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Energy Resouces

D. Yogi Goswami
University of Florida

Robert Reuther
U.S. Department of Energy

Richard Bajura
University of West Virginia

Larry Grayson
University of West Virginia

Philip C. Crouse
Philip C. Crouse and Associates, Inc.

Michael C. Reed
U.S. Department of Energy

Lynn L. Wright
Oak Ridge National Laboratory

Ralph P. Overend
National Renewable Energy Laboratory

Carlton Wiles
National Renewable Energy Laboratory

James S. Tulenko
University of Florida

Dale E. Berg
Sandia National Laboratories

Joel L. Renner
Idaho National Engineering Laboratory

Marshall J. Reed
U.S. Department of Energy

This chapter describes the primary as well as derived energy sources. The objective is to provide information on the extent, availability, measurements and estimation, properties, and limitations of each type of resource. These considerations are important for an engineer to know and understand before attempting selection and design of an energy conversion system. The chapter also includes environmental impacts of energy resources since the environmental aspects are expected to play a major role in the selection of energy resources. In addition, there is a brief discussion of the costs associated with each resource to help in the economic analysis and comparison the resources.

The chapter starts with an introduction and background of a historical perspective on energy use and projections of the future energy needs in the U.S., the industrialized countries, and the world. The primary energy sources described in this chapter include fossil fuels such as coal, natural gas, petroleum (including their synthetic derivatives), biomass (including refuse-derived biomass fuels), nuclear, solar radiation, wind, geothermal, and ocean. In addition there is a brief section on derived energy sources including electricity. So, the terminology and units used for each energy resource and their equivalence are provided.

7.1 Introduction

D. Yogi Goswami

Global energy consumption in the last 50 years has increased at a very rapid rate. Present trends in global population growth, rapid industrialization, and urbanization in major population centers of the world suggest that the world energy demand will continue to increase in the next 50 years (U.S. DOE, 1991). Figure 7.1.1 shows the historical and projected world energy consumption compiled by the Energy Information Agency.

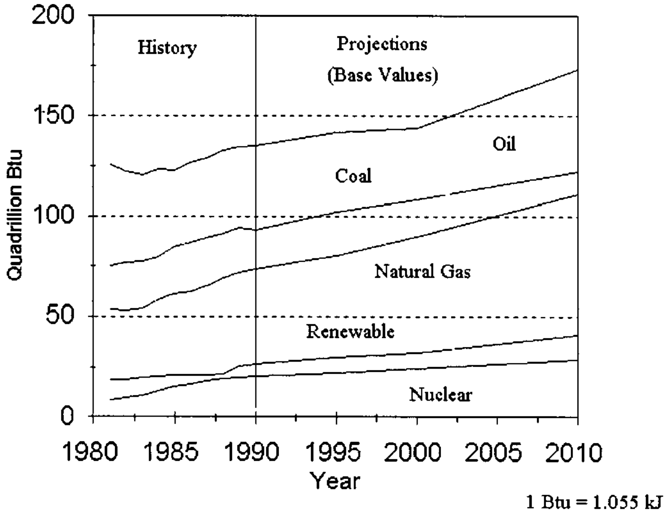

FIGURE 7.1.1 Historical and projected energy consumption. (From EIA. *Annual Energy Outlook 1992,* U.S. DOE, DOE/EIA-0484(92), Washington, D.C.)

The energy resources available to furfill the world demand include

Fossil fuels (oil, coal, natural gas)
Nuclear fuels
Geothermal
Solar radiation
Hydropower

Biomass (crops, wood, municipal solid waste)
Wind
Ocean

Out of all the energy resources, fossil fuels have been used the most (88% of total consumption) because of their extremely high energy densities and simplicity of conversion and use. Figure 7.1.2 shows the world energy production by resource.

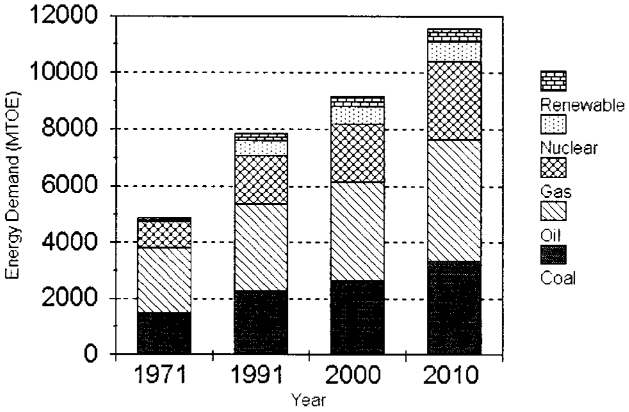

FIGURE 7.1.2 World energy production by resource. (From EIA. *World Energy Outlook*, International Energy Agency, Paris, 1994. With permission.)

Recent concerns about the environment are expected to increase the use of natural gas for power production. Renewable energy resources, such as solar energy, wind, and biomass, are also expected to increase their share of the energy use. There is a strong sentiment in the world in favor of exploiting renewable energy resources, especially because of environmental concerns. How far that sentiment translates into practical use will depend on the development of the renewable energy technologies and prices of the fossil fuels.

Defining Terms

MTOE: Mega tons of oil equivalent; 1 MTOE = 42.63×10^{12} Btu.
Quadrillion Btu: 10^{15} British thermal units (Btu), also known as Quad; 1 Btu = 1055 joules).

References

EIA. 1992. *Annual Energy Outlook* 1992, International Energy Outlook, Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. DOE, DOE/EIA-0484(92), Washington, D.C.

EIA. 1993. *Annual Energy Outlook 1993,* International Energy Outlook, Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. DOE, DOE/EIA-0383(93), Washington, D.C.

IEA. 1994. *World Energy Outlook*, Economic Analysis Division, International Energy Agency, Paris.

U.S. DOE. 1991. *National Energy Strategy — Powerful Ideas for America, 1991.* National Technical Information Service, U.S. Department of Commerce, Springfield, VA.

Further Information

Historial and projected energy consumption are published annually by the Energy Information Agency, U.S. Department of Energy, Washington, D.C., and International Energy Agency, Paris.

7.2 Types of Derived Energy

D. Yogi Goswami

Energy from renewable and nonrenewable fuels can be converted to the derived energy forms — thermal, mechanical, and electrical, which are useful for various end uses such as transportation, buildings (heating, cooling, lighting), agricultural, and industrial end uses. The derived energy forms are easily transformed from one type to the other. Figure 7.2.1 shows the projected U.S. energy use by end-use sector.

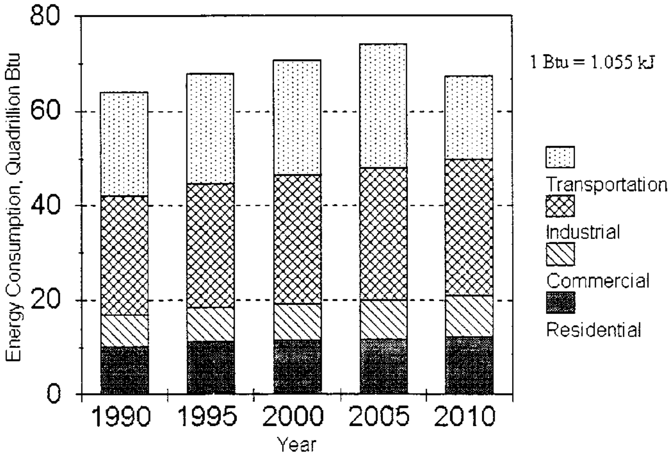

FIGURE 7.2.1 Projected U.S. energy use by end-use sector. (From EIA. *Annual Energy Outlook 1992*, U.S. DOE, DOE/EIA-0484(92), Washington, D.C., 1992.)

Transportation is mainly dependent on oil resources. Efforts to reduce urban air pollution are expected to increase the use of electricity as the preferred energy form for urban transportation. For most of the other end uses electricity will continue to be the preferred energy form. Therefore, it is important to understand the activity in the area of electricity production. Figure 7.2.2 shows the world installed electricity generation capacity by primary energy sources. The United States produces 700 GW (gigawatts or 10^9 W), representing more than 25% of the world electricity capacity. Other major electricity producers are Russia, Europe, Japan, and China. It is expected that China, India, and Southeast Asian countries will add major electricity capacity in the next 20 years.

Integrated resource planning (IRP), or least-cost planning, is the process used to optimize the resource options and minimize the total consumer costs including environmental and health costs that may be attributed to the resource. IRP examines all of the options, including the demand-side options, to minimize the total costs. There is considerable emphasis on IRP in a number of states in United States for future electric capacity and on **demand-side management** (DSM) for the current capacity (Kreith and Burmeister, 1993). The IRP process generally includes some combination of the following steps (Kreith and Burmeister, 1993): development of a load forecast; inventory of existing resources; identification of additional electrical capacity needs; demand-side management programs; screening and identification of options that are feasible; uncertainty analysis in view of uncertainty of future load, fuel prices, capital costs, etc; and selection of a resource or a mix of resources.

Demand Side Management DSM refers to a mix of electrical utility-sponsored custom incentives and disincentives that influence the amount and timing of customer demand in order to better utilize the available resources. Kreith and Burmeister (1993) and SERI (1991) list a number of DSM strategies.

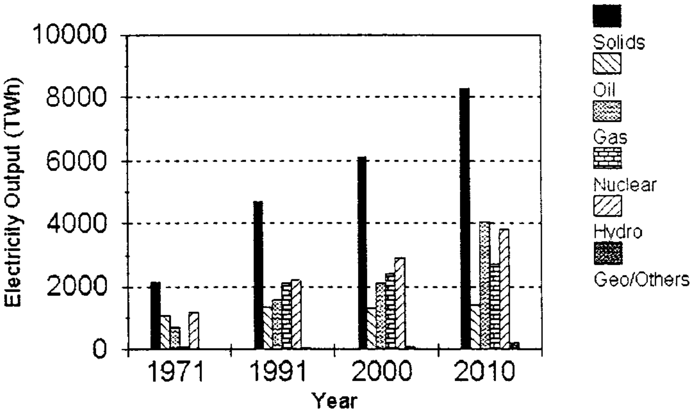

FIGURE 7.2.2 World electricity output. (From EIA, *World Energy Outlook*, International Energy Agency, Paris, 1994. With permission.)

Defining Terms

Demand-side management (DSM): Refers to a mix of incentives and disincentives that influence the amount and timing of energy use in order to better utilize the available resources.

Integrated resource planning (IRP): The process to optimize the resource options and minimize the total consumer costs including environmental and health costs that may be all attributed to the resource.

References

EIA. 1992. *Animal Energy Review.* DOE/EIA-0383(92). Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, D.C.

IEA. 1994. *World Energy Outlook*, Economic Analysis Division, International Energy Agency, Paris.

Kreith, F. and Burmeister, G. 1993. *Energy Management and Conservation.* National Conference of State Legislatures, Denver, CO.

SERI. 1991. Demand Side Management Pocket Guide Book, Volume 1: Residential Technologies; and Volume 2: Commercial Technologies. SERI (Now National Renewable Energy Laboratory), Golden, CO.

Further Information

Annual reviews published by the EIA, U.S. Department of Energy, and the International Energy Agency (see References) provide a wealth of information on electricity capacity and energy consumption by end-use sectors.

7.3 Fossil Fuels

Coal

Robert Reuther

Coal Composition and Classification

Coal is a sedimentary rock formed by the accumulation and decay of organic substances derived from plant tissues and exudates that have been buried over periods of geological time along with various mineral inclusions. Coal is classified by **type and rank.** Coal type classifies coal by the plant sources from which it was derived. Coal rank classifies coal by its degree of metamorphosis from the original plant sources and is therefore a measure of the age of the coal. The process of metamorphosis or aging is termed **coalification.**

The study of coal by type is known as coal petrography. Coal type is determined from the examination of polished sections of a coal sample using a reflected-light microscope. The degree of reflectance and color of a sample are identified with specific residues of the original plant tissues. These various residues are referred to as **macerals.** Macerals are collected into three main groups: vitrinite, inertinite, and exinite (sometimes referred to as liptinite). The maceral groups and their associated macerals are listed in Table 7.3.1 along with a description of the plant tissue from which each distinct maceral type is derived.

TABLE 7.3.1 Coal Maceral Groups and Macerals

Maceral Group	Maceral	Derivation
Vitrinite	Collinite	Humic gels
	Telinite	Wood, bark, and cortical tissue
	Pseudovitrinite	? (Some observors place in the inertinite group)
Exinite	Sporinite	Fungal and other spores
	Cutinite	Leaf cuticles
	Resinite	Resin bodies and waxes
	Alginite	Algal remains
Inertinite	Micrinite	Unspecified detrital matter, <10 μm
	Macrinite	Unspecified detrital matter, 10–100 μm
	Semifusinite	"Burned" woody tissue, low reflectance
	Fusinite	"Burned" woody tissue, high reflectance
	Sclerotinite	Fungal sclerotia and mycelia

Modified from Berkowitz, N., *An Introduction to Coal Technology.* Academic Press, New York, 1979.

Coal rank is the most important property of coal, since it is rank which initiates the classification of coal for use. Rank is a measure of the age or degree of coalification of coal. Coalification describes the process which the buried organic matter goes through to become coal. When first buried, the organic matter has a certain elemental composition and organic structure. However, as the material becomes subjected to heat and pressure, the composition and structure slowly change. Certain structures are broken down, and others are formed. Some elements are lost through volatilization while others are concentrated through a number of processes, including being exposed to underground flows which carry away some elements and deposit others. Coalification changes the values of various properties of coal. Thus, coal can be classified by rank through the measurement of one or more of these changing properties.

In the United States and Canada, the rank classification scheme defined by the American Society of Testing and Materials (ASTM) has become the standard. In this scheme, the properties of **gross calorific value** and **fixed carbon** or **volatile matter content** are used to classify a coal by rank. Gross calorific value is a measure of the energy content of the coal and is usually expressed m units of energy per unit mass. Calorific value increases as the coal proceeds through coalification. Fixed carbon content is a measure of the mass remaining after heating a dry coal sample under conditions specified by the ASTM.

Fixed carbon content increases with coalification. The conditions specified for the measurement of fixed carbon content result in being able alternatively to use the volatile matter content of the coal measured under dry, ash-free conditions as a rank parameter. The rank of a coal proceeds from lignite, the "youngest" coal, through subbituminous, bituminous, and semibituminous, to anthracite, the "oldest" coal. There exist subdivisions within these rank categories which are defined in Table 7.3.2. (Some rank schemes include meta-anthracite as a rank above, or "older" than, anthracite. Others prefer to classify such deposits as graphite. Graphite is a minimal resource and is valuable primarily for uses other than as a fuel.) According to the ASTM scheme, coals are ranked by calorific value up to the high volatile A bituminous rank, which includes coals with calorific values (measured on a moist, mineral matter-free basis) greater than 14,000 Btu/lb (32,564 kJ/kg). At this point, fixed carbon content (measured on a dry, mineral matter-free basis) takes over as the rank parameter. Thus, a high volatile A bituminous coal is defined as having a calorific value greater than 14,000 Btu/lb, but a fixed carbon content less than 69 wt%. The requirement for having two different properties with which to define rank arises because calorific value increases significantly through the lower-rank coals, but very little (in a relative sense) in the higher-ranks, whereas fixed carbon content has a wider range in higher-rank coals, but little (relative) change in the lower-ranks. The most widely used classification scheme outside of North America is that developed under the jurisdiction of the International Standards Organization, Technical Committee 27, Solid Mineral Fuels.

Coal Analysis

The composition of a coal is typically reported in terms of its **proximate analysis** and its **ultimate analysis.** The proximate analysis of a coal is made up of four constituents: volatile matter content, fixed carbon content, moisture content, and ash content, all of which are reported on a weight percent basis. The measurement of these four properties of a coal must be carried out according to strict specifications codified by the ASTM.

Volatile matter in coal includes carbon dioxide, inorganic sulfur- and nitrogen-containing species, and organic compounds. The percentage of various species present depends on rank. Volatile matter content can typically be reported on a number of bases, such as moist; dry, mineral matter-free (dmmf); moist, mineral matter-free; moist, ash-free; and dry, ash-free (daf); depending on the condition of the coal on which measurements were made.

Mineral matter and ash are two distinct entities. Coal does not contain ash, even though the ash content of a coal is reported as part of its proximate analysis. Instead, coal contains mineral matter, which can be present both as distinct mineral entities or inclusions and intimately bound with the organic matrix of the coal. Ash, on the other hand, refers to the solid inorganic material remaining *after combusting* a coal sample. Proximate ash content is the ash remaining after the coal has been exposed to air under specific conditions (ASTM Standard Test Method D 3174). It is reported as the mass percent remaining upon combustion of the original sample on either a dry or moist basis.

Moisture content refers to the mass of water which is released from the solid coal sample when it is heated under specific conditions of temperature and residence time as codified in ASTM Standard Test Method D 3173.

The fixed carbon content refers to the mass of organic matter remaining in the sample after the moisture and volatile matter are released. It is primarily made up of carbon with lesser amounts of hydrogen, sulfur, and nitrogen also present. It is typically reported by difference from the total of the volatile matter, ash, and moisture contents on a mass percent of the original coal sample basis. Alternatively, it can be reported on a dry basis; a dmmf basis; or a moist, mineral matter-free basis.

The values associated with the proximate analysis vary with rank. In general, volatile matter content decreases with increasing rank, while fixed carbon content correspondingly increases. Moisture and ash also decrease, in general, with rank. Typical values for proximate analysis as a function of the rank of a coal are provided in Table 7.3.3.

The ultimate analysis of a coal reports the composition of the organic fraction of coal on an elemental basis. Like the proximate analysis, the ultimate analysis can be reported on a moist or dry basis and on

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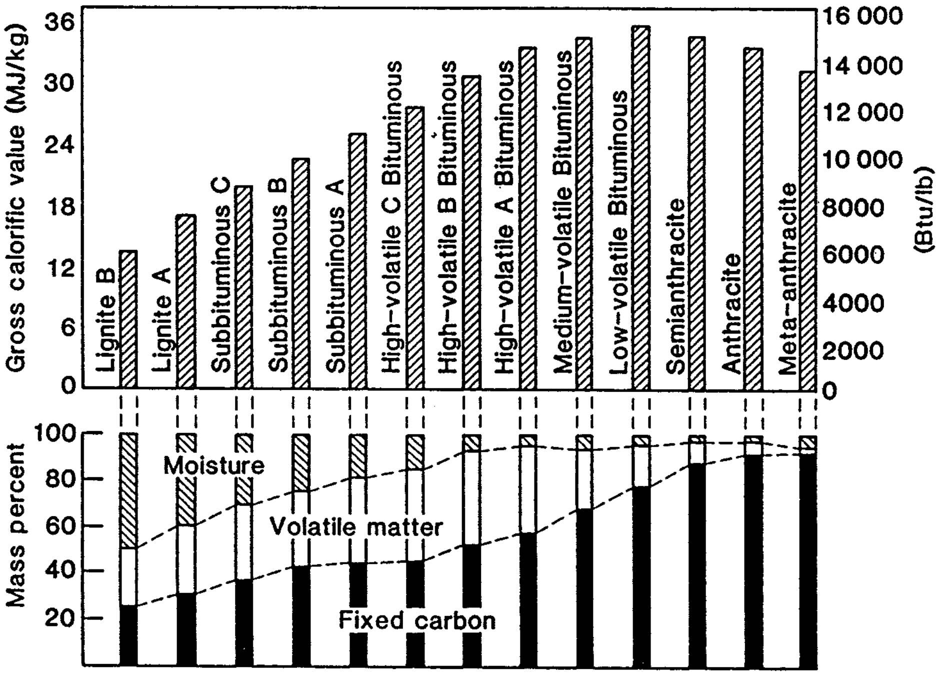
TABLE 7.3.2 Classification of Coals by Rank

		Fixed Carbon Limits, % (dmmf)		Volatile Matter limits, % (dmmf)		Gross Calorific Value Limits, Btu/lb (moist, mmf)		
Class	**Group**	**Equal or Greater Than**	**Less Than**	**Greater Than**	**Equal or Less Than**	**Equal or Greater Than**	**Less Than**	**Agglomerating Character**
Anthracitic	Meta-anthracite	98	—	—	2	—	—	Nonagglomerating
	Anthracite	92	98	2	8	—	—	Nonagglomerating
	Semianthracite	86	92	8	14	—	—	Nonagglomerating
Bituminous	Low volatile bituminous	78	86	14	22	—	—	Commonly agglomerating
	Medium volatile bituminous	69	78	22	31	—	—	Commonly agglomerating
	High volatile A bituminous	—	69	31	—	14,000	—	Commonly agglomerating
	High volatile B bituminous	—	—	—	—	13,000	14,000	Commonly agglomerating
	High volatile C bituminous	—	—	—	—	11,500	13,000	Commonly agglomerating
	High volatile C bituminous	—	—	—	—	10,500	11,500	Agglomerating
Subbituminous	Subbituminous A	—	—	—	—	10,500	11,500	Nonagglomerating
	Subbituminous B	—	—	—	—	9,500	10,500	Nonagglomerating
	Subbituminous C	—	—	—	—	8,300	9,500	Nonagglomerating
Lignitic	Lignite A	—	—	—	—	6,300	8,300	Nonagglomerating
	Lignite B	—	—	—	—	—	6,300	Nonagglomerating

From the American Society for Testing and Materials' Annual Book of ASTM Standards. With permission.

TABLE 7.3.3 Calorific Values and Proximate Analyses of Ash-Free Coals of Different Rank



From Averitt, P., Coal Resources of the United States, January 1, 1974. U.S. Geological Survey Bulletin 1412, Government Printing Office, Washington, D.C., 1975.

TABLE 7.3.4 Ultimate Analyses in Mass Percent of Representative Coals of the U.S.

Component	Fort Union Lignite	Power River Subbbituminous	Four Corners Subbbituminous	Illinois C Bituminous	Appalachia Bituminous
Moisture	36.2	30.4	12.4	16.1	2.3
Carbon	39.9	45.8	47 5	60.1	73.6
Hydrogen	2.8	3.4	3.6	4.1	4.9
Nitrogen	0.6	0.6	0.9	1.1	1.4
Sulfur	0.9	0.7	0.7	2.9	2.8
Oxygen	11.0	11.3	9.3	8.3	5.3
Ash	8.6	7.8	25.6	7.4	9.7
Gross calorific value, Btu/lb	6,700	7,900	8,400	10,700	13,400

Modified from Probstein, R. and Hicks, R., *Synthetic Fuels*. McGraw-Hill, New York, 1982. With permission.

an ash-containing or ash-free basis. The moisture and ash reported in the ultimate analyis are found from the corresponding proximate analysis. Nearly every element on Earth can be found in coal. However, the important elements which occur in the organic fraction are limited to a few. The most important of these include carbon, hydrogen, oxygen, sulfur, nitrogen, and, sometimes, chlorine. The scope, definition of the ultimate analysis, designation of applicable standards, and calculations for reporting results on different moisture bases can be found in ASTM Standard Test Method D 3176M. Typical values for the ultimate analysis for various ranks of coal found in the United States are provided in Table 7.3.4.

Coal Properties

Other important properties of coal include swelling, caking, and coking behavior; ash fusibility; reactivity; and calorific value.

Calorific value measures the energy available in a unit mass of coal sample. It is measured by ASTM Standard Test Method D 201 5M, Gross Calorific Value of Solid Fuel by the Adiabatic Bomb Calorimeter, or by ASTM Standard Test Method D 3286, Gross Calorific Value of Solid Fuel by the Isothermal-Jacket Bomb Calorimeter. In the absence of a directly measured value, the gross calorific value, Q, of a coal (in Btu/lb) can be estimated using the Dulong formula (Elliott and Yohe, 1981):

$$Q = 14,544\mathrm{C} + 62,028\left[\mathrm{H} - \left(\mathrm{O}/8\right)\right] + 4,050\mathrm{S}$$

where C, H, O, and S are the mass fractions of carbon, hydrogen, oxygen, and sulfur, respectively, obtained from the ultimate analysis.

Swelling, caking, and coking all refer to the property of certain bituminous coals, when slowly heated in an inert atmosphere to between 450 and 550 or 600°F, to change in size, composition, and, notably, strength. Under such conditions, the coal sample initially becomes soft and partially devolatilizes. With further heating, the sample takes on a fluid characteristic. During this fluid phase, further devolatilization causes the sample to swell. Still further heating results in the formation of a stable, porous, solid material with high strength. There are several tests which have been developed based on this property to measure the degree and suitability of a coal for various processes. Some of the more popular are the free swelling index (ASTM Test Method D 720), the Gray-King assay test (initially developed and extensively used in Great Britain), and the Gieseler plastometer test (ASTM Test Method D 2639), as well as a whole host of dilatometric methods (Habermehl et al., 1981). The results of these tests are often correlated with the ability of a coal to form a coke suitable for iron making. In the iron-making process, the high carbon content and high surface area of the coke are utilized to reduce iron oxide to elemental iron. The solid coke must also be strong enough to provide the structural matrix upon which the reactions take place. Bituminous coals which have good coking properties are often referred to as metallurgical coals. (Bituminous coals which do not have this property are, alternatively, referred to as steam coals because of their historically important use in raising steam for motive power or electricity generation.)

Ash fusibility is another important property of coals. This is a measure of the temperature range over which the mineral matter in the coal begins to soften and eventually to melt into a slag and to fuse together. This phenomenon is important in combustion processes; it determines if and at what point the resultant ash becomes soft enough to stick to heat exchanger tubes and other boiler surfaces or at what temperature it becomes molten so that it flows (as slag), making removal as a liquid from the bottom of a combustor possible.

