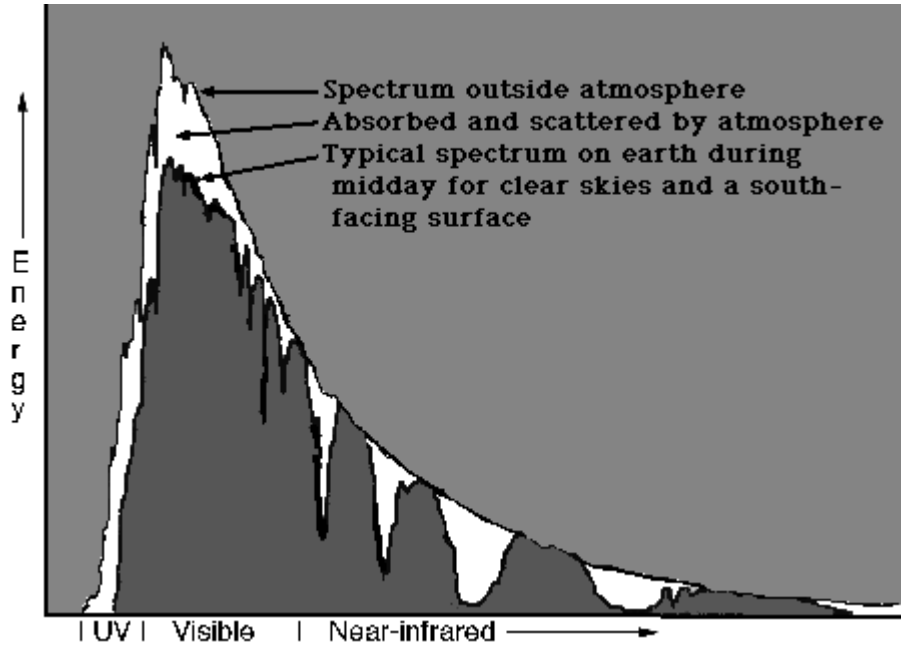

Figure G-1. Solar Spectrum at Top of Atmosphere and at Earth's Surface (courtesy of National Renewable Energy Laboratory)

As is required to maintain a constant average temperature, the earth must radiate energy at the same rate that it receives energy. The radiation emitted by the earth has a much different spectrum than the incoming solar radiation. The peak solar radiation intensity occurs at a wavelength of around 0.5 microns[1], while the radiation emitted by the earth into space has its peak intensity at a wavelength of around 10 microns[1]. This difference between the spectra of incoming and outgoing radiation is the basis for the operation of flat-plate solar collectors and for the greenhouse effect[1] (see Chapter 19).

Angle Effect

The angle between the surface at some location of interest on the earth and the incident solar flux at that location depends on the latitude, the season

and the time of day. Latitude is the angle between the plane of the equator and a line from the center of the earth to a selected point on the surface (see Figure G-2). Geometrical analysis can provide a model of the angular component of radiation intensity.

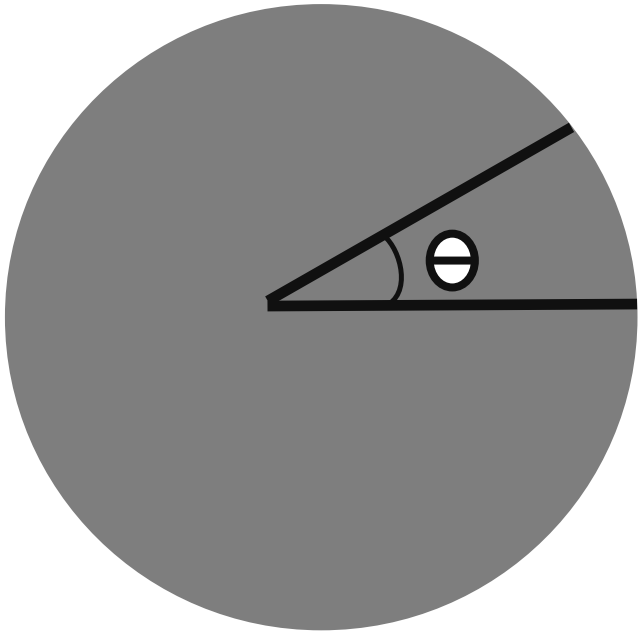

Figure G-2. Earth Latitude

Average Solar Radiation Striking the Earth's Upper Atmosphere

As a first step, let us evaluate the average solar flux impinging on the upper atmosphere. The earth, with radius, r, presents a target area of πr^2. Therefore, the total power in the beam aimed at the earth is $I\pi r^2$, where I is the solar constant. The total earth surface is $4\pi r^2$. Therefore, the average flux impinging on the upper atmosphere above the earth is **one-fourth of the solar constant** or 342 watts per square meter, or 108 BTU per hour per square foot, or 2610 BTU per day per square foot. Specific locations experience upper atmosphere average radiation intensities that vary around this average value.

Average Solar Flux as a Function of Latitude and Season

The average global solar flux is useful for worldwide energy flow assessments, but additional information is needed to assess a specific region. It is necessary to evaluate the effects of the seasonal variation in the angle between the surface and the solar flux and the daily variation due to the earth's rotation.

The angle between the solar beam and an area of surface depends on the season and the latitude of the surface of interest. Seasonal effects arise because the earth's axis of rotation is tilted by 23.5 degrees relative to the plane of its orbit around the sun (see Figure G-3). When the North Pole is tilted away from the sun, the Southern Hemisphere receives more power per unit of surface area. The opposite effect occurs when the North Pole is tilted towards the sun.

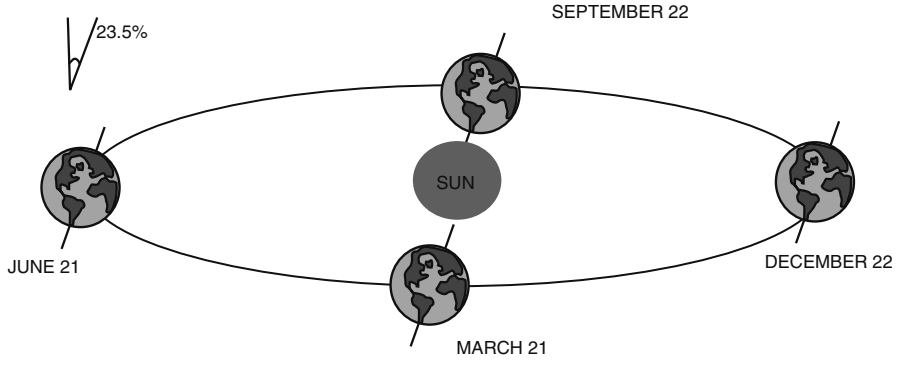

Figure G-3. Earth Orbit

A little geometry can provide the upper atmosphere energy flux as a function of latitude and season. The flux aimed at a specific surface area is depicted in Figure G-4. The angle, θ, is the angle between the solar beam and the surface of interest. The surface of interest is represented by the segment ac. The solar flux that reaches the surface passes through a projection of the surface onto a plane perpendicular to the solar beam, represented by segment ab. Consequently, the intensity of the beam aimed at the surface

(power per unit area of the surface) is (ab/ac)×(solar constant). The triangles cba and ade are similar. Therefore, $\cos\theta = ab/ac = de/ea$. That is, the fraction of the solar beam intensity at the top of the atmosphere that is aimed at the surface is given by the cosine of the angle between the solar beam and the line from the earth's center and the surface of interest.

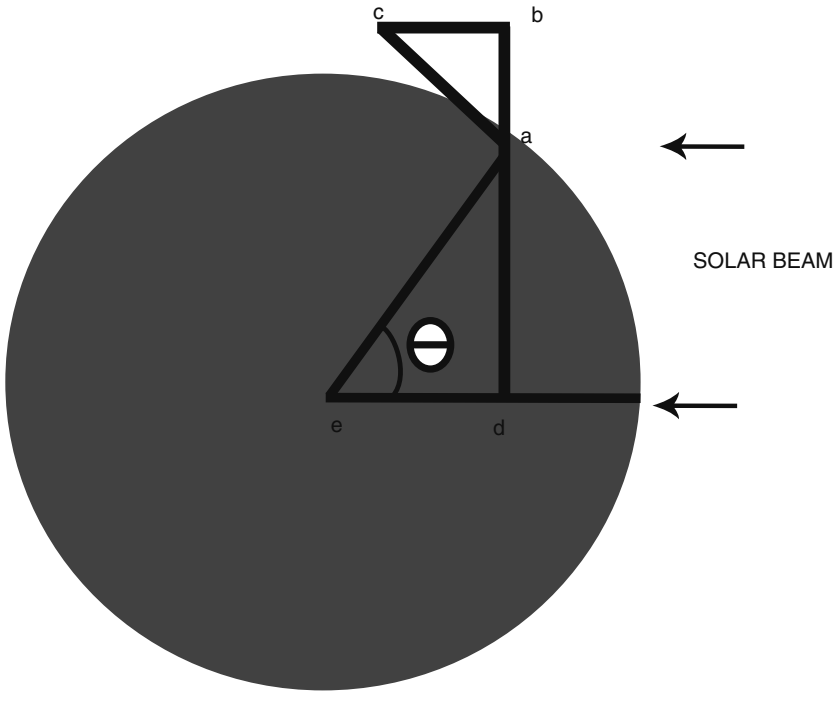

Figure G-4. Angles in Solar Incidence Analysis

To complete the analysis, determination of the seasonal variation of the angles between the solar beam and a surface of interest is also required. If the earth had no tilt relative to its plane of rotation around the sun, the angle would simply be the latitude of the surface of interest. In the northern hemisphere, the actual angle is 23.5 degrees less than the latitude in mid-summer and 23.5 degrees more than the latitude in midwinter. Since it takes half of a year to go from mid-summer to midwinter, the angle, θ, may be expressed as:

$$\theta = \text{latitude}+23.5-(47/182.5)t \quad \text{(G-1)}$$

or:

$$\theta = \text{latitude}+23.5-0.258t \quad \text{(G-2)}$$

where:

t = time measured from the shortest day (days).

The shortest day occurs 10 days before January 1, so referencing the time scale to January 1 gives:

$$\theta = \text{latitude}+23.5-0.258(t+10) \quad \text{(G-3)}$$

The intensity of the solar beam that is aimed at a surface of interest is:

$$I(\text{surface}) = I(\text{beam})\cos(L+23.5-0.258(t+10) \quad \text{(G-4)}$$

where:

I(surface)= intensity at the surface (power per unit area of surface)
I(beam)= intensity of the beam (power per unit of cross-sectional beam area)
L = latitude of the surface of interest

Solar Radiation Intensity Variations Due To Earth's Rotation

Since the earth rotates, the average surface intensity is lower than the peak surface intensity as given by Equation G-4. This intensity is experienced by the portion of the circumferential ring that directly faces the sun. The other parts of the semi-circular illuminated part of the ring receive lower intensities because the angle of incidence decreases, reaching zero at a point 90 degrees on either side of the point facing the sun. The target area presented to the incoming solar beam of the slice of the globe with height Δh is $2r\Delta h$. The area of the whole circumferential ring is $2\pi r\Delta h$. Therefore, the average daily intensity aimed at the surface is $1/\pi$ or 0.318 times the beam intensity.

Geometrical Model Summary

The geometrical component of the average daily radiation intensities seen on the surface of the earth is described by the following equation:

$$I(\text{Surface}) = F\times(10{,}434/(3.14159))\cos(L+23.5-0.258(t+10) \qquad \text{(G-5)}$$

or:

$$I(\text{surface}) = 3321.25F\cos(L+23.5-0.258(t+10)) \qquad \text{(G-6)}$$

where:

F	=	solar power per unit of area that escapes absorption and scattering back into space (see discussion below)
L	=	latitude (in degrees)
t	=	day of the year (January 1=0).

The factors in the equation are:

10,034 = the solar constant (BTU/sq ft-day)

3.14159 = π

23.5 = tilt of the earth's axis relative to the plane of motion around the sun (degrees)

0.258 = change in the angle between the solar beam and the surface of interest per day (degrees per day)

Radiation Absorption, Scattering, and Reflection

Measurements and analyses provide estimates of the fate of solar photons impinging on the earth's atmosphere. These studies are in substantial agreement. They provide energy flows for average conditions of the earth and its atmosphere. Incoming radiation has six possible fates:

1. Direct transmission to the surface and absorption by surface materials

2. Direct transmission to the surface and reflection back into space

3. Scattering by chemicals in the atmosphere with subsequent passage to and absorption by the surface

4. Scattering by chemicals in the atmosphere with subsequent transmission back out of the atmosphere into space

5. Reflection by clouds

6. Absorption by chemicals in the atmosphere

Figure G-5 shows the results of one energy budget analysis[1]. Other sources with comparable results are shown in References 2 and 3. These are typical values. Values for any location are specific to that location. Figure G-5 shows that 51 percent of incident radiation is absorbed by the surface. Of this, 28 percent is direct, unscattered radiation and 23 percent is scattered, diffuse radiation. It should be noted that unscattered radiation can be focused, but scattered radiation cannot. This is important in solar power applications using solar energy concentrated with lenses or mirrors to power a heat engine.

Clouds reflect 20 percent of solar beam power according to Figure G-5. In a cloudless environment (essentially a desert environment), this power is available for surface absorption (direct and diffused) and for retransmission to space by atmospheric scattering and surface reflection. That is, 81 percent of incoming radiation is available for these processes instead of the 61 percent in the model with clouds. Local conditions would also affect the chemical composition of the atmosphere (mainly water vapor). It is likely that atmospheric absorption and scattering would be smaller in desert regions than in verdant regions, but variations due to such local effects are not included in the simple model described here.

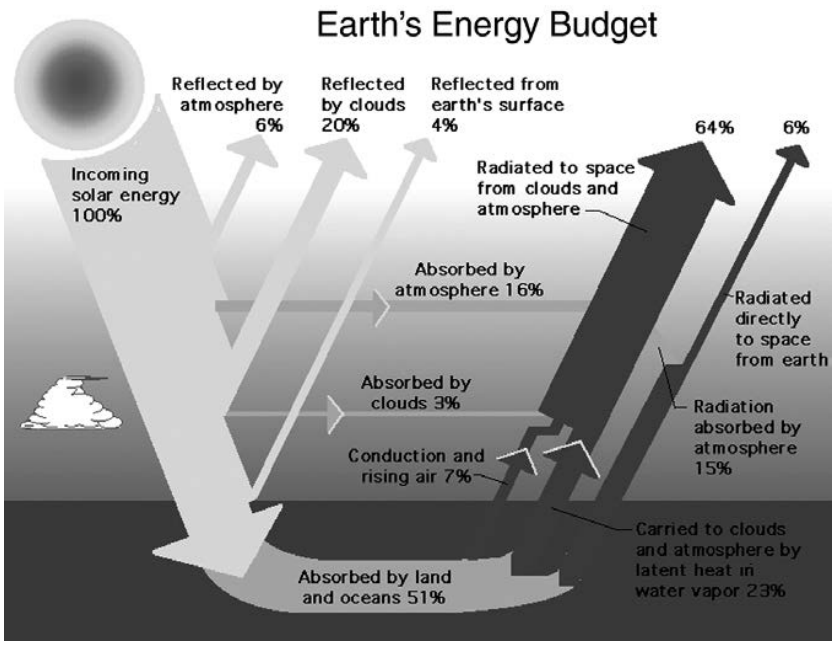

Figure G-5. Courtesy of U.S. National Aeronautics and Space Administration

Solar Absorption Analysis and Results

Solar absorption yearly average values obtained with the simple model described above were compared with measured data for selected U.S. cities reported by the National Renewable Energy Laboratory[4]. The NREL provides data for 239 U.S. locations. Results for 21 selected locations are shown in Table G-1.

It is tempting to embark on a detailed interpretation of these results, but that is not the purpose here. It is noted that the agreement between estimates for typical conditions and measurements is quite good except for desert areas, where the estimates are all lower than measured values. For desert locations (Phoenix, Albuquerque and Las Vegas), the estimates for typical conditions are 21 to 23 percent low and estimates for cloudless conditions are 4 to 7 percent low. This illustrates that desert conditions are predominantly cloudless and are better represented by a cloudless model. It should also be realized that the differences between estimated and measured values

Table G-1. Comparisons of Estimated and Measured Absorption Rates (Horizontal Surfaces)
Values in BTU per day per square foot

City	Latitude	Estimated		Measured	
		Typical	Cloudless	Typical	Cloudless
Miami, FL	25.80	1521	2028	1530	2020
Austin, TX	30.30	1465	1953	1540	1990
Phoenix, AZ	33.43	1420	1893	1810	1980
Atlanta, GA	33.65	1417	1889	1450	1890
Los Angeles, CA	33.93	1413	1884	1560	1860
Albuquerque, NM	35.05	1396	1871	1760	2020
Bakersfield, CA	35.42	1390	1853	1650	1870
Knoxville, TN	35.82	1384	1845	1340	1840
Las Vegas, NV	36.08	1380	1840	1790	1960
Greensboro, NC	36.08	1380	1840	1380	1840
Tulsa, OK	36.20	1378	1837	1420	1860
Lexington, KY	38.03	1348	1797	1280	1790
Topeka, KS	39.07	1330	1773	1360	1780
Dayton, OH	39.90	1316	1754	1250	1740
Omaha, NE	41.37	1290	1720	1330	1730
Lansing, MI	42.78	1264	1685	1190	1670
Buffalo, NY	42.93	1261	1681	1170	1690
Portland, ME	43.65	1247	1682	1230	1670
Portland, OR	45.60	1210	1613	1110	1600
Helena, MT	46.60	1190	1586	1250	1660
Bismarck, ND	46.77	1186	1581	1270	1620

are much greater on a month-by-month basis than on the yearly average basis as reported above.

It is clear that the yearly average surface radiation incidence in the continental United States ranges from 1200 to 1800 BTU per day per square foot (158 to 236 watts per square meter). In analyses whose purpose is to estimate the maximum annual yields of renewable energy sources, the average surface intensity cannot exceed 1800 BTU per day per square foot or 236 watts per square meter. Of course, summer intensities are higher and winter intensities are lower. For applications requiring unscattered (focusable) radi-

ation such as solar-powered heat engines, the yearly average surface intensity ranges from 660 to 980 BTU per day per square foot (87 to 129 watts per square meter).

