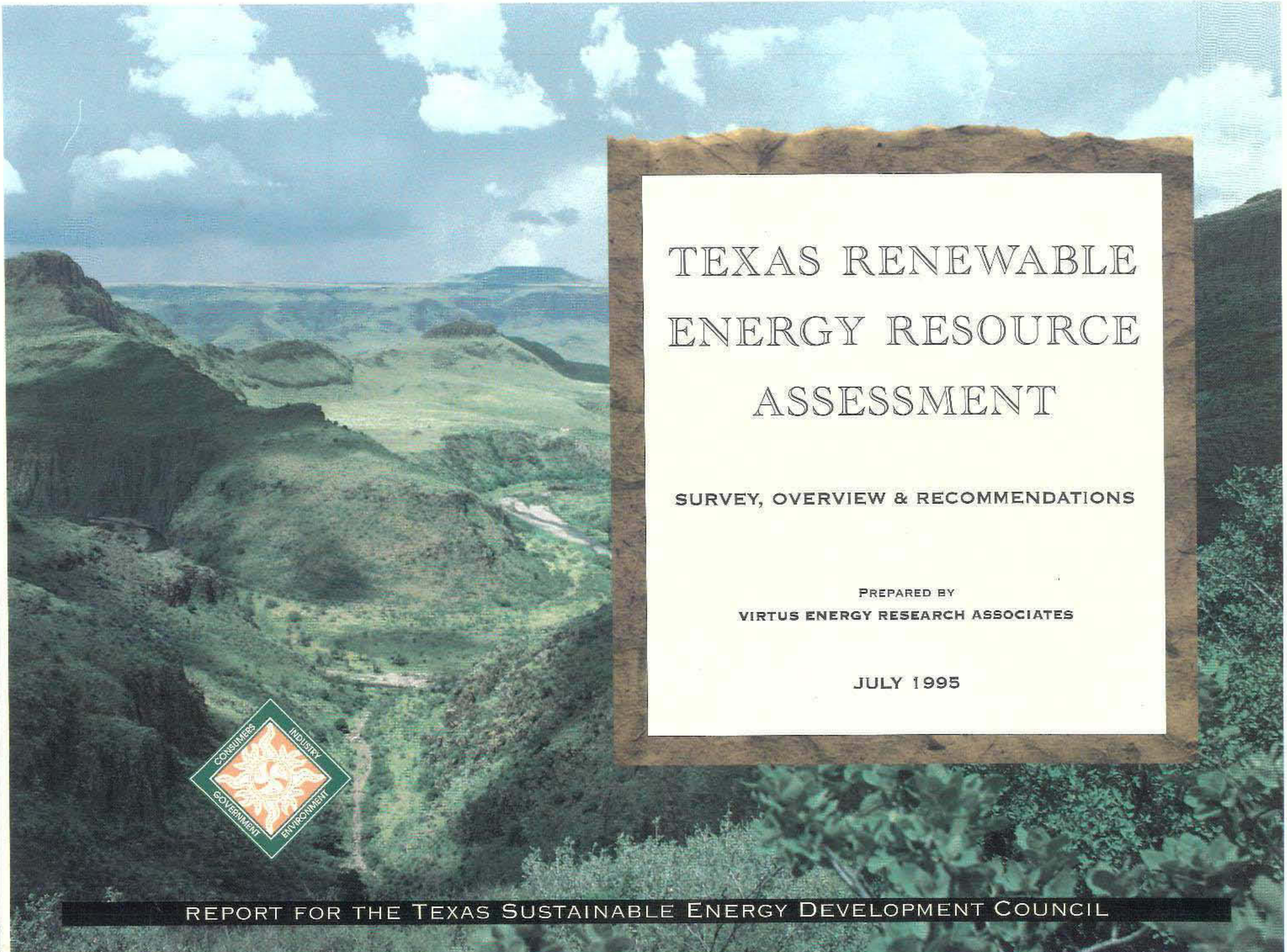

TEXAS RENEWABLE ENERGY RESOURCE ASSESSMENT

SURVEY, OVERVIEW & RECOMMENDATIONS

PREPARED BY
VIRTUS ENERGY RESEARCH ASSOCIATES

JULY 1995

REPORT FOR THE TEXAS SUSTAINABLE ENERGY DEVELOPMENT COUNCIL

Cover Photo
Davis Mountains
Jeff Davis County, Texas
By Paul Montgomery

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LESLIE TUGMAN
Texas Water Development Board

Technical Review Team

GARY VLIET (solar)
The University of Texas at Austin
Austin, Texas

DAVE RENNÉ (solar)
National Renewable Energy Laboratory
Golden, Colorado

TOM STOFFEL (solar)
National Renewable Energy Laboratory
Golden, Colorado

BILL MARION (solar)
National Renewable Energy Laboratory
Golden, Colorado

JOHN VANDENBOSCHE (wind)
The University of Texas at El Paso
El Paso, Texas

DENNIS ELLIOTT (wind)
National Renewable Energy Laboratory
Golden, Colorado

CHARLIE TISCHLER (biomass)
Blackland Research Center
Temple, Texas

DAVE SWANSON (biomass)
Western Regional Biomass Energy Program
Golden, Colorado

BILL HOFFMAN (water)
Texas Water Development Board
Austin, Texas

QUENTIN MARTIN (water)
Lower Colorado River Authority
Austin, Texas

JIM FRANCFORT (water)
Idaho National Engineering Laboratory
Idaho Falls, Idaho

STEVE SENI (geothermal)
The University of Texas at Austin
Austin, Texas

DAVE DUCHANE (geothermal)
Los Alamos National Laboratory
Los Alamos, New Mexico

GREGORY NUNZ (geothermal)
Los Alamos National Laboratory
Los Alamos, New Mexico

BRUCE HUNN (building climatology)
The University of Texas at Austin
Austin, Texas

STEVE COOK (building climatology)
The University of Texas at El Paso
El Paso, Texas

STUART NELSON (electric transmission)
Lower Colorado River Authority
Austin, Texas

ED ETHRIDGE (electric transmission)
Public Utility Commission of Texas
Austin, Texas

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Austin, Texas

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INTRODUCTION

Renewable energies are those forms of energy that derive from the natural movements and mechanisms of the environment—sunshine, wind, the heat of the earth, the growth of plants and animals, the movement of the seas and rivers. Prior to the industrial revolution, these sources were virtually the only forms of energy used by man. During the past 150 years, modern civilization has become increasingly dependent on fossil fuels such as coal, petroleum, and natural gas. The finite nature of these supplies implies that a transition to a sustainable energy future is inevitable.

Texas: At an Energy Crossroads

Texas is currently at an energy crossroads. For many years, excess energy production from Texas fueled a sizable portion of the national economy. During the past two decades, however, Texas' steadily increasing consumption has finally caught up with its waning energy production. Trends projected from this historical information, plotted in **Figure 1**, suggest that Texas will become more and more dependent on energy imported from out-of-state sources. Renewable energy sources, coupled with efficiency measures, represent a significant potential for meeting Texas' long-term energy demand and offer Texans the chance to maintain their energy independence. In March 1993, Governor Ann Richards created the Sustainable Energy Development Council (SEDC). The Governor specifically instructed the group "to develop a strategic plan to ensure the optimum utilization of Texas' renewable energy and energy efficiency resources."

Purpose of this Project

Before the realistic potential of renewables can be determined, it is essential to examine the natural renewable "fuel" resources of the state. Obvious questions come to mind, such as: How large are these resources?, Where are they located?, and How can they be used? To answer such questions, the SEDC contracted with Virtus Energy Research Associates (VERA) to evaluate Texas' renewable energy resource base. The assessment consists of three distinct components: survey, overview, and recommendations. It evaluates solar, wind, biomass, geothermal, water, and building climatology energy resources.

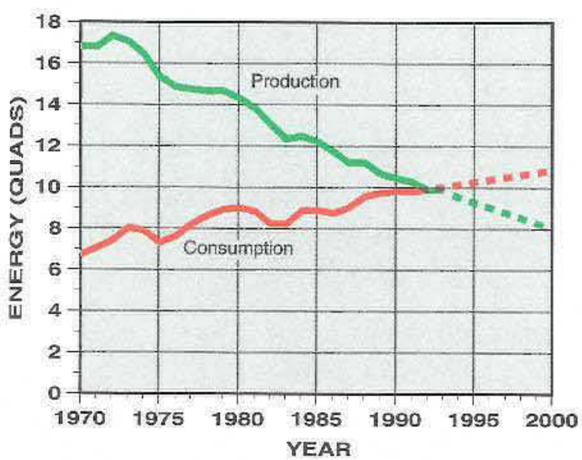


FIGURE 1. Texas Energy Production and Consumption. Texas Railroad Commission statistics for crude oil, natural gas, natural gas liquids, lignite, coal, and uranium are summarized in the green production line; consumption data are taken from the U.S. Energy Information Administration's *State Energy Data Report 1992.* Dashed segments represent projections.

The study's survey component identifies and reviews information sources relevant to Texas renewables. These include details on fundamental data collection activities such as solar and wind monitoring networks, and a review of significant summary documents, studies, and maps. The overview characterizes each resource with special attention given to spatial variability and the identification of "good" resource areas of the state. Finally, recommendations are made to prioritize Texas' future resource assessment needs.

This project comprehensively reviews information covering the full range of renewable energy resources in Texas. No formal effort has been made to ascertain the economic potential of these renewable resources, since this is contingent upon the status of conversion technologies. Future activities of the SEDC will make such assessments. Dissemination of results is one of the main goals of the SEDC. Page 17 of this summary lists sources for other project materials that may interest certain readers, and a short glossary of renewable resource and energy terminology.

OVERVIEW

Energy is a concept familiar to each of us, so much so that we will not attempt a rigorous definition. It powers our cars and appliances, heats our homes, and lights our workplaces. The science of thermodynamics teaches that energy can take on many different forms, each equivalent. Energy can be stored in a compressed spring, a rotating shaft, a pressurized vessel, a magnetic field, etc. Heat is a form of energy. Equivalency implies that each type of energy can be measured in the same units. For example, we could sell electricity in calories or measure food energy in kilowatt-hours. This would baffle consumers, of course, but would be perfectly correct thermodynamically.

Table 1 shows the basic energy types and other characteristics associated with each renewable energy resource. The type of energy may restrict how the resource can be used or at least imply that some uses may be more economical than others. The second characteristic, intermittence, is an issue for some resources but not others. In biomass, for example, the energy is locked in chemical bonds and can be released when needed, whereas the kinetic nature of wind means that it must be used when available. Spatial variability refers to the range of the resource across a given region. Sunshine, for example, changes only modestly; annual global solar radiation varies by a factor of two from the sunniest spots in the nation to the cloudiest. Biomass yields, on the other hand, can vary 30-fold from fertile regions to infertile ones, due to variations in soil and rainfall.

Although Table 1 lists seven resources, in reality almost all are derived from the sun. Solar energy is the source of our weather, heating up the atmosphere, driving winds, and dictating the hydrologic cycle. Ocean waves are in turn produced from winds, and ocean temperature gradients result directly from absorbed sunlight. The energy fixed in biomass is likewise converted from sunlight via photosynthesis. Only geothermal energy, derived from the vast thermal reserve of the earth's interior, and tidal energy, influenced mainly by the moon's mass, are not truly solar resources. Even fossil fuels, while not renewable, can be thought of as a form of solar energy, as they are simply fossilized biomass.

Resource Quantification

One of the main efforts of this project was to estimate the size of each of Texas' renewable energy resources. This quantification, summarized in **Table 2,** warrants discussion. The total energy for each resource comprises the amount incident upon or available within the entire state per year. The accessible resource base is defined as that amount of the total resource that is technically feasible to extract with existing or near-term technology. Units are quads per year (see the inset at right for the definition of a quad). Note that no economic discriminator was used in the definition of accessible base, only a judgement as to technical viability. Energy density compares the relative concentration of the resources at a prime Texas location for each. Finally, typical applications of the resources are listed.

TABLE 1. Fundamental Characteristics of Renewable Energy Resources.

RESOURCE	ENERGY TYPE	INTERMITTENCE	SPATIAL VARIABILITY
SOLAR	Radiative/ thermal	Yes	Low
WIND	Kinetic	Yes	High
BIOMASS	Chemical	No	Very High
WATER	Kinetic/ thermal	Some	Extreme
GEOTHERMAL	Thermal	No	High
BUILDING CLIMATOLOGY	(End use)	Some	Low
OIL & GAS	Chemical	No	Extreme

For reference, Texas consumed about 10 quads and the U.S. about 82 quads during 1992. Clearly then, the 4,300 quads of solar energy incident on the state each year is an immense resource. The other resources are substantially smaller since, as mentioned previously, most are derived from the solar resource. For example, only about a fourth of one percent of incident solar radiation is manifest in the kinetic energy of the wind, resulting in a statewide resource of 12 quads. Similarly, the annualized photosynthetic conversion efficiency of sunlight to biomass stands at just 0.3%. A low conversion efficiency, however, does not imply a poor resource. Wind energy may represent only a tiny fraction of the original sunlight, but at prime sites it is the most "energy dense" of the renewables. The 4 quads of accessible wind resource assumes that windy areas of the state are blanketed in turbines spaced 10 blade diameters apart.

The geothermal resource can be evaluated in two different ways. The continuous heat transfer from the earth's interior to its surface is minute, about 0.06 W/m^2 or about 10,000 times less than the incident solar radiation on a clear day. Integrated over an entire year it yields just 1 quad of resource. However, the total thermal energy stored within the first 4 miles of the earth's crust is staggering, some 2.3 million quads beneath Texas alone. The

TABLE 2. Quantification of Texas Renewable Energy Resource Base and Identification of Primary Uses.

RESOURCE	TOTAL PHYSICAL RESOURCE (quads/yr)	ACCESSIBLE RESOURCE (quads/yr)	ENERGY DENSITY: GOOD TEXAS SITE (MJ/m²/yr)	PRIMARY ENERGY USES**				NON-ENERGY USES
				ELEC.	HEAT	MECH.	TRANS.	
SOLAR	4,300	250	8,000	✓	✓			
WIND	12	4	15,000	✓		✓		
BIOMASS	13	3	45	✓	✓		✓	Food, feed, and fiber
WATER	3	1	10	✓	✓	✓		Water supply; flood control
GEOTHERMAL	1 (2,300,000 quads)*	1	3	✓	✓			
BUILDING CLIMATOLOGY	0.6	.26	430	✓	✓			

*see discussion in text ** ELEC. = Electricity, MECH. = Mechanical, TRANS. = Transportation

sustainability of the resource would depend on how it is exploited, but the number is so large that this would not likely be a pressing concern.

Finally, the building climatology numbers merit a brief comment. This resource refers to employing the climate as a resource to minimize building energy demands through techniques such as ventilation and evaporative cooling. Climatic energies are huge, but the upper bound in potential energy reductions is clearly limited by how much is presently consumed in Texas buildings. The potential to reduce these demands is not certain due to an incomplete knowledge of the present Texas building stock, but the values in the table represent reasonable estimates.

Renewable energies have the reputation for being diffuse in nature and therefore very land intensive. Land acquisition is a central aspect of major development projects. It is interesting, therefore, to contrast the relative land use of several key renewable resources with fossil fuels as in **Figure 2.** Each square in the figure is sized to represent the area required by the respective resource to yield either a quad of electricity or a quad of primary fuel. Typical conversion efficiencies and Texas' standard spacing for oil and gas wells were used to develop the map. The very large biomass squares point out this resource's land-intensive nature due to its poor solar conversion efficiency. Furthermore, biomass uses virtually all the land it is developed on whereas other resources may not. For example, cattle can graze around wind turbines and oil wells, and solar technologies can be installed on rooftops.

Texas has among the best renewable energy resources in the nation. In addition, most other parts of the U.S. that possess good resources—sunny states of the desert Southwest or windy states of the Great Plains—do not presently possess the energy demand nor anticipate the growth that is predicted for Texas. Texas makes up 8% of the U.S. population but consumes 12% of its energy due mostly to the energy-intensive petroleum industry along the Gulf Coast. This fact is significant as new energy facilities, renewable or otherwise, will be constructed most rapidly in the context of a large, growing energy economy. Understanding the state's complex renewable resources is only the first step toward their development.

What is a Quad?

A quad is a very large unit of energy equivalent to one quadrillion British Thermal Units (1,000,000,000,000,000 BTU's). In more practical terms, it is enough to serve all annual energy needs for about 3,000,000 Americans. Many medium-sized states like Colorado and Arizona consume a total of one quad of energy per year—roughly one-tenth the annual energy consumption in Texas. It is noted that the international and scientific communities would usually quote such numbers in units of exajoules (EJ, or 1×10^{18} Joules). Fortunately, the two units are almost equivalent (1 quad=1.055 EJ).

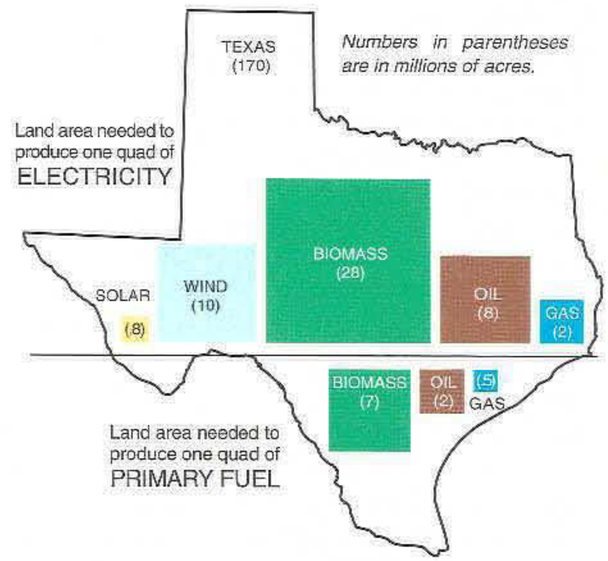


FIGURE 2. Land Requirements of Various Texas Energy Resources. Each square is sized to indicate the area needed to produce one quad of electricity or primary fuel. The location of squares within the state has no significance.

SOLAR

Solar energy is the most democratic of renewable energy resources. It is available everywhere on the earth in quantities that vary only modestly. Variations that do occur stem from cloud cover patterns and other lesser influences, including elevation and the prevalence of airborne gases and particles such as humidity, pollution, and dust. Solar radiation that avoids atmospheric scattering and arrives at the earth's surface in an unbroken line from the sun is termed *direct*, while the scattered radiation that reaches the earth from all parts of the sky is called *diffuse*. The distinction is important because diffuse radiation cannot be effectively focused; only direct radiation is relevant to the solar technologies that use mirrors and lenses to concentrate the sun's rays. The combined contributions of direct and diffuse result in the total, or *global* radiation, the quantity of interest for non-concentrating solar technologies such as rooftop solar panels.

Like most of the U.S., the various solar properties have been measured at only a small number of locations in Texas. Information from these limited measurements, coupled with estimates based on weather data and satellite images, provides the basis for the design of solar installations such as rooftop solar water and space heating systems, photovoltaic panels (electricity generated directly from solar cells), solar detoxification devices and large solar electric power plants. Solar radiation information is also important for building design and improved management of agriculture.

Global Radiation

Insolation is the total amount of solar radiation that strikes a particular location over a given period of time, typically a single day. *Horizontal* insolation is the amount received by a horizontal surface such as a lake, field, or office building rooftop. **Figure 3** depicts the average daily horizontal insolation for a number of Texas cities. The chart partitions the global insolation (blue plus orange) into its direct (orange) and diffuse (blue) components. The diffuse data, important for daylighting applications, indicate that a skylight in East Texas will provide more useful light than a comparable one located in West Texas. Across the state, global horizontal insolation averages about 5 kWh/m^2-day and varies by only 25% from Houston to El Paso. This is significant, as many people assume that only West Texas has the good sunshine necessary to use solar energy; in reality, fixed surface technologies can find application throughout the state.

Solar equipment is frequently installed on structures that are at some angle to the ground. The radiation on such a fixed, tilted surface will be more or less than on a horizontal one depending on the angle of tilt and orientation. A pitched, south-facing roof, for example, will generally receive about 10 to 15% more energy than suggested by Figure 3. Based on these levels of insolation, the average Texas family would need to cover about half of their roof with 10% efficient photovoltaic panels to generate as much electricity as they use. Or similarly, the majority of the family's hot water needs could be met with only a few large solar water heating panels. Many of these small-scale, fixed surface solar technologies intended for residential and "off-grid" use are already common in Texas. These systems, some of which can be directly integrated into buildings, often provide added value to the owner or embody unique characteristics that make them the most cost-effective option available.

Direct Radiation

The National Renewable Energy Laboratory (NREL) has developed estimates for solar radiation to complement the small number of solar measurements that are available. **Figures 4 and 5**, developed by NREL, show the average direct normal insolation in the conterminous United States and in Texas. *Normal* insolation refers to the amount that strikes a surface that always faces the sun. West Texas exhibits the highest levels of direct normal insolation in Texas as well as some of the highest levels in the entire nation. Compared to East Texas, West Texas experiences 75% more direct solar radiation.

Direct normal insolation is the quantity of interest for concentrating technologies that track the sun throughout the day and intensify natural sunlight to yield very high temperatures or generate electricity efficiently. Since wholesale energy markets are dictated almost solely on price, solar power plants trying to compete in this arena will need to be located in regions with very good direct radiation. To support prospective developments of this type, improved solar radiation data are needed throughout the Trans-Pecos and along the Rio Grande.

Potential Value of the Texas Resource

Solar radiation is available throughout the state in sufficient quantity to power distributed solar systems such as solar water heaters and off-grid photovolatic panels. On the other hand, large solar power plants will almost certainly be most cost-effective when sited in areas of West Texas that receive very high levels of direct solar radiation. Solar developments of both types can become major contributors to satisfying the future energy needs of Texas.

SOLAR ENERGY

Source: National Renewable Energy Laboratory

COLOR KEY	AVERAGE DIRECT NORMAL INSOLATION PER DAY (kWh/m²-day)	PER YEAR (MJ/m²)	PER YEAR (quads/100 mi²)
	<3.0	<3,940	<1.0
	3.0 - 3.5	3,940 - 4,600	1.0 - 1.1
	3.5 - 4.0	4,600 - 5,260	1.1 - 1.3
	4.0 - 4.5	5,260 - 5,910	1.3 - 1.5
	4.5 - 5.0	5,910 - 6,570	1.5 - 1.6
	5.0 - 5.5	6,570 - 7,230	1.6 - 1.8
	5.5 - 6.0	7,230 - 7,880	1.8 - 1.9
	6.0 - 6.5	7,880 - 8,540	1.9 - 2.1
	6.5 - 7.0	8,540 - 9,200	2.1 - 2.3
	>7.0	>9,200	>2.3

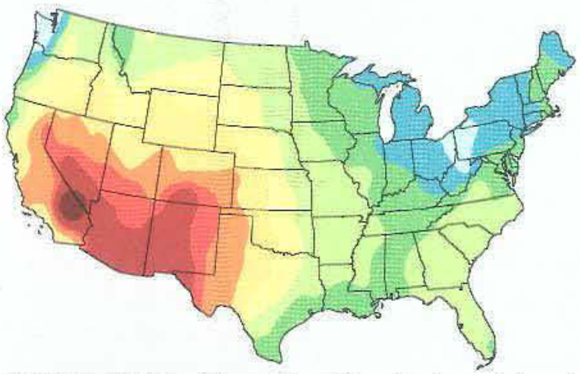


FIGURE 4. U.S. Direct Normal Insolation. (See legend above.)

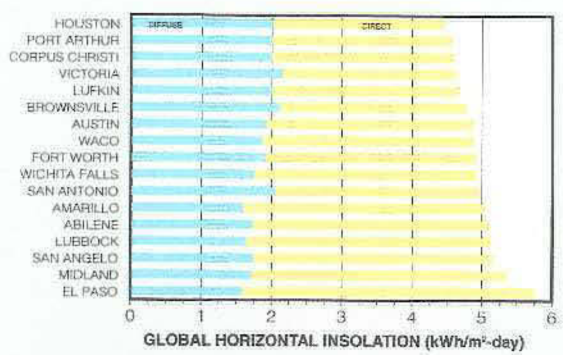


FIGURE 3. Global Horizontal Insolation for Texas Cities. Throughout Texas, sunshine is adequate to power rooftop systems such as photovoltaic or water heating systems.

