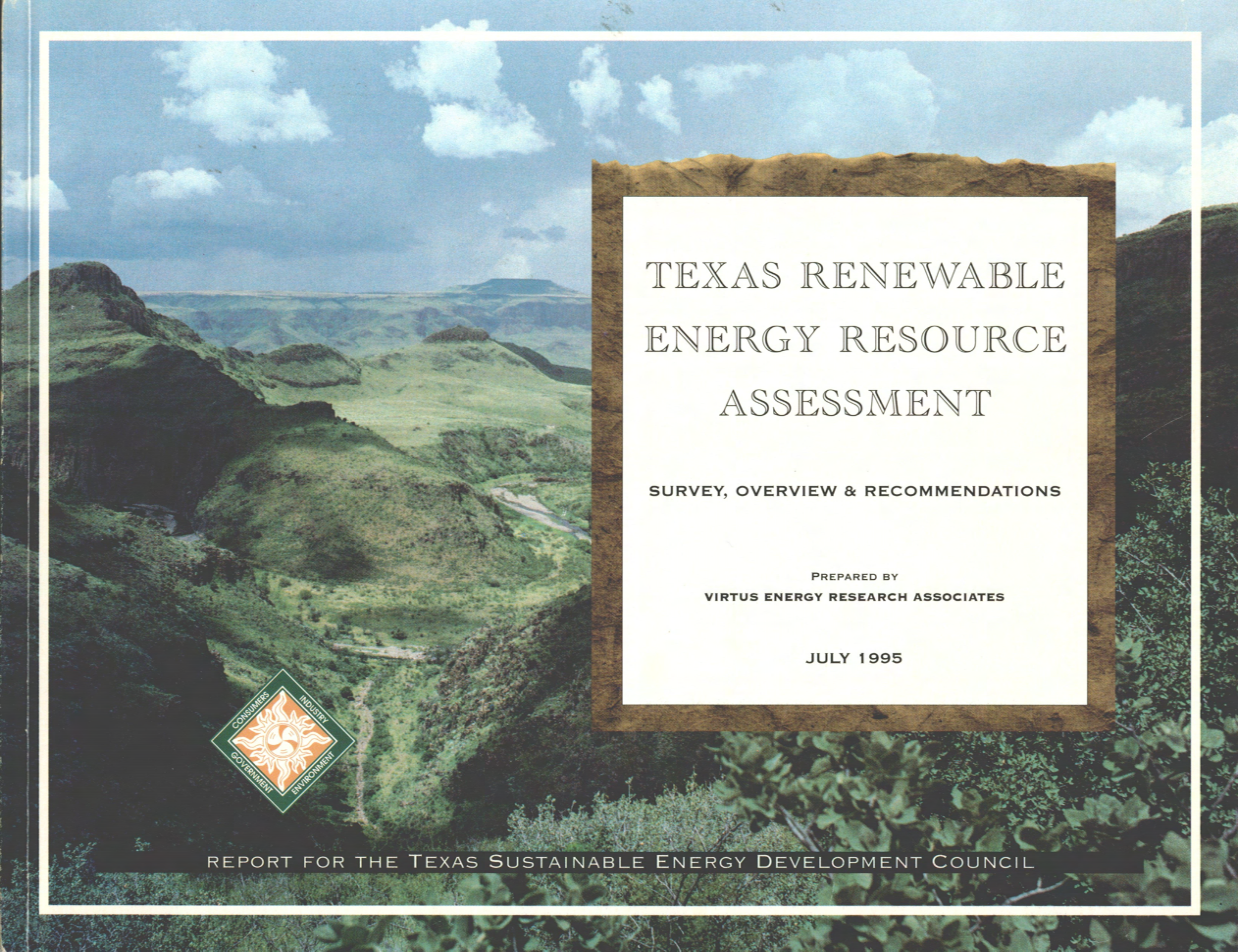


TEXAS RENEWABLE ENERGY RESOURCE ASSESSMENT

SURVEY, OVERVIEW & RECOMMENDATIONS

PREPARED BY
VIRTUS ENERGY RESEARCH ASSOCIATES

JULY 1995

REPORT FOR THE TEXAS SUSTAINABLE ENERGY DEVELOPMENT COUNCIL

GEOTHERMAL ENERGY

by Janet Valenza

INTRODUCTION

SIGNIFICANCE OF RESOURCE: HISTORICAL AND FUTURE USES

Geothermal energy derives from the vast and seemingly limitless heat energy of the earth's interior. Heat originating in molten rock under the earth's crust or arising from decay of naturally occurring radioactive elements conducts upwards to rocks and fluids closer to the surface, where it is accessible for exploitation. Hot waters from springs or wells are a familiar example of this phenomenon. These have been used in therapeutic baths since Greek and Roman times and in water and space heating applications since the 19th century. Indeed, the location of these waters has largely served as an indicator of geothermal energy sources.

Geothermal energy manifests itself in four distinct forms: hydrothermal resources (hot steam or water), geopressured-geothermal energy, hot dry rock, and magma. To date, only hydrothermal energy has been developed commercially. **Table 8.1** summarizes the applications and status while **Figure 8.1** portrays the general physical location of the four resources. Each resource type will be introduced in more detail prior to reviewing the Texas geothermal resource.

Hydrothermal energy. Water that becomes heated or vaporized after contact with surrounding hot rock is termed hydrothermal. As indicated in Table 8.1, hydrothermal energy may be classified as a low, medium, or high temperature resource. High-temperature geothermal resources are concentrated in the western states because of the region's recent volcanic activity and extensive faulting where crustal magma bodies underlie trapped water. Low temperature resources (water reservoirs below 90°C) are widespread in the United States, including Texas. These occur primarily in regional aquifers within sedimentary basins in the Great Plains and on the Atlantic and Gulf Coastal Plains. Typical applications of hot water from low temperature hydrothermal resources include space and district heating of public or private buildings; enhanced oil recovery; industrial drying processes; greenhouse heating; aquaculture (fish farming); and therapeutic and recreational bathing at resorts. Some of these applications can utilize temperatures as low as 100°F (38°C).

Technology to use hot water at moderate temperatures (194° F to 300° F) is in the development phase. Hot water power production systems have been developed, but the technology has only recently come into general use. A binary-cycle system is frequently employed. In this cycle, heat from the geothermal fluid is transferred to a secondary working fluid such as freon or propane that in turn drives a turbine. Such systems allow the use of relatively low temperature fluids, minimize corrosion problems, and, if the water is reinjected, leaves the fluid resource in the ground to avoid depletion.

