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ENERGY RESOURCES OF ARIZONA

Prepared in cooperation with the Energy Office of the Arizona Department of Commerce

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PREFACE

Arizona's population has increased tremendously since 1945 and is projected to continue this trend well into the 21st century. Demands on land, water, mineral, and energy resources have risen accordingly. Energy resources are important to Arizona for several reasons. Every person depends on reliable sources of energy to fill the needs of daily life, from driving to work to cooking dinner to reading the newspaper by lamp light. Revenues generated by the sale of energy benefit the State's economy. Energy production provides employment for many persons, including those in planning, exploration, mining, processing, transportation, reclamation, and management. The sale of needed equipment and supplies also stimulates employment and economic growth.

This publication describes Arizona's renewable and nonrenewable energy resources. Renewable resources result from present-day conditions at the surface of the Earth and are generated, used, and regenerated on a human time scale. Nonrenewable resources were formed by natural geologic processes millions or even hundreds of millions of years ago. These processes created the geologic foundation of this region and its contained mineral and energy resources, without regard for modern political boundaries. Some of the energy used by Arizonans is obtained from sources in state. Arizona does, however, have energy "roots" that extend beneath other states and nations. The energy "roots" of some states and nations, in turn, extend beneath Arizona.

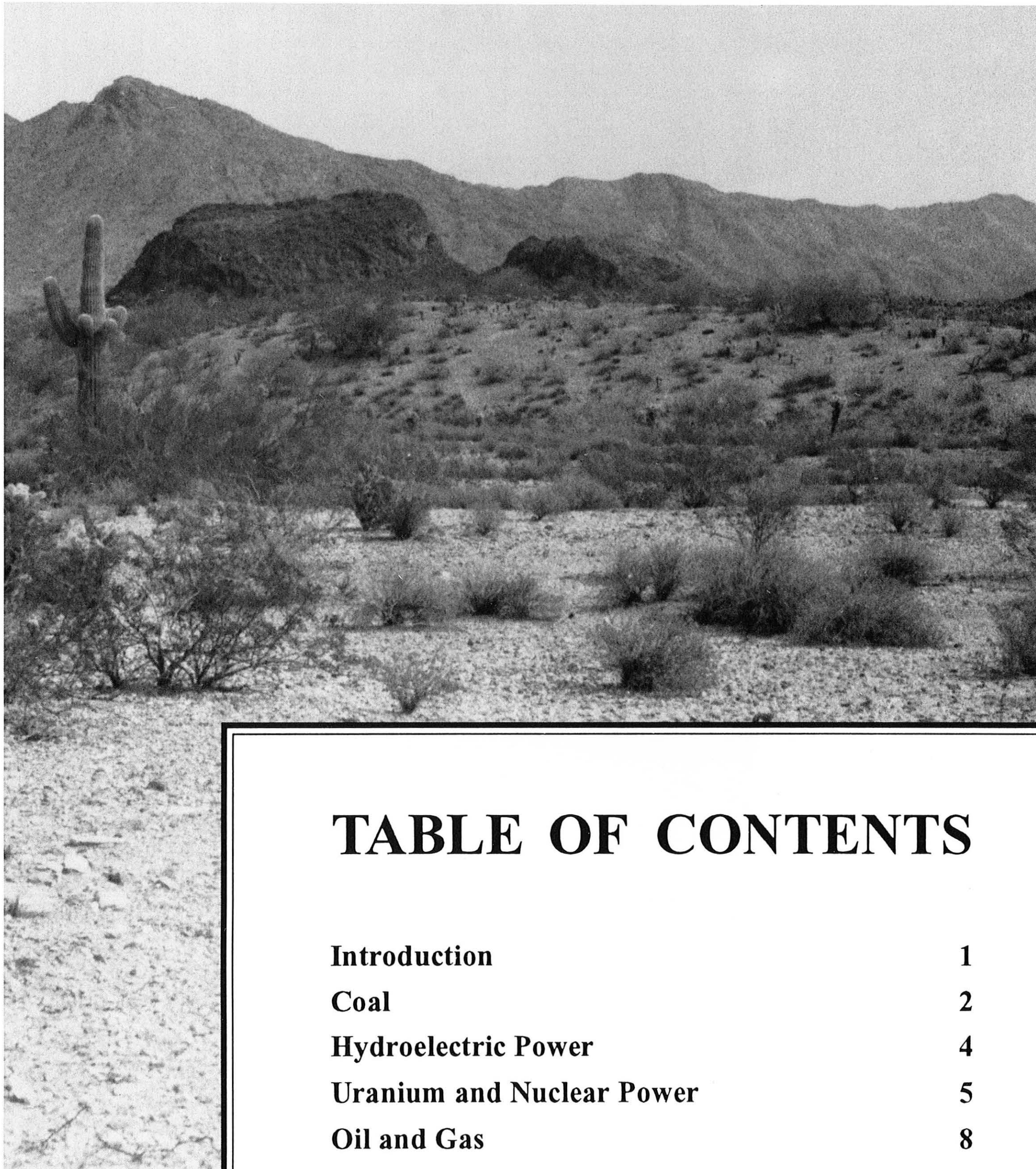
The Arizona Geological Survey (AZGS) is a primary source of geologic information and data, derived from scientific investigations, about the geologic framework, mineral and energy resources, natural hazards, and natural limitations to the use of Arizona's land and resources. AZGS staff members provide data and assistance to help government agencies, industry, and the interested public make informed land- and resource-management decisions.

This is the first in a series that the AZGS established to address geologic concepts and perspectives in a "down-to-earth" manner, that is, through the use of relatively few technical terms. This report and the accompanying map are the result of a cooperative project between the AZGS and the Energy Office of the Arizona Department of Commerce.

Larry D. Fellows
Director and State Geologist

ACKNOWLEDGMENTS

The authors wish to thank Dr. Daniel J. Brennan of the Arizona Oil and Gas Conservation Commission for his review and valuable contributions to the chapter on oil and gas. The chapters on solar, wind, and biomass energy benefited from contributions from the staff of the Energy Office of the Arizona Department of Commerce. We especially thank Mark Ginsberg, who approved this cooperative project, and Jerry Dion, who found the money to support it. Other persons, corporations, and government agencies, too numerous to mention, provided valuable information that was incorporated into this report and the accompanying map. We also gratefully acknowledge the staff members of the Arizona Geological Survey who prepared this manuscript for publication: Evelyn VandenDolder, who edited the text; Sherry Garner, who designed the cover and text layout; and Pete Corrao, who drafted the figures and map and prepared the map for publication.


John Field

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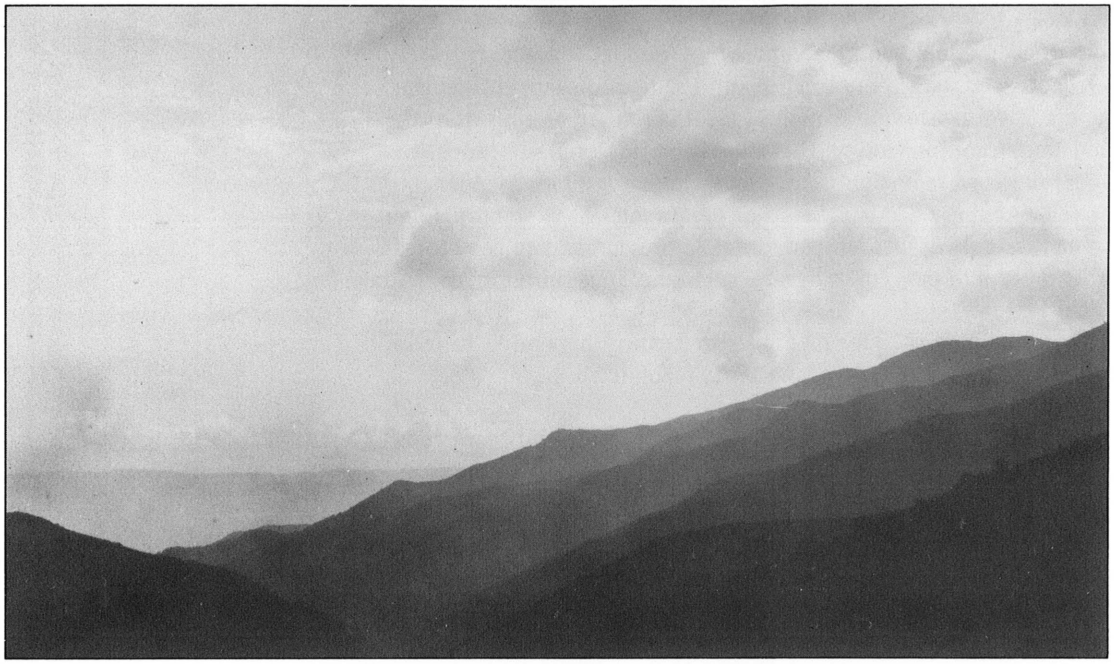

INTRODUCTION

This report is a nontechnical summary of the energy resources of Arizona intended to accompany the *Energy Resources Map of Arizona*. Arizona is endowed with a variety of energy resources and potential resources; each is given its own chapter in this report. Chapters are arranged according to the relative importance of each resource to the State, with the most important described first. Coal is discussed first; the next three chapters address hydroelectric power, uranium, and petroleum, the other important traditional energy resources. Geothermal, solar, wind, and biomass energy, usually considered ''alternative'' energy resources, are treated in the last four chapters of this report. They have considerable development potential, but as of 1991 have not been exploited on a significant scale.

Each chapter includes an introduction that defines and briefly describes the nature of the resource. Subsequent sections outline the locations, geologic settings, and size or importance of the resource in Arizona, as well as the extent of development, markets and uses, and potential for future development. The important energy production, processing, and transportation facilities identified on the *Energy Resources Map of Arizona* are also briefly discussed.

This report is intentionally brief and general in its treatment of the subject of Arizona's energy resources. For readers interested in pursuing any topic in greater detail, a list of selected references, which provide more specific and technical information, is included at the end of each chapter. Separate chapters at the end of the report contain lists of government agencies with energy-related responsibilities, along with brief descriptions of their specific functions.