Reactivity of a coal is a very important property fundamental to all coal conversion processes (the most important of which are combustion, gasification, and liquefaction). In general, lower-rank coals are more reactive than higher-rank coals. This is due to several different characteristics of coals, which vary with rank as well as with type. The most important characteristics are the surface area of the coal, its chemical composition, and the presence of certain minerals which can act as catalysts in the conversion reactions. The larger surface area present in lower-rank coals translates into a greater degree of penetration of gaseous reactant molecules into the interior of a coal particle. Lower-rank coals have a less aromatic structure than higher-rank coals, which, along with contributing to larger surface area, also corresponds to a higher proportion of lower-energy, more-reactive chemical bonds. Lower-rank coals also tend to have higher proximate ash contents, and the associated mineral matter is more distributed — down to the atomic level. Any catalytically active mineral matter is thus more highly dispersed, also. However, the reactivity of a coal also varies depending upon what conversion is being attempted. That is, the reactivity of a coal toward combustion (oxidation) is not the same as its reactivity toward liquefaction, and the order of reactivity established in a series of coals for one conversion process will not necessarily be the same as for another process.

Coal Reserves

Coal is found throughout the United States and the world. It is the most abundant fossil energy resource in the United States and in the world. It comprises 95% of United States fossil energy resources and

70% of world fossil energy resources on an energy content basis. All coal ranks can be found in the continental United States. The largest resources in the United States are made up of lignite and subbituminous coals, which are found primarily in the western United States and Alaska. Bituminous coals are found principally in the Midwest, northern Alaska, and the Appalachian region. Principal deposits of anthracite coal are found in northeastern Pennsylvania. The Alaskan coals have not been extensively mined because of their remoteness and the harsh climate. Of the other indigenous coal resources, the anthracite coals have been extensively mined to where there is little economic resource left; the bituminous coals are being heavily mined in the lower 48 states, especially those with low sulfur contents (less than 2.5 wt%); and the low-rank coals in the West have historically been less heavily mined because of their low calorific value, high moisture and ash contents, and their distance from large markets, although with the enactment of the 1990 Amendments to the Clean Air Act of 1970, these coals are replacing high-sulfur Eastern coals in the marketplace. A map showing the general distribution of coal in the lower 48 states is included as Figure 7.3.1.

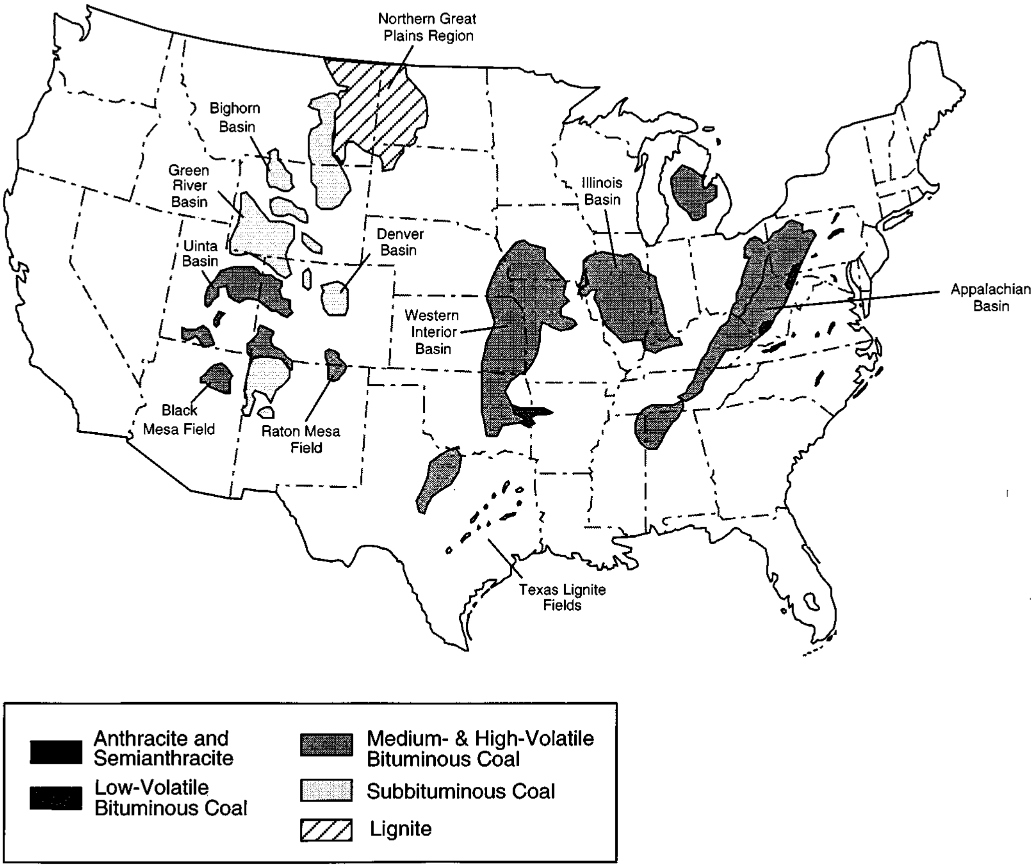


FIGURE 7.3.1 Coal fields of the conterminous (From Averitt, P., Coal Resources of the United States, January 1, 1974. U.S. Geological Survey Bulletin 1412, Government Printing Office, Washington, D.C., 1975.)

The amount of coal (or, for that matter, any minable resource) that exists is not known exactly and is continually changing as old deposits are mined out and new deposits are discovered or reclassified. Estimates are published by many different groups throughout the world. In the United States, the Energy Information Administration, an office within the U.S. Department of Energy, gathers and publishes estimates from various sources, including the World Energy Council and British Petroleum, Ltd. These latter groups subscribe to a set of definitions for classifying the estimates which are acknowledged both in the United States and the United Kingdom. The most commonly used terms are defined below (as taken from Averitt, (1981):

Resources: The total quantity of coal in the ground within specified limits of thickness of bed overburden. The thickness of overburden defining this term varies from region to region in the world.

Hypothetical Resources: The quantity of coal estimated to be in the ground in unmapped and unexplored parts of known coal basins to an overburden depth of 6000 ft; determined by extrapolation from the nearest areas of identified resources.

Identified Resources: The quantity of coal in the measured, indicated, and inferred resource categories.

Measured Resources: The quantity of coal in the ground based on assured coal bed correlations and on observations spaced about 0.5 mi apart.

Indicated Resources: The quantity of coal in the ground based partly on specific observations and partly on reasonable geological projections; the points of observation and measurement are about 1 mi apart but may be 1.5 mi apart for beds of known continuity.

Inferred Resources: The quantity of coal in the ground based on continuity of coal beds downdip from and adjoining areas containing measured and indicated resources. Generally, inferred resources lie 2 mi or more from outcrops or from points of more precise information.

Demonstrated Reserve Base: The quantity of coal in the ground in the measured and indicated resources categories; restricted primarily to coal in thick and intermediate beds less than 1000 ft below the surface and deemed to be economically and legally available for mining.

Reserves, or Recoverable Reserves: The quantity of coal in the ground that can be recovered from the demonstrated reserve base by application of the recoverability factor.

Recoverability Factor: The percentage of coal in the demonstrated reserve base that can be recovered by established mining practices.

The demonstrated reserve base for coals in the United States as of January 1, 1993, is approximately 474.1 billion (short) tons. It is broken out by rank, state, and mining method (surface or underground) in Table 7.3.5. As of December 31, 1990 (December 30, 1991, for the United States), the world recoverable reserves are estimated to be 1145 billion (short) tons. A breakdown by region and country is provided in Table 7.3.6. The recoverability factor for all coals can vary from approximately 40% to over 90% depending on the individual deposit. The recoverable reserves in the United States represent approximately 56% of the demonstrated reserve base. Thus, the United States contains (by weight) approximately 23% of the recoverable reserves of coal in the world.

Environmental Aspects

Richard Bajura

Along with coal production and use comes a myriad of potential environmental problems, most of which can be ameliorated or effectively addressed during recovery, processing, conversion, or reclamation.

Underground coal reserves are recovered using the two principal methods of room-and-pillar mining (60%) and longwall mining (40%). In room-and-pillar mining, coal is removed from the seam in a checkerboard pattern (the “room”) as viewed from above, leaving pillars of coal in an alternate pattern to support the roof of the mine. When using this technology, generally half of the reserves are left underground. Depending upon the depth of the seam and characteristics of the overburden, subsidence due to the removal of the coal may affect the surface many years after the mining operation is completed. Because of the danger of collapse and movement of the surface, undermined lands are not used as building sites for large, heavy structures.

Longwall mining techniques employ the near-continuous removal of coal in rectangular blocks with a vertical cross section equal to the height of the seam multiplied by the horizontal extent (width) of the panel being mined. As the longwall cutting heads advance into the coal seam, the equipment is

TABLE 7.3.5 Coal Demonstrated Reserve Base, January 1, 1993 (billion short tons)

Region and State	Anthracite	Bituminous Coal[1]		Lignite	Total		
	Underground and Surface[2]	Underground	Surface	Surface[3]	Underground	Surface	Total
Appalachian	7.4	81.8	16.6	1.1	85.7	21.1	106.8
Alabama	0	1.4	2.2	1.1	1.4	3.3	4.7
Kentucky, Eastern	0	7.1	1.5	0	7.1	1.5	8.6
Ohio	0	17.9	6.0	0	17.9	6.0	23.8
Pennsylvania	7.2	20.7	1.1	0	24.6	4.5	29.1
Virginia	0.1	1.6	0.7	0	1.7	0.7	2.5
West Virginia	0	31.8	4.7	0	31.8	4.7	36.5
Other[4]	0	1.2	0.4	0	1.2	0.4	1.6
Interior	0.1	92.7	26.7	13.7	92.8	40.4	133.3
Illinois	0	62.6	15.4	0	62.6	15.4	78.0
Indiana	0	8.9	1.2	0	8.9	1.2	10.1
Iowa	0	1.7	0.5	0	1.7	0.5	2.2
Kentucky, Western	0	16.4	3.8	0	16.4	3.8	20.2
Missouri	0	1.5	4.5	0	1.5	4.5	6.0
Oklahoma	0	1.2	0.3	0	1.2	0.3	1.6
Texas	0	0	0	13.2	0	13.2	13.2
Other[5]	0.1	0.3	1.1	0.5	0.4	1.6	2.0
Western	(6)	140.3	63.7	29.9	140.4	93.6	234.0
Alaska	0	5.4	0.7	(6)	5.4	0.7	6.1
Colorado	(6)	12.0	0.6	4.2	12.0	4.8	16.8
Montana	(6)	71.0	33.2	15.8	71.0	48.9	119.9
New Mexico	0	2.1	2.3	0	2.1	2.3	4.4
North Dakota	0	0	0	9.6	0	9.6	9.6
Utah	0	5.8	0.3	0	5.8	0.3	6.0
Washington	0	1.3	0.1	(6)	1.3	0.1	1.4
Wyoming	0	42.5	26.5	0	42.5	26.5	69.1
Other[7]	0	0.1	0.1	0.4	0.1	0.5	0.6
U.S. Total	7.5	314.8	107.1	44.7	318.9	155.1	474.1
States East of the Mississippi River	7.4	169.9	36.9	1.1	173.8	41.4	215.2
States West of the Mississippi River	0.1	145.0	70.1	43.6	145.1	113.7	258.8

[1] Includes subbituminous coal.
[2] Includes 3,396.4 million short tons of surface mine reserves, of which 3,380.8 million tons are in Pennsylvania and 15.6 million tons are in Arkansas.
[3] There are no underground demonstrated reserves of lignite.
[4] Georgia, Maryland, North Carolina, and Tennessee.
[5] Arkansas, Kansas, Louisiana, and Michigan.
[6] Less than 0.05 billion short tons.
[7] Arizona, Idaho, Oregon, and South Dakota.

Notes: Data represent 100 percent of known measured and indicated coal, with qualifying seam thicknesses and depths, in place as of January 1, 1993. Recoverability varies from less than 40 percent to more than 90 percent for individual deposits. Fifty-six percent of the demonstrated reserve base of coal in the United States is estimated to be recoverable.

Totals may not equal sum of components due to independent rounding.

Sources: Energy Information Administration (EIA), *Coal Production 1992* (October 1993), Tables A1, A2, A3, and A4, and EIA, *U.S. Coal Reserves: An Update by Heat and Sulfur Content* (February 1994, page 23.

TABLE 7.3.6 World Recoverable Reserves of Coal (million short tons)

Region and Country	Anthracite and Bituminous Coal		Subbituminous Coal and Lignite		Total	
	World Energy Council[1]	British Petroleum[1]	World Energy Council[1]	British Petroleum[1]	World Energy Council[1]	British Petroleum[1]
North America	123,741	123,741	152,544	152,342	276,285	276,083
Canada	4,970	4,970	4,535	4,535	9,505	9,505
Mexico	1,380	1,380	516	516	1,896	1,896
United States[2]	117,391	117,391	147,291	147,291	264,682	264,682
Other	—	—	202	—	202	—
Central and South America	6,226	6,226	4,478	4,476	10,703	10,702
Brazil	—	—	2,600	2,600	2,600	2,600
Chile	34	—	1,268	—	1,302	—
Colombia	4,674	4,674	330	330	5,003	5,003
Peru	1,058	—	110	—	1,168	—
Other	460	1,552	169	1,546	629	3,098
Western Europe	32,411	32,334	92,493	74,506	124,904	106,840
Germany	26,366	26,366	61,895	61,895	88,261	88,261
Greece	—	—	3,307	3,307	3,307	3,307
Spain	937	—	661	—	1,598	—
Turkey	179	179	7,701	7,701	7,879	7,879
United Kingdom	3,638	3,638	551	551	4,189	4,189
Yugoslavia	77	—	18,188	—	18,265	—
Other	1,215	2,152	189	1,052	1,404	3,204
Eastern Europe and U.S.S.R.	150,021	150,098	179,436	197,625	329,457	347,723
Bulgaria	33	—	4,079	—	4,112	—
Czechoslovakia	2,061	—	3,858	—	5,919	—
Hungary	657	—	4,260	—	4,917	—
Poland	32,628	32,628	12,787	12,787	45,415	45,415
U.S.S.R.	114,640	114,640	151,017	151,017	265,657	265,657
Other	1	2,830	3,436	33,821	3,437	36,651
Africa	67,024	67,033	1,397	1,397	68,420	68,429
Botswana	3,858	—	—	—	3,858	—
South Africa	60,994	60,994	—	—	60,994	60,994
Swaziland	—	—	1,101	—	1,101	—
Zimbabwe	809	809	—	—	809	809
Other	1,434	5,229	295	1,397	1,730	6,626
Far East, Oceania, and Middle East	188,450	188,523	146,710	146,668	335,160	335,194
Australia	49,979	49,979	50,265	50,251	100,244	100,230
China	68,564	68,564	57,651	57,635	126,215	126,198
India	66,853	66,853	2,094	2,094	68,947	68,947
Indonesia	1,060	1,060	34,283	34,273	35,343	35,334
Japan	912	912	19	19	930	930
Other	1,082	1,156	2,398	2,397	3,479	3,552
World	567,946	567,743	577,057	577,015	1,145,002	1,144,758

[1] See Note 3 at end of Section.

[2] U.S. data are more current than other data on this table. They represent recoverable reserves as of December 31, 1991; data for the other countries are as of December 31, 1990, the most recent period for which they are available. U.S. reserves represent both measured and indicated tonnage. The U.S. term "measured" approximates the term "proved," which is used by the World Energy Council and British Petroleum. The U.S. "measured and indicated" data have been combined prior to depletion adjustments and cannot be recaptured as "measured alone."

— = Not applicable.

Notes: The EIA does not certify the international reserves data but reproduces the information as a matter of convenience for the reader.

Totals may not equal sum of components due to independent rounding.

Source: EIA, *International Energy Annual 1992* (January 1994), Table 37.

automatically moved forward. The roof of the mine collapses behind the shields, and most of the effects of subsidence are observed on the surface within several days of mining. If the longwall mining operation proceeds in a continuous fashion, subsidence may occur smoothly so that little damage occurs to surface structures. Once subsidence has occurred, the surface remains stable into the future. Longwall mining operations may influence water supplies as a result of fracturing of water-bearing strata far removed from the panel being mined.

When coal occurs in layers containing quartz dispersed in the seam or in the overburden, miners are at risk of being exposed to airborne silica dust, which is inhaled into their lungs. Coal workers pneumoconiosis, commonly called black lung disease, reduces the ability of a miner to breathe because of the effects of fibrosis in the lungs.

Surface mining of coal seams requires the removal of large amounts of overburden, which must eventually be replaced into the excavated pit after the coal resource is extracted. When the overburden contains large amounts of pyrite, exposure to air and water produces a discharge known as acid mine drainage, which can contaminate streams and waterways. Iron compounds formed as a result of the chemical reactions precipitate in the streams and leave a yellow- or orange-colored coating on rocks and gravel in the streambeds. The acid caused by the sulfur in the pyrite has been responsible for significant destruction of aquatic plants and animals. New technologies have been and continue to be developed to neutralize acid mine drainage through amendments applied to the soil during the reclamation phases of the mining operation. Occasionally, closed underground mines fill with water and sufficient pressure is created to cause “blowouts” where the seams reach the surface. Such discharges have also been responsible for massive fish kills in receiving streams.

The potential for acid rain deposition from sulfur and nitrogen oxides released to the atmosphere during combustion is a significant concern. About 95% of the sulfur oxide compounds can be removed through efficient stack gas cleaning processes such as wet and dry scrubbing. Also, techniques are available for removing much of the sulfur from the coal prior to combustion. Combustion strategies are also being developed which reduce the formation and subsequent release of nitrogen oxides.

The potential for greenhouse warming due to emissions of carbon dioxide during combustion (as well as methane during mining and mine reclamation) has also been raised as a significant concern. Since coal is largely composed of carbon with relatively little hydrogen, its combustion leads to a higher level of carbon dioxide emissions per unit of energy released than for petroleum-based fuels or natural gas.

Transportation

Larry Grayson

According to figures compiled by the United States Department of Energy’s Energy Information Administration (Coleman, 1994), 878 million (short) tons of coal were distributed domestically in 1993, primarily via rail (59.6%), followed by barge (13.9%), truck (13.2%), and conveyor and slurry pipeline (10.8%). Shipments to electric utilities amounted to 773.5 million (short) tons during the same year, with 61.5% transported by rail, followed by 14.0% by barge, 11.7% by truck, and 11.0% by conveyor and slurry pipeline.

Villagran (1989) compared the cost advantage of barge transportation over rail transportation. For distances between 100 and 300 mi, the advantage is between $11 and 38/kilo ton-mi; while the advantage drops to $7 to 11/kilo ton-mi for distances greater than 300 mi. For distances less than 100 mi, rail hauls are very expensive, leading to the predominance of truck haulage in this range when river transportation is not possible.

Defining Terms:

Coalification: The physicochemical transformation which coal undergoes after being buried and subjected to elevated temperature and pressure. The classification of a particular coal by rank is a measure of the extent of its coalification. Thus, coalification is a measure of the “age” of a particular coal.

Fixed carbon content: Fixed carbon content is one of the constituents which make up the proximate analysis of a coal. It is normally measured by difference. That is, one measures the volatile matter content and the moisture and ash contents, if the fixed carbon content is reported on a basis containing one or both of those constituents, and subtracts the result(s) from 100% to find the fixed carbon content. One should not confuse the fixed carbon content of a coal with its (elemental) carbon content found in the ultimate analysis. Although there is certainly carbon in the material making up the fixed carbon content, it is not all of the carbon present in the original coal, and other elements are also present.

Gross calorific value: Calorific value is a measure of the energy content of a material, in this case, a coal sample. Calorific value is measured by ASTM Standard Test Method D 2015M, Gross Calorific Value of Solid Fuel by the Adiabatic Bomb Calorimeter, or by ASTM Standard Test Method D 3286, Gross Calorific Value of Solid Fuel by the Isothermal-Jacket Bomb Calorimeter. The *gross* calorific value takes into account the additional heat gained by condensing any water present in the products of combustion, in contrast to the *net* calorific value, which assumes that all water remains in the vapor state.

Maceral: Macerals are organic substances or optically homogeneous aggregates of organic substances in a coal sample that possess distinctive physical and chemical properties.

Proximate Analysis: Proximate analysis is a method to measure the content of four separately identifiable constituents in a coal: volatile matter content, fixed carbon content, moisture content, and ash content, all of which are reported on a weight percent basis. The standard method for obtaining the proximate analysis of coal or coke is defined by the ASTM in Standard Test Method D 3172.

Rank: Coal rank is a classification scheme for coals which describes the extent of coalification which a particular coal has undergone. The structure, chemical composition, and many other properties of coals vary systematically with rank. The standard method for determining the rank of a coal sample is defined by the ASTM in Standard Test Method D 388.

Type: Coal type is a classification scheme for coals which references the original plant material from which the coal was derived.

Ultimate Analysis: Ultimate analysis is a method to measure the elemental composition of a coal sample. Typical ultimate analyses include carbon, hydrogen, oxygen, sulfur, and nitrogen contents, but other elements can also be reported. These other elements are usually not present to any appreciable extent. However, if they are reported, the sum of all the elements reported (including moisture and ash content) should equal 100%. The standard method for the ultimate analysis of coal or coke is defined by the ASTM in Standard Test Method D 3176.

Volatile matter content: Volatile matter content measures the mass of material released upon heating the coal sample under specific conditions, defined by the ASTM Standard Test Method D 3175.

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Further Information

An excellent resource for understanding coal, its sources, its uses, and its limitations and potential problems is the book by Elliott referenced above under Averitt (1981), Habermehl et al. (1981), and Neavel (1981). A reader wishing an understanding of coal topics could find no better resource.

Another comprehensive book which includes more-recent information but is not quite as weighty as Elliott's (664 pages vs. 2374 pages) is *The Chemistry and Technology of Coal,* edited (second edition, revised and expanded) by James G. Speight.

For up-to-date information specific to the environmental problems associated with the use of coal, the reader is referred to Norbert Berkowitz's chapter entitled "Environmental Aspects of Coal Utilization" in *An Introduction to Coal Technology.*

For information on the standards for coal analyses and descriptions of the associated procedures, the reader is referred to any recent edition of the American Society for Testing and Materials's *Annual Book of ASTM Standards.* Section 5 covers petroleum products, lubricants, and fossil fuels, including coal and coke.

Oil

Philip C. Crouse, P.E.

Overview

Fossil fuel energy accounted for 86.3% of all world energy in 1990. The Energy Information Administration (EIA) of the U.S. Department of Energy estimates that in the year 2010, fossil fuels will account for 85.9% of all world energy consumption — only a 0.4% percentage decrease in usage (Figure 7.3.2). According to EIA estimates, coal is expected to decline slightly from about a 27% to about a 25% share of consumption, and consumption of natural gas is expected to increase from 21 to 24% over the 20-year period. Over the same period, oil is forecasted to continue to be world major energy source with only slight declines from the present 39% of consumption.

Recent efforts in the United States have been to foster growth in natural gas usage as an energy source, causing an estimated growth of 2.3% per year. Total energy usage is expected to grow from 345.6 to 476.0 quadrillion Btu — or a 38% growth in energy usage over 20 years.

Crude Oil Classification and World Reserves

Obtaining accurate estimates of world petroleum and natural gas resources and reserves is difficult and uncertain. Terminology used by industry to classify resources and reserves has no broadly accepted standard classification. Such classifications have been a source of controversy in the international oil and gas community. Confusion persists in regard to classification. This section uses information provided by the Department of Energy classification system. The next chart shows the relationship of resources to reserves. **Recoverable resources** include discovered and undiscovered resources. **Discovered resources** are those resources that can be economically recovered (Figure 7.3.3).

Discovered resources include all production already out of the ground and reserves. Reserves are further broken down into proved reserves and other reserves. Again, there are many different groups that classify reserves in different ways, such as *measured*, *indicated*, *internal*, *probable*, and *possible*. Most groups break reserves into producing and nonproducing categories. Each of the definitions is quite voluminous and the techniques for qualifying reserves vary globally.

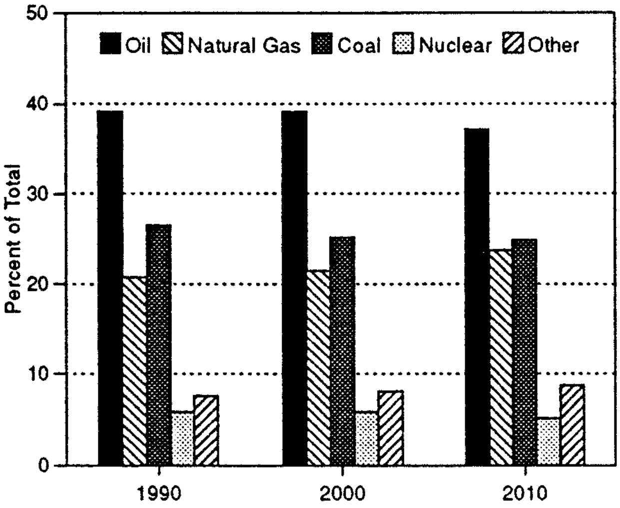
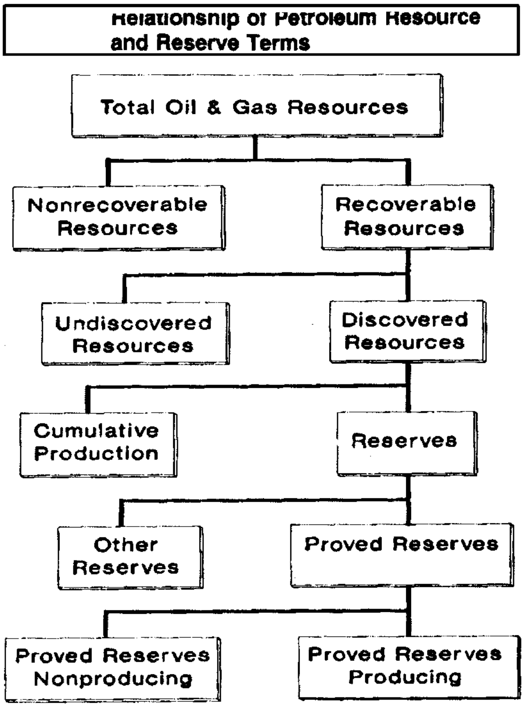


FIGURE 7.3.2 Share of world energy consumption by primary energy source, 1990–2010. (From EIA, *International Energy Outlook 1994,* EIA, Washington, D.C., July 1994.)


Relationship of Petroleum Resource and Reserve Terms

Source: Energy Information Administration, Office of Oil and Gas.