High temperature (>150°C) hydrothermal resources may be composed of dry steam (no water droplets) or wet steam (steam and water droplets combined). Wells ranging in depth from a few hundred to 4,000 meters (600 to 13,000 feet) yield hydrothermal water as hot as 360°C (680°F). Dry steam deposits, the preferred but rarest resource, are tapped by drilling a well into the reservoir to release the steam which then travels to turbine-generators to produce electricity. Wet steam deposits are more expensive to exploit for the production of electricity, since the liquid portion of wet steam, which is destructive to a turbine-generator, must be removed from the the water and vapor mixture. Since 1904, geothermal steam has generated electricity in Larderello, Italy. In the U.S., commercial power production began in 1960 with development of the Geysers geothermal field in northern California. The 2,000 megawatts of geothermal power now installed in California contribute over 2% of that state's total energy needs.[1] Texas, which has no vapor-dominated hydrothermal systems, cannot take advantage of the mature, cost-effective electric generation technology employed at the Geysers.

Geopressured geothermal. Since the 1940s, oil and gas drillers have hit high pressure water-bearing

TABLE 8.1. Summary Characteristics of Geothermal Energy.

ENERGY TYPE		CHARACTERISTICS	TYPICAL APPLICATIONS	STATUS*	IN TEXAS?
HYDROTHERMAL	Low temperature	water, <194°F; >10°F above mean ambient air temperatures	space heating, aquaculture	A	yes
	Medium temperature	water, 194-300°F	space heating, electricity generation, drying processes	A	no
	High temperature	water, >300°F	electricity generation, process heat	A	no
Geopressured		high temperature, high pressure underground reservoirs of water and methane	process heat, methane recovery, enhanced oil recovery, desalinization, electricity generation	B	yes
Hot Dry Rock		hotter than average subsurface rock	electricity generation	B	yes
Magma		<3 km deep molten rock; 650-1200°C	electricity generation	C	no

**A=Mature technologies, commercially developed; B=Undeveloped resource with pilot demonstrations; C=Research effort only*

formations on the Texas and Louisiana Gulf Coast. These geopressurized zones, buried below thick layers of shale or clay, include high-temperature, high-pressure water reservoirs, often saturated with natural gas. The fluids in the permeable sandstone that makes up the geopressured zones are tightly confined by surrounding impermeable rock and faults. Three forms of energy derive from these zones: thermal—from water at 110° to 230°C (230° to 450°F) at depths of more than 4,500 meters (15,000 feet), kinetic—from pressure gradients approaching 1 psi/ft, and chemical energy—from methane dissolved in water at levels averaging 25 to 40 standard cubic feet (scf) per barrel of water. (For reference, a barrel of crude oil contains the energy equivalent of 5,800 scf of methane). Exploitation of this resource would entail "mining" the thermal, kinetic, and chemical energy from the geothermal zones. The rate of resource removal will greatly exceed the rate of natural replacement.

To date, no commercial exploitation of the geopressured geothermal energy has occurred, although considerable research has been carried out to evaluate the resource. The Eaton Operating Company has successfully tested binary cycle technology for commercial use of moderate-temperature geopressured geothermal fluids.[2] Besides the obvious application of electricity production from extracted heat or methane, a number of process heat applications, such as water desalinization or use in aquaculture, have been proposed.

Hot dry rock (HDR). Hot dry rock zones represent a significant perpetual resource. Such zones exist everywhere, but they are nearest the surface where molten rock has penetrated the earth's crust and heats adjoining subsurface rock layers that contain little or no water. To extract heat from these hot, dry formations, it is necessary to artificially enhance the rock's permeability (a measure of the ability of rock to transmit fluids) and to inject a heat transfer fluid. To date, experimental wells drilled into impermeable granitic formations have successfully used hydraulic fluid pressure to create highly fractured networks within the rock. Cool surface water injected into the fractured formation can be extracted as superheated water suitable for the generation of electricity or for use as process steam. The success of the Los Alamos National Laboratory HDR facility at Fenton Hill has set the stage for advanced development and near-term commercialization of this technology.

Magma. The second long-lived geothermal resource consists of near-surface deposits of molten rock (magma) at temperatures between 650° to 1200° C. Water-cooled boreholes drilled into convecting magma solidify the liquid rock. The water circulated and heated through this structure could then be used to produce high temperature steam suitable for the generation of electricity. Magma energy extraction technology is presently in the earliest stages of development. The very high temperatures near magma bodies overwhelm the capabilities of conventional drilling equipment. A demonstration project at Kilauea Ili Lava Lake, Hawaii has shown promise of a high energy extraction rate. Elsewhere, Sandia National Laboratories' researchers are conducting experiments at the Long Valley volcanic crater in California, where a shallow potential magma body has been identified.

Other Geothermal Energy Sources

The enormous heat capacity of the earth prevents it from seeing the extremes of atmospheric weather conditions. At even very shallow depths temperature swings are moderated; at a depth of approximately 3 meters most locations will register a constant temperature equal to the region's average annual air temperature. Earth-sheltered housing, ground-source heat pumps, and ground-coupled heating are all schemes that take advantage of this phenomenon to reduce the heating and cooling demands of buildings. (In fact, the foundation of every concrete slab home is at least weakly coupled to the ground.) Each strategy uses the moderated temperatures of the earth as a sink for summertime cooling and a source for winter heating. These techniques have proven effective in countless installations, but a review of this resource in the context of potential demand side savings is beyond the scope of this chapter and will not receive further discussion.

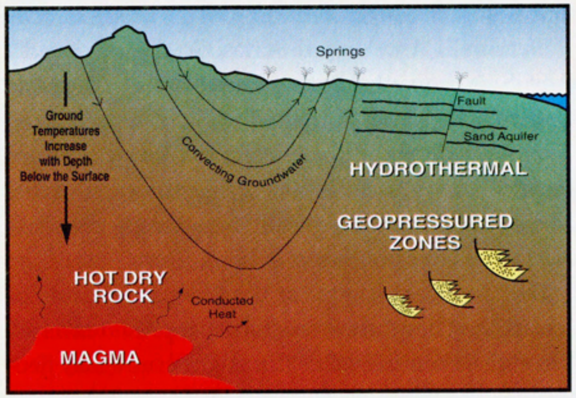


FIGURE 8.1. Portrait of the Four Geothermal Resources.

DEVELOPMENT ISSUES: SPECIAL CONSIDERATIONS FOR LARGE-SCALE USE

Not all geothermal resources can be classified as renewable or sustainable. Hydrothermal resources in particular are renewable only if hot aquifers are recharged from rainfall, snowmelt, or re-injection of fluid. Otherwise, energy in the form of hot water is drained from a field faster than it is replenished. The hydrothermal power plants at the Geysers in California experienced a reduction of steam pressures in the 1980s. New power plants there had doubled capacity in just seven years based on the expectation that there was adequate heat in the formation and also enough water to bring the heat to the surface. The developers did not fully understand the reservoir to exploit it properly. Geopressured energy is generally not considered renewable because the fluids are sealed in reservoir strata, similar to oil and gas, and are essentially mined along with the solution methane. Hot dry rock, on the other hand, does not rely on an existing geofluid reservoir; it is renewable over long time scales because extracted heat will slowly be replaced by conduction of heat from deeper within the earth. The same statement holds for magma resources.