John T. Duncan and Frank P. Mancini

COAL

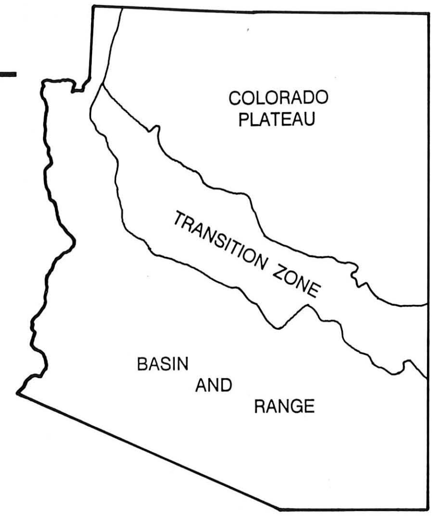

Figure 1. Physiographic provinces of Arizona.

GEOLOGY

Coal is a rock predominantly composed of organic carbon (possibly exceeding 98 percent), with some oxygen (up to about 30 percent), sulfur, hydrogen, and a few other minor elements. Coal is formed as a result of the accumulation, burial, compaction, and heating of plant material. The ancestors of today's coal fields were ancient swamps that supported large volumes of plants and trees. As these accumulations of plant material were buried and subjected to increasingly higher temperatures and pressures, they were transformed sequentially into peat, then lignite, subbituminous, bituminous, and anthracite coal.

Peat is not coal, but is used for fuel in some parts of the world. **Lignite**, the lowest rank of coal, is soft, brown, and easily recognized as plant material. It has the lowest carbon and energy content of the coals. Deeper burial forces more of the volatile elements, such as hydrogen and oxygen, from the plant material and results in higher ranked coals. **Subbituminous** and **bituminous** coal, the moderate ranks that compose the largest coal resources in the United States, satisfy an increasingly important proportion of the Nation's energy needs, particularly for generation of electricity. **Anthracite** is the highest ranked coal. Heat and pressure have baked virtually all volatile elements from the coal, leaving a hard, glassy black rock composed of at least 92 percent carbon. The coal fields of the Appalachian region, which fueled American civilization from the 1700's through the first half of this century and are still very important today, are mostly anthracite.

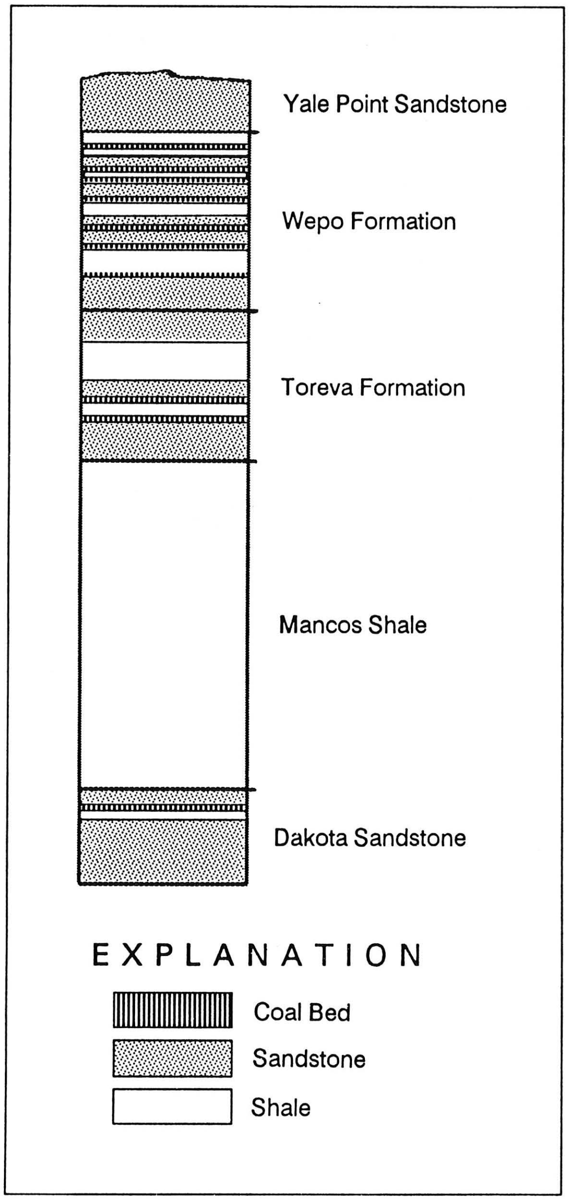

Figure 2. Generalized sequence of the coal-bearing rocks of the Black Mesa field.

RESOURCES

All of Arizona's known coal resources are of bituminous or subbituminous rank. The coal-bearing rocks probably covered much of the State at one time, but erosion has left only scattered remnants, mostly on the Colorado Plateau (**Figure 1**).

The most important coal resources in the State are in the rocks of Black Mesa, located entirely within the Navajo Reservation and the Navajo-Hopi joint-use area in the northeastern corner of Arizona (see the *Energy Resources Map of Arizona* [back pocket], hereafter referred to as **Plate 1**). Three separate rock units on Black Mesa are known to contain relatively thick and continuous coal beds that are considered to be potentially minable resources: the Dakota Sandstone, Toreva Formation, and Wepo Formation (**Figure 2**). The coal in these units composes the Black Mesa coal field.

The Dakota Sandstone, exposed near the base of Black Mesa around most of its perimeter, contains several coal seams up to 9 feet thick, but averaging 2 to 4 feet in thickness. The Toreva Formation, which also contains several coal seams of economic significance, is best exposed in the southeastern part of Black Mesa. The Wepo Formation, the youngest coal-bearing unit on Black Mesa, contains the thickest and purest coal beds. The resource consists of several coal beds that average 4 to 8 feet, but range up to 28 feet, in thickness. Because the Wepo is the uppermost unit of the three, it is also the shallowest and best exposed, especially in the northeastern part of Black Mesa. For these reasons, the Wepo coal

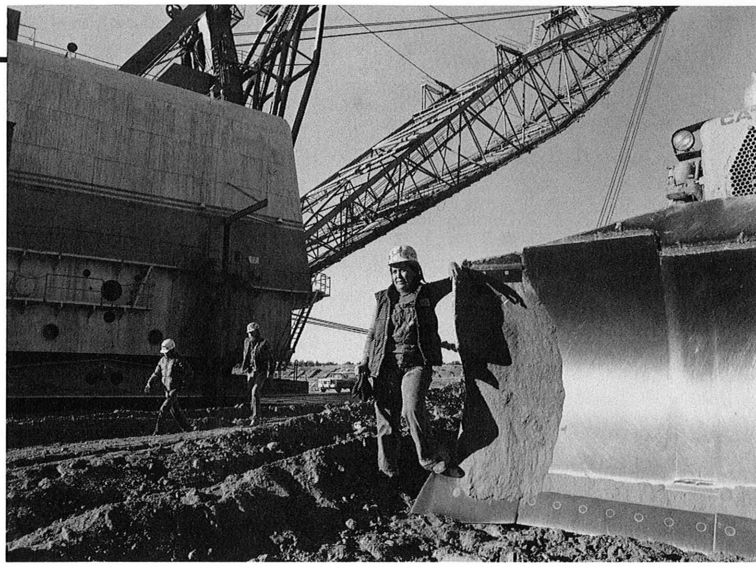

Figure 3. Large dragline and bulldozer used for mining coal at Peabody Coal Company's operations on Black Mesa. The coal is in nearly horizontal layers or beds within the rock. Strip mining involves removing the overlying soil and waste rock (overburden) to expose the coal bed, mining the coal using the dragline, and eventually replacing the overburden and reclaiming the disturbed area.

beds are the most economically significant and the only ones being exploited in Arizona in 1991.

Other named coal fields include the Pinedale field just north of the Mogollon Rim near Pinedale and the Deer Creek field west of Winkelman (**Plate 1**). The Pinedale field is sufficiently extensive and well exposed to generate sporadic exploration interest, but has not been commercially exploited. Coal beds of the Deer Creek field, thin and of poor quality, are not expected to be produced on a commercial scale within the foreseeable future. Rocks that host important coal resources in Utah and New Mexico extend slightly into the far northern and eastern parts of Arizona, but coal resources in these rocks are small and largely unevaluated.

The only coal beds that are known to be minable under present conditions are within the Black Mesa field. Estimates of total coal resources range up to 21 billion tons. Much of this total will probably never be exploited because of unfavorable mining conditions, such as thin or deeply buried seams, but up to 8 billion tons are considered potentially recoverable. Potential reserves of **stripping coal**, coal that is shallower than approximately 130 feet and therefore minable by open-pit methods, are estimated to be 1 billion tons. No reserves have been calculated for the other coal fields in the State.

PRODUCTION HISTORY

The Black Mesa field was first exploited by Native Americans, who mined an estimated 100,000 tons of coal between A.D. 1300 and 1600. No reliable records exist for the early days of European settlement. Several small underground mines, however, operated between 1926 and 1970 and produced an estimated 300,000 tons of coal for local use on the reservation and in towns in nearby areas.

Significant commercial coal production in Arizona began in 1970 with the opening of the first large open-pit (strip) mine by the Peabody Coal Company (**Figure 3**). Peabody now operates two large strip mines, the Black Mesa and Kayenta mines, on the northern part of Black Mesa south of Kayenta (**Figure 4**). These two mines together have the capacity to produce more than 12 million tons of coal per year. This constitutes all of Arizona's commercial coal production, which is between 1 and 2 percent of the Nation's total production.