FIGURE 7.3.3 Relationship of petroleum resource and reserve terms. (Courtesy of Energy Information Administration, Offiice of Oil and Gas.)

TABLE 7.3.7 Oil Reserves (Year End) — million barrels

	1970	1980	1990
North America	53,160	80,053	84,134
South America	25,557	26,922	69,686
Western Europe	5,698	18,698	21,289
Eastern Europe	59,880	84,140	65,412
Middle East	342,134	357,578	601,987
Africa	46,356	52,650	59,159
Asia-Pacific	21,973	38,517	56,151
Total	554,777	658,557	957,818
OPEC	404,441	428,139	715,502
Non-OPEC	150,336	230,418	242,316

Source: EIA, *International Oil and Gas Exploration and Development 1991*, Washington, D.C., December 1993, 36–39.

TABLE 7.3.8 Annual Oil Production — million barrels

	1970	1980	1990
North America	4,157	4,379	4,136
South America	1,738	1,331	1,574
Western Europe	116	869	1,478
Eastern Europe	2,706	4,550	4,204
Middle East	5,063	6,760	6,120
Africa	2,246	2,265	2,367
Asia-Pacific	651	1774	2371
Total	16,678	21,928	22,049
OPEC	8,545	9,839	8,645
Non-OPEC	8,133	12,089	13,604

Source: EIA, International Oil and Gas Exploration and Development 1991, Washington, D.C., December 1993, 30–33.

Proved reserves are generally defined as: “Those volumes of oil and gas that geological and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under existing economic and operating conditions.”

OPEC (the Organization of Petroleum-Exporting Countries) has been key in setting global fossil fuel prices over the last two decades. With very large reserves, OPEC can provide much of the world future needs for crude oil and petroleum products. About two-thirds of the world known petroleum reserves are located in the Middle East as shown in Table 7.3.7.

Table 7.3.8 shows that the annual world crude oil production has steadily grown from 16.7 billion barrels in 1970 to 22 billion barrels in 1990.

Both crude oil demand and production are forecast to increase over the next 20 years. OPEC production is relatively level at 8.6 billion barrels in 1990 compared with 8.5 billion barrels in 1970. During the same time, non-OPEC production increased from 8.1 to 13.6 billion barrels. As the “swing producer”, OPEC’s production in 1980 increased by over 1 billion barrels when non-OPEC production could not meet total demand. They then decreased production by a similar amount in 1990 when production in the rest of the world increased by 1 billion to a non-OPEC total of 13.6 billion barrels. With a low price environment, OPEC is expected to gain market share in global production over the next 20 years.

Standard Fuels

Petroleum is refined into petroleum products that are used to meet individual product demands. The general classifications of products are

1. NATURAL GAS LIQUIDS AND LIQUEFIED REFINERY GASES
   This category includes ethane (C_2H_6), ethylene (C_2H_4), propane (C_3H_8), propylene (C_3H_6), butane and isobutane (C_4H_{10}), and butylene and isobutylene (C_4H_8).
2. FINISHED PETROLEUM PRODUCTS
   This category includes motor gasoline, aviation gasoline, jet fuel, kerosene, distillate, fuel oil, residual fuel oil, petrochemical feed stock, naphthas, lubricants, waxes, petroleum coke, asphalt and road oil, and still gas.
   - *Motor gasoline* includes reformulated gasoline for vehicles and oxygenated gasoline such as gasohol (a mixture of gasoline and alcohol).
   - *Jet fuel* is classified by use such as industrial or military and naphtha and kerosene-type. Naphtha fuels are used in turbo jet and turbo prop aircraft engines and excludes ram-jet and petroleum rocket fuel.
   - *Kerosene* is used for space heaters, cook stoves, wick lamps, and water heaters.
   - *Distillate fuel oil* is broken into subcategories: No. 1 distillate, No. 2 distillate, and No. 4 fuel oil which is used for commercial burners.
   - *Petrochemical feedstock* is used in the manufacture of chemicals, synthetic rubber, and plastics.
   - *Naphthas* are petroleums with an approximate boiling range of 122 to 400°F.
   - *Lubricants* are substances used to reduce friction between bearing surfaces, used as process materials, and as carriers of other materials. They are produced from distillates or residues. Lubricants are paraffinic or naphthenic and separated by viscosity measurement.
   - *Waxes* are solid or semisolid material derived from petroleum distillates or residues. They are typically a slightly greasy, light colored or translucent, crystallizing mass.
   - *Asphalt and road oil*. Asphalt is a cementlike material containing bitumens. Road oil is any heavy petroleum oil used as a dust pallatine and road surface treatment.
   - *Still Gas* is any refinery by-product gas. It consists of light gases of methane, ethane, ethylene, butane, propane, and the other associated gases. Still gas typically used as a refinery fuel.

World Refining Capacity. Refining capacity grew from 48 million barrels per day in 1970 to about 75 million barrels per day in 1990 — a 55% growth in capacity. Table 7.3.9 shows world refining capacity beginning in 1970. The peak year was 1982 in which capacity was 81.4 million barrels per day. Utilization of refinery capacity was about 80% in 1990, pointing to underutilization.

TABLE 7.3.9 World Refining Capacity

	1970	**1980**	**1990**
North America	13.2	20.2	17.4
Latin America	4.8	8.6	7.2
Western Europe	14.7	20.3	14.1
Middle East	2.2	3.6	4.2
Africa	0.7	1.7	2.6
Asia-Pacific	5.1	10.4	10.3
Central Planned Economies	7.5	15.4	17.6
Total world	48.2	80.0	73.4

Natural Gas

Philip C. Crouse, P.E.

Natural gas has been called the environmentally friendly fossil fuel since it releases fewer harmful contaminants. World production of dry natural gas was 73.7 trillion ft^3 and accounted for over 20% of world energy production. In 1990 Russia accounted for about one third of world natural gas. The second largest producer was the United States having about one quarter of world 1990 natural gas production.

Natural Gas Production Measurement

Natural gas production is generally measured as “dry” natural gas production. It is determined as the volume of natural gas withdrawn from a reservoir less (1) the volume returned for cycling and repressuring reservoirs; (2) the shrinkage resulting from the removal of lease condensate and plant liquids; (3) the nonhydrocarbon gases. The parameters for measurement are 60°F and 14.73 lb standard per square inch absolute.

World Production and Reserves of Dry Natural Gas

From 1983 to 1992, dry natural gas production rose from 54.4 to 75 trillion ft^3. The breakdown by region of world is shown in Table 7.3.10.

TABLE 7.3.10 World Dry Natural Gas Production — trillion ft^3

	1983	1992
North, Central, and South America	21.20	25.30
Western Europe	6.20	7.85
Eastern Europe and former U.S.S.R.	21.09	28.60
Middle East and Africa	2.95	6.87
Far East and Oceania	2.96	6.38
World total	54.40	75.00

Source: EIA, *Annual Energy Review 1993*, EIA, Washington, D.C., July 1994, 305.

World natural gas reserves estimated by the *Oil and Gas Journal* as of December 31, 1991 are in Table 7.3.11. OPEC accounted for 40% of world reserves yet processes only about 12% of the world production. The former U.S.S.R. accounts for about 40% and Iran another 15% of world reserves.

TABLE 7.3.11 World Natural Gas Reserves — billion ft^3

North America	343,677
South America	166, 850
Western Europe	177,844
Eastern Europe	1,766,358
Middle East	1,319,823
Africa	310,241
Asia-Pacific	299,288
Total	4,384,081
OPEC	1,729,205
Non-OPEC	2,654,876

Compressed Natural Gas

Environmental issues have countries examining and supporting legislation to subsidize the development of cleaner vehicles that use compressed natural gas (CNG). Even with a push toward the use of CNG-burning vehicles, the numbers are quite small when compared with gasoline vehicles. Italy has used

CNG since 1935 and has the largest usage with 300,000 vehicles. The United States ranked fifth with an estimated 30,000 vehicles in 1994. Argentina, which ranked sixth, had 15,000 vehicles.

Liquefied Natural Gas (LNG)

Natural gas can be liquefied by lowering temperature until a liquid state is achieved. It can be transported by refrigerated ships. The process of using ships and providing special-handling facilities adds significantly to the final LNG cost. If oil prices stay low, prospects for LNG development will remain low in the future. However, LNG projects planned by OPEC member countries may become significant over the next 20 years with shipments of LNG exports ultimately accounting for up to 25% of all gas exports.

Physical Properties of Hydrocarbons

The most important physical properties from a crude oil classification standpoint are density or specific gravity and the viscosity of liquid petroleum. Crude oil is generally lighter than water. A Baume-type scale is predominantly used by the petroleum industry and is called the **API** (American Petroleum Institute) **gravity** scale (see Table 7.3.12). It is related directly to specific gravity by the formula:

$$\varphi = (141.5)\big/\left(131.5 + {}^{\circ}\text{API}\right)$$

where φ = specific gravity. Temperature and pressure are standardized at 60°F and 1 atm pressure.

TABLE 7.3.12 Relation of API Gravity, Specific Gravity, and Weight per Gallon of Gasoline

Degree API	Specific Gravity	Weight of gallon in lbs.
8	1.014	8.448
9	1.007	8.388
10	1.000	8.328
15	0.966	8.044
20	0.934	7.778
25	0.904	7.529
30	0.876	7.296
35	0.850	7.076
40	0.825	6.870
45	0.802	6.675
50	0.780	6.490
55	0.759	6.316
58	0.747	6.216

Note: The specific gravity of crude oils ranges from about 0.75 to 1.01.

Other key physical properties involve the molecular weight of the hydrocarbon compound and the boiling point and liquid density. Table 7.3.13 shows a summation of these properties.

Defining Terms

API Gravity: A scale used by the petroleum industry for specific gravity.

Discovered resources: Discovered resources include all production already out of the ground and reserves.

Proved resources: Resources that geological and engineering data demonstrate with reasonable certainly to be recoverable in future years from known reservoirs under existing economic and operating conditions.

Recoverable resources: Recoverable resources include discovered resources.

TABLE 7.3.13 Other Key Physical Properties of Hydrocarbons

Compound	Molecular Weight	Boiling Point at 14.7 psia in °F	Liquid Density at 14.7 psia and 60°F-lb/gal
Methane	16.04	–258.7	2.90
Ethane	30.07	–125.7	4.04
Propane	44.09	–43.7	4.233
Isobutane	58.12	10.9	4.695
n-Butane	58.12	31.1	4.872
Isopentane	72.15	82.1	5.209
n-Pentane	72.15	96.9	5.262
n-Hexane	86.17	155.7	5.536
n-Heptane	100.2	209.2	5.738
n-Octane	114.2	258.2	5.892
n-Nonane	128.3	303.4	6.017
n-Decane	142.3	345.4	6.121

Further Information

The Energy Information Agency of the U.S. Department of Energy, Washington, D.C., publishes *International Energy Outlook* periodically.

7.4 Biomass Energy

Michael C. Reed, Lynn L. Wright, Ralph P. Overend, and Carlton Wiles

Biomass energy encompasses a wide variety of renewable energy technologies that use plant matter, plant residues, or plant-derived process wastes as fuel. These biomass resources can be used directly as solid fuels to produce heat, or they can be converted to other energy carriers such as liquid and gaseous fuels and electricity. Because the energy in biomass is less concentrated than the energy in fossil fuels, high-efficiency conversion technologies are necessary to make this energy resource cost competitive.

Photosynthesis

Biomass fuels are derived from green plants which capture solar energy and store it as chemical energy through the **photosynthetic** reduction of atmospheric carbon dioxide. Plant leaves are biological solar collectors while the stems, branches, and roots are the equivalent of batteries storing energy-rich complex carbon compounds. Elemental analysis shows both wood and grasses to be about 50% carbon. The average photosynthetic efficiency of converting solar energy into organic carbon compounds on an annual basis varies from less than 0.5% in temperate and tropical grasslands to about l.5% in moist tropical forests (Cralle and Vietor, 1989). While quite low, it represents stored energy on an annual basis and the diversity and adaptability of plants allows this solar collection to occur on most parts of Earth's surface. The worldwide annual storage of photosynthetic energy in terrestrial biomass is huge, representing approximately ten times world annual use of energy (Hall et al., 1993).

Biomass Production, Yield, and Potential

Forest Land

The amount of harvestable woody biomass produced by natural forests on an annual basis ranges from about 2 to 6 dry t/ha/year (metric ton/hectare/year), or 0.9 to 2.7 dry ton/acre/year with the higher yields usually in tropical regions. Managed forests often accumulate biomass at approximately double the rate of natural unmanaged stands. The productivity rates of natural forests could be increased to 4 to 12 dry t/ha/year (1.8 to 5.4 dry t/acre/year) if brought under active management. Such management might include optimizing harvesting strategies for production, fertilization, and replanting natural stands with faster-growing species. At present 10% of world forests, or 355 million ha (876 million acres), are actively managed. If managed forests were increased to 20%, and if 20% of the harvested material were used for energy, the annual worldwide resource of wood for energy from currently forested land would amount to somewhere between 284 and 852 million t (315 to 946 million dry tons) of available wood or about 5.6 to 17 Exajoules (5 to 14.5 quadrillion Btu) of primary energy based on potential yield ranges of managed forests. The most optimistic estimates of biomass potential would provide a total primary energy resource of about 30 Exajoules from managed forests (Sampson et al., 1993).

Cropland and Grassland

The production of perennial plants (either woody crops grown for 3 to 10 years between harvests or perennial grasses), using genetically superior materials, established on agricultural land and managed as an agricultural crop is believed to be the method of choice for producing biomass for energy on a large scale. Temperate shelterbelts and tropical agroforestry plantings could also contribute greatly to biomass energy resources. Energy crop yields are highest in locations where genetically superior material is planted on land with plenty of access to sunshine and water. Operational yields in the range of 20 to 30 dry t/ha/year (9 to 13 dry ton/acre/year) are achievable now. Such yields have been observed over large areas with eucalyptus and tropical grasses in the moist tropics and subtropics, and with hybrid poplars in irrigated portions of the dry Pacific Northwest of the United States. In many areas, however, suitable genetically superior materials are not yet available, water is a limiting factor, and irrigation may not be an economically or environmentally desirable alternative. Temperate wood energy yields are more commonly in the range of 9 to 13 dry t/ha/year (4 to 6 dry ton/acre/year) today with the expectation that they could increase to the 12 to 20 dry t/ha/year (5.5 to 9 dry ton/acre/year) relatively rapidly with continued genetic improvement and clonal selection (Wright, 1994). Yields of properly managed perennial grasses in field test plots are currently in the range of 11 to 22 dry t/ha/year (5 to 10 dry ton/acre/year) with the expectation that yields of 16 to 27 dry t/ha/year (7 to 12 dry ton/ac/year) could be attained with further breeding and improvement of management regimes. The best current perennial grass yields on nonirrigated test plots have averaged around 25 dry t/ha/year (11 dry ton/acre/year) for 6 years in the southeastern U.S. where a long growing season favors warm season grasses.

The total amount of biomass potentially available from cropland conversion can only be speculated on since it requires making a number of assumptions involving such issues as land availability, food crop requirements, development of biomass energy markets, and crop yields. Such speculations have been made to attempt to evaluate the potential effect of biomass energy use on carbon emission reduction. These speculations have assumed that 10 to 15% of cropland worldwide could be available for the production of biomass resources as energy crops, shelterbelts, or for agroforestry use with energy as one product (Hall et al., 1993; Sampson et al., 1993). The primary energy resource potential of cropland conversion has been estimated to range from a low of 18 Exajoules to a high of 49 Exajoules (Sampson et al., 1993). Another 25 to 110 Exajoules has been estimated to be available from the conversion of grasslands and degraded areas to the production of biomass energy resources worldwide (Sampson et al., 1993).

Biomass Residues

Biomass residues are the organic by-products of food, fiber, and forest production and processing. Major sources of residues include the residues of grain crops such as corn, wheat, rice; animal dung; and forest roundwood harvest and processing. A signifiant portion of residues is not economically collectible for energy because of wide dispersal and low bulk density, which makes recovery, transport, and storage too costly. In many cases, residues have greater economic value being left on the land to restore nutrients, reduce erosion, and stabilize soil structure, or they may be recovered for other domestic, industrial, or agricultural uses. Recoverable crop residues in the United States are estimated to range between 70 and 190 million dry tons (Day, 1989) and recoverable forest residues are about double the level of crop residues (Hall et al., 1993). Recoverable crop and forest residues worldwide are estimated to have an energy value of 12.5 and 13.5 Exajoules respectively (Hall et al., 1993).

Terrestrial Limitations

The biomass productivity of forests, grasslands, and energy crop plantings is considerably less than theoretically possible based on calculations of maximum photosynthetic potential. Under artificially optimal conditions of temperature, water, and nutrients, average solar radiation near Des Moines, Iowa, would theoretically be aufficient to produce maximum total tree dry weight yields (above and below ground) as high as 102 t/ha/year (45 ton/acre/year) (Sampson et al., 1993). Actual seasonal temperature variations alone, however, reduce the maximum yield potential to 60 t/ha/year (27 ton/acre/year). Of that, the usable biomass portion of trees (the stems and branches only) amounts to only about 35 t/ha/year (15 ton/acre/year). Yet this is many times the harvestable biomass dry weight yield of trees from natural forest stands and more than double the best tree yields observed in experimental trials in that region. Water stress is a major reason for reduced yields. Perennial grasses may have a slightly higher harvestable yield potential in the region because of their higher water use efficiency and the more-efficient carbon metabolism of warm season grasses in temperate climates (Jones, 1985). While water stress, pests outbreaks, and inadequate nutrients all contribute to reduced yields, it is also clear that the genetic potential of perennials is yet to be fully explored. Genetic improvement of perennials for energy is only beginning in most regions of the United States; thus, the potential for finding substantially higher-yielding varieties and clones is excellent.

Environmental Impact

An emerging consensus of environmentalists, forestry organizations, researchers, and others is that if energy crops are treated as an agricultural crop and established and tended in a considered and informed way on appropriate land, environmental damage can be avoided. In fact, preliminary data suggests that there can be significant environmental and ecological benefits achieved in association with the development of a fully sustainable energy resource. Global benefits include the reduced emission of carbon into the atmosphere, while local benefits include soil conservation, reduction of chemical use, and wildlife biodiversity in an agricultural setting.

Biomass Conversion Technologies

As noted previously, biomass can be used to produce heat, electricity, and prepared fuels such as charcoal and liquid fuels. To do this, the biomass conversion technologies have to treat a wide range of biomass resources efficiently and convert them into the desired products. For example, biomass resources may include fuelwood, agricultural residues, farm animal wastes, forest industry processing residues (e.g., sawdust, black liquor from pulping processes), agricultural processing by-products (e.g., bagasse from sugarcane processing, food-processing by-products such as olive pits), and crops (e.g., grains, oil seeds, energy crops).

Each of these resources has different handling requirements and different process characteristics. Worldwide, the most common biomass resources are fuelwood and agricultural residues such as cereal straws. However, many other biomass resources offer opporturuties notjust for heat, but also in improving the environment (as when animal wastes are converted into methane and fertilizer through anaerobic fermentation processes). Each conversion process must take into account the differences in biomass composition which can vary widely in terms of moisture and ash content.

Biomass Composition

As received, biomass can range from very clean wood chips at 50% moisture to urban wood residues that are dry but contaminated with ferrous and other materials, animal residues, sludges, and the organic component of murucipal solid waste (MSW). Most biomass is a **lignocellulosic** material, such as wood or straw, which is composed of **cellulose**, **hemicellulose**, and **lignin**. Although different plant species have differing proportions of these polymers, it turns out that on a moisture and ash-free basis, the majority have essentially the same calorific values in the range of 16 to 19.6 GJ/t (8000 to 8500 Btu/lb). Biomass ash content varies considerably, being lowest in the clean wood fraction and very high in cereal straws such as rice straw, as can be seen in Table 7.4.1.

TABLE 7.4.1 Some Fuel Properties of Four Different Biomass Types

Property	Pine Shavings	Switchgrass	Rice Hull	Rice Straw
Ash %	1.43	10.10	18.34	15.90
Carbon	48.54	47.79	40.96	41.78
Hydrogen	5.85	5.76	4.30	4.63
Nitrogen:	0.47	1.17	0.40	0.70
Sulfur	0.01	0.10	0.02	0.08
Oxygen	43.69	35.07	35.86	36.57
Btu/lb	8337	7741	6944	7004
GJ/t	19.38	17.99	16.14	16.28

Direct Combustion, Combined Heat, and Power and Steam Electric Generation

By far the most frequent use of biomass is in direct-combustion applications, with combustion devices ranging from 5 kW cook stoves (Prasad, 1985) to 125 MW boilers burning wood chips and producing 150 thm/hr of steam at 11 MPa and 540°C superheat temperatures (Anonymous, 1994). The available types of combustors range from pile burners or Dutch-oven-type burners, which can accept biomass in a large size range, to units that are suspension fired and require not only extensive fuel preparation but also fuel drying. The most popular types of boilers seem to be stoker-fired units with moving grates. More recently, the trend has been to bubbling and circulating fluidized-bed units, which offer a high degree of fuel flexibility by accepting fuel mixes ranging from coal to paper mill sludges that have very high moisture and ash contents. Boiler efficiency for typically moist biomass feedstocks ranges from 65 to 75%.

Biomass-fired steam turbine power generation technology is very similar to that of conventional fossil-fueled cycles. Biomass is combusted in a boiler, and the heat which is liberated is used to produce steam with conditions ranging from 28 bar and 398°C (400 psig and 750°F) for typical 25 MW units to 86 bar and 510°C (1250 psig and 950°F) for larger systems. The superheated steam generated in the boiler is used to drive a steam turbine generator. Net plant efficiency ranges from 20 to 30% (17,060 to 11,373 Btu/kWhr). Larger-scale boilers would permit several stages of reheat and the use of supercritical steam cycles. Developers of the Whole Tree Energy™ System have proposed the combustion of whole trees that are dried in a flue gas-assisted dome in order to provide supercritical steam to a turbine. System efficiencies are projected to be in the range of 40% (heat rate 8530 Btu/kWhr) and would be comparable to gas turbine-based combined-cycle units. The ability to utilize whole trees, as opposed to having to process wood feedstocks to “chip” size is a key advantage of the Whole Tree Energy System, as it can significantly reduce feedstock-handling costs.

Gasification

Biomass gasification processes can convert biomass materials into gaseous fuels (carbon- and hydrogen-rich fuel gases) that can be more easily utilized, often with a gain in efficiency and environmental performance. Gasification is a two-step, endothermic process in which a solid fuel (biomass or coal) is thermochemically converted into a low- or medium-Btu gas (see Figure 7.4.1). In the first reaction, pyrolysis, the volatile components of the fuel are vaporized at temperatures below 600°C (1100°F) by a set of complex reactions. Included in the volatile vapors are hydrocarbon gases, hydrogen, carbon monoxide, carbon dioxide tar, and water vapor. Because biomass fuels tend to have more volatile components (70 to 86% on a dry basis) than coal (30%), pyrolysis plays a larger role in biomass gasification than in coal gasification. Char (fixed carbon) and ash are the by-products of pyrolysis which are not vaporized. The second reaction, char conversion, involves the gasification and/or combustion of the carbon that remains after pyrolysis. In this reaction a portion of the char is burned to provide the heat required for pyrolysis and for gasification of any remaining char.

Thermal gasification is typically 80 to 85% efficient in converting the organic content of the feed into a fuel gas mixture mainly composed of hydrogen, carbon monoxide, and methane along with inert constituents. As a comparison, natural gas energy content, measured on a dry gas basis, is typically 37.8 $MJ \cdot m^{-3}$, or 1000 Btu/ft^3. Biomass gases produced through thermal gasification with air as the oxidant typically have gas energy content of less than 5.6 $MJ \cdot m^{-3}$ or 150 Btu/ft^3, while gasification with oxygen and steam or indirect gasification (which elimmintes the nitrogen dilution of the product) results in a heating value of 13 to 17 $MJ \cdot m^{-3}$ or about 350 to 450 Btu/ft^3. Typically, an air-blown gasifier would have over 50% nitrogen, a 25 to 30% by volume mix of hydrogen and carbon monoxide, and a small amount of methane, and the balance would be carbon dioxide.

Gasifier systems usually comprise the biomass fuel-handling and -feeding system which is coupled by means of air locks to the gasifier. In the thermal processes, the gasifier is usually a refractory-lined vessel and the gasification is carried out at high temperatures of approximately 850°C, at either atmospheric or elevated pressures. In a fluidized-bed gasifier, a continuous feed of biomass and inert heat-distributing material (e.g., sand) is “fluidized” by an oxidant and/or steam, and heat is supplied to the gasifier either “directly” or “indirectly” (U.S. Department of Energy, 1992).

In a directly heated fluidized-bed gasifier, heat required for gasification comes from char combustion in the gasifier reactor. The Institute of Gas Technology RENUGAS™ Pressurized Gasifier is an example of a direct-gasification technology. In the RENUGAS process, biomass is fed into a single, fluidized-bed gasifier vessel that operates at 300 to 500 psig. Inert solids in the vessel form the stable fluidized

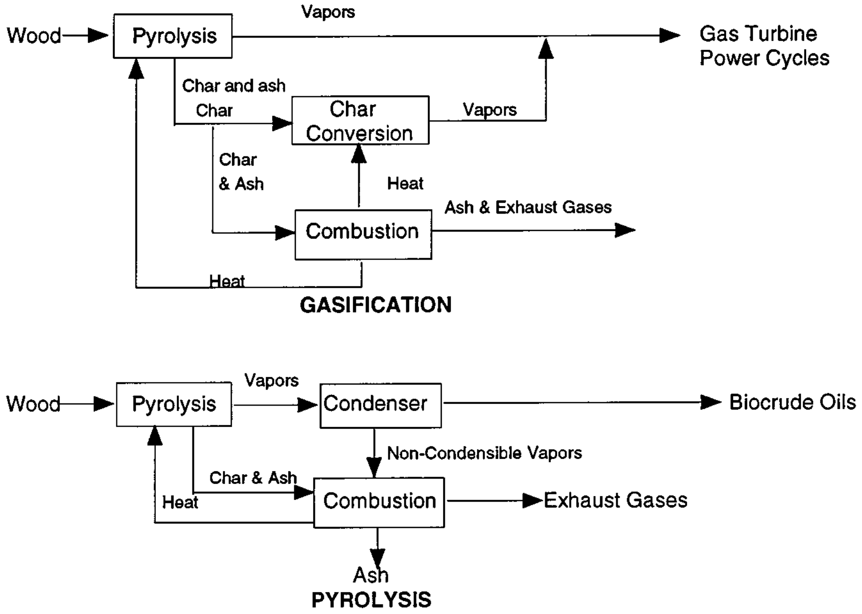


FIGURE 7.4.1. A diagram illustrating biomass gasification and pyrolysis processes. (From U.S. Department of Energy, *Electricity from Biomass: A Development Strategy.* DOE/CH10093-l52, DE920l0590. Washington, D.C., 1992.)

bed into which the biomass is fed. All of the biomass ash is carried overhead with the product gases. By using a deep, single-stage bed of inert solids, the RENUGAS process is able to achieve high carbon conversion with low oils and tars production. The gasifier is capable of producing either an industrial fuel gas or a chemical synthesis gas, depending on air- or oxygen-blown operation.