Negative impacts from the use of geothermal energy tend to be site-specific. These may depend on the quality of the resource, conversion technologies, local geology, and climate, or other environmental or social factors. Common issues related to hydrothermal development include water availability and disposal, emissions and noise. Additional concerns related to the exploitation of geopressured resources may include surface subsidence, brine disposal, and increased seismicity. Each prospective geothermal facility will face its own set of constraints that can range from insignificant to a developmental impasse.

Because of their relatively low operating temperatures and resulting low thermal efficiencies, geothermal power plants typically require very large quantities of cooling water—significantly more than fossil fueled plants. For instance, a 50 megawatt hydrothermal plant requires more than 5,000,000 gallons of cooling water every day. Throughout the western United States, access to and disposal of large quantities of water can pose a significant constraint to development.

Trace air emissions of naturally occurring chemicals such as hydrogen sulfide, hydrogen chloride, methane, ammonia, arsenic, boron, mercury, and radon can occur with geothermal development but will vary depending on the resource and the extraction technology. If a closed-loop, binary technology is used, air emissions might be largely eliminated. At steam and flash plants, hydrogen sulfide can occur at low concentrations but can be controlled using hydrogen sulfide abatement systems. Alternatively, hydrogen sulfide and other noncondensible gases can be reinjected into the reservoir. Compared to fossil fuel generation other emissions are small: a typical geothermal plant produces only 1% of the sulfur dioxide, less than 1% of the nitrous oxides, and 5% of the carbon dioxide released by a comparably sized coal-fired plant.[3]

Noise pollution can be a problem at generation, drilling, and pumping sites, especially if located near population centers. Additionally, sludges produced from the processing of high salinity brine, which may contain traces of toxic metals such as arsenic, mercury, and vanadium, can pose solid waste disposal problems.

Commercial development of geopressured resources would produce prodigious quantities of brine. When large quantities of fluids are removed from geopressured formations, the possibility of land subsidence arises. Measurements at geopressure test wells suggest that subsidence has not been a problem. Questions about liability exist because understanding of the geophysical interactions between the reduction of pressure at depths beneath 15,000 feet and surface subsidence is still incomplete.[4]

After geopressurized brine is produced and used it must be disposed of. Typically, wells would be employed to inject the cooled brine into a suitable formation, such as a shallow saline aquifer or the brine could be reinjected into the geothermal reservoir. Special care must be taken to prevent the contamination of fresh water resources in the area. In addition, some geopressured wells could produce small amounts of hydrocarbon condensate materials, including benzene, toluene, and xylenes, which would require appropriate handling.

The withdrawal and injection of large volumes of fluid can influence the local seismicity in an area. From 1978 to 1983 a seismic monitoring program at Chocolate Bayou, Brazoria County, found that brine production at the Pleasant Bayou geopressured/geothermal energy well enhanced seismicity, but the number and size of events did not constitute a serious hazard.[5] These findings, however, did not determine with any degree of certainty whether the enhanced seismicity was related to withdrawal or injection of the brine, nor whether the cumulative effects could pose a potential subsidence risk.

SURVEY

FUNDAMENTAL DATA COLLECTION

Few Texas aquifers have been measured specifically to assess their thermal characteristics. Most knowledge of the hydrothermal resource has been gleaned from over a century's experience in drilling for oil and water coupled with sound geological interpretations. This is not a significant handicap since more than a million wells have been drilled in the state. The resulting resource evaluations for low-grade hydrothermal reservoirs existing in sedimentary basins are fairly reliable.

After the 1973 energy crisis, the National Science Foundation implemented a research program on this geopressured geothermal resource. After poring over logs of wells drilled into geopressurized formations, geologists began to examine the nature and extent of the resource. Thereafter, researchers drilled long-term test wells to determine flow rates. Initially, the Department of Energy funded research, conducted by the Bureau of Economic Geology (BEG) and the Center for Geosystems Engineering at the University of Texas, to assess the potential for electrical generation from deep subsurface brines in Tertiary strata. Thereafter, interest shifted from extracting heat to turn turbines to examining solution methane.

INFORMATION SOURCES

Data Bases and Organizations

In Texas, The Railroad Commission regulates the exploration, development, and production of geothermal energy on public and private land and accordingly keeps files on each geothermal well in the state. The public may access these files which include such forms as the production test and completion report and log, the producer's monthly report of geothermal wells, the monthly geothermal gatherer's report, the producer's certification of compliance and the authority to transport geothermal energy, and the application to inject fluid into reservoirs.

Computer files on the water well data used by Woodruff (1979)[6] and Bliss[7] can be accessed at the Texas Natural Resources Conservation Commission. Each data is located by county numbers and a state well number system.

Information on Texas' geopressured resources had been gathered at the now defunct Geopressured-Geothermal Information Systems (GGIS) under the auspices of the Center for Energy Studies at the University of Texas at Austin. This information included digitized well logs, well header information, salinity data, sand profiles, and a bibliography. UT's Department of Petroleum Engineering now has what is left of this database, but there has been no funding to create access to the information that is now in rough format.

Nationally, the United States Geological Survey (USGS) is the authoritative source on the country's geothermal resources. In 1982 USGS compiled the Geotherm database that inventoried and summarized thermal wells and springs throughout the United States. State compilations from the data base were later published in book form.

The Geo-Heat Center at the Oregon Institute of Technology conducts research and provides assistance to potential users (local governments, geothermal developers, pump manufacturers) of the direct-heat resource base of the country. The Center provides technical and development assistance, research to resolve developmental problems, and distributes educational and promotional materials to stimulate development. Requests for assistance have targeted geothermal heat pumps, space and district heating, greenhouses, aquaculture, industrial, and electric power.

The Geothermal Resources Council of Davis, California has instituted an on-line information system containing material from a variety of sources. Information available on-line includes the Geothermal Power Plant Data Base that covers most geothermal power plants worldwide (228 outlines), the Oregon Institute of Technology's Geothermal Heat Pump/Direct-Use Data Base (with over 3,400 citations), a U.S. Vendors Data Base which lists companies and contractors who supply goods and services ranging from aerial photography to power production and financing, and geothermal Resources Council Bulletins dating back to the 1970s.

Summary Documents

The list below contains a short set of documents that characterize the geothermal resources of Texas. They are organized according to topic and listed in the same order in which they have been discussed in this chapter: geothermal (general), hydrothermal, geopressured and hot dry rock. As this document listing suggests, there has been little recent research activity evaluating geothermal resources in Texas.