References

1. http://physicalgeography.net

2. http://stephenschneider.stanford.edu/Climate/Overview.html

3. http://marine.rutgers.edu/mrs/education/class/yuri/erb.html

4. "Solar Radiation Data Manual for Buildings" at http://rredc.nrel.gov/solar/pubs/bluebook/intro.html

APPENDIX H: ORIENTATION OF SOLAR COLLECTORS

Orientation Options

Figure H-1 shows a schematic diagram of a typical fixed orientation solar collector system. Installations such as rooftop systems often dictate a fixed orientation, but solar energy absorption rates per unit area of collector surface can be increased by the use of collectors that are tilted or that track the sun during the day.

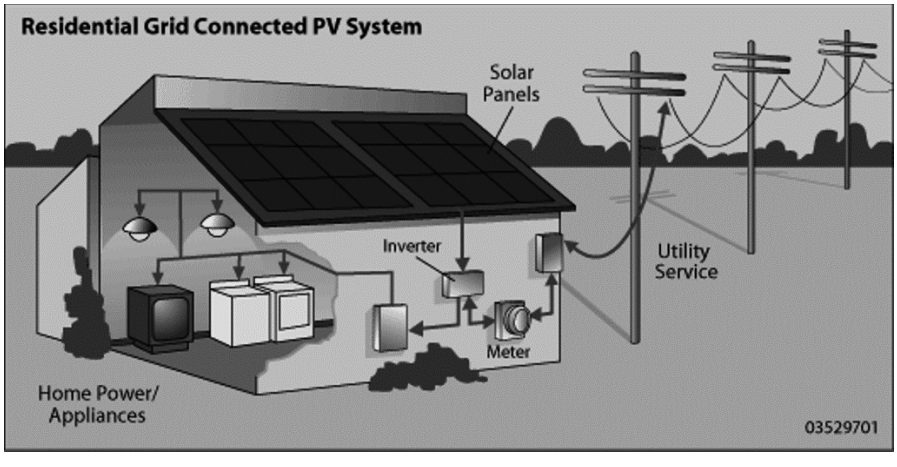

Figure H-1. A Residential Photovoltaic System (courtesy of U.S. Dept. of Energy)

The purpose of tilting a collector is to position the absorbing surface so as to be closer to perpendicular to the incident solar radiation beam than is possible with a horizontal collector. Tilted collectors may have a fixed orientation, an occasionally-adjusted orientation or a continuously-adjusted orientation. Continuously-adjusted, or tracking, collectors track the motion of the sun during its daily variation of angular position in the sky. Tracking collectors may rotate around a single axis (east-to-west) or around two axes

(east-to-west and elevation in the sky). Figures H-2 through H-4 show fixed, single axis and two axis flat-plate collector arrangements.

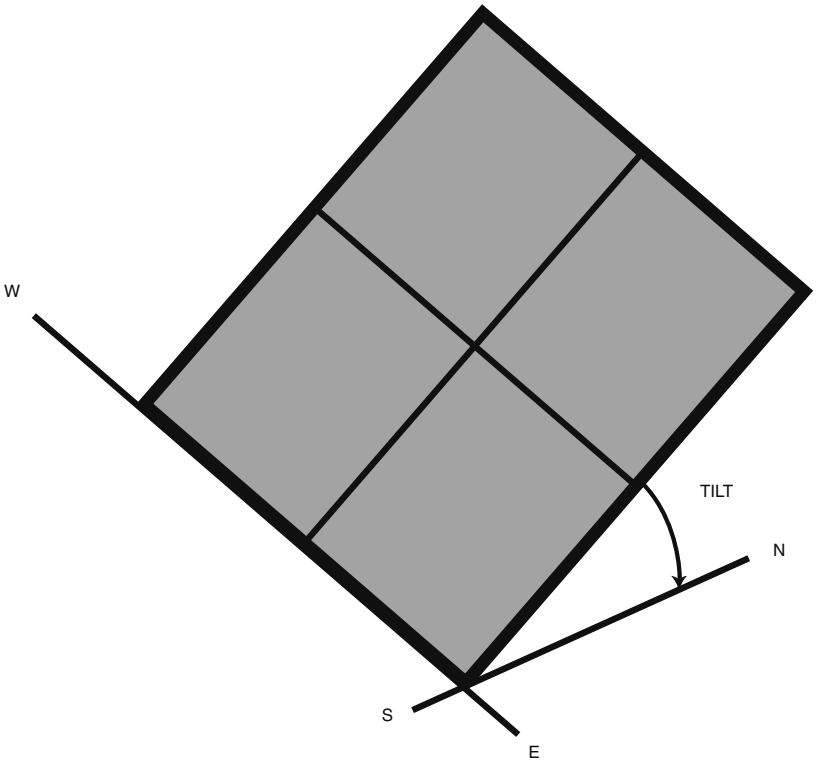

Figure H-2. A Fixed-Axis Collector

The optimum orientation of a solar collector depends on the latitude at which the collector is located, the season and the time of day. The National Renewable Energy Laboratory publishes information on solar radiation intensity for numerous U.S. locations and for fixed tilt angles, single axis tracking and dual axis tracking. (See the NREL web site[1] for "Solar Radiation Data Manual for Flat Plate and Concentrating Collectors.")

Since the amount of local solar intensity information on the NREL web site is so large, its use is illustrated here by choosing one location: Knoxville, Tennessee. Knoxville is located at a latitude of 35.82 degrees.

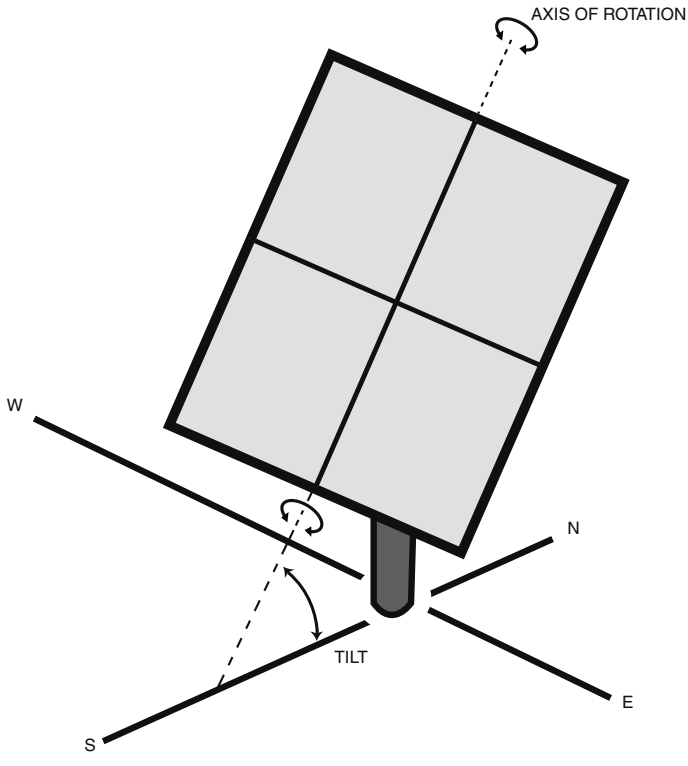

Figure H-3. A Single-Axis Collector

The NREL fixed orientation data are for a south-facing collector with orientations of zero (horizontal), latitude-15 degrees, latitude, latitude+15 degrees and 90 degrees (vertical). Data for Knoxville are shown graphically in Figure H-5. This figure shows that a fixed orientation collector can be optimized for the season of the year in which maximum performance is required. For example, an orientation of +15 is better for winter and -15 is better for summer. The figure also shows the possibility of improving fixed orientation collectors by manually re-orienting the collectors. Orienting at latitude -15 degrees or (20.82 degrees) is best in summer and latitude + 15 degrees (50.82 degrees) is best in winter. Orienting at an angle equal to latitude is a reasonable year-round compromise. Horizontal is good in summer, but poor in winter. Vertical collectors are comparable to tilted collectors in midwinter, but are much less effective in summer.

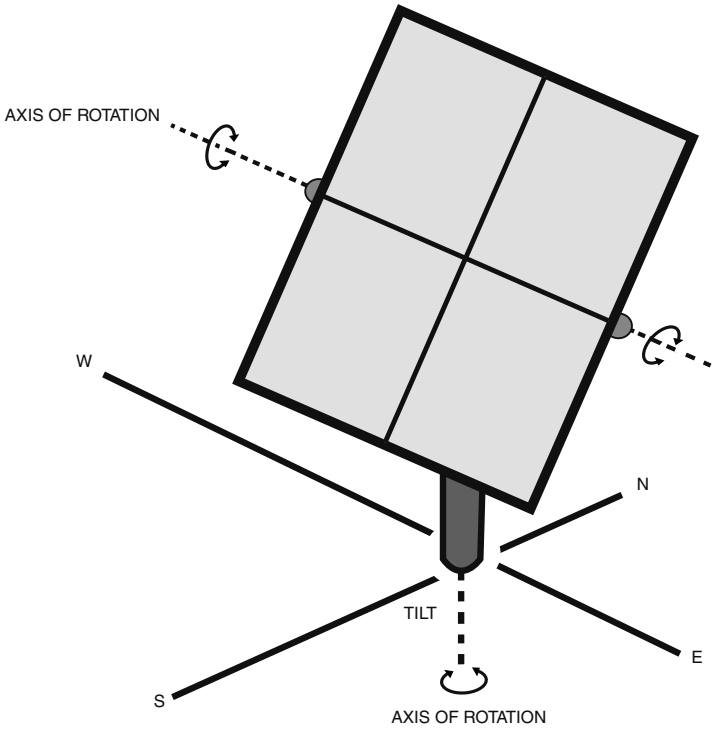

Figure H-4. A Dual-Axis Collector

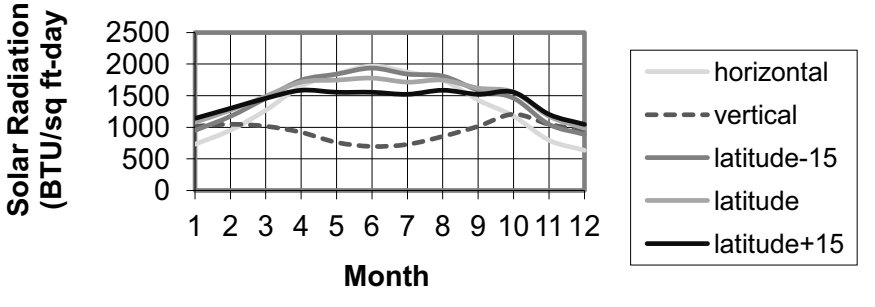

Figure H-5. Solar Energy Absorption by Fixed-Orientation Collectors in Knoxville, TN (data from National Renewable Energy Laboratory)

NREL data for a south-facing single axis collector, a dual axis collector, a horizontal fixed collector and a vertical fixed collector located in Knoxville are shown in Figure H-6. This figure shows the benefits of tracking to energy collection capability. This increase, however, comes at the expense of increased initial cost. Decisions about collector design for a particular application depend on an evaluation of capital cost versus performance. Single axis tracking is almost as good as dual axis tracking and the yearly average for either tracking system is about 28 percent better than a fixed orientation collector set at an angle equal to Knoxville's latitude.

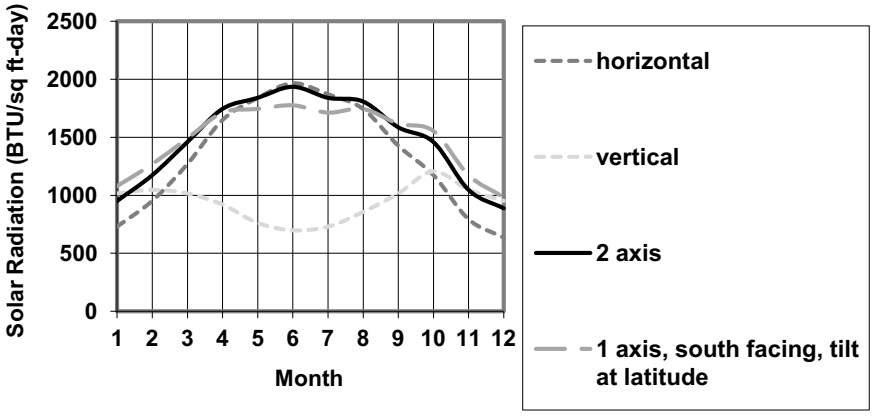

Figure H-6. Solar Energy Absorption by Fixed-Orientation and Tracking Collectors in Knoxville, TN (data from National Renewable Energy Laboratory)

While each location is unique and has its own best choices for collector orientation, the results presented above for Knoxville illustrate the trade-offs between performance and collector design features.

Daily Variations in Orientation of Tracking Collectors

The daily variations in the sun's azimuth (east-west orientation) and elevation relative to a horizontal surface determine the aiming of tracking collec-

tors. Sunrise is in the east, and sunset is in the west. The sun's elevation increases during the morning, peaks at noon and decreases in the afternoon.

A single axis tracking collector with rotation around a vertical axis would begin the day facing the sun when it rises in the morning. The collector would rotate westward until sunset.

A dual axis collector would begin the day oriented vertically and facing the sun when it rises. During the day, the collector would rotate westward around its vertical axis. The collector would increase its tilt as the morning progressed, then decrease its tilt as the afternoon progressed until it was again vertical at sunset.

Charts are available that show the sun's azimuth and elevation as a function of day of the year and time of day. (The University of Oregon provides such charts and makes them available on the Internet[2].) For example, Figure H-7 shows a chart for Knoxville, Tennessee. The chart shows that the sun rises at a compass bearing of 60 degrees on June 21 (the longest day of the year) and sets at 300 degrees. On December 21 (the shortest day), the sun rises at 120 degrees and sets at 240 degrees. The chart shows that the maximum elevation is about 78 degrees on June 21 and 31 degrees on December 21.

Since the azimuth and elevation are known for every location, on every day of the year and at every time of day, controllers for tracking collectors can be pre-programmed. They can also use a feedback controller to maximize solar incidence at any time.

Shadowing Effects

Daily solar radiation incidence on a collector decreases if the collector is shadowed by buildings, trees or hills. This effect is strongest in mornings and afternoons, when the sun is lower in the sky.

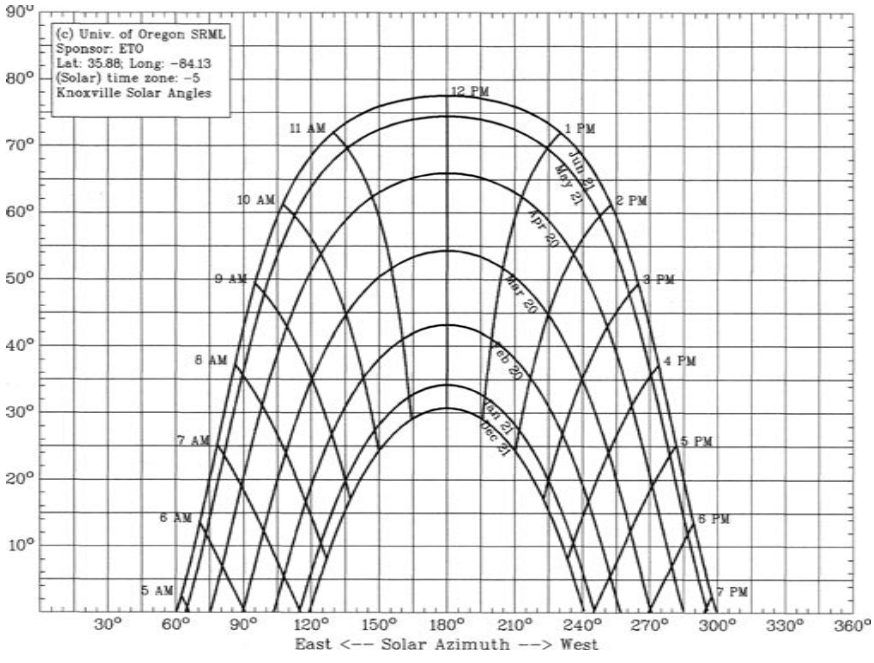

Figure H-7. The Sun's Azimuth and Elevation in Knoxville, TN (data from The University of Oregon)

References

1. http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/mon2/state.html

2. http://solardat.uoregon.edu/SunChartProgram.html

APPENDIX I: PHOTOVOLTAICS

Photovoltaic devices convert light energy directly into electrical energy. Light photons can dislodge electrons from atoms in certain materials, rendering them capable of motion. With proper selection and arrangement of the materials, these electrons can be put to work as an electrical current.

Various materials can be used to make photovoltaic devices. The most common are semiconductor devices made from silicon, but other materials, including organic polymers, are also suitable for use as photovoltaic devices. The principle of operation of silicon solar cells will be described here to illustrate solar cell fundamentals.

Silicon is a very common substance. Its atomic number is 14, meaning that it has 14 protons in the nucleus and 14 orbiting electrons. The outer, or valence, shell contains four electrons. Since eight electrons are needed to fill the outer shell, four additional electrons are needed to fill the shell. Silicon acquires these electrons by sharing with adjacent silicon atoms through covalent bonds.

Incoming photons can transfer their energy to an electron in a silicon atom and kick the electron out of the valence shell. This is the photoelectric effect. The freed electron can then move through the lattice of silicon atoms.

Before the loss of an electron, the balance of positively charged protons and negatively charged electrons in each silicon atom resulted in a neutral atom. After the loss of the electron, there are 14 positive charges and only 13 negative charges, giving the atom a net positive charge. This positive charge will attract any electron in the vicinity of the atom. In essence, the initial loss of an electron creates a "hole" into which an electron can fall. If an electron leaves a nearby atom to fall into the hole, it leaves behind a hole in the atom from which it came. Thus the hole can move from atom to atom.

Consequently, kicking an electron out of a silicon atom creates two mobile charge carriers: a negative electron and a positive hole. If the substance is silicon alone, the freed electrons will eventually fall into holes and give back the energy received from the photon. Light can create free electrons in silicon, but there is no directed flow of charge carriers as is required for an electric current.

