



## CHAPTER 7

## GEOTHERMAL ENERGY

## Introduction

Texas has the ability to be a U.S. leader in reducing the environmental impact of fossil fuel electrical generation by using renewable geothermal resources that range from just below the Earth's surface to deep within the Earth. This geothermal resource is important because its production inside the Earth is constant and independent of the many natural, changing surface conditions that affect other renewable energy resources. Multiple studies of Texas geothermal resources have been completed. The Department of Energy funded geothermal research projects in the 1970s and 1980s as part of a geopressured-geothermal resources study for the Gulf Coast region. There are many reports on Texas geopressured-geothermal resources available at <http://www.osti.gov>. On a statewide scale, the Texas geothermal resource was initially investigated and mapped by Charles Woodruff, et al. (1982). The map they produced is still available through the University of Texas, Bureau of Economic Geology. As part of the Texas Renewable Energy Resource Assessment in 1995, Janet Valenza completed the Geothermal Assessment, Chapter 8. In 2006 the Massachusetts Institute of Technology (MIT) Report: The Future of Geothermal Energy, Impact of Enhanced Geothermal Systems for the 21<sup>st</sup> Century was published describing all of the United States' geothermal resources, including specific tables on resources for Texas. Recently, the Texas Comptroller of Public Accounts released a report on energy in Texas, including a section on geothermal resources (May 2008). This chapter is an extension of these reports with the goal to update and augment the knowledge base of geothermal resources specifically in Texas.

### Significance of Resource: Historical, Present and Future Uses

Geothermal energy can be defined by splitting it into its components, *geo* meaning 'Earth' and *thermal* meaning 'heat', making geothermal the heat within the Earth. Geothermal energy represents the natural, internal heat of the Earth that is stored within the rock and fluid. In this chapter, the "geothermal resource" is the energy from inside the Earth that is accessible for humans to use.

Most of the heat inside the Earth originates from the natural decay of radioactive elements. Through various thermal processes, this heat is slowly transferred to the surface of the Earth where it can be accessed to provide for various human needs. The Geo-Heat Center at the Oregon Institute of Technology (<http://geoheat.oit.edu>) devised a simplified geothermal classification system based on the temperature of the resource (**Exhibit 7-1**). This classification system defines geothermal energy in terms of temperature (low, moderate, and high temperature resources) and how the geothermal heat can be utilized. As **Exhibit 7-1** indicates, geothermal energy has many uses besides the most well-known applications—electrical power production and geothermal heat pumps. For the purposes of this chapter, geothermal resources are divided into three main categories: Geothermal HVAC systems, Direct Use of heated water, and electrical power production.

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**EXHIBIT 7-1** Temperature-Based Classification of Geothermal Energy

Resource Temperature	Best Applications For Geothermal Heat*
Surface Temperature (40°F to 80°F)	Geothermal HVAC systems for homes and buildings
Low Temperature (70°F to 165°F)	Direct Use: agriculture and greenhouses, aquaculture (fish farming), mineral water spas and bath facilities, district water heating, soil warming, fruit & vegetable drying, concrete curing, food processing
Moderate Temperature (165°F to 300°F)	Binary fluid generators for electrical production; Direct Use: absorption chillers, fabric dyeing, pulp and paper processing, lumber and cement drying, sugar evaporation
High Temperature (>300°F)	Electricity production, minerals recovery, hydrogen production, ethanol and biofuels production

\*Uses of geothermal energy adapted from the Geothermal Education Office materials.

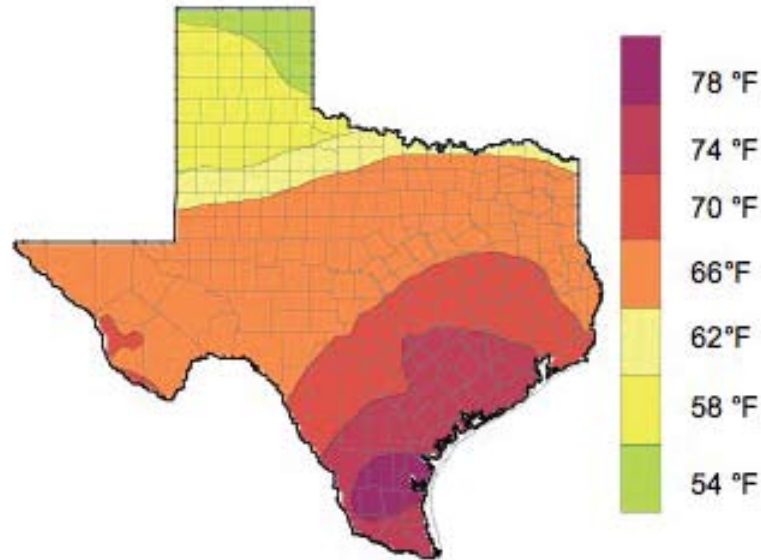
**Geothermal HVAC Systems.** One of the simplest ways to make use of the geothermal resource is through Geothermal Heating, Ventilation and Air Conditioning (HVAC) systems for homes and buildings. It is also known as geothermal heat pumps (GHP), ground source or ground coupled heat pumps (GSHP or GCHP), or geexchange systems. This application of geothermal resources in Texas can be used by anyone from the average homeowner to the large commercial developer for the heating and cooling of buildings. According to the U.S. Environmental Protection Agency (EPA), geothermal heat pumps are the most energy-efficient, environmentally clean, and cost-effective systems for temperature control.<sup>2,3</sup> From 2002 to 2006 there was a 71 percent increase in Geothermal HVAC system installations for residential applications in the United States.<sup>4</sup>

There are three components to a Geothermal HVAC system: 1) the local soil and geological environment; 2) the thermal transfer exchange system, or “loop field;” and 3) the mechanical system or heat pump and the ventilation ducts inside the building. Most installations are done by small to medium sized mechanical engineering or HVAC companies who coordinate with the building contractor. Project coordination includes design of the loop system, a bore-hole drilling contractor, pump installation inside the building, and a ventilation contractor for the building. These systems have reduced maintenance costs because the equipment is typically inside the building and loops are below ground so they are not susceptible to vandalism or extremes in weather conditions.

Once considered primarily a technology for the colder climates, geothermal heat pumps have advanced with improved system designs that are sized for both air conditioning and heating needs. These can work anywhere in Texas if the system is properly designed for the local climate. The geothermal heat pump uses a fluid loop to exchange the excess heat or cold inside the building with the upper few hundred feet of the Earth. Anyone who has gone underground into a natural cavern has experienced the constant temperature that exists within the subsurface. The temperature of the ground and/or groundwater from 10 to 50 feet (3–15 m) beneath the Earth’s surface remains relatively constant year round and is able to stabilize the inside air temperature changes from outside weather. In this depth range, the ground temperature in the Panhandle is as low as 54°F ± 2°F (12°C) and in South Texas it is as high as 78°F ± 2°F (25°C) (**Exhibit 7-2**).<sup>5</sup>

By using the constant ground temperature as a starting point for additional cooling or heating of a building, less energy is used when compared to a conventional HVAC system which relies on heat transfer from outside air temperatures. Various studies by the Geothermal Heat Pump Consortium have shown that approximately 70 percent of the efficiency is derived by the Geothermal HVAC system through the ground loop fluids exchanging with the Earth.<sup>5</sup> These systems are referred to as an “offset” technology because of the reduction in electrical power production resulting from their installation. This can reduce monthly cooling and heating energy usage by 40 to 70 percent depending on the heat pump unit, energy efficiency of the building, and the local climate.<sup>5</sup> In addition to reduction in expenses for cooling and heating, excess heat may also be used to heat hot water tanks and swimming pools.