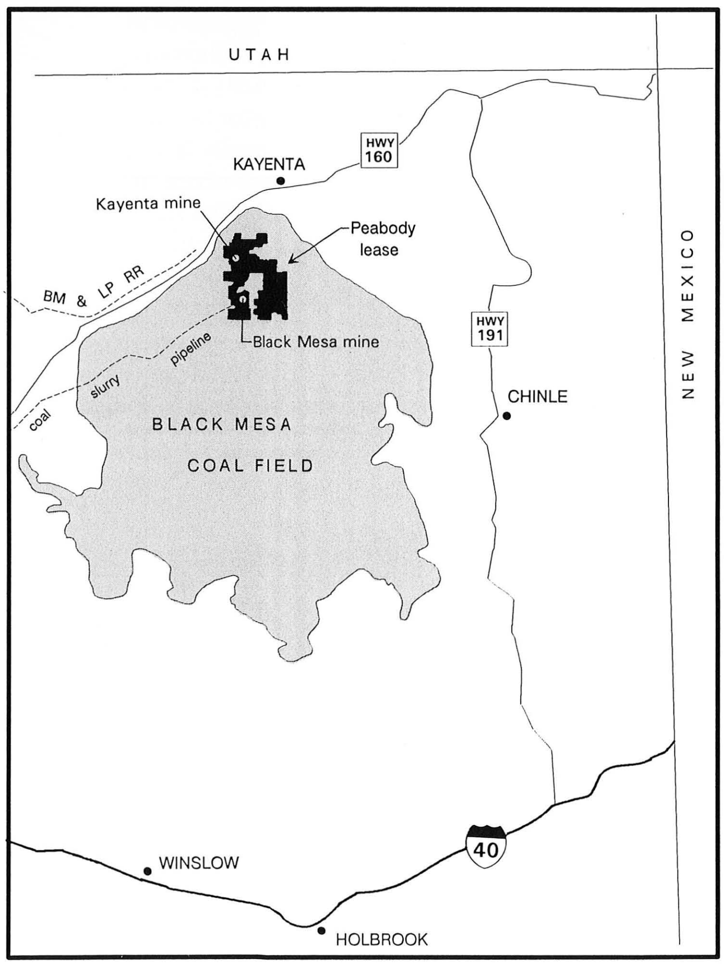

Figure 4. Map of the Black Mesa region showing the coal field and the area under lease to the Peabody Coal Company(black shaded area), as well as production and transportation facilities. BM & LP RR is the Black Mesa and Lake Powell Railroad.

Black Mesa coal is sold by long-term contracts to utility companies for generating electricity. The Black Mesa mine supplies coal via an 18-inch-diameter coal slurry pipeline to the Mojave Power Plant in southern Nevada near Davis Dam. Production from the Kayenta mine goes to the Navajo Generating Station near Page via the Black Mesa and Lake Powell Railroad, a dedicated, electrified coal-haul railway.

DEVELOPMENT POTENTIAL

Coal is Arizona's most important energy resource today and will probably continue to be well into the future. Reserves within Peabody's leaseholdings can sustain the present level of mining for approximately 25 years, and it is highly likely that more reserves will be developed as they are required. The development of minable reserves on other parts of Black Mesa or in other fields is uncertain and largely dependent on future energy prices, but reasonable potential exists in both the Black Mesa and Pinedale fields.

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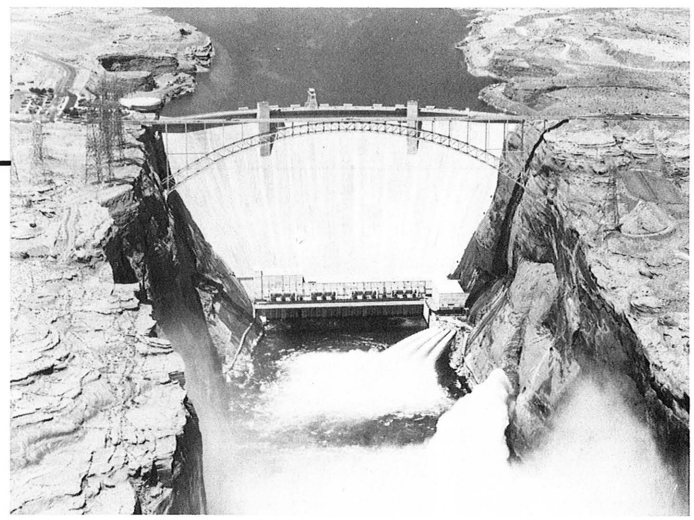
HYDROELECTRIC POWER



U.S. Bureau of Reclamation

Figure 5. *Glen Canyon Dam on the Colorado River near Page, Arizona. The dam, completed in 1963, impounds Lake Powell (visible in background).*

INTRODUCTION

Hydroelectric power is electric power generated by falling water. Because the source of the power is gravity, the factors controlling the amount of electricity that can be generated are the amount of water falling (or flowing) and the vertical distance of the fall (**hydraulic head**). The falling water is used to turn turbines, which are connected to electric generators. Waterfalls and rapids are commonly exploited to generate electricity directly by diverting part of the stream above the falls or rapids, sending the water via large pipes or penstocks to the generating station, and returning the water to the stream below the falls or rapids. Most areas, however, do not have natural waterfalls, so dams are built to develop the hydraulic head necessary to generate electricity.

RESOURCES

The amount of energy potentially available for conversion to hydroelectric power in Arizona is a crude function of the amount of water that flows across the State and the distance that water descends. Although the topography of Arizona is favorable, with a range of elevations from more than 12,000 feet to nearly sea level, very little surface water flows over much of the State.

The primary hydroelectric resource in Arizona is the Colorado River, the largest and most important river in the region. It runs through or along the border of Arizona for more than 500 miles from the Utah State line near Page to southwest of Yuma, where it crosses the international border into Mexico. Between Utah and Mexico, the Colorado River descends more than 3,000 feet. Other important hydroelectric resources include the Salt and Verde Rivers, which flow into the Phoenix area from the east and north, respectively, and the Gila River, which originates in New Mexico and flows through southeastern Arizona. Smaller flowing streams in the State represent minor hydroelectric resources.

GENERATING FACILITIES

The U.S. Bureau of Reclamation constructed and maintains authority over four hydroelectric dams on the Colorado River within Arizona or on its border. Glen Canyon Dam, upstream from the Grand Canyon near Page (**Figure 5**), is wholly within Arizona and has the capacity to generate 1,288 megawatts of electricity (1 megawatt = 1 million watts). Hoover Dam, with 2,074 megawatts of generating capacity, is on the Arizona-Nevada border southeast of Las Vegas. Davis Dam, near Bullhead City on the Arizona-

Nevada line, has 240 megawatts of generating capacity; Parker Dam, on the Arizona-California line north of Parker, has 120 megawatts of capacity (**Plate 1**).

The electric power generated by the Colorado River plants is controlled by the Western Area Power Administration, a division of the U.S. Department of Energy, and distributed between the States in the region. Only a fraction comes into Arizona for local consumption.

The only other important sources of hydroelectric power within the State are the facilities operated by the Salt River Project (SRP) on the Salt River east of Phoenix. The SRP originated as the U.S. Bureau of Reclamation project that built Roosevelt Dam. Now a quasi-governmental State agency, the SRP operates hydroelectric facilities at four dams on the Salt River. These dams have a total generating capacity of 238 megawatts. Two small facilities on Fossil Creek and the Verde River northeast of Phoenix are operated by the Arizona Public Service Company and total 5.6 megawatts in generating capacity.

DEVELOPMENT POTENTIAL

Arizona produces a large amount of hydroelectric power for a State with so little surface water. Only minor untapped potential exists. The stretch of the Colorado River between Lake Mead and the Glen Canyon Dam has the greatest potential; however, because most of this stretch is within Grand Canyon National Park, it is very unlikely that it will ever be developed for hydroelectric power.

Small-scale hydroelectric projects could be developed on many of the smaller streams in Arizona. Total potential capacity of such projects, however, is estimated to be only about 200 megawatts.

The factors that will ultimately determine the extent to which potential hydroelectric resources will be developed are the economic and environmental costs of alternatives. These costs are likely to rise, making hydroelectric power, one of the few completely renewable and clean forms of energy, more attractive.

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URANIUM AND NUCLEAR POWER

INTRODUCTION

Uranium is an element that is valuable because of its ability to produce energy through the natural process of nuclear decay. **Nuclear decay** occurs when atoms of an element are unstable and spontaneously disintegrate, emitting energy and particles in the process. The result of each decay is a new atom, either of an entirely different element, or of a different form, or **isotope,** of the original element. An unstable element that is subject to nuclear decay is said to be **radioactive**.

Naturally occurring uranium exists as two isotopes: one is highly radioactive, but constitutes less than 1 percent of natural uranium; the other is much less radioactive and composes more than 99 percent of natural uranium. The rate of nuclear decay in uranium may be increased by concentrating or enriching the more radioactive isotope. Sufficient enrichment of a sufficient mass of uranium can cause the decay of some atoms to induce the decay of neighboring atoms, creating a nuclear chain reaction. This self-sustaining reaction may be controlled to provide a steady source of heat for the generation of electricity.

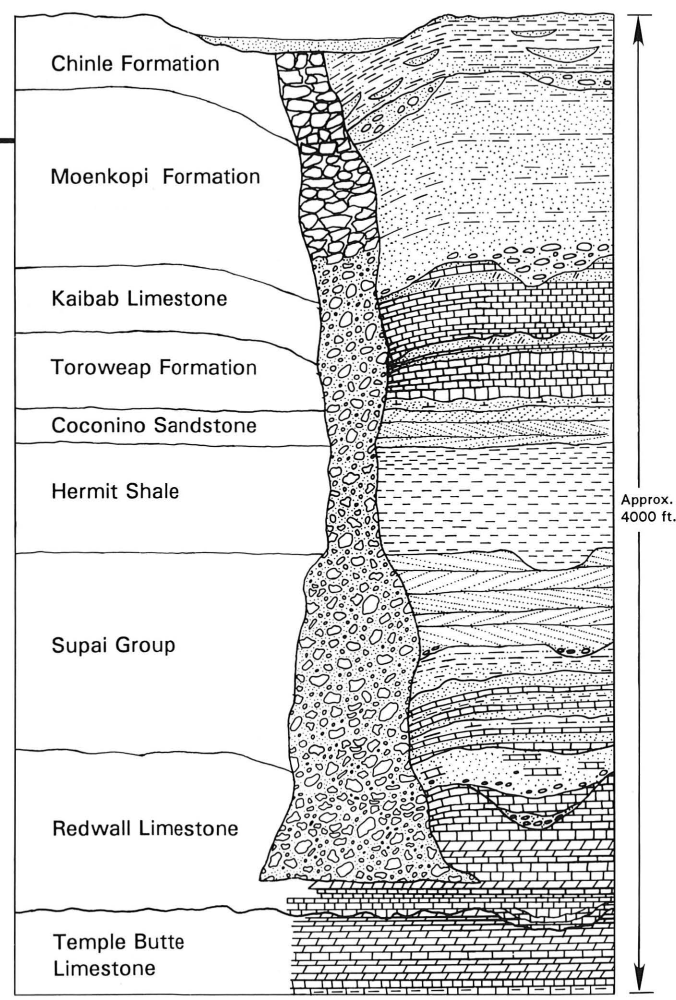

__Figure 6.__ Generalized diagram of a uranium-bearing breccia pipe on the Colorado Plateau. Drawn by K.J. Wenrich and B.S. Van Gosen of the U.S. Geological Survey.