In an indirectly heated fluidized-bed gasifier, char is removed from the gasifier and burned in a separate vessel. The resulting heat is transferred to the gasifier by either in-bed heat exchangers or by recirculating the inert bed material heated in the char combustor. The advantage of indirect heating of the gasifier is that the gasification product is not diluted with the char combustion by-products (U.S. Department of Energy, 1992). The Battelle Gasification System is an example of an indirect gasification technology (see Figure 7.4.2). The Battelle system is a two-zone circulating-bed gasifier that produces a medium-energy content gas with a heating value of 500 Btu/ft^3 (18.63 MJ/m^3). The product gas can be used in existing natural gas-fired equipment including boilers, kilns, or gas turbines. The Battelle process produces this medium-Btu gas without the need for an oxygen plant, and uses two physically separate reactors (a gasification reactor in which biomass is converted into the product gas and residual char, which is then burned in a separate combustion reactor to provide the heat required for gasification). Heat transfer between the reactors is accomplished by circulating sand between the gasifier reactor and the combustor reactor. The separation of the gasifier from the combustor provides a means to maintain a constant heating value of the product gas regardless of changes in the feed moisture or ash content.

Biomass fuels can provide significant environmental advantages over competing fossil fuels, especially with regard to coal products. These advantages include little or no sulfur content and zero net carbon dioxide production. Additionally, chemicals produced during biomass combustion are absorbed in the photosynthesis process of new biomass growth. However, the fuel conversion process (gasification/combustion) generates emissions such as particulates, tar, and alkali that can cause erosion, corrosion, and deposition problems within the components of advanced conversion systems, especially combustion turbines. As such, some form of gas cleanup must be employed to ensure dependable system performance.

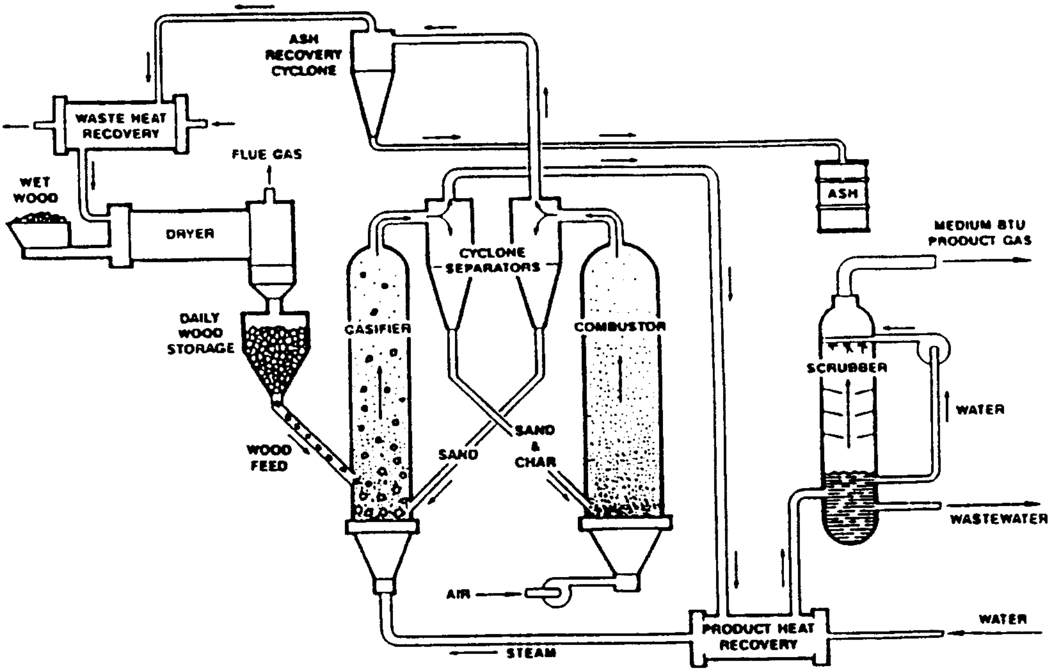


FIGURE 7.4.2. A diagram illustrating the Battelle Biomass Indirect Gasification System.

Biological Gasification or Anaerobic Digestion

The biological gasification process is carried out on feedstock which is either dissolved or slurried in water and typically produces a medium-energy-content gas composed of methane and carbon dioxide. A variety of designs are available, but all of them put anaerobic and methane-forming bacteria in contact with the biomass, the products are the gas (a mixture of methane and carbon dioxide) and a slurry of nonreacted feedstock which can usually be converted into a compost/fertilizer. In the case of landfill gas, the landfill "naturally" produces methane, which is currently being managed for greenhouse gas emissions. The contaminants, which can be highly odoriferous and include hydrogen sulfide, are removed with available technology prior to combustion in either a medium-speed diesel or turbine engine.

Liquefaction to Produce a Biofuel Oil

Biomass feedstocks can also be utilized to create biofuel oils, also known as biocrude. Through a process known as rapid pyrolysis, biofuel oils can be produced and used as fuel for gas turbines, diesel engines, or by co-firing the oil in an existing pulverized coal- or oil-fired boiler. Rapid pyrolysis occurs when heat is transferred to prepared biomass feedstocks (typical thickness <2 mm, moisture <8%) and the solid particles are thermochemically converted to a mixture of noncondensible gases, water vapor, char particles, and pyrolysis oil vapors. The pyrolysis oil vapors typically have a yield of 60 to 80% and are condensed to form a black, viscous, medium-Btu (9000 Btullb or 18.6 MJ/kg) mixture of organic compounds. Because the fuel oils can be stored and transported, the pyrolysis process can be decoupled from the power generation cycle, increasing the flexibility with respect to the proximity of the pyrolysis process to the end user.

Biofuel oil can be produced by pyrolyzing dried wood chips in a **vortex reactor**, followed by removal of solids and condensation of the vapors to recover the higher-molecular-weight hydrocarbons (see Figure 7.4.3). Noncondensible and light hydrocarbons are recycled as carrier gas, or burned with char to generate steam and/or electricity for internal use and export. Table 7.4.2 contains a comparison of biocrude oil characteristics and those of No. 6 fuel oil.

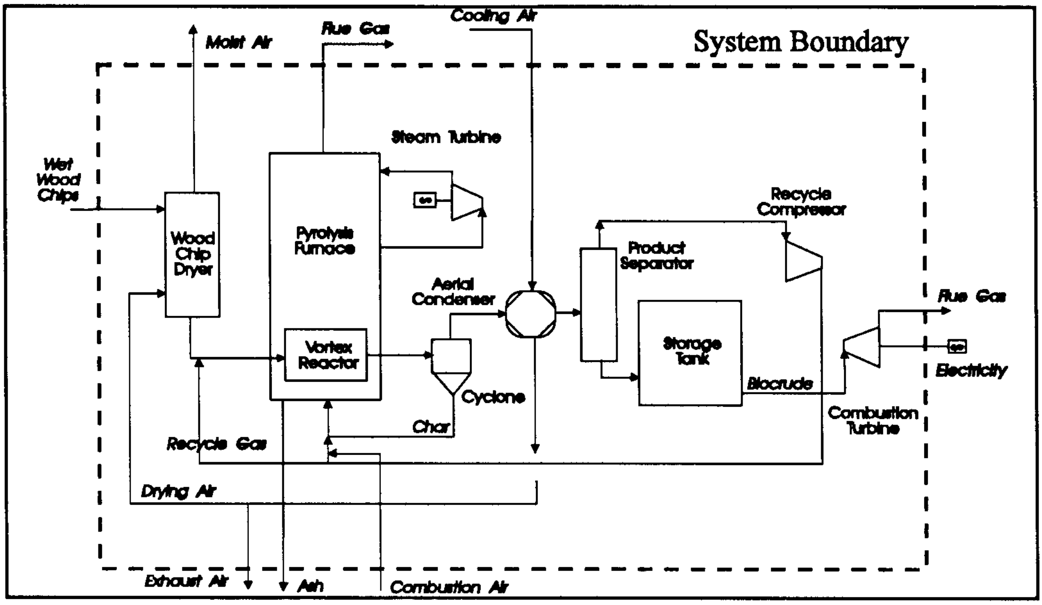


FIGURE 7.4.3. A diagram illustrating the biomass fast pyrolysis process for biocrude oil production.

TABLE 7.4.2 Fuel Oil Characteristics

Type	Biocrude Oil	No. 6 Fuel Oil
Source	Biomass pyrolysis	Petroleum distillation
Sulfur, ppm	5	3,000–30,000
Ash %	0.1–1.0	0.2–1.5
HHV, MJ/kg (BTU/lb)	21–24 (9,000–10,300)	43 (18,400)
HHV, MJ/l (Btu/gal)	25.2 (90,000)	42.1 (150,500)
Density, kg/m^3 @ 16°C (lb/gal @ 60°F)	1,200 (10.14)	950 (8.0)

Source: U.S. Department of Energy, *Biomass Power: A Development Strategy,* DOE/CH10093-152, DE92010590, Washington, D.C., 1992, 31.

Biomass Liquefaction

Ethanol

Ethanol (CH_3CH_2OH) is a renewable liquid fuel that can be produced by fermenting a wide range of biomass materials, including sugars, starches, and lignocellulosics. It is an excellent fuel for spark-ignition internal combustion engines with a high octane number. The automobile industry has developed specifications for E85, an 85% by volume blend with gasoline. Lower-level blends such as El0 are in broad commercial use. Heavy-duty compression ignition engines are usually modified to provide ignition assistance such as glow or spark plugs because of the low cetane and poor autoignition qualities. Although the volumetric energy density of ethanol is two thirds that of gasoline, it has properties, such as the increased octane number, that allow the use of more-efficient high-compression engines. The heat of vaporization is twice that of gasoline, thus increasing the cooled fuel/air mixture that reaches each cylinder. This same property, however, increases cold-starting difficulties.

Currently, corn is used to provide the starch substrate for ethanol production in the United States which is about 1.4 billion gal. Lignocellulosic materials, such as short-rotation woody crops (SRWC) and herbaceous energy crops (HEC), offer an alternative feedstock, one that is dependent on the development of new technology that will allow the cellulose and hemicelluloses that make up approximately 70% of the lignocellulosic feedstocks to produce ethanol. Technology developments in the last decade in lignocellulosic-to-ethanol conversion have shown major potential for cost reductions that have positioned ethanol from lignocellulosics as a near commercial opportunity. These improvements have been in pretreatment, cellulase enzyme production, xylose fermentation, and cellulose conversion.

A typical flow sheet for ethanol production from lignocellulosics such as SRWC or HEC comprises the following operations: feedstock handling; pretreatment to expose the polymers such as hemicellulose and cellulose; production of the biocatalysts such as **cellulase** and hemicellulase that liberate the sugars glucose and xylose; fermentation to convert sugars into ethanol; ethanol recovery process such as distillation; and waste treatment with combined heat and power production from the lignin and other unconverted process residues. A combination of revolutionary advances and incremental improvements in this process chain has reduced costs of ethanol from $3.60 in 1980 to an estimated $1.27/gal in 1996; this latter is already below the cost of production of ethanol from corn. Further development promises to bring the cost into the range of $0.7 to 0.8/gal. This projected cost is competitive with equivalent fuels produced from oil costing $25/barrel.

Pretreatments to expose the carbohydrate polymers have been systematically optimized and developed to be low cost and to have low environmental impact. Dilute acid **hydrolysis** has been found to be effective at exposing cellulose for further hydrolysis. This pretreatment step is followed by a separation of the soluble hemicellulose sugars from the lignin and cellulose fiber. The cellulose material is used both to produce the cellulase enzymes for the hydrolysis and as the major source of sugar that produces ethanol in a combined saccharification and fermentation step. This combines the release of glucose with its immediate fermentation to ethanol in a single process step that results in a large capital cost saving, decreased fermentation times, and increased enzyme productivity, factors that have made a major reduction in overall cost. Work continues on improving the cellulase productivity, the tolerance of the fermentation yeasts to ethanol, and increases in the solids concentration in the fermenters. The current yield of xylose from the hemicellulose polymer, xylan, is also being improved from 80 to 90% (Zhang et al., 1995).

Methanol from Biomass

Methanol (CH_3OH) can easily be produced by gasifying biomass and then catalytically combining the carbon monoxide and the hydrogen. It is the one-carbon analog of ethanol and shares many of the same fuel properties such as a very high octane number. For spark-ignition engine use, M85, an 85% by volume blend with gasoline, is usually specified. The 15% gasoline provides added fuel volatility, which assists cold starting and adds luminosity to the flame for added safety since neat methanol (M100) burns with a nearly invisible flame.

Methanol is very toxic to humans, but is not a great threat to either soil or water environments, and like ethanol, it is essentially nonthreatening to the environment. In any case, methanol is an important industrial chemical and represents one third of the mass of the MTBE (methyl tertiarybutylether) oxygenate used in auto-fuel oxygenate programs. Currently, it is produced from natural gas using technology that has existed for over 50 years.

Biodiesel

Biodiesel is a diesel fuel that in the United States is derived from oil seed crops such as sunflower, soybean, and rape seed (canola). The oil is esterified in a simple process by reacting it with an alcohol such as methanol or ethanol to produce an ester that has been shown to be an attractive diesel fuel with an excellent cetane number and with much-reduced particulate emissions. The oil is isolated by pressing and solvent extraction from the seed cake, and the meal that remains is a nutritious animal feed. The esterification process produces a glycerine by-product. Both the meal and the glycerine have to be marketed in parallel with the oil production and currently the basic price of the oil seed — a food or feedstuff — is still too high, even though in subsidized markets in Europe production is increasing.

Municipal Solid Waste

Quantities, Characteristics, and Fuel Value

MSW contains energy, typically ranging from about 4000 to 6500 Btu/lb. MSW includes waste discarded from residential, commercial, institutional, and industrial sources. In 1993, over 200 million tons were generated with approximately 16% combusted for energy recovery. The quantities and heating values available will vary depending on the materials collected and processed into fuel. For instance, tires may be defined as MSW, but most will not be collected and processed into refuse-derived fuel (RDF). Yard waste contains some fuel value but may be composted. Of the approximate 207 million tons of MSW generated in the United States in 1993, paper and paperboard contributed about 77.8 million tons; plastics, 19.3 million tons; wood, 13.7 million tons. Paper has a typical heating value of 7200 Btu/lb; cardboard, 7000 Btu/lb; plastics, 14,000 Btu/lb; and wood, 8500 Btu/lb. Other components, such as leather, textiles, yard trimmings, rubber, etc., also have significant heating values. Processed RDF will have higher heating values depending on the degree of processing to remove noncombustibles and the components used to prepare the fuel. The average passenger tire has a heating value of 13,000 to 15,000 BtuAb. However, there are only two dedicated tires-to-energy facilities in the United States combusting tires for energy recovery; a third was scheduled to begin operation some time in 1995. There are a number of cement kilns, pulp and paper mills, electric-generating utility boilers, and industrial boilers that use tire-derived fuel as a portion of their fuel.

Refuse-Derived Fuels

Fuels derived from MSW have been classified according to the degree of processing. They range from waste used as a fuel in its discarded form with only bulky waste removed (RDF-1) to the combustible fraction of the waste processed into gaseous fuel (RDF-7). Some RDF may be densified (d-RDF) into pellets, cubes, or briquets for use in industrial and utility boilers as a supplement to coal.

MSW-to-Energy Conversion Technologies

Although there are several potential methods to recover energy from MSW (e.g., conversion to ethanol, anaerobic digestion, gasification, pyrolysis, etc.), combustion is the most-advanced and the most-applied conversion technology.

Combustion. Direct combustion is the most prevalent technology used to reclaim the energy value in MSW. In 1993, there were 125 municipal waste-to-energy facilities in the United States with a rated MSW capacity of approximately 2500 MW of energy. The most common options are mass burn and RDF facilities, with mass burn being the most prevalent.

In a typical mass burn facility, waste is received into a pit where an overhead crane mixes the waste and removes oversize materials. The waste is fed onto a grate of the furnace, which agitates and moves the waste across the combustion chamber. Air for combustion is introduced from under the grate (underfire air) and from nozzles located above the grate (overfire air). The formation and emission of pollutants (e.g., CO, NO_x, SO_x, hydrocarbons, dioxins, etc.) are affected significantly by the design and operation of the combustor. Energy is recovered from the hot flue gases in a waterwall boiler and is recovered as hot water and steam.

The cooled flue gases then pass through air pollution control (APC) equipment which normally includes combinations of scrubbers to remove acid gases (e.g., HCl) electrostatic precipitators (particulate removal), and/or fabric filters (fine particulates).

Anaerobic Digestion. Anaerobic digestion is the biological degradation of biodegradable materials, in the absence of oxygen. Anaerobic microorganisms convert the biodegradable fraction of the waste to carbon dioxide and methane, which can be collected and used as an energy source. Commercial-scale anaerobic digestion of MSW has not been successful in the U.S. There are approximately 24 plants operating outside of the U.S.

Defining Terms

Cellulase: A group of enzymes, found in many fungi and bacterial organisms, that hydrolyze the cellulose molecule into the component glucose molecules.

Cellulose: A complex carbohydrate found in stems, bark, and fibrous parts of plants and in products such as paper made from plant material. The insoluble molecule is a long chain of six carbon, glucose molecules linked together.

Hemicellulose: A complex carbohydrate molecule also found in plant material. This molecule is more soluble than cellulose and made up of five carbon sugars such as xylose.

Hydrolysis: Chemical decomposition involving the formation of water. Enzymes are capable of catalyzing the breakdown of cellulose resulting in the release of a water molecule and glucose molecules.

Lignin: A hard material embedded in the cellulose matrix of vascular plant cell walls. The molecule is a branched chain of organic rings, and gives strength to the fibers. This material is insoluble and must be removed in order to hydrolyze the cellulose.

Lignocellulosics: Substances composed of lignin and cellulose and/or hemicellulose, for example, wood. Lignocellulosic materials are the initial form of biomass feedstock before pretreatment removes or loosens the lignin and liberates the cellulose for further treatment

Photosynthesis: A process by which plants combine water and carbon dioxide in the presence of light and chlorophyll to make carbohydrates for food.

Vortex reactor: A pyrolysis reaction chamber design whereby a carrier gas and a dry feed stream are injected into a cylindrical reaction chamber, entering the reactor in a helical pattern and flowing over the inside surface of the cylinder, where heat is transferred to the biomass.

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Further Information

Additional information on energy efficiency and renewable energy technologies can be obtained from the Energy Efficiency and Renewable Energy Clearinghouse (EREC), which can provide publications, tailored technical and business responses, and referrals to energy organizations. Contact EREC at P.O. Box 3048, Merrifield, VA, 22116.

7.5 Nuclear Resources

James S. Tulenko

The Nuclear Fuel Cycle

Sources of Nuclear Fuels and World Reserves

Nuclear power can use two naturally occurring elements, uranium and thorium, as the sources of its fissioning energy. Uranium can be a fissionable source (fuel) as mined (Candu Reactors in Canada), while thorium must be converted in a nuclear reactor into a fissionable fuel. Uranium and thorium are relatively plentiful elements ranking about 60th out of 80 naturally occurring elements. All isotopes of uranium and thorium are radioactive. Today, natural uranium contains, in atomic abundance, 99.2175% Uranium-238 (U^{238}); 0.72% Uranium-235 (U^{235}); and 0.0055% Uranium-234 (U^{234}). Uranium has atomic number 92, meaning all uranium atoms contain 92 protons, with the rest of the mass number being composed of neutrons. Uranium-238 has a half-life of 4.5×10^9 years (4.5 billion years), U-235 has a half-life of 7.1×10^8 years (710 million years), and U-234 has a half-life of 2.5×10^5 years (250 thousand years). Since the age of the earth is estimated at 3 billion years, roughly half of the U-238 present at creation has decayed away, while the U-235 has changed by a factor of sixteen. Thus, when the earth was created, the uranium-235 enrichment was on the order of 8%, enough to sustain a natural reactor of (there is evidence of such an occurrence in Africa). The U-234 originally created has long disappeared, and the U-234 currently present occurs as a product of the decay of U-238.

Uranium was isolated and identified in 1789 by a German scientist, Martin Heinrich Klaproth, who was working with pitchblend ores. No one could identify this new material he isolated, so in honor of the planet Uranus which had just been discovered, he called his new material Uranium. It wasn't until 1896, when the French scientist Henri Becquerel accidentally placed some uranium salts near some paper-wrapped photographic plates, that radioactivity was discovered.

Until 1938, when the German scientists Otto Hahn and Fritz Shassroen succeeded in uranium fission by exposure to neutrons, uranium had no economic significance except in coloring ceramics, where it proved valuable in creating various shades of orange, yellow, brown, and dark green. When a uranium atom is fissioned it releases 200 million electron volts of energy; the burning of a carbon (core) atom releases 4 electron volts. This diffenence of 50 million times in energy release shows the tremendous difference in magnitude between chemical and nuclear energy.

Uranium is present in the earth's crust to the extent of four parts per million. This concentration makes uranium about as plentiful as beryllium, hafnium, and arsenic; and greater in abundance than tungsten, molybdenum, and tantalum. Uranium is an order of magnitude more plentiful than silver and a hundred times more plentiful than gold. It has been estimated that the amount of uranium in the earth's crust to a depth of 12 miles is of the order of 100 trillion tons.

Thorium, which is composed of only one isotope, Thorium-232, has a half-life of 14 billion years (1.4×10^{10} yr), is more than three times more abundant than uranium, and is in the range of lead and gallium in abundance. Thorium was discovered by Berjelius in 1828 and named after Thor, the Scandinavian god of war. For reference, copper is approximately five times more abundant than thorium and twenty times more abundant than uranium.

Uranium is chemically a reactive element; therefore, while it is relatively abundant, it is found chemically combined as an oxide (U_3O_8 or UO_2) and never as a pure metal. Uranium is obtained in three ways, either by underground mining, open pit mining, or in situ leaching. An economic average ore grade is normally viewed as .2% (4 pounds per short ton), though recently ore grades as low as .1% have been exploited. A large quantity of uranium exists in sea-water which has an average concentration of 3×10^{-3} ppm, yielding an estimated uranium quantity available in sea-water of 4000 million tons. A pilot operation was successfully developed by Japan to recover uranium from sea-water, but the cost was about $900/lb, and the effort was shut down as uneconomical.

The major countries with reserves of urnaium in order of importance are Australia, United States, Russia, Canada, South Africa, and Nigeria. The countries with major thorium deposits are India, Brazil, and the United States. It is estimated that for a recovery value of \$130/kg (\$60/lb), the total uranium reserves in these countries are approximately 1.5 million tonnes of uranium in the U.S., 1 million tonnes of uranium in Australia, .7 million tonnes of uranium in Canada, and 1.3 million tonnes of uranium in the former Soviet Union. As mentioned earlier, thorium reserves are approximately four times greater. With the utilization of breeder reactors, there is enough uranium and thorium to provide electrical power for the next thousand years at current rates of usage.

Processing of Nuclear Fuel

Once the uranium ore is mined it is sent to a concentrator (mill) where it is ground, treated, and purified. Since the ore is of a grade of .1 to .2% uranium, a ton of ore contains only between 1 to 2 kilograms of uranium per 1000 kilograms of ore. Thus, thousands to tonnes of ore have to be extracted and sent to a mill to produce a relatively small quantity of uranium. In the concentration process approximately 95% of the ore is recovered as U_3O_8 (yellowcake) to a purity grade of about 80%. Thus, assuming 0.15% uranium ore, the milling and processing of a metric ton (1000 kg) of ore yields a concentrate of 1.781 kg (1.425 kg of uranium and 0.356 kg of impurities). For this reason the mills must be located relatively close to the mine site. The ore tailings (waste) amounts to 998.219 kg and contains quantities of radon and other urnaium decay products and must be disposed of as a radioactive waste.

The U_3O_8 concentrate is then taken to a conversion plant where the concentrate is further purified (the 20% impurities are removed) and the uranium yellowcake is converted to uranium hexafluoried UF_6). The uranium hexafluoride is a gas at fairly low temperature and is an ideal material for the U-235 isotope enriching processes of either gaseous diffusion or gaseous centrifuge. The UF_6 is shipped in steel cylinders in a solid state, and UF_6 is vaporized by putting the cylinder in a steam bath.

If the uranium is to be enriched to 4% U^{235}, then 1 kilogram of 4% U^{235} product will require 7.4 kilograms of natural uranium feed and will produce 6.4 kilograms of waste uranium (tails or depleted uranium) with a U^{235} isotope content of 0.2%. This material is treated as a radioactive waste. Large quantities of tails (depleted uranium) exist as UF_6 in their original shipping containers at the enriching plants. Depleted uranium (a dense material) has been used as shields for radioactive sources, armor piercing shells, balancing of helicopter rotor tips, yacht hold ballast, and balancing of passenger aircraft.