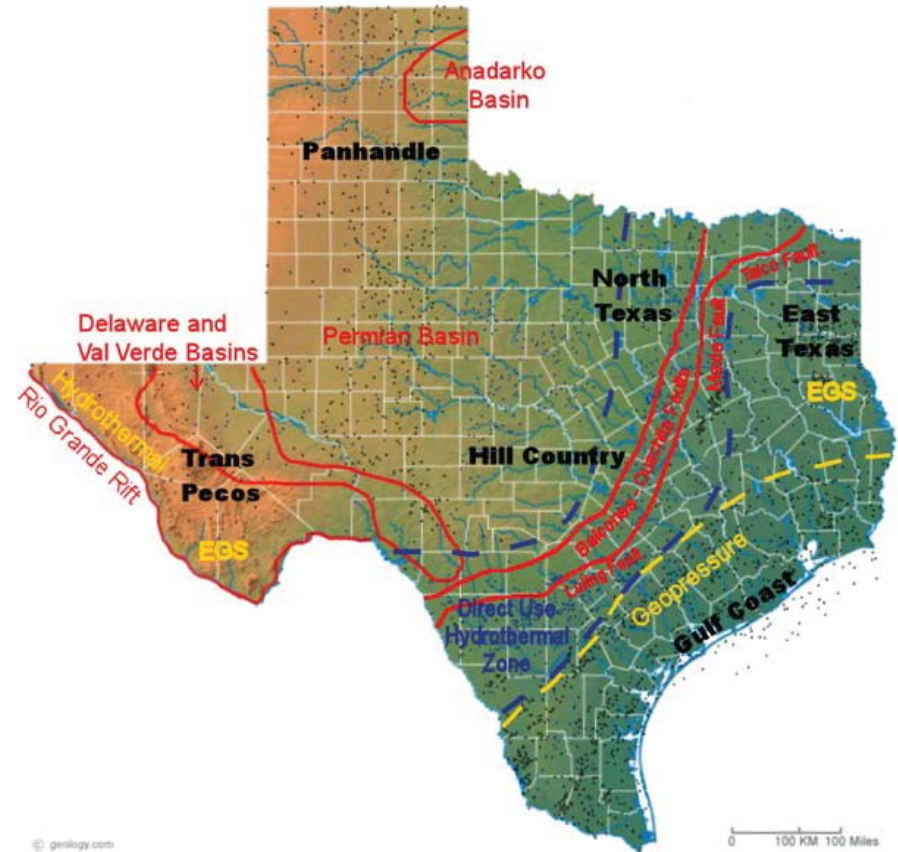
EXHIBIT 7-2 Average Texas Surface Groundwater Temperatures, a subset of the U.S. map by Gasss, 1982.<sup>9</sup>



**Direct Use of Geothermal Resources.** The Geo-Heat Center at the Oregon Institute of Technology identified 271 cities and communities in the United States with access to water for Direct Use geothermal applications. Forty three of these communities are in Texas.<sup>10</sup> The geothermal resources in the low to moderate temperature range (shown in **Exhibit 7-1** and **Exhibit 7-3**—Central Texas Hydrothermal Zone) can be extracted from subsurface warm water and used in various industrial and commercial processes including commercial spa health facilities and therapy pools, greenhouses, aquaculture, various food processing facilities, and a host of other applications (**Exhibit 7-1**). Spent fluids from geothermal electric plants can also be collected and used again for other industrial applications in a “cascading” process.

Developing the direct use of geothermal energy typically involves a production facility, a well and pump to bring the warm water to the surface, a mechanical system (piping, heat exchanger, controls, etc.) to deliver the heat to the processing space, and a disposal system in the form of an injection well or storage pond that receives the cooled geothermal fluid.

EXHIBIT 7-3 Generalized geographic and geothermal location map. Wells locations shown by blue dots (less than 4000 feet) and black dots (greater than 4000 feet). High temperature resources are shown in yellow text and low to intermediate temperatures are in blue. Geologic features are highlighted in red. Map produced by the SMU Geothermal Laboratory.



The following are types of Direct Use applications to focus on in Texas for development.

**Community District Systems** During the 19<sup>th</sup> century, hot water began to be used for local space heating applications in the United States. However, it wasn't until the 20<sup>th</sup> century that more widespread use of geothermal heat became popular. District geothermal systems distribute hydrothermal water from one or more geothermal wells through a series of pipes to several houses and buildings, or to blocks of buildings. District heating can save consumers 30 to 50 percent of the cost of heating compared with natural gas.<sup>7</sup> The geothermal production well and distribution piping replace the fossil-fuel burning heat source of the traditional heating system.

**Spa Health Facilities and Therapy Pools** Warm water from hot mineral springs or shallow geothermal wells have been used by humans for bathing, soaking and recreation throughout history. Today's spa facilities and therapy pools use warm water with methods similar to those used in ancient times as the primary means of health care and restorative recreation.

This past decade has seen a revival in the spa industry with 1 in 4 Americans having visited a spa and over 32 million active spa-goers worldwide. In 2006 there were 110 million spa visits generating \$9.4 billion of revenue in the U.S. with an increase of 16 percent from 2005 to 2006.<sup>8</sup> Spa facilities and pools range from multi-million dollar resorts with luxury spas to reasonably priced public bathhouses and natural pools. The economic impact to communities is largely due to the draw of visitors into the area, with related expenses for food, lodging, and recreation needs as well as employment and housing for staff of the facilities.<sup>9</sup> Currently there are approximately 200,000 people employed in the U.S. Spa industry. In West Texas for example, at Chianti Hot Springs there are over 80,000 visitors annually.<sup>8</sup>

**Agribusiness Industry** Direct use of geothermal resources has been well received within the agribusiness industry, with the two primary uses being greenhouses and aquaculture (fish farming). Geothermal water (100°F/38°C and above) has been used in at least 40 greenhouses since the late 1970s, in the western states.<sup>10</sup> Many of these facilities cover several acres, raising vegetables, flowers, houseplants, and tree seedlings. The DOE Energy Efficiency and Renewable Energy program reports that greenhouse operators using geothermal resources estimate energy savings of about 80 percent compared to fuel costs for traditional energy sources.<sup>7</sup> Aquaculture ponds and ground heating to extend the growing season for specialty crops (85°F water and above) exist in 12 states. These Direct Use applications are usually in relatively rural settings due to the need for large amounts of land and can stimulate the economy for a rural area..

**Geothermal Electric Generation Application.** Electric power generation development using geothermal energy has been very active worldwide, with systems in the United States developed since the 1960s. Most of the focus and knowledge are on geological locations that are tectonically active, such as volcanoes, geyser fields, and hot springs in the western United States. These are areas where heat from within the Earth has reached sufficiently shallow depths to make the economics of heat recovery feasible for large scale power production. As of 2008, geothermal electricity is produced in California, Nevada, Utah, Idaho, Hawaii, Alaska, New Mexico, and Wyoming, with projects currently under development in Oregon. With increased research on Enhanced Geothermal Systems (EGS) by the U.S. Department of Energy and private companies, many other states, including Texas, are being considered for the development of geothermal energy production.

Depending on the technology used and the location, geothermal electric power can be generated using temperatures as low as 165°F (74°C) in Alaska, to approximately 200°F (93°C) in the Texas Gulf Coast region. The variation in useable temperatures is primarily due to the temperature differential needed between the surface cooling cycle and the hot fluid temperatures in the binary fluid turbine. These binary systems use a secondary fluid in a closed loop for the working fluid, which flashes to steam and turns a turbine. This allows the geothermal fluid that is lower than the boiling point of water to be used for heat extraction before being injected back into the ground.