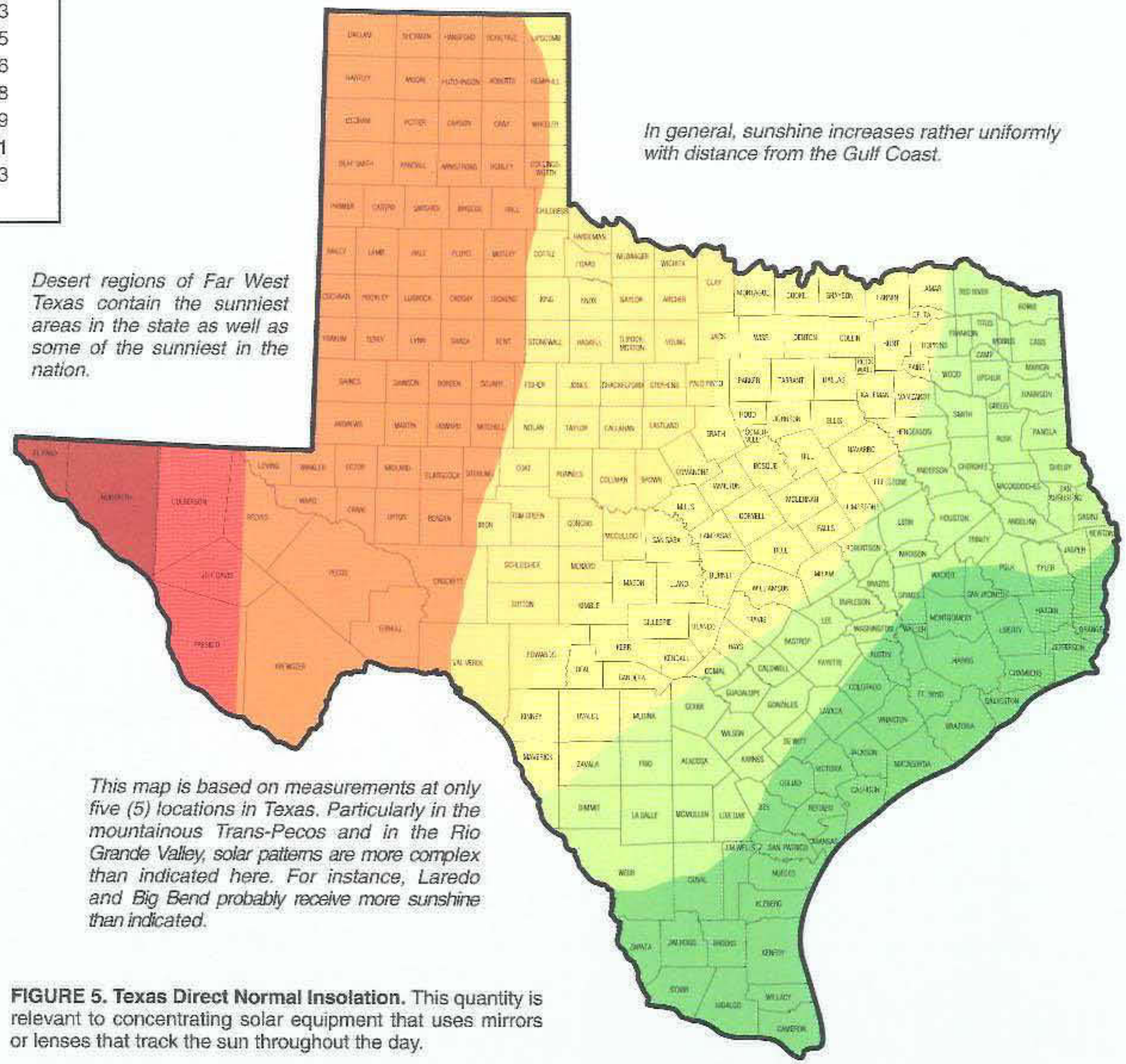


FIGURE 5. Texas Direct Normal Insolation. This quantity is relevant to concentrating solar equipment that uses mirrors or lenses that track the sun throughout the day.

WIND

The use of wind as an energy source has its roots in antiquity. At one time, wind was the major source of power for pumping water, grinding grain and transporting goods by sailing ships. Present day applications of wind power include water pumping and the generation of electricity.

In 1994, wind turbines generated approximately 4 billion kWh of electricity worldwide—enough power for about half a million Texas households. While utility-scale electricity generation from wind is in its infancy in Texas, the industry is already experiencing vigorous activity. In 1993, the Lower Colorado River Authority contracted to purchase competitively priced electricity from Kenetech's 50 MW wind plant in the Delaware Mountains. Royalty payments from this project to the General Land Office (the leaseholder of the site) will provide a new source of funding for the Permanent School Fund. Several of the state's large investor owned utilities, including Texas Utilities and Central and South West Services, have also recently committed to wind power projects.

Characterization of the Resource

Vast areas with high wind power potential exist in Texas. **Figures 6 and 7** on the facing page show average annual wind power for the United States and Texas. Wind power is categorized according to Wind Power Class. Wind class 1 (light blue) denotes very light winds; higher numbers indicate stronger winds. In the United States, wind farms are presently built on tracts with winds of class 5 (orange) and higher. Technology currently being developed should make class 4 (yellow) wind regimes viable. Eventually, even class 3 (green) wind regimes are expected to be capable of supporting utility-scale ventures.

The U.S. map was assembled by the Pacific Northwest Laboratory (PNL) from available measured wind data. In many areas there were no measured data. To address this shortcoming, PNL scientists partitioned the country into thousands of uniformly sized pieces and to each piece assigned a constant value for wind class. This is what gives the map its jagged, "pixelized" appearence.

The Alternative Energy Institute (AEI) at West Texas A&M University constructed the improved resolution Texas wind map as a refinement of the PNL map. It incorporates additional ground exposure information. A hilltop, for example, will experience stronger winds than the base of a valley. The AEI used elevation and prevailing wind data to compute exposure and reclassify wind power throughout the state.

While helpful, this technique is not a precise tool. Some areas on the map may, with improved data, turn out to be windier than indicated, while others may be worse. Overall, the reclassified map simply identifies promising regions in which to focus future assessment activities and development; the true potential of a specific site can only be determined from long-term, quality measurements.

The Texas map identifies three major areas with good wind power potential: the Great Plains, the Gulf Coast, and specific ridgetops and mountain passes throughout the Trans-Pecos. The electric generation potential of the windy areas of Texas is summarized in **Table 3**, below. These values reflect exclusions for various technical and environmental constraints. The table points out that Texas contains enough class 4 resource to produce all of the electricity currently consumed in the state. Even when utilizing only class 5 and 6 lands, wind power could generate a significant portion of the state's electricity.

Potential Value of Resource in Texas

Wind is a highly variable resource, but with proper understanding it can be readily incorporated into an electric utility's generation mix. This fact has already been recognized by Texas wind developers and electric utilities active in the state's nascent industry. The Panhandle, mountainous parts of West Texas, and perhaps even the lower Gulf Coast, contain areas with winds presently suitable for electric power generation. The number of commercially attractive sites will only expand as development costs continue to drop and wind turbine technology improves.

TABLE 3. Potential Electricity Production on Windy Lands in Texas.

WIND POWER CLASS	AREA (km^2)	PERCENT OF STATE LAND	POTENTIAL CAPACITY (MW)	POTENTIAL PRODUCTION (Billion kWh)	% OF TEXAS ELECTRIC CONSUMPTION
3	143,400	21.13%	396,000	860	371%
4	29,700	4.38%	101,6000	231	100%
5	5,000	0.74%	21,600	48	21%
6	300	0.04%	1,600	4	2%
Total	178,400	26.29%	524,800	1,143	493%

TEXAS WIND POWER POTENTIAL				
WIND POWER CLASS		WIND CHARACTERISTICS 50 METERS ABOVE GROUND*		
		POWER (W/m²)	SPEED (mph)	COMMERCIAL VIABILITY
1	1-	0 – 100	0 – 9.8	VERY POOR
	1+	100 – 200	9.8 – 12.5	
2	2-	200 – 250	12.5 – 13.5	POOR
	2+	250 – 300	13.5 – 14.3	
3	3-	300 – 350	14.3 – 15.0	MARGINAL
	3+	350 – 400	15.0 – 15.7	
4	4-	400 – 450	15.7 – 16.3	GOOD
	4+	450 – 500	16.3 – 16.8	
5	5-	500 – 550	16.8 – 17.4	VERY GOOD
	5+	550 – 600	17.4 – 17.9	
6	6-	600 – 700	17.9 – 18.8	EXCELLENT
	6+	700 – 800	18.8 – 19.7	

** Fifty meters (164 feet) is a common tower heighth for large wind turbines.*

WIND ENERGY

Sources: Pacific Northwest Laboratory, Alternative Energy Institute

The Panhandle contains the state's greatest expanse with high quality winds. Well-exposed locations atop the caprock and hilltops experience particularly attractive wind speeds. As in all locations throughout the state, determination of areas appropriate for development must include consideration of environmental and social factors as well as technical viability.

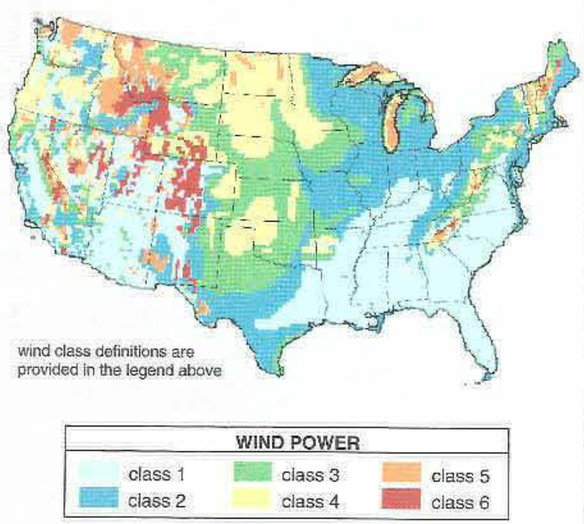
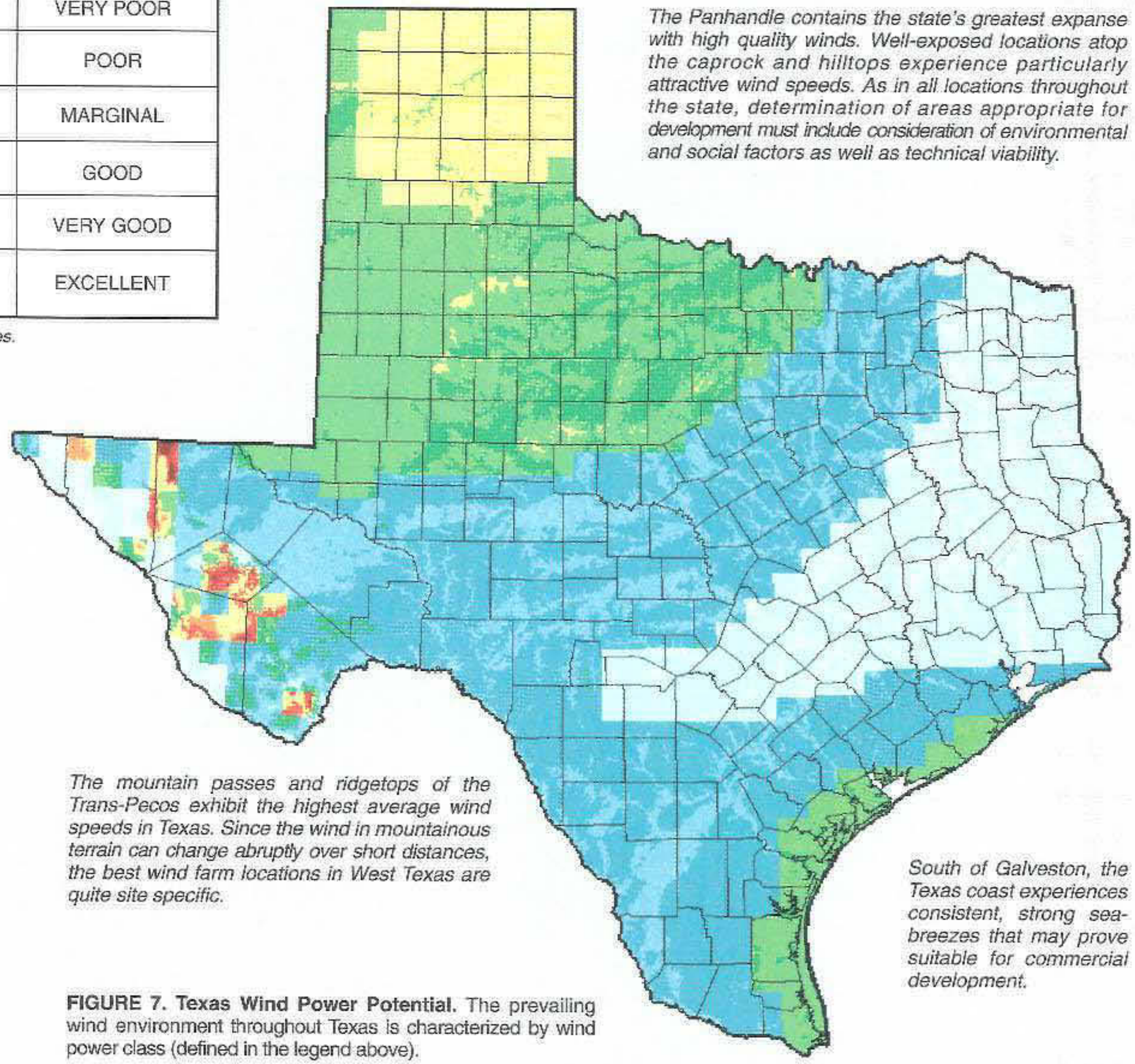


FIG. 6. U.S. Wind Power Potential. While the strongest winds are located along ridgetops in mountainous areas, the Great Plains from Texas to North Dakota contain the preponderance of the nation's wind power potential.



The mountain passes and ridgetops of the Trans-Pecos exhibit the highest average wind speeds in Texas. Since the wind in mountainous terrain can change abruptly over short distances, the best wind farm locations in West Texas are quite site specific.

South of Galveston, the Texas coast experiences consistent, strong sea-breezes that may prove suitable for commercial development.

FIGURE 7. Texas Wind Power Potential. The prevailing wind environment throughout Texas is characterized by wind power class (defined in the legend above).

BIOMASS

Biomass is plant or animal matter. Using biomass (or fuels or wastes derived from biomass) as a source of energy entails burning it to yield heat that can then drive engines or generate electricity. The energy in biomass is chemical in nature; it does not suffer from the problem of intermittence that is inherent to wind and solar resources. In this respect, biomass more nearly resembles fossil fuels than it does other renewables. Indeed, geologists tell us that fossil fuels are simply fossilized biomass.

For most of recorded history, biomass was mankind's principal energy source, mainly in the form of wood used for cooking and heating and as foods to "fuel" human labor and beasts of burden. With the industrial revolution, fossil fuels captured this dominant role. Today biomass still accounts for 15% of worldwide primary energy consumption, but, significantly, the fraction is much higher in developing nations than in developed ones.

Perhaps the most important factor to remember about biomass' potential role in the energy sector is that, again unlike most renewables, stiff competition will always exist for both the biomass and the requisite land resource to grow it. This is often capsulized in the five "f's" of biomass usage: food, feed, fiber, forage, and fuel. Fuel—growing biomass to burn it—will normally be the least valuable on this list. Even among wastes derived from biomass, higher value applications may diminish their use as fuel: manures have value as fertilizers; waste paper can be recycled; cottonseed hulls find their way into oil drilling muds, wood chips into landscape mulches, restaurant greases into pet food. Although many specialists have envisioned a role for biomass in which it is grown extensively and solely for fuel (energy crops), it is probable that this can only happen with at least some valued dual use or co-product derived from the crop.

The Texas Resource

As one of the nation's leading agricultural states and with a large forest industry, Texas is a major biomass producer (see **Figure 8**). Additionally, the state's very large urban base contributes substantial amounts of biomass-derived wastes. **Figure 9** identifies Texas' major production areas and the types of biomass that each generates.

Prime agricultural areas include regions along the Gulf Coast, the central Blackland Prairie, the High Plains of the Panhandle, and delta lands near the mouth of the Rio Grande. Switchgrass, a tall native grass proposed as an energy crop by the Department of Energy (DOE), can be grown in all of these regions, but in the Panhandle only under irrigation. By far, the state's major agricultural process residue is cotton gin trash. Cotton is grown throughout the state, but its production is concentrated in the Panhandle. Other locally abundant agricultural wastes include rice hulls, sugarcane bagasse, and cottonseed hulls. Manures generated throughout the state, but again concentrated in the Panhandle, also form an important resource.

Wastes generated by the forest products industry of East Texas include logging residues left behind after harvest as well as bark, wood chips, and sawdust generated at mills. In general, the wood wastes generated by modern mills are highly utilized; indeed, forest mills are the largest biomass energy users in the nation today, generating more than half of their large energy requirement on-site. Many mills, including currently five in Texas, generate electricity for local use or occasionally for resale to the grid. East Texas also holds potential for the cultivation of woody energy crops, mainly hybrid poplars (cottonwoods) presently being studied by the DOE.

Urban sources of biomass may represent some of the best opportunities for increasing biomass' near-term presence in the energy mix. Wastes that would otherwise be landfilled are a particularly good potential fuel source since the producer is charged a tipping fee for their disposal. Texans landfilled over 20 million tons of refuse in 1993, nearly 75% of which comes from biomass. Methane gas generated and captured at existing landfills or at municipal sewage treatment facilities is another important form of urban bioenergy. A final advantage of these wastes is that their supply is surprisingly reliable, much more so than agricultural commodities that fluctuate annually with the vagaries of markets, weather, and government policy.

Importance to Texas Energy

Texas is a major biomass producer with a number of very good resources. The variety of plants, animals, residues, and biofuels that fall under the biomass heading is difficult to recount in a short space, but in general, wastes will remain the most important biomass energy sources, with those that currently present a disposal problem having the greatest near-term potential. Energy crops may make longer term contributions to the energy sector and could help farmers and rural communities by establishing new markets for their products.

BIOMASS FOR ENERGY

Sources: Virtus Energy Research Associates, Blacklands Research Center

TEXAS BIOMASS: GENERAL RESOURCE TYPES		
AGRICULTURE	FORESTS	URBAN BIOMASS
Harvest Residues Process Wastes Energy Crops	Logging Residues Mill Residues Woody Energy Crops	Municipal Solid Waste Sewage Landfill Gas Used Cooking Oils

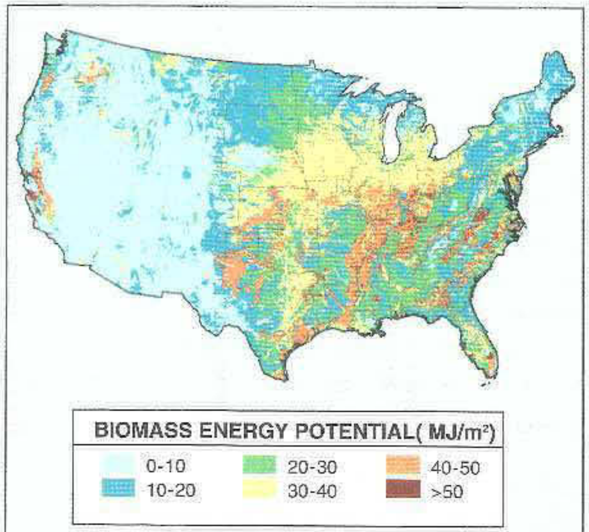


FIGURE 8. Total U.S. Biomass Energy Potential. Annual photosynthetic energy fixed by a single species typical of local land cover. Assumes typical management practices (including irrigation).

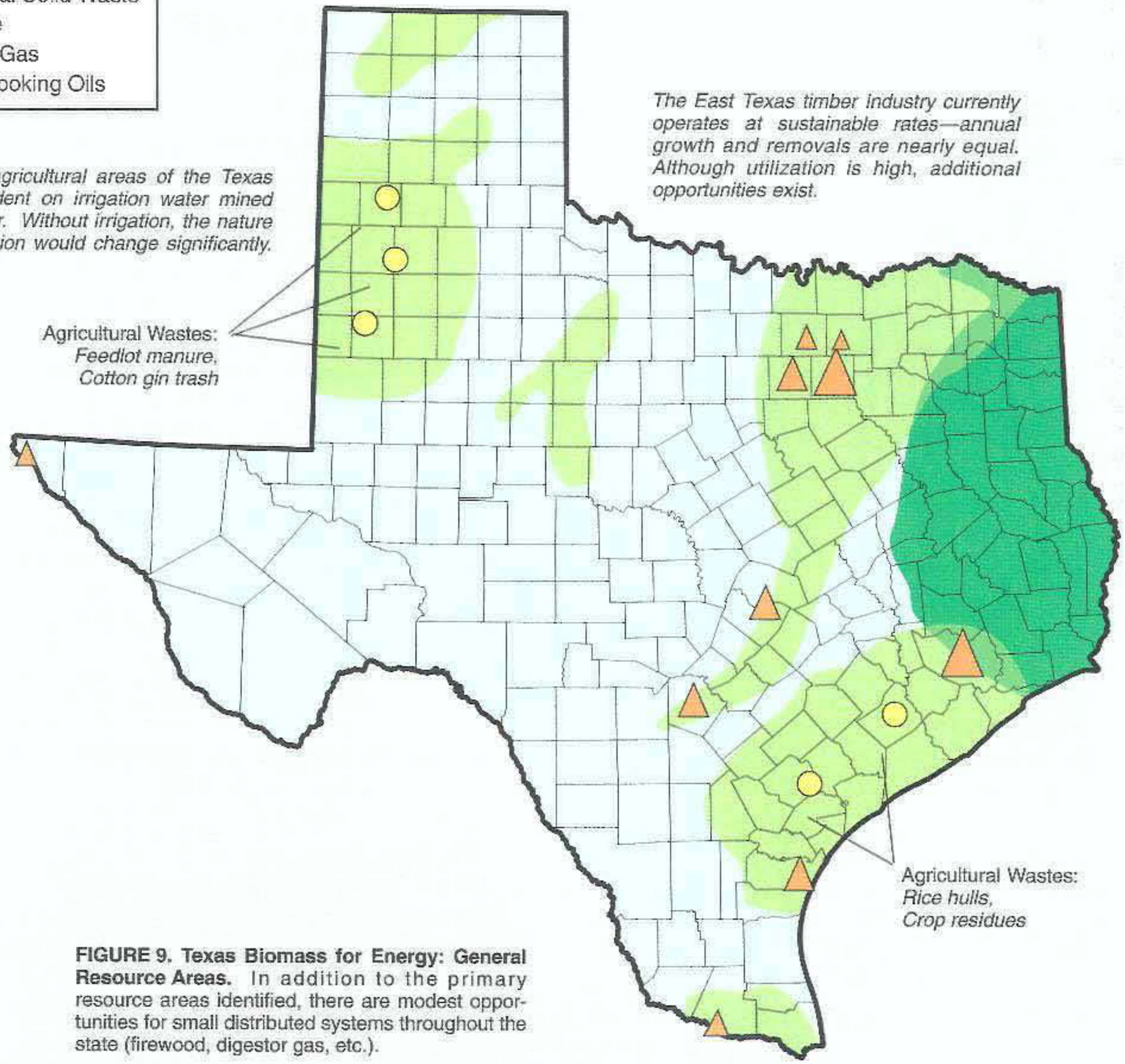


FIGURE 9. Texas Biomass for Energy: General Resource Areas. In addition to the primary resource areas identified, there are modest opportunities for small distributed systems throughout the state (firewood, digestor gas, etc.).

WATER

Water energy resources include hydroelectric power from lakes and rivers, ocean energy in its various forms, and energy technologies that take advantage of saline water. Texas possesses these resources in varying degrees, ranging from poor in the case of ocean resources to excellent for salt water. Each one is outlined below.

Hydroelectric Power (Hydropower)

Hydropower makes use of the kinetic energy water gains when it drops in elevation. Typically, water dammed in a lake or reservoir is released through turbines and generators to produce electricity. Hydropower has been a staple of electricity generation since the beginnings of the electric age. Historically, U.S. hydroelectric generation expanded until about 1975, but its share of the national electrical energy mix steadily declined from a peak of about 40% in the 1930's to approximately 10% today.

In Texas, hydropower's contribution is much smaller, accounting for only 1% (640 MWe) of the state's electrical generating capacity and less than 0.5% of the energy produced. The red dots in **Figure 12** identify the location of the state's existing hydro facilities. A 1993 study by the Idaho National Egineering Laboratory identified an additional 1,000 MW of undeveloped hydro resource (identified as the green dots in Figure 12 and summarized with existing generation by river basin in **Figure 10**). Very little of this potential is currently slated for development. Significant legal and regulatory impediments, such as land acquisition and environmental protection, will be a part of any major hydro project. Additionally, reservoirs are typically built and managed primarily as municipal water supply and flood control systems and secondarily for power production. This fact lowers the potential impact of hydro development on the state's energy picture.

Ocean Energy

Three distinct types of ocean resource are commonly mentioned as possible energy sources: tides, waves, and ocean temperature differentials (ocean thermal energy conversion, or OTEC). None are significant resources in Texas and, to date, have not been commercially exploited elsewhere. Tidal energy schemes capture water at high tide and release it at low tide. But Texas, with a median Gulf Coast tidal range of just 1.3 feet, does not have the large tides necessary for such a system to be feasible. The wave resource is slightly better. Gulf Coast waves are comparable in size to those off the U.S. Atlantic Coast. However, Gulf Coast waves tend to dissipate close in to shore due to relatively shallow waters, a fact that would hinder development since electricity would have to be transmitted significant distances to land. Finally, the closest potential OTEC site to Texas is more than 100 miles offshore. This distance makes it difficult to classify it as a Texas resource, and, at any rate, the site is of marginal quality.

Saline Water

Saline and brackish water is common throughout much of Texas (Figure 12). Normally it poses a problem for fresh water supplies. Several technologies, however, can take advantage of saline water for energy production. These include solar ponds and algae production. Solar ponds use the salt water in such a manner that heat from sunlight is effectively locked in the pool and can be used for a number of process heat applications or electricity production. The ability of the pond to store solar thermal energy is unique and overcomes the resource variability that is a drawback of traditional solar development. Salt water algaes grow prolifically under cultivated conditions and can be pressed to extract biodiesel feedstocks or dried and burned for power production. Although neither technology has been demonstrated beyond pilot levels, Texas is fortunate in that regions with saline water resources also tend to be very sunny. If coupled with ongoing fresh water chloride control efforts, exploitation of the saline water resource for energy production may be possible for modest additional investment.

Potential Energy Value of Texas Water Resources

Hydropower is a mature renewable energy source. The relatively gentle terrain, low rainfall, and moderate changes in elevation throughout much of Texas means the state's hydropower resource is mediocre by national standards (see **Figure 11**), and, due to a variety of factors, will see only modest continued development. Ocean energy technologies are immature, but this point may be moot as Texas has poor ocean energy resources. Readily accessible saline water in much of West Texas coupled with the region's high annual insolation means that this area is among the best candidate solar pond sites in the U.S. Proposed projects to safeguard freshwater supplies from salt water intrusion may provide opportunities for feasibly employing saline water technologies.

ENERGY FROM WATER

Sources: Texas Water Development Board, Texas Natural Resources Information System, Idaho National Engineering Laboratory, Federal Energy Regulatory Commission

ENERGY FROM TEXAS WATER RESOURCES		
HYDROPOWER	OCEAN	SALINE
Existing Site (red)	Ocean Thermal Gradients	Saline Surface Water
Undeveloped Site (green)	Waves	Proposed Chloride Control Project
	Tides	

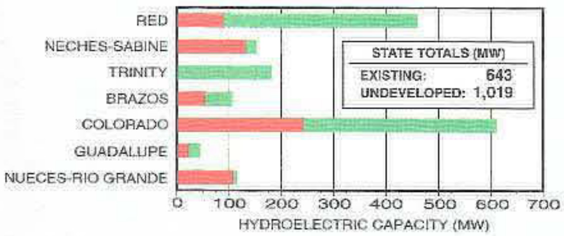


FIGURE 10. Hydro Potential of Texas River Systems.