Geothermal Resource Assessment for the State of Texas, Woodruff, et al. 1982.[8] From well data and remotely sensed lineaments, this report analyzed and interpreted the hydrothermal/geothermal data to the year 1980.

***Geothermal Resource of Texas* (Map),** Woodruff, 1983.[9] A concise but thorough summary of Texas hydrothermal and geopressured resources on a single full color map (scale 1:1,000,000). A highly recommended summary reference for anyone interested in these resources.

Assessment of Geothermal Resources of the United States—1978. Geological Survey Circular 790, Muffler, 1979.[10] This circular is the most comprehensive assessment performed by the USGS in evaluating the nation's geothermal resources.

Texas: Basic Data for Thermal Springs and Wells as Recorded in Geotherm. Bliss, 1983.[7] This compilation of the information stored in the database geotherm includes thermal wells and springs by county, location by latitude and longitude, well depth, water temperature, and aquifer.

"Low-Temperature Geothermal Resources in the Western United States," Mariner, 1983.[11] This article identified the resources of the Western U.S., including the Rio Grande Rift province of West Texas.

"Low Temperature Geothermal Resources in the Central and Eastern United States," Sorey, 1983.[12] This article identified low-temperature geothermal resources, including the accessible resource base and the total identified resource, in the Central and Eastern United States. They occur primarily in regional aquifers within sedimentary basins in these areas.

Geopressured Geothermal Energy: Proceedings of the Sixth U.S. Gulf Coast Geopressured Geothermal Energy Conference. Dorfman and Morton, 1985.[13] This compendium of papers presented to a 1985 geopressured/geothermal conference held in Austin, Texas, included topics on the production characteristics of design wells, the deformation history of geopressured sediments, the detection of microseismic events, the anomalous occurrences of liquid hydrocarbons in geothermal brines, and the transfer of technology to improve recovery from gas reservoirs.

The Xerolithic Geothermal ("Hot Dry Rock") Energy Resource of the United States: An Update. Nunz, 1993.[14] This report presents revised estimates, based on the most current geothermal gradient data, of the hot dry rock energy resources of the United States. A tabulation of the Texas HDR resource is included in the state-by-state listings. The report also includes a color contour map of mean geothermal gradient for the United States.

OVERVIEW

ANNUAL AVERAGE SUMMARY

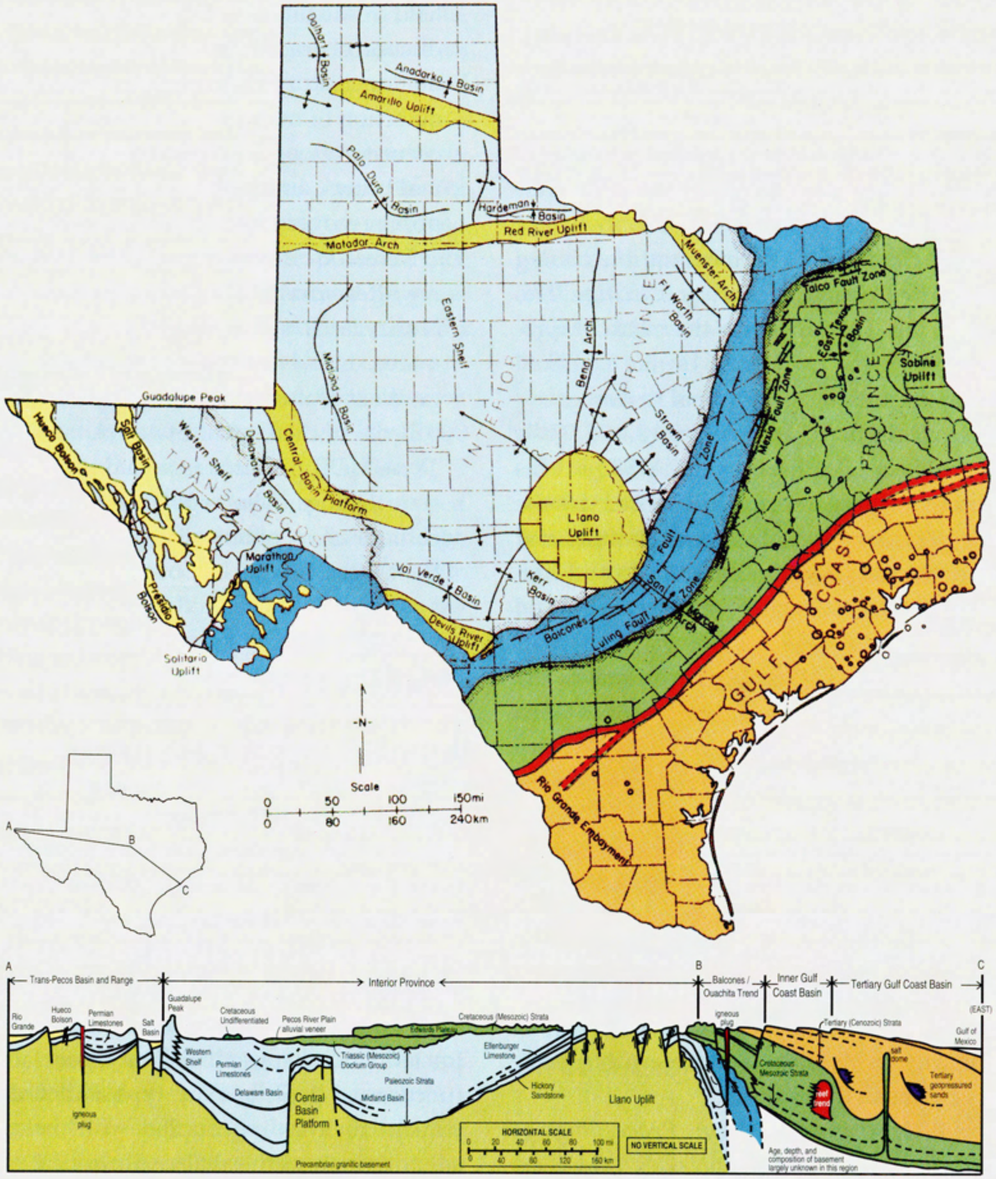
For a geothermal resource to be commercially viable, sizable quantities of heat must be removed from the ground at relatively low cost. The economics associated with accomplishing this feat depend on the quality of the resource—principally its temperature, depth, and fluid characteristics—and the ease and rate with which geofluids can be extracted and disposed. All of these factors are a function of geology. The type and order of constituent rock layers coupled with their respective age, origin, and thermal and physical characteristics will determine a geothermal site's viability. By necessity then, mention will be made to a variety of geothermal zones and geologic structures that may be somewhat baffling to those unfamiliar with this discipline. The reader is referred to **Figure 8.2**, a generalized summary of structural/tectonic features of Texas (reproduced from the *Geothermal Resources Map of Texas*[9]) to locate all regions and formations described in the text.