Much of Texas has geothermal resources that are accessible for geothermal electrical production. The three primary resource areas are shown in Figure 8.2 as the conventional hydrothermal and Enhanced Geothermal Systems (EGS) of West Texas, the geopressed formations along the Gulf Coast, and the EGS of East to South Texas.

## Development Issues for Texas: Special Considerations for Large-Scale Use

Each of the different types of geothermal development has preferred implementation areas in Texas. Geothermal HVAC systems have the most widely distributed potential for installation, with all regions of Texas being included. The most expensive places for installation are those with basement rock at the surface, such as the Hill Country and parts of North Texas due to the increased cost related to drilling boreholes instead of installing a horizontal loop field. The most immediate Direct Use application of geothermal resources is limited to the Balcones—Ouachita, Luling—Mexia—Talco Fault structures which form the northern and western boundary of the Texas Coastal Plain. Here the heated water is less than 4,000 ft (1.2 km) below the surface and is in certain places already being produced

for community water supplies.<sup>17,18</sup> Use of this water can be as general as preheating of hot water for commercial buildings, or as focused as use in high-end spas. The concern about widespread development is the ability of the aquifers to sustain long term high flow rates. Since community water systems use these aquifers for drinking water, a constant supply is necessary. One way to reduce stress due to over development of the aquifers is to allow the thermal energy to be extracted initially then cascade the cooler water into a community water supply. This procedure would eliminate the existing need for cooling towers.

Generating electricity from Texas' geothermal energy has increased the value of the resource because of the widespread potential for development and its minimal environmental impact. Geothermal power plants have additional considerations compared to the other geothermal resource categories because of size and resource demands. Below is a list of concerns that can be expected to be raised during project development, along with appropriate solutions.

The most common concern about geothermal power development relates to water: availability, quality, and disposal. Geothermal energy production requires large volumes of water (thousands of barrels per day) at temperatures in the range of 200°F (93°C) and above. Billions of barrels of water are currently being produced across Texas from oil and gas wells. This water is typically high in minerals and salt, and thus would contaminate surface waters and soil if disposed of at the surface, because of this the water is injected back into the subsurface. Similarly developed geothermal fields are a closed loop, where water is produced from one well, its heat extracted using a binary electrical unit, and then injected back into the ground. In this case the purpose is three fold: 1) reducing the potential for surface impacts, 2) extracting more heat from the system, and 3) preventing drawdown of fluids in the system. Thus reinjection prevents overproduction of the reservoir and extends the life of the power plant.

The surface environmental impact on an area with a geothermal power plant is limited to the plant, wells, and pipelines with the common concern being noise levels around the wellhead. Most of the areas favorable for geothermal electricity production have an existing infrastructure already built by the oil and gas industry; therefore, only limited additional impact is expected on-site.

Geothermal binary fluid turbines produce little to no air contaminants because of the closed loop working fluid design. In flash steam plants (not likely to be used in Texas) trace amounts of hydrogen sulfide, nitrous oxide, sulfur dioxide, and carbon dioxide may be emitted but only at levels less than present air emission standards.<sup>16</sup> Projects incorporating co-production or geopressure wells could produce small

amounts of hydrocarbon condensates, which require appropriate handling when these resources are extracted from the fluid as regulated by the Texas Railroad Commission. The extracted hydrocarbons can be collected and sold or used as part of a preheating system.

Binary geothermal power plants can be air or water cooled. In areas with limited access to surface water, such as lakes or rivers, a forced air cooling tower is the recommended method for the cooling cycle of the binary system. Forced air cooled plants use no fresh water.<sup>16</sup>

Geothermal resources have a competitive edge compared to some other renewable energy resources. Unlike electricity from wind and solar, geothermal is considered baseload capacity and is competitive with other baseload technologies such as coal and natural gas plants. Geothermal power projects can be located in major population centers or in rural communities and scaled to meet existing needs. For the oil and gas industry, it enhances the economics and increases the longevity of their oil and gas fields by decreasing the cost of water production.

## Texas Geothermal Resources

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The Texas geothermal resource is as extensive as the state is big. The entire state has geothermal resources that can be used by individuals, businesses, schools, and the government. The accessibility of the geothermal resource varies by geographic region and in some instances by county. One aspect of the geothermal resource that is fairly consistent throughout Texas is the Geothermal HVAC system resources. Although the ground level geologic setting will not be covered in this section, these systems are an important part of the geothermal economic package because they can reduce overall energy consumption in Texas by thousands of MW. The following section will detail the resources for Direct Use applications and electrical production from geothermal resources.

## Texas Geothermal Resource Details

For a geothermal resource to be commercially viable, heat must be removed from the ground at a rate and a cost that returns a reasonable profit. The economics associated with accomplishing this depend on: 1) the quality of the resource, principally its temperature, depth, and fluid characteristics; and 2) the ease and rate with which geofluids can be extracted and then reinjected. These factors are a function of geology, i.e., rock type and layer thickness, porosity and permeability, and thermal history. First the resources related to Direct Use applications are discussed, then the deeper resources for geothermal electrical production.

## Direct Use Geothermal Resources

Low to moderate temperature wells and springs have been in use in Texas for decades.<sup>17, 18</sup> Shown in **Exhibit 7-3**, Texas has multiple major hydrothermal regions with the two most prominent ones discussed below—the Central Texas fault zones and Trans-Pecos region of far West Texas.

**Central Texas.** Central Texas has had a history of geothermal activity from springs and mineral waters which has supported over 50 spas since the late 1800s through today. The faults in the area allow for deep circulation of fluids that upwell along fractures bringing the heat to an accessible depth. They contain waters with acceptable temperatures, salinities, quantities, and drilling depths for many Direct Use geothermal projects (**Exhibit 7-1**). Springs such as San Pedro Springs, Comal Springs, San Marcos Springs, Barton Springs, and Salado Springs are found along the Balcones—Ouachita fault trend. Shallow aquifers (4,000 feet or less) along the Balcones—Ouachita structural trend have elevated temperatures reaching as high as 153°F (67.2°C) in Marlin. Some areas have artesian flow. Waco used to be named “Geyser City” because of this feature, although today with increased water consumption the water table has dropped and wells are no longer artesian. Beyond the main Balcones—Ouachita faults are other warm zones. To the east and north are the Luling—Mexia—Talco Faults which bring warm water to Bryan (117°F (47°C) at 3,000 ft (915 m)) and as far north as Paris (115°F (46°C) at 3,400 ft (1030 m)). On the western side of the Hill Country the Hickory aquifer, (with water of 130°F (54°C) from approximately 4,000 ft (1220 m)) is used for municipal water for communities such as Eden. In the Dallas County area the drinking water wells ranged in temperature from 106°F (41°C) at 2,600 ft to 135°F (57°C) at 4,000 ft and reported to be cooled before using. These areas are considered prime locations for geothermal Direct Use applications. The total resource stretches in a band from Val Verde County to Red River County and includes many of Texas’ major cities that currently spend resources to cool the water rather than using the excess heat (**Exhibits 7-2 and 7-3**).<sup>17, 18</sup>