GEOLOGY

The most important uranium ore mineral is **uraninite** (UO_2). Uranium, which is present in small concentrations in most rocks, is easily dissolved by oxygen-rich water, such as rain water. When water containing dissolved uranium encounters conditions that reduce the availability of oxygen, uraninite is precipitated from the solution.

Although there are many types of uranium deposits in Arizona, two have been, and will probably continue to be, the most important: sandstone-hosted deposits and breccia-pipe deposits. Both of these are present exclusively in rocks on the Colorado Plateau.

Sandstone-hosted deposits, common in the northeastern part of the Colorado Plateau (**Plate 1**), are contained in sandstones and conglomerates that fill ancient stream channels cut into the underlying rock. The orebodies are commonly long, narrow, and nearly horizontal, conforming to the patterns of the original stream channels. The uranium itself is commonly associated with carbonaceous material, the remains of ancient plants that were buried and preserved in the stream sediments. These uranium deposits formed from ground water, derived from rain and snow, that leached the element from common uranium-bearing rocks; locally abundant volcanic ash was probably the major source of the uranium. The ground water then flowed preferentially through the buried stream channels because of the high permeability of the stream sands and gravels. (**Permeability** is a measure of the ease with which fluids move through a material.) Much of the oxygen was removed as the migrating ground water reacted with the carbonaceous (plant) material. This chemical change (lower oxygen content) in the water caused the dissolved uranium to be deposited as uraninite.

As a result of similar processes, vanadium is also present in sandstone-hosted deposits. It has been recovered from the uranium ores and has significantly added to their value.

Breccia-pipe deposits in the western part of the Colorado Plateau (**Plate 1**) differ from the sandstone-hosted deposits in form, mineralogy, and host rocks, but probably resulted from similar chemical processes. As their name implies, these deposits are hosted by nearly vertical cylindrical bodies (**pipes**) composed of broken and recemented rock (**breccia**). The breccia pipes were formed as limestone caverns collapsed and were filled by the overlying rocks. In some cases, this process of collapse migrated upward through thousands of feet of overlying rock to form vertical breccia pipes a few hundred feet in diameter and thousands of feet "tall" within the flat-lying sedimentary rocks of the Colorado Plateau (**Figure 6**).

Like the ancient stream channels of the sandstone-hosted deposits, the breccia pipes provided a highly permeable route for the flow of uranium-bearing fluids. Unlike sandstone-hosted deposits, however, the breccia-pipe deposits were formed by moderately hot (200°F to 300°F) water that moved upward through the pipes. The ultimate source of uranium and the paths that the hot (**hydrothermal**) solutions followed before they entered the pipes are not known. The uranium minerals in breccia-pipe deposits are usually accompanied by iron- and copper-sulfide minerals, which were deposited in the breccias before the uranium. The sulfide minerals in the breccia pipes, like the organic materials in the sandstone-hosted deposits, may have reduced the concentration of oxygen in the solutions and caused the deposition of uraninite. Significant uranium deposits are also present in the Basin and Range Province and Transition Zone of Arizona. More than 99 percent of the State's uranium production, however, has come from the Colorado Plateau and the deposit types described above.

PRODUCTION HISTORY

The history of uranium production in Arizona is rather short, because until the middle of the 20th century, uses for uranium were limited. Uranium was known to be present in the sedimentary rocks of the Colorado Plateau in the late 19th century, and minor production occurred in the 1920's. Major production, however, began with the formation of the U.S. Atomic Energy Commission and its initiation of a uranium procurement program in 1947. Between 1947 and 1970, when the buying program was discontinued, approximately 18 million pounds of uranium oxide were produced from Arizona mines. The guaranteed, government-set prices made exploration for and development of uranium reserves profitable in the 1950's and 1960's.

During that period, sandstone-hosted deposits produced the most uranium, the majority of which was used by the Federal government for nuclear research and weapons production. These generally shallow deposits were mined either by open pits or horizontal tunnels that followed the old stream channels. During this time (1956 to 1965), the Rare Metals Mill, which processed the uranium-vanadium ores, operated near Tuba City.

During the 1970's, after the government buying program was discontinued and before the domestic nuclear-generating industry had developed significantly, little uranium was produced in Arizona. Since then, nuclear power has continued to increase in importance worldwide, but large uranium discoveries outside the United States and slower-than-expected growth in the U.S. nuclear power industry have kept uranium prices low and the domestic industry weak. Uranium production, which declined in the Nation through most of the 1980's, continues to fall.

Even though the U.S. uranium industry is depressed, Arizona's breccia-pipe uranium industry is healthy, owing to the high ore grades. As of early 1991, Arizona ranks first in the Nation in uranium production. Before the late 1970's, only one breccia-pipe-hosted deposit in the State had been mined for uranium. Since then, several pipes have been developed and mined, and more are expected to be discovered and developed (**Figure 7**). More than 13 million pounds of uranium oxide were produced from breccia-pipe deposits from 1980 to 1988. This represents more than two-thirds of Arizona's total production during the boom years of 1947 to

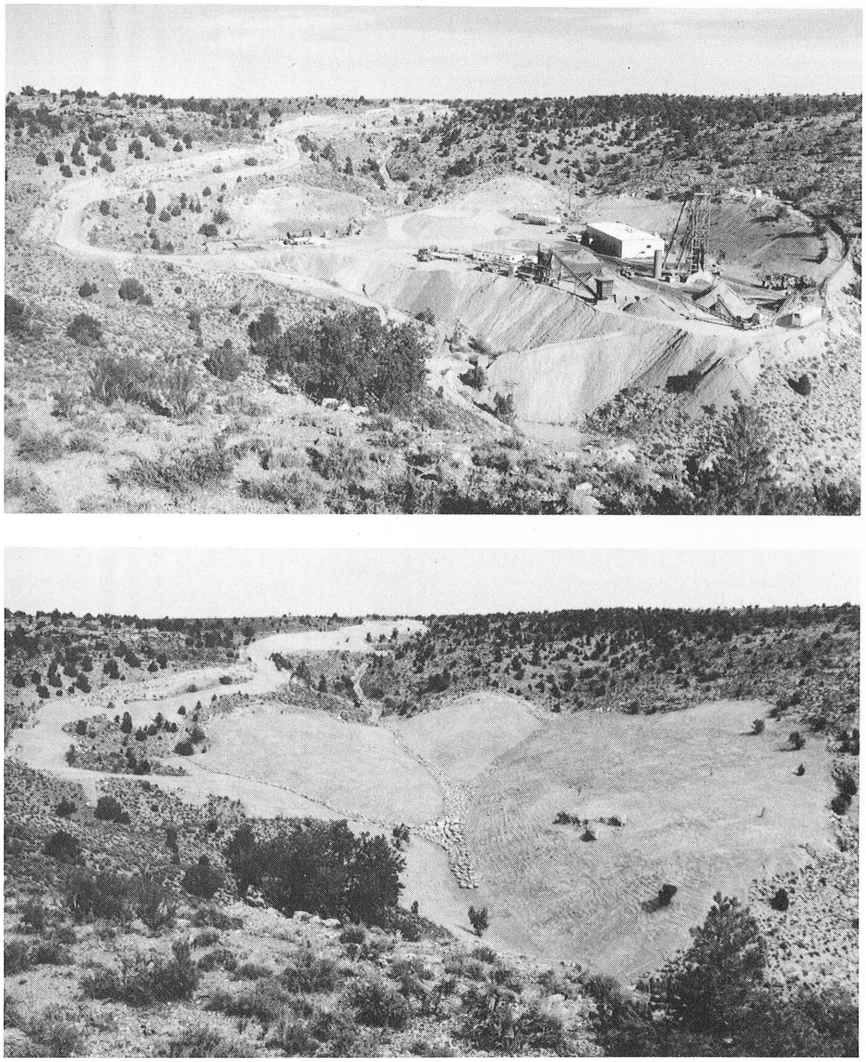

***Figure** 7. Pigeon mine, north of the Grand Canyon (top). The mine was developed on a uranium-bearing breccia pipe and operated by Energy Fuels Nuclear, Inc. between 1982 and 1990, when ore reserves were depleted. The mine has since been shut down and the site reclaimed (bottom).*

1970. The breccia-pipe deposits discovered to date have been near the Grand Canyon, but a large portion of the western Colorado Plateau in Arizona (**Plate 1**) probably contains uranium-bearing breccia pipes. These deposits are generally mined by underground methods and accessed by vertical shafts. Because the surface disturbance caused by this type of mining is relatively minor and all ore is trucked out of State for processing, the impact of these mines on the environment is minimal.

USES AND MARKETS

The primary market for Arizona's (and the world's) uranium production is the nuclear power industry. Although nuclear weapons research and production were the first major users of uranium, today the generation of electricity is far more important.

The nuclear power industry uses enriched uranium to make fuel rods, which generate heat through controlled nuclear reactions in the confines of the power plant. The generated heat is used to boil water to form steam, which drives turbines and generates electricity in much the same fashion as conventional coal- or petroleum-fired power plants.

The Palo Verde Nuclear Generating Station west of Phoenix near Wintersburg is the only nuclear power plant in the State. With a capacity of 3,810 megawatts, Palo Verde is by far the largest electrical generating station in Arizona (**Figure 8**). It provides electricity to several utilities both within and outside of the State.