Texas has three main geothermal regions: the Central Texas hydrothermal area, the Trans-Pecos hydrothermal area, and the geopressured-geothermal resource of the Gulf Coast. There are also indications that Paleozoic strata further west of the Balcones/Ouachita trend and Tertiary strata in the Gulf Coastal Plain may contain additional geothermal potential. The low-temperature hydrothermal area of Central Texas, defined by the Balcones and Mexia-Talco Fault Zones, has experienced the most commercial applications to date. The geopressured zones, with their high brine temperatures and associated natural gas, were the focus of numerous assessments during the early 1980's. Although research activity has dropped off markedly in the past 10 years, interest could return if energy prices were to increase. These resources and other secondary ones are reviewed below.

Hydrothermal Resources

Thermal wells and springs have been in use in Texas for many years. **Figure 8.3** shows the relative density of thermal wells and springs by county as compiled by the Geotherm data base to the year 1981. From this figure, Texas' two major hydrothermal regions are evident: the Central Texas band, along the Balcones/Ouachita structural trend, and the Trans-Pecos.

Central Texas. Woodruff, et al,[6,8] have shown that geothermal resources within Cretaceous aquifers in



Section ABC. Schematic section showing generalized geologic features of Texas (modified from American Association of Petroleum Geologists, 1973).

FIGURE 8.2. Generalized Map of Texas Structural/Tectonic Features.[9] The section (lower figure) identifies geopressured zones in east Texas (purple) and, secondly, faults along the Balcones/Ouachita trend yielding good hydrothermal resource.

Central Texas stretch in a band from Val Verde County to Red River County and include many of Texas' major cities. Along this Balcones/Ouachita structural trend, a wedge of Mesozoic sedimentary rocks bury the Ouachita Mountains. These Cretaceous rocks form thermal aquifers. High geothermal gradients (up to 36°C/km or, equivalently, 2.0°F/100 ft) normally occur along fault planes in the region, and along areas penetrated by igneous plugs, although there are anomalies with closures of more than 3.0°F. High gradients are marked near oil fields along parts of the Luling and Mexia Fault Zones along the eastern boundary of this region. Deep circulating water apparently upwells along these faults. Two other high gradient zones include the Brushy Creek zone in Williamson and Milam Counties and the junction of Hill, Johnson, and Ellis Counties.

Table 8.2. Leading Texas Counties for Hydrothermal Wells and Springs.

COUNTY	NUMBER OF WELLS/SPRINGS	RANGE OF DEPTH (meters)	RANGE OF TEMPERATURE (°C)
Atacosa	96	146 to 1463	31 to 68
Frio	94	169 to 661	29 to 41
Bexar	55	124 to 1377	25 to 56
La Salle	50	152 to 1280	32 to 62
McLennan	48	287 to 1076	26 to 63
Dallas	43	272 to 1253	29 to 57
Zavala	41	224 to 1432	31 to 46
Dimmit	37	167 to 606	33 to 41
Ellis	34	244 to 1001	29 to 49
Gonzales	30	266 to 904	31 to 54

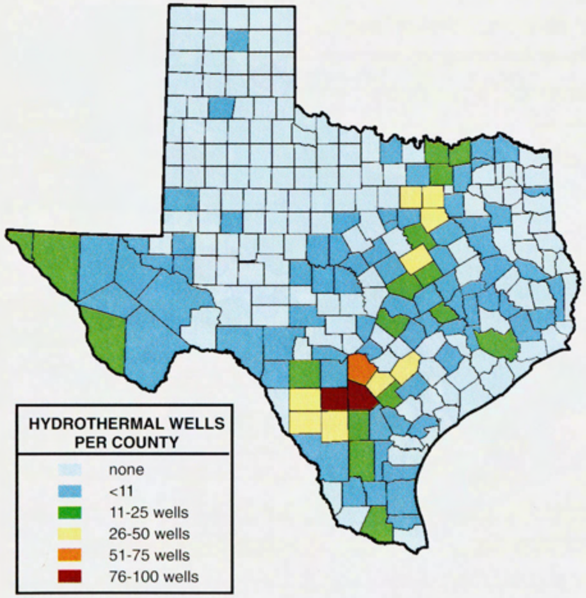


FIGURE 8.3. Texas Hydrothermal Wells and Springs.[17]

Four aquifers in Central Texas contain waters with acceptable temperatures, salinities, quantities, and drilling depths for development: Hosston/Trinity, Paluxy, Edwards, and Woodbine.[8] Of these, the Hosston/Trinity aquifer contains the most favorable resource because of its breadth, uniform thickness, rock properties, and the quality and temperature of its waters. Relative to the Hosston/Trinity, the Woodbine and Paluxy Sands aquifers in north central and northeast Texas have lower temperatures and a higher concentration of dissolved solids. Since these sands have not been extensively tapped for water supply, their hydrologic properties are conjectural. Nevertheless, several municipalities in Central Texas draw water from the four geothermal aquifers but, unfortunately, do not take advantage of the heat from their withdrawals.

Woodruff et al (1982)[15] surveyed areas for alternate energy sources on Air Force Bases in Val Verde, Bexar, and Travis Counties. In Bexar County, deep wells in the Hosston Sand aquifer yield water with temperature greater than 120°F and dissolved solids of less than 2,000 mg/l. The downdip portion of the Edwards aquifer (bad water line) produces water with high dissolved solids (2,800 to 4,700 mg/l), hydrogen sulfide, and over saturation with calcite. The Edwards aquifer is a limited geothermal resource, despite temperatures as high as 118°F. Because of higher salinities associated with warmer waters, there is a greater likelihood for corrosion and scaling of geothermal piping and equipment. Calcite and iron compounds may pose problems for some Central Texas wells.

Sorey identifies five Central Texas counties with particularly good low-temperature sedimentary basins in Cretaceous sandstone aquifers, namely Hunt, Limestone, Navarro, Falls, and Caldwell.[12] Since 1982, a U.S. Department of Energy geothermal demonstration project in Marlin (Falls County) has employed geothermal hot waters for space and water heating at the Torbett-Hutchings-Smith Memorial Hospital.[16] The facility's 3,900 foot deep well yields 600 gallons of water per minute from the Hosston Sands aquifer, with temperatures from 140° to 155°F.