**Trans-Pecos, West Texas.** Another area with significant geothermal potential is the tectonically active area of the Rio Grande Rift, an extensional zone that runs from Colorado to New Mexico and into Texas, near El Paso, and continues along the Rio Grande for over 300 miles to the Big Bend region (**Exhibit 7-3**). Igneous and sedimentary rocks both at the surface and deep within the structure have elevated the regional temperatures.<sup>11, 20, 21</sup> Along the Rio Grande floodplain are Indian Hot Springs, located in Hudspeth County, where geothermal fluids surface from a series of springs, the hottest is 117°F (47°C). Other springs are the Boquillas Hot Springs in Big Bend National Park and in the Chianti Mountains of West Texas; the Chianti Hot Springs has 110°F (43°C) geothermal waters. The area

is known for its recharging ground water that circulates to a depth of over 3,400 ft (1030 m) creating known geothermal resources in the Presidio Bolson, Hueco Bolson, and the Big Bend area. This represents the best potential for conventional hydrothermal geothermal development in Texas and includes El Paso, Culberson, Hudspeth, Jeff Davis, Presidio, and Brewster Counties.<sup>20, 21</sup>

## Geothermal Resources for Electrical Production

### Geopressured Resources

A geopressured resource consists of highly pressurized hot brine, due to water trapped during the burial process. These resources often are saturated with methane and found in large, deep aquifers. Wells drilled into this resource flow pressurized to the surface. Water temperature can range from 190 to over 400°F (90—200°C). Three forms of energy are useable in geopressured wells: 1) *thermal* from the high temperatures, 2) *hydraulic* from the high fluid flow pressure, and 3) *chemical* from the dissolved methane in the fluids.

There are two parallel geopressured bands of very thick sand deposits that follow the Texas Gulf Coast line (**Exhibit 7-3**). These are in fact, layers or lenses of sands that were deposited by ancient delta systems, cut off from other water sources by subsidence and rapid burial. The weight of the impervious rock above the entrapped sand pockets, coupled with the decomposition of ancient organic matter into methane, resulted in high pressure zones. These are considered the most important resource of its type in the U.S. These rocks can be up to 50,000 feet thick (15 km), but more commonly are drilled to depths of 8,500 to 18,000 ft (2.6 to 6 km).<sup>15</sup>

Because of their thickness and lateral extent, huge geopressured brine reservoirs exist within the deep, porous rocks of the Gulf Coast. Thick sandstone units within the Frio and Wilcox Formations contain prospective geothermal resource areas called fairways, with their large brine reservoirs.<sup>22, 23</sup> Sands in the fairways can be several hundred feet thick with temperatures over 300°F (150°C) and relatively high permeability. In these geopressured zones, thermal gradients averaging 18°F/1,000 ft (30°C/km), coincide with geopressure gradients that approach 1 psi per foot (more than twice the hydrostatic gradient resulting from water pressure alone).<sup>22</sup>

A U.S. Department of Energy (DOE) program that spanned from the 1970s to the mid 1990s culminated in a geopressure power plant in Brazoria County at Pleasant Bayou between 1989–1990 that produced one MW of electricity.<sup>24</sup> The production well was 16,500 ft (5 km) deep and sustained flow rates of 20,000 to 23,000 barrels of brine per day, with an average wellhead temperature of 268°F

(131°C) and a gas content of 29 cubic feet per barrel. At this production rate (600 Mcf/day) the natural gas produced with the geopressured brine is roughly two and a half times higher than the average (230 Mcf/day) natural gas well in Texas.<sup>25</sup> The five-year geopressure well test revealed a large sandstone aquifer estimated to contain enough fluid for a three MW power plant to operate at least 10 years.<sup>26</sup>

Other wells used in the DOE “Wells-of-Opportunity” program (oil and gas wells drilled by industry and used for short-term tests) revealed that the brine in Gulf Coast deposits contained natural gas in quantities close to saturation. Results showed that it is feasible to produce brine at rates of thousands of barrels per day and to inject the spent brine into relatively shallow saline aquifers for disposal without adverse environmental impact.<sup>26</sup>

The temperatures prevailing within this large geopressure reservoir represent a significant amount of heat. It has been estimated that over 5,100 EJ are contained within the Texas sandstone deposits.<sup>27, 28</sup> Uncertainties remain about the reservoir mechanics, particularly the capability of these aquifers to produce brine for extended periods of time, and the amount of energy recoverable. Models of conventional reservoir dynamics must be modified to account for the pressures prevailing in geopressurized zones and the system interconnectivity through faults. The hot brine temperatures (200 to 400°F (93—204°C) could be best used for binary cycle conversion power plants.

There are other, less studied geopressured reservoirs in Texas. The geopressured Delaware Basin of West Texas (**Exhibit 7-3**) extends from 8,000 ft to a depth of nearly 30,000 ft (2.4—9 km), with pressures of 0.65 to 0.94 psi/ft and temperatures from 140 to 400°F (60—200°C).<sup>31, 32</sup> Recent funding by the DOE and SECO assisted in expanding existing data to over 5,000 wells and over 8,000 temperature-depth points for analysis as part of an investigation of the Delaware and part of the Val Verde Basins.<sup>31, 32</sup> The counties included in this study are Ward, Loving, Winkler, Reeves, Pecos, Terrell, Crockett and Hudspeth. Analysis of the temperature data suggests there is complex variability in the thermal gradient throughout the region. Numerous strata from the Devonian 31 formation through the Ordovician Ellenberger formation show porosity and permeability sufficient for heat extraction for absorption chillers and electrical power generation.

A small fraction of the Anadarko Basin extends into the Panhandle of Texas from Oklahoma (**Exhibit 7-3**). The basin contains between 6,000 to 30,000 ft of sediment and has a fluid-pressure range of 0.52 to 0.85 psi/ft, and a temperature range from 140 to 425°F (60—220°C).<sup>32</sup> A recent geothermal investigation of South—Central U.S., including this basin, has been conducted by Negraru, Blackwell, and Erkan, (2008).<sup>49</sup>

## Coproduced and Stranded Resources

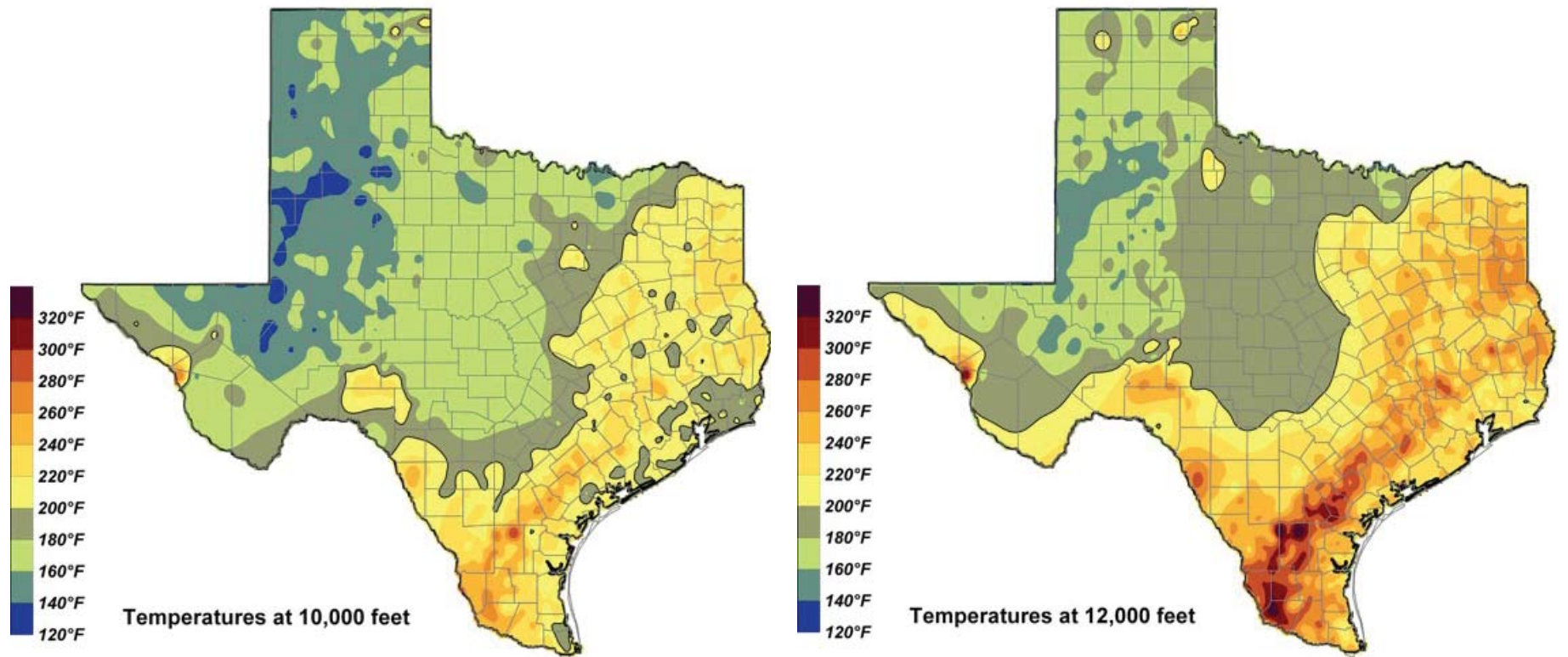
Within sedimentary basins, two distinct geothermal resource categories are found: coproduced and stranded.<sup>31, 32</sup> Stranded geothermal resources are geothermal fluids left in an oil and gas field after the extraction of hydrocarbons is completed. Oil and gas companies try to avoid water production due to the additional expenses for separation and disposal. This resource estimate is included in the overall geopressure and Enhanced Geothermal Systems (EGS) estimates, but is unique in that it is a resource known in detail from drilling, but currently being avoided by oil and gas companies rather than developed. The use of horizontally drilled wells are specifically of interest in developing Texas geothermal resources, since their large intercepted area makes them good heat exchangers for EGS designs.