DEVELOPMENT POTENTIAL

The future of the uranium industry is largely dependent on the development of the Nation's and world's nuclear power industries. The growth of nuclear power in the United States has been slower than expected partly because of opposition from those concerned about potential environmental and health dangers. Over the long term, however, nuclear power is likely to become an increasingly important source of electric power. This will be partly due to heightened debate on the potential health and environmental risks associated with the burning of coal and petroleum fuels. In addition, the limited reserves and rapid consumption of petroleum will probably lead to increasingly higher prices that may result in the use of alternative energy sources, including nuclear power.

Large uranium resources still remain in the sandstone-hosted deposits, but they are generally low grade and cannot be profitably mined at current or immediately foreseeable prices. A rise in prices to the levels of the late 1970's would certainly stimulate exploration and mining activity in Arizona; however, abundant low-cost reserves in other countries, especially Canada and Australia, make major price increases unlikely. Moderate increases in uranium demand and prices will probably not revive exploration and mining activity in sandstone-hosted or other non-breccia-pipe resources in the State. The breccia-pipe deposits are, however, much higher grade (averaging two to three times the produced grade of the sandstone-hosted deposits) and represent significant potential for future production. Any increase in uranium prices would stimulate this segment of the industry.

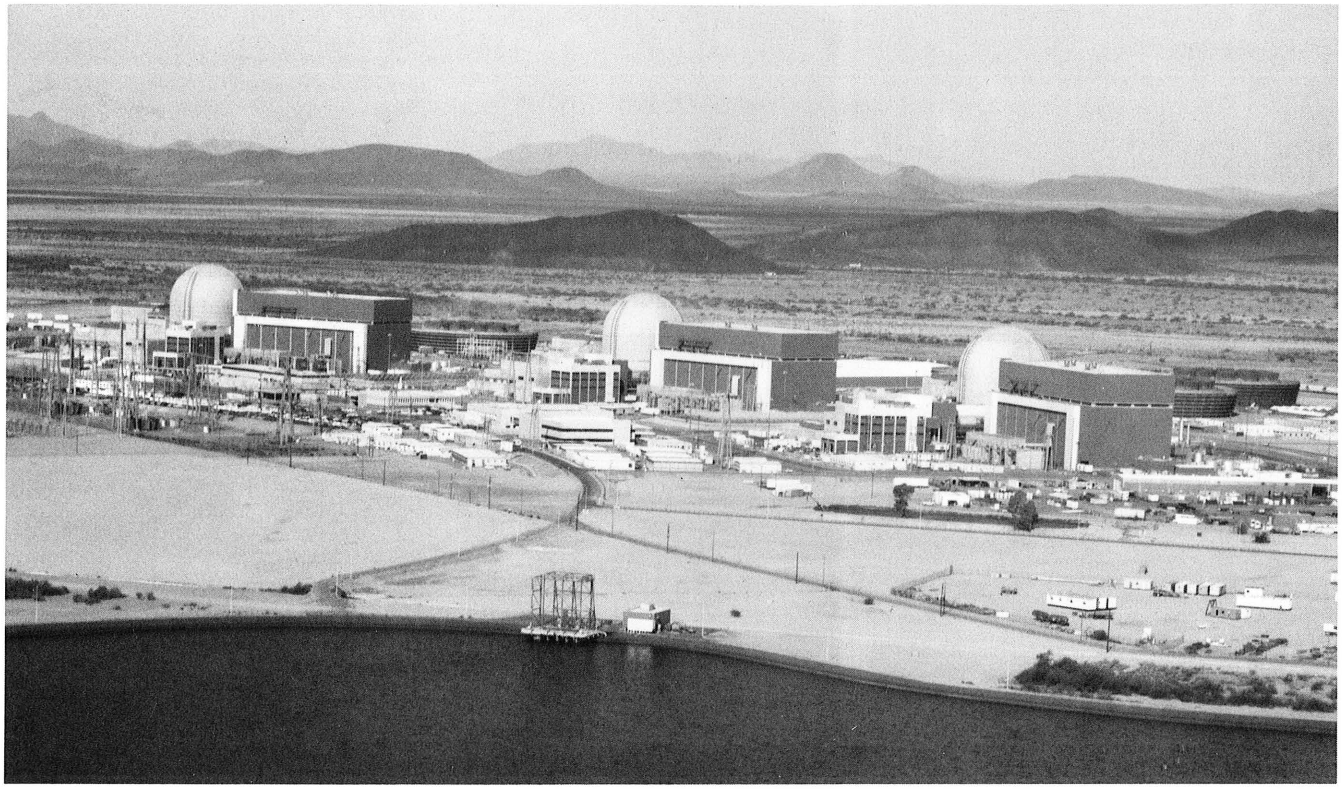

Figure 8. Palo Verde Nuclear Generating Station, west of Phoenix, operated by Arizona Public Service Company.

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OIL AND GAS

INTRODUCTION

Oil and gas are extremely important energy resources, responsible for fueling most of the transportation and generating much of the electricity in the world. Petroleum fuels also have important domestic uses, such as for space and water heating and for cooking. Nonenergy uses for petroleum include the manufacture of lubricants, petrochemicals, plastics, synthetic rubber, paving materials (asphalt), and a wide variety of specialty products.

GEOLOGY

Petroleum is a mixture of naturally occurring **hydrocarbons**, which consist of hydrogen (H) and carbon (C) and include molecules of many sizes and shapes, but with approximately the same chemical formula. The smaller molecules, which include such familiar compounds as methane (CH_4), ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}) exist in the gaseous state under normal conditions and make up what is known as **natural gas**. Hydrocarbons containing

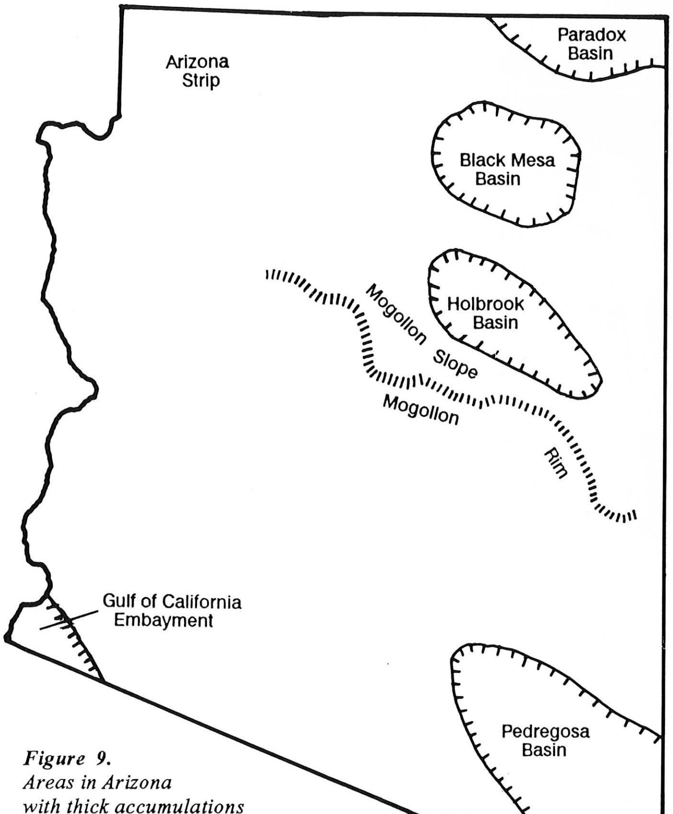


Figure 9. *Areas in Arizona with thick accumulations of sedimentary rocks that have been explored for oil and gas. All have potential for future discoveries, but only the rocks of the Paradox Basin have produced petroleum in commercial quantities.*

from 5 to 20 carbon atoms per molecule are normally liquids and make up most of the **crude oil** produced in the world. Still larger hydrocarbon molecules are normally solid or semisolid and form **waxes** and **tars**.

Deposits of oil and gas are present almost exclusively in sedimentary rocks and only rarely in igneous or metamorphic rocks. Petroleum is believed to be of organic origin, having been produced from anaerobic (without oxygen) decay of plant and animal materials, such as the abundant micro-organisms that live in the oceans.

Recoverable volumes of petroleum may accumulate if the following four elements are present: (1) an organic-rich source rock, which provides the hydrocarbon "raw materials"; (2) the proper temperatures and time to convert the "raw materials" into petroleum; (3) permeable reservoir rocks through which petroleum can migrate; and (4) a setting in which petroleum accumulates in one confined location within the reservoir rock.

RESOURCES

In Arizona, the proper conditions for formation and accumulation of commercial reservoirs of oil and gas are known to have existed only in the extreme northeastern corner of the State, from which all production has come. The productive rocks in that area are mostly marine sedimentary rocks, mainly limestones, that were deposited when the area of the present Colorado Plateau was covered by a shallow ocean.

The Paradox Basin, a thick accumulation of sedimentary rocks, is located in the Four Corners area, mostly in Utah and Colorado. Only its southern edge extends into northeastern Arizona (**Figure 9**). The sedimentary rocks of the Paraodox Basin are the source and host of most of Arizona's petroleum resources.

The most important oil field in the State is the Dineh-Bi-Keyah field northeast of Lukachukai on the southern edge of the Paradox Basin (**Figure 10**). This field is unusual because the petroleum is contained within a body of igneous rock that was squeezed, in a molten state, into the surrounding sedimentary rocks long after they were deposited. It is thought that the heat from the igneous rock aided in the generation of oil. The igneous rock is fractured and porous and provides an excellent reservoir for the oil.

PRODUCTION HISTORY

Arizona has historically been a minor producer of petroleum. Total production through 1989 is approximately 20 million barrels of oil and 25 billion cubic feet of natural gas, compared with the many billions of barrels of oil and quadrillions of cubic feet of gas produced from States such as Texas and California.