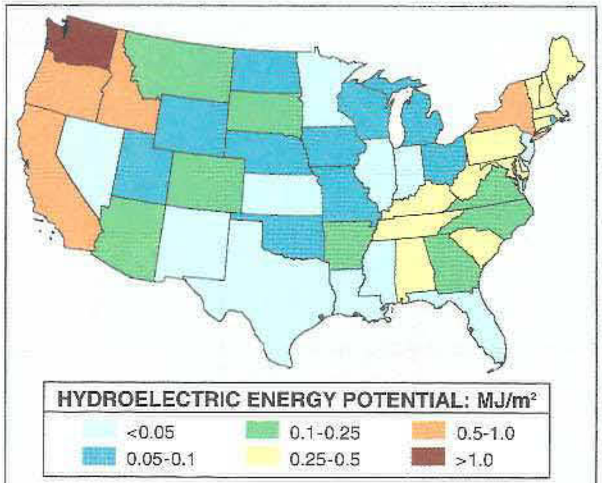


FIGURE 11. U.S. Hydroelectric Energy Potential. This map depicts the hydroelectric potential of each state relative to its area. Washington, with 25% of the nation's potential, has 75 times more hydro energy per unit area than Texas, which ranks only 43rd out of the 50 states.

The saline water resources of the High Plains, suitable for conversion to solar ponds or for growing aquatic biomass, may represent the most significant new energy opportunities of all Texas water resources.

Existing (red) and undeveloped (green) hydroelectric capacity are totaled for major Texas river systems in Figure 10 based on all sites identified in Figure 12.

Texas hydro development is mature, with water management centered on municipal supply, irrigation, and flood control needs rather than energy production.

Ocean resources near Texas are poor and/or are far from shore.

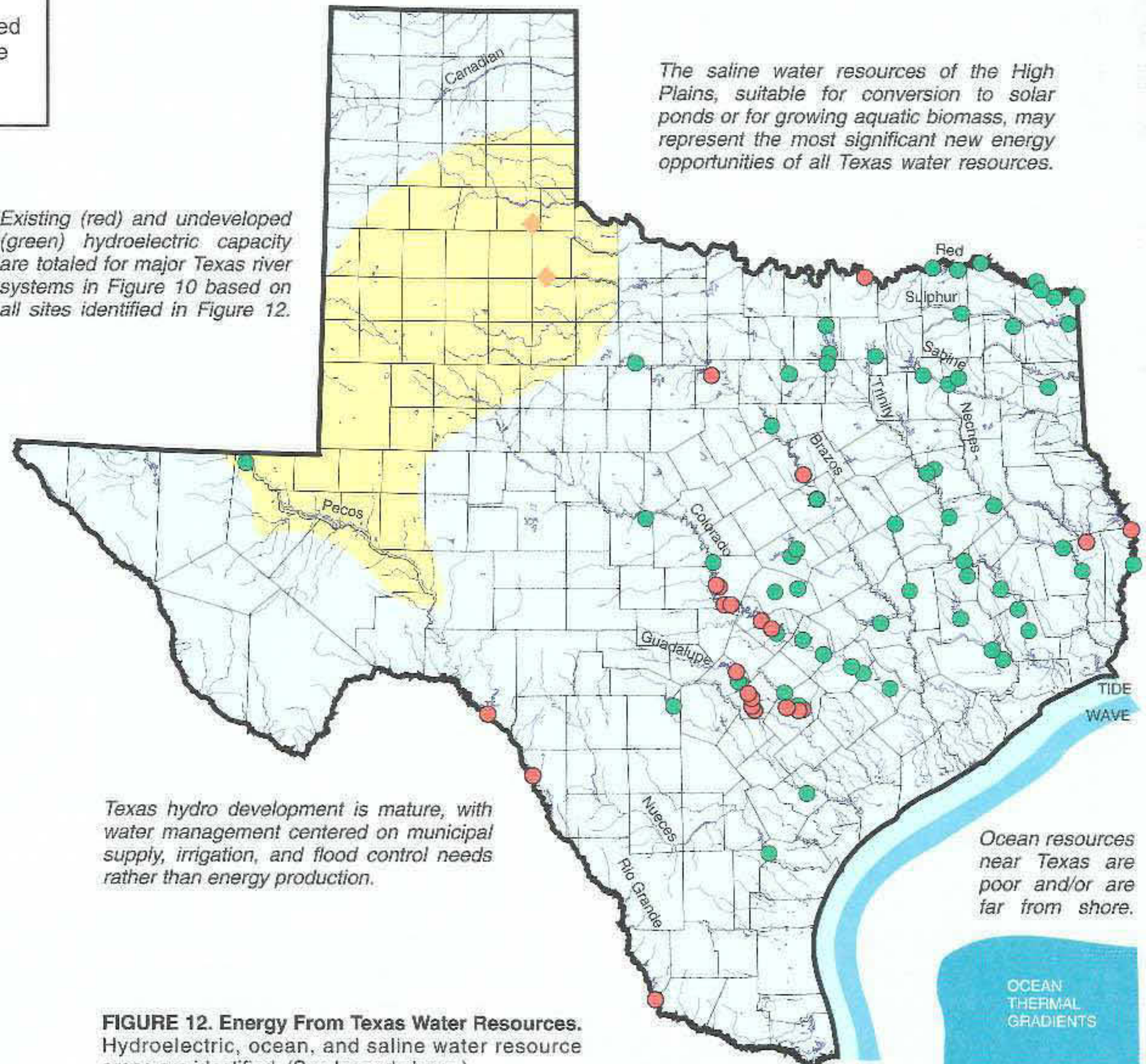


FIGURE 12. Energy From Texas Water Resources. Hydroelectric, ocean, and saline water resource areas are identified. (See legend above.)

GEOTHERMAL

Geothermal energy derives from the immense thermal reservoir of the earth's interior. Heat from molten rock (magma) beneath the earth's crust or from natural radioactive decay transfers to rock and water closer to the surface. In certain regions of the earth, the hot waters are close enough to the surface to be commercially exploited in heating applications, or, in the case of high-grade steam reserves, in electrical power generation.

One question that commonly arises regarding geothermal energy is whether or not it is a renewable resource. The answer hinges on how the resource is developed. Certainly the heat within the earth, like the sun, is limitless compared to human activity. However, the waters that are tapped in geothermal development are finite. Hydrothermal (hot water) aquifers will be diminished whenever water is withdrawn faster than it is recharged. Overexploitation at some facilities in California, for example, resulted in a lower than expected output. If water is reinjected into the field after extracting heat (as is done in some locations), then the resource may be said to be truly renewable. Otherwise, it is simply mined, much as a petroleum reserve.

Areas with significant geothermal resource occur where the earth's crust is relatively thin, such as along the boundaries of tectonic plates. Geysers, hot springs, volcanoes, and seismic activity, all of which are noticeably absent in Texas, mark such regions. In the U.S., the best geothermal resources occur along the Pacific rim (California to Alaska) and in Hawaii (see **Figure 13**). California has the largest geothermal electric facilities in the nation, with about 1100 MWe, most concentrated at the Geysers steam field in the northern part of that state.

A significant portion of the energy consumed in the United States requires relatively low temperatures. Energy needed for space and water heating, fish farming and greenhouse heating, enhanced oil recovery, and desalinization can take advantage of low temperature hydrothermal resources if such resources are present where the energy is consumed.

The Texas Resource

Texas does not possess any easily accessible field with the high temperatures required for electric power generation. It does, however, possess some low-temperature hydrothermal reserves that have seen limited use. As shown in **Figure 14**, these resources occur mainly in two bands, one that cuts a swath through the central part of the state, and a second that borders the Rio Grande in the Trans-Pecos. Temperatures in the Central Texas hydrothermal aquifers range from about 90° to 160°F at depths from 500 to 5,000 feet. Historically the waters have seen some application in spas and therapeutic baths. Where waters are potable, a number of smaller communities have tapped them for their municipal supply, without making use of the heat. A recent project in Marlin, however, employed geohermal well water to heat a local hospital. In the Trans-Pecos, thermal waters have likewise supplied resort baths, with scant need for more extensive development owing to the region's remoteness.

In addition to the state's low-temperature hydrothermal resource, large zones of hot, highly pressurized fluids occur in deep strata under the Gulf Coast. This so-called "geopressured-geothermal" resource was studied extensively in the 1970's and 1980's and a test well was operated by the Department of Energy at Pleasant Bayou near Houston. Typically, geopressured zones are at depths on the order of 15,000 feet and the fluid itself is a hot (about 300°F), high-pressure brine with methane dissolved in it. Interest in the resource is probably driven as much by the potential methane recovery as by its geothermal character. To date, development has not proven economical. Hot brine, however, may someday be used in enhanced oil recovery schemes. Since the resource is not renewable, it must be mined to be used.

A final, long-term geothermal energy prospect is the extraction of heat from zones of "hot dry rock" (HDR). In the envisioned HDR facility, high-pressure water injected underground at one point is collected at a distance well after it has been heated by passing through fractured, hot rock. The scheme is presently in its infancy. One study suggested that Texas has moderately good resource in the eastern part of the state (see Figure 13).

Value of the Texas Resource

Texas does not have the sort of readily accessible, high-temperature hydrothermal resource that can be used to generate electricity. The resource in the central part of the state can, however, have an impact in low-temperature applications such as space heating or aquaculture. Several municipalities that presently introduce warm aquifer water in drinking supplies could capture beneficial heat with the addition of a heat exchanger. The geopressured-geothermal resource will become more attractive only in the context of higher energy prices. Hot dry rock's potential value is presently unknown.

GEOTHERMAL ENERGY

Sources: Bureau of Economic Geology,
Los Alamos National Laboratory

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

Use of low temperature hydrothermal for various heating needs represents the best near-term application of Texas Geothermal resources.

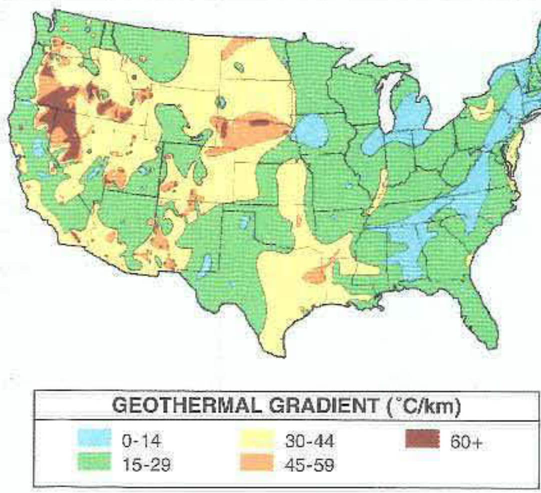


FIGURE 13. Geothermal Gradient Contour Map of the United States. The increase in temperature with depth below the ground is highest in areas with volcanic and seismic activity. This map indicates Hot Dry Rock potential.

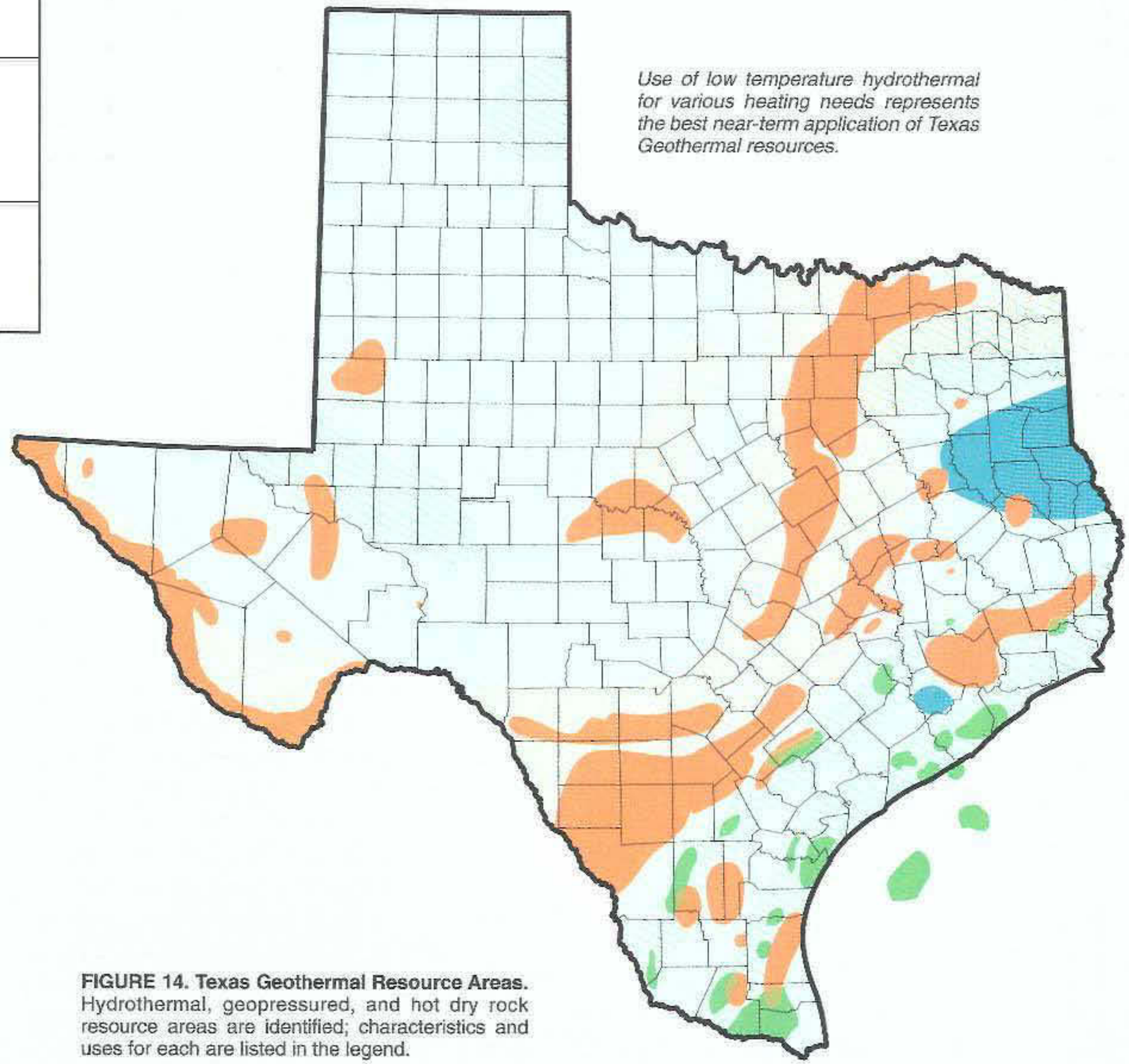


FIGURE 14. Texas Geothermal Resource Areas. Hydrothermal, geopressured, and hot dry rock resource areas are identified; characteristics and uses for each are listed in the legend.

BUILDING CLIMATOLOGY

Building climatology refers to the study of climate as it affects human comfort and to strategies that use the climate as a resource to lower the energy demands of buildings. These strategies, which are mostly passive in nature, all involve working with the climate rather than against it to minimize space conditioning and lighting loads. Some of the strategies, like shading windows to minimize solar heat gain, will be familiar to any Texan, while others are not so intuitive. They can be summarized as follows:

Shade—providing external shading of windows and structures during hot, sunny periods.

Solar gain—using sunshine incident on vertical, south-facing surfaces to warm structures when temperatures drop below comfort levels.

Ventilation—employing natural or fan-forced air flow to maintain comfort during hot, humid conditions.

Mass—constructing building envelopes of massive, heat-retaining materials (like adobe structures) to moderate the high diurnal temperature swings of arid climates.

Night ventilation—flushing building structures with cool, nighttime air to minimize the next day's cooling load; works best in conjunction with massive envelopes.

Evaporative cooling—evaporating water directly into hot, dry airstreams to produce cooling; limited to arid climates.

Daylighting—substituting sunlight for artificial lighting through skylights and windows.

Resource Potential in the Texas Climate

From a building climatology perspective, Texas has a fundamentally temperate climate in that all parts of the state have both heating and cooling loads. Within this framework, however, there exists considerable variation, ranging from the humid Gulf Coast to the arid Trans-Pecos, and from comfort needs dominated by cooling loads in the Rio Grande valley to heating-dominated conditions in the panhandle. As a result, different passive design strategies will be appropriate in different parts of the state. **Figure 15** identifies seven climatic regions and the various options appropriate for each. The comments and suggested tactics are geared toward residential structures—buildings whose energy needs are driven by climatic loads rather than internal load-dominated structures such as offices.

An additional resource not mentioned in the figure that has potential across the entire state is daylighting. Daylighting is particularly pertinent for commercial buildings. About 25% of a typical office building's total electricity consumption is in lighting. Lighting also contributes substantial heat that must be removed during the cooling season.

Passive strategies can improve any building's energy demand, but will only reach their full potential when incorporated into design and construction. Certain techniques simply cannot be retrofitted. Decisions about siting, orientation, and mass can have an enormous impact on a building's energy consumption and are permanent. For example, simple decisions about the structure's location relative to trees and which rooms face south will help define a building's "metabolism." Although we know that incorporating passive design into new buildings can greatly reduce their energy consumption (perhaps by as much as half), no research has been carried out to quantify the effectiveness of such strategies on Texas' existing buildings. Furthermore, no thorough canvass of the state's existing building stock exists that defines a typical structure. Building climatology's potential impact on state energy consumption can only be approximated in the absence of these data.

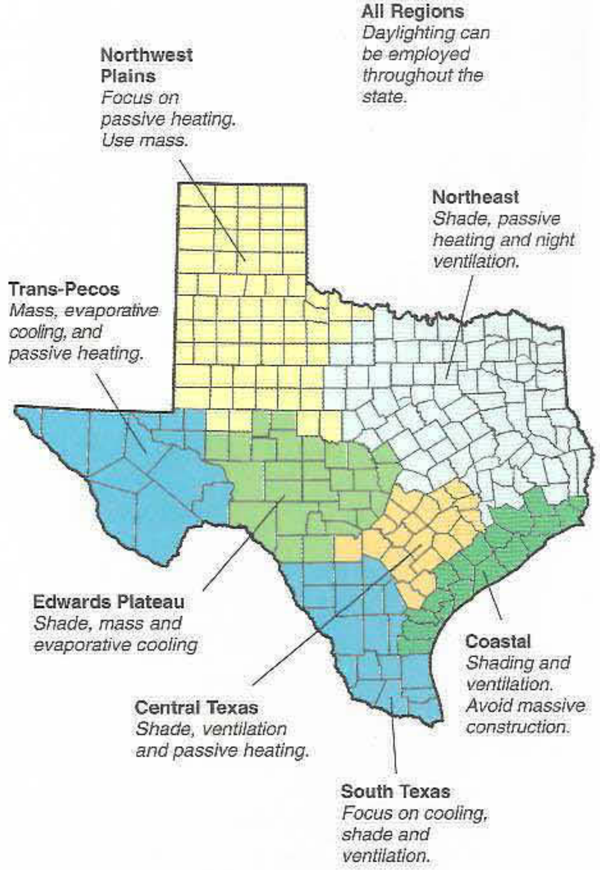


FIGURE 15. Passive Strategies Generally Suitable for the Seven Climatic Regions of Texas. The strategies above can often be incorporated to reduce energy demands and to improve comfort in buildings. Of course, actual recommendation are specific to the characteristics of the building site.

RESOURCE TRANSPORTATION

Texas clearly possesses abundant renewable energy resources. The presence of a good resource area alone, however, does not guarantee that it will be exploited to provide useful energy services. Issues such as potential environmental and social impacts, public acceptance, and a host of technical and financial matters will dictate whether a site is acceptable for development. One significant technical issue relates to the ability to economically move energy from a good resource area to a location where it can be used.

Distributed Resources

Many technologies employing renewable energy sources are well suited to small-scale, distributed applications located where the energy service is needed. Examples include daylighting of structures, properly designed roof overhangs (to reduce cooling requirements), rooftop solar panels, ranch and farm wind turbines, and space heating from firewood or geothermal sources.

Distributed generation serving end-use loads incurs neither the losses associated with the delivery of electricity (losses of about 10%) nor the transportation energy required for the delivery of solid and gaseous fuels. Additionally, distributed generation frees up capacity of conventional energy delivering systems, thereby reducing the need for additional investment in transportation infrastructure.

Electric Transmission Studies

In a study for the SEDC, several of the state's major electric utilities evaluated the cost of electric transmission facilities needed to transport electricity from five renewable energy resource areas to major population centers such as Dallas, Houston, and San Antonio. Their results, summarized in **Figure 16** below, indicate that renewable energy installations at different locations in Texas may incur significantly different transmission costs. For instance, transmission improvements needed to carry electricity from some areas of West Texas may add as much as 35% to the total price tag for a large wind power plant. Yet, if this same wind plant were located near Kleberg in South Texas, transmission costs would amount to less than 5% of the total project cost.

A second study that examined the Texas electric grid was performed by Electric Power Engineers (EPE) in conjunction with this resource assessment project. Their goal was to evaluate limits of the Texas transmission network in distributing electric power generated from renewable resources. Twenty-nine prospective renewable energy generation sites distributed throughout the state were considered. Even with no new power lines, the EPE load flow analysis suggests that many large renewable energy power plants could be added to the grid (**Figure 17**). The small numbers in the Panhandle and Trans-Pecos suggest that new transmission lines will be required to build sizable power plants in these good resource areas.

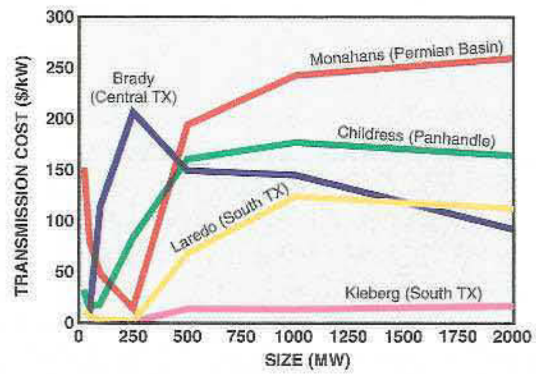


FIGURE 16. Electric Transmission Costs. Summarizes improvements required at five prospective power plant sites.

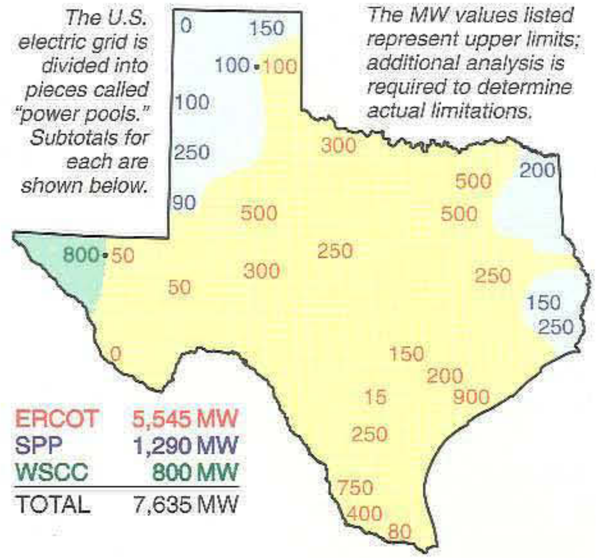


FIGURE 17. Capacity Limits. Each value is an estimate of the maximum generation potential (MW) at that site assuming no new power lines are built. For reference, in 1993, total installed generation capacity in Texas was 68,163 MW.

Transportation Sector

In addition to electricity, one of the most promising near-term market pathways for Texas renewables is in the transportation sector. A new federal regulation requires that a portion of the oxygenates used in the making of reformulated gasoline (RFG) be derived from renewable sources. RFG will be mandated in many cities with air pollution problems. Much of the nation's capacity for manufacturing fuel oxygenates is in Texas, and Texas biomass could someday be a source for the alcohols from which they are derived.

RECOMMENDATIONS

Texas is blessed with abundant renewable energy resources. In fact, Texas' solar, wind, and biomass potential rank among the very best in the nation. As summarized in **Figure 18** below, many areas of the state have sufficient "commercial quality" resources to support large investments such as electric power production, cogeneration, and alcohol manufacturing, as well as multitudes of distributed, small-scale projects. Texas' excellent endowment suggests that renewable energy offers exceptional potential to help meet the state's future energy needs.

Development of the state's renewable energy resources could provide meaningful employment opportunies and stimulate local economies. The Northwest Plains, with sizable wind, solar, and biomass potential, is well positioned to reap rural economic benefits associated with the growth of renewables. In the urban areas of East and Central Texas, distributed renewable energy systems can satisfy a large portion of local energy needs. In addition, many renewable energy sytems mesh synergistically with efforts to control various wastes. Examples include distributed electric generation facilities fueled by landfill gas and other urban wastes, and solar ponds constructed in conjunction with facilities that prevent saline water from contaminating fresh water supplies.

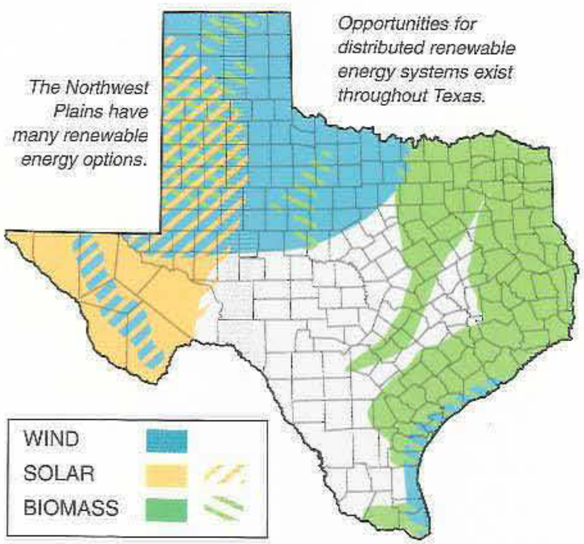


FIGURE 18. Areas of high Solar, Wind, and Biomass Potential. Striped areas indicate more than one good resource.

This project has gathered information from a wide variety of sources. In total, these sources determine that Texas has plentiful renewable resources. But in order to optimally utilize the renewable energy resource base of the state, additional information will be required. The recommendations which follow are designed to provide a better understanding of resources that have the potential to make significant near-term contributions towards the state's energy needs.