Adding certain minor impurities, called dopants, can change the properties of silicon in a way that enables the creation of a useful electric current. Consider first the addition of a substance such as phosphorous, with five electrons in its outer shell. A phosphorous atom can bond covalently with a silicon atom. Four of the phosphorous valence electrons bond covalently with a silicon atom, leaving one spare (and loosely bound) electron. This material is called an n-type material (n for negative).

Now consider a second modification of silicon. This time, add a dopant with three valence electrons, such as boron. A boron atom can bond covalently with a silicon atom, but lacks the electron needed to complete the valence shell. The modified material needs an electron to fill the outer shell and will capture an available electron for that purpose. It is called a p-type material (p for positive).

Even though n-type materials have an excess of loosely-bound electrons and p-type materials have a deficiency of electrons, each material is independently neutral. This is because nothing has been done to disturb the balance between protons and electrons in the atoms.

The electrical neutrality can be upset if n-type material and p-type materials are brought together. Electrons from the n-type material are more strongly attracted to nearby holes in the p-type material than they are attracted by the protons in their own atoms. Electrons cross the interface between the materials and fill holes in the p-type material near the interface. Since electrons are thereby added to previously neutral material, the p-type region becomes negatively charged. Similarly, the n-type material becomes positively charged because of holes created by the loss of electrons. Buildup of the negative charge on the p-type material near the interface inhibits further

passage of electrons from the n-type material and inhibits the further creation of holes in the n-type material.

This barrier prevents further electron flow from n-type material to p-type material, but allows electron flow from the p-type material to the n-type material. When an electron leaves the p-type material, it leaves behind a hole. The hole cannot accompany the electron into the n-type material because of the positive charge on the n-type material at the interface. The p-n junction is a diode, a configuration that allows current flow in one direction and prevents current flow in the other direction.

If a photon creates an electron-hole pair far from the interface, it is likely that the electron will recombine with a hole and the hole will recombine with an electron. However, if an electron-hole pair is born near the interface, the electron and the hole will be forced to move in opposite directions.

Consider an electron-hole pair created in n-type material near the interface. Since the n-type region is positive, the hole will be repulsed and will move into the negatively charged p-type region, thereby adding positive charge to the p region. The electron left behind will add negative charge to the n region. Similarly, the creation of an electron-hole pair in the p region will result in the electron being repulsed and moving into the positively charged n region, and the hole left behind will add positive charge to the n region. Every electron-hole pair creation near the interface adds positive charge to the n region and negative charge to the p region. If an external conductor connects these regions, electrons will flow through the conductor from the p region to the holes in the n region. This electron flow is an electric current.

APPENDIX J: RADIATION ABSORPTION PHYSICS

Radiation Emission

All substances whose temperatures are above absolute zero emit electromagnetic radiation. The radiation has a dependence of emissive power on wavelength given by Planck's Radiation Law:

$$E = C1/(\lambda^5(e^{C2/(\lambda T)}-1) \quad \text{(J-1)}$$

where:

E = emissive power of a black body (watts/m^2-micron)
T = absolute temperature (kelvins)
λ = wavelength (microns)
C1 = 3.74×10^8
C2 = 1.44×10^4

Note that emissive power is expressed in units of energy flux (watts/m^2) per unit of wavelength.

Planck's Law applies for a so-called "black body," a theoretical body that is a perfect emitter and perfect absorber of electromagnetic radiation. Radiation impinging on a black body experiences absorption but no reflection or transmission. No actual substance can absorb or emit as much radiation as a black body at the same temperature, but many are quite close.

Figures J-1 and J-2 show the black body emission spectra for the sun (average surface temperature = 5800 kelvins) and the earth (average surface temperature = 288 kelvins or 15°C or 59°F).

The peak in a radiation spectrum, L(peak), is given by Wien's Law:

$$L(peak) = 2898/T \quad \text{(J-2)}$$

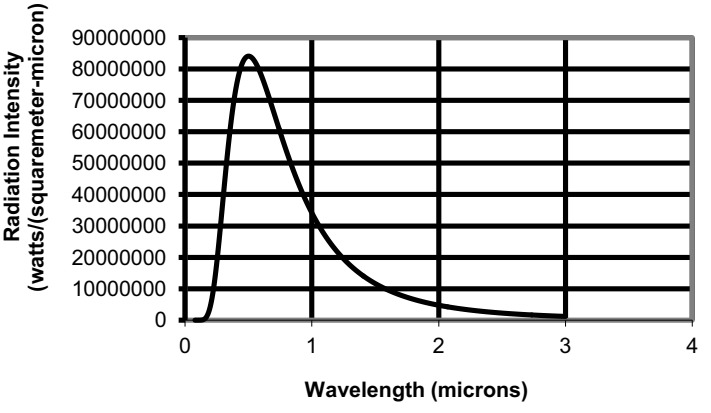

Figure J-1. The Solar Spectrum

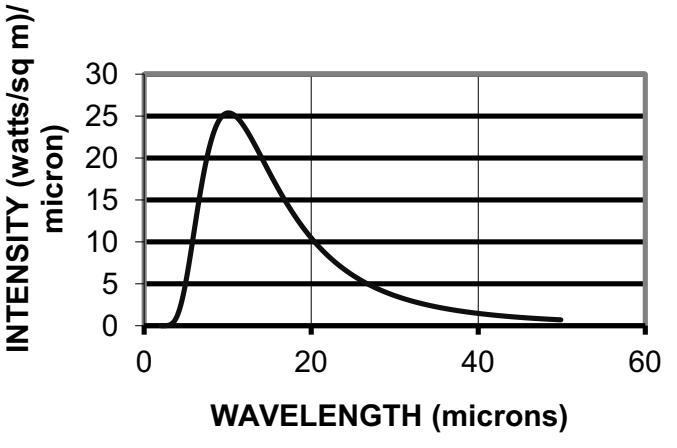

Figure J-2. The Earth's Emission Spectrum

The sun's spectrum peaks at 0.5 microns, and the earth's spectrum peaks at 10.1 microns.

The total energy emitted at all wavelengths is obtained by integrating the Planck's Law formula over all wavelengths. The result, called the Stephan-Boltzmann Law, is:

$$E_t = 5.67\times10^{-8}AT^4 \qquad \text{(J-3)}$$

where:

E_t = power emitted at all wavelengths (watts)
A = emitter surface area (m^2)
T = temperature (kelvins)

For example, the predicted solar energy flux (watts per square meter) at the surface of the sun is:

$$\begin{aligned} E_t/A &= 5.67\times10^{-8}\times(5.8\times10^3)^4 \\ &= 6.42\times10^7 \text{ watts per square meter} \\ &= 64.2 \text{ megawatts per square meter} \end{aligned}$$

Emitting 64.2 megawatts from a square meter of surface is **very intense** power delivery.

Radiation Absorption

Radiation is absorbed by the transfer of photon energy to electrons in an absorbing substance. Substances have absorption spectra characterized by absorption "lines" at specific wavelengths that are unique to the substance. The lines are smeared somewhat rather than sharp spikes. The smearing is due to motion of the electrons, a function of temperature and pressure.

Of course, an absorber substance must also emit radiation as long as its temperature is above absolute zero. Any heating due to photon absorption must be balanced by subsequent radiation from the absorber. This radiation will be called *re-emitted radiation*, but it is important to note that the radiation is not simply the release of the same photons that were absorbed. The re-emitted radiation consists of photons with a spectrum determined by the absorber's temperature. For example, absorption of photons of a single wavelength will give rise to photons with a spectrum of wavelengths determined by the temperature of the absorber. Furthermore, the photons emit-

ted from the absorber emerge in all directions. Consequently, half of the photons emitted from the absorber are directed back towards the source of the absorbed photons.

Photon interactions with matter can be viewed as the passage of photon packets through a cloud of discrete absorber sites, where some of the photons are absorbed. The remaining fraction of unabsorbed photons decreases exponentially with distance through the absorber. One may speak of an "extinction distance" as the distance through an absorber required to absorb essentially all (say 99 or 99.9 percent) of the incident photons.

Radiation Energy Balances

Bodies (such as the earth) receive incident radiation and emit radiation. To achieve and maintain a constant temperature, the emitted radiation must equal the absorbed radiation. For example, the earth receives radiation from the sun. In order to have a constant average temperature, the earth's temperature must be such that the radiation emitted to outer space equals the radiation from the sun.

Absorption Windows

Absorption windows are ranges of wavelengths over which absorption is small. Photons within this range of wavelengths will pass through with little or no absorption. Absorption windows occur at those wavelengths where the photon energy does not equal allowed electron energy transitions (see Section 2.9.1).

The effective windows for a mixture of gases are located at wavelengths where all of the windows for the constituent gases coincide.

Gas Concentration and Absorption

One of the arguments used by those who dispute global warming is the claim that the atmospheric absorption of photons emitted by the earth in carbon dioxide has reached saturation. That is, they say that the absorptions in atmospheric carbon dioxide have already reached their maximum and further increases in concentration would have no effect. However, the consensus among climate experts is that the saturation argument is invalid.

The arguments for and against the saturation argument will not be presented here, but it will be shown that the issue involves more than just the fate of photons emitted from the earth. It is important to recognize that a photon's energy does not disappear when the photon is absorbed. Instead, it heats the absorber which, in turn, emits photons with a spectrum determined by the absorber's temperature. Thus absorption does not stop energy flow.

If an atmospheric gas absorbs photons of a certain wavelength to extinction before they have traveled very far through the atmosphere, then increasing the concentration of the gas does not change the rate of absorption of **incident** photons. However, increasing the gas concentration will decrease the depth in the gas at which the extinction of incident photons occurs. The absorptions of incident photons will heat the absorber and result in the production of re-emitted photons that emerge in all directions. If they are to escape the atmosphere into outer space, the re-emitted photons released in the outward direction must pass through a greater thickness of absorber than they would with a lower absorber concentration. Of course, the outward-directed re-emitted photons may be absorbed before exiting the atmosphere, and these absorptions will heat the absorber and produce new re-emitted photons that emerge in all directions. Consequently, absorption to extinction of incident photons creates a cascade of sorts, and the re-emitted photons may escape (and carry energy) into outer space even though the incident photons do not.

So the energy loss to outer space depends on absorptions of re-emitted photons as well as of incident photons. It is wrong to say that increases in the

concentration of a gas that absorbs to extinction have no effect on energy loss to outer space. Increases in concentration cause re-emitted photons to face longer routes through the gas and greater probability of absorption rather than transmission and escape into outer space, but some re-emitted photons can escape when incident photons are absorbed to extinction.

Since re-emitted photons have a spectrum determined by the temperature of the absorber, they experience absorption only in that portion of their spectrum where they encounter strongly absorbing gases. Thus the re-emitted photons have a different probability of absorption in atmospheric gases than incident photons, and this further affects the energy loss to outer space.

APPENDIX K: AIR CONDITIONERS AND HEAT PUMPS

Introduction

There are five types of air conditioning systems: vapor compression, vapor absorption, evaporative, thermoelectric and gas depressurization. Vapor compression systems are the most common. They are widely used in home air conditioners and refrigerators and in commercial and industrial applications. Vapor compression, vapor absorption and evaporative systems are all phase-change systems (they use the evaporation of a liquid to absorb heat). Thermoelectric systems use a process called Peltier cooling. Gas depressurization systems are based on the compression and subsequent release of gas from a high-pressure reservoir. Details of the principles of operation of these systems appear below.

Heat pumps provide heating as well as cooling by a phase-change process. They exploit the condensation of a vapor to release heat.

Air conditioners and heat pumps based on vapor compression and vapor absorption transfer heat from a colder region to a hotter region. This is opposite to the direction of spontaneous heat flow. This cold-to-hot heat flow is accomplished by the use of external sources of mechanical or thermal energy.

A summary of key features of phase-change cooling systems appears in Table K-1 (a repeat of Table 15-3, included here for the reader's convenience):

Table K-1. Features of Phase-Change Coolers

System Type	Open or Closed	Fluid	Energy Supply	Relative Complexity
Compression	C	single refrigerant	mechanical	intermediate
Absorption (two-component)	C	refrigerant, absorber	heat, low power pump	intermediate
Absorption (three-component)	C	refrigerant, absorber, inert gas	heat	high
Evaporative	O	water	low power fan	low

Cooling Systems

Vapor Compression Systems

A vapor compression cooling system is a closed cycle system, meaning that all vapors and liquids are contained in the system and they recycle through the system to accomplish cooling. In vapor compression systems, evaporation of liquid refrigerant absorbs heat from the space that is to be cooled. The subsystem where this occurs is called the evaporator. In order to repeat this process, the refrigerant must be returned to the liquid state. A compressor uses mechanical energy to raise the pressure of the refrigerant. This process also raises the refrigerant's temperature. The hot refrigerant is cooled and condensed by transferring heat to the surroundings in a condenser. The cooled liquid refrigerant is then ready to re-enter the evaporator and begin repeating the process. Energy flows into the system from the compressor and the evaporator and leaves the system through the condenser.

A vapor compression air conditioner is shown in Figure K-1.

Vapor Absorption Systems

Vapor absorption air conditioners use externally-supplied heat as the energy source. It may be counter-intuitive for heat to be used to provide cooling, but these systems work quite well. The heat source may be fossil fuel, electricity or solar energy.

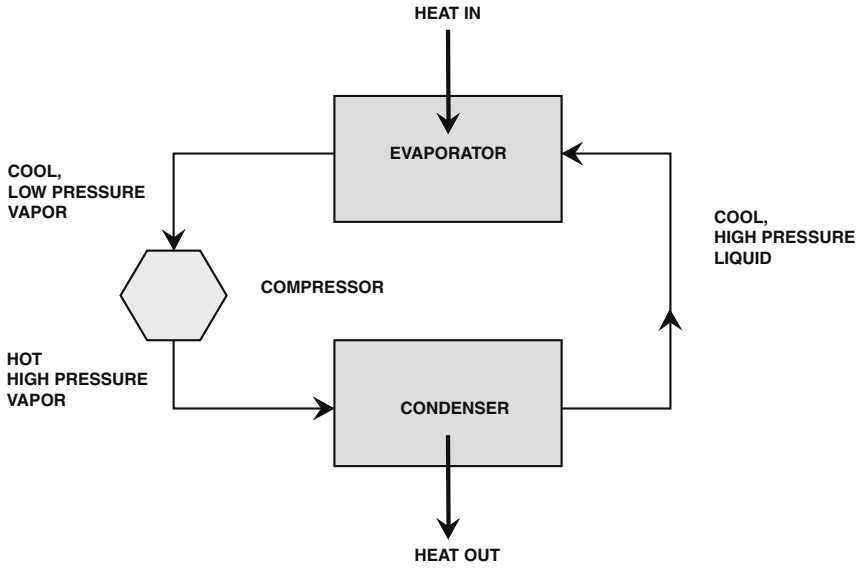

Figure K-1. Vapor Compression Air Conditioner or Heat Pump

There are two main types of vapor absorption systems. A two-component system uses a refrigerant and an absorber fluid. A three-component system uses a refrigerant, an absorber fluid and an inert gas. In both types, energy is removed from the cooled space by evaporation of the refrigerant, and the vapor exiting the evaporator is absorbed into the absorber fluid. The subsystem where this occurs is called the absorber. The two vapor absorption types differ in the way that they process the refrigerant-absorber mixture from the absorber. The processing provides refrigerant in the proper state for re-entry into the evaporator, where evaporation and cooling occur.

A two-component system uses a pump to raise the temperature and pressure of the refrigerant-absorber liquid mixture. Heat is then applied to boil off the refrigerant from the mixture. The high-pressure, heated vapor then goes to a condenser, where the refrigerant is cooled to become a pressurized liquid. This pressurized liquid is then ready for re-introduction into the evaporator. The two-component system requires some mechanical energy to drive the pump, but this is much less than the energy required to drive a compressor in a vapor compression system.

Common two-component vapor absorption systems are those that use ammonia as a refrigerant and water as an absorber, or use water as a refrigerant and a lithium bromide solution as an absorber. An ammonia-based two-component vapor absorption air conditioner is shown in Figure K-2.

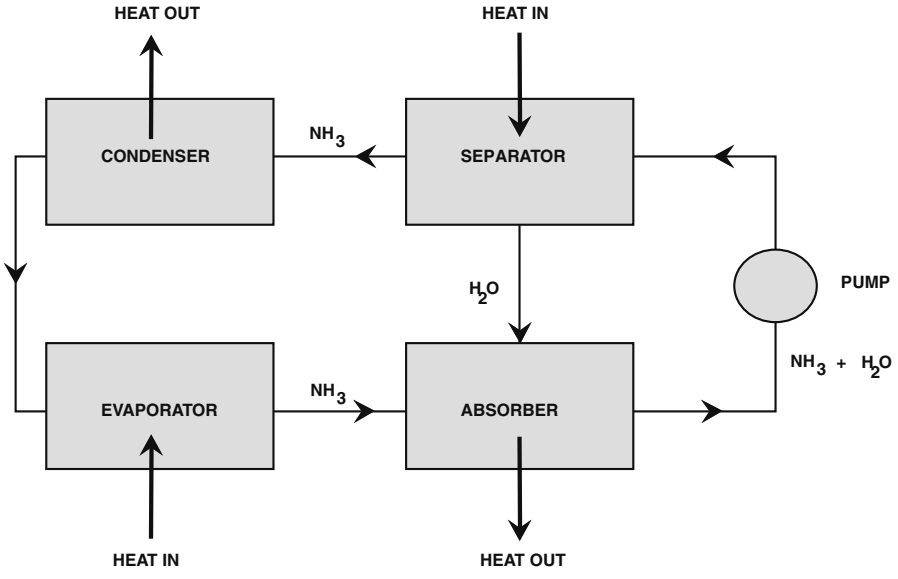

Figure K-2. A Two-Component Vapor Absorption System

Before starting a description of the three-component vapor absorption cooling process, it is helpful to explain Dalton's Law of Partial Pressures. This law is the basis for the unique feature of the three-component vapor absorption cooling system: it does not require a pump. Dalton's Law states that the total pressure is the sum of the partial pressures of the vapors present. In a mixture of vapors, the partial pressure of any vapor is reduced by the presence of the other vapor or vapors.