All current and historical petroleum production and all known reserves in Arizona are in northern Apache County. A total of 74 wells have produced oil and gas from 13 separate fields (**Figure 10**). Oil has been and continues to be the primary product. The only natural gas field in the State,

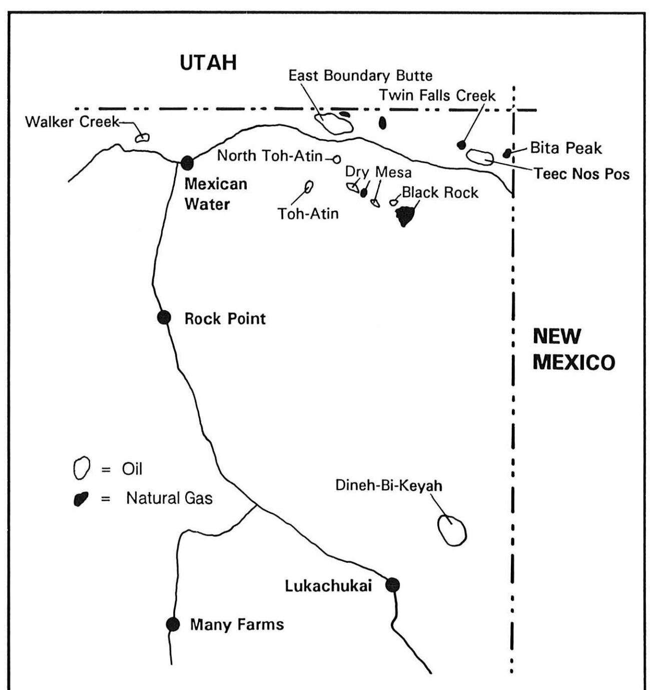
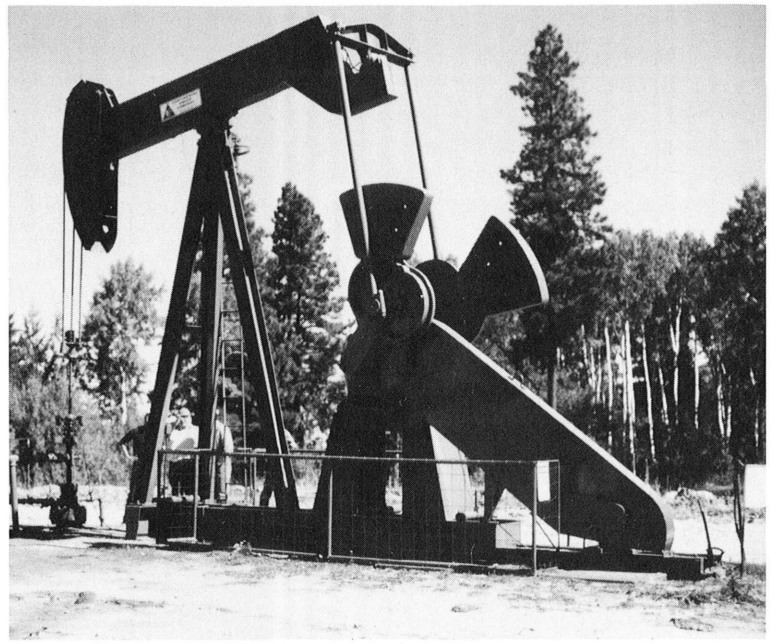


Figure 10. *Oil and gas fields of Arizona.*



Daniel Brennan

Figure 11. *Producing oil well in the Dineh-Bi-Keyah field, near Lukachukai, Arizona. The apparatus, known as a pump-jack, pumps oil from the underground reservoir to the surface.*

the Black Rock field approximately 10 miles southwest of Teec Nos Pos, was shut in for many years owing to lack of right-of-way for a pipeline, but was connected to a pipeline and began producing in 1989.

As of early 1991, only three oil fields, the Dry Mesa, East Boundary Butte, and Dineh-Bi-Keyah fields, were producing (**Figure 11**). All are contained in sedimentary rocks of the Paradox Basin. The Dineh-Bi-Keyah field, however, has an unusual origin, as explained above. Discovered in 1967, this oil field is by far the largest in Arizona. It has generated nearly 90 percent of the State's total oil production and more than 20 percent of its natural gas production. Production from the Dineh-Bi-Keyah field has declined steadily, however, from a high of more than 3 million barrels in 1968 to approximately 100,000 barrels in 1989.

TRANSPORTATION AND PROCESSING

As noted earlier, petroleum products are vital to modern society. Because of this, petroleum transportation, distribution, and processing facilities are also important, even in Arizona, where relatively little petroleum is produced. Oil produced from the Dineh-Bi-Keyah field is transported out of State via pipeline; all other oil is trucked from the fields. All natural gas produced in Arizona is collected by pipelines, which carry the gas out of State for processing.

Two oil pipelines that cross the northern and southern parts of the State transport oil from the large petroleum fields of California to markets farther east. Arizona has two refineries that process crude oil into usable products: one in Fredonia in northwestern Coconino County and another near Coolidge southeast of Phoenix. Products of the refineries are trucked to users.

Oil products pipelines bring large amounts of refined products into Arizona storage and distribution centers. The El Paso Natural Gas Company, the only important supplier of gas to the State's utilities, operates a network of natural gas pipelines that distribute gas, largely from Texas, to most populated areas of Arizona. The Transwestern natural gas pipeline crosses the northern part of the State, but is not a significant local supplier. Underground liquified petroleum gas (LPG) storage facilities are located near Adamana northeast of Holbrook and in the Luke basin west of Phoenix (**Plate 1**). The LPG is stored in manmade solution caverns within natural underground salt bodies. Other large salt bodies in Arizona have the potential for similar uses.

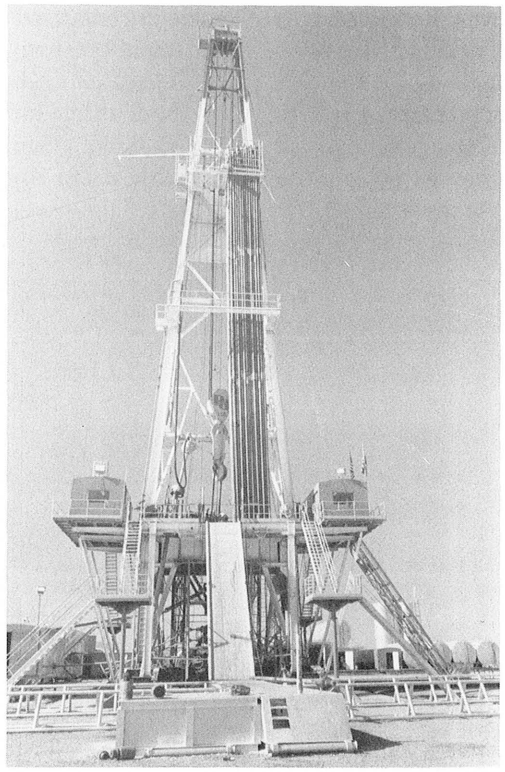
EXPLORATION POTENTIAL

Even though Arizona is not a major producer of petroleum, it has potential for future discoveries. Sedimentary rocks with the potential to produce oil and gas exist on the Colorado Plateau and in parts of the Basin and Range Province (**Figure 1**).

The Colorado Plateau generally consists of a thick sequence of only slightly folded and fractured sedimentary rocks, many of which have oil- and gas-producing potential. Several areas are considered the most prospective. The Paradox Basin, described earlier, currently produces petroleum and holds the most promise for new production in the immediate future. The area from Black Mesa south to the Mogollon Rim includes the Black Mesa Basin, Holbrook Basin, and Mogollon Slope (**Figure 9**), all of which contain thick sequences of incompletely explored sedimentary rocks. Two exploration wells north and east of Show Low have reportedly encountered traces of natural gas, but have not produced. The ''Arizona Strip'' country north and west of the Grand Canyon is attractive to explorationists because it is underlain by an exceptionally thick sequence of sedimentary rocks and because petroleum is being produced from equivalent rocks in adjacent areas of Utah and Nevada. Some traces of oil and gas have been recorded from exploration wells in this area, but no production has occurred to date. The area of northern Arizona from west of Fredonia to Monument Valley is attracting increased interest. A thick sequence of very ancient organic-rich shales, which have the characteristics of petroleum source rocks, are believed to underlie much of that region.

Areas within the Basin and Range Province of Arizona may also contain oil and gas resources. This region may include an ''overthrust belt,'' in which large areas of potentially productive sedimentary rocks are buried by unproductive rocks that were thrust over them along large, nearly

Figure 12. Large drilling rig used to explore for and develop oil and gas resources. These rigs can drill miles into the Earth to test for oil and gas. If petroleum is discovered, it can be pumped or allowed to flow naturally up to the surface through the same borehole.



horizontal faults. The existence of this "overthrust belt" in Arizona, however, has not been confirmed, and the results of test drilling are not encouraging. Another interesting exploration target area is the Pedregosa Basin in the far southeastern corner of the State (**Figure 9**). It is attractive because of its thick accumulation of marine sedimentary rocks and its geologic similarity to the extremely productive Permian Basin of southeastern New Mexico and West Texas. More than 40 exploration wells have been drilled into the rocks of the Pedregosa Basin; traces of petroleum were found, but no production has occurred. The Gulf of California embayment near Yuma contains a thick sequence of marine sedimentary rocks. These attracted exploration interest in the late 1980's, owing to a natural gas discovery in equivalent rocks in Mexico. Other valleys within the Basin and Range Province hold some potential, both in the down-dropped bedrock blocks and in the younger sedimentary and volcanic rocks that fill the basins. Recent discoveries in similar basins in Nevada provide some encouragement for further exploration within Arizona.

Although potential exists in all the areas just described, whether they will yield oil and gas is unknown and largely dependent on the intensity with which they are explored (**Figure 12**). Relatively depressed petroleum prices since the mid-1980's have caused exploration expenditures to decline precipitously. Because petroleum is a limited resource that is being rapidly depleted, prices should rise again, perhaps triggering intense exploration and oil and gas discoveries in Arizona.