Specific Resource Assessment Needs

Future investments in renewable energy resource assessment should be focused in areas where they are expected to have the greatest near-term impact, and secondly when and where opportunities present themselves to participate in other ongoing resource assessment activities.

1) **Building Climatology:** *Characterize the state's building stock and examine the potential impact of passive strategies.* Building structures that are more in tune with their environmental surroundings makes sense economically. However, passive strategies do not operate independent of one another; additional validation of optimal strategies for structures built in Texas climates is warranted.
2) **Wind:** *Establish more wind monitoring stations throughout the state. Secondly, evaluate wind data that are already available.* The recent interest in wind energy development in the state has motivated the need for additional resource information, particularly in windy areas. The numerous existing wind data that have not yet been considered should be evaluated.
3) **Solar:** *Establish more solar monitoring stations throughout the state, particularly in the Trans-Pecos and along the Rio Grande.* The best solar resource areas of Texas have almost no measured solar data available. Major solar development will require substantially improved resource information to reasonably locate facilities.
4) **Biomass:** *Fully participate in federally sponsored programs.* Although active in certain areas such as switchgrass field trials, Texas researchers have been absent from other assessment opportunities relevant to the state's biomass resource.

In addition to the recommendations above, organizations that are considering investments in assessment of renewable energy resources should be attentive to special opportunities for co-funding projects with entities with related interests. For instance, the Texas Natural Resource Conservation Commission is leading an effort to establish a Texas mesoscale weather observing network (MESONET). Such a network would prove extremely valuable to the Texas renewable energy community. Secondly, if water agencies contemplate the construction of new chloride control lakes, it may be prudent to investigate the feasibility of utilizing the project as a solar pond.

INTRODUCTION

by Mike Sloan

BACKGROUND

Renewable energies are those forms of energy that derive from the natural movements and mechanisms of the environment—sunshine, wind, the heat of the earth, the growth of plants and animals, the movement of the seas and rivers. Prior to the industrial revolution, these sources were virtually the only forms of energy used by man. During the past 150 years, modern civilization has become increasingly dependent on fossil fuels such as coal, petroleum, and natural gas. The finite nature of these supplies implies that a transition to a sustainable energy future is inevitable.

Texas produces and consumes more natural gas, oil, lignite, electricity and total energy than any other state.[1,2,3,4,5] It also ranks near the forefront of coal and nuclear power consumption. As shown by the summary on Page 18 (Ranking Texas Energy), Texas dominates practically every major energy statistic. Yet one area that Texas is not among the nation's leaders is the use of renewable resources. With respect to the use of renewable energy, Texas currently ranks only 49th out of the 50 states.[6]

For more than half a century, petroleum was the lifeblood of the Texas economy. Early in the state's history, Texans recognized and developed their abundant native energy resources. As a result, an energy-related economic base flourished, and a burgeoning petroleum industry was born. The energy sector demands enormous inputs of capital, labor, and other resources and indirectly benefits practically every sector of the Texas economy. This multiplier effect, which magnifies the overall economic impact of a direct investment, is higher for energy production than for most other sectors of the Texas economy.

The early Texas oil fields served as fertile ground for the growth of numerous support industries from heavy equipment fabricators to oilfield service providers and fire control experts to specialized petroleum landmen and lawyers. In many cases, members of these fledgling groups have come to be recognized as the world's most knowledgeable and capable experts in their respective fields. Even during local economic downturns, Texas' energy-support industries foster economic activity and tax dollars for the state through the global sales of products and services.

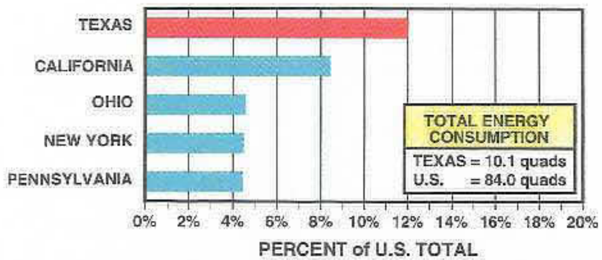
Demand for energy services and expertise are growing and will continue to grow. By the year 2010, U.S. energy demand is expected to grow by more than 20 quads, reaching a total of 105 quads.[7] Along with this growth is the need to replace a large fraction of the nation's aging energy infrastructure. Yet these needs in the U.S are dwarfed in comparison with projected global energy markets. Driven by rapidly growing demand in Latin America, Asia, and the rest of the developing world, global primary energy may grow by as much as 200 quads by the year 2010.[8]

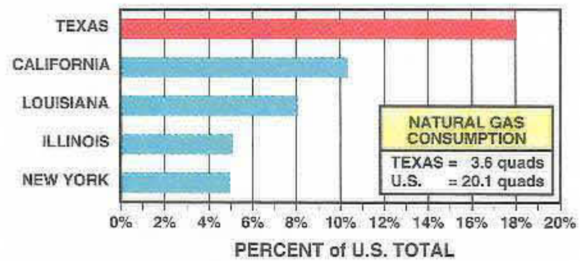
Although hydropower and biomass have long contributed to our nation's energy mix, the renewable energy industry is in its early stages of development. Wind and solar technologies, in particular, are seemingly on the verge of capturing a significant share of new energy markets. If renewable energy sources emerge as a dominant contributor to future energy markets, economic benefits will accrue to those regions that pioneer the development of successful renewable energy technologies. Enlightened by the rich history of the Texas oil industry, Texans have the opportunity to recapture that "wildcatter" experience and capitalize on the enduring benefits possible from nurturing a vibrant domestic renewable energy industry through the early development of the State's vast renewable resources.

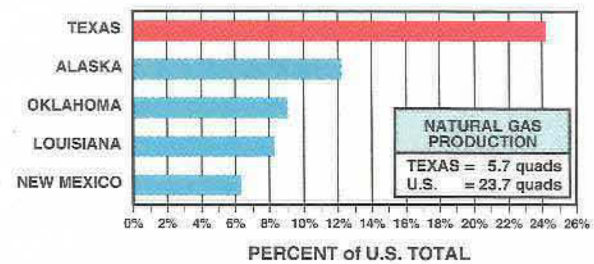
Unique Factors—Unique Opportunity

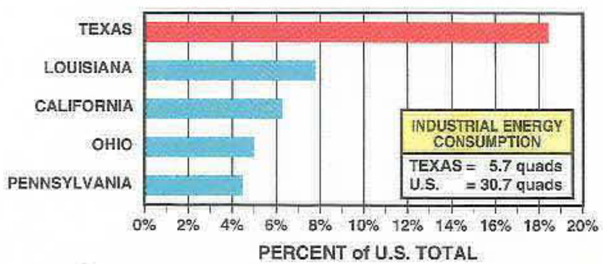
Texas, perhaps more than any other state, stands to benefit from the rapid development of renewables. Several exceptional factors position Texas favorably to pioneer the widespread use of renewable energy resources:

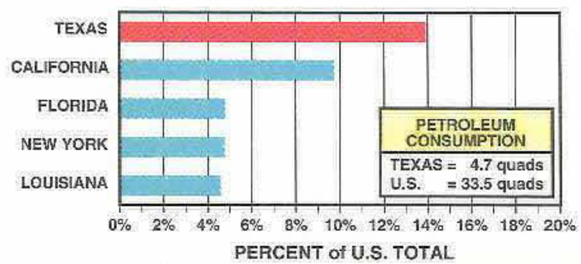
1. Texas has high total renewable energy resource potential;
2. Texas has high current and projected energy needs;
3. Texas has considerable existing energy infrastructure; and
4. Texas is strategically located relative to markets in Latin America.

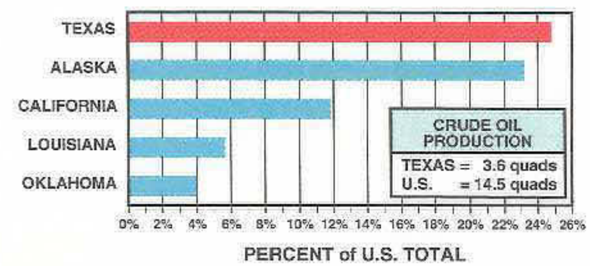


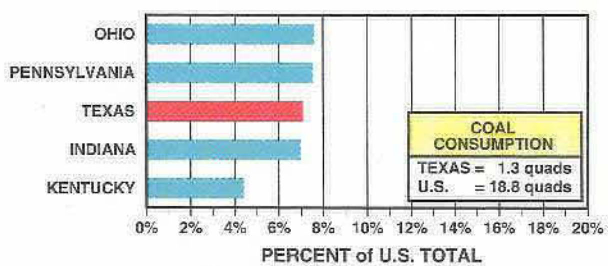


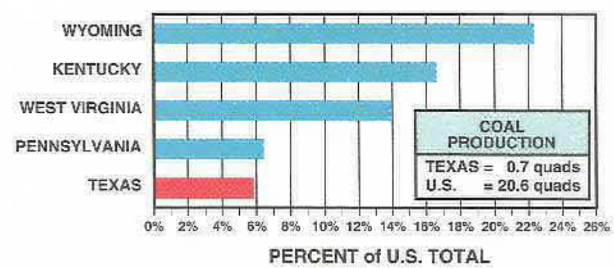






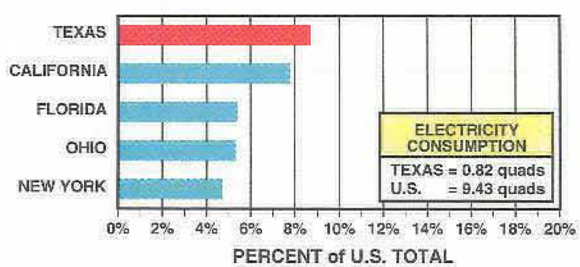


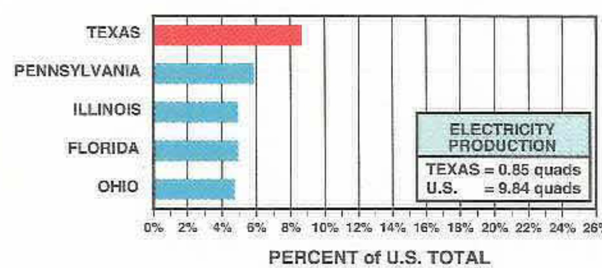




Ranking Texas Energy [1,2,3,4,5]

State energy statistics from various Energy Information Administration (EIA) documents have been compiled and presented to convey the extent of energy production and consumption in Texas. Each figure shows the top 5 states as a percentage of the U.S. total based on published data for 1993. Texas tops nearly every category. Texas recently regained its position as the nation's top oil producer, moving ahead of Alaska. In 1992 Texas passed up Illinois to move into the #5 spot for coal production (by tonnage). It is noted that energy statistics from different sources (even different EIA documents) may result in slightly different totals.





Texas has significant potential to develop its solar, wind, and biomass resources. **Figure 1.1** shows the top ten states for hydrogen production potential from renewable energy sources as determined by a recent study conducted for the United Nations.[9] This figure indicates that Texas ranks first in practically all renewable energy resource categories (number one for solar and biomass; number two nationally for wind).

While abundant availability of a resource is a prerequisite to widespread use, development of any resource is strictly limited by the demand for it. As **Figure 1.2** (energy consumption) and **Figure 1.3** (projected population growth) suggest, coincident with Texas' abundant renewable resource base is a large and growing need for energy. The renewable resource potential and growing energy demand of Texas are noteworthy, since Figures 1.1 through 1.3 strongly suggest that most states with large renewable energy potential tend to have relatively low energy consumption and low future energy needs. In fact, as shown in these figures, Texas' energy demand is almost double the combined total demand of the nation's nine next best states for renewable energy potential.

As one of the major energy production and consumption centers in the world, Texas has extensive energy infrastructure. Even though competition for access to available energy transportation infrastructure poses a near-term challenge for renewable energy projects, it also represents a considerable long-term opportunity. The Permian Basin, Texas Panhandle, and Texas/Louisiana Gulf Coast are among the largest gathering regions and transportation hubs for pipeline gas in North America.[11] As it becomes increasingly difficult to construct new energy transmission projects, existing energy infrastructure and transmission right-of-ways may prove to be a strategic asset that benefits Texas renewables. Hydrogen generated by solar plants in the Permian Basin, wind plants in the Panhandle and geopressure facilities along the Gulf Coast, could some day trace the same routes currently used by Texas natural gas to reach markets across North America.

Growing demand in Latin America for raw energy, energy technology and services represents opportunity for all Texas energy enterprises. Texas' physical proximity to and prominence with Mexico, Central America and South America, must be considered a strategic advantage for trade with those regions. More than half of the United States' border with Mexico is within Texas. Furthermore, 60 percent of the electrical interconnection points and 75 percent of the major gas pipelines between the two nations meet at the Texas border.[11,12] The recent passage of the North American Free Trade Agreement (NAFTA) has also enhanced significantly Texas' inherent advantages in dealing with Latin American markets.

Renewables provide a promising opportunity with long-term growth potential. As the U.S. seeks new ways to compete in the global marketplace, Texas' combination of resource potential, growing demand, existing infrastructure and location present a unique opportunity for the development of renewable energy resources, not only for the State, but for the nation as well. When decision makers contemplate priorities for investing in the development of renewable resources, Texas offers a logical proving ground with superior potential for high return on investment. In short, Texas is well positioned to reap the benefits from the early development of renewable resources.

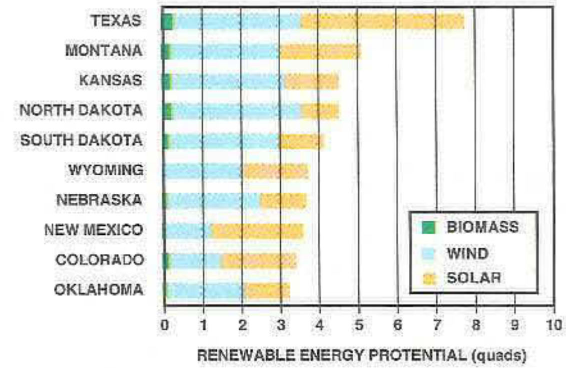


FIGURE 1.1. Relative Renewable Energy Potential.[9]

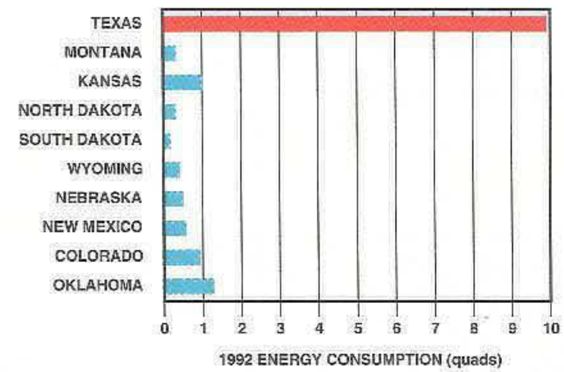


FIGURE 1.2. Energy Consumption, 1992.[5]

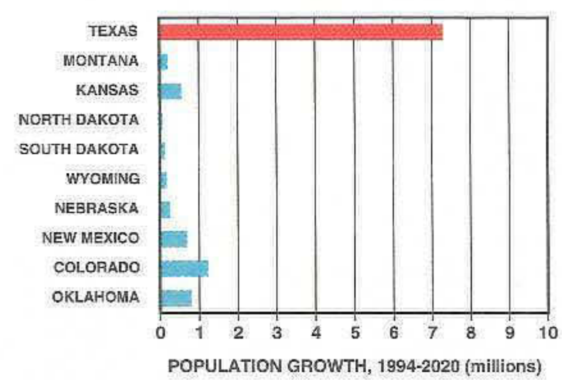


FIGURE 1.3. Projected Population Growth, 1994-2020.[10]

Environment

The global community has become increasingly sensitive to the value and importance of its natural surroundings. Governments worldwide are establishing standards for clean air and water to ensure the preservation of functional ecosystems. Safeguards designed to protect the environment typically make it more expensive to harness and use energy by conventional methods. Additionally, new environmental legislation, such as the Energy Policy Act (EPACT) and amendments to the Clean Air Act, carry regulatory mandates with serious economic consequences for energy industries. As global population increases, environmental regulation will likely result in additional economic pressure and uncertainty for traditional energy companies.

Perhaps the most compelling reason to reexamine current methods of producing energy is the increasing level of atmospheric carbon dioxide. Carbon dioxide is an integral component of the carbon cycle—the characteristic process that distinguishes Earth from the lifeless planets in our solar system. The ramifications of any human activity that threatens to fundamentally alter the natural balance of this cycle must be carefully considered.

The carbon cycle is depicted in **Figure 1.4** in its most rudimentary form. Growing plant matter takes in atmospheric carbon dioxide. When plants and foliage die, carbon dioxide is released back into the atmosphere. Additionally, small amounts of carbon work into the soil as organic matter decomposes. Over millions of years, underground carbon deposits may become petroleum, natural gas, or coal. When such fossil fuel deposits are extracted from the ground and burned, carbon is reintroduced into the atmosphere as carbon dioxide. The widespread combustion of fossil fuels, therefore, tends to increase atmospheric levels of carbon dioxide above natural levels.

Since 1958, continuous measurements of atmospheric concentrations of carbon dioxide have been

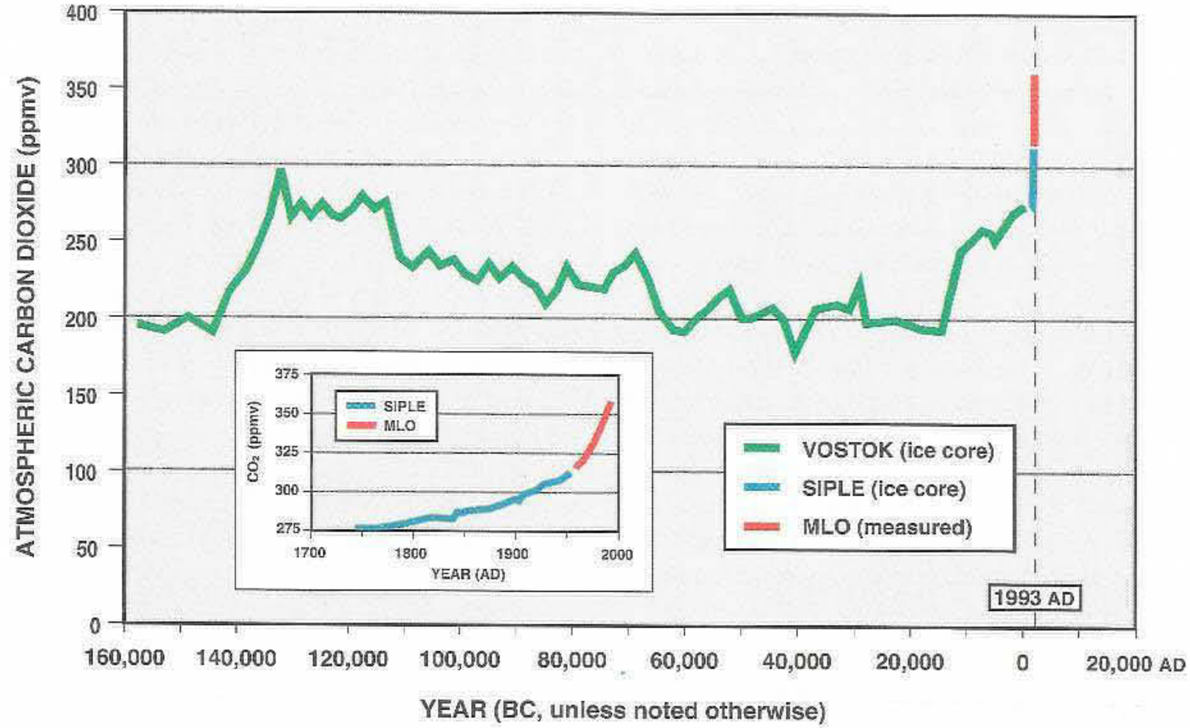


FIGURE 1.5. Atmospheric Concentration of Carbon Dioxide (160,000 BC - 1993). A compilation of atmospheric carbon dioxide records from three historical sources: Mauna Loa Observatory measurements,[13] Siple ice core,[14] and Vostok ice core[15] (ppmv = parts per million by volume). The data shown in the inset correspond to the industrial age. During this period, anthropogenic (man-caused) sources such as deforestation (primary contributor prior to 1940) and the burning of fossil fuels (primary contributor after 1940) have resulted in steady increases of atmospheric carbon dioxide.

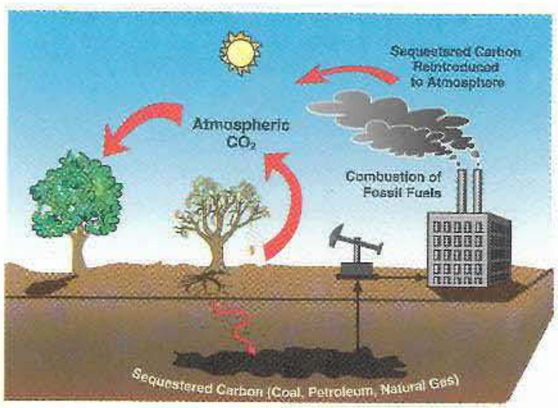


FIGURE 1.4. Sketch of Simplified Carbon Cycle.

recorded at the Mauna Loa Observatory in Hawaii. The Mauna Loa data are regarded as a precise record of regional carbon dioxide levels in the middle layers of the troposphere.[13] Testing of ancient air samples entombed in glaciers provide information on historic levels of carbon dioxide.[14,15] Data from both sources are presented in **Figure 1.5**, and suggest that: 1) at no time during the historical period of record were average carbon dioxide levels as high as they are presently; and 2) carbon dioxide levels appear to be consistently increasing.

While the ultimate effects of increased levels of atmospheric carbon dioxide are unknown, fundamental atmospheric science suggests that a rebalancing of the net heat exchange of the planet will occur. It seems reasonable to surmise from the carbon dioxide trends that there is an increased possibility of global climate change. The mere prospect of this potentially catastrophic event may trigger regulatory action that will require decision makers to factor in the consequences of global climate change, whether the phenomenon is real or perceived.

Recent actions of the international community suggest such regulation is at hand. Due in part to international concern for increased carbon dioxide levels, 161 nations participating in the United Nations Conference on Environment and Development signed the Framework Convention on Climate Change.[16] This treaty includes commitments by each developed nation to return to 1990 levels of greenhouse gas emissions from manmade sources by the year 2000.[17] On April 21, 1993, President Clinton reaffirmed the U.S. commitment to comply with this goal.[16] Since Texas produces more carbon dioxide than any other state, this national commitment has particular significance for the future of Texas.

Texas: At an Energy Crossroads

Texas is currently at an energy crossroads, as shown in **Figure 1.6**, a compilation of state energy statistics from the Texas Railroad Commission (RRC), Texas Comptroller of Public Accounts (TCPA) and the federal Energy Information Administration (EIA). The blue energy production line labeled "Production" represents RRC records of actual statewide production of crude oil, natural gas, condensate, lignite, coal, and surface-mined uranium.[18,19] A second measure of energy production—the green "Production (TCPA)" line—reflects the Comptroller's records for taxable production of crude oil, natural gas and condensate, appended to RRC production figures for lignite, coal, and surface-mined uranium.[20] The red line labeled "Consumption" reflects total state energy consumption as calculated by the EIA.[5] The dashed orange line labeled "GSP" represents Gross State Product data scaled to parallel historical energy consumption data in Texas. The dashed orange line has been extended into the future, based on 1993 GSP projections by the Comptroller's Office, to provide a

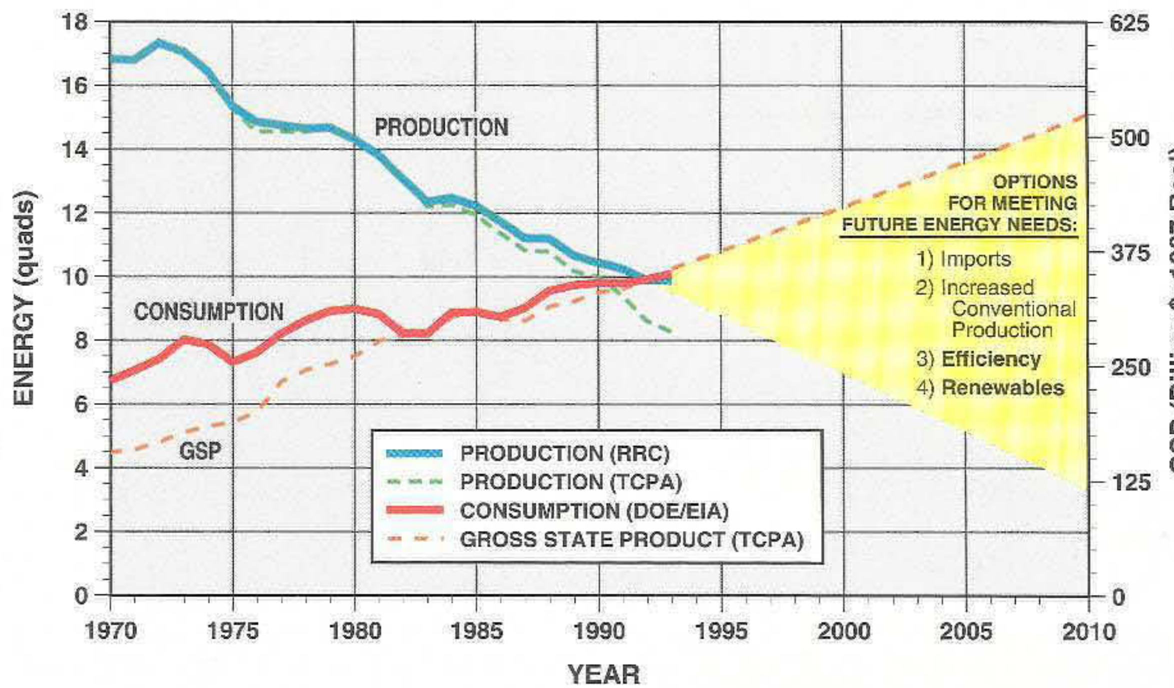


FIGURE 1.6. Texas Energy Production and Consumption.[18,19,20,21,5] Historical trends in Texas energy production (blue line) and energy consumption (red line) suggest that traditional energy sources will not be able to meet future energy demand. Four distinct options may satisfy future energy needs of the State. Of these, development of native renewable energy resources and the use of energy efficiency measures are the most desirable and promising long-term solutions for Texas.

baseline for estimating future state energy consumption.[21]

For decades, excess energy production in Texas fueled a sizable portion of the national economy. Yet, as shown in Figure 1.6, steadily increasing state consumption finally caught up with waning energy production during 1992. Based on the historical trends, there will be a growing differential between state energy consumption and state energy production during future years. In other words, Texas has become a net energy importer.