The enriched UF_6 is then sent to a fabrication plant where it is converted to a uranium dioxide (UO_2) powder. The powder is pressed and sintered into cylindrical pellets which are placed in zircaloy tubes (an alloy of zirconium), pressurized with helium, and sealed. The rods are collected in an array (~17 × 17) bound together by spacer grids, with top and bottom end fittings connected by tie rods or guide tubes. Pressurized water reactor fuel assemblies, each containing approximately 500 kilograms of uranium, are placed in a reactor for 3 to 4 years. A single fuel assembly produces 160,000,000 kilowatt hours of electricity and gives 8,000 people their yearly electric needs for its three years of operation. When the fuel assembly is removed from the reactor it must be placed in a storage pond to allow for removal of the decay heat. After approximately five years of wet storage, the fuel assembly can be removed to dry storage in concrete or steel containers. In the United States the current plan is to permanently store the nuclear fuel, with the Department of Energy assuming responsiblility for the “spent” fuel. The money for the government to handle the storage comes from a fee of 1 mill per kilowatt hour paid by consumers of nuclear-generated electricity. A mill is a thousandth of a dollar or a tenth of a penny. Thus, the fuel assembly described above would have collected \$160,000 in the waste fund for the Department of Energy to permanently store the fuel. In Europe, when the fuel is taken out of wet storage it is sent to a reprocessing plant where the metal components are collected for waste disposal; and the fuel is chemically recovered as 96% uranium, which is converted to uranium dioxide for recycling to the enrichment plant, 1% plutonium, which is converted to fuel or placed in storage, and 3% fission products which are encased in glass and permanently stored.

The important thing to remenber about the fuel cycle is the small quantitiy of radioactive fission products (1.5 kilograms) which are created as radioactive waste in producing power which can serve the yearly eletricity needs of 8,000 people for the three years that it operates. The schematic of the entire fuel cycle showing both the United States system (once-through) and the European (recycle) system is given in Figure 7.5.1.

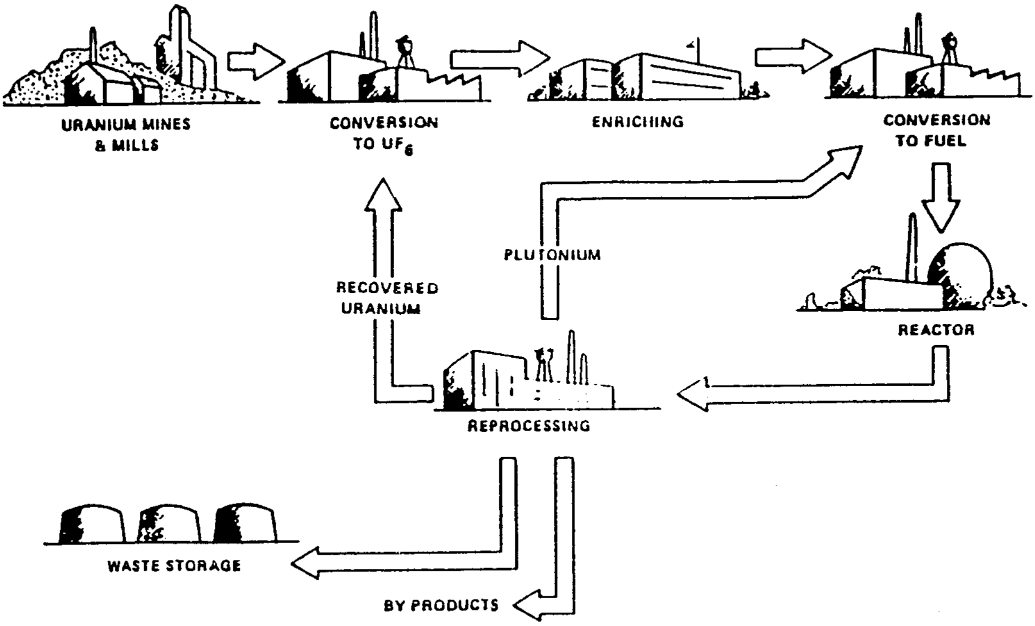

FIGURE 7.5.1 The nuclear fuel cycle.

7.6 Solar Energy Resources

D. Yogi Goswami

The sun is a vast nuclear power plant of the fusion variety which generates power in the form of radiant energy at a rate of 3.8 × 10^{23} kW. An extremely small fraction of this is intercepted by Earth, but even this small fraction amounts to the huge quantity of 1.8 × 10^{14} kW. On the average, about 60% of this energy, incident at the outer edge of the atmosphere, reaches the surface. To compare these numbers with our energy needs, consider the present electrical-generating capacity in the United States, which is approximately of 7 × 10^8 kW. This is equivalent to an average solar radiation falling on only 1000 square miles in a cloudless desert area. It must, however, be remembered that solar energy is distributed over the entire surface of Earth facing the sun, and it seldom exceeds 1.0 kW/m^2. Compared to other sources, such as fossil fuels or nuclear power plants, solar energy has a very low energy density. However, solar radiation can be concentrated to achieve very high energy densities. Indeed, temperatures as high as 3000 K have been achieved in solar furnaces.

Solar energy technology has been developed to a point where it can replace most of the fossil fuels or fossil fuel-derived energy. In many applications it is already economical, and it is a matter of time before it becomes economical for other applications as well.

This section deals in the availability of solar radiation, including methods of measurement, calculation, and available data.

Solar Energy Availability

Detailed information about solar radiation availability at any location is essential for the design and economic evaluation of a solar energy system. Long-term measured data of solar radiation are available for a large number of locations in the United States and other parts of the world. Where long-term measured data are not available, various models based on available climatic data can be used to estimate the solar energy availability. The solar energy is in the form of electromagnetic radiation with the wavelengths ranging from about 0.3 µm (10^{-6} m) to over 3 µm, which correspond to ultraviolet (less than 0.4 µm), visible (0.4 and 0.7 µm), and infrared (over 0.7 µm). Most of this energy is concentrated in the visible and the near-infrared wavelength range (see Figure 7.6.1). The incident solar radiation, sometimes called **insolation,** is measured as irradiance, or the energy per unit time per unit area (or power per unit area). The units most often used are watts per square meter (W/m^2), British thermal units per hour per square foot (Btu/hr-ft^2), and Langleys (calories per square centimeter per minute, cal/cm^2-min).

The amount of solar radiation falling on a surface normal to the rays of the sun outside the atmosphere of the earth (extraterrestrial) at mean Earth-sun distance (D) is called the **solar constant**, I_o. Measurements by NASA indicated the value of solar constant to be 1353 W/m^2 (±1.6%). This value was revised upward and the present accepted value of the solar constant is 1377 W/m^2 (Quinlan, 1979) or 437.1 Btu/hr-ft^2 or 1.974 langleys. The variation in seasonal solar radiation availability at the surface of Earth can be understood from the geometry of the relative movement of Earth around the sun.

Earth-Sun Relationships

Figure 7.6.2 shows the annual motion of Earth around the sun. The **extraterrestrial solar radiation** varies throughout the year because of the variation in the Earth-sun distance (D) as:

$$I = I_o \left(D / D_o \right)^2 \qquad (7.6.1)$$

which may be approximated as (Spencer, 1971)

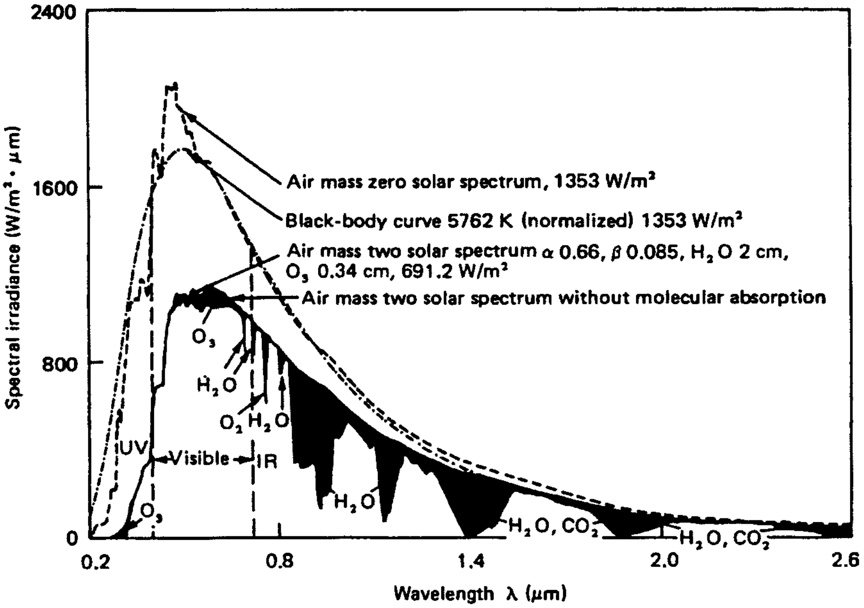

FIGURE 7.6.1 Spectral distribution of solar energy at sea level. (Reprinted by permission from Kreith, F. and Kreider, J.F., *Principles of Solar Engineering*, Hemisphere, Washington, D.C., 1978.)

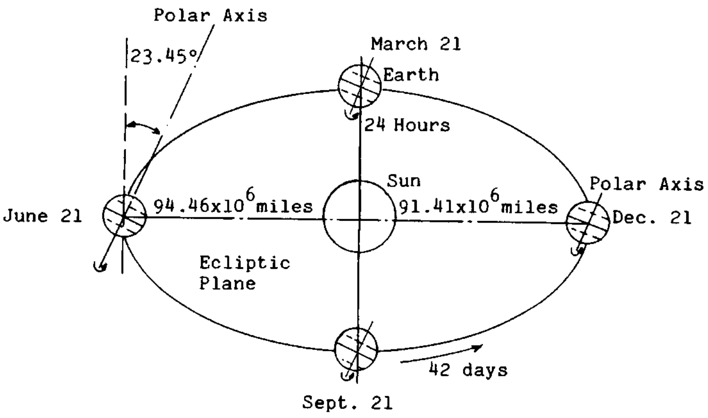

FIGURE 7.6.2 Annual motion of the Earth around the sun.

$$(D/D_o)^2 = 1.00011 + 0.034221\cos(x) + 0.00128\sin(x) + 0.000719\cos(2x) + 0.000077\sin(2x) \qquad (7.6.2)$$

where

$$x = 360(N - 1)/365° \qquad (7.6.3)$$

and N = Day number (starting from January 1 as 1). The axis of the Earth is tilted at an angle of 23.45° to the plane of its elliptic path around the sun. This tilt is the major cause of the seasonal variation of solar radiation available at any location on Earth. The angle between the Earth-sun line and a plane through the equator is called **solar declination**, δ. The declination varies between –23.45° to +23.45° in 1 year. It may be estimated by the relation:

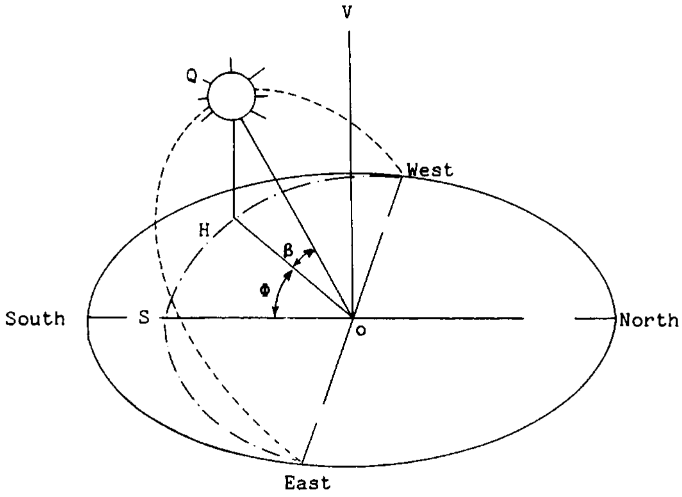

FIGURE 7.6.3 Apparent daily path of the sun across the sky from sunrise to sunset, showing the solar altitude and azimuth angles.

$$\delta = 23.45° \sin\left[360(284 + N)/365°\right] \tag{7.6.4}$$

The apparent motion of the sun around the earth is shown in Figure 7.6.3. The **solar altitude angle**, β, and the **solar azimuth angle**, Φ, describe the position of the sun at any time.

Solar Time

The sun angles are found from the knowledge of solar time, which differs from the local time. The relationship between solar time and local standard time (LST) is given by

$$\text{Solar Time} = \text{LST} + \text{ET} + 4\left(L_{\text{st}} - L_{\text{loc}}\right) \tag{7.6.5}$$

where ET is the **equation of time**, which is a correction factor in minutes that accounts for the irregularity of the motion of the Earth around the sun. L_{st} is the standard time meridian and L_{loc} is the local longitude. ET can be calculated from the following empirical equation:

$$\text{ET(in minutes)} = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B \tag{7.6.6}$$

where $B = 360(N - 81)/365°$.
The sun angles β (altitude) and Φ (azimuth) can be found from the equations:

$$\sin\beta = \cos\ell \cos\delta \cos H + \sin\ell \sin\delta \tag{7.6.7}$$

where ℓ = latitude angle,

$$\sin\Phi = \cos\delta \sin H / \cos\beta \tag{7.6.8}$$

and

$$H = \text{Hour angle} = \frac{\text{Number of minutes from local solar noon}}{4\ \text{min/degree}} \tag{7.6.9}$$

(At solar noon, $H = 0$, so $\beta = 90 - |\ell - \delta|$ and $\Phi = 0$.)

Solar Radiation on a Surface

As solar radiation, I, passes through the atmosphere, some of it is absorbed by air and water vapor, while some gets scattered by molecules of air, water vapor, aerosols, and dust particles. The part of solar radiation that reaches the surface of the Earth with essentially no change in direction is called **direct or beam normal radiation**, I_{bN}. The scattered radiation reaching the surface from the atmosphere is called **diffuse radiation**, I_d.

I_{bN} can be calculated from the extraterrestrial solar irradiance, I, and the atmospheric optical depth τ as (Goswami et al., 1981; ASHRAE, 1995)

$$I_{\text{bN}} = Ie^{-\tau \sec \theta_z} \tag{7.6.10}$$

where θ_z is the solar zenith angle (angle between the sun rays and the vertical). The atmospheric optical depth determines the attenuation of the solar radiation as it passes through the atmosphere. Threlkeld and Jordan (1958) calculated values of τ for average atmospheric conditions at sea level with a moderately dusty atmosphere and amounts of precipitable water vapor equal to the average value for the United States for each month. These values are given in Table 7.6.1. To account for the differences in local conditions from the average sea level conditions Equation (7.6.10) is modified by a parameter called Clearness Number, Cn, introduced by Threlkeld and Jordan (1958):

$$I_{\text{bN}} = \text{Cn}Ie^{-\tau \sec \theta_z} \tag{7.6.11}$$

values of Cn vary between 0.85 and 1.15.

TABLE 7.6.1 Average Values of Atmospheric Optical Depth (τ) and Sky Diffuse Factor (C) for 21st Day of Each Month

Month	1	2	3	4	5	6	7	8	9	10	11	12
τ	0.142	0.144	0.156	0.180	0.196	0.205	0.207	0.201	0.177	0.160	0.149	0.142
C	0.058	0.060	0.071	0.097	0.121	0.134	0.136	0.122	0.092	0.073	0.063	0.057

Source: Threlkeld, J.L. and Jordan, R.C., *ASHRAE Trans.*, 64, 45, 1958.

Solar Radiation on a Horizontal Surface

Total incident solar radiation on a horizontal surface is given by

$$I_{t,\text{Horizontal}} = I_{\text{bN}} \cos\theta_z + CI_{\text{bN}} \tag{7.6.12}$$

$$= I_{\text{bN}} \sin\beta + CI_{\text{bN}} \tag{7.6.13}$$

where θ_z is called the solar zenith angle and C is called the sky diffuse factor, as given in Table 7.6.1.

Solar Radiation on a Tilted Surface

For a surface of any orientation and tilt as shown in Figure 7.6.4, the angle of incidence, θ, of the direct solar radiation is given by

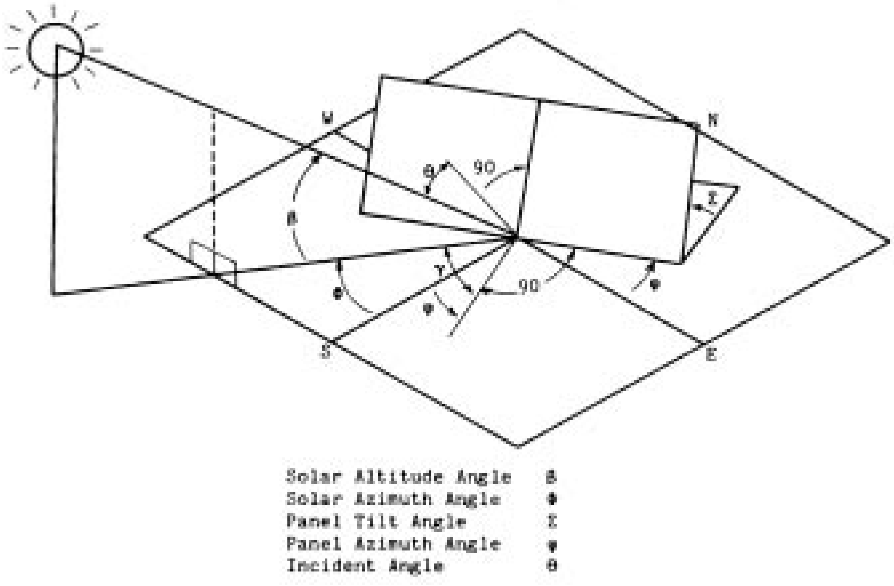

FIGURE 7.6.4 Definitions of solar angles for a tilted surface.

$$\cos\theta = \cos\beta\cos\gamma\sin\Sigma + \sin\beta\cos\Sigma \tag{7.6.14}$$

where γ is the angle between horizontal projections of the rays of the sun and the normal to the surface. Σ is the tilt angle of the surface from the horizontal.

For a tilted surface with angle of incidence θ, the total incident solar radiation is given by

$$I_b = I_{\text{bN}}\cos\theta + I_{\text{diffuse}} + I_{\text{reflected}} \tag{7.6.15}$$

where

$$I_{\text{diffuse}} = CI_{\text{bN}}(1 + \cos\Sigma)/2 \tag{7.6.16}$$

and

$$I_{\text{reflected}} = \rho I_{\text{bN}}(C + \sin\beta)(1 - \cos\Sigma)/2 \tag{7.6.17}$$

where ρ is the reflectivity of the surroundings. For ordinary ground or grass, ρ is approximately 0.2 while for ground covered with snow it is approximately 0.8.

Solar Radiation Measurements

Two basic types of instruments are used in measurements of solar radiation. These are (see Figure 7.6.5):

1. *Pyranometer:* An instrument used to measure global (direct and diffuse) solar radiation on a surface. This instrument can also be used to measure the diffuse radiation by blocking out the direct radiation with a shadow band.
2. *Pyrheliometer:* This instrument is used to measure only the direct solar radiation on a surface normal to the incident beam. It is generally used with a tracking mount to keep it aligned with the sun.

More-detailed discussions about these and other solar radiation measuring instruments can be found in Zerlaut (1989).

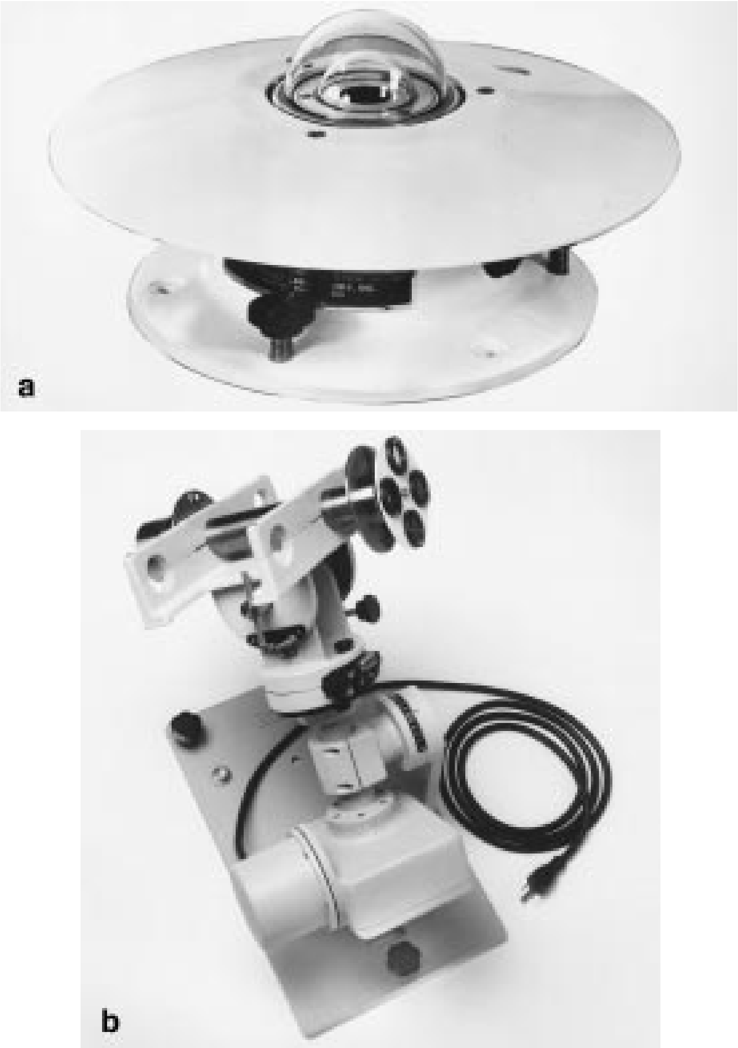

FIGURE 7.6.5 Two basic instruments for solar radiation: (a) pyranometer; (b) pyrheliometer.

Solar Radiation Data

Measured values of solar radiation data for locations in the United States are available from the National Climatic Center in Asheville, NC. A number of states have further presented solar radiation data for locations in those states in readily usable form. Weather services and energy offices in almost all the countries have available some form of solar radiation data or climatic data that can be used to derive solar radiation data for locations in those countries. Tables 7.6.2 to 7.6.8 give solar radiation data for clear days for south-facing surfaces in the Northern Hemisphere (and northern-facing surfaces in the Southern Hemisphere) tilted at 0°, 15°, 30°, 45°, 60°, 75°, and vertical, for latitudes 0°, 10°, 20°, 30°, 40°, 50°, and 60°. The actual average solar radiation data at a location is less than the values given in these tables because of the cloudy and partly cloudy days in addition to the clear days. The actual data can be obtained either from long-term measurements or from modeling based on some climatic parameters, such as percent sunshine. Tables 7.6.9 to 7.6.12 give hourly solar angles for northern latitudes 0°, 20°, 40°, and 60°.

TABLE 7.6.2 Average Daily Total Solar Radiation on South-Facing Surfaces in Northern Hemisphere; Latitude = 0°N

Month	Horiz.	15°	30°	45°	60°	75°	90°
1	31.11	34.13	35.13	34.02	30.90	25.96	19.55
2	32.34	33.90	33.45	31.03	26.80	21.05	14.18
3	32.75	32.21	29.79	25.67	20.12	13.53	6.77
4	31.69	29.13	24.93	19.39	12.97	6.59	4.97
5	29.97	26.08	20.81	14.64	8.34	4.92	5.14
6	28.82	24.43	18.81	12.54	6.66	5.07	5.21
7	29.22	25.08	19.66	13.48	7.45	5.17	5.31
8	30.59	27.48	22.87	17.13	10.82	5.58	5.32
9	31.96	30.51	27.34	22.65	16.78	10.18	5.33
10	32.18	32.82	31.54	28.44	23.73	17.72	10.84
11	31.33	33.80	34.28	32.72	29.24	24.08	17.58
12	30.51	33.90	35.27	34.53	31.73	27.05	20.83

TABLE 7.6.3 Average Daily Total Solar Radiation on South-Facing Surfaces in Northern Hemisphere; Latitude = 10°N

Month	Horiz.	15°	30°	45°	60°	75°	90°
1	27.19	31.27	33.48	33.67	31.83	28.08	22.69
2	29.64	32.43	33.31	32.20	29.17	24.45	18.35
3	31.84	32.63	31.51	28.56	23.98	18.08	11.27
4	32.71	31.37	28.23	23.55	17.65	11.09	5.63
5	32.48	29.58	25.07	19.35	12.96	6.95	5.50
6	32.01	28.46	23.42	17.36	10.97	5.78	5.68
7	32.13	28.88	24.10	18.23	11.87	6.33	5.75
8	32.31	30.28	26.57	21.48	15.42	9.10	5.58
9	31.93	31.74	29.73	26.05	20.95	14.79	8.17
10	30.25	32.14	32.16	30.29	26.67	21.54	15.25
11	27.85	31.43	33.14	32.87	30.64	26.60	21.02
12	26.30	30.66	33.19	33.71	32.20	28.75	23.59

TABLE 7.6.4 Average Daily Total Solar Radiation on South-Facing Surfaces in Northern Hemisphere; Latitude = 20°N

Month	Horiz.	15°	30°	45°	60°	75°	90°
1	22.47	27.33	30.55	31.91	31.32	28.83	24.59
2	25.96	29.83	31.92	32.10	30.34	26.77	21.63
3	29.83	31.91	32.12	30.43	26.97	21.97	15.78
4	32.65	32.59	30.67	27.02	21.91	15.74	9.16
5	34.01	32.26	28.73	23.73	17.68	11.23	6.09
6	34.31	31.79	27.57	22.05	15.73	9.44	6.05
7	34.11	31.93	28.03	22.76	16.59	10.26	6.09
8	33.00	32.16	29.53	25.30	19.83	13.57	7.51
9	30.80	31.87	31.11	28.58	24.44	18.98	12.61
10	27.28	30.32	31.58	30.97	28.54	24.44	18.97
11	23.50	27.95	30.73	31.67	30.68	27.85	23.36
12	21.34	26.38	29.83	31.47	31.18	28.99	25.03

Note: Values are in megajoules per square meter. Clearness number = 1.0; ground reflection = 0.2.