Coproduced fluids occur when oil and/or gas is pumped from a well along with hot water and economically extracting all of them at the same time. In these cases the well produces adequate hydrocarbon volumes for the well to remain economical with the additional expense of water disposal. In other instances, a well is drilled primarily for gas but the reservoir is water wet and the gas is dissolved in the water. Production of the gas results in excessive amounts of water. If the water is sufficiently hot (~200°F/93°C or more) and the flow volume is suitably high, then electric power can be produced. By developing electrical energy from these fluids, it extends the life of the well through the value added of the electricity.

Temperatures at 10,000 to 12,000 ft (3 to 3.7 km) have been calculated using uncorrected bottom-hole temperatures from oil and gas well logs (**Exhibit 7-4**). Actual temperatures in the ground are normally higher than the well log bottom-hole temperature because the circulation of drilling fluids cools the deep formations. The Permian Basin is the coldest region with temperatures starting at 120°F (49°C) at 10,000 feet (3 km). South Texas has the highest temperatures at 10,000 ft, reaching 282°F (138°C) (Figure 8.3).<sup>36</sup> At 12,000 ft (3.6 km) the South Texas uncorrected temperatures reach 318°F (159°C). The areas shown in yellow to brown are zones with the highest initial potential for stranded and coproduced geothermal resources.

McKenna et al. (2005)<sup>34</sup> point out that numerous states produce substantial amounts of water in conjunction with hydrocarbon production. In Texas, approximately 12 billion barrels of water (1 barrel equals 42 gallons) are produced and injected each year. If this coproduced water has temperatures of 212°F (100°C), then over 1,099 MW of electrical power could be generated from the heat extraction before the water is reinjected into the ground.<sup>39</sup> This is enough energy to power at least 275,000 homes.

EXHIBIT 7-4 Uncorrected temperatures of formations at 10,000 and 12,000 feet depth from oil and gas well logs. The maps were produced by the SMU Geothermal Laboratory.





## Enhanced Geothermal Systems Resource

The Enhanced Geothermal Systems (EGS), category represents geologic formations with limited quantities of water but with high temperatures that can be produced if a fluid is injected into the rock to act as a carrier for the heat. In the previous Texas Assessment (1994) Hot Dry Rock was discussed. This is now considered one aspect of EGS development. This resource is huge in comparison to other categories in Texas because it can utilize deeper resources and could be produced anywhere. The minimum EGS resource temperature usually starts at about 300°F (150°C) to be economically viable (**Exhibit 7-4**, Table 8.3).<sup>39</sup>

The geothermal resource suitable for sustaining EGS technology is inferred from subsurface temperatures and rock types. Because of heat conducting from the Earth's interior, subsurface temperatures increase with depth. Depending upon the conductivity of rock types, the composition of the Earth's crust (conductivity and radioactivity), and the mantle heat flow, the temperatures at depth will vary (**Exhibit 7-4**). The basement rock of East Texas is considered the area with the highest heat flow in Texas (Blackwell and Richards, 2004).<sup>42</sup> Here the potential

for EGS is the greatest, especially if combined with coproduction of oil and gas. The calculated temperatures of the basement rock in East Texas are 400°F (200°C) at 20,000 ft (6 km) (Negraru et al., 2008).<sup>49</sup>

Oil and gas well drilling temperature records were used to calibrate the the available heat models for the most accessible EGS resources—300°F (150°C) to 480°F (250°C) between 10,000 and 20,000 ft (3 to 6 km) in Texas. Even at just these depths the Texas EGS resource is immense reaching 90,000 EJ. The resource is listed as thermal energy because the conversion factor to electric energy varies with technology. To give perspective though of how much energy is available, using an average binary turbine conversion rate of 10% from thermal energy to electrical, and a very conservative availability rate of 0.2% there is still over 100 times more power capacity than the total Texas yearly electrical consumption.<sup>1,39,49</sup> Even modest utilization of this EGS resource could supply a large portion of the State's energy and most likely do so on a permanent basis.

**EXHIBIT 7-5** Geothermal Resource Base for Texas. The amount of heat is based entirely on temperature. Each depth shows the amount of thermal energy available for extraction from different temperature levels. Based on Table 3 of Negraru, Blackwell, and Erkan, 2008.<sup>49</sup>

		Geothermal Resource Base for Texas					
		Exajoules, EJ (10 <sup>18</sup> J)					
		°F	212	300	390	480	575
		°C	100	150	200	250	300
Feet	KM						
10,000	3.0		24,246	14			
13,000	4.0		40,939	1,147			
16,000	5.0		47,596	37,521	36		
20,000	6.0		50,194	48,788	2,509		
23,000	7.0		34,753	61,997	34,701	38	
26,000	8.0		22,029	68,170	61,945	2,086	
30,000	9.0			83,462	68,030	26,402	278
33,000	10.0			76,176	68,656	57,743	1,929
Energy (EJ)			219,757	376,975	235,877	86,269	2,207
Total Thermal Energy (EJ)							921,085

Table 7-6 Texas Geothermal Resources by category.

	Total Resource (EJ)	Accessible Resource (EJ)	Percent Available	Depth Range (ft)
Hydrothermal (<180°F or 82°C)	84	84	100	< 5000
Geopressured*	5,100	3,570	70	8000—18,000
EGS (> 300°F)	700,000	90,000	13	12,000—33,000
Coproduced/Stranded (212°F or 100°C)	220,000	55,000	25	7000—26,000
Total Geothermal Energy Resource	925,184	148,654		

\*Geopressured resource includes the dissolved methane content. This number is only for extraction from the sandstone formations, not the shale formations.