At this crossroads, there are four distinct courses of action that, individually or collectively, will serve to satisfy this energy differential: 1) increase imports from out-of-state sources; 2) increase conventional production; 3) reduce consumption; or 4) drastically increase the utilization of renewable energy resources.

The Texas Response

Recognizing the need to articulate a coherent statewide energy policy, leaders from the Texas Railroad Commission and the Governor's Energy Office organized the State of Texas Energy Policy Partnership (STEPP) to develop a realistic energy policy blueprint for Texas. More than 300 people representing a broad range of expertise met in 1992 to achieve this goal.

Imports. The STEPP process determined the strong preference of Texas to maintain its long tradition of energy independence. Relying on foreign sources to supply Texas future energy needs represents a great loss, not only in dollars, but also in jobs. As articulated by STEPP, Texans are not willing to concede future energy supply to out-of-state sources without pursuing domestic options first.

Increasing Conventional Production. Texas has initiated policies (tax exemptions) during recent years aimed at bolstering domestic production of oil and gas. In spite of such efforts—indicated by the widening gap between the actual production (RRC; blue) and taxable production (TCPA; green) lines in Figure 1.6—total production from conventional energy sources has continued to decline. **Figure 1.7** reproduces the long-term outlook for Texas crude oil and natural gas adopted by STEPP.[23] Even under the most optimistic scenarios, future oil and gas production in Texas are expected to decline from current levels. Hence, efforts to increase production of Texas' conventional energy resources will likely struggle to satisfy current levels of consumption, much less keep pace with long-term growth.

Efficiency and Renewables. Of the four options proposed for meeting future energy needs, only decreased consumption through efficiency measures and increased supply through renewable energy resources appear to be acceptable long-term solu-

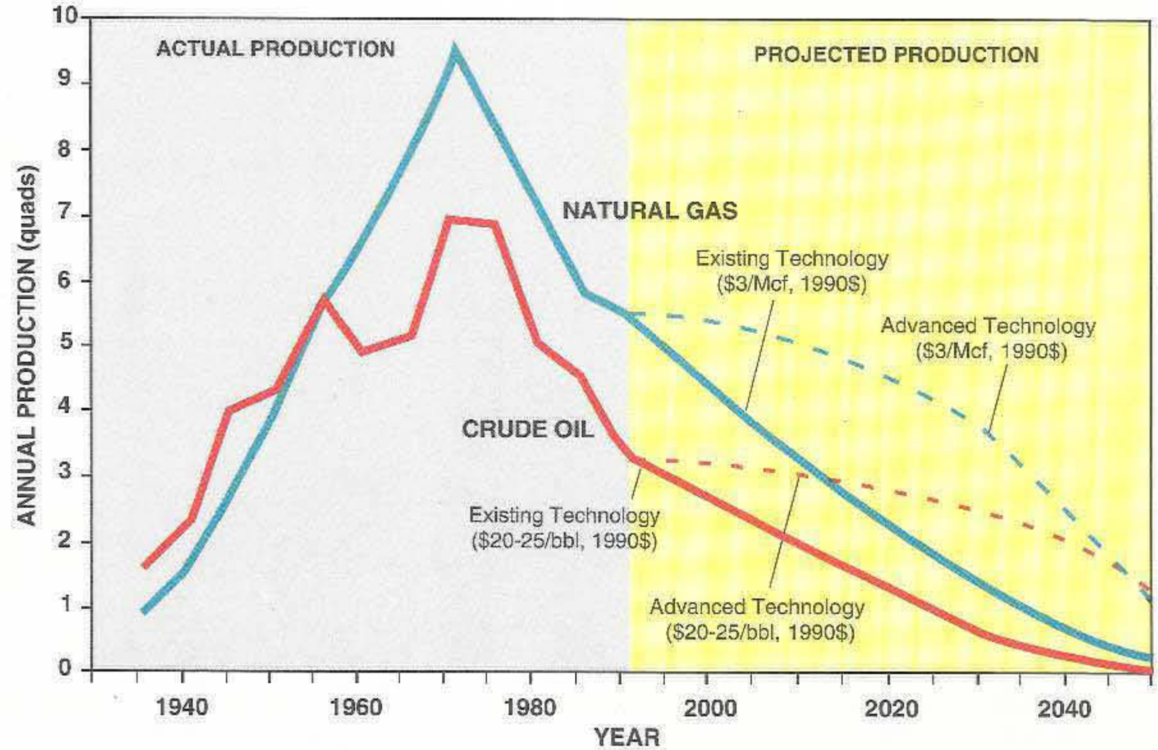


FIGURE 1.7. Long-Term Outlook for Texas Crude Oil and Natural Gas. Crude oil (red line) and natural gas (blue line) production history through 1991 and forecasts by W.L. Fisher[22] are plotted together on the basis of energy. Even with the use of advanced technology, future oil and gas production in Texas are expected to decline from current levels.

tions for Texas. The potential for energy efficiency is clearly demonstrated in Figure 1.6 as reductions in energy consumption relative to GSP during the mid-1970s (following the OPEC oil embargo) and in the early 1980s (coincident with high energy prices). Although current energy prices are low, there is nonetheless potential for reducing energy demand through cost-effective efficiency measures. The ultimate potential contributor for meeting future energy needs with domestic resources may, however, be renewable energy. *Renewable energy sources, coupled with efficiency measures, represent a significant potential for meeting Texas' long-term energy demand while also achieving environmental goals such as the reduction of anthropogenic carbon emissions.*

STEPP declared that "...adequate price levels, the inclusion of renewable resources and energy efficiency in the overall mix, advanced technology and policies encouraging the foregoing are required if Texas is to retain its historical role as an energy exporter; without them, it will become an energy importing state well before the turn of the century."[23] Data presented in Figure 1.6 suggest this crossroads has already been reached.

In March 1993, the same month during which the STEPP report was released, Governor Ann Richards created the Sustainable Energy Development Council (SEDC). The Governor instructed the group "... to develop a strategic plan to ensure the optimum utilization of Texas' renewable energy and energy efficiency resources." The executive order specifically instructs the Council to conduct studies of the renewable energy resource base.

Purpose of this Project

The SEDC, through the State Energy Conservation Office (SECO), contracted with Virtus Energy Research Associates (VERA) to evaluate Texas' renewable energy resource base, including solar, wind, biomass, water, geothermal, and building climatology. The project's fundamental purpose is to identify a broad range of information and data sources pertaining to Texas renewable energy and to disseminate the information to a broad audience.

Because the information needs of various user groups are so broad, the project consists of three distinct components: survey, overview, and recommendations. The project components are summarized below with respect to their intended purpose and target audience.

Survey. The survey identifies available information relevant to Texas' renewable energy resources. A survey, thorough literature review and direct solicitation were used to identify existing fundamental resource information. One focus of these efforts was the investigation of fundamental data collection activities such as solar and wind monitoring stations. This information is reported in sufficient detail to be useful to renewable energy developers, researchers and the academic community.

Overview. The overview characterizes each renewable energy resource in Texas from available information and limited original work. Summaries for each resource include a map conveying the spatial distribution of the annual average resource as well as information on typical daily, seasonal, and year-to-year fluctuations. Lastly, each resource is quantified with respect to its absolute size (total resource) and the portion potentially suitable for development (accessible resource base). This component is intended primarily to support the strategic planning efforts of the SEDC.

Recommendations. Recommendations are made to prioritize future public investments in renewable energy resource assessment. Significantly, these recommendations anticipate that future expenditures for resource assessment will be intended to accelerate the commercialization of renewable energy projects, rather than be conducted primarily for academic purposes. The recommendations are provided for entities that may fund resource assessment projects in Texas.

This project is an initial attempt by SECO and the SEDC to comprehensively identify and acquire information covering the full range of renewable energy resources in Texas. It is anticipated that an appropriate entity will ultimately be identified to serve as a permanent clearinghouse for continuous information gathering and dissemination. (Yet, as of press time, no entity has yet been identified; see Appendix A for further discussion.) Information sources collected and generated through the project include a library of maps, documents, computer software, data files, and Geographic Information System (GIS) data layers.

Structure of the Report

The report is organized into a project summary, eleven chapters, three supporting appendices, and a glossary. Initial elements of the report include the project summary and this introduction. Two additional introductory chapters cover the fundamentals of renewable energy and an overview of the Texas Climate. These chapters provide insight into the relative size of and interrelationships between the State's various renewable resources.

Individual chapters on solar, wind, biomass, water, and geothermal resources represent the main body of the report. Texas Biomass, due to the breadth of the topic and the lack of a previous comprehensive assessment, is substantially longer than the other resource chapters in the book. The water resource chapter includes consideration of energy from the state's rivers (hydropower), saline lakes (solar ponds), and the Gulf of Mexico (OTEC, tides, waves, and salinity gradients). Each resource chapter is similarly structured with the following sections: introduction, survey, overview, and recommendations.

Each resource chapter's introduction provides a brief discussion of what the resource can be used for and introduces some of the major developmental issues associated with the resource. The survey section identifies and describes fundamental data collection, major information sources, and summary documents. Each chapter overview describes the average annual resource, offers insight into temporal variability and quantifies the total and accessible resource base. Each chapter concludes with recommendations that prioritize future resource assessment needs to further commercial development opportunities.

The next two chapters cover building climatology and resource transportation issues—topics not normally addressed in renewable energy resource assessment documents. Building climatology is a passive approach for meeting energy requirements in buildings by taking advantage of the natural climatic influences of the building site. This often overlooked resource warrants inclusion due to its sustainability and its potential for significant reductions in total energy demand in the state. The chapter on resource transportation issues provides a general overview of how various renewable energy sources are delivered to energy consumption markets, with a particular focus on the Texas electric transmission grid.

The last chapter summarizes overall recommendations for future resource assessment in Texas. These recommendations are prioritized based on the perceived near-term development potential of the respective resources.

Three appendices supplement the material included in the main body of this report. Project functions detailed in separate documents as well as different survey techniques employed by the project are described in Appendix A. Renewable energy contacts, many of whom contributed information, are provided in Appendix B. Geographical Information System (GIS) information maintained by the Texas Natural Resource Information Service (TNRIS) for the SEDC is presented in Appendix C. The report concludes with a glossary defining specialized terminology used throughout the report.

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FUNDAMENTALS

by Richard Faidley and Mike Sloan

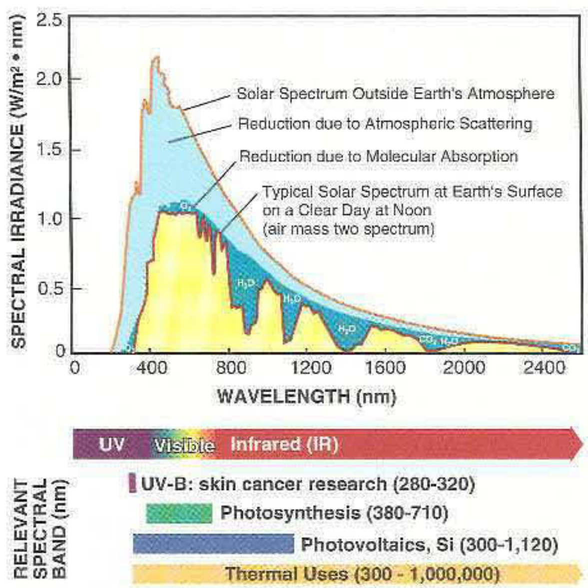
INTRODUCTION

Energy is a concept familiar to each of us, so much so that we will not attempt a rigorous definition. It powers our cars and appliances, heats our homes, and lights our workplaces. The science of thermodynamics teaches that energy can take on many different forms, each equivalent. Energy can be stored in a compressed spring, a rotating shaft, a pressurized vessel, a magnetic field, or many other storage devices. Heat is a form of energy. Equivalency implies that each type of energy can be measured in the same units. For example, we could sell electricity in calories or measure food energy in kilowatt-hours. This would baffle consumers, of course, but would be perfectly correct thermodynamically.

Renewable energy resources also come in many different forms: some are stored energy, some are thermal in nature, others are kinetic (energy in motion). Nearly all renewable and fossil energy supplies derive from solar energy. Consideration of the fundamental relationships between the various energy resources provides insight into the relative size of resources, their nature, and how they vary over time and space. This chapter includes a brief discussion of some of these fundamental issues as well as a comparison of the total and accessible resource base and land requirements of the various renewable resources.

Origin of Renewable Energy Resources

Most renewable energy resources derive from the vast energy supplied by the sun. Radiant energy from the sun bombards the earth across a spectrum of wavelengths as shown in **Figure 2.1**. Outside earth's atmosphere, solar radiation is very predictable and reliable, delivering a nearly constant power level, averaging 1367 W/m^2 over the course of the year.[4] For this reason, solar energy has long been a preferred power source for space-borne satellite applications. Within the earth's atmosphere, however, various scattering and absorption processes manipulate the incoming solar radiation, resulting in spectra that vary with atmospheric conditions, time of day, and season. It is the interaction of the planet with the incoming solar energy supply that results in the diverse complement of renewable energy sources we observe. **Table 2.1** introduces these renewable energy sources according to the categorization adopted for this report.



F.2.1 **Generalized Solar Spectrum.** Radiant energy from the sun comes over a range of wavelengths and is altered by earth's atmosphere. The relevant band of wavelengths for several typical solar applications are also shown. (Adapted from Kreith and Kreider[1] and other sources.[2,3])

About one third of the incident solar radiation is reflected by clouds back into space. Of the remainder, the largest fraction is directly absorbed by the surface of the earth or by gases in the atmosphere and acts to raise their temperature. We sense this ourselves anytime we stand in direct sunlight. Ocean temperature gradients, used in ocean thermal energy conversion schemes, and similarly, solar ponds, result from this direct absorption of solar radiation. The earth, however, does not absorb radiation uniformly. Water and land, for example, will have different absorption characteristics, and different regions of the earth will experience seasonal changes in the solar input. This uneven heating gives rise to temperature and air pressure variations that are the major driving mechanism of winds. Winds in turn produce ocean waves through friction between air and water.

TABLE 2.1 Taxonomy of Renewable Energy Resources. The following organization of renewable resources will be used throughout this report.

RESOURCE	MAJOR CATEGORIES
SOLAR	Direct Normal Diffuse Horizontal Global Horizontal Global Tilt
WIND	Wind Power Class
BIOMASS	Sugars and Starches Dry Ligno-Cellulosic Feedstocks Agricultural Sources Forest Sources Urban Sources Wet Feedstocks / Wet Wastes Fats and Oils
WATER	Hydroelectric Power Ocean Resources Thermal gradients Tides Waves Salinity Gradients Solar Ponds Osmotic Pressure
GEOTHERMAL	Hydrothermal Geopressured Hot Dry Rock Magma
BUILDING CLIMATOLOGY	Passive Strategies based on Psychrometric data

Almost all of the rest of the solar input, or about one fourth of the total incident, does not impact sensible temperatures directly but rather evaporates water from oceans and lakes, forming clouds and driving the hydrologic cycle. Hydroelectric potential results after water lifted by solar radiation returns to earth via precipitation and begins its return from high elevation to an ocean or other water body where it can perpetuate the hydrologic cycle.

In addition, a very small fraction of incident solar radiation, perhaps 0.2%, is absorbed by plants at specific wavelengths and, through the process of photosynthesis, converted into living matter, or biomass. Biomass is a form of stored solar energy. It is evident then that solar energy is not only the engine that drives our climate but also the source of energy for life itself. Only geothermal energy, derived from the vast thermal reserve of the earth's interior, and tidal energy, influenced mainly by the moon's mass, are not truly solar resources. Even fossil fuels, while not renewable in human time scales, can be thought of as a form of solar energy, as they are simply fossilized biomass. In fact, the process of fossilizing fuel through ages of pressure and temperature is the only natural way in which the planet accumulates a store of solar energy.

The fact that the earth's temperature does not continue to rise over periods of days, weeks and years informs us that there is a balance between the energy transferred to the earth and from it. In other words, all of the solar energy absorbed by the earth (with the small exception of that stored photosynthetically as biomass) is eventually re-radiated to space. Changes in this energy balance—resulting in changes in global temperature—have occurred subtly over eons of time and have normally been associated with small precessions or wobbles in the earth's rotation that affect the amount of radiation intercepted by the planet. Recently, however, concerns have been raised about a possible global warming trend due to an abundance of anthropogenic "greenhouse gases." These gases are effective absorbers at the longer wavelengths at which the earth radiates energy to space. The solar spectrum of Figure 2.1 indicates some of the absorption bands of carbon dioxide, one of the main greenhouse gases. The warming theory suggests that a profusion of carbon dioxide or similar gases will tend to lock heat in the atmosphere that would normally have been radiated to space. Although it is presently unclear if this will indeed happen, it is reasonable to expect that substantial changes in CO_2 levels over an extremely short time period will effect changes to the global climate and the biosphere. The large increases in carbon dioxide levels in this century are a byproduct of deforestation and, more recently, the burning of fossil fuels (see Figure 1.5);[5] adoption of renewable energies, which release no sequestered carbon, can help mitigate potential greenhouse gas problems.

Fundamental Characteristics

Table 2.2 shows the basic energy types and other characteristics associated with each renewable energy resource. The type of energy may restrict how the resource can be used or at least imply that some

TABLE 2.2. Fundamental Characteristics of Renewable Energy Resources.

RESOURCE	ENERGY TYPE	INTERMITTENCE	SPATIAL VARIABILITY
SOLAR	Radiative/ thermal	Yes	Low
WIND	Kinetic	Yes	High
BIOMASS	Chemical	No	Very High
WATER	Kinetic/ thermal	Some	Extreme
GEOTHERMAL	Thermal	No	High
BUILDING CLIMATOLOGY	(End use)	Some	Low
OIL & GAS	Chemical	No	Extreme

TABLE 2.3. Quantification of Texas Renewable Energy Resource Base and Identification of Primary Uses.

RESOURCE	TOTAL PHYSICAL RESOURCE (quads/yr)	ACCESSIBLE RESOURCE (quads/yr)	ENERGY DENSITY: GOOD TEXAS SITE ($MJ/m^2/yr$)	PRIMARY ENERGY USES**				NON-ENERGY USES
				ELEC.	HEAT	MECH.	TRANS.	
SOLAR	4,300	250	8,000	✔	✔			
WIND	12	4	15,000	✔		✔		
BIOMASS	13	3	45	✔	✔		✔	Food, feed, and fiber
WATER	3	1	10	✔	✔	✔		Water supply; flood control
GEOTHERMAL	1 (2,300,000 quads)*	1	3	✔	✔			
BUILDING CLIMATOLOGY	0.6	.26	430	✔	✔			

*see discussion in text ** ELEC. = Electricity, MECH. = Mechanical, TRANS. = Transportation

uses may be more economical than others. The second characteristic, intermittence, is an issue for some resources but not others. In biomass, for example, the energy is locked in chemical bonds and can be released when needed, whereas the kinetic nature of wind means that it must be used when available. Spatial variability refers to the range of the resource across a given region. Sunshine, for example, changes only modestly; annual global solar radiation varies by a factor of two from the sunniest spots in the nation to the cloudiest. Biomass yields, on the other hand, can vary 30-fold from fertile regions to infertile ones, due to variations in soil and rainfall.

Resource Quantification

One of the main efforts of this project was to estimate the size of each of Texas' renewable energy resources. This quantification, summarized in **Table 2.3**, warrants discussion. The total energy for each resource comprises the amount incident upon or available within the entire state per year. The accessible resource base is defined as that amount of the total resource that can be captured or extracted with existing or near-term technology. Units are quads per year (see the sidebar at right for definitions). Note that no economic discriminator was used in the definition of accessible base, only a judgement as to technical viability. Energy density compares the relative concentration of the resources at a prime Texas location for each. Finally, typical applications of the resources are listed.

For reference, Texas consumed about 10 quads and the U.S. about 82 quads during 1992.[6] Clearly then, the 4,300 quads of solar energy incident on the state each year is an immense resource. The other resources are substantially smaller since, as mentioned previously, most are derived from the solar resource. For example, only about a fourth of one percent of incident solar radiation is manifest in the kinetic energy of the wind, resulting in a statewide resource of 12 quads. A low conversion efficiency, however, does not imply a poor resource. Wind energy may represent only a tiny fraction of the original energy in sunlight, but at prime sites it is the most "energy dense" of the renewables. The 4 quads of accessible wind resource assumes that windy areas of the state are blanketed in turbines spaced 10 blade diameters apart. This spacing, which may prove to be typical of industry practice for the Texas Panhandle (or other areas with relatively inexpensive land), is necessary so that a given turbine is largely unaffected by the wake of other turbines upstream of it. Winds that are predominantly from one direction or in areas with high land prices, may allow closer turbine spacing.

Similar to the wind resource, the annualized photosynthetic conversion efficiency of sunlight to biomass was calculated at just 0.3%. (This number was based on annual ground level insolation in

Definitions

Total Resource Base - The total energy incident upon or available within the entire state per year.

Accessible Resource [7] - That subset of the total resource base that can be captured, mined, or extracted by current technology or technology that will be available in the near future.

Quad - A quad is a very large unit of energy equivalent to one quadrillion British Thermal Units (1,000,000,000,000,000 BTU's). In more practical terms, it is enough to serve all annual energy needs for about 3,000,000 Americans. A quad is almost equivalent to the unit exajoule, which is favored by the international community (1 quad = 1.055 EJ).

Texas, and hence is higher than the 0.2% cited above, which is based on extra-terrestrial radiation intercepted by the entire earth, including oceans.) The total resource, as discussed in Chapter 6, was derived from a simulation of the growth of a single species typical of local ground cover throughout the entire state. The accessible resource assumes that an area equivalent to approximately half the area now dedicated to agriculture, or about 15% of the state, is used for the production of energy crops.

The resource numbers provided for water stem largely from the potential of solar ponds developed from natural saline lakes. Hydroelectric potential currently accounts for practically all electricity generated from renewables in Texas, however, additional potential is very limited. The energy density value for water was based on the pondage and hydroelectric generation capacity of Lake Travis.

The geothermal resource can be evaluated in two different ways. The continuous heat transfer from the earth's interior to its surface is minute, about 0.06 W/m^2 or about 10,000 times less than the incident solar radiation on a clear day.[8] Integrated over an entire year it yields just 1 quad of resource. However, the total thermal energy stored within the first 4 miles of the earth's crust is staggering, some 2.3 million quads beneath Texas alone.[9] The sustainability of the resource would depend on how it is exploited, but the number is so large that this would not likely be a pressing concern.

Finally, the building climatology numbers merit a brief comment. This resource refers to employing the climate as a resource to minimize building energy demands through techniques such as ventilation and evaporative cooling. Climatic energies are huge, but the upper bound in potential energy reductions is clearly limited by how much is presently consumed in Texas buildings. The potential to reduce these demands is not certain due to an incomplete knowledge of the present Texas building stock, but the values in the table represent reasonable estimates. The energy density value is based on Texas average residential statistics for energy consumption and dwelling size.

Land Requirements

Renewable energies have the reputation for being diffuse in nature and therefore very land intensive. Land acquisition is a central aspect of major development projects. It is interesting, therefore, to contrast the relative land use of several key renewable resources with fossil fuels as in **Figure 2.2.** Each square in the figure is sized to represent the area required by the respective resource to yield either a quad of electricity or a quad of primary fuel. Typical conversion efficiencies and Texas' standard spacing for oil and gas wells were used to develop the map.[10] The very large biomass squares point out this resource's land-intensive nature due to its poor solar conversion efficiency. Furthermore, biomass uses virtually all the land it is developed upon whereas other resources may not. For example, cattle can graze around wind turbines and oil wells, and solar technologies can be installed on rooftops.

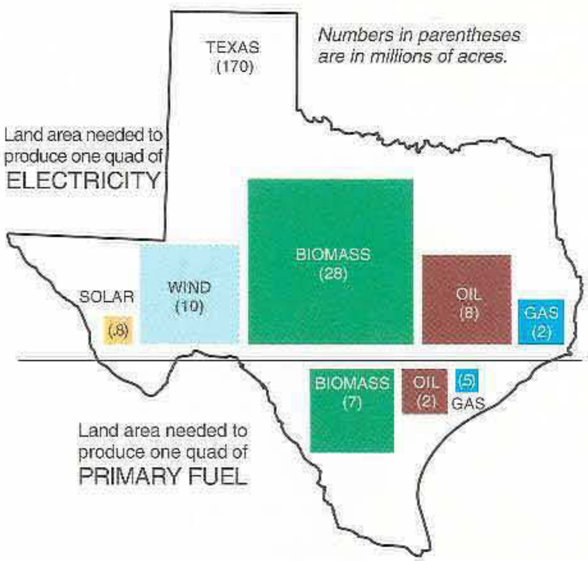


FIGURE 2.2. Land Requirements of Various Texas Energy Resources. Each square is sized to indicate the area needed to produce one quad of electricity or primary fuel. The location of squares within the state has no significance.

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THE TEXAS CLIMATE

by George Bomar

INTRODUCTION

No state in the Union, with the possible exception of California, can match the diversity of weather experienced in Texas in any given year. The vast array of weather elements that characterizes the climate of the Lone Star State is attributed, not merely to its inordinate size, but as well to its strategic position on the North American continent. Its proximity to the relatively warm waters of the Gulf of Mexico, as well as its susceptibility to a seldom-interrupted wind flow from the eastern North Pacific, ensure that its atmosphere will be amply fed with enough energy to keep its weather in an almost constant state of flux. With Texas well within reach, during much of the year, of the migration of cool (cold) air from Canada, the inevitable interaction of air masses of varying densities impacts the quality and variety of renewable energy resources available to Texans on a daily basis.