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GEOTHERMAL ENERGY

GEOLOGY

Geothermal energy is natural heat from the interior of the Earth. At great depths below the Earth's surface, high temperatures exist everywhere, mainly because of energy released by the nuclear decay of radioactive elements. In most areas, geothermal energy is so diffuse by the time it reaches the surface that it is not usable or even recognizable as an energy source. In some places, however, high temperatures reach, or nearly reach, the surface and create abnormally high heat flow from the ground. These areas, known as **geothermal anomalies**, include regions of active or recent volcanism (e.g., the Hawaiian Islands, Yellowstone National Park [**Figure 13**], and the Cascade Mountains) and places in which the Earth's crust has been thinned by stretching, which allowed deeper, hotter rocks to approach the surface (e.g., the Basin and Range Province). When a geothermal anomaly becomes economically exploitable as an energy source, it is known as a **geothermal resource.**

DEVELOPMENT HISTORY

With the recognition of geothermal energy as an economically viable and important energy source, the need to regulate its exploitation on public lands became apparent. As a result, the Geothermal Steam Act of 1970 established geothermal energy as a leasable commodity subject to the same laws that apply to coal, oil and gas, and other resources.

The same act defined a **Known Geothermal Resource Area (KGRA)** as one in which the geology, nearby discoveries, competitive interests, or other factors indicate that the potential for extraction of geothermal resources is high enough to risk spending money on developing them. These favorable areas may be leased only through competitive bidding. Federal land outside the KGRA's may be leased by the first applicant, without competition.

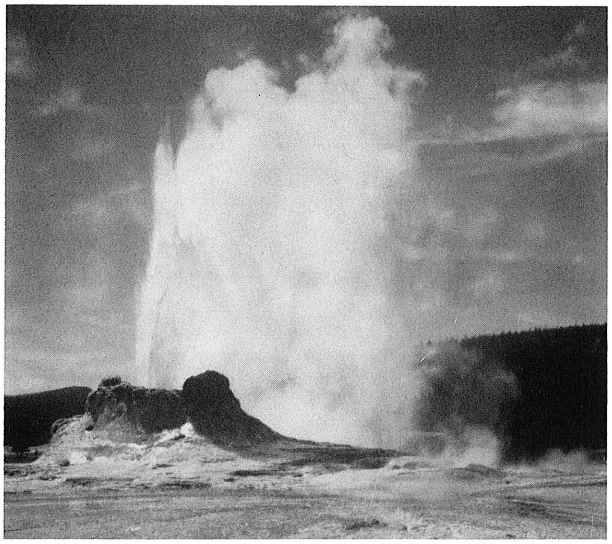

Figure 13. Geyser in Yellowstone National Park. Arizona has no such spectacular geothermal phenomena, but the State has many hot springs and low-temperature geothermal reservoirs that may be developed as energy sources in the future.

RESOURCES

Arizona has two KGRA's: the Clifton KGRA (780 acres) and the Gillard KGRA (2,920 acres). Both are in the Clifton-Morenci area of southeastern Arizona (**Plate 1**). The Clifton KGRA centers on the Clifton Hot Springs immediately east of Clifton on the San Francisco River; the Gillard KGRA surrounds the Gillard Hot Springs near the confluence of the San Francisco and Gila Rivers. The Clifton and Gillard Hot Springs are the State's highest temperature springs, at 158°F and 180°F, respectively. Water temperatures at depth, however, may exceed 284°F in both KGRA's. To date, geothermal resources have not been developed in either area.

In addition to the KGRA's, many areas in Arizona are known to have low-temperature geothermal water in the subsurface. An extensive study of Arizona's geothermal potential was conducted from 1977 to 1982 by the Arizona Bureau of Geology and Mineral Technology (now called the Arizona Geological Survey), with funding from the U.S. Departments of Energy and the Interior. Research geologists used well data to outline areas that may be underlain by low-temperature (<212°F) geothermal water. These are predominantly in the Basin and Range Province, especially in the deeper basins in southern and southeastern Arizona (**Plate 1**).

The Basin and Range Province hosts large quantities of low-temperature geothermal water as a result of some special aspects of its geology. The basins are controlled by faults or fractures that penetrate deep into the Earth's crust. Extensional (stretching) forces allowed large blocks of rock to sink along these faults while other blocks remained high, forming the mountain ranges. The down-dropped blocks were subsequently covered by sediments eroded from the adjacent mountains, creating the present-day valleys or basins. These geologic conditions allow ground water within the basins to migrate downward along the faults and come in contact with deeply buried hot rocks. The heated, and therefore buoyant, ground water then rises to form geothermal aquifers within the basin sediments.

Some of the more important potential reservoirs in the State are in the San Simon, Safford, and San Pedro Valleys in southeastern Arizona. The Tucson basin near Tucson and the Luke and Higley basins near Phoenix also contain geothermal water. The proximity of these basins to large cities makes them prime candidates for development should the economics of energy warrant it.

USES

The most important use of geothermal energy in this country is to generate electricity. High-temperature geothermal systems that boil and produce steam when penetrated by wells are the best for this purpose. The steam is commonly used to turn turbines and generate electricity directly; it may also be used as a heat source to boil water to generate electricity. California is the most advanced State in exploiting geothermal energy to generate electricity. Well-known producing geothermal fields include The Geysers north of San Francisco and the Salton field in southeastern California.

Some exploration for high-temperature geothermal water has been done in Arizona, including areas within the two KGRA's, but as yet resources suitable for generating electricity have not been located. Apparently, what Arizona does have in abundance is low-temperature geothermal water. Although this water is not currently valuable for generating electricity, it has many other potential uses, including heating and cooling (via heat-pump technology) both residential and commercial space, such as greenhouses, nurseries, and fish farms. Geothermal water is also very effective in improving metal recoveries and recovery rates in ore processing, an important industry in Arizona. Other uses for low-temperature geothermal water are possible; in fact, almost any process that requires moderately elevated temperatures may use this resource.

DEVELOPMENT POTENTIAL

The future of geothermal energy in Arizona is uncertain. Discovery of high-temperature geothermal systems is unlikely, but continuing development of the State's low-temperature geothermal resources is probable. The speed and extent of development largely depend on future energy prices and new technological developments, both of which could make the low-temperature reserves more attractive as energy sources.

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SOLAR ENERGY

INTRODUCTION

The sun is the ultimate source of most of the energy used by humans. All of the familiar energy resources, except for nuclear and geothermal energy, result from natural intermediate processes that convert the sun's energy into more usable forms. **Solar energy**, however, is energy that is derived directly from solar radiation. The exploitation of solar energy involves only human ingenuity and technology to convert solar radiation into usable energy.

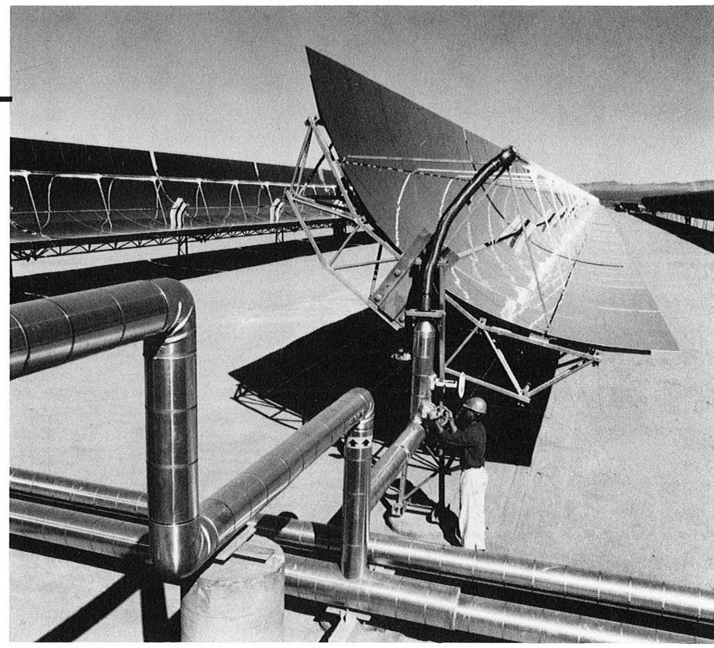

Figure 14. *Solar-thermal generating station, developed by Luz International, Inc. in southeastern California.*

RESOURCES

Arizona, with its southern location and sunny climate, has one of the most abundant supplies of solar energy in the United States. The **solar flux**, or flow rate of solar energy through the atmosphere to the Earth's surface, is not very dependable, however. In addition to predictable diurnal and seasonal variations, the solar flux can vary greatly from day to day, even from hour to hour, because of vagaries in the weather. Moreover, long-term monitoring has provided reliable (i.e., reasonably accurate) solar-flux data for relatively few areas in the State. Most applications of solar energy depend on estimates of the solar flux obtained from numerical solar-radiation models. Because these computer-generated models are not always accurate, many solar-energy systems do not perform to design specifications.

TECHNOLOGY

The average solar flux in Arizona, although quite high compared to that in other States, is generally very low (about 60 watts per square foot [W/ft^2] or 660 watts per square meter [W/m^2]) when compared to most other sources of energy. Without the benefit of large tax credits for the use of solar energy, it becomes cost effective only when the price of solar collectors is about \$10/ft^2 (\$108/m^2). This price is now feasible because of **solar-thermal technology**, which converts solar energy to heat that is then used to generate electricity. Luz International, an Israeli-American company headquartered in Los Angeles, began developing **concentrating parabolic troughs** in Israel in 1979. These are essentially curved mirrors that focus sunlight onto a small area to generate high temperatures. The company has also identified a market for solar-thermal power generation in California. With the utility company, Southern California Edison, Luz International negotiated contracts to construct power-generation plants. The first, completed in 1984, has been followed by nine others (**Figure 14**). The use of this energy source to generate electricity commercially has become economically feasible because the cost of the parabolic troughs has declined from \$56/ft^2 (\$600/m^2) in 1984 to \$12.50/ft^2 (\$135/m^2) in 1988.

Photovoltaic technology, which uses the physical properties of specifically engineered materials to convert solar energy directly into electricity, has also improved significantly since the early 1970's. The conversion efficiency has increased from about 5 percent to more than 15 percent, and the price for commercially available modules has dropped from more than \$100 to about \$7 per watt of potential generating capacity.

Passive-solar technology integrates various architectural features into the overall design of a building. These features enhance the building's ability to "collect" sunshine for space heating in the winter, but decrease its collecting ability in the summer, when such high internal heat would become intolerable. South-facing windows that collect the maximum solar energy in the winter when the sun is low, but are shaded by an overhanging roof in the summer when the sun is high, are an example of simple, yet highly effective, passive-solar architecture.