The vapor pressure of a liquid is a measure of the tendency of the liquid to evaporate. A liquid boils when its vapor pressure is equal to its partial pressure in the surrounding environment.

A typical three-component vapor absorption cooler contains ammonia, water and hydrogen. A convenient place to start in describing the cycle is the evaporator, where cool liquid ammonia is present. At this point, hydrogen gas is introduced. The hydrogen serves to reduce the partial pressure of the ammonia. Boiling ensues when the ammonia vapor pressure equals the ammonia partial pressure. The ammonia evaporates, thereby drawing heat from the surroundings.

The rest of the cycle serves to return the ammonia to the liquid state. This begins with mixing the ammonia-hydrogen mixture with water in the absorber. The ammonia dissolves in the water, and the hydrogen does not. (The hydrogen is recycled to again perform its function of reducing the ammonia partial pressure in the evaporator.) The ammonia-water mixture is then heated by an external heat source, causing ammonia vapor to boil off. (Thus the role of the heat source is to separate the ammonia from the water in which it is dissolved.) The subsystem where the ammonia is separated from the water is called the generator. The resulting ammonia vapor is cooled in a condenser by transferring heat to the surroundings. The cool liquid ammonia is the condition existing at the start of the cycle. Note that no mechanical energy is required. A three-component vapor absorption air conditioner is shown in Figure K-3.

Interest in vapor absorption systems is increasing because of the reduction or elimination of the need for grid electricity and the possibility of using solar energy as the heat source.

Evaporative Systems

Of course, vapor compression and vapor absorption systems rely on the evaporation of a refrigerant to achieve cooling, but the term evaporative cooling usually refers to open cycle coolers that cool by evaporating water with ambient air. The systems for residential coolers are quite simple: a fan that blows air over a wet wick. The chilled air may be blown directly into a residence (a direct type cooler), or it may be used to cool a second fluid that subsequently is used to extract heat from the living space (an indirect type cooler). An evaporative air conditioner is shown in Figure K-4.

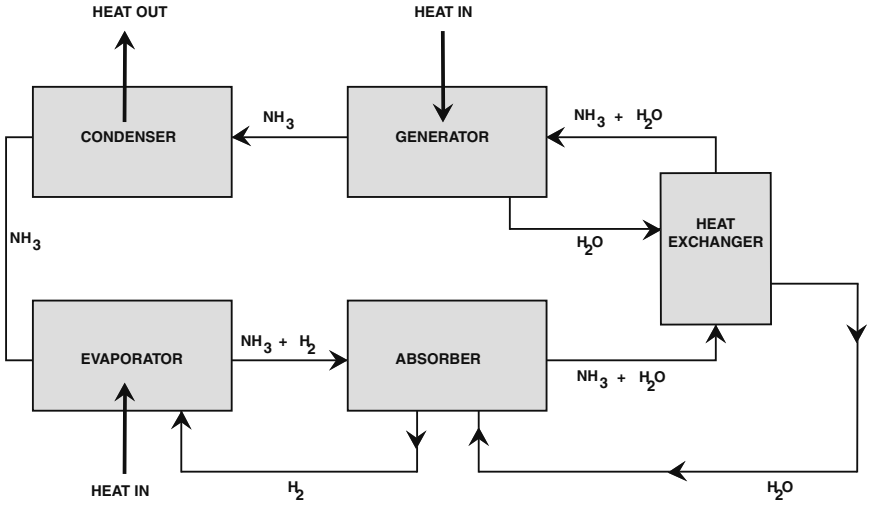

Figure K-3. A Three-Component Vapor Absorption System

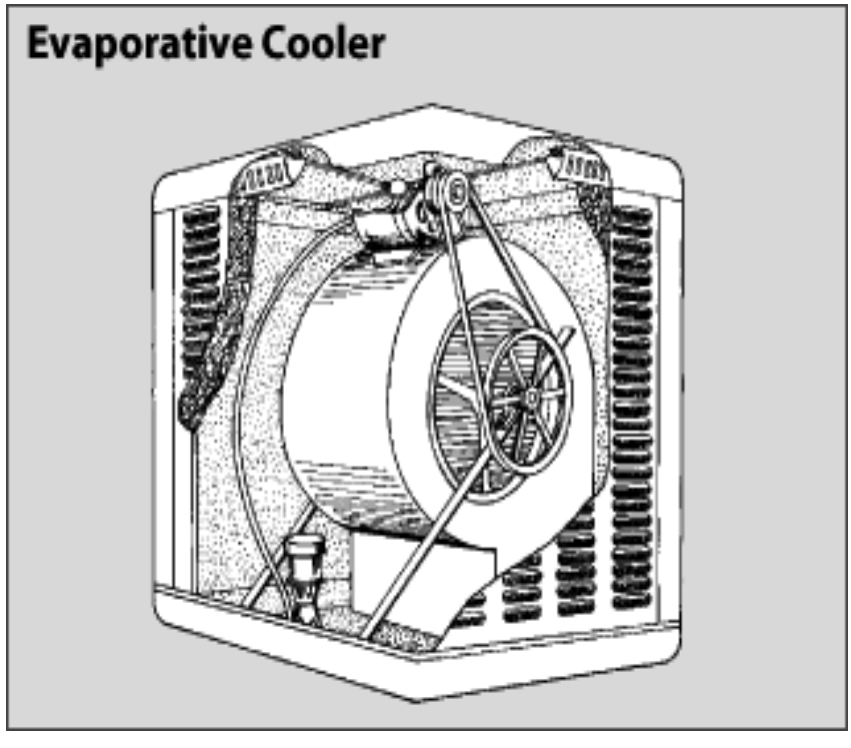

Figure K-4. An Evaporative Cooler (courtesy of U.S. Dept. of Energy)

Evaporative coolers are effective in regions where the air is hot and dry, such as the southwestern United States. Advantages of these coolers are low initial cost and low operating costs. Disadvantages are water consumption (typically 3.3 to 10.5 gallons per hour for a home unit) and elevated indoor humidity for direct type coolers.

Evaporative cooling is also used in large-scale industrial applications. Cooling towers use water evaporation to provide cooling in many electric-power and manufacturing plants. These systems transfer waste heat to the air rather than to a river or body of water. Concerns about heating aquatic environments often dictate the use of cooling towers.

Thermoelectric Systems

Thermoelectricity involves using a temperature difference to create an electric voltage or using an electric current to create a temperature difference. Thermoelectric devices can be used to measure temperature, to produce electrical energy or to provide heating and cooling. Thermoelectric systems are very simple, involving only two different conductors with dissimilar thermoelectric properties.

If two conductors made of different materials are joined at both ends, and one end is at a higher temperature than the other, a voltage will be produced, and a current will flow (see Figure K-5). This configuration is a thermoelectric power generator. Conversely, if a current is passed through a circuit in which the dissimilar materials are joined at both ends, one junction will cool, and the other will warm (see Figure K-6). This configuration is a thermoelectric heater/cooler.

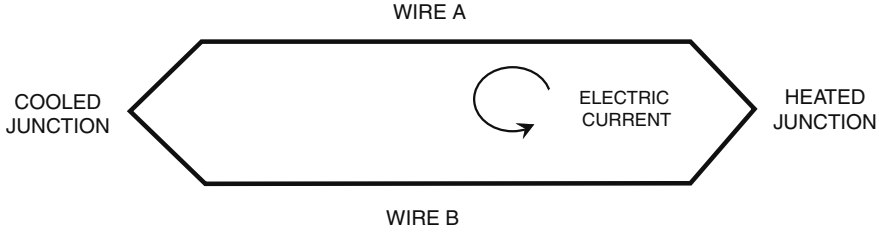

Figure K-5. A Thermoelectric Generator

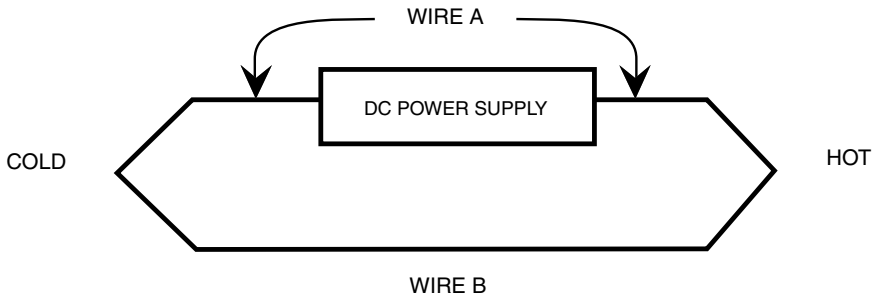

Figure K-6. A Thermoelectric Heater/Cooler

If the dissimilar wires are joined at only one end and a temperature differential exists between the two ends, a voltage will appear across the conductors. Open circuit conditions are adequately approximated if the wires are connected to a voltage measuring system with high input impedance. This voltage increases as the temperature difference between the open end and the closed end increases (see Figure K-7). This configuration is a thermocouple, the most common instrument used in industry for measuring temperature.

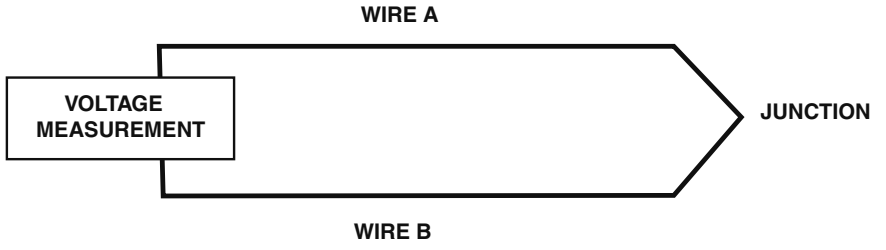

Figure K-7. A Thermocouple

Thermoelectric heating and cooling systems are useful in small-scale applications such as temperature control in instrumentation and in beverage heaters and coolers. They are not used for large cooling systems such as in residence air conditioning applications.

Gas Depressurization Systems

Pressurizing a gas raises the temperature of the gas, and depressurizing a gas cools it. Cooling can be achieved by releasing stored pressurized gas after it has been cooled by heat transfer to the environment. This is an inefficient cooling method, but it is sometimes used in special applications such as aircraft air conditioning systems. (See Figure K-8.)

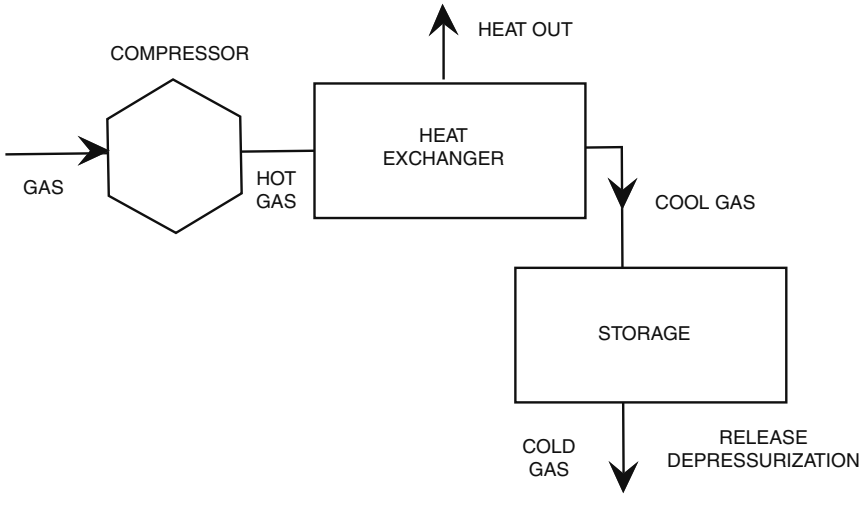

Figure K-8. A Gas Decompression Cooler

Heat Pumps

We have seen that closed-cycle refrigeration systems operate by collecting heat from a cooler region in an evaporator and dumping that heat into a warmer region in a condenser. For an air conditioning application, the space of interest is the space to be cooled by evaporation in the evaporator. Conversely, heat can be transferred to a warmer space by transferring heat from the condenser. Basically, heating with a heat pump is simply the use of an air conditioner with the transfer to the space of interest from the condenser rather than the evaporator.

Performance Measures

Air conditioner cooling capacity is usually quantified by "tons of capacity." This metric is equal to 12,000 BTU per hour. The term arose in early refrigeration applications and is the amount of heat energy that must be removed from a ton of water at 32^{o}F in one day to produce ice.

The performance of a vapor compression refrigeration system may be quantified by the "Coefficient of Performance" or COP, which is defined as follows:

> COP = (energy removed from cooled space)/(energy supplied to the compressor).

The COP can be greater than unity, indicating that more energy can be removed from the cooled space than the mechanical energy supplied by the compressor.

The maximum theoretical COP is determined by the temperatures, T_{cool} of the cooled space and the temperature T_{hot} of the space that receives heat from the condenser (this space is called the *heat sink*). The temperatures must be in absolute temperature units (degrees Rankine or kelvins). The maximum COP is given by:

$$COP_{max} = T_{cool}/(T_{hot}-T_{cool})$$

Example K.1
Consider a cooler with T_{hot}= 90^{o}F or 90+460 = 550^{o}R and T_{cool} = 60^{o}F or 60+460 = 520^{o}R. In this case the maximum theoretical Coefficient of Performance is:

$$COP_{max} = 520/(550-520) = 17.3.$$

Actual values of the COP in real systems are less than COP_{max} because of energy losses within the process. Typical values of the COP achieved in actual air conditioner operation are in the range of 3 to 5. Nevertheless, the

formula for COP_{max} reveals some important aspects of air conditioner performance. For example, the possibility of achieving some value of T_{cool} is diminished as T_{hot} increases. Since cooling is usually needed when the weather is hot, using hot ambient air as the heat sink limits cooling capability. However, other heat sink options besides ambient air are available, though at some cost. Using subsurface earth as the heat sink, where temperatures are generally lower than ambient air temperature in summer, increases the COP. These systems are called ground-effect or geothermal systems.

Heat pump effectiveness may be characterized by a Coefficient of Performance in the same manner as for air conditioners. The COP for heating with heat pumps is given by:

> COP = (energy added to the heated space)/(energy supplied to the compressor).

The maximum theoretical COP for heating is given by:

$$COP_{max} = T_{hot}/(T_{hot}-T_{cool})$$

The possibility of achieving some value of T_{hot} is diminished as T_{cool} decreases. Since heating is usually needed when the weather is cool, using cool ambient air as the heat source limits heating capability. Heat pumps are not effective for heating in cold climates. As with air conditioners, heating performance may be improved by supplying heat to the evaporator from subsurface regions, where temperatures are higher than ambient air temperature in winter.

The U.S. Department of Energy has developed a measure of air conditioner efficiency called the Energy Efficiency Ratio (EER). The EER rating is the ratio of the BTUs removed under specified ambient conditions to the watt-hours of electrical energy used to produce the cooling. Another measure, the Seasonal Energy Efficiency Ratio, or SEER, addresses the performance on a typical day rather than for a specific ambient air condition. The SEER rating is the ratio of BTUs removed on a "typical" day with an air condi-

tioner divided by the watt-hours of electrical energy used to produce the cooling.

The Department of Energy mandates minimum SEER ratings for new equipment. SEER ratings are useful to the consumer in comparing the performance of different equipment options. Most current air conditioners and heat pumps have SEER ratings in the low teens. New systems with higher efficiency have SEER ratings as high as the low twenties.

A performance measure for heating with a heat pump is called the Heating Seasonal Performance Factor (HSPF). HSPF is the ratio of heat output (in BTUs) to watt-hours of electricity used. HSPF values of 8 or greater are considered to be indicative of efficient performance. The HSPF is less well known by consumers than SEER ratings, and it is therefore less frequently considered in making equipment selections.

The Department of Energy and the Environmental Protection Agency identify energy-efficient systems by granting them an ENERGY STAR rating. ENERGY STAR ratings are assigned to appliances, heating and cooling systems, electronics lighting, and buildings. These ratings serve to indicate systems that use energy efficiently.

APPENDIX L: TRIGLYCERIDES

Vegetable oils and animal fats contain triglycerides. Triglycerides are members of a family of chemicals called esters. Esters are compounds that are composed of linked alcohols and fatty acids. Fatty acids are chains of carbon atoms (usually 16 to 18 carbon atoms) with hydrogen atoms attached along the chain and with a carboxyl group at one end. A carboxyl group is a section containing one carbon atom, one oxygen atom and one hydrogen atom. A fatty acid molecule is shown symbolically in Figure L-1. The saw tooth portion is a hydrocarbon chain.

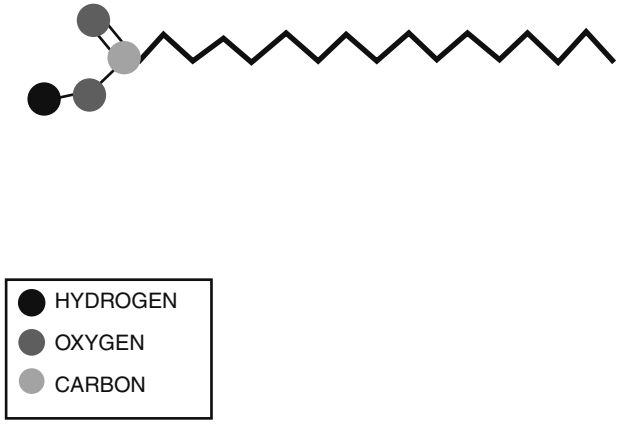

Figure L-1. A Fatty Acid Molecule

Triglycerides may be modified to improve their properties for use as a liquid fuel by basic transesterification, acid transesterification and hydroprocessing.

The alcohol spine in the triglyceride ester is glycerol. Glycerol is an alcohol with three carbon atoms. It provides three sites for linking with fatty acids. The structure of the glycerol molecule is shown symbolically in Figure L-2. The structure of the triglyceride molecule is shown symbolically in Figure L-3.