Trans-Pecos. Another area with significant geothermal potential is the Rio Grande trough, a basin that extends from New Mexico into Texas near El Paso and continues along the Rio Grande for about 50 miles. The Trans-Pecos area is part of the Basin and Range province of the western United States. Here the crust is stretched and faulted into parallel mountain ranges and bolsons or long valleys filled with debris from nearby eroding mountains. A single thermal spring or closely spaced such springs can be indicative of a geothermal reservoir. In West Texas, the Basin and Range heat flow province provides from 1.5 to 2.5 heat flow units (1 heat flow unit (HFU) equals $0.0418\ W/m^2$). Here recharging ground water circulates to a depth of over one kilometer in a region of a relatively high thermal gradient. Henry proposed that the heat from hot springs emerging from the Presidio Bolson, Hueco Bolson, and the Big Bend region comes from an abnormally high thermal gradient (30° to 40° C/km) and a higher heat flow in this area due to the presence of a thin crust. He contended that the Presidio and Hueco Bolsons, a likely extension of the Rio Grande Rift into Texas, represented the best potential for geothermal development in this area. This is an area of extensive outcrops of extrusive and intrusive Cenozoic igneous rocks. Henry also noted that the Lobo Valley was a potential geothermal area because the ambiguity of its heat flow and the similarity in setting and proximity to the Presidio bolson, although hot springs and wells are absent.[18]

Geopressured Geothermal Resource

As has been stated throughout this document, the Gulf Coast geopressured geothermal energy reserve is essentially a resource to be mined. Given its non-renewable nature and the fact that detailed assessment documents are available from the extensive research of the late 70's and early 80's , the following discussion will only cover the resource's most salient characteristics.

Along the Texas Gulf Coast are two geopressurized bands of very thick sedimentary deposits. These deposits—up to 50,000 feet thick—are comprised of ancient bodies of sands that sunk into muds of older delta systems between the landward boundary of Miocene deposits and the edge of the outer continental shelf. Over time, the sedimentary sand deposits transformed into alternating series of sandstones and shales. The porous sandstone bodies became hydrologically isolated (cut off from other water sources) by subsidence and rapid burial within fault blocks. The weight of the impervious rock above the entrapped sedimentary pockets coupled with the decomposition of ancient organic matter into methane resulted in high pressure. In such geopressured zones, thermal gradients averaging 30°C per kilometer (18°F per 1,000 feet) coincide with pressure gradients that approach 1 psi per foot (more than twice the hydrostatic gradient resulting from water pressure alone).[13]

Because of their thickness and lateral extent, huge geopressured brine reservoirs can exist within the deep, porous rock deposits. These can be tapped using conventional drilling technology. Along the Texas Gulf Coast, thick sandstone units within the Frio and Wilcox Formations contain prospective geothermal resource areas called fairways with potential brine reservoirs.[19,20] The most promising of these is the Brazoria Fairway underlying Brazoria and Galveston Counties. It contains a several hundred foot thick section of sandstone over 13,500 feet deep with fluid temperatures greater than 300°F and relatively high permeabilities (between 40 and 60 millidarcy). Because of the characteristically low permeabilities of Wilcox sandstones, none of the fairways within the Wilcox Formation are as attractive as the Frio's Brazoria.

In the late 70's, the U.S. Department of Energy designed a program to gather data on the feasibility of obtaining geothermal energy from wells in the geothermal zones along the northern Gulf of Mexico. Data from DOE's "Wells-of-Opportunity" program (oil and gas wells drilled by industry and used for short-term tests) revealed that the brine in these deposits contained natural gas in quantities close to saturation. Other results showed that it was feasible to produce brine at rates of thousands of barrels per day and to inject the spent brine into relatively shallow hydropressured saline aquifers for disposal without adverse environmental impact.[21]

At Pleasant Bayou, Brazoria County, the U.S. Department of Energy sought to determine the technical feasibility of long-term brine production at high flow rates. The 16,500 feet deep test well drilled at Pleasant Bayou sustained production of 20,000 to 23,000 barrels of brine per day at an average wellhead temperature of 268° F and a gas/water ratio of 29 cubic feet per barrel. At this production rate (600 Mcf/day), the natural gas contained within the geopressured brine is roughly two and a half times higher than the average (230 Mcf/day) natural gas well in Texas.[22] The design

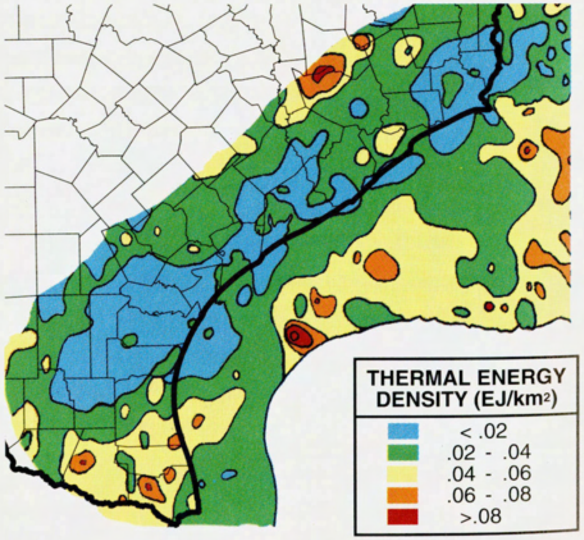


FIGURE 8.4. Distribution of Thermal Energy in the Geopressured Zones Along the Texas Gulf Coast.[17] Identifies total thermal energy contained down to a depth of 22,500 feet.

well test revealed a large sandstone aquifer estimated to be an 8 billion barrel fluid reservoir.[2]

The temperatures prevailing within this large reservoir represent a significant amount of low-grade heat. It has been estimated that over 3,000 quads of thermal energy are contained within the waters of sandstone deposits above 18,000 foot depth in the Northern Gulf of Mexico Basin.[17] **Figure 8.4** indicates the distribution of the thermal deposits within this region.

Major uncertainties remain about the reservoir drive mechanisms, the capability of these aquifers to produce brine for extended periods of time, and how much energy can be recovered. While subsidence may not be as severe as originally suggested, it warrants continued surveillance. From reservoir drawdown measurements, it has been discovered that models of conventional reservoir dynamics must be modified to account for the pressures prevailing in geopressurized zones. Further, although brine temperatures are warm by hydrothermal standards, they are still low for steam power plants and may therefore find more use in binary cycle conversions and direct heat applications. Seni and Walter (1993)[2] have shown the suitability of using geopressured geothermal fluids to improve oil recovery in South Texas, particularly in the heavy-oil reservoir of the Jackson Group. The possibility also exists of utilizing geopressured resources to produce potable water by desalination in areas of limited water supplies such as the lower Rio Grande Valley, to meet aquaculture and agriculture needs, to use in pulp and paper mills and sugar refineries, and to recover sulfur from salt dome deposits.[23]