For example, the coupling of Texas' location in the mid latitudes of the northern hemisphere with its predominantly flat, or gently-rolling terrain, contributes to an almost incessant flow of air at the surface of earth in every season of the year. In the more poleward sectors of the state, where the topography consists largely of vast open spaces with minimal vegetation, windflow is particularly substantial. The state's climate is sufficiently subtropical to ensure that, even when the lower atmosphere is quite moist, the sun shines the majority of the time, thereby furnishing a generous supply of solar radiation (insolation). What is more, a liberal amount of water vapor often present, especially in the eastern half of the state, is potentially convertible, through the agency of cloud seeding, into additional supplies of fresh water that may translate into increases in hydroelectric generation.

Fundamental to any understanding of available and renewable energy resources is the realization that energy is transferred from one place to another either through radiation, convection, or conduction. Obviously, a superabundance of energy is propagated throughout the Texas atmosphere on a daily basis through the means of radiation. Particularly during the warmer half of the year, the process of convection also plays an integral role in the free exchange of energy, much of which is renewable. Whereas radiation transfer occurs with the speed of light and can be effected without the presence of matter between the object radiating and that which receives the energy, the other two avenues of transfer require the presence of some intermediate substance such as air. The lower atmosphere of Texas, with its deep boundary layer of heat and moisture, is well suited for the expeditious processing of reradiated energy through the mechanism of convection.

Extremes in the Weather

Any attempt to assess the weather's role in sustaining the renewable-energy resources of Texas must begin with the recognition that the incoming supply of energy, and moisture (water), varies widely over both space and time. This huge disparity in available energy, and moisture, is responsible for the existence of both desert and tropical rain forest-type conditions in the Lone Star State. The dissimilarities that typify Texas weather are punctuated by a wide range of extremes in temperature and precipitation across the state **(Table 3.1)**.

The state's weather history illuminates how virtually any brand of weather imaginable—from an epic drought to devastating floods, and catastrophic Arctic cold waves to relentless killer heat—has been endured by Texans, even within the current century. It is the extremes in the weather that distinguish the state as a land of contrast and emphasize the degree to which Texas has at its disposal an immense atmospheric reservoir of renewable energy resources. An accurate characterization of Texas weather could not be made without due regard to the extent to which the weather oscillates from one atypical level to another.

Average Weather as Indicator of Available Resources

Yet, it is not the extremes that provide clues as to how much renewable energy is available in Texas for consumption and preservation. Rather, it is the mean, or average, set of climatic conditions that best defines the extent to which Texas has been endowed with replenishable natural assets. For sure,

TABLE 3.1. Extremes in Texas Weather.[1]

CATEGORY	RECORD	LOCATION	DATE
TEMPERATURE			
Coldest	-23°F	Tulia Seminole	February 12, 1899 February 8, 1933
Hottest	120°F	Seymour Monahans	August 12, 1936 June 28, 1994
RAINFALL			
Greatest in 24 hours	29.05 inches	Albany	August 4, 1978
Greatest in 1 month	35.70 inches	Alvin	July, 1979
Greatest in 1 year	109.38 inches	Clarksville	1873
SNOWFALL			
Greatest in 24 hours	24.0 inches	Plainview	February 3, 1956
Greatest in single storm	61.0 inches	Vega	February, 1956
Greatest in one season	65.0 inches	Romero	1923-1924
WIND			
Highest sustained speed	145 mph	Matagorda Port Lavaca	September 11, 1961 September 11, 1961
Highest peak gust	180 mph	Aransas Pass Robstown	August 3, 1970 August 3, 1970

several elements of the weather are particularly influential in the realm of renewable energy resources. These elements exert more than mere nuisance value on a host of operations, and even on whole industries. For example, high humidities can lead to deterioration, mildew, and rotting of raw materials or corrosion of metals. Poor visibilities (due to fog, smoke, or dust) may impair the movement of workers and materials, though the restrictions imposed may be short-lived. Electrical storms, or lightning, when accompanied by heavy rainfall, or a strong, straight-line thunderstorm wind, can contribute to a significant curtailment of industrial operations.

Thus, it is imperative that a concerted effort be made to measure, and quantify, the whole array of climatic parameters that defines the state's renewable energy resources. Some parameters, most notably temperature and precipitation, have been well documented by a network of cooperative-weather observing stations maintained by the National Weather Service, and its predecessor, the U. S. Weather Bureau. But many of the parameters (such as measures of wind speed and incoming solar radiation) that are critical to an accurate assessment of renewable resources have been poorly, and inconsistently, quantified over the years. The instrumentation deployed has been shown to be only marginally helpful in characterizing how much energy is available, especially in sparsely-populated areas of the state. Much of the modern weather-observing equipment (such as anemometers and pyrheliometers) historically has been clustered around airports in the state's most heavily populated areas, where only a modest fraction of the total amount of renewable energy resources is distributed. In those parts of Texas where such resources as solar radiation and windflow are particularly ample, the sensors that detect such are sparse and poorly positioned. Existing networks of weather observations have been geared, over the years, to serve, foremostly, the interests of aviation, not those of energy capture, distribution, and consumption.

Precipitation. Nevertheless, enough data have been secured for long enough periods of time to allow a reasonable characterization of renewable climatic resources to be drawn. The best documented climatic resource, without a doubt, is precipitation, the bulk of which occurs in liquid form as rainfall. In a typical year, more than half of Texas collects less than 30 inches of precipitation **(Figure 3.1)**. The mean annual rainfall distribution is so diverse and disparate that the extreme western sector of Texas gathers a mere 8 inches, while the easternmost sector adjacent to the Sabine River garners over 55 inches in a year. A rule of thumb is that precipitation, on an annual basis, decreases about 1 inch for each 15-mile displacement from east to west across Texas. So, the Trans-Pecos region, with an average region-wide precipitation for the year of under 12 inches, perennially is the driest sector of the state. By contrast, the upper half of the coastal plain and the eastern half of Northeast Texas are customarily the wettest regions of the state, with mean annual precipitation totals of 46 inches and 45 inches, respectively.

Rarely is precipitation spread even remotely uniformly throughout the year. Virtually every region

TABLE 3.2 Average Seasonal Precipitation (inches) for Selected Locations in Texas.[2]

LOCATION	WINTER	SPRING	SUMMER	AUTUMN
Abilene	3.22	6.23	7.75	7.20
Amarillo	1.54	4.43	9.54	4.05
Austin	5.76	9.21	7.81	9.10
Brownsville	3.87	5.03	7.40	10.31
Corpus Christi	4.93	5.99	9.08	10.13
Dallas-Fort Worth	5.85	11.15	7.50	9.20
Del Rio	2.12	4.70	5.43	5.99
El Paso	1.38	0.74	3.79	2.90
Fort Stockton	1.51	2.58	4.65	5.15
Galveston	9.02	8.25	12.87	12.14
Houston	10.14	11.07	15.76	13.86
Laredo	2.72	4.77	7.06	6.87
Longview	11.71	13.29	9.77	12.50
Lubbock	1.60	4.21	7.63	5.21
Lufkin	10.57	11.39	9.24	11.20
Midland-Odessa	1.58	3.39	4.94	5.05
Port Arthur	12.96	12.46	16.31	15.45
San Angelo	2.66	5.58	5.32	6.89
San Antonio	5.03	8.24	8.51	9.20
Texarkana	11.37	13.04	11.12	11.36
Victoria	6.20	8.46	11.24	11.51
Waco	5.60	10.10	6.95	9.31
Wichita Falls	3.79	9.29	7.72	8.10

of the state has its "dry" and "wet" seasons (**Table 3.2**). Spring is the wettest season of the year in most of Texas, with the month of May somewhat more generous with rain than April. The exception is the western third of Texas (Northwestern Plains and Trans Pecos), where the summer and early autumn furnish the bulk of the year's usual rainfall. Thunderstorms, some of which are nocturnal, are responsible for the bulk of rainfall in the warmest portion of the year in these regions.

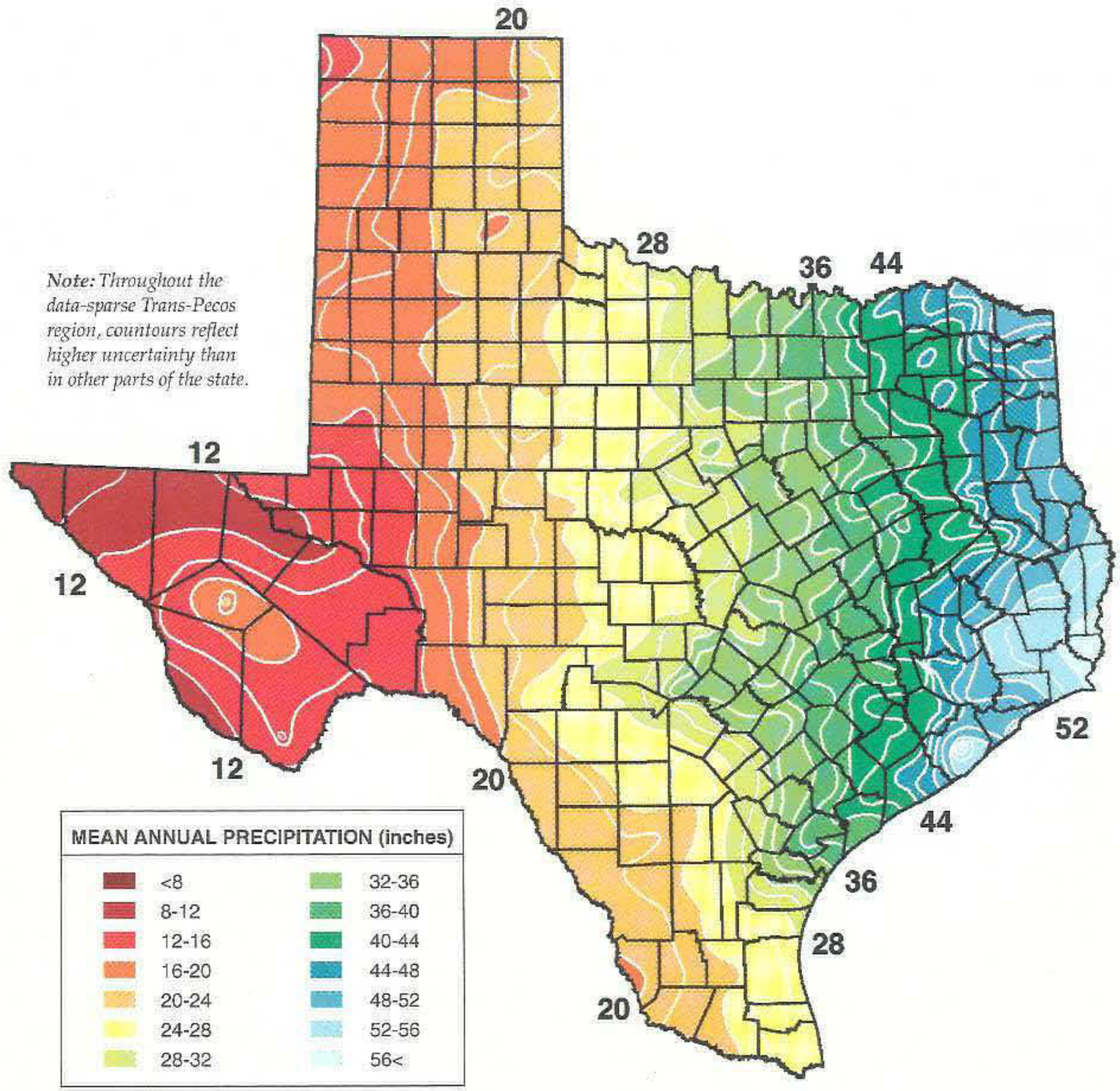

FIGURE 3.1. Average Annual Precipitation. Based on 1961-1990 precipitation data from the cooperative weather observing network of the National Weather Service.[2] Intermediate contours (white lines) are indicated at 2 inch intervals.

Temperature. Assessing the state's renewable energy resources must also acknowledge how energy, in the form of heat, is expressed as temperature, the distribution of which is influenced to a very large degree by the amount of insolation reaching the surface. This quantity of energy is of no small value owing to the fact that Texas covers a broad range of latitude (26°N in the extreme south to 36°N in the northern fringe) and hence is on the equatorial side of the mid-latitude regions. But its subtropical latitude is but one of the controlling factors related to the way in which solar radiation is used; another is the influence of the Gulf of Mexico, which is best evidenced by the prevailing winds that blow from the sea surface to the land for much of the year. Cold-air outbreaks in winter are quickly moderated once they reach Texas because they are readily mixed with air emanating from the Gulf.

Unlike mean annual precipitation, mean annual temperature varies not so much from east to west as it changes, quite consistently, from north to south (latitudinally). Coldest temperatures anywhere in Texas are observed in the extreme northern sector of the Northwestern Plains, which also features the lowest mean annual temperatures anywhere in the state **(Figure 3.2)**. Conversely, the highest (warmest) mean annual temperatures are registered in Southern Texas, along the Rio Grande, from Eagle Pass to Falcon Reservoir. In some years, the hottest temperatures of summer are observed in this region. (Average maximum daily temperature is shown in **Figure 3.3**; minimum average daily temperature in **Figure 3.4**.) In winter (January), coldest minimum temperatures (in the low 20s), on the average, are observed in the Northwestern Plains (at Amarillo, for example), while in the summer (July), hottest daytime readings (in the upper 90s), on the average, are measured in the area along the Red River (at locations such as Dallas and Wichita Falls) **(Table 3.3)**.

In spite of Texas' proximity to the Gulf of Mexico, day-to-night (diurnal) variations in temperature across the state are appreciable. On most days the moisture content of the lower atmosphere is sufficiently dry that, with the setting of the sun, the amount of solar radiation quickly drops, only to be supplanted by an equally marked amount of outgoing terrestrial radiation. Thus, mean annual diurnal temperature variations (30°F or more) are observed in much of Texas west of the Pecos River, where the air is exceptionally dry, while along the upper Texas coastline (most notably, Galveston Island), more than ample moisture most of the time keeps extreme minimum and maximum temperatures from varying more than 10°F **(Figure 3.5)**.

Occasionally, and particularly in winter, the air may be so laden with moisture that the diurnal range in temperature can be only a few degrees. A blanket of clouds excludes much of the incoming solar radiation, thereby preventing the temperature from rising substantially above morning minimum values, and the same cloud cover can restrict outgoing heat energy at night, so that minimum temperatures do not fall appreciably. The preponderance of cloud cover is the reason why diurnal readings in the coastal plain, on the average in January, is markedly less than those in higher

TABLE 3.3. Average Monthly Minimum and Maximum Temperatures (°F).

LOCATION	JANUARY		APRIL		JULY		OCTOBER	
Abilene	31	55	53	78	73	95	55	72
Amarillo	21	49	42	72	66	92	45	73
Austin	39	59	60	79	74	95	60	82
Brownsville	50	69	67	84	76	93	66	85
Corpus Christ	45	65	63	82	75	93	64	84
Dallas-Fort Worth	33	54	55	76	74	97	56	79
Del Rio	39	62	59	83	74	96	60	82
El Paso	29	56	48	79	68	94	50	78
Fort Stockton	30	60	50	82	68	94	50	80
Galveston	47	58	65	74	79	87	68	78
Houston	43	62	61	79	75	92	61	81
Lubbock	25	53	47	75	68	92	48	75
Lufkin	37	58	56	79	72	93	55	80
Midland-Odessa	29	57	49	80	69	95	51	71
Port Arthur	42	60	60	78	74	92	59	80
San Angelo	32	59	53	80	72	97	54	79
San Antonio	39	62	59	80	74	95	59	82
Victoria	43	64	62	80	75	94	61	83
Waco	36	57	57	78	75	97	57	80
Wichita Falls	28	52	51	77	73	99	52	78

Note: Throughout the data-sparse Trans-Pecos region, countours reflect higher uncertainty than in other parts of the state.

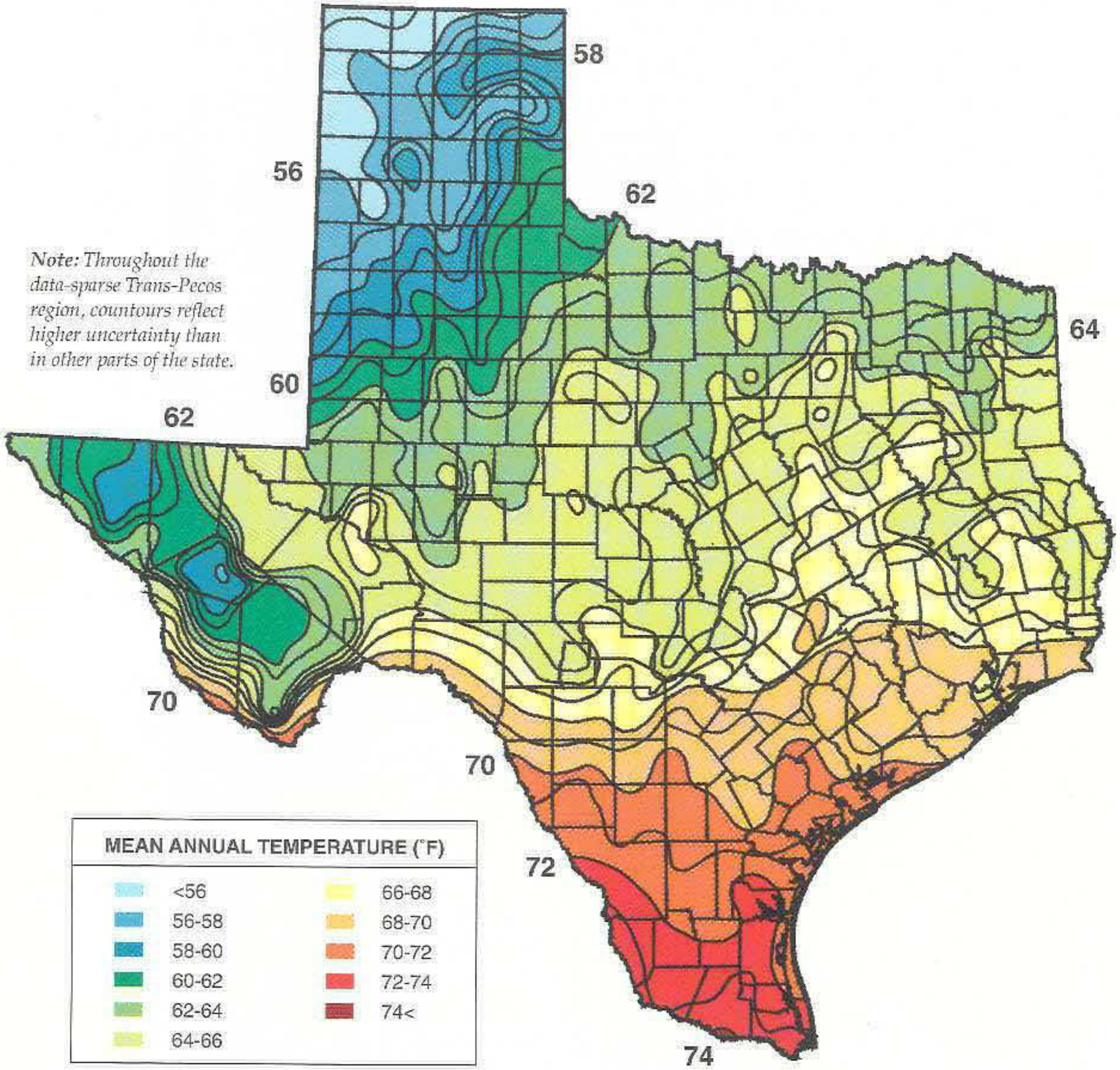

FIGURE 3.2. Average Annual Temperature. Based on 1961-1990 data from the cooperative weather observers network of the National Weather Service.[2] Intermediate contours (black lines) are generally indicated at 1 degree intervals.

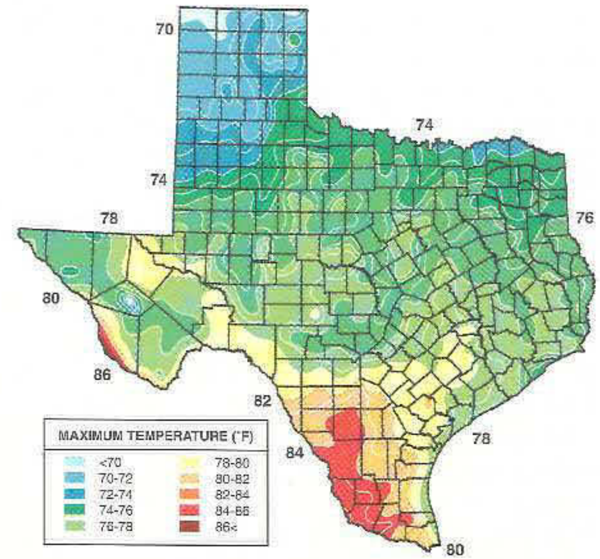

FIGURE 3.3. Average Daily Maximum Temperature.

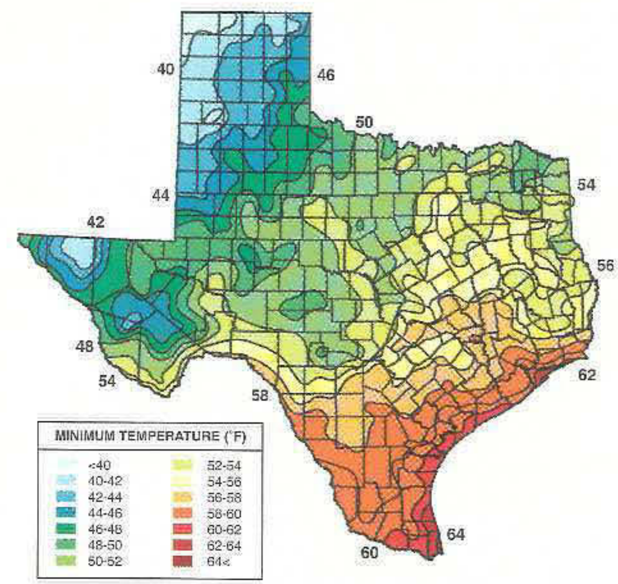

FIGURE 3.4. Average Daily Minimum Temperature.

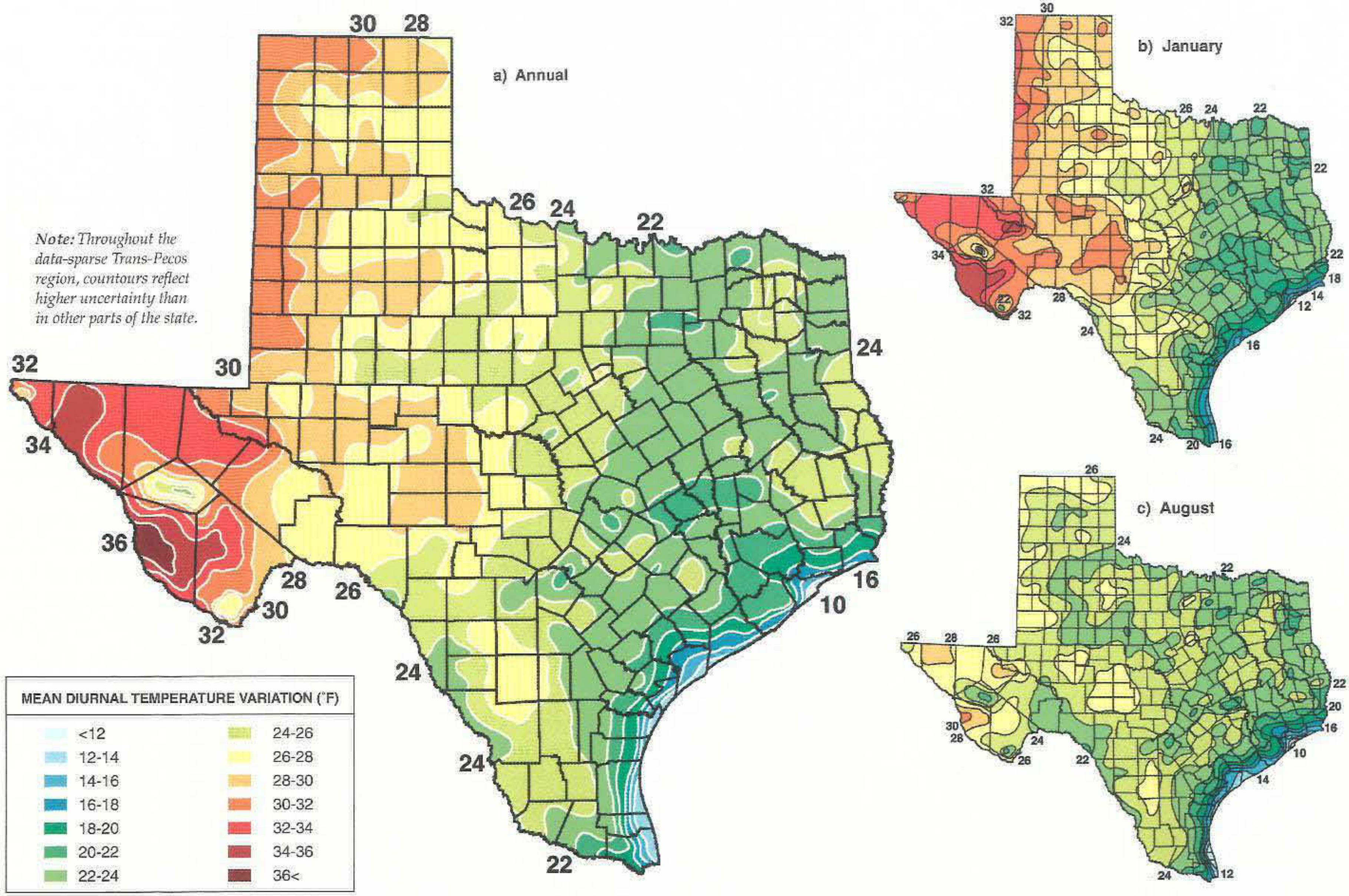

FIGURE 3.5. Mean Diurnal Temperature Variation (˚F): a) Annual, b) January, and c) August. All three maps use the legend located at the bottom left of the page.[2]

elevations in the western half of Texas, where the air is much drier and the sky customarily is largely cloud-free **(Figure 3.5b)**. While the average diurnal variation is as little as 15-20° in that strip of coastal terrain within 20-30 miles of the coastline, on as many as a half-dozen days in each of the months of December, January, and February, the variation can be as small as 5° or less. In the summer, because the air is warmer (and hence capable of holding more moisture), the diurnal temperature variation is not quite so small in the coastal plain **(Figure 3.5c)**.