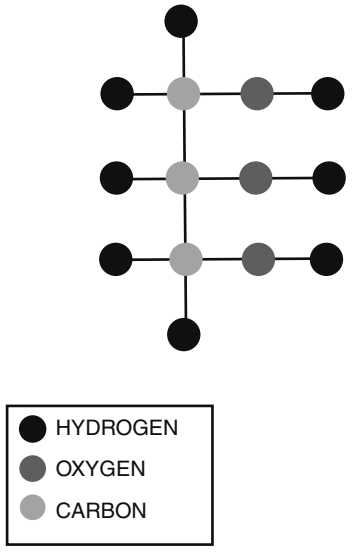

Figure L-2. A Glycerol Molecule

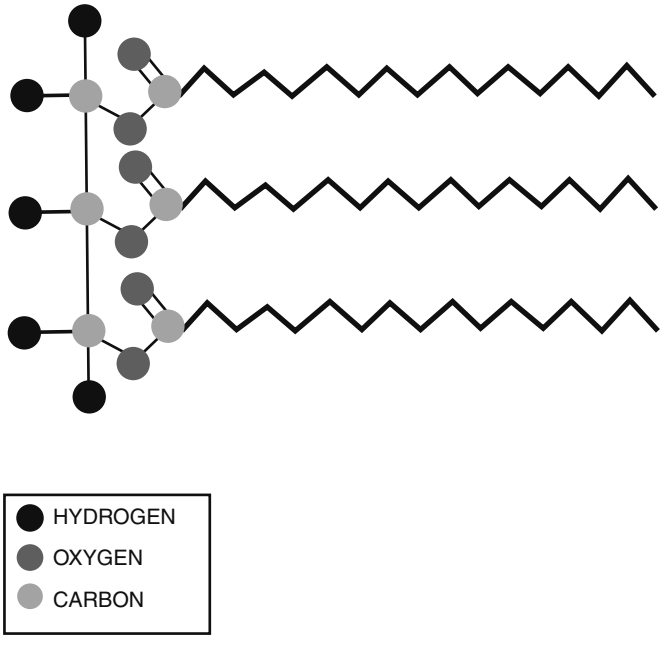

Figure L-3. A Triglyceride Molecule

The three fatty acids in a triglyceride may be the same or different. An important feature of the fatty acids is whether they are saturated or unsaturated. Saturated fatty acids have the maximum number of hydrogen atoms per carbon atom that is chemically possible. Unsaturated fatty acids have fewer hydrogen atoms per carbon atom than is chemically possible. Most animal fats are saturated triglycerides and most vegetable oils are unsaturated. Saturated triglycerides are solid at room temperature, and unsaturated triglycerides are liquid.

In the transesterification processes, the glycerol spine is replaced by another alcohol that connects with only a single fatty acid, rather than three. Methanol and ethanol are capable of the transesterification of triglycerides. In the basic transesterification process, the glycerol-fatty acid bond is broken with a strong base, usually sodium hydroxide (lye) or potassium hydroxide. This is done in the presence of methanol or ethanol. The fatty acid chains link with the methanol or ethanol to form single-chain esters, either a methyl fatty acid ester or an ethyl fatty acid ester. The process also yields glycerol. The esters are separated from the glycerol. They are suitable for use as a liquid fuel.

The acid transesterification process is similar, but acid is used to break the glycerol-fatty acid link.

Hydroprocessing involves breaking the glycerol-fatty acid bond catalytically or thermally, removing the oxygen from the resulting fatty acids and hydrogenating to obtain saturated hydrocarbon chains. Basically, this approach consists of deconstructing the triglyceride molecules and constructing hydrocarbons from the contained carbon and hydrogen.

APPENDIX M: BIOETHANOL

Ethanol is an important biofuel. It is a clear liquid that readily mixes with water. Ethanol is more volatile than water (it has a boiling point of 78.4°C, or 173.1°F). The low heating value (LHV) of ethanol is 11,500 BTU per pound or 75,700 BTU per gallon, and the high heating value (HHV) is 12,800 BTU per pound or 84,000 BTU per gallon. The chemical formula for ethanol is C_2H_5OH. Combustion yields water and carbon dioxide as follows:

$$C_2H_5OH+3O_2 \rightarrow 3H_2O+2CO_2+\text{energy}$$

The molecular structure of ethanol is shown symbolically in Figure M-1.

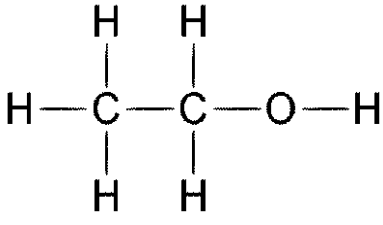

Figure M-1. An Ethanol Molecule

Ethanol is an excellent solvent. It reacts with certain rubbers and plastics, making it necessary to avoid these materials in ethanol production, storage, transport and use in engines. Because ethanol also mixes readily with water, fuel ethanol must be isolated from water in order to avoid degrading its usefulness as a fuel.

Ethanol from Carbohydrates

Ethanol is a renewable liquid fuel that is most often made from carbohydrates (plant materials that are composed entirely of three elements: carbon, hydrogen and oxygen). They include sugar, starch, cellulose and hemicellulose. Carbohydrates all consist of linkages of simple sugars (monosaccharides). The number of sugar units in other carbohydrates range from two (in sucrose, common table sugar, a disaccharide) to over 1,000 (in cellulose, a polysaccharide).

It should be noted that ethanol production from carbohydrates can capture energy contained in stalks, stems and leaves (residues from traditional farming) as well as from seeds and fruit. The gathering of farm residues requires harvesting efforts, but no commitment of new, dedicated farmland.

Biochemical production of ethanol from carbohydrates involves three steps:

1. Transforming the naturally occurring carbohydrates into monosaccharides. This process is called hydrolysis.

2. Transforming the monosaccharides into ethanol and CO_2. This process is called fermentation.

3. Separation of the ethanol from the water remaining from the previous steps. Separation requires two processes: distillation, capable of producing a maximum ethanol concentration of 96 percent; and subsequent dewatering with water-absorbing material to obtain 100 percent ethanol.

Complex biochemical processes play a crucial role in transforming carbohydrates into liquid fuels. Two of the terms needed to describe the production of ethanol from plants are as follows:

- Enzyme: 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.

- Fermentation: The enzyme-controlled process of transforming an organic material into another organic material. Enzymatic conversion of sugars to ethanol is an example of fermentation.

Monosaccharides have two hydrogen atoms and one oxygen atom per carbon atom. Six carbon sugars (called hexoses) and five carbon sugars (called pentoses) have the following chemical formulas:

Hexoses: $C_6H_{12}O_6$

Pentoses: $C_5H_{10}O_5$.

Fermentation of monosaccaharides to produce ethanol is represented by the following chemical reactions:

Hexoses: $C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$

Pentoses: $3C_5H_{10}O_5 \rightarrow 5C_2H_5OH + 5CO_2$

Carbon dioxide is produced in the fermentation of both.

When ethanol oxidizes, it releases quantities of carbon dioxide and water that are exactly equal to the quantities of carbon dioxide and water initially consumed in photosynthesis by the plant. The energy released also is the same as the solar energy initially captured during photosynthesis.

Enzymes play a crucial role in ethanol production from biomass. They are used both in hydrolyzing disaccharides and polysaccharides into fermentable monosaccharides and in the conversion of the monosaccharides into ethanol. All animals, green plants, fungi and bacteria produce enzymes. They are very specific proteins that serve as highly selective facilitators for certain biochemical reactions. They enable or hasten reactions, but are not

consumed in the process. Enzymes are thought of as molecules that are shaped so as to fit only with a specific host molecule. After the fit occurs, the host molecule undergoes some specific reaction, then releases the enzyme to do its work somewhere else.

Even though enzymes are not consumed in the reactions that they facilitate, process conditions can inhibit or stop enzymatic action. Temperature, pH and the presence of heavy metal ions can alter the shape of enzyme molecules and thereby prevent them from facilitating reactions. Also, the enzymes may be destroyed when the concentration of reaction products gets too high.

Nature provides a vast array of enzymes that enable many essential biochemical reactions, and new enzymes with new capabilities are now being produced by genetic engineering. It is indeed fortunate that this vast array of useful enzymes is available from nature and that modern technology is now capable of expanding this resource.

Ethanol from Natural Sugars

Some plants, such as sugar cane and sugar beets, produce sucrose. Sucrose is a disaccharide, a combination of two monosaccharide components called glucose and fructose. Hydrolysis of sucrose into glucose and fructose may be accomplished by enzymatic action. Processes facilitated by enzymes are generally simpler and more economical than other types of processes (such as thermochemical processes).

Sugar cane is the raw material for a huge ethanol production program (around 7 billion gallons per year in the early twenty-first century) in Brazil.

Ethanol from Starch

Some plants, such as potatoes and corn, are rich in starch. Starch is made up of a string of glucose components. Hydrolysis of starch into glucose may be accomplished by enzymatic action.

Ethanol from Cellulose

Cellulose is the most abundant carbohydrate in nature. Grasses, leaves, plant stalks, bushes and trees are mostly cellulose and hemicellulose.

Like starch, cellulose consists of a chain of linked glucose elements, but the structural orientation of the cellulose molecule is different than that of starch. An enzyme called cellulase exists in the digestive systems of certain animals and insects, including cows and termites. It can hydrolyze cellulosic materials (humans cannot). A problem in large-scale ethanol production from cellulose is the unavailability of a plentiful and inexpensive supply of effective enzymes for processing cellulosic materials. Scientists are searching for genetically engineered enzymes that can accomplish the hydrolysis of cellulose (and maybe hemicellulose simultaneously) efficiently and inexpensively.

Industrial hydrolysis also may be accomplished with an acid process, usually involving sulfuric acid. Cellulose hydrolysis requires use of concentrated acid. Acid hydrolysis is well developed, but the process requires use of hazardous and corrosive liquids. Consequently, there is a strong incentive to develop an effective and inexpensive enzymatic process.

The production of cellulosic ethanol suffers from another significant problem. Cellulose and hemicellulose in plant material exist in packets encased in a tough, fibrous non-carbohydrate material called lignin. It is necessary to free the cellulose (and hemicellulose) from its lignin envelope before hydrolysis can ensue. This requires grinding the material or solvent extraction.

Sugars and starches are valuable as human foodstuffs, so there is an incentive to overcome the greater difficulty of using cellulose and hemicellulose for ethanol production since the raw material is abundant, cheap and unsuitable as a human foodstuff. Agricultural and forest wastes are potential feedstocks. In addition, crops such as switchgrass may be grown for cellulosic feedstock on farmland that is too poor in quality for traditional agricultural production.

Ethanol from Hemicellulose

Hemicellulose is found along with cellulose enclosed in lignin sheaths in plants. Hemicellulose is a polysaccharide consisting of different types of sugar components. Some of the sugars are six carbon sugars (hexoses like glucose and fructose), and some are five carbon sugars. The presence of an array of different sugar types after hydrolysis complicates the development of suitable fermentation enzymes.

Hemicellulose, like cellulose, also can be hydrolyzed by an acid process. Dilute acid is used to hydrolyze hemicellulose as opposed to the concentrated acid needed for cellulose hydrolysis.

Lignin in Biochemically-Produced Ethanol

Lignin is the fibrous structural material in plants. It is an organic polymer with a high molecular weight. It makes up one-fourth to one-third of plant materials. Lignin cannot be hydrolyzed and fermented into ethanol like sucrose, starch, cellulose or hemicellulose, and consequently, is not a source material for the biochemical production of ethanol. However, lignin will burn and is therefore used in the ethanol production process as a fuel to provide needed process heat.

As will be discussed in Appendix N, butanol, whose fermentation does not require monosaccharide intermediates, can be produced with lignin as well

as with carbohydrates. Lignin can also be processed thermochemically to break down the molecules and reconstruct the components as useful biofuels (see Section 7.5).

Bioethanol Energy Balance

The efficiency of bioethanol production is important for assessing the practicality of large-scale production. However, one should realize that different energy efficiency metrics can be defined. For example, if the objective is reducing the need for petroleum by switching to bioethanol, the logical efficiency metric is the ratio of bioethanol energy content to the energy content of the petroleum products used in producing the bioethanol. Another objective is maximizing the conversion of biomass stored energy into energy in the bioethanol produced. The metric in this case is the ratio of bioethanol energy to the energy stored in the biomass. Greater values of this metric indicate that less land is required grow the amount of biomass needed to produce a given amount of bioethanol.

The National Renewable Energy Laboratory performed detailed design studies of two types of bioethanol manufacturing plants. One plant used enzymatic processing of corn stover[1], and the other used thermochemical processing of biomass[2]. In both studies, the energy and material flows in the plants were such that no external energy inputs were required. The computed efficiencies (energy in produced biofuel/energy contained in biomass feedstock) were around 50 percent. These studies illustrate the point that no fossil fuels are necessary for the conversion of biomass into bioethanol. Process energy is required, but it derived from the biomass, some of which could have otherwise been converted into bioethanol. Additional energy is required to plant, fertilize, harvest, transport and (possibly) dry the biomass. These energy expenditures are usually attributed to oil and gas in energy efficiency assessments, but all of these requirements could also be met with bioethanol.

Of course, it may be economical and convenient to use some fossil fuel energy in producing bioethanol. In this case, bioethanol production may be increased at the expense of fossil fuel consumption.

Energy efficiency is a metric whose misuse or misunderstanding can cause confusion about the viability of bioethanol production. For example, assume that some process captures 33 percent of the energy in biomass feedstock as energy contained in the bioethanol produced and no fossil fuel or electricity is used. One way to state the energy efficiency is:

> *This production method uses more energy than is contained in the bioethanol product. In fact, two BTUs are wasted for every BTU available in the ethanol produced.*

Another way to state the energy efficiency is:

> *This production method captures one-third of the energy contained in the biomass feedstock as energy contained in the bioethanol produced without requiring any external energy inputs.*

Both statements are true, but one is designed to convey an impression of unacceptability, and the other is designed to convey an impression of acceptability. These examples illustrate that the technique called "spin" in political discourse also can be employed in energy discussions.

The efficiency of bioethanol production has been the subject of heated debate. The debate hinges on an assessment of the BTU expenditure required to produce a BTU of bioethanol energy. If the energy available from the biofuel is less than the energy required to produce the biomass, transport it and convert it into bioethanol, then external sources (oil, natural gas, coal or electricity) must be used to make up the deficit. Many studies have been performed to assess energy efficiency and almost all conclude that the energy balance is positive, even for the technology used for producing bioethanol from corn.

It should also be noted that the desirability of a specific fuel production process depends on other factors in addition to energy efficiency. Some of these factors are:

- A protein-rich by-product of starch-to-ethanol production is valuable as a livestock feed.

- Biomass can be converted into materials that can replace oil and natural gas as a feedstock to make chemicals needed to sustain modern civilization. Thus, biomass can reduce fossil fuel dependency in more ways than solely as an energy source.

- Conversion of an energy resource into a more useful form can override energy efficiency concerns. For example, hydrogen production always consumes more energy than is contained in the hydrogen produced. Electricity production in power plants fueled by coal, natural gas, oil or uranium always results in wasting about two BTUs for every BTU of electricity produced. Liquid biofuel is more useful than the solid biomass from which it was produced.

The bottom line on the issue of energy efficiency in biofuel production is that greater efficiency is a good thing, but it is not a basis for dismissing biofuel as a major part of our energy future. Emphasis on energy efficiency in judging the desirability of ethanol production should diminish to its appropriate level of secondary importance compared to the importance of reducing fossil fuel dependence. Diminished emphasis will reduce misleading reports in the popular press by poorly-informed journalists and inappropriate prioritizations by poorly-informed politicians.

Ethanol Imports

Just as the U.S. counts on domestic and imported petroleum, ethanol imports will certainly be used to supplement domestic production. The yield of biofuels in tropical regions is as much as five times higher than in temperate regions. This greater productivity is due to crops with higher

growth rates and longer, even year-round, growing seasons. Brazil is poised to become a major supplier of biofuels, largely because of its huge capacity for producing ethanol from sugarcane. It has developed the agricultural and processing infrastructure needed to eliminate the need for oil imports and to provide a foundation for developing a large export industry.

The countries with the greatest biofuel production potential may be tempted to maximize production at the expense of environmental degradation. Nations and businesses will face policy decisions that will have lasting impacts.

If exporters become dependent on exported biofuel income to sustain their economies, and importers become dependent on imported biofuels to satisfy their energy needs, new patterns of political and economic opportunity and vulnerability will evolve. The current concern about the stability of oil-exporting countries could be replaced by a similar concern about biofuel-exporting countries.

Ethanol as a Transportation Fuel

Ethanol may be used as a fuel in internal combustion engines, but use of pure ethanol requires engine modification. Because ethanol contains significant oxygen (one oxygen for every two carbon atoms and every five hydrogen atoms), less oxygen is needed for combustion than for gasoline. This contained oxygen reduces the need for oxygen from the air and necessitates a leaner fuel/air mixture.

Ethanol will mix with gasoline, and this mixture may be used to fuel internal combustion engines. Ethanol/gasoline mixtures are designated by the letter E, followed by the numerical percentage of ethanol in the mixture. Common mixtures are E10 and E85.

Ethanol is not compatible with some plastics and metals commonly used in engines and fuel systems, requiring modifications that eliminate these materials for pure ethanol or E85.

A gallon of ethanol has only about two-thirds as much energy content as a gallon of gasoline. Ethanol use would require a larger fuel tank to achieve the same range as gasoline. However, ethanol has a higher octane rating than gasoline. Higher octane fuels have a lesser tendency to ignite prematurely in an engine. Use of ethanol fuel may permit higher compression ratios in engines and thereby improve the efficiency of conversion of chemical energy into mechanical energy.

Transportation of liquid and gaseous fuel is best done in pipelines. Oil and natural gas pipelines crisscross the United States. If bioethanol becomes a major fuel, dedicated pipelines for ethanol transportation from source to consumer will be required. Existing pipelines do not provide the isolation from water required for ethanol. Dedicated pipelines for ethanol will be required.

Ethanol Environmental Effects

Manufacturing and burning ethanol release carbon dioxide, a gas that contributes to global warming. However, the amount of carbon dioxide released is exactly equal to the carbon dioxide removed from the air during production of the biomass during photosynthesis. Consequently, biofuels are neutral with respect to carbon dioxide release and resulting contributions to global warming. The concentrated carbon dioxide released during ethanol production may facilitate collection for sequestration or for providing a CO_2-rich environment to increase the growth rate in special algal growth chambers. It may even prove viable to use nuclear energy to provide the energy required to recombine the carbon dioxide released in ethanol production with water to construct synthetic carbohydrates. All of these possible steps serve to reduce increases in atmospheric carbon dioxide.