DEVELOPMENT POTENTIAL

Solar energy is, for all practical purposes, inexhaustible; its use is largely pollution-free; and the technology for its exploitation is established and improving. The remaining problems are how to tap this energy in the most efficient and economical ways and how to promote its widespread use.

Energy use for space conditioning and water heating accounts for more than 20 percent of the total energy consumption in the United States. Passive-solar technology for such uses is well developed and can now replace conventional-energy technologies economically. Large-scale electrical production from solar-thermal systems is also currently economical. Photovoltaic technology has been established as a viable alternative to remote-site diesel power up to 10 kilowatts and for emergency power in disaster areas.

Solar energy is not, of course, appropriate for all applications. It cannot provide constant power, and because of the low intensity of the solar flux, solar-energy systems (excluding those based on passive-solar technology) require more space than do comparable conventional-energy systems. Solar-energy systems, however, have an important competitive advantage in that sunlight does not introduce CO_2 or other pollutants into the atmosphere. This attribute will become a powerful economic incentive for using solar energy when the environmental effects of using other energy sources is adequately incorporated into their cost to the consumer. Because of Arizona's climate and technological base, the prospects for future solar development in the State look very promising.

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WIND POWER

INTRODUCTION

The wind is an energy source that has been used by humans for centuries. Technologies designed to exploit it vary from the sailing ships, which made possible the exploration of the globe and the growth of modern society, to the windmills that pump scarce ground water for livestock and have become a symbol of the American West (**Figure 15**). Although these uses will undoubtedly continue, the future development of wind power as an energy resource hinges on its potential for generating electricity.

RESOURCES

The energy-resource potential of wind is almost entirely dependent on its average speed. Sites that are best suited for the development of wind power have relatively constant, strong winds. Wind speed and direction are, of course, highly dependent on the season and the local terrain. Wind speed (hence, wind power) may be significantly affected by a change in air flow caused by topographic conditions, such as the narrowing of a canyon. The wind speed at such a site could differ by as much as 50 to 100 percent from the average wind speed of the region, potentially creating a local wind-power resource in an area of generally inadequate winds. Wind speed also typically increases with altitude. Friction due to obstacles at the Earth's surface reduces wind speed considerably.

Sherry Garner

Figure 15. *Windmill of the type used to pump ground water for livestock in southeastern Arizona.*

Wind-power resources are classified according to power density (W/m^2), which is measured and averaged over a long period (generally years) at various locations in a given region. After enough data have been collected, a wind-resource map is prepared along with a wind-resource model.

Several classifications have been established for wind-power sites based on average annual power density or wind-power flux: **Class 1**, 0 to 100 W/m^2; **Class 2**, more than 100 to 150 W/m^2; **Class 3**, more than 150 to 200 W/m^2; **Class 4-5**, more than 200 to 300 W/m^2; and **Class 6-7**, more than 300 to 1,000 W/m^2. Generally, satisfactory wind-power sites are Class 4 or higher, i.e., where the wind-power flux is more than 200 W/m^2. The class 4 category corresponds to a daily average wind speed of about 13 mph or more.

Wind resources in Arizona are limited. A large Class 3 area in the east-central part of the State includes the highest crests and summits (areas above 9,000 feet) of the White Mountains, and a Class 2 zone occupies the slightly lower elevations surrounding the Class 3 zone. Another Class 2 wind corridor has been identified near Kingman in northwestern Arizona. The rest of the State is considered to be a Class 1 wind-power zone.

DEVELOPMENT POTENTIAL

Because a satisfactory wind-power resource is usually a Class 4 or higher, Arizona does not have high potential for developing this resource. It is likely that only sporadic and sparse development will occur at specific locations where the terrain favors high wind speeds and where there is a local need for power.

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BIOMASS ENERGY

Figure 16. Firewood stacked for use as fuel for space heating. Wood burning is a popular use of biomass energy in Arizona and much of the West. Modern wood stoves are much more energy efficient than traditional fireplaces, but even the most efficient stoves produce a large quantity of pollution compared with their useful energy yield.

INTRODUCTION

Biomass is the amount, or mass, of living organisms in a particular area or volume of habitat. In areas where the floral (plant) biomass is large, it can be a significant energy resource when used as a fuel, called a **biofuel**.

The ultimate source of biomass energy is the sun. In the process of **photosynthesis**, plants use the energy from sunlight to form **carbohydrates**, molecular compounds of carbon, hydrogen, and oxygen, from carbon dioxide and water molecules. The energy from the sunlight is incorporated into the molecular structures of the carbohydrates and "stored" as chemical potential energy in the biomass material. This same energy is released from the carbohydrates, along with the original water and carbon dioxide, when the material is burned, or **oxidized**, by reaction with atmospheric oxygen.

One of the simplest and most familiar uses of biomass energy is the burning of wood in fireplaces or stoves (**Figure 16**). Biomass material may also be transformed by chemical or biological processes (e.g., distillation or digestion) into more widely useful intermediate biofuels, such as methane (the primary component of natural gas), liquid ethanol (added to gasoline to make gasohol), or charcoal.

DEVELOPMENT POTENTIAL

The major constraint on biofuel production in Arizona is lack of water. The U.S. Geological Survey's National Water Summary for 1983 indicates that water consumption in Arizona outstrips its replacement by 5 percent per year. Typical crops in the State require 20 to 30 inches of water in a growing season, but most of Arizona's most productive farmland receives less than 10 inches of rainfall per year. The shortfall is offset by irrigation, including the pumping of ground water.

Competition for fresh water in Arizona continues to increase between the agricultural sector and growing urban centers. In the future, this competition will probably restrict fresh-water farming and, therefore, biofuel production in the State. Production could become feasible if the **feedstock** (biofuel plants) are able to use water that would otherwise go to waste. This includes water that has been used for waste transport or treatment, irrigation, or industrial purposes and is no longer suitable for most uses. Examples of such adaptive feedstock are water hyacinths and microalgae, which grow well in polluted, brackish, and saline waters. Because the use of waste water would probably not increase overall water consumption, growing biofuel feedstocks using these water sources might be feasible in Arizona.

Wood could be an important biofuel in northern Arizona, with its extensive forests. Burning wood, however, is generally not a very efficient way to heat living space, and it can cause serious air pollution if widely practiced.

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ARIZONA STATE AGENCIES WITH ENERGY-MANAGEMENT RESPONSIBILITIES

The **Arizona Geological Survey** (AZGS) conducts geological investigations and provides information and assistance on Arizona's geological framework, mineral and energy resources, and geologic hazards and limitations. As of July 1, 1991 the Oil and Gas Conservation Commission was merged with the AZGS. With this merger, the AZGS has the responsibility of regulating the drilling, development, and production of oil, gas, helium, and geothermal resources, as well as the underground storage of oil and gas.

The **Energy Office of the Arizona Department of Commerce** has statutory responsibilities for administering Federal and State energy programs, solar-energy programs, and oil-overcharge-restitution-funded programs. The Arizona Energy Office carries out these responsibilities through four programs: (1) Energy Conservation focuses on energy efficiency in buildings, energy education, and low-income weatherization; (2) Community Energy addresses energy-related air-quality issues, transportation energy efficiency, energy-related economic development, and local-government energy efficiency; (3) Solar Energy promotes the use of solar and other renewable-energy resources through educational, promotional, and demonstrational activities; and (4) Energy Planning and Policy encompasses the Arizona Energy Data System, State energy-policy support, program evaluation, economic and environmental impact assessment, and management-assistance functions.

The **Arizona Corporation Commission, Utilities Division**, is partly responsible for regulating utilities within the State. Among its duties are least-cost planning, which helps provide the lowest utilities costs by recommending policies based on projected demand, conservation, and demographic and engineering considerations. The Utilities Division is also responsible for regulating utilities rates and local natural-gas distribution pipelines. It has the authority to approve power-line siting permits.

The **Salt River Project** (SRP) operates four hydroelectric dams on the Salt River, as well as two dams on the Verde River and a network of canals in the Phoenix area. As a quasi-governmental agency and the second largest public utility in Arizona, SRP distributes water from its projects and power from the hydroelectric generating stations and other sources.

The **Arizona State Land Department** has the responsibility of managing Arizona State Trust lands, which total approximately 9.7 million acres. Energy-related responsibilities are in the hands of the **Nonrenewable Resources and Minerals Section**, which issues prospecting permits and mineral, oil and gas, coal, and geothermal leases.

The **Arizona Power Authority** has the responsibility of marketing and distributing hydroelectric power from Hoover Dam to individual customers, most of which are irrigation and electrical districts.

FEDERAL AGENCIES WITH ENERGY-MANAGEMENT RESPONSIBILITIES

The **U.S. Bureau of Land Management** (BLM) directs the mining-law program, making Federal lands available for prospecting, exploration, and locating mining claims for valuable minerals, including uranium. The BLM issues patents to the owners of mining claims when valuable deposits have been discovered. Until patenting, the BLM manages mining operations to prevent unnecessary degradation of surface resources. The BLM also leases Federal lands for development of oil and gas resources and issues all Federal drilling permits. Although Native American tribes lease their own mineral rights, the BLM approves mining and exploration plans, inspects lease operations, and verifies production for royalty purposes.

The **Western Area Power Administration**, a division of the U.S. Department of Energy, administers the operation, including power generation, of the dams on the Colorado River and other Federal hydroelectric projects in the western United States. The Western Area Power Administration also handles all aspects of the marketing and distribution of hydropower from these Federal projects.

The **U.S. Forest Service** has authority over national forests. It oversees mineral claims and prospecting activities and approves all drilling, exploration, and mining activities that impact the surface resources of the national forests.

The **U.S. Bureau of Reclamation** constructs dams, canals, and other water projects. The agency operates some hydroelectric generating stations, such as those at Glen Canyon and Hoover Dams, and retains ultimate authority over most hydroelectric stations that it built, but does not operate.

The **Nuclear Regulatory Commission**, a division of the U.S. Department of Energy, regulates the production, handling, and disposal of all radioactive materials. This includes the mining and milling of uranium, disposal or storage of mine waste and mill tailings, manufacture and transport of nuclear fuels, and operation of nuclear power plants.