There are other, less studied geopressured reservoirs in Texas in many places besides the Gulf Coast. The geopressured Delaware Basin of southeastern New Mexico and west Texas extends in depth from 8,000 feet to 23,000 feet, with pressures of 0.65 to 0.94 psi/ft and temperatures from 140°F to 340°F. No thermal resource assessments have been conducted for this basin. A small fraction of the Anadarko-Ardmore Basin extends into the Panhandle of Texas from Oklahoma. The basin lies 6,000 to 30,050 feet deep, has a fluid-pressure range of 0.52 to 0.85 psi/ft, and a temperature range from 140°F to 425°F.[24]

Hot Dry Rock

The geothermal resource suitable for sustaining hot dry rock technology can be inferred from subsurface temperature gradients. Because of heat conducting from the earth's interior, subsurface temperatures increase with depth. The resulting "geothermal gradient" depends upon the respective conductivity of various underground rock layers and the thickness of the earth's crust. Throughout Texas and the rest of the United States, the average thermal gradient results in a temperature increase of 30°C per kilometer of increasing depth (17°F per 1,000 feet). Where the crust is thin or where there is tectonic activity, thermal gradients can be higher than 30°C/km. **Figure 8.5** reveals general geothermal gradient ranges for Texas as compiled by Kron, Wohletz, and Tubb in 1991 for the Los Alamos National Laboratory.[25] The HDR resource is classified as low-grade in regions of normal to near-normal thermal gradients of 15° to 44°C/km, mid-grade with 45° to 59°C/km thermal gradients, and high-grade with gradients greater than 60°C/km. Figure 8.5 indicates that Texas contains a preponderance of low-grade HDR resource, a few regions with mid-grade resource, but no areas currently identified as high-grade. (A finer resolution map would no doubt identify some areas with locally high geothermal gradients; possibly even areas with high-grade HDR resource.) It is also observed that geothermal gradients tend to be higher in East Texas than West Texas. Although the Trans-Pecos hydrothermal region previously discussed exhibits gradients in the 30° to 40°C/km range—characterized as high relative to typical geothermal gradients in the area—the West Texas resource is not considered good enough to exploit hot dry rock for power generation.[26]

While no substantial exploration or experimentation on hot dry rock geothermal resources in Texas has occurred, an assessment by Los Alamos Na-

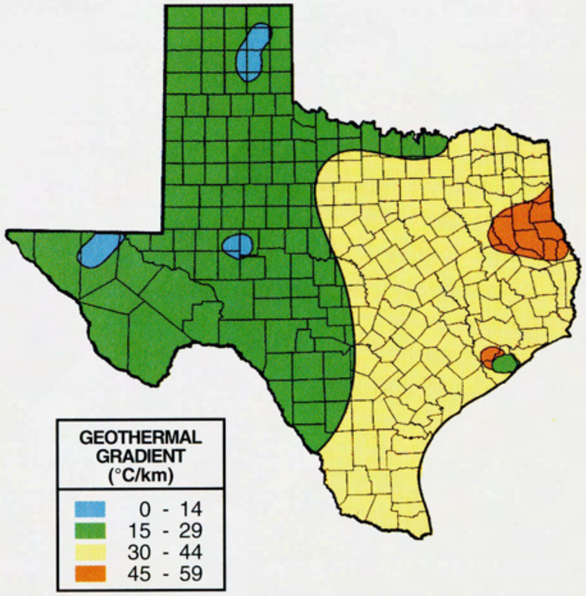


FIGURE 8.5. Typical Geothermal Gradients in Texas.[25] Texas does not have any major regions of high-grade (>60°C/km) resource for Hot Dry Rock technology.

tional Laboratory showed that Texas has an immense HDR resource base. Nunz identifies the total HDR resource in Texas as 2,300,000 quads, of which 825,000 quads is potentially useful. (See glossary for definitions of "total resource base" and "potentially useful resource base".) Of this potentially useful resource base, 506,000 quads is considered suitable for electricity generation, 233,000 quads suitable for process heat applications, and 87,000 quads suitable for space heat.[14] These values dwarf the current 10 quad per year energy requirement of the state.

Importantly, resource potential values provided in other chapters within this document are based on sustainable annual resource contributions. In contrast, the numbers quoted by Nunz represent the total heat energy derived from a thermal "snapshot" of the top seven kilometers of rock beneath Texas. Geothermal resource values are not typically quoted in terms of sustainable, annual extraction rates (although such values might be derived from the thermal "recharge" of the accessible geothermal layer). Nonetheless, even modest utilization of this HDR resource could supply a large portion of the State's energy, and likely on a perpetual basis.

Magma Resources

On average the crust that covers the molten rock of the earth's interior is approximately 30 kilometers thick. Although magma is the hottest of the geothermal resources, ranging from 650-1200°C, it still must be accessible to be of any value. For the foreseeable future, technology to extract energy from magma does not appear to be feasible in Texas. Magma underneath Texas is simply too deep to provide much promise as a future energy resource for the state. However, where magma is found closer to the earth's surface such as in the tectonically active western coastal region of the U.S., it may prove to be an immense perpetual resource.

Summary

The regions of Texas containing good hydrothermal, geopressured, and hot dry rock resources are summarized in **Figure 8.6**. The map suggests that hydrothermal resources distributed through Central Texas and the Trans-Pecos contain many sites with low grade heat suitable for such applications as space and district heating of buildings, enhanced oil recovery, aquaculture (fish farming), and various heating and drying processes. The geopressured-geothermal resources located along the Texas Gulf Coast provide somewhat higher temperatures, but since they are much deeper and more expensive to exploit, may be of most value in limited industrial applications such as enhanced oil recovery and water desalinization. High geothermal gradient areas throughout the state may also be suitable for utilization.

TABLE 8.2. Total Texas Thermal Resource From Three Geothermal Sources.

RESOURCE	TOTAL RESOURCE (Quads)	ACCESSIBLE RESOURCE (Quads)
Hydrothermal	80	80
Geopressured	3,020	2,100
Hot Dry Rock	2,300,000	825,000

Quantification of Resource Base

The thermal energy potential of each of the resources described above is summarized in **Table 8.2.** These numbers represent the total thermal energy reserve of hydrothermal, geopressured, or hot dry rock resources as defined by sources cited above. Geothermal resource values are not typically quoted in terms of sustainable, annual extraction rates.[27] The "Total Resource" values of Table 8.2 are therefore computed as the total thermal energy contained in a material layer of some appropriate depth and in reference to a threshold temperature (specific definitions are provided in the Glossary). In addition, accessible resource values are achieved by assuming an appropriate fraction of the total resource base. The following fractions are assumed: hydrothermal = 100% accessible, geopressured = 70% accessible, hot dry rock = about 40% accessible (the HDR accessible value listed in the table is adopted from Nunz[14]).