TABLE 7.6.5 Average Daily Total Solar Radiation on South-Facing Surfaces in Northern Hemisphere; Latitude = 30°N

Month	Horiz.	15°	30°	45°	60°	75°	90°
1	17.19	22.44	26.34	28.63	29.15	27.86	24.85
2	21.47	26.14	29.25	30.59	30.06	27.70	23.68
3	26.81	30.04	31.50	31.09	28.84	24.90	19.54
4	31.48	32.71	32.06	29.57	25.44	19.96	13.60
5	34.49	33.96	31.56	27.49	22.08	15.82	9.49
6	35.61	34.24	31.03	26.28	20.40	13.97	8.02
7	35.07	34.06	31.21	26.76	21.11	14.77	8.68
8	32.60	33.00	31.54	28.35	23.68	17.89	11.57
9	28.60	30.87	31.35	30.02	26.97	22.42	16.67
10	23.41	27.38	29.74	30.33	29.10	26.14	21.66
11	18.50	23.48	27.05	28.98	29.14	27.51	24.20
12	15.90	21.19	25.21	27.68	28.44	27.43	24.71

TABLE 7.6.6 Average Daily Total Solar Radiation on South-Facing Surfaces in Northern Hemisphere; Latitude = 40°N

Month	Horiz.	15°	30°	45°	60°	75°	90°
1	11.62	16.72	20.82	23.63	24.96	24.72	22.93
2	16.36	21.45	25.25	27.51	28.07	26.90	24.07
3	22.86	27.03	29.61	30.41	29.39	26.60	22.25
4	29.26	31.69	32.29	31.04	28.01	23.44	17.67
5	33.92	34.63	33.42	30.43	25.88	20.15	13.77
6	35.91	35.73	33.64	29.84	24.65	18.52	12.10
7	35.02	35.20	33.48	30.03	25.13	19.19	12.82
8	31.15	32.73	32.48	30.43	26.73	21.68	15.68
9	25.41	28.72	30.36	30.23	28.35	24.83	19.93
10	18.78	23.37	26.59	28.21	28.12	26.33	22.96
11	13.09	18.11	22.05	24.64	25.70	25.16	23.06
12	10.29	15.25	19.29	22.14	23.60	23.57	22.06

TABLE 7.6.7 Average Daily Total Solar Radiation on South-Facing Surfaces in Northern Hemisphere; Latitude = 50°N

Month	Horiz.	15°	30°	45°	60°	75°	90°
1	6.16	10.32	13.85	16.51	18.13	18.60	17.88
2	10.89	15.84	19.83	22.59	23.95	23.81	22.17
3	18.13	22.92	26.36	28.20	28.33	26.73	23.51
4	26.04	29.52	31.29	31.26	29.41	25.90	20.96
5	32.36	34.22	34.21	32.37	28.83	23.87	17.91
6	35.29	36.23	35.28	32.55	28.25	22.71	16.42
7	34.01	35.32	34.75	32.39	28.42	23.14	17.01
8	28.70	31.35	32.26	31.37	28.76	24.62	19.27
9	21.33	25.43	28.06	29.04	28.32	25.92	22.03
10	13.59	18.36	22.05	24.40	25.26	24.56	22.36
11	7.62	11.98	15.62	18.30	19.82	20.10	19.11
12	4.95	8.70	11.93	14.41	15.98	16.53	16.02

Note: Values are in megajoules per square meter. Clearness number = 1.0; ground reflection = 0.2.

TABLE 7.6.8 Average Daily Total Solar Radiation on South-Facing Surfaces in Northern Hemisphere; Latitude = 60°N

Month	Horiz.	15°	30°	45°	60°	75°	90°
1	1.60	3.54	5.26	6.65	7.61	8.08	8.03
2	5.49	9.38	12.71	15.25	16.82	17.32	16.72
3	12.82	17.74	21.60	24.16	25.22	24.73	22.71
4	21.96	26.22	28.97	30.05	29.38	27.00	23.09
5	30.00	32.79	33.86	33.17	30.73	26.72	21.45
6	33.99	35.82	35.93	34.29	31.00	26.26	20.46
7	32.26	34.47	34.97	33.71	30.78	26.36	20.80
8	25.37	28.87	30.80	31.02	29.53	26.42	21.94
9	16.49	21.02	24.34	26.22	26.54	25.27	22.51
10	8.15	12.39	15.90	18.45	19.85	20.01	18.92
11	2.70	5.27	7.53	9.31	10.51	11.03	10.84
12	0.82	2.06	3.16	4.07	4.71	5.05	5.07

Note: Values are in megajoules per square meter. Clearness number = 1.0; ground reflection = 0.2.

Defining Terms

Diffuse radiation: Scattered solar radiation coming from the sky.

Direct or beam normal radiation: Part of solar radiation coming from the direction of the sun on a surface normal to the sun's rays.

Equation of time: Correction factor in minutes, to account for the irregularity of the Earth's motion around the sun.

Extraterrestrial solar radiation: Solar radiation outside Earth's atmosphere.

Insolation: Incident solar radiation measured as W/m^2 or Btu/hr-ft^2.

Solar altitude angle: Angle between the solar rays and the horizontal plane.

Solar azimuth angle: Angle between the true south horizontal line and the horizontal projection of the sun's rays.

Solar constant: Extraterrestrial solar radiation at the mean Earth-sun distance.

Solar declination: Angle between the Earth-sun line and a plane through the equator.

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TABLE 7.6.9 Hourly Sun Angles for Latitude = 0° N

Solar time		Jan. 21		Feb. 21		March 21	
AM	PM	Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	69.9	0.0	79.1	0.0	89.9	0.0
11	1	65.1	35.3	71.5	53.4	75.0	89.5
10	2	54.4	53.8	58.3	69.0	60.0	89.7
9	3	41.6	62.6	44.0	74.8	45.0	89.8
8	4	28.0	67.1	29.4	77.5	30.0	89.8
7	5	14.1	69.2	14.7	78.7	15.0	89.9
6	6	0.0	69.9	0.0	79.1	0.0	89.9
		April 21		May 21		June 21	
		Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	78.5	180.0	70.0	180.0	66.6	180.0
11	1	71.2	128.3	65.2	144.6	62.4	149.2
10	2	58.1	112.2	54.5	126.0	52.6	130.9
9	3	43.9	106.1	41.6	117.2	40.4	121.5
8	4	29.3	103.3	28.0	112.8	27.3	116.6
7	5	14.7	101.9	14.1	110.6	13.7	114.2
6	6	0.0	101.5	0.0	110.0	0.0	113.4
		July 21		Aug. 21		Sept. 21	
		Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	69.3	180.0	77.6	180.0	88.9	180.0
11	1	64.7	145.5	70.6	130.4	75.0	94.1
10	2	54.1	127.0	57.7	113.8	60.0	92.1
9	3	41.4	118.1	43.7	107.3	45.0	91.5
8	4	27.9	113.5	29.2	104.3	30.0	91.2
7	5	14.0	111.3	14.6	102.9	15.0	91.1
6	6	0.0	110.7	0.0	102.4	0.0	91.1
		Oct. 21		Nov. 21		Dec. 21	
		Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	79.6	0.0	70.3	0.0	66.6	0.0
11	1	71.8	54.8	65.4	35.8	62.4	30.8
10	2	58.4	69.9	54.6	54.4	52.6	49.1
9	3	44.1	75.5	41.7	63.1	40.5	58.5
8	4	29.5	78.1	28.1	67.5	27.3	63.4
7	5	14.7	79.3	14.1	69.7	13.7	65.8
6	6	0.0	79.6	0.0	70.3	0.0	66.6

Note: To convert from solar time to local time, apply corrections for longitude and equation of time.

Further Information

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TABLE 7.6.10 Hourly Sun Angles for Latitude = 20° N

Solar time		**Jan. 21**		**Feb. 21**		**March 21**	
AM	**PM**	**Altitude**	**Azimuth**	**Altitude**	**Azimuth**	**Altitude**	**Azimuth**
12	0	49.9	0.0	59.1	0.0	69.9	0.0
11	1	47.3	21.0	55.8	26.9	65.1	37.9
10	2	40.3	38.0	47.3	46.3	54.4	59.2
9	3	30.4	50.4	36.0	59.1	41.6	71.0
8	4	18.9	59.3	23.4	67.9	28.0	78.7
7	5	6.4	65.9	10.0	74.4	14.0	84.6
6	6	−6.8	71.0	−3.7	79.8	0.0	89.9
		April 21		**May 21**		**June 21**	
		Altitude	**Azimuth**	**Altitude**	**Azimuth**	**Altitude**	**Azimuth**
12	0	81.5	0.0	90.0	0.0	86.6	180.0
11	1	73.3	61.8	75.9	92.5	75.7	106.6
10	2	60.0	78.2	61.8	95.2	62.0	102.5
9	3	46.0	86.0	47.8	98.1	48.2	103.2
8	4	31.9	91.4	33.9	101.2	34.5	105.3
7	5	17.9	96.1	20.2	104.7	21.1	108.3
6	6	3.9	100.9	6.7	108.9	7.8	112.2
		July 21		**Aug. 21**		**Sept. 21**	
		Altitude	**Azimuth**	**Altitude**	**Azimuth**	**Altitude**	**Azimuth**
12	0	89.3	0.0	82.4	0.0	71.1	0.0
11	1	75.9	95.3	73.7	64.5	66.1	39.6
10	2	61.9	96.6	60.3	79.9	55.1	60.9
9	3	47.9	99.0	46.3	87.2	42.1	72.4
8	4	34.1	101.9	32.2	92.4	28.4	80.0
7	5	20.4	105.4	18.1	97.0	14.5	85.8
6	6	6.9	109.5	4.2	101.7	0.4	91.0
		Oct. 21		**Nov. 21**		**Dec. 21**	
		Altitude	**Azimuth**	**Altitude**	**Azimuth**	**Altitude**	**Azimuth**
12	0	59.6	0.0	50.3	0.0	46.6	0.0
11	1	56.2	27.3	47.7	21.2	44.2	19.3
10	2	47.6	46.9	40.6	38.3	37.6	35.4
9	3	36.3	59.7	30.7	50.7	28.3	47.4
8	4	23.6	68.4	19.1	59.6	17.2	56.3
7	5	10.2	74.9	6.5	66.2	5.0	62.8
6	6	−3.5	80.3	−6.6	71.4	−7.8	67.8

Note: To convert from solar time to local time, apply corrections for longitude and equation of time.

TABLE 7.6.11 Hourly Sun Angles for Latitude = 40° N

Solar time		Jan. 21		Feb. 21		March 21	
AM	PM	Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	29.9	0.0	39.1	0.0	49.9	0.0
11	1	28.3	16.0	37.2	18.6	47.6	22.6
10	2	23.7	30.9	32.0	35.4	41.4	41.8
9	3	16.7	43.9	24.2	49.6	32.7	57.2
8	4	8.0	55.2	14.8	61.6	22.4	69.5
7	5	−2.0	65.2	4.2	72.0	11.3	80.1
6	6	****	74.3	−7.0	81.6	−0.1	89.9
		April 21		May 21		June 21	
		Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	61.5	0.0	70.0	0.0	73.4	0.0
11	1	58.6	29.1	66.2	37.1	69.2	41.9
10	2	51.1	51.3	57.5	60.9	59.8	65.8
9	3	41.2	67.1	46.8	76.0	48.8	80.2
8	4	30.3	79.2	35.4	87.2	37.4	90.7
7	5	18.8	89.4	24.0	96.6	25.9	99.7
6	6	7.4	98.9	12.7	105.6	14.8	108.4
5	7	−3.8	108.5	1.9	114.7	4.2	117.3
		July 21		Aug. 21		Sept. 21	
		Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	70.7	0.0	62.4	0.0	51.1	0.0
11	1	66.8	37.9	59.4	29.8	48.8	23.1
10	2	57.9	61.8	51.8	52.2	42.5	42.7
9	3	47.2	76.8	41.9	68.0	33.6	58.1
8	4	35.8	87.8	30.8	80.0	23.3	70.5
7	5	24.3	97.2	19.4	90.1	12.1	81.1
6	6	13.1	106.1	8.0	99.6	0.7	90.8
5	7	2.4	115.2	−3.2	109.1	****	100.6
		Oct. 21		Nov. 21		Dec. 21	
		Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	39.6	0.0	30.3	0.0	26.6	0.0
11	1	37.8	18.8	28.7	16.1	25.0	15.2
10	2	32.5	35.7	24.1	31.0	20.7	29.4
9	3	24.7	49.9	17.0	44.1	14.0	42.0
8	4	15.1	61.9	8.3	55.5	5.5	53.0
7	5	4.6	72.4	−1.7	65.5	−4.2	62.7

Note: To convert from solar time to local time, apply corrections for longitude and equation of time.

TABLE 7.6.12 Hourly Sun Angles for Latitude = 60° N

Solar time		Jan. 21		Feb. 21		March 21	
AM	PM	Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	9.9	0.0	19.1	0.0	29.9	0.0
11	1	9.0	14.2	18.1	15.5	28.7	17.2
10	2	6.3	28.2	15.2	30.6	25.5	33.6
9	3	2.0	41.6	10.6	44.9	20.6	49.1
8	4	−3.6	54.6	4.7	58.6	14.4	63.4
7	5	****	67.1	−2.1	71.7	7.3	76.9

		April 21		May 21		June 21	
		Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	41.5	0.0	50.0	0.0	53.4	0.0
11	1	40.3	19.4	48.6	21.6	52.0	22.7
10	2	36.7	37.7	44.7	41.4	47.9	43.2
9	3	31.3	54.2	38.9	58.7	42.0	60.8
8	4	24.7	69.1	32.1	73.8	35.0	76.0
7	5	17.5	82.8	24.7	87.5	27.6	89.6
6	6	10.0	95.8	17.2	100.3	20.1	102.2
5	7	2.7	108.7	10.0	112.8	13.0	114.5

		July 21		Aug. 21		Sept. 21	
		Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	50.7	0.0	42.4	0.0	31.1	0.0
11	1	49.2	21.8	41.2	19.6	29.9	17.4
10	2	45.3	41.7	37.5	38.0	26.7	34.0
9	3	39.5	59.1	32.1	54.6	21.7	49.5
8	4	32.6	74.2	25.5	69.6	15.4	63.9
7	5	25.3	87.9	18.2	83.3	8.4	77.5
6	6	17.8	100.7	10.7	96.3	0.9	90.5
5	7	10.6	113.1	3.4	109.1	−6.5	103.6

		Oct. 21		Nov. 21		Dec. 21	
		Altitude	Azimuth	Altitude	Azimuth	Altitude	Azimuth
12	0	19.6	0.0	10.3	0.0	6.6	0.0
11	1	18.6	15.6	9.4	14.3	5.7	13.8
10	2	15.7	30.7	6.6	28.3	3.0	27.3
9	3	11.1	45.1	2.3	41.8	−1.1	40.5
8	4	5.2	58.8	−3.2	54.7	−6.6	53.1
7	5	−1.6	71.9	−9.8	67.3	****	65.5

Note: To convert from solar time to local time, apply corrections for longitude and equation of time.

7.7 Wind Energy Resources[*]

Dale E. Berg

The mechanical devices that are used to convert kinetic energy in the wind into useful shaft power are known as windmills (the earliest machines were used to mill grain), wind machines, or wind turbines. The earliest use of wind machines appears to have been in ancient Persia, where they were used for grinding grain and pumping water. By the 14th century, completely different types of mills known as post and cap mills had become a major source of energy for milling, water pumping, and other tasks throughout northern Europe, and they remained so well into the 19th century, when the steam engine displaced them in many applications.

A new form of windmill appeared in United States in the second half of the 19th century — the multivane or annular windmill, also sometimes known as the American windmill (see Figure 7.7.1). These small, lightweight machines were designed to survive high winds with no human intervention by automatically shedding power, and they played a large role in the settlement of the American West — an arid country where little surface water is available. Many windmills of this basic type are still in use for water pumping around the world today.

FIGURE 7.7.1 The multiblade American windmill Photograph by Paul Gipe. (Adapted from *Wind Power for Home & Business*, Chelsea Green Publishing. 1993).

By the end of the 19th century, efforts to adapt wind power to electricity generation were underway in several countries. In the early 20th century, small wind turbine generators utilizing only two or three aerodynamic blades and operating at a higher rotational speed than the multibladed windmills were developed. Many thousands of generators of this type have been used to provide electricity in the remote areas of the world over the past 85 years.

Large-scale wind turbines designed to generate electrical power were built and tested in several European countries and the U.S. between 1935 and 1970. However, economic studies showed that the electricity generated by the machines would be every expensive, and no effort was made to develop the machines as a serious alternative energy source.

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As a result of research and development since the mid 1970s, the cost of energy or wind-generated electricity has decreased from around 30¢ per kilowatt-hour (kWhr) in the early 1980s to less than 5¢/kWhr for a modern wind farm at a good site in 1995, and wind turbine availability (the fraction of time the machine is operational; i.e., not disabled for repairs or maintenance) has increased from 50 to 60% to better than 95% over the same period. At the end of 1995, there were over 26,000 wind turbines operating worldwide with an installed capacity of over 5000 MW. Twenty-five percent of that capacity was installed in 1995, and plans for 1996 call for the installation of an additional 25%. About 2500 MW of the 5000 MW was in Europe, 1700 MW was in the U.S., and over 400 MW was in India.

Wind Characteristics

Wind Speed and Shear

The primary cause of atmospheric air motion, or wind, is uneven heating of Earth by solar radiation. For example, land and water along a coastline absorb radiation differently, and this creates the light winds or breezes normally found along a coast. Earth's rotation is also an important factor in creating winds.

Wind moving across Earth's surface is slowed by trees, buildings, grass, rocks, and other obstructions in its path. The effect of these obstructions decreases with increasing height above the surface, typically resulting in a wind speed that varies with height above the Earth's surface — phenomenon known as **wind shear**. For most situations, wind shear is positive and wind speed increases with height, but situations in which the wind shear is negative or inverse are not unusual. In the absence of actual data for a specific site, a commonly used approximation for wind shear is

$$U/U_o = \left(h/h_o\right)^{\alpha} \tag{7.7.1}$$

where U is the velocity at a height h, U_o is the measured velocity at height h_o, and α is the non-dimensional wind shear exponent.

The wind shear, α, varies with terrain characteristics, but usually is between 0.10 and 0.25. Over a smooth, level, grass-covered terrain such as the United States Great Plains, α is normally about 0.14. For wind over row crops or low bushes with a few scattered trees, a value of 0.20 is more common while a value of 0.25 is normally a good value for wind over a heavy stand of trees, several buildings, or hilly or mountainous terrain.

A specific site may display much different wind shear behavior than that given in Equation 7.7.1, and that will dramatically affect site energy capture, making it important to measure the wind resource at the specific site and height where the wind turbine will be located, if at all possible.

Wind Energy Resource

The available power in the wind passing through a given area at any given velocity is due to the kinetic energy of the wind and is given by

$$\text{Power} = \frac{1}{2}\rho A U^3 \tag{7.7.2}$$

where the power is in watts, ρ is the air density in kg/m^3, A is the area of interest perpendicular to the wind in m^2, and U is the wind velocity in m/sec.

Air density decreases with increasing temperature and increasing altitude. The effect of temperature on density is relatively weak and is normally ignored, as these variations tend to average out over the period of a year. The density difference due to altitude, however, is significant and does not average out. For example, the air density at sea level is approximately 14% higher than that at Denver, CO (elevation 1600 m or 5300 ft above sea level), so wind of any velocity at sea level contains 14% more power than wind of the same velocity at Denver.

From Equation 7.7.2, it is obvious that the most important factor in the available power is the velocity of the wind — available wind power is proportional to the cube of the wind speed, so doubling the wind speed increases the available power by a factor of 8. An increase in wind velocity of only 20%, say, from 5 to 6 m/sec (11.2 to 13.4 mph), yields a 73% increase in available power.

The available wind power at a site can vary dramatically with height due to wind shear. For example, for $\alpha = 0.20$, Equations (7.7.1) and (7.7.2), reveal that the available power at a height of 30 m is approximately $\{(30/10)^{0.2}\}^3 = 1.93$ times the available power at 10 m. The amount of energy available from the wind (the **wind energy resource**) is the average amount of power available from the wind over a specified period of time, frequently a year. If the wind speed is 20 m/sec, the available power is very large, but if it only blows at that speed for 10 h/year and the rest of the time the wind speed is 0, the resource for the year is very small. Therefore, the site **wind speed distribution**, or frequency at which each wind speed occurs, is very important. The distribution is often presented in histogram form as the probability that the wind occurs at any particular wind speed between 0 and the maximum wind speed (see Figure 7.7.9). If the actual wind speed distribution is not available, it is frequently approximated with a Rayleigh distribution based on the yearly average wind speed. The Rayleigh distribution is given by

$$f(U) = \frac{\pi}{4} \cdot \frac{U}{\overline{U}} \exp\left[\frac{-\pi U^2}{4\overline{U}^2}\right] \tag{7.7.3}$$

where $f(U)$ is the frequency of occurrence of wind speed U and $\overline{U}$ is the yearly average wind speed.

How big is the wind energy resource? It varies dramatically from site to site. In 1981, scientists at Battelle Pacific Northwest Laboratory (PNL) in the U.S. analyzed national weather data, ship data, and terrain and made an estimate of the world-wide wind energy resource. That estimate is summarized in Figure 7.7.2. Very little data is available over much of the world, but even where excellent data is available, only very crude estimates can be portrayed on a map of this scale. More detailed analysis of available data for a specific country can yield a much better estimate of the wind resource for that country.

For example, the PNL scientists have carefully analyzed and interpreted the available long-term wind data for the U.S. and have summarized their estimate of the wind energy resource in a series of maps in the *Wind Energy Resource Atlas of the United States* (Elliott et al., 1987). A summary for the entire U.S. is reproduced in Figure 7.7.3 which presents the resource in terms of the power class rating. Sites with power class 4 (at least 250 W/m^2 at 10 m height or 500 W/m^2 at 50 m height) and above are considered economic for utility-scale wind power development with available wind technology, while sites with power class 3 are not considered economic today but are likely to become economic with near-term wind technology advances. Sites in power classes 2 or lower are not considered economic for utility-scale wind power development, but may well be economic for remote or hybrid wind power systems.

Much of the land in the United States is not available for wind energy development because it is in environmental exclusion areas such as parks, monuments, wilderness areas, wildlife refuges, and other protected areas, or only a portion of it may be developed because of land-use restrictions for forest, agriculture, range, and urban lands. Schwartz et al. (1992) estimated the wind energy that could be generated (the **wind energy potential**) for the United States land available for wind energy development. For the purposes of this study, they assumed that turbines with a 50-m hub height, arranged in arrays with 10 diameter by 5 diameter spacing, operating at 25% efficiency, and experiencing 25% power losses, were used to capture the available wind. Their results for power class 4 and above are summarized in Figure 7.7.4 and Table 7.7.1. They estimate that the average power that could be produced from this resource is 512,000 MW, significantly above the 1994 U.S. average electricity generation of 350,000 MW. They also estimate that the available windy lands with power class 3 or better resources could yield an average power of 1,241,000 MW, more than three times the current United States electricity generation. However, since wind energy is intermittent, is typically concentrated away from the major