Wind energy. As evidence of differences in atmospheric pressure between locations, the strength, and virtually ever-present nature, of the wind offer substantial promise as a source of renewable energy. While the wind is not merely a horizontal flow of air (its myriad of circular-moving eddies provides both upward and downward-moving pulses of energy), it is the lateral component of air motion that is of primary interest to energy providers and consumers. Though it has been poorly documented, the action of these individual eddies, and the sum total of the vertical movement of the air, at a particular place over a period of time, may prove to be an additional, and appreciable, source of energy.

A southerly wind—or some component of it (southwesterly or southeasterly)—is the predominant wind condition in Texas for much of the year. In most sections of the state, the average wind speed varies between 7 and 15 miles per hour **(Table 3.4)**. A southerly wind is especially dominant in summer, when wind shifts induced by advancing cool fronts are quite infrequent. In the southern half of Texas, or usually beyond the reach of cool fronts, a southerly wind is present some 90 percent of the time. In the north, northerly winds do blow on occasion, but southerly winds are observed at least 80 percent of the time. By contrast, the frequent intrusion of polar air in winter ensures a northerly wind about half of the time in much of Texas. Northerly winds are far from uncommon in both spring and autumn, though southerly flow remains dominant.

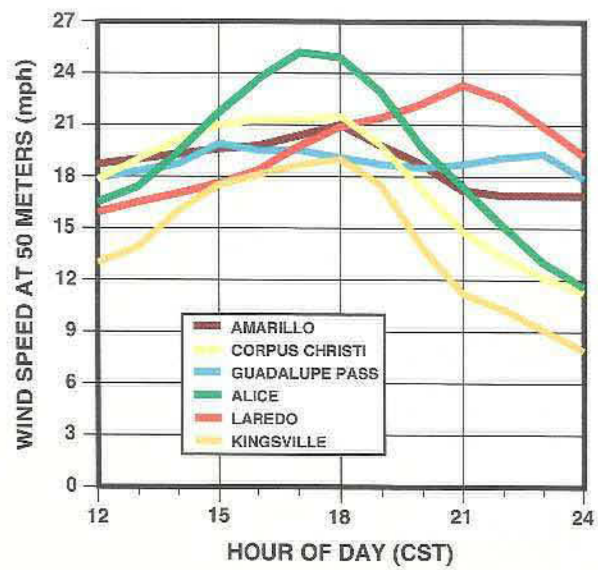

FIGURE 3.6. Average Summer Afternoon Wind Speed at 50 Meters Above the Ground. Estimated from measurements taken closer to the ground, typically at 7-10 meters.

TABLE 3.4. Average Wind Direction and Speed (mph) for the Middle Month of the Four Seasons.*

LOCATION	JANUARY	APRIL	JULY	OCTOBER
Abilene	S 12	SSE 14	SSE 11	SSE 11
Amarillo	SW 13	SW 15	S 13	SW 13
Austin	S 10	SSE 11	S 8	S 8
Brownsville	SSE 11	SE 14	SE 11	SE 10
Corpus Christi	SSE 12	SE 14	SSE 12	SE 10
Dallas-Fort Worth	S 11	S 13	S 10	S 10
El Paso	NW 7	WSW 10	ESE 8	SSW 7
Houston	NNW 8	SSE 9	S 7	ESE 7
Lubbock	SW 12	SW 15	S 11	S 11
Midland-Odessa	S 10	SSE 13	SSE 11	S 10
Port Arthur	N 11	S 12	S 8	N 9
San Angelo	SW 10	S 12	S 10	S 9
San Antonio	N 9	SE 10	SSE 9	N 8
Waco	S 12	S 13	S 11	S 10
Wichita Falls	N 11	S 13	S 11	S 11

Typically measured at heights of 7 to 10 meters above the ground.

For the year as a whole, the vast tableland known as the Northwestern Plains is the windiest region in the state, though some coastal locations also feature vigorous wind movement much of the time. Winds in the spring months average from 13 to 17 miles per hour in the High Plains of northwestern Texas, making it one of the windier sectors of the North American continent. But on many days in those months, and not infrequently in other months, the wind habitually gusts to a velocity two or three times as much; gusts in the vicinity of thun-

TABLE 3.5. Average Number of Days With Various Sky Conditions.

LOCATION	JANUARY			APRIL			JULY			OCTOBER		
	CR	PC	CD	CR	PC	CD	CR	PC	CD	CR	PC	CD
Abilene	11	6	14	11	8	11	14	10	7	15	7	9
Amarillo	13	7	11	11	9	10	13	12	6	16	7	8
Austin	9	6	16	8	7	15	12	13	6	13	9	9
Brownsville	6	7	18	5	11	14	11	14	6	11	13	7
Corpus Christi	7	7	17	6	9	15	11	14	6	13	10	8
Dallas-Ft Worth	10	6	15	9	8	13	15	10	6	14	7	10
Del Rio	10	7	14	8	8	14	12	11	8	12	9	10
El Paso	16	11	4	16	11	3	7	18	6	26	3	2
Houston	8	5	18	8	7	15	7	15	9	11	9	11
Lubbock	13	6	12	13	8	9	14	11	6	16	7	8
Midland-Odessa	13	6	12	13	8	9	13	11	7	17	6	8
Port Arthur	7	6	18	6	8	16	6	15	10	12	10	9
San Angelo	12	6	13	11	8	11	14	10	7	15	7	9
San Antonio	9	6	16	7	8	15	9	15	7	12	10	9
Victoria	7	6	18	5	8	17	7	15	9	11	10	10
Waco	9	6	16	9	7	14	14	10	7	13	8	10
Wichita Falls	11	7	13	11	7	12	15	9	7	15	7	9

CR = clear; PC = partly cloudy; CD = cloudy

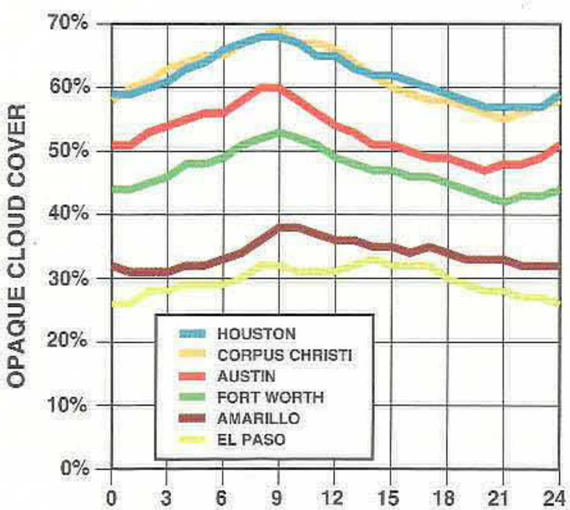

FIGURE 3.7. Average Opaque Cloud Cover for January.

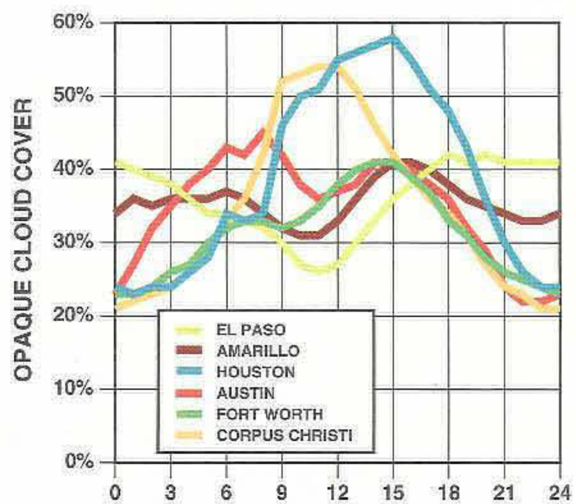

FIGURE 3.8. Average Opaque Cloud Cover for August.

derstorms may exceed 60 miles per hour several times in any one season. The winter in the High Plains is almost as windy, however, as frequent invasions of polar, even Arctic, air roll unimpeded across the area, sometimes making outdoor activity hazardous for human beings and livestock.

Wind speeds vary in relation to time of day. As a general rule, and in the absence of a "forcing mechanism" such as an approaching frontal system or a nearby thunderstorm, the wind attains a maximum velocity from midday through the late afternoon, in response to the peak flow of incoming solar energy (warmth). This is especially true during the warmest season of the year, when the demand for electric power for cooling also is maximized during the hottest portion of the day. Yet, as **Figure 3.6** (previous page) illustrates, even at locations near one another and within the same climatic region, wind speeds can vary dramatically. The peak wind of 20 miles per hour, or greater, at some coastal sites may evidence the influence of the sea breeze, while locations more distant from the coastline may feel less effect from the phenomenon and, hence, sustain lower maximum wind speeds.

The intensity, and timing, of maximum winds may also depend upon a community's proximity to marked topographic features, such as mountain ranges and basins. In more arid climes (such as Guadalupe Pass), where the dry air allows the temperature to reach a maximum earlier in the afternoon, the peak wind occurs not much beyond midday. Some locales within reach of the sea breeze (such as Corpus Christi) experience highest winds in concert with the migration of the breeze inland, or some four hours after high noon. Cities (such as Laredo) far removed from the effect of the sea breeze, but in the path of outflow from a desert, may not experience fastest winds until nearly sunset, or when the gust from hot air radiating from the desert reaches the city.

Insolation and cloud cover. The availability of incident solar radiation (insolation) as an abundant renewable energy resource is evidenced in a number of ways. One means of quantifying the resource is by the number of days characterized by cloudy, or cloud-free, skies **(Table 3.5)**. Clear skies, hence a maximum of incoming solar energy, are most common in the western sector of Texas, particularly during the colder half of the year. In much of the Trans-Pecos, for instance, the sky, on the average, is cloud-free on two of every three days during both the autumn and winter. Even in the warmer half of the year, the sky in this region is overcast on only one day of every six. By contrast, over half of the days in winter and spring are overcast in southeastern Texas, and only one in four days during these seasons is free of cloud cover. In that part of Texas east of the 100th meridian, the least likelihood of overcast skies occurs during the summer, even though partial cloud cover is more prevalent in this season than in any other.

Obviously, the time of day when cloud cover is most likely to occur has an appreciable impact on available solar energy. In winter, for instance, an opaque cloud layer has a peak occurrence in the few hours following sunrise **(Figure 3.7)**; it is least likely during the mid-afternoon hours, or just after the peak period of incoming solar insolation. This pattern of maximum cloud cover at mid-morning and minimum cloud cover in mid-afternoon is observed in most of Texas. It is most pronounced in the coastal plain (at locations such as Houston, Corpus Christi, and Brownsville). Only in the area west of the Pecos River (for example, El Paso) is the frequency of occurrence of opaque cloud cover spread almost uniformly throughout the day.

During the peak heating season, however, when solar insolation is at a maximum, the pattern of opaque cloud cover is not nearly so uniform statewide. In semi-arid West Texas, where the bulk of the year's substantive rainfall is produced by deep convective cloud formations, opaque cloud cover reaches a maximum at midday, or in the early afternoon hours, when thunderstorms have matured and spread a shield of far-reaching cirrus clouds across the sky **(Figure 3.8)**. The near-surface layer of air is hardly moist enough to allow a morning overcast to form, hence the frequency of occurrence of opaque cloud cover is quite small (less than 35 percent of the time). The pattern is almost reversed in lower elevations, however. A thick near-surface layer of moist Gulf air foments the formation of a deck of stratus clouds on nearly half of the mornings in the month of August. The rising sun usually dissipates the stratus by late morning. A secondary peak of opaque cloud cover results from the eruption of scattered convection (thunderstorms) during the peak heating period of the day.

An even better indicator of available solar energy, for specific sites in Texas, is the measure of sunshine, usually expressed as the percent of the total possible for the given location **(Table 3.6)**. As a general rule, sunshine is more abundant in the higher elevations of western Texas, no matter the season of the year. The region where sunshine is superabundant almost year-round is the area west of the Pecos River, particularly in the vicinity of the Rio Grande. There, from mid-winter until midsummer, uninhibited sunshine is available more than 90 percent of the time during daylight hours.

TABLE 3.6. Average Amount of Sunshine (as % of Total Possible).

LOCATION	WINTER			SPRING			SUMMER			AUTUMN		
	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV
Abilene	64	62	64	70	71	70	78	79	77	70	72	68
Amarillo	67	69	68	71	74	73	78	79	78	73	75	72
Austin	50	49	52	55	54	57	69	76	75	67	64	55
Brownsville	43	42	48	53	58	65	74	80	76	68	65	51
Corpus Christi	45	45	50	55	56	60	73	80	77	68	68	55
Dallas-Ft. Worth	55	55	56	60	64	61	70	76	74	69	62	58
El Paso	79	90	91	92	93	96	96	89	85	78	92	79
Galveston	49	48	50	56	61	67	75	72	71	67	71	59
Houston	51	43	48	50	54	58	64	66	65	62	61	49
Lubbock	65	66	66	73	76	77	78	79	73	76	70	72
Midland-Odessa	65	69	66	73	76	77	78	79	73	76	70	72
Port Arthur	47	42	52	52	52	64	69	65	63	62	67	57
San Antonio	49	48	52	57	55	55	67	74	73	66	64	55

On the other hand, sunshine is most scarce in the coastal plain during the three coldest months of the year (December through February). In this region of low elevation, sunshine is most plentiful (at least two-thirds of the time) during the summer.

Direct measurements of incoming solar energy reflect a maximum in semi-arid West Texas that is coincident with the occurrence of the summer solstice (June 21) (**Figure 3.9**). The rainy season west of the Pecos River does not get underway until some weeks after the solstice; the onset of an almost daily occurrence of significant thunderstorm development sometime in July brings about a rather sharp diminution of normal insolation. In the east, especially in the coastal plain, a seasonal rainfall maximum in the late spring coincides with a relative minimum in normal insolation at locations such as Houston, Corpus Christi, and Brownsville. This is followed by a respite in thunderstorm frequency in early summer, when normal insolation increases appreciably. However, with a tropical-cyclone season increasing the frequency of occurrence of daytime showers and thunderstorms along and tens of miles inland from the coastline in late July or early August, insolation drops proportionately.

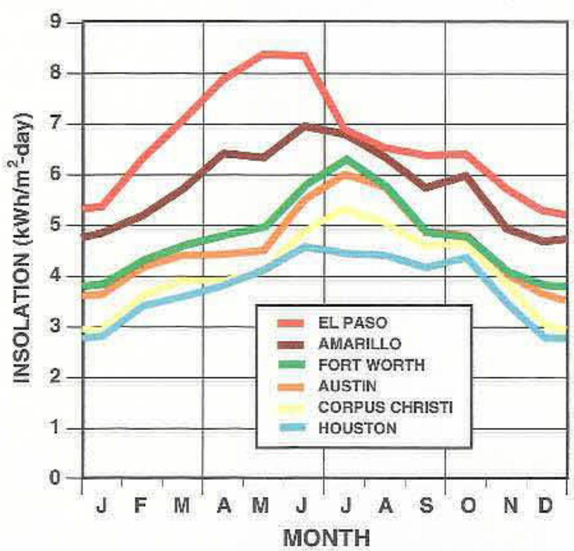

FIGURE 3.9. Average Direct Solar Radiation by Month.

Regrettably, while it is a key element in the spectrum of renewable energy resources in Texas, solar radiation may be the most poorly quantified, and hence least understood, of those resources. This is due to the lack of an extensive observation network in Texas, and where sensors are deployed, most have operating characteristics that are hardly uniform from one location to another. Solar energy is a resource marked by great variability over short distances, owing to cloud or turbidity conditions that are highly erratic. For the most part, reliable sunshine data are available for only the largest metropolitan areas of the state. This means that vast areas of the Edwards Plateau, Trans-Pecos, and Southern Texas are not well represented by existing data on sunshine availability. Even the more densely populated regions of northeastern and East Texas are lacking in good-quality sunshine data. That is all the more reason why the need for expanded coverage of radiation sensors and better standardization of instrument usage should be recognized and addressed. Nonetheless, the reliable data that do exist point to the observation that Texas is well endowed with this resource.

Summary

Texas, by virtue of its proximity to a surface energy source (Gulf of Mexico) and its strategic position beneath a potent stream of energy aloft in the atmosphere (the subtropical jet), is rich in renewable energy resources. The degree of abundance of each climate-related resource can be attributed to the intensity of solar insolation and by the gradient of that insolation from place to place across the state. After all, it is the disparity in incoming solar energy, from season to season and from locale to locale, that dictates the temperature gradients observed from west to east, and from north to south, across the expansive Lone Star State. These temperature gradients ultimately determine the pressure gradients and the fluctuations in wind associated with them. The differential in pressure, in turn, determines the origin of air masses that migrate into and out of Texas with a striking degree of regularity throughout much of the year. How closely the weather behaves from year to year, in relation to this intricate energy budget, provides us with some measure of just how energy-rich the state really is.

REFERENCES

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SOLAR ENERGY

by Mike Sloan

INTRODUCTION

The sun is nature's ultimate energy source. It is vast, perpetual, and environmentally benign. With such qualities, sustainably powering all future world energy consumption with solar energy is indeed technically possible. The enduring capability and adequacy of the solar energy supply is certain; however, technology must still be developed and successfully marketed that can harness this immense resource to provide desired energy services reliably and at an acceptable cost. During the past decade, numerous solar technologies have made impressive improvements and reduced costs to the point where they are currently recognized as the clear-cut, best alternatives for satisfying specific energy needs. The continued progress that will certainly accompany these emerging technologies as they mature leads to an almost inevitable conclusion that solar energy conversion systems will become a major contributor for meeting future energy needs.

As solar technologies tackle larger, more competitive energy markets, the need for a clearer understanding of solar energy as a fuel becomes critical. The solar resource is certainly huge, but not accurately defined. For solar energy conversion devices to be as competitive in future energy markets as possible, much improved solar resource information will be required to optimize system design and facilitate accurate assessment of performance.

SIGNIFICANCE OF RESOURCE: HISTORICAL AND FUTURE USES

The earliest humans to inhabit the earth no doubt recognized and utilized the light and heat energy provided by the sun. As civilization progressed, humans developed uses for sunshine in addition to lighting the day and warming the skin. Shelter evolved to control sunlight to moderate the climate as well as provide interior lighting. The sun was also used to dry food, heat water, and, according to legend, even destroy enemy sailing ships.

In simplest terms, sunshine is bright and hot. A more sophisticated knowledge of these basic solar characteristics allows for the utilization of solar radiation in a broad assortment of thermal, electrical, photobiological and photochemical applications. Technologies in these areas, some under development and others available today, represent an important opportunity for the energy future of Texas.

Perhaps the most common application of solar energy is to provide heat (thermal energy). The sun can be practically used to heat water or other materials in residential, commercial, and industrial applications using relatively simple equipment such as flat-plate collectors or solar ponds. When concentrated by mirrors or other optical devices, solar radiation can produce very high temperatures (>5,000 °C), higher in fact than the temperatures attainable with fossil fuels. At more modest levels of concentration, solar radiation results in temperatures suitable for the production of electricity from conventional steam power plants or heat engines. Examples of such solar thermal electric technologies are parabolic troughs, central receivers and dish-Stirling systems. While natural sunlight has become underutilized in modern building design, daylighting can be successfully incorporated into almost any structure, even underground buildings such as the Texas State Capital Annex. Photovoltaic (PV) solar cells are fabricated from special materials that convert sunlight directly into electricity. The overwhelming list of desirable characteristics of this electric technology—they have no moving parts, do not make noise or produce any wastes or emissions, do not require water, and can be packaged in any size desired—renders photovoltaics a particularly promising technology for the future.

Significantly, the wide variety of solar energy applications have different needs regarding solar resource information. Because of the directional and spectral ("color") nature of solar radiation, it is necessary to break the resource into fundamental components prior to a more in-depth discussion. **Table 4.1** identifies and describes the fundamental solar parameters and provides examples of solar conversion technologies that are dependent upon them. Because the remainder of this chapter requires a general understanding of solar energy terminology, a brief review follows.

TABLE 4.1. Classification of Solar Resource Quantities with Examples of Relevant Conversion Technologies.

RESOURCE TYPE			RELEVANT CONVERSION TECHNOLOGY		
PARAMETER		DESCRIPTION	EXAMPLE	PRODUCT	STATUS*
BROADBAND	Direct Normal	Principal component of sunshine, directly from the sun	Solar thermal (parabolic trough, dish-Stirling, central receiver)	Electricity, Heat	A, B
			Concentrating PV	Electricity	A
	Diffuse Horizontal	Secondary component scattered by sky	Building climatology (daylighting)	Light	A
	Global Horizontal	Total (direct and diffuse) on a horizontal surface	Agriculture	Food, feed, fiber, energy	A
			Solar ponds	Heat, electricity	B
	Global Tilt	Total on tilted or tracking surfaces	Photovoltaic (PV)	Electricity	A
			Domestic water heating (DWH)	Hot water	A
SPECTRAL		Wavelength band relevant to specific technology	Solar detoxification (photo chemical)	Toxic waste disposal	B

A = Commercialized processes and products. B = Pilot level process demonstrations or infant industry.

Components of solar radiation. Solar radiation, which is available throughout all portions of the daytime sky, is summarized graphically in **Figure 4.1**. "Direct" solar radiation is the powerful stream of radiation that comes directly from the sun. Within the earth's atmosphere, clouds can obviously block and reflect direct sunlight. But also, in more subtle fashion, various gases, liquids, and suspended solid particles that comprise the atmosphere manipulate the incoming solar radiation through absorption and scattering processes. As partial compensation for robbing the earth of this direct sunshine, some fraction of the reduction in the direct component arrives at the earth's surface from all directions of the sky and is termed "diffuse" solar radiation. On a clear day, direct radiation acts as a bright spotlight pouring from the disk of the sun, while diffuse solar radiation can be thought of as less powerful floodlights emanating rather uniformly from the entire sky. On an overcast day when the sun is not visible (too weak to cause a shadow), the direct radiation is zero; all light that is available during such conditions is diffuse solar radiation. The direct and diffuse components together are referred to as the "global" radiation.

Surface Orientation. Surfaces that directly face the sun receive more solar radiation than surfaces that face in other directions. The propensity for people's noses to get sunburned before the rest of their face illustrates this fact. When discussing the solar resource, it is most common to define two reference orientations: 1) "horizontal," and 2) "normal," a geometric term meaning always facing the sun.

Fundamental solar quantities. It would be impractical to attempt to measure solar radiation for every potentially useful solar orientation. Therefore the reference orientations are combined with the three solar components to define fundamental solar parameters. Solar energy accumulated over some standard period of time, such as a single day or year, is called "insolation" (incident solar radiation). In practice, global and diffuse insolation are measured with horizontal instruments that see the whole sky, summing solar radiation received from all directions. Solar radiation measurements conducted in this manner quantify "global horizontal insolation" (GHI) and "diffuse horizontal insolation" (DHI), respectively. "Direct normal insolation" (DNI) is measured using an instrument that tracks the sun continuously throughout the day. These three fundamental solar quantities, which appear continually throughout this chapter, are related by the equation shown at the top of Figure 4.1.

Flat-plate photovoltaic devices, solar water heaters, and crops utilize diffuse as well as direct radiation. For solar equipment or crop land that is level (horizontal), the global horizontal insolation encompasses all solar radiation received. More commonly however, solar equipment is tilted relative to horizontal, such as on a sloped rooftop. In such cases, both direct normal and global (or diffuse) horizontal information can be used to compute the effective solar radiation in the plane of interest ("global tilt"). Mirrors and other concentrating optics are not able to focus diffuse solar radiation, hence, direct normal is the only relevant component of solar radiation for the full host of concentrating solar technologies.

Spectral nature. The nuclear reaction occurring at the sun sheds radiant energy over a broad spectrum of wavelengths. As observed on earth, this spectrum is modified somewhat due to absorption within the atmosphere. The term "broadband" implies consideration over the entire solar spectrum, for practical purposes, wavelengths from about 300 to 3,000 nanometers. Yet many solar processes are only concerned with a limited spectral band. Photosynthesis for example, occurs in the range of 400 to 700 nanometers. While the specific ranges of spectral sensitivity for different solar conversion processes are an added complication when describing the solar resource, they typically have less impact than directionality and weather. For this reason, spectral information will receive limited additional coverage in this chapter.

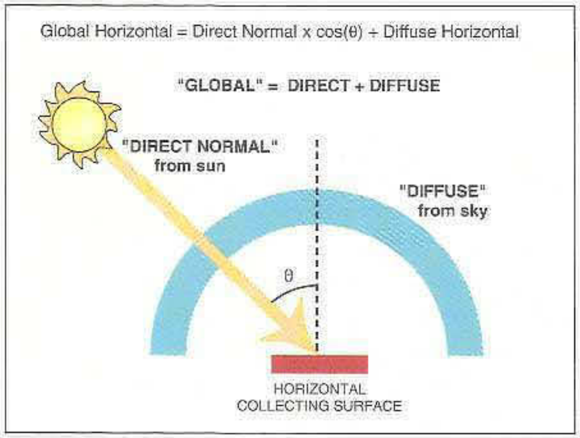


FIGURE. 4.1. Relationship Between the Three Fundamental Solar Quantities.

Development Issues: Special Considerations For Large-scale Use

Two major technical considerations for large solar energy conversion installations are land use and water availability. Solar radiation has a low energy density relative to other common energy sources. While this fact lends inherent safety advantages over conventional combustible and radioactive fuels, it does require that a large total acreage be utilized to gather an appreciable amount of energy. Typical solar to electric power plant designs require between 5 to 10 acres for every megawatt of generating capacity. More specifically, a large (200 MW) solar plant in West Texas would need about 1,300 acres (two square miles) of land. While the construction of large facilities like solar power plants or new airports are within the realm of common, successfully implemented projects, their shear size requires that a host of social and environmental issues be considered. Another pathway for solar energy development is through distributed installations of small-scale systems. Photovoltaics in particular represent a significant opportunity for low-impact installations on existing structures or parcels already used for other purposes, thereby circumventing the need for dedicated land to produce energy.