Space heating in the 120° to 170°F range represents the largest potential use of low temperature hydrothermal energy in Texas. Generally high up-front capital costs compared to conventional resources, low fossil fuel costs and neglect of accounting for environmental impacts serve as barriers for exploration of geothermal resources. In small projects, the resource can last a long time if proper management procedures are followed, especially if spent geothermal water is injected into the reservoir and pumping does not exceed the natural discharge rate from springs. With the addition of a heat exchanger to already drilled wells, many Central Texas municipalities could take advantage of the now wasted heat from the underground waters they pump for various purposes.

Direct use of the geopressured geothermal resource for thermally enhanced oil recovery could be economically viable in South Texas because of the collocation of resources below heavy-oil reservoirs. Possibilities exist for other direct uses of geopressured-geothermal resources, with desalination, agriculture/aquaculture projects, and supercritical fluid processing for waste remediation as the most promising for near term development. In areas of natural subsidence, the exploitation of this resource is questionable. Long-term flow tests and verification are required for development of geopressurized resources.

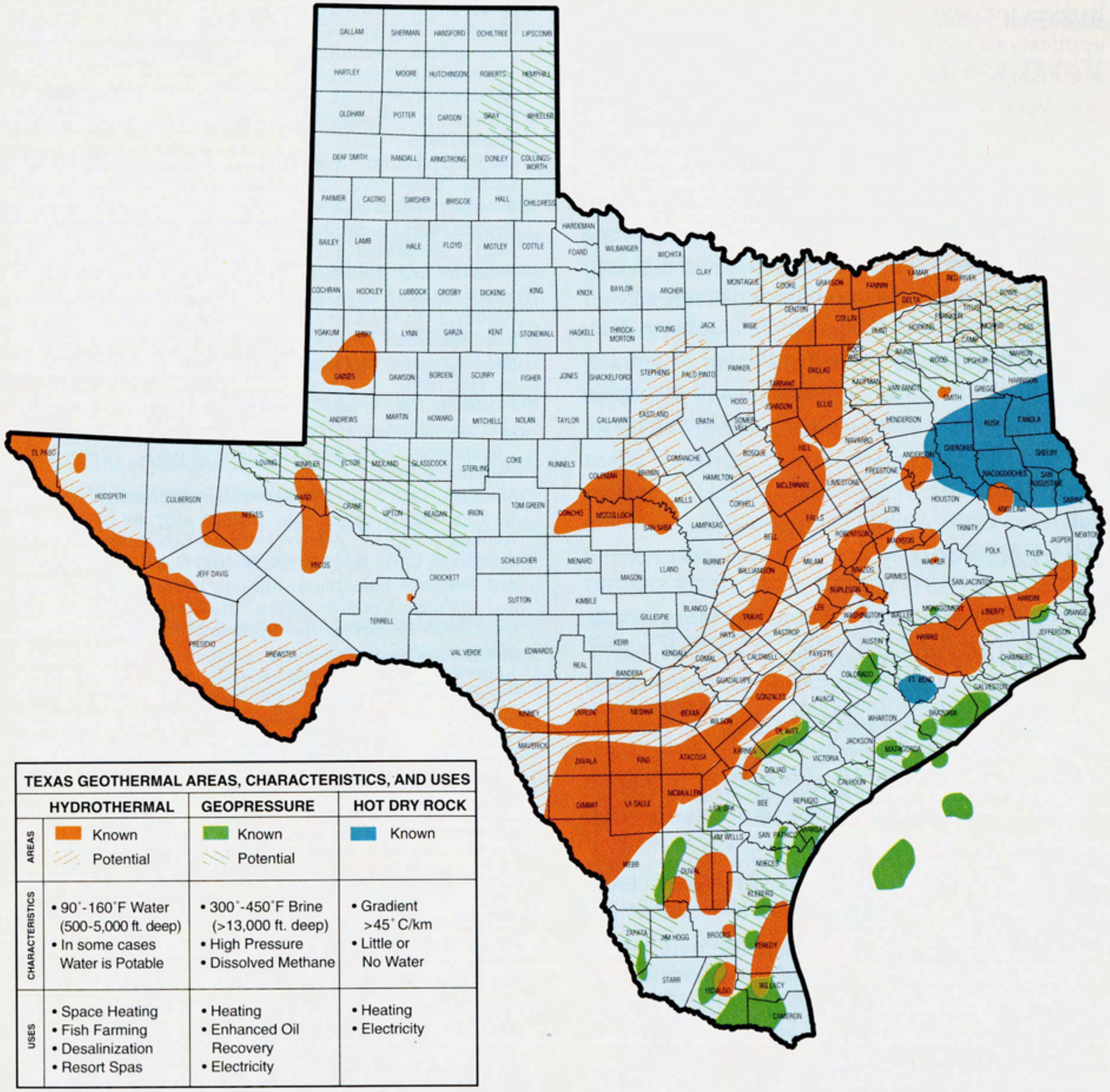
Support for hot dry rock and magma development has yet to be determined, but they hold promise as abundant and perpetual sources of energy.

Resource Variability

To its advantage, geothermal utilization does not depend upon cyclical forces as does wind and solar energy. Heat from within the earth does not vary with day or season, but rather, on geologic time scales of millions of years. Long-term variations in climate can, however, affect aquifer recharge rates which in turn will impact the storage and use of the geothermal resource.

RECOMMENDATIONS

Texas has an abundance of low temperature hydrothermal resources. Cities such as Marlin, Corsicana, Hubbard, and Ottine can demonstrate successful utilization of the waters for space heating. Primary



TEXAS GEOTHERMAL AREAS, CHARACTERISTICS, AND USES

	HYDROTHERMAL	GEOPRESSURE	HOT DRY ROCK
AREAS	🟧 Known ▨ Potential	🟩 Known ▨ Potential	🟦 Known
CHARACTERISTICS	• 90°-160°F Water (500-5,000 ft. deep) • In some cases Water is Potable	• 300°-450°F Brine (>13,000 ft. deep) • High Pressure • Dissolved Methane	• Gradient >45° C/km • Little or No Water
USES	• Space Heating • Fish Farming • Desalinization • Resort Spas	• Heating • Enhanced Oil Recovery • Electricity	• Heating • Electricity

FIGURE 8.6. Summary Map of Texas Geothermal Resources. Location and boundaries of geothermal areas are approximate.

barriers for development of direct use geothermal applications seem to be the difficulty of finding locations where the resource is adequate for exploitation. Because of indications of some hydrothermal resource in older Paleozoic strata further west of the Balcones/Ouachita trend (the hot water well at South Bend, Young County, for example), a more thorough characterization of these strata seems warranted. The Trans Pecos region also, could benefit from a more thorough characterization.

Texas should update the USGS Geotherm database for the State by including the last 13 years of thermal well records and then make it readily available to researchers, industry, and local governments.

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