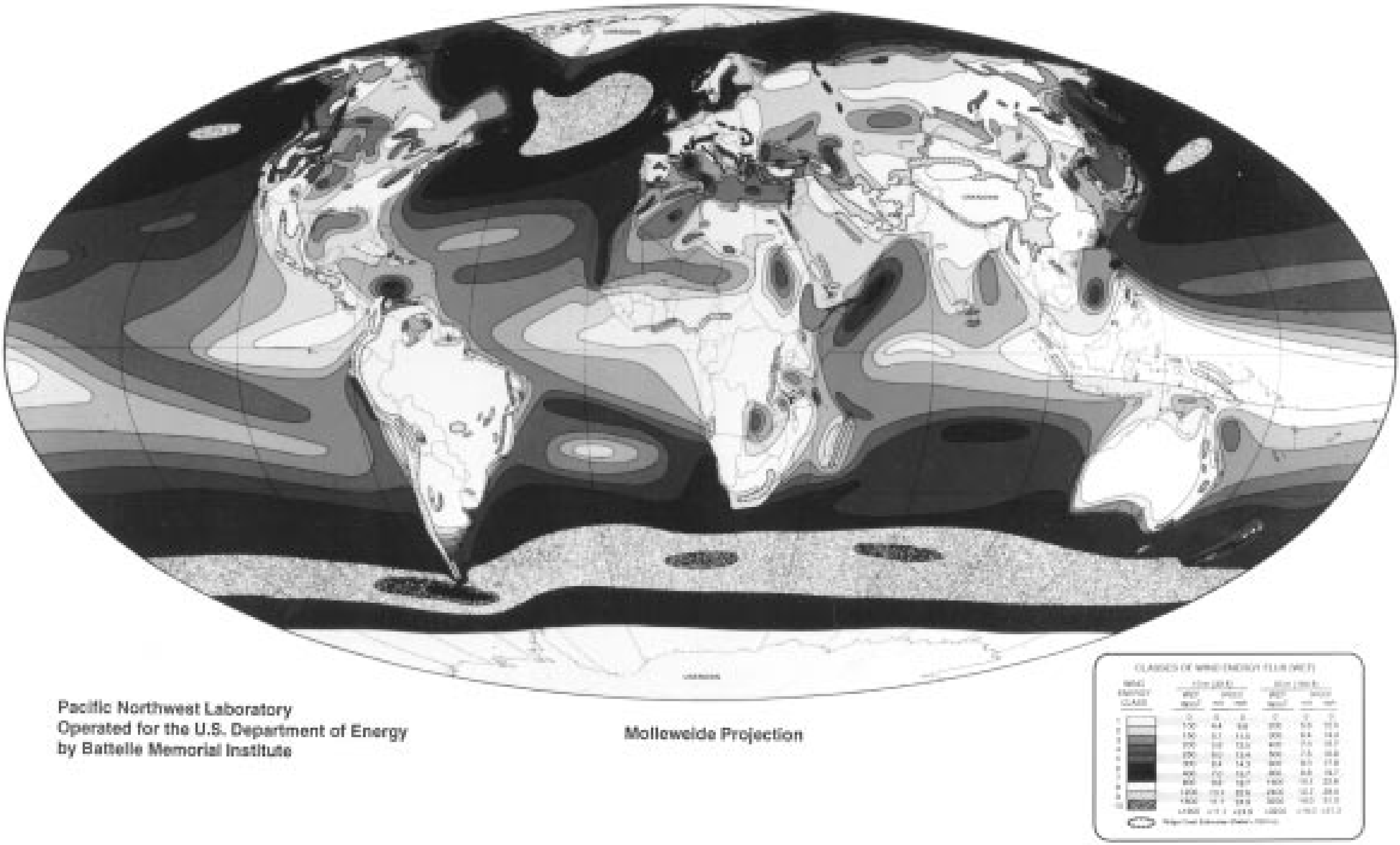
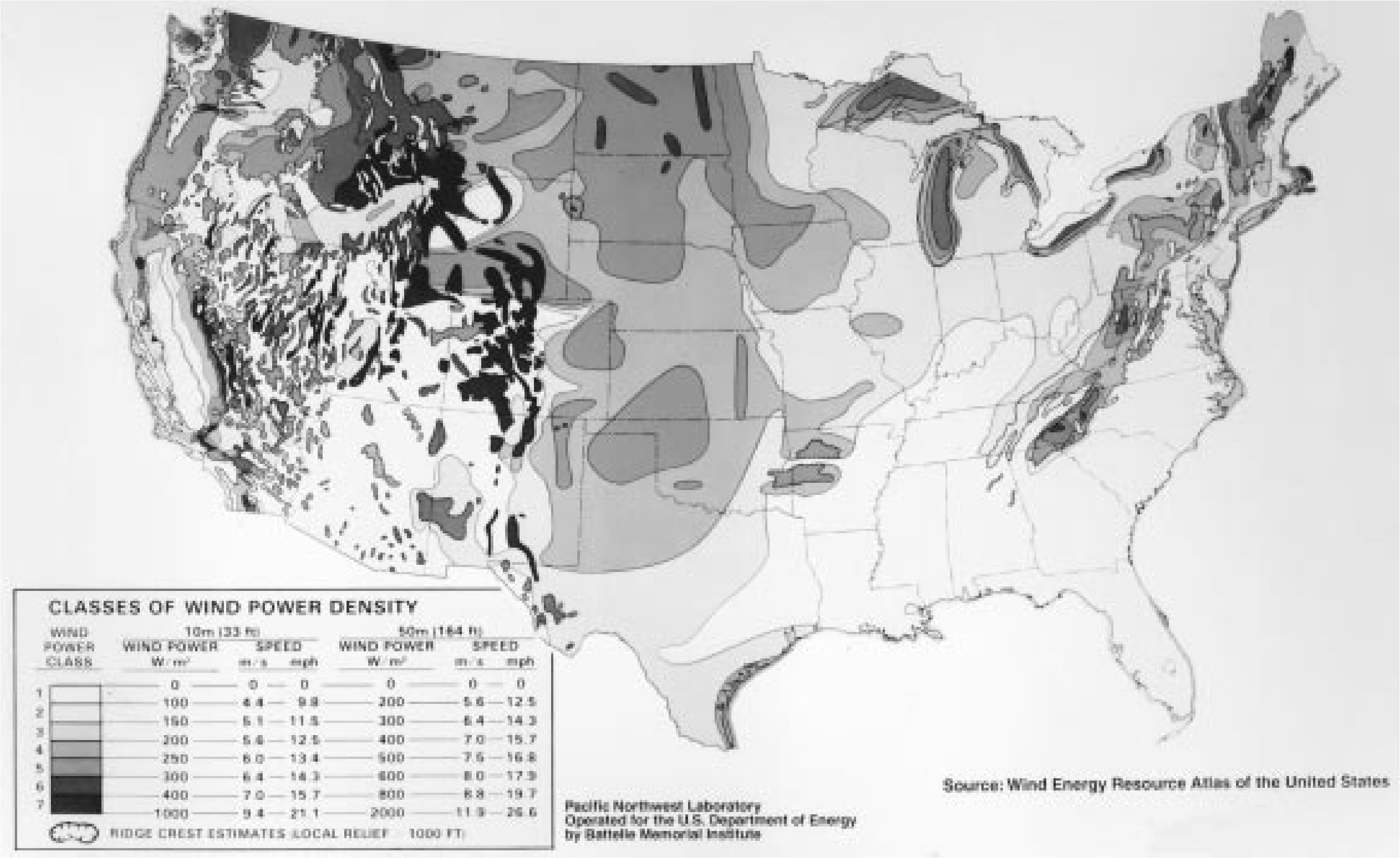


FIGURE 7.7.2 Map of world-wide wind energy resources. (Courtesy of Pacific Northwest Laboratory, Richmond, Washington.)



CLASSES OF WIND POWER DENSITY

WIND POWER CLASS	10m (33 ft) WIND POWER W/m²	10m (33 ft) SPEED m/s	10m (33 ft) SPEED mph	50m (164 ft) WIND POWER W/m²	50m (164 ft) SPEED m/s	50m (164 ft) SPEED mph
1	0	0	0	0	0	0
2	100	4.4	9.8	200	5.6	12.5
3	150	5.1	11.5	300	6.4	14.3
4	200	5.6	12.5	400	7.0	15.7
5	250	6.0	13.4	500	7.5	16.8
6	300	6.4	14.3	600	8.0	17.9
7	400	7.0	15.7	800	8.8	19.7
	1000	9.4	21.1	2000	11.9	26.6

RIDGE CREST ESTIMATES (LOCAL RELIEF > 1000 FT)

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

Source: Wind Energy Resource Atlas of the United States

FIGURE 7.7.3 Map of United States wind energy resources. Reproduced from Elliott, Barchet, Foote, and Sandusky, 1987. *Wind Energy Resource Atlas of the United States*. (Courtesy of Pacific Northwest Laboratory, Richmond, Washington.

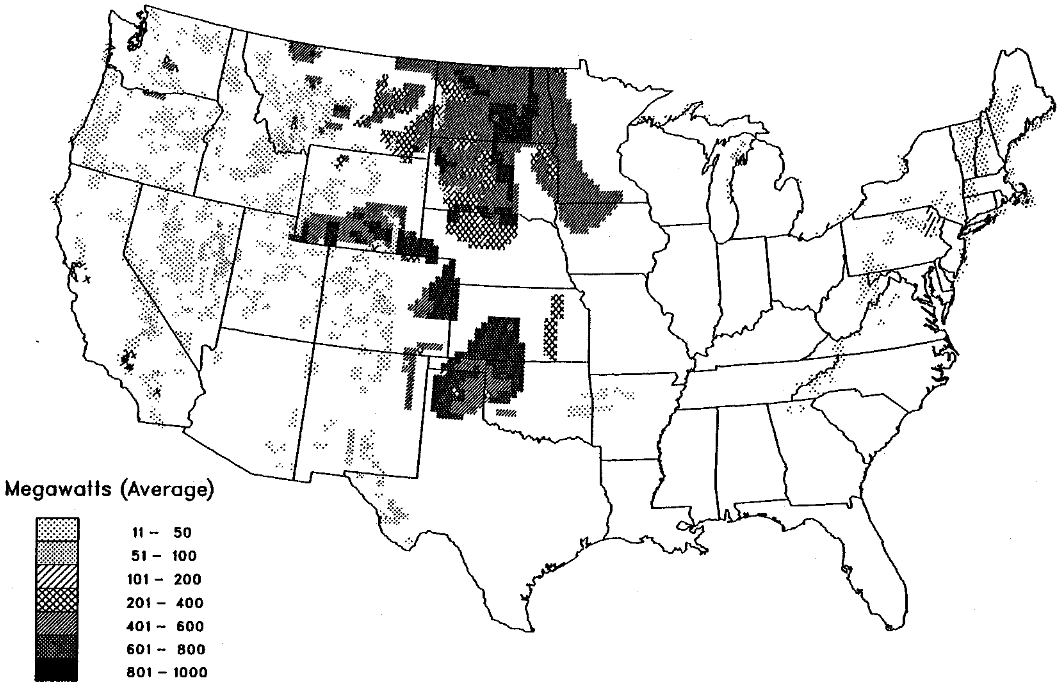


FIGURE 7.7.4 Map of United States wind electric potential. Reproduced from Schwartz, Elliott, and Gower, 1992. *Gridded State Maps of Wind Electric Potential*. (Courtesy of Pacific Northwest Laboratory, Richmond, Washington.)

TABLE 7.7.1 Estimates of Class 4 Wind Land Area and Wind Energy Potential

State	Average Power, MW	Windy Land, km^2
North Dakota	108,000	98,000
South Dakota	70,900	66,500
Wyoming	49,800	39,600
Montana	48,400	42,800
Minnesota	44,800	42,100
Kansas	35,700	33,600
Texas	28,900	27,100
Oklahoma	27,200	25,500
Colorado	26,400	24,300
Nebraska	22,200	20,900
Iowa	15,800	14,900
New Mexico	5,200	4,600
National	512,300	464,200

Note: The top 12 states and total for 48 contiguous states. Wind resource class 4 and above, for a 30-m hub height.

population centers where the electricity demand is highest, and is not always available when the demand is great, it will probably never supply more than 15 to 20% of the U.S. electricity needs.

Similar assessments may be performed for any country of interest. The PNL scientists have recently performed a similar assessment of the available long-term wind data for Mexico and have estimated the wind resource there (Schwartz and Elliott, 1995), as shown in Figure 7.7.5. While wind resources in class 2 are too low to be economic for grid-connected wind power, they are useful for rural power applications. Scientists at Denmark's Risø National Laboratory have done similar work in Europe,

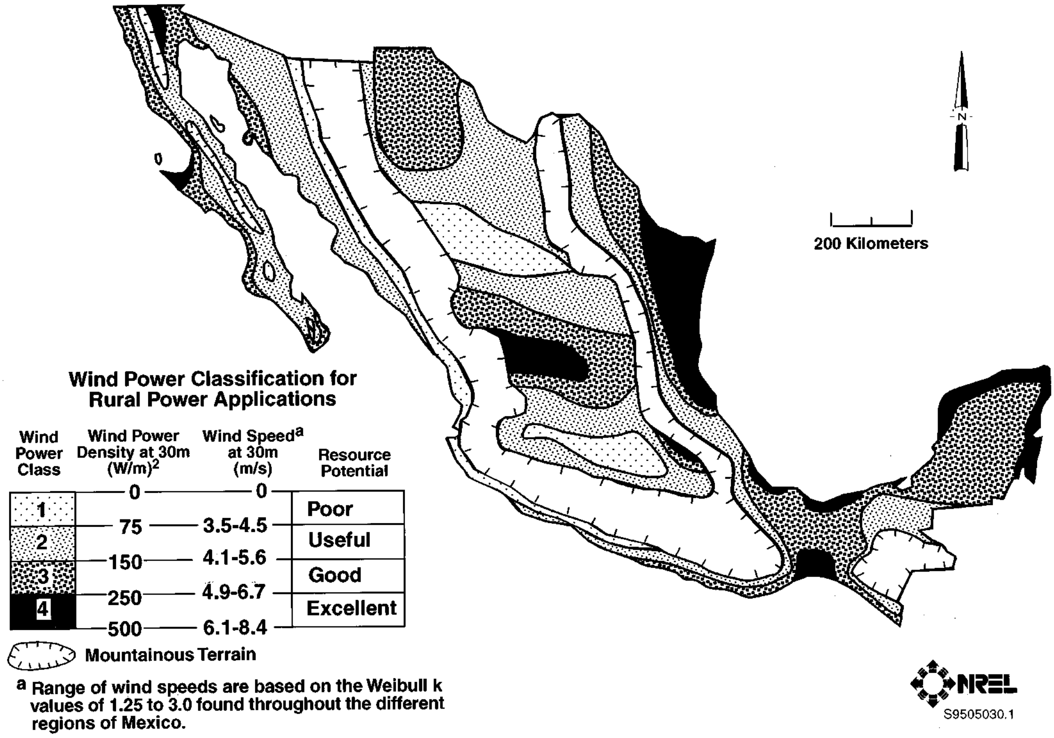


FIGURE 7.7.5 Map of Mexican remote application wind energy resources. Reproduced from Schwartz and Elliott, 1995. *Mexico Wind Resource Assessment Project.* (Courtesy of National Renewable Energy Laboratory, Golden, Colorado.)

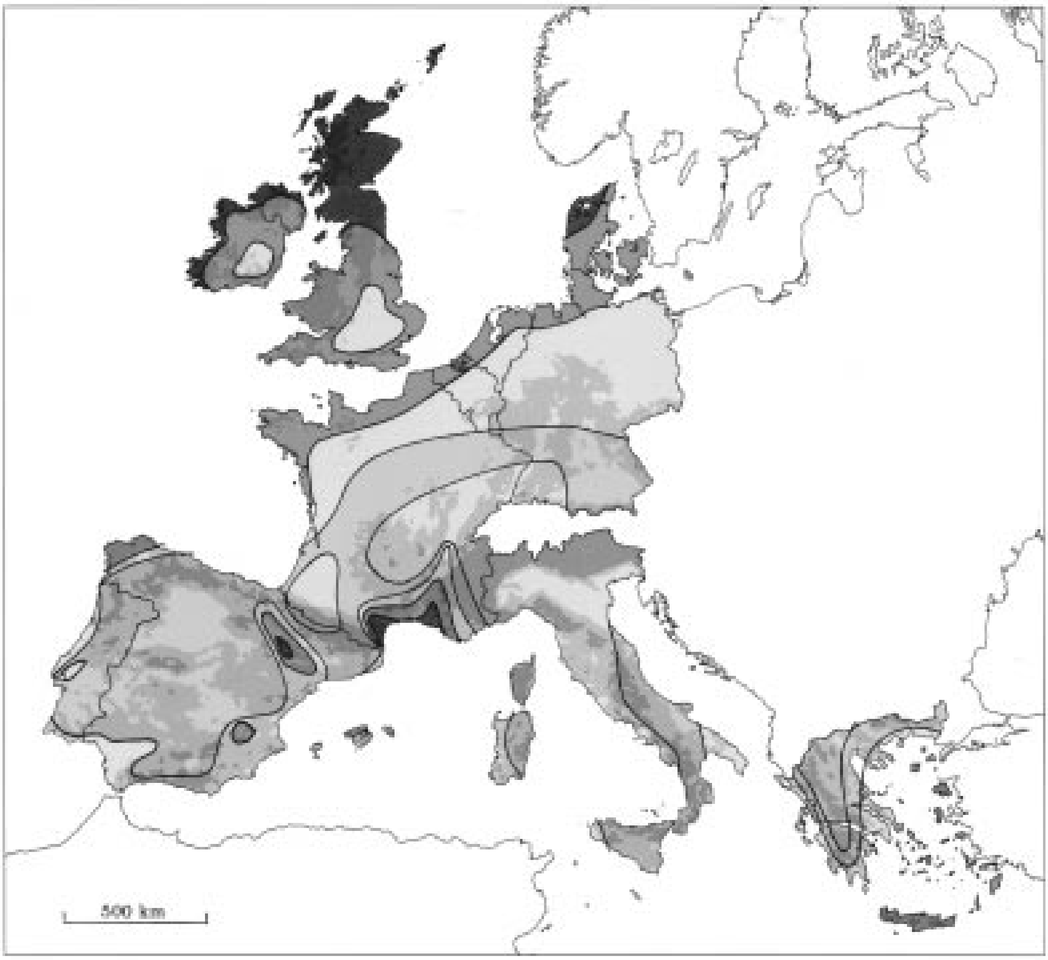
producing a *European Wind Atlas* (Troen and Petersen, 1989) that examines the wind resources of the European Community countries and summarizes the resource available at a 50 m height above smooth, flat terrain, with no obstacles. These results are presented in Figure 7.7.6. Finland, Sweden, Algeria, and Jordan have produced similar reports, and atlases for Poland, Canada, Egypt, Syria, and Turkey are currently in preparation. Resource maps for several other countries may be found in Rohatgi and Nelson (1994).

Existing meteorological station data, in general, significantly underestimate the wind energy resources because of lack of maintenance of wind sensors, poor locations at which they are placed, and cursory methods used in analyzing these data. Assessments such as these only identify the wind energy resource or potential on a very coarse grid. The actual wind resources in any specific area can vary dramatically from those estimates and must be determined with site-specific measurements. Even areas with a very low large-scale resource may contain small areas with a very high resources.

Site Analysis and Selection

Biological Indicators

Many different methods may be used to identify areas of high wind resource. Persistent winds can cause plant deformation, and careful observation of these plants can be used to compare candidate sites and, in at least some cases, to estimate the average wind speed. The Griggs-Putnam index, shown in Figure 7.7.7 and explained in Hewson, Wade, and Baker (1979), is an example of a genus-specific correlation of tree deformation with wind speed. It should be noted that although wind-flagged trees (i.e., trees with branches bent away from a prevailing wind) may indicate that the annual average wind speed is quite strong, unflagged trees do not necessarily indicate that the winds are light. Unflagged trees may be



Wind resources[1] at 50 metres above ground level for five different topographic conditions

	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m\,s^{-1}$	$W m^{-2}$	$m\,s^{-1}$	$W m^{-2}$	$m\,s^{-1}$	$W m^{-2}$	$m\,s^{-1}$	$W m^{-2}$	$m\,s^{-1}$	$W m^{-2}$
█	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
▓	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
▒	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
░	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
□	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

1. The resources refer to the power present in the wind. A wind turbine can utilize between 20 and 30% of the available resource. The resources are calculated for an air density of 1.23 kg m^{-3}, corresponding to standard sea level pressure and a temperature of 15°C. Air density decreases with height but up to 1000 m a.s.l. the resulting reduction of the power densities is less than 10%.
2. Urban districts, forest and farm land with many windbreaks (roughness class 3).
3. Open landscapes with few windbreaks (roughness class 1). In general, the most favourable inland sites on level land are found here.
4. The classes pertain to a straight coastline, a uniform wind rose and a land surface with few windbreaks (roughness class 1). Resources will be higher, and closer to open sea values, if winds from the sea occur more frequently, i.e. the wind rose is not uniform and/or the land protrudes into the sea. Conversely, resources will generally be smaller, and closer to land values, if winds from land occur more frequently.
5. More than 10 km offshore (roughness class 0).
6. The classes correspond to 50% overspeeding and were calculated for a site on the summit of a single axisymmetric hill with a height of 400 metres and a base diameter of 4 km. The overspeeding depends on the height, length and specific setting of the hill.

FIGURE 7.7.6 Map of European wind energy resources. Reproduced from Troen and Petersen, 1989. *European Wind Atlas.* (Courtesy of Rise National Laboratory, Roskilde, Denmark.

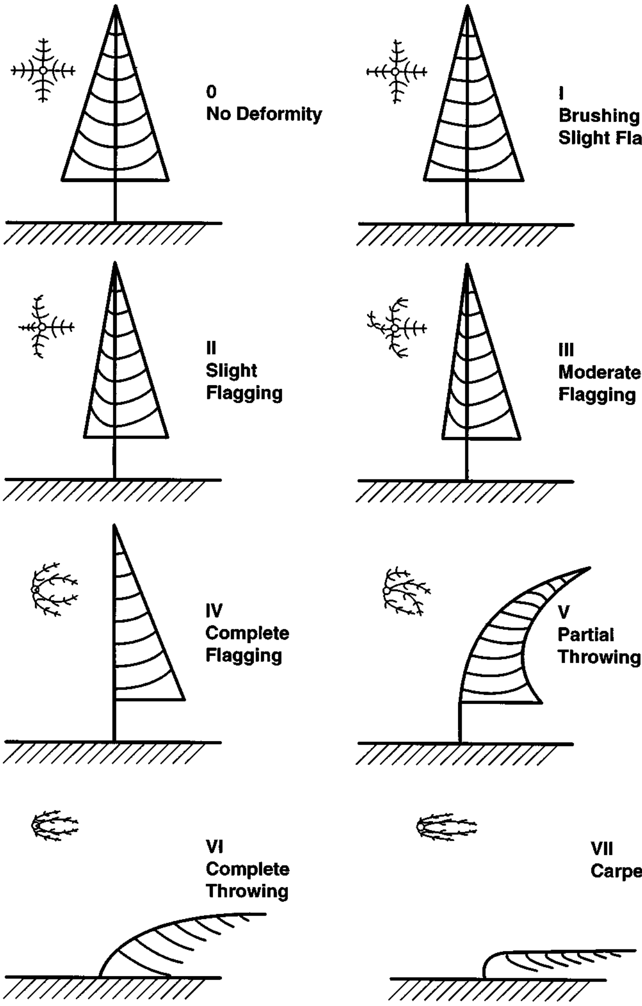


FIGURE 7.7.7 The Griggs-Putnam index of wind-induced tree deformation..

exposed to strong winds from all directions, with insufficient persistence in any one direction to cause flagging.

Effects of Topography

The effects of surrounding terrain on the wind speed at a specific site can be significant. If the proposed site is flat, the terrain texture is the area of most concern. The rougher the terrain, the more the wind flowing over it is retarded near the surface. Flat terrain, such as a large area of flat, open grassland, is the simplest type of terrain for selecting a turbine site. If there are no nearby obstacles (i.e., buildings, trees, or hills), the wind speed at a given height is nearly the same over the entire area, and the best way to increase the available power is to raise the rotor higher above the ground to take advantage of positive wind shear.

Siting turbines on elevated terrain such as hills, ridges, and cliffs takes advantage of the generally higher wind speed at increased altitudes. It may also help keep the turbine exposed to the winds above the calm, cool air that frequently accumulates in valleys and lowlands at night. In some cases, the elevated terrain may cause an acceleration of the wind and thus further improve the resource available to the turbine (see Figure 7.7.8). Depressions include such terrain features as valleys, basins, gorges, and passes. If the depressions channel the wind flow, they may provide good turbine sites. However, the power is

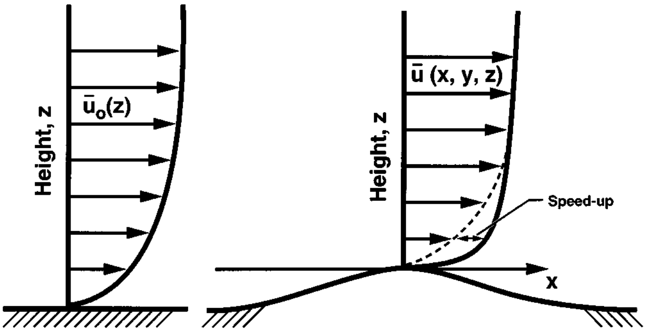


FIGURE 7.7.8 Effect of wind flow over a hill.

more likely to vary by time-of-day or by season than it is for elevated terrain. The impact of terrain on the wind resource and the best places to site turbines for various types of terrain are discussed by Wegley, et al. (1980).

Wind Speed Measurements

The amount of wind energy that can be captured at a site depends on the characteristics of the wind speed at that site. Wind characteristics (speed, direction, distribution, and shear) can vary widely over fairly short distances in either the horizontal or vertical direction. Therefore, in order to predict the energy capture of a turbine with the greatest possible accuracy, wind measurements at the precise site where the turbine will be located are needed. If the rotor, is relatively small, measurements at the hub height (or middle of the rotor) will suffice; for larger rotors, simultaneous measurements at several heights will be required to model the wind speed variation across the rotor disk.

Complete characterization of the wind resource at a specific site is a very time-consuming and expensive effort. A comprehensive site characterization normally requires measuring the wind for at least 12 months, according to Wegley et al. (1980). Even after acquiring the data, questions remain. Long-term data from the nearest airport or long-term weather recording station can help determine whether or not this was a normal wind year for the site and whether the winds were higher or lower than the long-term average (Gipe, 1993). If the costs and time requirements for on-site measurement are excessive, Wegley et al. (1980) and Gipe (1993) give suggestions on methods of using available data from nearby sites, together with a minimum of on-site data to estimate site wind speed.

In the absence of actual site data a Rayleigh distribution (Equation 7.7.3) for the proper yearly average wind speed may be used to estimate the site wind speed distribution. Wind resource estimates that are made with these approximations to the site wind speed and wind distribution will contain significantly larger errors than would be found if the measured site characteristics were used. Figure 7.7.9 illustrates the discrepancies between the measured wind speed distributions at the Amarillo, TX airport and a Bushland, TX test site 20 miles away, and a Rayleigh distribution for the same average wind speed. The measured distribution at the airport has far more energy in the 9 to 12 m/sec range, and this will yield far more energy production than that estimated with the Rayleigh distribution.

Wind Energy Capture Potential

With a wind speed distribution and a turbine power curve (power generated as a function of wind speed) properly adjusted for the local air density, the wind energy potential, or gross annual energy production for a specific site, can be estimated as:

$$\text{Energy} = 8760 \sum_{i=1}^{n} f(U_i) \cdot \Delta U_i \cdot P(U_i) \tag{7.7.4}$$

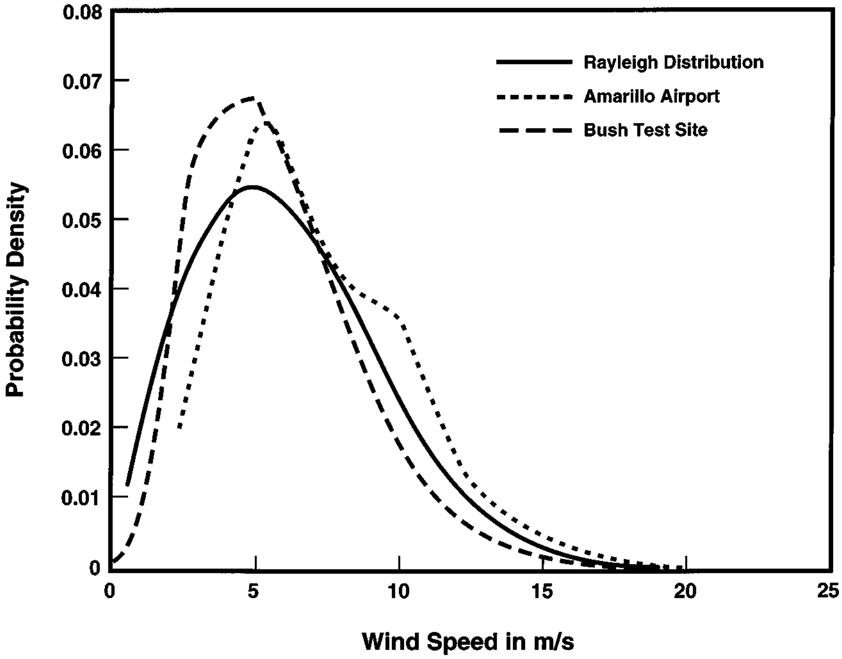


FIGURE 7.7.9 Rayleigh and measured wind frequency distributions.

where 8760 is the number of hours in a year, n is the number of wind speeds considered, $f(U_i) \cdot \Delta U_i$ is the probability of a given wind speed occurring, and $P(U_i)$ is the power produced by the turbine at wind speed U_i. If the measured wind speed distribution is used, replace $f(U_i) \cdot \Delta U_i$ by the probability for the appropriate wind speed (the height of the histogram bar for that wind speed times the wind speed increment). If the power curve is for the turbine aerodynamic or rotor power rather than the electrical power, subtract 10% to approximate the losses due to the turbine bearings and drivetrain. To estimate the net annual energy production, or amount of energy actually delivered to the grid by the turbine, subtract an additional 10% to approximate the electrical losses between the turbine and the grid, the control system losses, and the decreased performance due to dirty blades. If the turbine will be operated in an array, subtract another 5% for array-induced losses.