Of course, growing biomass requires water. If biomass is grown specifically for biofuel production in areas that require irrigation, then water use may become an environmental issue in biofuel production.

Since ethanol is free of problematic chemicals such as sulfur, using ethanol as a fuel does not cause the release of pollution related to these materials. Burning ethanol in air does expose atmospheric nitrogen to high temperatures, resulting in the production of oxides of nitrogen.

An important, but rarely mentioned, consequence of removing biomass from the fields where it was grown is the effect on soil fertility. Plants need nutrients in the soil in order to grow. This includes nitrogen, phosphorous, potassium and small amounts of many different minerals. When dead plant matter in the form of farming residue is left in the field, these nutrients return to the soil for use by subsequent generations of plants. If the biomass is removed for conversion to biofuel, the nutrients are also removed. If the needed nutrients are not restored, plant growth will stop eventually. Fertilizers are used to provide these nutrients. Introducing a large biofuel industry will create a related large increase in fertilizer requirements. Some of these materials will be recoverable at the biofuel production facilities as by-products, but producing, delivering and using the increased fertilizer quantities will create new costs and energy use requirements.

References

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2. Philips, S., Aden, A., Jechura, J. and Dayton, D. "Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass" *National Renewable Energy Laboratory Report NREL/TP-510-41168* April 2007.

APPENDIX N: BIOBUTANOL

Butanol Properties

Butanol is a four-carbon alcohol, C_4H_9OH. It is a clear liquid with a specific gravity of 0.81. Like bioethanol, it may be produced by biochemical means, but the currently developed production technology for biobutanol is a bit more complex than bioethanol production technology. Biobutanol has some advantages over bioethanol as a fuel, and there are some who say that emphasis should shift from bioethanol production to biobutanol.

Some advantages of butanol properties relative to its use as a fuel are as follows:

- Butanol has a low heating value (LHV) of 14,800 BTU per pound (99,800 BTU per gallon) and a high heating value (HHV) of 16,100 BTU per pound (108,500 BTU per gallon). Butanol heating values are about 30 percent higher than ethanol heating values and about 86 percent of gasoline heating values.

- Butanol is compatible with common metals and plastics.

- Butanol is immiscible with water. Contact with liquid water or water vapor does not contaminate butanol. This property would facilitate transport in pipelines.

- Butanol has a low vapor pressure (it does not readily evaporate).

- Butanol is more viscous than gasoline or ethanol (more flow resistant, a disadvantage).

Combustion of butanol proceeds as follows:

$$C_4H_9OH + 6O_2 \rightarrow 4CO_2 + 5H_2O$$

Butanol Production

Butanol was produced biochemically in 1916 as an unwanted byproduct of a process to produce acetone needed in munitions manufacture. The biochemical process produced acetone, butanol, and ethanol. It is usually referred to as the A.B.E. process. Subsequent research has focused on developing processes with greater butanol yields. One such process operates in two stages, with different enzymes for each stage. The first stage enzyme causes conversion of biomass into butyric acid ($C_4H_8O_2$) and hydrogen, and the second stage, using the same enzyme as originally used in the A.B.E. process, converts butyric acid into butanol. This process does not involve the hydrolysis of starch, cellulose, or hemicellulose into simple sugars. It can use the lignin as well as the carbohydrate components of biomass. The two-stage process produces butanol and hydrogen, both useful in energy production.

APPENDIX O: BIOMETHANE

Methane is valuable as a fuel and as a feedstock for producing other useful compounds. Methane, CH_4, is the simplest hydrocarbon. It is a colorless gas with a high heating value (HHV) of 1,011 BTU per cubic foot and a low heating value (LHV) of 910 BTU per cubic foot (measured at standard temperature and pressure). Methane may be extracted from underground deposits (as natural gas, a fossil fuel), or it may be produced from coal (as a fossil fuel derivative) or from biomass.

Biomass decay occurs in the presence of oxygen (aerobic) and in the absence of oxygen (anaerobic). Both decay processes involve microbes that digest the biomass. Dead biomass that falls to the ground encounters aerobic microbes that feed on the biomass as long as they have access to atmospheric oxygen. If biomass is denied oxygen by burial under dirt or accumulated biomass or by being submerged in water, then anaerobic microbes take over and digest the material.

The biochemical route to methane production is by the anaerobic digestion of organic matter by certain microorganisms. Landfills and accumulated animal waste are potential sources of biomethane.

The products of aerobic digestion are carbon dioxide and water. These substances, used in photosynthesis, are returned to the environment. Materials left in the soil after microbial digestion (aerobic or anaerobic) include nutrients necessary for subsequent plant growth. These nutrients include nitrogen, potassium phosphorous, and a number of other elements needed for plant growth. Without the recycling of these substances, plant growth would stop.

Methane release into the atmosphere contributes to global warming. Its potency per molecule of its greenhouse effect is over 20 times stronger than that of carbon dioxide.

The products of anaerobic digestion are primarily methane and carbon dioxide. Methane produced in natural settings escapes to the atmosphere, where it contributes to global warming. Methane produced in landfills and in accumulated animal waste will also escape to the atmosphere unless it is captured.

Some newer landfills have collection pipes buried along with the waste material being buried. Fans draw gas, called *biogas*, from the landfill as it is being produced. This biogas can be used as a fuel, but its heating value is less than pure methane because of the associated carbon dioxide.

The modest quantity of biogas from landfills will never be a major source of energy. However, the reduction of methane release to the atmosphere is at least as important as the energy obtained from biogas.

Methane is also produced in the digestive systems of certain animals and insects and is released into the atmosphere. Cows are one such source of methane, and any increase in their numbers is accompanied by a proportional increase in methane release.

APPENDIX P: PHYSICS OF FALLING AND MOVING FLUIDS

Hydroelectric dams and river diversion systems use the kinetic energy of falling water to produce electrical energy by the use of turbine-generators. Wind turbines and water turbines use the kinetic energy of flowing wind or water to produce electrical energy. This Appendix describes the assessment of the energy and power available from these sources and the important issue of the units used in these assessments.

Falling Water

In a dam-based hydroelectric facility, a dam creates an elevated water reservoir. Turbine-generators use water released from the reservoir to produce electricity.

A river diversion system uses water from a river that drops naturally over a short distance. Water passes from a higher upstream point through a tunnel or pipes to a turbine at a lower elevation.

The power of the falling water is the rate at which potential energy, PE, is released (the energy per unit of mass times the rate at which mass falls). That is:

$$PE = mgh \tag{P-1}$$

where:

m = mass
g = gravitational constant
h = height

The potential energy per unit of mass is given by:

$$PE/m = gh \tag{P-2}$$

The power delivered in falling from a height, h, is:

$$P = (PE/m) \times (dm/dt) = fgh \tag{P-3}$$

where:

P = power
f = dm/dt = flow rate (mass per unit time)

Use of Equation P-3 requires caution. One must properly distinguish between mass and weight. Mass, m, is an intrinsic property that measures the inertia of a quantity of material. Weight, W, is the force acting on a quantity of material caused by gravity and is equal to:

$$W = mg \tag{P-4}$$

where:

W = weight

Rewriting Equation P-1 gives:

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

The potential energy per unit of weight is:

$$PE/W = h \tag{P-6}$$

The power delivered in falling from height h is:

$$P = (PE/W) \times (dW/dt) = Fh \tag{P-7}$$

where:

F = dW/dt = weight flow rate (weight per unit time)

Example P-1

Parts of the upper Tennessee River flow at a rate of around 30,000 cubic feet per second or about 1.9 million pounds per second. Practical dam heights in this region are around 70 feet. Therefore, based on Equation P-7, the power of water flowing from a reservoir to the river below is about $1.9\times10^6\times70 = 1.33\times10^8$ foot pounds per second. Using the conversion from foot pounds to Joules (1.356 Joules per foot pound) gives a result of about 1.8×10^8 Joules per second. Since a watt is defined as one Joule per second, the power of the falling water is about 180 megawatts. This is the maximum power available. Electrical power generation capacity is limited by the efficiency of the turbine-generator.

Now let us repeat the calculation using SI units. A weight flow of 1.9 million pounds per second equals a mass flow (in SI units) of 864,000 kilograms per second. The dam height, 70 feet in U.S. Customary units, is 21.3 meters in SI units. Using Equation P-3 gives $864{,}000 \times 9.81 \times 21.3 = 1.8 \times 10^6$, illustrating the consistency of calculations in the U.S. Customary and SI systems.

Flowing Wind and Water

Wind turbines or water turbines operate by capturing part of the kinetic energy in a flowing stream of wind or water. The power contained in the stream is the kinetic energy per unit of mass times the rate at which the mass is flowing. That is:

$$KE = (1/2)mv^2 \tag{P-8}$$

$$KE/m = (1/2)v^2 \tag{P-9}$$

$$P = (1/2)v^2\, f \tag{P-10}$$

where:

m = mass
v = velocity
KE = kinetic energy

P = power
f = mass flow rate

But the mass flow rate, f, is given by:

$$f = \rho A v \tag{P-11}$$

where:

ρ = mass density of air or water (mass per unit volume)
A = area of turbine blades facing the air or water flow

Consequently:

$$P = (1/2)\rho A v^3 \tag{P-12}$$

Caution: weight density (weight per unit volume) must be converted to mass density (mass per unit volume) for use in Equation P-12.

Example P-2

Consider a wind turbine with blades 100 feet long in air flowing at 15 miles per hour. The density of air is about 0.0749 pounds per cubic foot or, converting to mass density by dividing by 32.2, 0.00233 slugs per cubic foot. The velocity of 15 miles per hour is equal to 22 feet per second. The power in the air stream aimed at the turbine is:

$$P = (1/2) \times 0.00233 \times 3.14159 \times 100^2 \times 22^3$$

$$= 389{,}000 \text{ foot pounds per second}$$

This power is equal to 389,000 × 1.356 (Joules per foot pound) = 529,000 Joules per second or 0.529 megawatts. This power is contained in the wind, only part of which can be captured by the wind turbine.

Now let us repeat the calculation using SI units. The density of air is 1.2 kilograms per cubic meter. The 100 foot blades are 30.48 meters long, and a wind speed of 15 miles per hour corresponds to 6.71 meters per second. The power is:

$$P(\text{Joules per second}) = (1/2) \times 1.2 \times 3.14159 \times 30.48^2 \times 6.71^3$$

$$= 529{,}000 \text{ (Joules per second)}$$

$$= 0.529 \text{ megawatts}$$

Example P-3

Consider a turbine with 10 foot blades immersed in a stream of water flowing at 2 miles per hour (or 2.93 feet per second). The weight density of water is about 62.4 pounds per cubic foot or a mass density of 1.94 slugs per cubic foot. The kinetic energy of the water stream aimed at the turbine is:

$$E \text{ (foot pounds per second)} = (1/2) \times 1.94 \times 3.14159 \times 10^2 \times 2.93^3$$

$$= 7{,}665$$

Conversion to Joules per second by multiplying by 1.356 gives 10,400 watts or 10.4 kilowatts.

Summary

The results presented above may be summarized concisely to facilitate assessments of energy production potential. The formulas presented below use typical values for the densities of air and water, and mass density and weight density are handled correctly.

The maximum power in falling water released from a reservoir is:

$$\text{P(watts)} = 1.356 \times \text{flow (in pounds per second)} \times \text{height (in feet)} \qquad \text{(P-13)}$$

or:

$$\text{P(watts)} = 0.188 \times \text{flow (in gallons per minute)} \times \text{height (in feet)} \quad \text{(P-14)}$$

or:

$$\text{P(watts)} = 84.6 \times \text{flow(in cubic feet per second)} \times \text{height (in feet)} \quad \text{(P-15)}$$

or:

$$\text{P(watts)} = 9.81 \times \text{flow(in kilograms per second)} \times \text{height (in meters)} \quad \text{(P-16)}$$

The maximum power in an air stream aimed at the turbine is:

$$\text{P(watts)} = 0.00497 \times (\text{blade radius in feet})^2 \times (\text{wind speed in feet per second})^3 \quad \text{(P-17)}$$

or:

$$\text{P(watts)} = 0.0157 \times (\text{blade radius in feet})^2 \times (\text{wind speed in miles per hour})^3 \quad \text{(P-18)}$$

or:

$$\text{P(watts)} = 1.89 \times (\text{blade radius in meters})^2 \times (\text{wind speed in meters per second})^3 \quad \text{(P-19)}$$

For water turbines, the relations are:

$$\text{P(watts)} = 4.13 \times (\text{blade radius in feet})^2 \times (\text{water flow rate in feet per second})^3 \quad \text{(P-20)}$$

or:

$$P(\text{watts}) = 13.1 \times (\text{blade radius in feet})^2 \times (\text{water flow in miles per hour})^3 \quad \text{(P-21)}$$

or:

$$P(\text{watts}) = 1571 \times (\text{blade radius in meters})^2 \times (\text{water flow in meters per second})^3 \quad \text{(P-22)}$$

Of course, the delivered power will be less than the maximum power given by these formulas. Energy loss occurs in converting kinetic energy into mechanical energy and in converting mechanical energy into electrical energy. The Lanchester-Betz-Joukowsky kinetic to mechanical energy conversion limit (59 percent) applies to wind and water turbines.

There is some interest in using ducted water turbines. These funnel the water from a larger diameter entrance opening into the smaller diameter opening around the turbine blades. These systems provide higher efficiencies for a given turbine blade diameter than the Lanchester-Betz-Joukowsky limit, but this limit still applies to the size of the entrance opening. That is, the system can extract no more than 59 percent of the kinetic energy in a stream with a cross-sectional area equal to that of the duct entrance.

APPENDIX Q: ENERGY USE IN SPECIFIC INDUSTRIES

Energy use in the main energy-consuming industries is shown in Table Q-1 (a repeat of Table 17-1).

Table Q-1. Delivered Energy Consumption by Industry (1998)[1]

Manufacturing	Consumption Trillion BTU
Food	1,029
Paper	2,726
Bulk Chemicals	6,697
Petroleum Refining	3,127
Glass	198
Cement	356
Steel	1,590
Aluminum	454
Metal-Based Durables	1,466
Others	2,904
Total Manufacturing	**20,546**
Non-Manufacturing	
Agriculture-Crops	711
Agriculture-Other	412
Coal Mining	87
Oil and Gas Extraction	1,509
Other Mining	310
Construction	1,776
Total Non-Manufacturing	**4,805**
Total for All Industry	**25,353**

The following sections provide information about each of these industries, along with charts that illustrate the relative contributions of the various energy sources.

Food

The food industry uses about 4 percent of delivered industrial energy. See Figure Q-1 for the relative contributions of energy sources used in the food industry. Natural gas provides slightly more than half of the delivered energy.

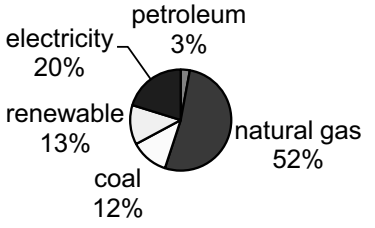

Figure Q-1. Energy Sources in the Food Industry
(data from the U.S. Dept. of Energy)

The main uses of energy in the food industry include process heating, process cooling, and machine drives.

Paper

The paper industry uses about 11 percent of delivered industrial energy. See Figure Q-2 for the relative contributions of energy sources used in the paper industry. The paper industry is unique in that it derives almost half of the delivered energy used for paper manufacture from renewables. The wood waste and waste from the pulp wood processing are burned to produce heat.

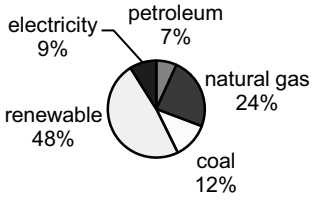

Figure Q-2. Energy Sources in the Paper Industry
(data from the U.S. Dept. of Energy)

The main uses of energy in the paper industry include wood preparation, pulping, bleaching, drying, and paper fabrication.

Bulk Chemicals

The bulk chemicals industry is the largest energy consumer in the industrial sector, using about one-fourth of delivered industrial energy. See Figure Q-3 for the relative contributions of energy sources used in the chemical industry. No single energy source is dominant in the chemical industry.

The bulk chemicals industry uses energy resources as fuel and as feedstocks for producing various chemicals. Petroleum and natural gas are used heavily for fuel and feedstock. Feedstocks account for over half of delivered energy consumption in the bulk chemicals industry.

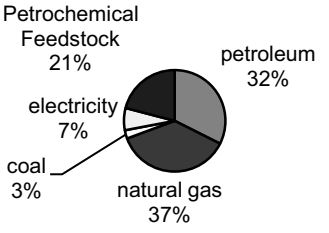

Figure Q-3. Energy Sources in the Bulk Chemicals Industry
(data from the U.S. Dept. of Energy)

The main energy-related uses for fuel in the bulk chemicals industry include process heating, process cooling and refrigeration, machine drives, and electrochemical processes. Chemicals produced from energy resource feedstocks include fertilizers, insecticides, and plastics.

Petroleum Refining

Petroleum refining uses about 12 percent of delivered energy consumed by U.S. industry. See Figure Q-4 for the relative contributions of energy sources used in petroleum refining. Two-thirds of the energy needed for petroleum refining is derived from petroleum delivered to the refinery. Refineries also provide non-fuel products such as petrochemical feedstocks and asphalt, which are treated as energy inputs for other appropriate industries.

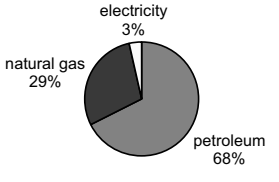

Figure Q-4. Energy Sources in the Petroleum Refining Industry
(data from the U.S. Dept. of Energy)

Operations in a refinery include separating the components in crude oil, breaking large molecules into smaller molecules, changing the chemical structure of the components of crude oil, combining small molecules into larger molecules, and eliminating unwanted components of crude oil.

The main uses of energy in petroleum refining are fluid heating and steam generation.