## Quantification of Resource Base

The thermal energy potential of each of the geothermal resources described above is summarized in **Exhibit 7-6**. These numbers represent the total thermal energy reserve of hydrothermal, geopressured, and EGS resources. The Texas geothermal resource values of **Exhibit 7-6** are computed as the total thermal energy contained within the depth range of the resource as described above. In addition, accessible resource values are achieved by assuming an appropriate fraction of the total resource base according to technology, geologic setting, and current economic threshold. The following fractions are assumed: hydrothermal is 100 percent accessible, geopressured is 70 percent accessible, EGS uses the mid-range MIT value of 13 percent accessible,<sup>38</sup> and coproduced is about 25 percent accessible based on drilling records.<sup>36</sup>

The use of sedimentary basins and geopressured formations are the highlight for Texas electrical production. Developing existing oil and gas fields into geothermal electrical production areas has the greatest potential for tapping into the  $925 \times 10^{21}$  J of thermal energy stored under Texas.<sup>39, 49</sup> Using information from previously drilled oil and gas wells, tens of thousands of temperature data points can be used as an exploration tool for defining the most accessible resources. The use of geopressured geothermal resources for thermally enhanced oil recovery seems especially viable in South Texas because of the collocation of resources below heavy-oil reservoirs.

Geopressured-geothermal resources can also be used for other applications such as absorption chillers, desalination, agriculture, and aquaculture projects.

The economical viability of the East and South Texas EGS potential has yet to be determined. There are wells drilled to 20,000 feet (6 km) but unlike the geopressure areas, the wells have limited natural flow capacity. As EGS projects are completed in Australia and Europe, the likelihood of project development in Texas increases. The 2006 MIT Future of Geothermal Report, suggests EGS could be a sustainable source of energy.<sup>39</sup>

Space heating and agribusiness applications using water in the 100°F to 170°F temperature range represent the largest potential use of low to moderate temperature hydrothermal energy in Texas. This is based on successful applications in New Mexico and Idaho. In small projects, the resource can last decades if proper management procedures are followed, i.e., the geothermal water is injected back into the reservoir or pumping does not exceed the natural recharge rate. With the addition of a heat exchanger to wells that have already been drilled, many Central Texas municipalities could take advantage of the currently wasted heat from the water they pump for various purposes.

## Geothermal Resource Variability

To its advantage, geothermal resource utilization is not dependent upon intermittent forces, such as wind and solar energy. Rather it is available 24 hours a day, 365 days a year, and is considered baseload energy technology. Heat from within the Earth does not vary with day or season, but instead, on geologic time scales of millions of years. While long-term variations in climate can impact aquifer recharge rates, which in turn may change the availability of producing fluids, water already in the subsurface is usually reinjected into a connected reservoir to be reheated for eventual multiple production runs. As long as a balance is maintained between heat extraction and recharge, the resource has an infinite lifespan, thus being truly sustainable.

## Geothermal Energy Utilization

Geothermal resources have been used in Texas for over a century. From the use of warm water for recreation and health spas to cooling and heating homes around the state, this is not a new resource. It is certainly under-developed when considering the possibility of  $925 \times 10^{21}$ J as the starting resource base for Texas.<sup>39,49</sup> Education of the public and businesses is needed to accelerate the transfer of new technology and increase project funding for the use of geothermal resources in Texas.

## Current Geothermal Resource Use in Texas

### *Geothermal HVAC Systems*

The Crawford Ranch of President George W. Bush is the most prominent Geothermal HVAC system in Texas. Based on geothermal heat pump sales in Texas for the past decade, there are approximately 10,000 residential systems installed. This equates to only a 0.004 percent energy offset (reduced electrical production) for Texas from Geothermal HVAC systems; for comparison, Florida's offset is 0.23 percent.<sup>3</sup> With a 30 to 70 percent energy savings, there is much potential for future energy savings from Geothermal HVAC systems. Most Texas systems have been installed since the 1980s, yet as shown by homeowners in the McAllen area residential systems have been installed for over 50 years and are still working.<sup>40</sup> Although it is rare, there are systems that have been installed upfront by developers for entire neighborhoods, for example in the Valley Ranch subdivision in Irving, Texas in the 1980s.<sup>41</sup> It is difficult to determine how many total systems have been installed since there is no single organization keeping records. There are some records for commercial buildings with Geothermal HVAC systems from engineering firms who installed the system, but this information is collected on a company by company basis. Older installations are usually not recorded or the company no longer exists.

With the prestige of LEED certification, installing Geothermal HVAC systems is becoming increasingly common. Under the LEED criteria a Geothermal HVAC system can add up to 19 points and be the difference between Silver, Gold or Platinum LEED Certification. Completed in 2006, the McKinney Green Building (McKinney, Texas) is an example of the first Platinum commercial office structure in Texas, and it uses a Geothermal HVAC system. School districts are likely to use the SECO LoanSTAR program for Geothermal HVAC systems. Because of the LoanSTAR program there is more available information on schools with installations. Cotulla High School is the first Texas school to use geothermal for heating of its 10 campus buildings, and the Austin Independent School District was the first heating and cooling installation in the state of Texas. At present there are at least 34 school districts and 140 schools in Texas with Geothermal HVAC systems installed.

### *Direct Use Applications*

Geothermal Direct Use applications are often considered the “buried treasure” since many of the uses are in private ownership or only locally known. Usually the only person who knows that a geothermal resource is in use is the mechanical staff. The best known example in Texas is a project that started in the 1970s as geothermal well developed in Marlin, Texas for heating the Falls Community Hospital & Clinic.<sup>42</sup> This project was funded by the U.S. Department of Energy, Natural Resources Advisory Council and the Farmers Home Administration with the objective to demonstrate the technical feasibility of using a geothermal resource to meet the hospital's space heating and water heating needs. Since 1982, the facility has used the 3,900 ft (1.2 km) deep well, yielding 600 gallons of water per minute from the Hosston Sands aquifer, with temperatures from 140 to 155°F (60—68°C). The water is used directly in the summer for the hot water needs and in the winter months to heat the hospital with a secondary use of preheating the hot water.

One of the more common applications of Direct Use wells in Texas has been for spa facilities. Spa facilities can range from hi-end destination locations to user-friendly community bath house facilities. Although there have been tens of geothermal wells and mineral springs used for such purposes in Texas, currently the only existing hot springs destination is in West Texas at Chianti Hot Springs with over 80,000 visitors annually.<sup>8</sup>

In the past geothermal artesian wells flow steadily from sources in Marlin, Ottine, and San Antonio, Texas. Marlin received over 500,000 visitors to their spas from the early 1900s through 1950s with well water temperatures at 130°F (54°C).

Ottine was the site of a children's polio treatment center but moved away from mineral water therapy with the advent of the sulfa drug. The active well has a temp of 102°F (39°C). Hot Wells Resort in San Antonio was an active mineral water site through 1925 when a fire destroyed the hotel. The bath house remains with its artesian well flowing at 103°F (39°C) water; private owners are considering restoring the bath facilities after the San Antonio River Authority completes the river improvement projects.<sup>43</sup> A simple application based on a warm well (98°F/37°C) is Stacy Pool in Austin. This Austin recreation pool well has been flowing since the 1930s.

According to the Oregon Institute of Technology, Texas has 43 communities with access to water for Direct Use applications which could be attracting businesses to use this resource. Wells providing water from 100 to 140°F (38—60°C) are currently available for use in the following communities: Eden, Marlin, Taylor, Austin, Ottine, San Antonio, and Kennedy.

### Geothermal Electrical Power

Commercial electrical production from geothermal resources is still in the development stage in Texas. The DOE geopressured-geothermal demonstration in 1989-90 of a one MW power plant at Pleasant Bayou, Brazoria County, is bringing much renewed interest with rising energy prices and the desire for renewable energy. This project showed that geothermal electrical power generation can be accomplished in Texas.