Environmental Impacts

Although wind turbines generate electricity without causing any air pollution or creating any radioactive wastes, they have an impact on the environment. Wind turbines require a lot of land, but most of that land (90% or so) will remain available for other uses such as farming or livestock grazing. Roads must be built to facilitate installation and maintenance of the wind turbines. Turbines generate noise, but newer turbines are much quieter than earlier models. Current industry standards call for characterization of turbine noise production and rate of decay with distance from the turbine as part of the turbine-testing process. In addition, turbines are large structures that will significantly change the landscape where they are installed, creating visual impact pollution. Another environmental issue facing the wind industry is that of bird deaths as a result of collisions with wind turbines. Preliminary studies indicate that the magnitude of the problem is site specific, and avoiding known bird migration corridors and areas of high bird concentrations when siting turbines and using tubular towers to offer fewer bird perch sites will help to minimize bird collisions with new turbine installations.

Defining Terms

Wind energy potential: The total amount of energy that can actually be extracted from the wind, taking into account the efficiency of the wind turbines and the land available for wind turbine siting.

Wind energy resource: The total amount of energy that is present in the wind.

Wind shear: The change in wind velocity with increasing height above the ground.

Wind speed distribution: The frequency of occurrence of each wind speed over the course of a year. This is site specific.

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Further Information

Wind Characteristics — An Analysis for the Generation of Wind Power, by J. S. Rohatti and V. Nelson, Alternative Energy Institute, West Texas A&M University, Canyon, TX, 1994, is an excellent source for additional information on the wind resource. *Wind Turbine Technology, Fundamental Concepts of Wind Turbine Engineering,* D. Spera, editor, ASME Press, New York, 1994, contains a wealth of information on wind energy history and technology, together with extensive reference lists. Resources for European-community countries are given in the *European Wind Atlas*, by I. Troen and E. L. Petersen, Risø National Laboratory, Roskilde, Denmark, 1989.

7.8 Geothermal Energy

Joel L. Renner and Marshall J. Reed

The word *Geothermal* comes from the combination of the Greek words *gê*, meaning Earth, and *thérm*, meaning heat. Quite literally, geothermal energy is the heat of the Earth. Geothermal resources are concentrations of the Earth's heat, or geothermal energy, that can be extracted and used economically now or in the reasonable future. Currently, only concentrations of heat associated with water in permeable rocks can be exploited. Heat, fluid, and permeability are the three necessary components of all exploited geothermal fields. This section of Energy Resources will discuss the mechanisms for concentrating heat near the surface, the types of geothermal systems, and the environmental aspects of geothermal production.

Heat Flow

Temperature within the Earth increases with depth at an average of about 25°C/km. Spatial variations of the thermal energy within the deep crust and mantle of the Earth give rise to concentrations of thermal energy near the surface of the Earth that can be used as an energy resource. Heat is transferred from the deeper portions of the Earth by conduction of heat through rocks, by the movement of hot, deep rock toward the surface, and by deep circulation of water. Most high-temperature geothermal resources are associated with concentrations of heat caused by the movement of magma (melted rock) to near-surface positions where the heat is stored.

In older areas of continents, such as much of North America east of the Rocky Mountains, heat flow is generally 40 to 60 mWm^{-2} (milliwatts per square meter). This heat flow coupled with the thermal conductivity of rock in the upper 4 km of the crust yields subsurface temperatures of 90 to 110°C at 4 km depth in the Eastern United States. Heat flow within the Basin and Range (west of the Rocky Mountains) is generally 70 to 90 mWm^{-2}, and temperatures are generally greater than 110°C at 4 km. There are large variations in the Western United States, with areas of heat flow greater than 100 mWm^{-2} and areas which have generally lower heat flow such as the Cascade and Sierra Nevada Mountains and the West Coast. A more detailed discussion of heat flow in the United States is available in Blackwell et al. (1991).

Types of Geothermal Systems

Geothermal resources are hydrothermal systems containing water in pores and fractures. Most hydrothermal resources contain liquid water, but higher temperatures or lower pressures can create conditions where steam and water or only steam are the continuous phases (White et al., 1971; Truesdell and White, 1973). All commercial geothermal production is expected to be restricted to hydrothermal systems for many years because of the cost of artificial addition of water. Successful, sustainable geothermal energy usage depends on reinjection of the maximum quantity of produced fluid to augment natural recharge of hydrothermal systems.

Other geothermal systems that have been investigated for energy production are (1) geopressured-geothermal systems containing water with somewhat elevated temperatures (above normal gradient) and with pressures well above hydrostatic for their depth; (2) magmatic systems, with temperature from 600 to 1400°C; and (3) hot dry rock geothermal systems, with temperatures from 200 to 350°C, that are subsurface zones with low initial permeability and little water. These types of geothermal systems cannot be used for economic production of energy at this time.

Geothermal Energy Potential

The most recent report (Huttrer, 1995) shows that 6800 MW_e (megawatts electric) of geothermal electric generating capacity is on-line in 21 countries (Table 7.8.1). The expected capacity in the year 2000 is

TABLE 7.8.1 Installed and Projected Geothermal Power Generation Capacity

Country	1995	2000
Argentina	0.67	n/a[b]
Australia	0.17	n/a
China	28.78	81
Costa Rica	55	170
El Salvador	105	165
France	4.2	n/a
Greece[a]	0	n/a
Iceland	49.4	n/a
Indonesia	309.75	1080
Italy	631.7	856
Japan	413.705	600
Kenya	45	n/a
Mexico	753	960
New Zealand	286	440
Nicaragua	35	n/a
Philippines	1227	1978
Portugal (Azores)	5	n/a
Russia	11	110
Thailand	0.3	n/a
Turkey	20.6	125
U.S.	2816.7	3395
Totals	6797.975	9960

[a] Greece has closed its 2.0 MWe Milos pilot plant.

[b] n/a = information not available.

Source: Huttrer, G.W., in *Proceedings of the World Geothermal Congress, 1995*, International Geothermal Association, Auckland, N.Z., 1995, 3–14. With permission.

9960 MW_e. Table 7.8.2 lists the electrical capacity of U.S. geothermal fields. Additional details of the U.S. generating capacity are available in DiPippo (1995) and McClarty and Reed (1992). Geothermal resources also provide energy for agricultural uses, heating, industrial uses, and bathing. Freeston (1995) reports that 27 countries had a total of 8228 MW_t (megawatts thermal) of direct use capacity. The total energy used is estimated to be 105,710 TJ/year (terajoules per year). The thermal energy used by the ten countries using the most geothermal resource for direct use is listed in Table 7.8.3.

The U.S. Geological Survey has prepared assessments of the geothermal resources of the U.S. Muffler(1979) estimated that the identified hydrothermal resource, that part of the **identified accessible base** that could be extracted and utilized at some reasonable future time, is 23,000 MW_e for 30 years. This resource would operate power plants with an aggregate capacity of 23,000 MW_e for 30 years. The undiscovered U.S. resource (inferred from knowledge of Earth science) is estimated to be 95,000 to 150,000 MW_e for 30 years.

Geothermal Applications

In 1991, geothermal electrical production in the United States was 15,738 GWh (gigawatt hours), and the largest in the world (McLarty and Reed, 1992).

Most geothermal fields are water dominated, where liquid water at high temperature, but also under high (hydrostatic) pressure, is the pressure-controlling medium filling the fractured and porous rocks of the reservoir. In water-dominated geothermal systems used for electricity, water comes into the wells from the reservoir, and the pressure decreases as the water moves toward the surface, allowing part of the water to boil. Since the wells produce a mixture of flashed steam and water, a separator is installed

TABLE 7.8.2 U.S. Installed Geothermal Electrical Generating Capacity in MW_e

Rated State/Field	Plant Capacity	Type
California		
Casa Diablo	27	B
Coso	240	2F
East Mesa	37	2F
East Mesa	68.4	B
Honey Lake Valley	2.3	B
Salton Sea	440	2F
The Geysers	1797	S
Hawaii		
Puna	25	H
Nevada		
Beowawe	16	2F
Brady Hot Springs	21	2F
Desert Peak	8.7	2F
Dixie Valley	66	2F
Empire	3.6	B
Soda Lake	16.6	B
Steamboat	35.1	B
Steamboat	14.4	1F
Stillwater	13	B
Wabuska	1.2	B
Utah		
Roosevelt	20	1F
Cove Fort	2	B
Cove Fort	9	S

Note: S = natural dry steam, 1F = single flash, 2F = double flash, B = binary, H = hybrid flash and binary.

TABLE 7.8.3 Geothermal Energy for Direct Use by the Ten Largest Users Worldwide

Country	Flow Rate, kg/sec	Installed Power, MWt	Energy Used, TJ/year
China	8,628	1,915	16,981
France	2,889	599	7,350
Georgia	1,363	245	7,685
Hungary	1,714	340	5,861
Iceland	5,794	1,443	21,158
Italy	1,612	307	3,629
Japan	1,670	319	6,942
New Zealand	353	264	6,614
Russia	1,240	210	2,422
U.S.	3,905	1874	13,890
Total	37,050	8,664	112,441

Source: Freeston, D.H., in *Proceedings of the World Geothermal Congress, 1995*, International Geothermal Association, Auckland, N.Z., 1995, 15–26. With permission.

between the wells and the power plant to separate the two phases. The flashed steam goes into the turbine to drive the generator, and the water is injected back into the reservoir.

Many water-dominated reservoirs below 175°C used for electricity are pumped to prevent the water from boiling as it is circulated through heat exchangers to heat a secondary liquid that then drives a turbine to produce electricity. **Binary geothermal plants** have no emissions because the entire amount of produced geothermal water is injected back into the underground reservoir. The identified reserves of lower-temperature geothermal fluids are many times greater than the reserves of high-temperature fluids, providing an economic incentive to develop more-efficient power plants.

Warm water, at temperatures above 20°C, can be used directly for a host of processes requiring thermal energy. Thermal energy for swimming pools, space heating, and domestic hot water are the most widespread uses, but industrial processes and agricultural drying are growing applications of geothermal use. In 1995, the United States was using over 500 TJ/year of energy from geothermal sources for direct use (Lienau, et al., 1995). The cities of Boise, ID; Elko, NV; Klamath Falls, OR; and San Bernardino and Susanville, CA have geothermal district-heating systems where a number of commercial and residential buildings are connected to distribution pipelines circulating water at 54 to 93°C from the production wells (Rafferty, 1992).

The use of geothermal energy through ground-coupled heat pump technology has almost no impact on the environment and has a beneficial effect in reducing the demand for electricity. Geothermal heat pumps use the reservoir of constant temperature, shallow groundwater and moist soil as the heat source during winter heating and as the heat sink during summer cooling. The energy efficiency of geothermal heat pumps is about 30% better than that of air-coupled heat pumps and 50% better than electric-resistance heating. Depending on climate, advanced geothermal heat pump use in the United States reduces energy consumption and, correspondingly, power-plant emissions by 23 to 44% compared to advanced air-coupled heat pumps, and by 63 to 72% compared with electric-resistance heating and standard air conditioners (L'Ecuyer et al., 1993).

Environmental Constraints

Geothermal energy is one of the cleaner forms of energy now available in commercial quantities. Geothermal energy use avoids the problems of acid rain, and it greatly reduces greenhouse gas emissions and other forms of air pollution. Potentially hazardous elements produced in geothermal brines are removed from the fluid and injected back into the producing reservoir. Land use for geothermal wells, pipelines, and power plants is small compared with land use for other extractive energy sources such as oil, gas, coal, and nuclear. Geothermal development projects often coexist with agricultural land uses, including crop production or grazing. The average geothermal plant occupies only 400 m^2 for the production of each gigawatt hour over 30 years (Flavin and Lenssen, 1991). The low life-cycle land use of geothermal energy is many times less than the energy sources based on mining, such as coal and nuclear, which require enormous areas for the ore and processing before fuel reaches the power plant. Low-temperature applications usually are no more intrusive than a normal water well. Geothermal development will serve the growing need for energy sources with low atmospheric emissions and proven environmental safety.

All known geothermal systems contain aqueous carbon dioxide species in solution, and when a steam phase separates from boiling water, CO_2 is the dominant (over 90% by weight) **noncondensible gas.** In most geothermal systems, noncondensible gases make up less than 5% by weight of the steam phase. Thus, for each megawatt-hour of electricity produced in 1991, the average emission of carbon dioxide by plant type in the United States was 990 kg from coal, 839 kg from petroleum, 540 kg from natural gas, and 0.48 kg from geothermal flashed-steam (Colligan, 1993). Hydrogen sulfide can reach moderate concentrations of up to 2% by weight in the separated steam phase from some geothermal fields.

At The Geysers geothermal field in California, either the Stretford process or the incineration and injection process is used in geothermal power plants to keep H_2S emissions below 1 ppb (part per billion). Use of the Stretford process in many of the power plants at The Geysers results in the production and disposal of about 13,600 kg of sulfur per megawatt of electrical generation per year. Figure 7.8.1, shows a typical system used in the Stretford process at The Geysers (Henderson and Dorighi, 1989).

The incineration process burns the gas removed from the steam to convert H_2S to SO_2, the gases are absorbed in water to form SO_3^{-2} and SO_4^{-2} in solution, and iron chelate is used to form $S_2O_3^{-2}$ (Bedell and Hammond, 1987). Figure 7.8.2 shows an incineration abatement system (Bedell and Hammond, 1987). The major product from the incineration process is a soluble thiosulfate which is injected into the reservoir with the condensed water used for the reservoir pressure-maintenance program. Sulfur emissions for each megawatt-hour of electricity produced in 1991, as SO_2 by plant type in the United

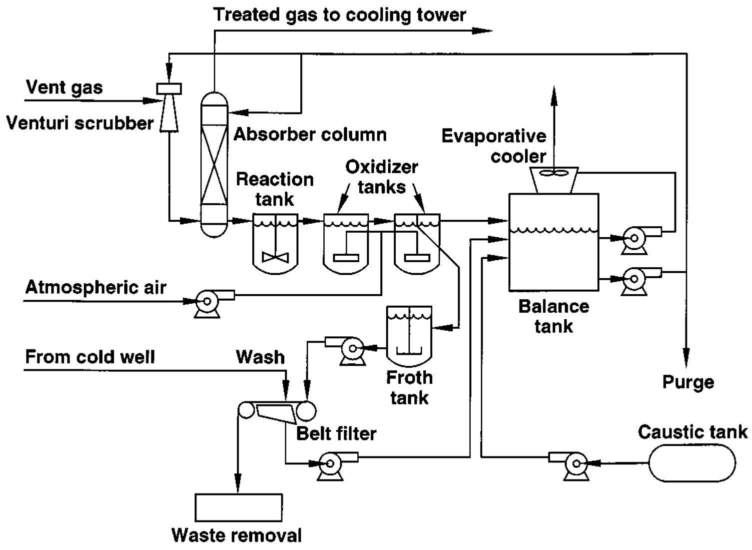

FIGURE 7.8.1 Typical equipment used in the Stretford process for hydrogen sulfide abatement at The Geysers geothermal field. (Based on the diagram of Henderson, J.M. and Dorighi, G.P., *Geotherm. Resour. Counc. Trans.*, 13, 593–595, 1989.)

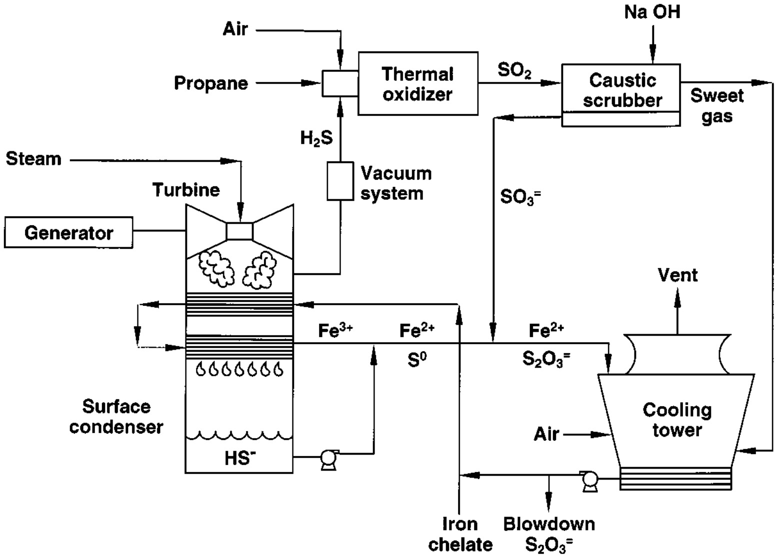

FIGURE 7.8.2 Equipment used in the incineration process for hydrogen sulfide abatement at The Geysers geothermal field. (Based on the diagram of Bedell, S.A. and Hammond, C.A., *Geotherm. Resour. Counc. Bull.*, 16(8), 3–6, 1987.)

States was 9.23 kg from coal, 4.95 kg from petroleum, and 0.03 kg from geothermal flashed-steam (Colligan, 1993). Geothermal power plants have none of the nitrogen oxide emissions that are common from fossil fuel plants.

The waters in geothermal reservoirs range in composition from 0.1 to over 25 wt% dissolved solutes. The geochemistry of several representative geothermal fields is listed in Table 7.8.4. Temperatures up to 380°C have been recorded in geothermal reservoirs in the United States, and many chemical species have a significant solubility at high temperature. For example, all of the geothermal waters are saturated

TABLE 7.8.4 Major Element Chemistry of Representative Geothermal Wells

Field	T(°C)	Na	K	Li	Ca	Mg	Cl	F	Br	SO_4	Total[a] CO_2	Total[a] SiO_2	Total[a] B	Total[a] H_2S
Reykyavik, Iceland	100	95	1.5	<1	0.5	—	31	—	—	16	58	155	0.03	—
Hveragerdi, Iceland	216	212	27	0.3	1.5	0.0	197	1.9	0.45	61	55	480	0.6	7.3
Broadlands, N. Zealand	260	1050	210	1.7	2.2	0.1	1743	7.3	5.7	8	128	805	48.2	<1
Wairekai, New Zealand	250	1250	210	13.2	12	0.04	2210	8.4	5.5	28	17	670	28.8	1
Cerro Prieto, Mexico	340	5820	1570	19	280	8	10420		14.1	0	1653	740	12.4	700
Salton Sea, California	340	50400	17500	215	28000	54	155000	15	120	5	7100	400	390	16
Roosevelt, Utah[b]	<250	2320	461	25.3	8	<2	3860	6.8	—	72	232	563	—	—

[a] Total CO_2, Sio_2 etc. is the total CO_2 + $HCO_2^- + CO_3^{2-}$ expressed as CO_2, silica + silicate as SIO_2, etc.

[b] From Wright (1991); remainder of data from Ellis and Mahon (1977).

in silica with respect to quartz. As the water is produced, silica becomes supersaturated, and, if steam is flashed, the silica becomes highly supersaturated. Upon cooling, amorphous silica precipitates from the supersaturated solution. The high flow rates of steam and water from geothermal wells usually prevent silica from precipitating in the wells, but careful control of fluid conditions and residence time is needed to prevent precipitation in surface equipment. Silica precipitation is delayed in the flow stream until the water reaches a crystallizer or settling pond. There the silica is allowed to settle from the water, and the water is then pumped to an injection well.

Operating Conditions

For electrical generation, typical geothermal wells in the United States have production casing pipe in the reservoir with an inside diameter of 29.5 cm, and flow rates usually range between 150,000 and 350,000 kg/hr of total fluid (Mefferd, 1991). The geothermal fields contain water, or water and steam, in the reservoir, and production rates depend on the amount of boiling in the reservoir and the well on the way to the surface. The Geysers geothermal field in California has only steam filling fractures in the reservoir, and, in 1987 (approximately 30 years after production began), the average well flow had decreased to 33,000 kg/hr of dry steam (Mefferd, 1991) supplying the maximum field output of 2000 MW_2. Continued pressure decline has decreased the production.

In the Coso geothermal field near Ridgecrest, CA initial reservoir conditions formed a steam cap at 400 to 500 m depth, a two-phase (steam and water) zone at intermediate depth, and a liquid water zone at greater depth. Enthalpy of the fluid produced from individual wells ranges from 840 to 2760 kJ/kg (Hirtz et al., 1993), reservoir temperatures range from 200 to 340°C, and the fluid composition flowing from the reservoir into the different wells ranges from 100% liquid to almost 100% steam. Production wells have a wide range of flow rates, but the average production flow rate is 135,000 kg/hr (Mefferd, 1991). Much of the produced fluid is evaporated to the atmosphere in the cooling towers of the power plant, and only about 65% of the produced mass is available for injection into the reservoir at an average rate of 321,000 kg/hr (Mefferd, 1991).

The Salton Sea geothermal system in the Imperial Valley of southern California has presented some of the most difficult problems in brine handling. Water is produced from the reservoir at temperatures between 300 and 350°C and total dissolved solid concentrations between 20 and 25% by weight at an average rate of 270,000 kg/hr (Mefferd, 1991). When up to 20% of the mass of brine boils during production, the salts are concentrated in the brine causing supersaturation with respect to several solid phases. Crystallizers and clarifier and thickener tanks are needed to remove solids from the injection water. Figure 7.8.3 shows the flow stream for removal of solids from the vapor and brine (Signorotti and Hunter, 1992). Other power plants use the addition of acid to lower the pH and keep the solutes in solution (Signorotti and Hunter, 1992). The output from the crystallizers and clarifiers is a slurry of brine and amorphous silica. The methods used to dewater the salt and silica slurry from operations in the Salton Sea geothermal system are described by Benesi (1992). Approximately 80% of the produced water is injected into the reservoir at an average rate of 310,000 kg/hr.

Acknowledgments

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Defining Terms

Binary geothermal plant: A geothermal electric generating plant that uses the geothermal fluid to heat a secondary fluid that is then expanded through a turbine.

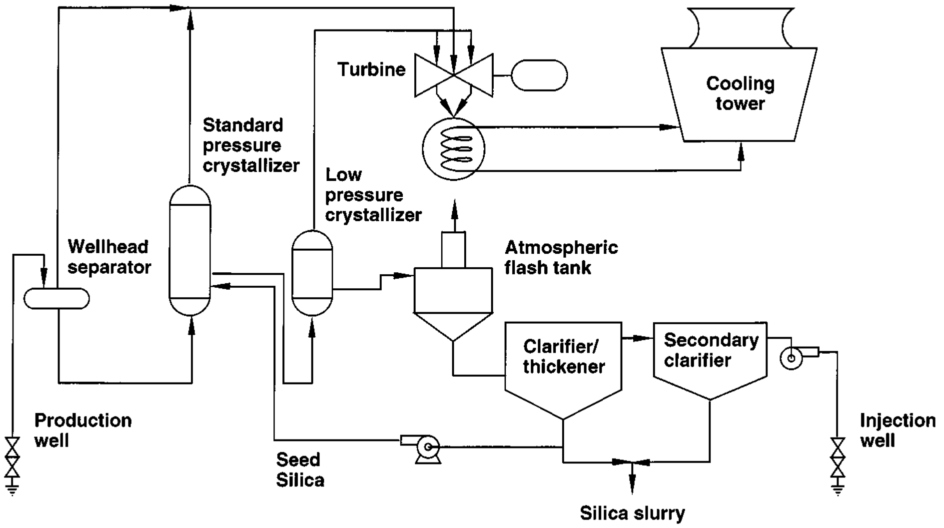

FIGURE 7.8.3 The flow stream for removal of solids from the vapor and brine in typical power plants in the Salton Sea geothermal field. (Modified from the diagram of Signorotti, V. and Hunter, C.C., *Geotherm. Resour. Counc. Bull.*, 21(9), 277–288, 1992).

Identified accessible base: That part of the thermal energy of the Earth that is shallow enough to be reached by production drilling in the foreseeable future. *Identifed* refers to concentrations of heat that have been characterized by drilling or Earth science evidence. Additional discussion of this and other resource terms can be found in Muffler (1979).

Noncondensible gases: Gases exhausted from the turbine into the condenser that do not condense into the liquid phase.

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Further Information

Geothermal education materials are available from the Geothermal Education Office, 664 Hilary Drive, Tiburon, CA 94920.

General coverage of geothermal resources can be found in the proceedings of the Geothermal Resources Council's annual technical conference, *Geothermal Resources Council Transactions,* and in the Council's *Geothermal Resources Council Bulletin,* both of which are available from the Geothermal Resources Council, P.O. Box 1350, Davis, CA 95617–1350.

Current information concerning direct use of geothermal resources is available from the Geo-Heat Center, Oregon Institute of Technology, Klamath Falls, OR 97601.

A significant amount of geothermal information is also available on a number of geothermal home pages that can be found by searching on "geothermal" through the Internet.