A discussion of refining technology appears in Chapter 3.

Glass

The glass industry uses less than 1 percent of delivered industrial energy. See Figure Q-5 for the relative contributions of energy sources used in the glass industry. The main energy source for the glass industry is natural gas.

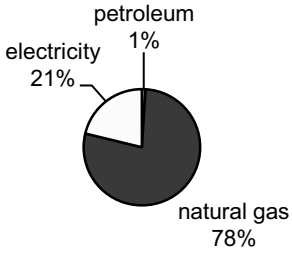

Figure Q-5. Energy Sources in the Glass Industry
(data from the U.S. Dept. of Energy)

Silica (SiO_2) is the main component of glass (usually 70 to 74 percent). Other components are added to simplify glass making or to obtain desired glass properties for certain applications. Common additives are sodium carbonate, lime (calcium oxide), magnesium oxide, and aluminum oxide. Materials added for certain specialty glasses include lead (for "leaded" glass) and boron (for Pyrex).

The main use of energy in the glass industry is for gas-fueled melting furnaces. The silica and other components are melted and then cooled to form solid glass. The resulting glass lacks a crystal structure (it is an amorphous solid) and is therefore similar to liquids in structure.

Cement

The cement industry uses less than 2 percent of delivered industrial energy. See Figure Q-6 for the relative contributions of energy sources used in the cement industry.

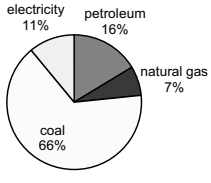

Figure Q-6. Energy Sources in the Cement Industry
(data from the U.S. Dept. of Energy)

The main use of energy in the cement industry is for heating the minerals (mainly alumina, silica, lime, iron oxide, and magnesia) used to produce cement. Kilns are used to heat the materials to around 2700°F to achieve the necessary reactions and phase changes. The main uses of cement are for concrete and mortar in construction applications.

Coal provides about three-fourths of the energy used in cement production.

Steel

The steel industry uses about 8 percent of delivered industrial energy. See Figure Q-7 for the relative contributions of energy sources used in the steel industry.

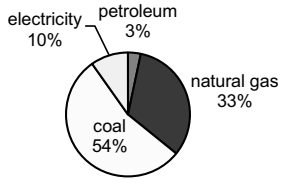

Figure Q-7. Energy Sources in the Steel Industry
(data from the U.S. Dept. of Energy)

Steelmaking from iron ore involves three main steps:

- Producing coke from coal. Coke, essentially pure carbon, results from heating pulverized bituminous coal to a high temperature in the absence of oxygen.

- Separating iron from iron ore in a blast furnace. Iron ore, coke, air, and limestone are fed into blast furnaces. The coke burns to produce the necessary heat and also provides the small concentration of carbon needed in steel.

- Refinement of iron into steel in a basic oxide furnace. Basic oxide furnaces use high purity oxygen to combust carbon and silicon in the iron from a blast furnace. Alloying materials are combined with the purified iron to make steel.

Steel is also recycled. Electric arc furnaces for processing scrap steel use electrical energy and oxygen to process scrap steel and prepare it for re-use.

Coal accounts for more than half of the delivered energy in the steel industry. Coal is used mainly to produce coke that is used in blast furnaces.

Steel industry energy is used mainly for blast furnaces, electric arc furnaces, casting, rolling, and finishing.

Aluminum

The aluminum industry uses about 2 percent of delivered industrial energy. See Figure Q-8 for the relative contributions of energy sources used in the aluminum industry.

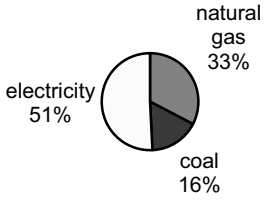

Figure Q-8. Energy Sources in the Aluminum Industry
(data from the U.S. Dept. of Energy)

Producing aluminum metal from aluminum ore (bauxite) involves three steps:

- Separation of aluminum oxide from other components in bauxite. The Bayer process is based on reaction of aluminum oxide with sodium hydroxide at high temperature and pressure.

- Crystallization and drying of the aluminum oxide.

- Reducing aluminum oxide to aluminum metal. The Hall-Heroult process involves electrolytic production of aluminum metal from aluminum oxide.

Aluminum is also recycled. Scrap is melted and purified to prepare aluminum for re-use.

Aluminum production requires large quantities of energy for heating and electrolytic processes. The aluminum industry is unique in its use of electricity for about half of its energy.

Metal-Based Durables

The metals-based durables industry uses about 6 percent of delivered industrial energy. See Figure Q-9 for the relative contributions of energy sources used in the metals-based durables industry. The metals-based durables industry includes fabricated metal products, machinery, electric and electronic equipment, transportation equipment, and instruments and related products.

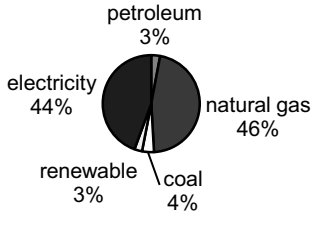

Figure Q-9. Energy Sources in the Metal-Based Durables Industry
(data from the U.S. Dept. of Energy)

One industry in this group, the transportation equipment manufacturing industry (cars, trucks, airplanes, ships, rail), warrants special mention. Transportation equipment manufacture accounts for about 2 percent of delivered industrial energy. This energy expenditure, along with other energy used to enable transportation (such as energy for oil refining, steel manufacture for equipment, and road construction), adds to the energy used for transportation and contributes to the true total energy cost for transportation.

Balance of Manufacturing

The balance of the manufacturing sector includes all manufacturing processes other than those energy-intensive industries described above. These industries use about 11 percent of delivered industrial energy. See Figure Q-10 for the relative contributions of energy resources used in these industries.

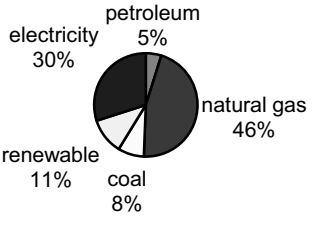

Figure Q-10. Energy Sources in Other Manufacturing Industries
(data from the U.S. Dept. of Energy)

Agriculture

Agriculture is a small user of energy compared to total U.S. consumption[3]. Delivered energy consumption in agriculture is about 4 percent of total industrial consumption. See Figure Q-11 for the relative contributions of energy sources used in agriculture.

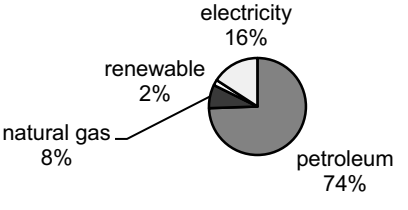

Figure Q-11. Energy Sources in Agriculture (data from the U.S. Dept. of Energy)

Delivered energy is used primarily for growing crops, producing animals, forestry and logging, fishing, and various support activities.

Agricultural activities also require indirect energy use to produce farm chemicals (mainly fertilizers and pesticides). Energy for the production of farm chemicals is counted in data tabulations as energy use in the industries that produce the chemicals. However, the energy use is ultimately for agricultural purposes. Agricultural chemical production accounts for about 0.6 percent of industrial delivered energy consumption.

Mining

The mining industry uses less than 2 percent of delivered industrial energy[2]. See Figure Q-12 for the relative contributions of energy sources used in the mining industry. Mining involves the removal of solid materials from the earth. These are classified as coal, metals (primarily iron, copper, lead, and zinc), and industrial minerals (primarily potash, soda ash, borates, phosphate rock, limestone, and other crushed rock).

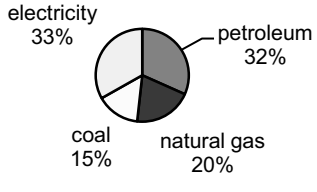

Figure Q-12. Energy Sources in the Mining Industry
(data from the U.S. Dept. of Energy)

In addition to domestic mining products, America also uses minerals mined in other countries. For example, bauxite for aluminum manufacture is mined abroad, as are most of the gold and gemstones used for jewelry.

Petroleum and electricity are the main energy sources for the mining industry. Energy uses are about 19 percent for ore extraction, 42 percent for materials handling, and 39 percent for processing (mostly grinding and crushing). The desired materials constitute only a portion of the material that must be handled and processed in mining operations. The proportions of desired materials in ores range from about one-half for industrial materials to about 4 percent for metals.

Oil and Gas Extraction

The oil and gas extraction industry uses about 6 percent of delivered industrial energy. See Figure Q-13 for the relative contributions of energy sources used in the oil and gas extraction industry. "Lease and plant fuel" is natural gas used in well, field, and lease operations (such as gas used in drilling operations, heaters, dehydrators, and field compressors) and as fuel in natural gas processing plants.

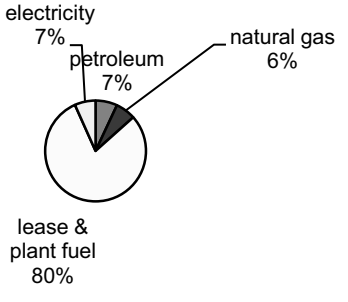

Figure Q-13. Energy Sources in Oil and Gas Extraction
(data from the U.S. Dept. of Energy)

Construction

The construction industry uses about 7 percent of delivered industrial energy. See Figure Q-14 for the relative contributions of energy sources used in the construction industry.

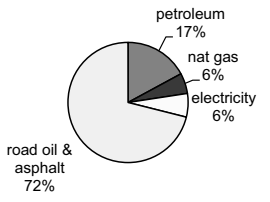

Figure Q-14. Energy Sources in Construction (data from the U.S. Dept. of Energy)

Asphalt, used mainly for road construction, accounts for over 70 percent of delivered construction energy.

References

1. Unruh, B. "Delivered Energy Consumption Projections by Industry" *Annual Energy Outlook 2002* Energy Information Administration Document, 2002 at http://www.eia.gov/oiaf/analysispaper/industry/consumption.html.

2. U.S. Department of Energy, Energy Efficiency and Renewable Energy Report "Energy and Environmental Profile of the U.S. Mining Industry" at http://www1.eere.energy.gov/industry/mining/analysis.html.

3. Schnepf, R. "Energy Use in Agriculture: Background and Issues" Congressional Research Service, the Library of Congress, 2004.

GLOSSARY

The following is a glossary of terms used in this book. It is provided to serve as an easy-to-use reminder of terms whose meaning may have been forgotten by the reader.

Definitions presented here include only those terms that appear in the body and appendices of this book and are pertinent to the terms' usage in the book. A more comprehensive glossary of energy-related terms appears on the Energy Information Administration web site: http://www.eia.doe.gov.

Abiogenic: Having been produced without the involvement of biological matter.

Actinide: A member of a group of heavy elements with atomic numbers between 89 and 103. Some actinides are produced by neutron capture in nuclear reactor materials and contribute to radioactivity in nuclear waste.

AFUE (Annual Fuel Utilization Efficiency): The percentage of the energy released by burning fuel that enters a building as warm air.

Air Source: An air conditioner or heat pump that extracts heat from, or dumps heat to, ambient air.

Alcohol: A family of chemicals composed of carbon, hydrogen and oxygen and having a hydroxyl (OH) radical.

Alternative Energy: Non-traditional, sustainable energy.

Ampere: A measure of electrical current.

Anaerobic: Occurring in the absence of air.

Anode: The negative terminal of a battery.

Anthracite: Hard coal.

Anthropogenic: Resulting from human activity.

Atom: The fundamental building block of matter, consisting of electrons swarming around a nucleus composed of protons and neutrons (except in the case of ordinary hydrogen, which has no neutrons).

Bacteria: Microscopic plants.

Barrel of Oil: A standard measure of oil quantity. Equal to 42 U.S. gallons.

Base Load Power Plant: A power plant that operates at constant power output as opposed to a load-following plant that changes power production in response to demand.

Battery: A device for converting chemical energy into electrical energy.

Bergius Process: A process for hydrogenating coal.

Biobutanol: Butanol produced from biomass.

Biochemical Process: A process involving living organisms that enable and/or facilitate chemical reactions.

Biodiesel: Diesel fuel made from biomass.

Biofeedstock: Raw material for chemical processes that comes from biomass.

Biofuel: Fuel made from biomass.

Biogas: A mixture of gases, mostly methane and carbon dioxide, produced in the absence of oxygen from buried organic matter by microbes.

Biohydrogen: Hydrogen made from biomass.

Biomass: Organic material from plants and animals.

Biomethane: Methane made from biomass.

Bio-oil (also, Bio Oil): Oil produced by the pyrolysis of biomass.

Biophotolysis: The process by which plants produce molecular hydrogen through photosynthesis.

Biorefinery: A facility for processing biomass into biofuel.

Biosynthesis: A process wherein chemical compounds are produced within living organisms and are generally catalyzed by enzymes

Bitumen: Hydrocarbons found in oil sand.

Bituminous: Soft coal.

Breeder Reactor: A nuclear reactor that produces more fuel than it consumes (usually by converting U-238 into Pu-239).

British Thermal Unit: The amount of heat needed to raise the temperature of one pound of water by one degree Fahrenheit.

BTU: Abbreviation for British Thermal Unit.

Butane: A hydrocarbon (C_4H_{10}) found in natural gas. Gaseous at normal temperature and pressure.

Butanol: An alcohol (C_4H_9OH).

Calorie: The amount of heat needed to raise the temperature of one gram of water by one degree Celsius.

Calthrate: A substance in which a molecule resides in a cage made of other molecules. Methane calthrate (also called methane hydrate) in the oceans contains large quantities of methane that may someday be recoverable.

Cap and Trade: An agreement in which greenhouse gas emitters are assigned emission quotas and in which unused allowances can be sold to emitters who cannot meet their quotas.

Carbohydrate: A component of biomass consisting of molecules made of carbon, hydrogen and oxygen.

Carbon Sequestration: Isolation of carbon from the atmosphere (generally via underground storage of carbon dioxide).

Catalyst: A material that hastens or enables a chemical reaction without being consumed.

Cathode: The positive terminal of a battery.

CDD: Abbreviation for Cooling Degree Day.

Cellulase: An enzyme that can hydrolyze cellulose.

Cellulose: A carbohydrate component of biomass that consists of linked hexose sugars.

Celsius: The temperature scale in which water freezes at 0 degrees and boils at 100 degrees (at normal, i.e., sea level, atmospheric pressure).

CFL: Abbreviation for Compact Fluorescent Light or Lamp

Chlorophyll: The pigment in plants where photosynthesis occurs.

Closed Cycle Heat Engine: A heat engine in which the working fluid is contained and recycled.

Coal: a solid fossil fuel composed of carbon and hydrocarbons.

Coalbed Methane: Methane trapped in pores in underground coal.

Coalification: The process of converting dead biomass into coal (a slow process that takes place at elevated temperature and pressure).

Coke: A carbonaceous solid material obtained by heating coal or petroleum to drive off hydrogen-bearing components.

Compact Fluorescent Light: A spiral-shaped fluorescent lamp that screws into a standard lamp socket.

Condenser (Heat Exchanger): A heat exchanger that causes a vapor to condense.

Conduction (Heat): Heat transfer through a solid.

Conservation (of Energy): The principle that energy cannot be created or destroyed, but it can change from one form to another.

Convection (Heat): Heat transfer by the motion of a liquid, vapor or gas.

Conventional Gas or Oil: Gas or oil from formations in which natural permeability and porosity permit significant flow to a low pressure region created by a well.

Cooling Degree Days: The number of days when the average temperature is above 65°F times the difference between 65° and the average temperature on a given day.

Corn Stover: The stalks and leaves of corn plants.

Cornucopian: A term for people who believe that there will always be ample energy.

Covalent Bond: A type of chemical bond in which the valence electrons of constituent atoms are shared.

Cracking (Oil): The process of breaking large petroleum hydrocarbon molecules into smaller molecules.

Current (Electric): The flow of electrical charges through a conductor.

Delivered Energy: Energy delivered to a user with no consideration of the energy losses incurred in producing and delivering the energy. See also Primary Energy Consumption.

Demographic Transition: The shift from an era of high birth rates and high death rates to an era of low birth rates and low death rates.

Diesel Engine: A piston-type internal combustion engine in which the fuel is ignited by the compression of air.

Diffusion: Motion of a transportable quantity as the result of a concentration gradient.

Dimethyl Ether: Abbreviated as DME (CH_3OCH_3). DME has the same chemical formula as ethanol, but a different molecular structure.

Dimethylfuran: Abbreviated DMF (C_6H_8O). DMF has properties that make it potentially attractive as a biofuel.

Diode: A device that permits the flow of electric current in one direction but prevents flow in the opposite direction.

Disaccharide: A carbohydrate composed of two linked sugar molecules after removal of a water molecule.

Distillate Fuel Oil: Hydrocarbons separated from crude oil by distillation (composed mostly of Diesel fuels and fuel oils).

Distillation: The separation of volatile liquids by exploiting the difference in their boiling points.

Distribution (Electric): The transport of electricity from distribution centers to users.

District Heat: Heating for multiple users that comes from a single source.

Dry Weight: Weight of dried material such as biomass.

Earth Cooling Tubes: Tubes buried in the earth and carrying liquid or air for the purpose of dumping heat into cool subterranean earth.

Efficiency (Thermal): The ratio of energy transformed into a desired form by a thermal process to the maximum energy that could be transformed in a perfect (lossless) transformation.

Electric Power: Power obtained from or conveyed by an electric current.

Electrical Losses: Energy losses incurred in transporting electricity, mainly due to heating in conductors.

Electrochemistry: The branch of chemistry concerned with chemical reactions that occur because of an imposed electric current or with the production of electricity by chemical reactions.

Electrolysis: Dissociation of molecules by the passage of an electric current through a liquid.

Electrolyte: A substance that becomes an ionic conductor of electricity when dissolved.

Electromotive Force: The force that causes an electric current to flow (usually measured in volts).

Electron: A negatively charged atomic particle. Electrons orbit around atomic nuclei and can also exist outside of atoms.

Embodied Energy: The energy used to produce a product.

Energy: The capacity to do work.

Energy Balance: The energy available from using a fuel versus the energy required to get that fuel.

Energy Carrier: Energy that is produced by transforming from another energy source.

Energy Ratio: (Energy available in fuel)/(energy consumed in getting fuel).