### Conversion Technology

The geothermal power industry is in the process of undergoing a paradigm shift. Until 2006 there was no technology or energy pricing that would cause consideration of fluids less than 250°F (121°C) for geothermal electrical production. Then in 2006, the project in Chena Hot Springs, Alaska produced electricity with 165°F (74°C) water and the geothermal world took a new look at many previously ignored resources, such as the sedimentary basins in the Gulf Coast and the West Texas. New interest in project development from existing oil and gas fields has spurred new technology from binary fluid designs to gas compressors. An increased need for micropower plants (30 kW to 500 kW) as part of distributed power development has resulted in companies designing new systems for geothermal energy production. Examples of companies today with existing or demonstrating power plant technology for electrical generation in Texas are ORMAT Technologies, UTC Power, ElectraTherm, Inc, and Deluge, Inc.

Another technology that can use the geothermal fluids is absorption chillers. Large commercial applications can use the heated fluids directly for air conditioning, increasing the energy efficiency of the system. This is currently being done in Chena Hot Springs, Alaska, using their hot water to keep an ice hotel frozen throughout the summer.

Each year Geothermal HVAC companies improve their products for residential and commercial applications. The highest rated systems are currently at 30 SEER, which is the highest efficiency level of the Energy Star government ratings for home applications. A list of companies manufacturing geothermal heat pumps can be found on the U.S. Government Energy Star website: <http://www.energystar.gov/>.

### Infrastructure Considerations

Electrical production from geothermal energy will most likely be situated along with existing oil and gas field wells. Field equipment needs electricity and could be the first major use of geothermal electricity. Baseload or peak power contracts for the excess energy could be offered into ERCOT's wholesale market or sold directly to load serving entities and transmitted using existing transmission lines. Lines with insufficient carrying capacity would need to be upgraded from the generation location to the major line. Most of the geothermal resources available for immediate electrical development projects are near existing population centers, so transmission lines are already in place. The Trans-Pecos region has a limited transmission grid and oil and gas fields often utilize diesel fuel for generating electricity in rural areas. In these instances, the onsite need for the produced electricity is even greater. As large fields are converted to geothermal electrical production in West Texas, working with the other renewable industries to ensure the transmission of the electricity will be important.

The largest expense for a Geothermal HVAC system is the ground loop field. The ground loop depth varies according to local geology and ground water movement in the area; if there is 10 feet of soil below the surface, then a horizontal loop can be installed. More typically a vertical loop is installed and includes between 200 to 300 ft (61—91 m) per borehole per ton of air exchange. Vertical systems have increased upfront costs but are shown to improve system efficiency compared to horizontal designs.<sup>5-7</sup> The payback period is about two to ten years, depending on the heat pump and energy efficiency of the building. The loop field materials are usually guaranteed to last at least 50 years. Since much of the expense is in the ground loop, with a guaranteed time frame, one consideration would be for ground loops to be paid for by municipalities, rural electric cooperatives, or even neighborhood associations, who could then lease them back to homeowners in order to spread the expense over the life of the system.

## Economics

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### Costs

Residential Geothermal HVAC systems cost approximately \$3,000 to \$5,000 per ton of air conditioning capacity.

Geothermal power plants have not yet been installed in Texas. Therefore the Return on Investment (ROI) is an estimate based on current technology, drilling expenses, and the cost of existing western U.S. geothermal power plants.<sup>50</sup> Using a binary fluid turbine for the power plant and basic transmission line hook-up, the estimated cost to build a power plant is:

\$750,000 to \$1,500,000 for a 250 kW system

\$2,500,000 to \$5,000,000 for a 1MW system

### Benefits

1. Geothermal energy is a geologically sourced renewable resource that is basically constant in a human timeframe.
2. Geothermal energy is versatile. It can cool and heat through Geothermal HVAC systems, it can produce direct heat for various industries, and it can generate electrical power in Texas.
3. Geothermal energy is considered pollution free and does not contribute to greenhouse heating. Some of the newest binary power plants have no emissions while others emit only 0.3 lb of carbon (CO<sub>2</sub>) per MWh of electricity generated. This figure compares with 282 lb/MWh of carbon for a natural gas plant and 497 lb/MWh of carbon for a bituminous coal plant (this does not include 'clean coal' approach). Nitrogen oxide emissions, which can combine with hydrocarbon vapors to produce ground-level ozone, are at or close to zero in geothermal power plants and are much lower than fossil fueled power plants.<sup>16</sup>
4. Geothermal power plants have a smaller surface footprint than many conventional power plants, and therefore have less of an impact on the surrounding environment. Other land uses are possible with little interference.
5. Geothermal power plants have a high capacity factor, running 98% of the time, with routine maintenance constituting the primary downtime. They supply baseload electrical power.
6. Geothermal power generation is capable of being a distributed source. Over 600,000 oil and gas wells have been drilled in Texas and are scattered over much of the state, but with distinct high density regions. The advent of smaller (50 kW to 250 kW) binary power plants provides the opportunity for using many of these wells for a distributed system of power generation.
7. Geothermal energy is its own source. No outside sources of energy are necessary to maintain power output, thus making the expenses for the life of the power plant stable regardless of the market demands for the resource as in natural gas and coal.
8. Geothermal energy can be an economic boom for rural areas when oil and gas fields are converted to geothermal electrical power production since similar oil and gas well-related jobs are still needed. Also, by using geothermal waters for Direct Use applications, new businesses are brought into a community as well as tourism with spas and therapy pools.
9. Geothermal HVAC systems typically have lower maintenance than conventional systems, as all of the equipment is installed inside the building or underground. Unoccupied parts of a building can easily be shut down due to the more modular nature of this system.
10. Although the Geothermal HVAC system infrastructure costs are slightly higher, the payback is better in the long run. They have lower operating costs and are far more energy efficient than conventional systems, and the money saved on energy bills usually covers the initial investment in two to ten years.

## Key Issues

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The price of electricity needs to stay high (over 8 cents per kWh) for geothermal electricity production in Texas to be economically competitive. As it becomes a normal business practice for oil and gas wells with fluid temperatures over 200°F to switch to geothermal electrical production, rather than be plugged and abandoned, then the pricing is expected to decrease along with new technology becoming available. A future carbon tax is a concern for hydrocarbon related companies and they are looking at geothermal as an offset mechanism. Also the ability to use CO<sub>2</sub> as a working fluid for heat extraction is currently being researched because of its reduced surface friction and increased heat capacity over water.<sup>44</sup> This would create a geothermal power plant that is carbon negative.

Geothermal electrical power production projects have a different business structure than the oil and gas companies. Oil and gas companies operate on a short-term, quick turnaround time for investment. Geothermal power projects are high in upfront investment and they have long-term paybacks of 10 to 30 years. Another difference is that oil and gas wells often have many leaseholders on a well and even at different depths. Geothermal power companies usually limit the number of investors and mineral right holders because of the long-term structure of the business plan.<sup>50</sup> Therefore, using certain existing oil and gas wells may initially be challenging. In Texas, the Railroad Commission lists geothermal as a separate mineral from oil and gas creating a new royalty for the mineral right owner.

Increased education and marketing concerning geothermal resources for Direct Use and Geothermal HVAC systems are both important in order to give potential users the knowledge that the technologies even exist. Geothermal resources are not easily seen or felt and thus are not a widely known resource. This gives geothermal a disadvantage compared to other resources such as wind, biomass, and solar. As for electricity production, once there are a few geothermal power plants online in Texas producing baseload electricity, the important advantages of geothermal will be enjoyed by both producers and consumers.