Energy Return on Investment: The ratio of the amount of usable energy acquired from a particular energy resource to the amount of energy expended to obtain that energy from the resource.

ENERGY STAR: An international standard for energy efficient consumer products.

Engine: A device for producing mechanical energy from a non-mechanical source of energy. See also Motor.

Enhanced Geothermal System: A geothermal energy system in which the subsurface rock has been modified and a fluid (usually water) is introduced to transport energy to the surface.

Enzyme: A protein that can serve as a catalyst for a biochemical process.

Ethane: A hydrocarbon (C_2H_6). Found in natural gas. Gaseous at normal temperature and pressure.

Ethanol: An alcohol (C_2H_5OH).

Ether: A family of chemical compounds composed of carbon, hydrogen and oxygen with an oxygen atom attached to two carbon atoms.

Evaporative Refrigeration: A term usually reserved for cooling devices that reduce temperature by evaporating water into ambient air.

Evaporator: A heat exchanger in which a liquid evaporates.

Exajoule: 10^{18} Joules.

External Cost (or Externality): The cost of an activity that is incurred by other than the initiator of the activity. The cost may be any undesirable consequence, including financial loss, impaired health, death, and property devaluation.

Fahrenheit: The temperature scale in which water freezes at 32 degrees and boils at 212 degrees (at sea level atmospheric pressure).

Fermentation: An enzymatic conversion.

Fertility Rate (Population): Average number of children per woman.

Field: A region in space where a given effect (such as magnetism) exists.

Fischer-Tropsch Process: A process for producing various compounds of carbon, hydrogen and oxygen from syngas (see also Syngas) in the presence of iron or cobalt catalysts.

Fissile: A term indicating that a material will readily undergo nuclear fission when reacting with a neutron of any energy (slow neutrons to fast neutrons).

Fission (Nuclear): The process in which a reaction between a neutron and a heavy nucleus causes the nucleus to split, producing two or more lighter nuclei, neutrons, gamma rays and energy.

Fission Product: A lighter nucleus produced by the fission of a heavy nucleus.

Fissionable: A term indicating that a material will undergo fission when reacting with a fast neutron.

Food Mile: The distance that a food item travels from grower to consumer.

Force: That which is capable of causing or changing the motion of a body.

Fossil Fuel: A fuel produced from dead plant and animal material that was subjected to elevated heat and pressure when buried beneath the earth for a long period of time.

FPS (Units): An abbreviation for foot, pound, second (units used in the U.S. Customary system of measurement).

Fracking: See Hydrofracturing.

Fractional Distillation: Separation of components in a liquid mixture by repeated vaporization and condensation in a single unit.

Freight Energy Intensity: The energy consumed in freight hauling (BTU per ton-mile).

Fructose: A monosaccharide, $C_6H_{12}O_6$,

Fuel Cell: A device for converting chemical energy into electrical energy via the use of continuously replenished chemicals (typically hydrogen or methane and air).

Fungus: A parasitic lower order plant that lacks chlorophyll.

Fusion: The process in which two atomic nuclei combine, producing a heavier nucleus, neutrons and energy.

Futilitarian: A term for those people who believe that disaster is inevitable.

Gas Absorption: A type of refrigeration system in which the required energy is supplied by heat.

Gas Compression: A type of refrigeration system that achieves cooling by evaporating a liquid in one part of the system, then compressing the resulting vapor and cooling the resulting liquid by heat transfer to the surroundings in another part of the system.

Gas Turbine: A rotary heat engine that extracts energy from a flow of combustion gas.

Gasification: The thermal disassembly of molecules in the presence of limited oxygen.

Gasoline: A liquid hydrocarbon with 5 to 12 carbon atoms per molecule and approximately 2 hydrogen atoms per carbon atom.

Generator (Electric): A device for converting mechanical energy into electrical energy.

Geothermal: Having to do with thermal energy from subsurface regions of the earth.

Geothermal Gradient: The temperature increase per unit of depth in the earth.

Geothermal Heat Pump: A ground-source heat pump. See also Ground Source.

Global Warming: An increase in average atmospheric temperature (natural or anthropogenic).

Glucose: A monosaccharide, $C_6H_{12}O_6$,

Glycerol: An alcohol, $C_3H_5(OH)_3$.

Green Power: Power sources that are environmentally friendly and non-polluting.

Greenhouse Effect: Heating of the atmosphere by trapping radiated heat energy from the earth.

Greenhouse Gas: An atmospheric gas that preferentially absorbs heat energy radiated by the earth.

Ground Source: A type of air conditioner or heat pump that extracts heat from or dumps heat to subsurface earth and/or water.

HDD: The abbreviation for Heating Degree Days.

Heat Dumping: Transferring heat to a thermal mass (see Thermal Mass).

Heat Engine: A device for converting heat energy into mechanical energy.

Heat of Combustion: The quantity of energy released as heat per unit of mass completely combusted.

Heat of Fusion: The quantity of heat energy released per of unit mass from a material upon freezing or absorbed by a material upon melting.

Heat of Vaporization: The quantity of heat energy released per unit of mass vaporized.

Heat Pump: A system that heats by transferring heat from a condenser to a heated space and cools by transferring heat to an evaporator from a cooled space.

Heating Degree Days: The number of days when the average temperature is below 65°F times the difference between 65° and the average temperature on a given day.

Heating Value: The quantity of heat released per unit mass of material oxidized (burned).

Hemicellulose: A carbohydrate component of biomass, consisting of linked hexose and pentose sugars.

Hexose Sugar: A six-carbon sugar molecule.

High Heating Value: The quantity of heat released per unit mass of material oxidized (burned) in such a way that any water produced or released exits in the liquid state.

Hubbert's Peak: A peak in resource production, usually a peak in an energy resource, as predicted by logistic function modeling.

Hybrid Vehicle: A vehicle having more than one propulsion system and associated sources of energy.

Hydrocarbon: A chemical compound composed entirely of hydrogen and carbon.

Hydroelectricity: Electricity produced from flowing or falling water.

Hydroenergy: Energy extracted from flowing or falling water.

Hydrofracturing: A drilling technique in which pressurized water is pumped into underground rock formations to create permeability. See also Fracking.

Hydrogen: An element with one orbiting electron and either no neutrons (ordinary hydrogen), one neutron (deuterium or "heavy hydrogen") or two neutrons (tritium).

Hydrogenation: The process of adding hydrogen to a chemical compound.

Hydrolysis: A type of reaction involving water and a molecule that splits apart; one part combines with hydrogen from the water and the other part combines with a hydroxyl radical (OH).

Hydrothermal System: A geothermal system in which suitable rock formations and water supplies occur naturally.

Hydroxyl Radical: A combination of oxygen and hydrogen (OH) that exists in a chemical compound.

Insolation: A measure of the quantity of solar power received per unit of surface (typically watts per square meter or BTU per day per square foot).

Internal Combustion Engine: A type of heat engine in which fuel combustion occurs within the engine.

Ionic Bond: A chemical bond in which valence electrons are transferred from one atom to another.

Ionic Solution: A solution that contains free ions and is capable of conducting electricity.

Isomer: A term for compounds that have the same chemical composition but different molecular structures.

Isotope: A term for elements that have the same number of protons in their nuclei, but different numbers of neutrons.

Joule: A unit of energy in the SI system, equal to the work done by a force of one Newton when it moves an object a distance of one meter.

Karrick Process: A process for coal pyrolysis.

Kelvin (Temperature): A temperature scale in which the lowest possible temperature (absolute zero) is assigned a value of zero and the size of temperature increments is the same as in the Celsius scale.

Kerogen: A type of hydrocarbon found in oil shale.

Kerosene: A hydrocarbon fuel having 11 to 13 carbon atoms and approximately 2 hydrogen atoms per carbon atom.

Kilowatt: 1,000 watts.

Kinetic Energy: The energy of motion.

kW: Abbreviation for kilowatt. Also, kw.

Kyoto Protocol: An agreement between some of the nations of the world to limit greenhouse gas emissions (the protocol came into force in 2005).

Lanchester-Betz-Joukowsky limit: The maximum energy extraction efficiency of a wind or water turbine (approximately 59 per cent).

Landfill Gas: Gas (mainly methane, carbon dioxide and water) produced anaerobically by microbes in landfills.

LED: Abbreviation for Light Emitting Diode.

Light Emitting Diode: A diode that emits light when a voltage is applied.

Lignin: The fibrous polymer that provides a plant's structural strength.

Lignite: A brownish coal that lies between peat and bituminous coal in the coalification process.

Lignocellulose: Plant matter composed of lignin, cellulose and hemicellulose.

Lipids: A broad group of naturally-occurring compounds, including some (such as fats and vegetable oils) that store energy and find application as a transportable energy source.

Liquefied Natural Gas: Natural gas that has been liquefied by reducing its temperature to -260°F.

Liquid Energy Ratio: The ratio of the energy in manufactured liquids to the energy in the liquids used in the manufacturing.

LNG: Abbreviation for liquefied natural gas.

Load-Following Power Plant: A power plant that changes production continuously to match demand.

Load Leveling: Actions taken to reduce variations in electrical power production and consumption.

Logistic Function: A sigmoid function commonly used in forecasting.

Low Heating Value: The quantity of heat released per unit mass of material oxidized (burned) in such a way that any water produced or released exits in the vapor state.

Megawatt: 1,000,000 watts.

Methane: A hydrocarbon that has the formula CH_4 and is gaseous at ordinary temperatures and pressures.

Methane Calthrate: A substance that consists of methane residing in a cage made of other molecules (typically water molecules).

Methane Hydrate: A methane calthrate in which water is the host molecule.

Methanogenic Bacteria: Bacteria that generate and release methane when digesting biomass.

Methanol: An alcohol (CH_3OH).

MKS: An abbreviation for meter, kilogram, second (units used in the SI system of measurement).

Moderator (Nuclear): Material used in a nuclear reactor to reduce neutron energy by scattering.

Momentum: The product of the mass of a moving object and the velocity of its motion.

Monosaccharide: A simple sugar having the general formula $(CH_2O)_n$, where n is an integer greater than 2.

Motor (Electric): A device for converting electrical energy into mechanical energy.

MW: The abbreviation for megawatt.

Natural Gas: A mixture of methane, ethane, butane and pentane that is extracted from wells.

Natural Gas Liquid: Heavier hydrocarbons (butane and propane) that exist along with methane in natural gas and that can be liquefied with modest pressurization.

Natural Uranium: Naturally-occurring uranium (contains 99.3 percent U238 and 0.7 percent U235).

Neutron: A subatomic particle having no electric charge.

Newton: A measure of force in the SI system, equal to the amount of force required to accelerate a mass of one kilogram at a rate of one meter per second per second.

Nuclear Reactor: A device in which controlled nuclear reactions take place.

Nuclear Waste: Waste (generally radioactive) from nuclear processes.

Nucleus: The central part of an atom, consisting of protons and neutrons (except in the cases of ordinary hydrogen, which has no neutrons in its nucleus).

Ohm: A measure of electrical resistance.

Oil (Petroleum): A mixture of liquid hydrocarbons.

Oil (Vegetable): Liquid lipids derived from plants and composed of triglycerides.

Oil Sand (also called tar sand): Bitumen impregnated sand.

Open-Cycle Heat Engine: A heat engine in which the working fluid is expelled after use in the engine.

Passive Safety (Nuclear): Accident prevention or mitigation processes in a nuclear reactor that occur naturally and spontaneously.

Peak Oil: The rate of oil production at the time when production peaks.

Pentane: A hydrocarbon (C_5H_{12}).

Pentose Sugar: A five-carbon sugar molecule.

Permeability (Rock): The relative ability of openings in rock to permit the flow of liquids or gases under a pressure gradient.

Phantom Load: Energy consumption by appliances when in the standby mode.

Phase Change Air Conditioner: A cooling system that extracts heat from a region by evaporating a fluid.

Photolysis: The decomposition of chemical compounds by photon energy.

Photon: A packet of electromagnetic radiation.

Photosynthesis: The process by which plants use solar energy to produce sugars from carbon dioxide and water.

Photovoltaic: A term for the process of producing electricity by the capture of solar photons in a suitable semiconductor.

Plug-In Hybrid: A hybrid vehicle with batteries that can be recharged with grid electricity.

Polysaccharide: A carbohydrate consisting of linked sugar components.

Porosity (Rock): The percentage of open spaces within rock.

Potential Energy: The energy of position.

Power: The rate of energy flow.

Power Factor: The ratio of real power (usable power) to apparent power (volts times current) in alternating current. The ratio has a value of 1 when voltage and current are in phase and lower values when they are not in phase.

Primary Energy Consumption: User energy consumption plus the losses that occur in producing and delivering that quantity of energy.

Propane: A hydrocarbon (C_2H_6). Found in natural gas. Gaseous at normal temperature and pressure.

Proved Reserves: Estimated quantities of non-renewable energy sources that are recoverable under existing economic and operating conditions.

Pumped Storage (Hydroelectric): The pumping of water into an elevated reservoir for subsequent release through a turbine-generator when power is required.

Pyrolysis: The thermal disassembly of molecules in the absence of oxygen.

Quad: A unit of energy measurement used for large quantities of energy (equal to one quadrillion BTU).

R Value (Insulation): A measure of resistance to heat transfer through insulation, equal to the temperature drop across the insulation per unit of heat flux (typically temperature in degrees Fahrenheit and heat flux in BTU per square foot). Higher values of R indicate greater resistance to energy transfer.

Radiation (Thermal): Energy transfer by photons.

Radioactivity: The spontaneous emission of nuclear radiation from an atom.

Renewable Energy: Energy from sources that can be renewed continuously.

Replacement Rate (Population): The total fertility rate required for replacing an existing population under actual conditions.

Resistance (Electrical): A measure of a material's tendency to retard the flow of electricity (usually expressed in ohms).

Retorting: Heating a material in order to change its properties.

SEER: The abbreviation for Seasonal Energy Efficiency Ratio. A measure of air conditioner efficiency that is equal to the BTUs of heat removed in cooling during a typical cooling season, divided by the total electric energy input in watt-hours during the same period.

Shale Gas: Natural gas found in shale deposits.

Shale Oil: Kerogen impregnated rock.

SI Units: The abbreviation for Systeme International d'Unites, a measurement system based on meters for length, kilograms for mass and seconds for time.

Sigmoid Curve: An S-shaped curve that is thought to represent the general course of depletion of a non-renewable resource.

Sigmoid Function: The mathematical function that defines a sigmoid curve.

Solar Chimney: A solar energy system that uses the energy in heated air as it rises through a tall chimney.

Solar Constant: The average solar radiation energy reaching the earth's upper atmosphere (1353 watts per square meter).

Solar Tower: A solar energy system that uses focused sunlight to heat a working fluid.

Solvent Extraction: The separation of components in a mixture by exploiting differences in their solubilities in a solvent.

Sour Oil: High sulfur oil (oil with a high sulfur content).

Specific Heat Capacity: The quantity of heat required to raise the temperature of a unit quantity of matter by one degree. Typically expressed as calories per gram or BTUs per pound.

Specific Heat Capacity at Constant Pressure: The heat capacity of a compressible fluid when it is heated at constant pressure (heating causes the fluid to expand and thereby do work).

Specific Heat Capacity at Constant Volume: The heat capacity of a compressible fluid when it is heated at constant volume (heating causes no fluid expansion and therefore no work is done).

Starch: A carbohydrate composed of linked hexose sugars.

Steam Turbine: A system in which a pressure difference causes steam to flow over turbine blades to produce mechanical energy.

Stirling Engine: A heat engine that uses the external heating and cooling of a gas to produce mechanical energy.

Stover: Stalks and leaves of grain plants (see Corn Stover).

Stranded Gas: Natural gas located in deposits that are uneconomical to exploit because of limited capacity or difficulty in transporting.

Sucrose: A disaccharide of fructose and glucose, $C_{12}H_{22}O_{11}$.

Sugar (Simple): A monosaccharide with the general formula $(CH_2O)_n$ where n is greater than 2.

Sweet Oil: Low sulfur oil (oil with a low level of sulfur).

Syngas: A manufactured mixture of hydrogen and carbon monoxide.

Thermal Depolymerization: The disassembly of large polymer molecules by heating.

Thermal Efficiency: The ratio of the heat energy converted into a different and desired form of energy divided by the heat energy expended in the conversion.

Thermal Mass: Material used to store thermal energy during heat dumping or release thermal energy during heat extraction.

Thermochemical Process: A process that uses heat to enable and/or facilitate chemical reactions.

Tight Gas: Gas contained in unusually low-permeability deposits, usually hard rock or non-porous limestone.

Ton Mile: The product of the distance that freight is hauled and the weight of that freight.

Torque: The tendency of a force to rotate an object about its axis, equal to the product of the force and the perpendicular distance from the line of action of the force to the axis of rotation.

Transesterification: A type of chemical reaction between an alcohol and a triglyceride (an ester) to produce different esters.

Transformarian: A term for those who believe that energy production and consumption habits must change.

Transmission (Electric): The transport of electricity from power plants to distribution centers.

Triglycerides: Compounds with three fatty acid chains connected to a glycerol spine.

Trombe Wall: A south-facing wall located behind a glass window, used to capture solar energy.

Turbine: A device in which fluid flow causes blades mounted on a shaft to rotate.

U Value (Windows): A measure of heat transfer through windows, equal to the number of BTUs transferred per square foot of window per degree Fahrenheit temperature difference across the window. Low values of U indicate greater resistance to energy transfer.

Unconventional Gas or Oil: Gas or oil that is extracted from reservoirs in which additional operations besides simply penetrating the reservoir formation with a well are required.

U.S. Customary Units: Units in the foot, pound, second system of measurement.

Valence Electron: An electron in the outer shell of an atom.

Volt: A measure of electrical potential (the driving force that causes current to flow).

Waste Heat: Heat produced during the conversion of energy from one form to another.

Watt: A measure of power, equal to one Joule per second.

Wind Turbine: A device for producing mechanical energy by capturing wind energy

Work (Mechanical): The product of the force acting on a body and the distance of the resulting motion of the body in the direction of the force.

Zero Energy Building: A building that has a net absence of energy inputs from external sources.

Zero Energy Home: A residential zero energy building.

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