## Information Sources

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### Fundamental Data Collection

Few Texas aquifers have been measured specifically to assess their thermal characteristics. Bottom hole temperature measurements have been logged for most oil and gas wells and included on the well headers from the more than 600,000 wells drilled in the state. Although only a small portion of those wells have been examined for current reports, the data is available for others to access if interested in site specific locations. Coupled with the oil and gas data is water well drilling information for community wells, which includes temperature and fluid chemistry. The geopressure studies from the 1970s and 1980s along the Gulf Coast also include data. The resulting geothermal resource evaluation given in this chapter is a summary of all of this information. With the ability to access much data online, only key reports, organizations, and maps have been listed below.

### 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 and oil and gas 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. (<http://www.rrc.state.tx.us>).

The SMU Geothermal Laboratory has conducted United States regional and Texas geothermal resource assessments coordinated by David Blackwell and Maria Richards. Both raw data and maps are available online at <http://www.smu.edu/geothermal>. The Geothermal Resource Assessment for the I35 Corridor East to the state boarder includes new oil and gas data and resource maps available on the SMU Geothermal Lab website and the SECO website.

Research efforts by Swift and Erdlac at the West Texas Earth Resources Institute (WTERI), and later continued by Erdlac at The University of Texas of the Permian Basin Center for Energy and Economic Diversification (UTPB-CEED), produced a 5,000+ well database of over 8,000 temperature-depth points from oil and gas well log headers for the Delaware Basin, the northern part of the Val Verde Basin,

and parts of the Trans-Pecos region in Texas. This data was uploaded to the DOE Field Office in Golden, CO and a copy of the data along with an additional report was also provided to the SECO office in Austin in 2006.

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. (<http://geoheat.oit.edu>).

International Ground Source Heat Pump Association is a non-profit, member driven organization established in 1987 to advance geothermal heat pump technology on local, state, national and international levels. They host a yearly conference and workshops on designing, installing, drilling, regulations, etc. related to Geothermal HVAC systems. (<http://www.igshpa.okstate.edu/>)

Geothermal Heat Pump Consortium is the national non-profit trade association for the geothermal heat pump industry. They are a member-driven trade association consisting of manufacturers, architects, engineers, heating and cooling businesses, drilling companies and earth loop installers, and others involved with geothermal heat pump technology. They have case studies and an open forum for people to submit questions. (<http://www.geoexchange.org/>)

[US Dept. of Energy](#) Geothermal Resource Division has information on all three types of geothermal resources located on the Energy Efficiency and Renewable Energy (EERE) website under Geothermal Technologies Program. The EERE works in partnership with the U.S. industry to establish geothermal energy as an economically competitive contributor to the U.S. energy supply. There are reports for many states, including Texas, on their individual resource base. Also basic information shown through animated examples of how geothermal energy is developed, grants, and current news related to geothermal energy. (<http://www1.eere.energy.gov/geothermal/>)

The Geothermal Resources Council is an international, non-profit educational association which has yearly meetings, publications and an on-line information system containing material from a variety of sources including a) the Geothermal Power Plant Data Base that covers most geothermal power plants worldwide, b) a U.S. Vendors Data Base which lists companies and contractors who supply goods

and services, and c) the Geothermal Resources Council Bulletins dating back to the 1970s. (<http://www.geothermal.org>)

The Geothermal Education Office (GEO) produces and distributes educational materials about geothermal energy to schools, energy/environmental educators, libraries, industry, and the public. GEO collaborates frequently with education and energy organizations with common goals, and, through its website, responds to requests and questions from around the world. (<http://www.geothermal.marin.org>).

Information on Texas' Geopressured Resources is available online at <http://www.otsi.gov>. There are volumes of reports with detailed geology and economics for resource development projects.

The American Association of Petroleum Geologists (AAPG) geothermal database covers North America. This database contains 28,744 bottom hole temperature recordings from oil and gas well log headers covering the United States, Canada, and Mexico collected from 1969 to 1972. The AAPG Bookstore sells a cd-rom with the data titled: DP—AAPG DataRom (CSDE, COSUNA, GSNA), ISBN: 1588611884. They also sell the Geothermal Map of North America (2004) ISBN: 0791815722. ([www.aapg.org](http://www.aapg.org)).

### *Summary Documents*

The list below contains a short set of documents that characterize the geothermal resources of Texas.

#### **The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems on the United States in the 21st Century, Tester, Jefferson, 2006 MIT Report.**<sup>39</sup>

The report was prepared by an MIT-led interdisciplinary panel, was released to the public January 22, 2007. The report suggests that 100,000 MWe of electrical generation capacity can be met through EGS within 50 years with a modest investment in R&D. There is a table in Chapter 2 with state by state geothermal resource information for various depths. (<http://geothermal.inel.gov/>)

**A Resource Assessment of Geothermal Energy Resources for Converting Deep Gas Wells in Carbonate Strata into Geothermal Extraction Wells: A Permian Basin Evaluation,** Erdlac, et al., 2006.<sup>31</sup> This report was the first year of a proposed 3-year study to evaluate the Delaware Basin portion of the larger Permian Basin for its geothermal power generation potential. Project built off of previously conducted investigations and was funded for one year by DOE.

**Geopowering Texas: A Report to the Texas State Energy Conservation Office on Developing the Geothermal Energy Resource of Texas**, Erdlac, 2006.<sup>32</sup> This report was conducted in tandem with the DOE investigation of the deep Delaware Basin and looked at all aspects of geothermal energy development: Geothermal HVAC, direct use, and power generation. Project was funded by Texas SECO.

**West Texas Renewable Energy Strategies: Natural and Human Resources**, Erdlac, 2006.<sup>48</sup> This report was funded by the Department of Commerce Economic Development Administration (DOC-EDA) to discuss geothermal, solar, and wind energy in West Texas. The report was designed for the general public to read and included information on how the public could use these resources more directly, the strengths and weaknesses of the resources, and how they might be nested together for mutual benefit.

**Factors Affecting Costs of Geothermal Power Development**, Hance, 2005.<sup>50</sup> This report discusses in detail the various costs of developing a geothermal power plant. From the beginning steps in exploration to the financing of the long term loan after a power purchase agreement has been set, it gives details and equations to help individuals work through what is needed for development.

**Geothermal Resource Assessment for the State of Texas**, Woodruff, et al. 1982.<sup>18</sup> 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, 1982.<sup>19</sup> A concise but thorough summary of Texas hydrothermal and geopressed resources on a single full color map (scale 1:1,000,000).

**Geopressed Geothermal Energy: Proceedings of the Sixth U.S. Gulf Coast Geopressed Geothermal Energy Conference**, Dorfman and Morton, 1985.<sup>14</sup> This compendium of papers presented to a 1985 geopressed/geothermal conference held in Austin, Texas, included topics on the production characteristics of design wells, the deformation history of geopressed 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.

**Texas: Basic Data for Thermal Springs and Wells as Recorded in Geotherm**, Bliss, 1983.<sup>46</sup> 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. This is available on the SMU Geothermal Lab website.

**Assessment of Geothermal Resources of the United States—1978**, Geological Survey Circular 790, Muffler, 1979.<sup>45</sup> This circular is the most comprehensive assessment performed by the USGS in evaluating the nation's geothermal resources.

**Low-Temperature Geothermal Resources in the Western United States**, Mariner, 1983.<sup>47</sup> This article identified the resources of the Western U.S., including the Rio Grande Rift province of West Texas.

**The Xerolithic Geothermal (“Hot Dry Rock”) Energy Resource of the United States: An Update**, Nunz, 1993.<sup>38</sup> 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.

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