Solar thermal electric technologies, as with natural gas, coal, and nuclear steam cycle power plants, typically require considerable water supplies. While the quantity of water needed per acre of use is similar to or less than that needed for irrigated agriculture, dependability of the water supply will be an important issue in the sunny, dry areas of the state favored for large scale solar power plants. To their advantage, photovoltaics and dish-Stirling systems do not require water.

SURVEY

Fundamental Data Collection

Solar measurements in the United States date back to the beginning of the twentieth century. Starting in about 1950, solar energy information began to be gathered regularly in connection with fundamental weather data collection. Since the energy crisis of the 1970's, additional solar monitoring efforts intended primarily for the evaluation of solar energy conversion devises have also been periodically undertaken.

Solar Monitoring Stations

Instrumentation. The measurement of solar radiation is not a straightforward task. Solar radiation comes over a broad spectrum of wavelengths, predominantly from a moving target (the sun) but also from the constantly changing sky. Equipment designed to quantify this resource must accommodate the spectral and directional nature of sunlight, near-instantaneous changes in radiation (such as when the sun goes behind a cloud), and perform these tasks accurately throughout the day to determine the total energy available. Furthermore, accurate measurement requires that optical surfaces remain clean, which can be a daily chore in dusty or polluted environments.

Instrumentation type, quality assessment procedures and period of record all influence the usefulness of a solar monitoring station to the solar energy community. Through the years various types of sensors have been used, including sunshine switches, photosensors, and high quality instruments. Sunshine switches are of limited value for quantifying insolation since the switches merely tabulate the weather condition as sunny or cloudy but provide no information on radiation intensity. (Texas summary statistics derived from equipment of this type are included in Table 3.6 of the Climate chapter.) High quality instruments, such as broadband thermopile-type pyranometers and pyrheliometers, typically are capable of measurement uncertainties of less than 5%,[1] but require frequent if not daily maintenance. They are favored by research institutions.

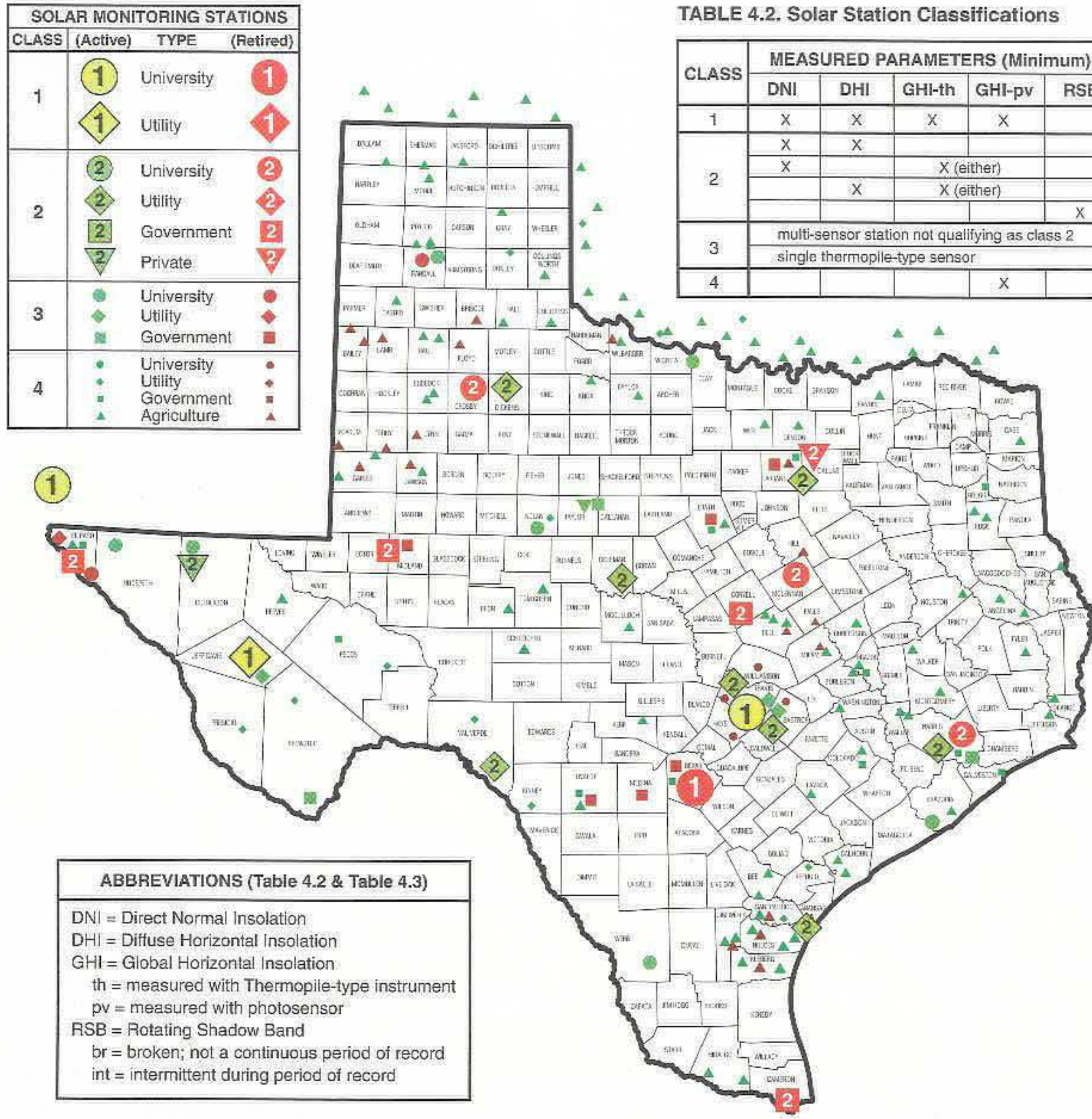
Because of their relative robustness and low cost, simple photosensors are the most common type of sensor in the field. Photosensor-type instruments, which are simply calibrated photovoltaic cells, have two potential drawbacks. First, they operate over a limited portion of the solar spectrum (300-1120 nm), introducing uncertainty for broadband applications. Secondly, many networks utilizing these instruments seldom if ever clean them, thus limiting the value of the data for many prospective users.

A Rotating Shadow Band (RSB) instrument couples a robust photosensor with a motorized rotating band that periodically blocks direct sunlight from the sensor. This single instrument is able to measure global and diffuse radiation and from these measured quantities calculates the direct normal. The RSB is becoming the instrument of choice for many electric utilities and others conducting measurements in remote areas.

Station summary. Numerous ongoing and retired solar monitoring stations of interest to Texas are identified in **Figure 4.2** using the classification system summarized in **Table 4.2**. Limited details about the major stations and networks are provided in **Table 4.3**. The remainder of this section

TABLE 4.2. Solar Station Classifications

CLASS	MEASURED PARAMETERS (Minimum) DNI	DHI	GHI-th	GHI-pv	RSB
1	X	X	X	X	
2	X	X			
	X		X (either)		
		X	X (either)		
					X
3	multi-sensor station not qualifying as class 2				
	single thermopile-type sensor				
4				X	



ABBREVIATIONS (Table 4.2 & Table 4.3)

DNI = Direct Normal Insolation
DHI = Diffuse Horizontal Insolation
GHI = Global Horizontal Insolation
th = measured with Thermopile-type instrument
pv = measured with photosensor
RSB = Rotating Shadow Band
br = broken; not a continuous period of record
int = intermittent during period of record

FIGURE 4.2. Location of Active and Retired Solar Monitoring Stations in Texas. All active (green) and retired (red) sites are depicted according to the station type and class as identified in the key above. Station classifications are defined in Table 4.2.

TABLE 4.3 Solar Monitoring Stations in Texas. Stations are still active if no ending date is provided.

CLASS	NETWORK/PROGRAM	TYPE	SITES	LOCATION	PERIOD OF RECORD	MEASURED SOLAR PARAMETERS DNI	DHI	GHI	RSB	OTHER
1	University of Texas at Austin	univ	1	Austin	1984-	X	X	X		X
	New Mexico State University, SWTDI	univ	1	Las Cruces, NM	1989-	X	X	X		
	CSW - Solar Park	utility	1	Ft. Davis	1994-	X	X	X	X	
	Trinity University	univ	1	San Antonio	1980-1981	X	X	X		X
2	City of Austin Electric Utility (COA) - 3M	utility	1	Austin	1990-	X		X		
	COA - Town Lake Center	utility	1	Austin	1993-				X	
	CSW - Wind/Solar network	utility	9	various	1994-				X	
	Texas Utilities Electric Co. - Solar Park	utility	1	Dallas	1995-				X	
	Houston Lighting & Power	utility	1	Houston	1994-				X	
	Kenetech, Inc.	private	1	Culberson Co.	1995-				X	
	Trinity University	univ	1	Waco	1979-1982	X		X		
	University of Houston	univ	1	Houston	1979-1982	X		X		
	Texas Tech University	univ	1	Crosbyton	1979-1982	X		X		
	Aerospace Corp.	govt	1	Ft. Hood	1974-1976 (int)	X		X		
	Lawrence Berkeley Lab	govt		various	1976-1981 (int)	X		X		
	NOAA - SOLRAD/SOLMET	govt	1	El Paso	1952-1994 (br)	X	X	X		
	NOAA - SOLRAD/SOLMET	govt	1	Midland	1978-1994 (br)	X	X	X		
	NOAA - SOLRAD/SOLMET	govt	1	Brownsville	1952-1994 (br)	X	X	X		
	Entech, Inc.	private	1	Dallas	1982-1988	X		X		
3	COA - PV300	utility	1	Austin	1987-			X		
	COA- Convention Center	utility	1	Austin	1992-			X		X
	CSW - Ft. Davis PV project	utility	4	Ft. Davis	1994-			X		X
	NASA	govt	1	Houston	1994-			X		X
	AEI-SEDC Wind/Solar network	govt	7	various	1994-			X		X
	US National Park Service/EPA	govt	1	Big Bend	1991-			X		
	NREL - Material Test Site	govt	1	Abilene	1994-			X		X
	Cummins Power	private	1	Abilene	1991-	X				
	University of Texas at El Paso	univ	1	El Paso	1985-1991			X		
	West Texas A&M University	univ	1	Canyon	1983-1984			X		
	EPRI - WEST Associates	utility	1	El Paso	1976-1982			X		
	J.M.Lord, Inc.	govt	1	Uvalde	1973-1983			X		
	NOAA - SOLMET	govt	1	Ft. Worth	1952-1975			X		
	NOAA - SOLMET	govt	1	Stephenville	1974-1975			X		
	NOAA - SOLDAY	govt	1	Midland	1952-1976			X		
	NOAA - SOLDAY	govt	1	San Antonio	1952-1974			X		
	NOAA - SOLDAY	govt	1	Hondo	1975-1975			X		
4	CSW - Wind/solar network	utility	12	various	1994-			X		
	LCRA - Hydro network	utility	2	East Texas	1994-			X		
	TAMU/LoneSTAR	govt	6	Statewide	1990-			X		
	TAMU-Agriculture Experiment Stations	ag	29	Statewide	various			X		
	TAMU-Peanut Network	ag	4	High Plains	various			X		
	TAMU-High Plains PET Network	ag	6-11	High Plains	various			X		
	TAMU/TRMM	ag	18	Brazos Valley	various			X		
	TAMU/TAES Corpus Christi -Cotton	ag	7-10	Coastal Bend	various			X		
	Texas & US Forest Service	ag	13	East Texas	various			X		
	USDA/SCS	ag	2	Central Texas	various			X		
	Lubbock private network	ag	6	High Plains	various			X		
	NOAA - NWS AGO network	ag	3	various	various			X		
	UT-Austin: Austin microclimate study	univ	5	Austin Area	various/retired			X		
	TAMU/TAES Blacklands-TAWAP	ag	23	Statewide	various/retired			X		
	Oklahoma MESONET	govt	108	Oklahoma	various			X		

describes some of the significant programs and networks identified.

Federal networks. Since 1949, the United States Government has sponsored several sporadic efforts to implement and maintain a national solar data collection network. The first network, called SOLMET, measured hourly global horizontal insolation at 26 National Weather Service (NWS) stations from 1952 through 1975 using an assortment of solar instruments.[2] After a layoff of two years, a renewed initiative called SOLRAD monitored global horizontal and direct normal insolation with uniform instrumentation and thorough quality control at 38 of the nation's NWS stations. This program produced the highest quality solar data record of any national program until funding was cut off in 1981.[3] By 1988, the SOLRAD program was revived at about 25 NWS stations using upgraded equipment but was eventually disbanded by 1994. The 14 station Integrated Solar Insolation System (ISIS) network is expected to be operational by the end of 1995, consisting of 10 refurbished SOLRAD stations and 4 new, high quality SURFRAD stations.[4] While both the SOLMET and SOLRAD networks contained three stations in Texas, the ISIS program will not conduct measurements in Texas.

To supplement the modest federal networks currently planned, the National Renewable Energy Laboratory, (NREL) has proposed the Cooperative Networks For Renewable Resource Measurements (CONFRRM), a multi-year effort with the goal of supporting solar radiation and wind measurement activities in as many climatalogically-dispersed locations in the U.S. as possible.[5] When fully implemented, CONFRRM may include 80-360 solar measurement stations and 50-100 wind benchmark stations. These measurement programs will be administered by approximately 10 regional centers using uniform standards developed by NREL. Aside from these official networks, a host of federal agencies such as the Environmental Protection Agency, the Bureau of Reclamation, and the Department of Energy conduct solar measurements for a variety of purposes.

Utilities. Many of the State's electric utilities have established solar monitoring programs to assess the long-term value of this resource within their service territory. The City of Austin Electric Utility Department, with its long-standing interest in solar energy, has sponsored solar monitoring at several locations in the Austin area over the past 10 years. Other utilities have become involved more recently. Central and South West Services (CSW), which provides electricity in many rural, sunny areas, is currently establishing Texas' most extensive solar (and wind) monitoring network.

Universities. Most of the state's major universities have conducted solar measurements at some point during the past 20 years. Since 1985, the University of Texas at Austin has had an ongoing monitoring effort that includes measured direct, diffuse, and global insolation for Austin.[6] Solar data measured at New Mexico State University's Southwest Technology Development Institute (SWTDI) in Las Cruces, provides the most representative measured data set available for Texas' Trans-Pecos region (areas west of the Pecos River). Also noteworthy is Trinity University's now-defunct DOE/SEMRTS program that recorded detailed measurements of broadband and spectral radiation in San Antonio during the early 1980s.

Photosensor-based networks. In terms of number of sites, more solar data are collected through photosensor-based networks than by any other source. Most of these are concentrated in the agriculture regions of the State such as the High Plains, Coastal Bend, and Rio Grande Valley.[7] Also, most of Texas' neighbors maintain statewide networks to support a variety of missions including public safety, agriculture, and education.

Significant non-solar networks. Many networks that currently do not measure solar radiation may prove useful for future efforts to expand solar resource assessment in Texas. The Texas Coastal Ocean Observing Network (TCOON, see Chapter 7), TNRCC's Continuous Air Monitoring Sites (CAMS) network and the weather monitoring efforts of the Texas Department of Transportation each have many stations in place that may have the capability to add additional sensors, including instrumentation to measure solar radiation.

Information Sources

Data Base Descriptions

Attempts to quantify and characterize the solar environment over the entire United States have generally been limited to the readily available data bases archived from the solar monitoring efforts of the National Weather Service (NWS). Because of the shortage of quality solar measurements, national solar data bases rely principally on modeled estimates derived from long-term meteorological data for parameters such as cloud cover, humidity, and visibility. Several available data bases are described below.

NSRDB.[8] The National Solar Radiation Data Base (NSRDB) is a 30 year data base (1961-1990) consisting of 56 Primary stations (containing some measured solar data, from 1-27 years) and 183 Secondary stations (solar data are entirely modeled). The data base contains solar and meteorological values for 17 locations in Texas (5 primary, 12 secondary). Ninety-three percent (93%) of the solar information in the data base is modeled from meteorological parameters. The NSRDB serves as the basis for practically all solar information products developed by NREL since 1992.

SOLMET/ERSATZ.[2] Prior to the NSRDB, the best available national solar data were from the 26 station SOLMET data base. The period of record for nearly all stations spans the period 1952-1975. Additionally, 222 ERSATZ sites were created that consist entirely of data modeled from weather parameters.

TMY.[9] Typical Meteorological Year (TMY) is a specialized subset of a long-term data base consisting of a single, composite year of data that is representative of long-term average conditions. This is probably the most popular design set available, as it can be used to quickly predict the average long-term performance of solar systems.

SOLDAY.[10] SOLDAY stations (distinct from SOLMET sites) archived daily totals of global horizontal insolation from 1952 to 1975. This data set is rarely used today.

WEST Associates. A consortium of electric utilities measured solar data throughout the Southwestern United States during the late 1970's. This network produced high quality measurements, but only had a single station in Texas, located at El Paso.[11]

Data Sources

Readily available, quality controlled data sets of measured solar radiation data are available for only a few of the monitoring stations identified in Table 4.3. For non-federal solar programs, inquiries regarding data should be made directly to the entity involved. (Contact information for many of these are included in Appendix B). The National Climatic Data Center (NCDC) is officially responsible for dissemination of the various solar data bases archived by the U.S. Government. Two of the major products that are available are described below.

CD-SAMSON. The hourly data sets that comprise the 239 station National Solar Radiation Data Base are available from NCDC on 3 compact disks titled *Solar and Meteorological Surface Observing Network, 1961-1990.*[12] All Texas stations are included on Volume II (Central U.S.). The CD's operate on DOS computers and cost $100 per CD, or $300 for the three volume set.

TMY2 CD.[13] A new Typical Meteorological Year data set derived from the NSRDB and designated TMY2 has just become available (the original TMY, which is also available, is based on SOLMET). While individual stations can be retrieved online, the entire 239 station TMY2 set is being made conveniently available on CD directly from NREL.

Internet Resources

The burgeoning information superhighway offers instant access to a rapidly growing list of solar resource information. A few relevant online resources are described below. Additional information on the internet and Geographical Information Systems (GIS) is available in Appendix C.

World Wide Web (WWW). The following sources can be reached by entering their Universal Resource Locator (URL) address (shown in parentheses below) while using WWW browsing software such as Mosaic.

RReDC (http://rredc.nrel.gov) NREL has just established the Renewable Resource Data Center (RReDC) to provide online access to a host of solar resource products. Initial offerings include measured solar data (WEST Associates, SEMRTS, Spectral), NREL data bases (NSRDB Daily Statistics Files, TMY2), complete documents, glossaries, bibliographies and maps.[14]

NCDC (http://www.ncdc.noaa.gov) Homepage for the National Climatic Data Center—the agency officially responsible for dissemination of federal solar products and data.

WRDC (http://wrdc-mgo.nrel.gov) Link to the archives of the World Radiation Data Center in St Petersburg, Russia.

WeatherNet (http://cirrus.sprl.umich.edu/wxnet) The University of Michigan's extensive weather information network.

EREN (http://www.eren.doe.gov) DOE's Energy Efficiency and Renewable Energy Network gateway to a wide array of federal information.

Solstice (http://solstice.crest.org) Abundant solar resource through the Center for Renewable Energy and Sustainable Technology (CREST).

SEDC (http://sedc.twdb.texas.gov) The Texas Sustainable Energy Development Council maintains information on Texas natural resources.

USENET News groups. Postings in the following news groups may contain information on solar resources. Inquiries for solar information are appropriate in these news groups as well as directly to the webmaster for the WWW sites listed above.

- sci.geo.meteorology
- sci.energy
- alt.energy.renewable
- alt.solar.thermal
- bit.listserv.wx-talk

Summary Documents

The documents listed below cover a range of topics contributing to the current knowledge base of solar radiation information for Texas. Introductory and reference documents are identified first.

Shining On, A Primer on Solar Radiation Data. NREL, 1992.[15] This short booklet provides a good introductory discussion of solar fundamentals, instrumentation, and resource assessment networks. It suggests additional readings for those interested in more technical information.

Solar Resources. Roland Hulstrum, editor, 1989.[16] This technical reference examines insolation data bases, models and algorithms, networks, instrumentation, spectral issues, forecasting, and illuminance models.

Assessment of the Potential for Solar PV in the Central and South West Services Territory. Gary Vliet and Leslie Libby, 1992.[17] The University of Texas at Austin investigated the feasibility of grid-connected bulk power generation from photovoltaic systems for Central and South West Services, including an assessment of the solar resource throughout CSW's service territories.

Solar Radiation Resource Assessment of Texas. Sloan Solar Engineering, 1992.[11] This report, submitted to the City of Austin Electric Utility Department, recaps solar resource assessment information throughout Texas and the U.S., with a focus on direct normal insolation information needed to support the development of concentrating solar-to-electric facilities in West Texas. Included are solar radiation maps from numerous sources, a listing of Texas solar monitoring stations, and discussion of a novel technique to infer insolation microclimates based on diurnal temperature variation.

National Solar Radiation Data Base (1961-1990) User's Manual. NREL, 1992.[8] Manual supplying details on the recently developed data base that is the basis for practically all solar resource assessment products produced by NREL since 1992.

Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors. NREL, 1994.[18] A must-have for designers and engineers of solar energy-related systems, this document summarizes monthly average solar radiation available for numerous collector types and orientations for all 239 NSRDB sites in the U.S. and its territories. The diskette version of the manual contains additional tables not found in the hard copy publication. The use of this manual is recommended rather than NREL's older summary documents (*Insolation Data Manual*[19] and *Direct Normal Solar Radiation Data Manual*[20]); although Del Rio, Laredo, Kingsville, and Sherman listings are not included in the new NSRDB-based manual but are available in the older documents.

Solar Radiation Data Manual for Buildings. NREL, 1995 (pending).[21] A companion document to *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors*, this reference provides tabulated data of particular interest to building designers. Tabulated monthly quantities for horizontal and east, west, south and north facing vertical surfaces include incident solar radiation, average transmitted solar radiation through double glazed windows, and average incident illuminance. Monthly statistics for temperature, humidity, degree days, and clear day solar radiation are also included.

Solar Radiation Energy Resource Atlas of the United States. SERI, 1981.[22] The "Solar Atlas", as it is commonly called, is the best known, most widely accepted reference for insolation contour maps in circulation today. Eventually, NREL will replace this document with a new version based on the NSRDB.

Texas Mesonet: A Plan for a Mesoscale Meteorological Monitoring Network. Texas A&M University and TNRCC, 1995.[7] The Texas Mesonet proposes the establishment of a network of several hundred meteorological stations to provide citizens and decision makers with timely and user-friendly access to local, regional, and statewide environmental data. This report contains a wealth of information on meteorological networks in Texas and, together with other available documents,[23,11] identifies existing data collection sites that may be useful for efforts to expand solar monitoring activities in Texas.

A Cloud Cover Climatology for the State of Texas. Keith Hutchison, 1994.[24] Satellite techniques hold great promise for improved mapping of solar resources. This short report, developed specifically for this project, makes recommendations for producing insolation maps of Texas from available satellite data bases.

OVERVIEW

Due to the lack of quality measurements of solar radiation throughout the United States, the National Renewable Energy Laboratory developed statistical models to estimate solar radiation from meteorological parameters. These modeled data complement various measured solar data sets to form the National Solar Radiation Data Base (NSRDB)—the best statewide solar radiation data base currently available for Texas.[8] While the data base includes a preponderance of modeled (rather than measured) solar data and relatively few stations (only 17 stations in Texas), it does provide a consistent basis to discuss the general levels and spatial variability of solar radiation across the state.

Average Annual Summary

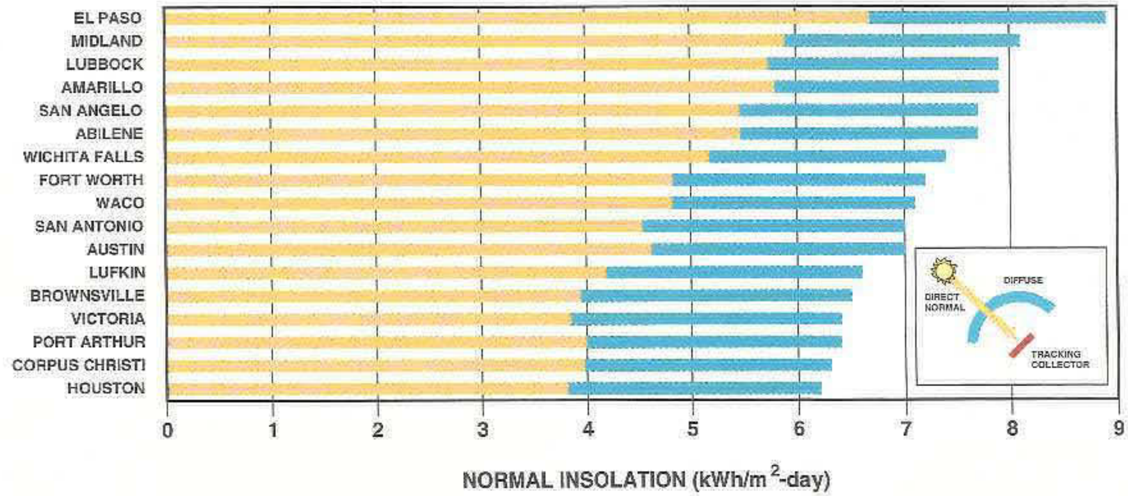
The total amount of solar radiation that is available at a site over the course of the entire year, termed average annual insolation, is the foremost statistic of interest to the solar designer. Since most solar equipment performs proportionally to available sunshine, average annual insolation is a good indicator of the long-term performance of solar systems. Quantifying average annual insolation accurately across the entire State is difficult due to the scarcity of solar radiation data. This is particularly a problem for vast expanses of West and South Texas—regions that are suspected of being the sunniest in the state but which have virtually no solar data readily available.

Annual insolation averages for all Texas stations contained in the NSRDB are summarized in the two bar charts on the facing page. **Figure 4.3a** depicts Normal Insolation, that is, solar radiation received by a surface that always faces the sun, while **Figure 4.3b** summarizes Horizontal Insolation—the solar radiation received by any flat, horizontal surface, such as a lake, hay field, or warehouse roof.

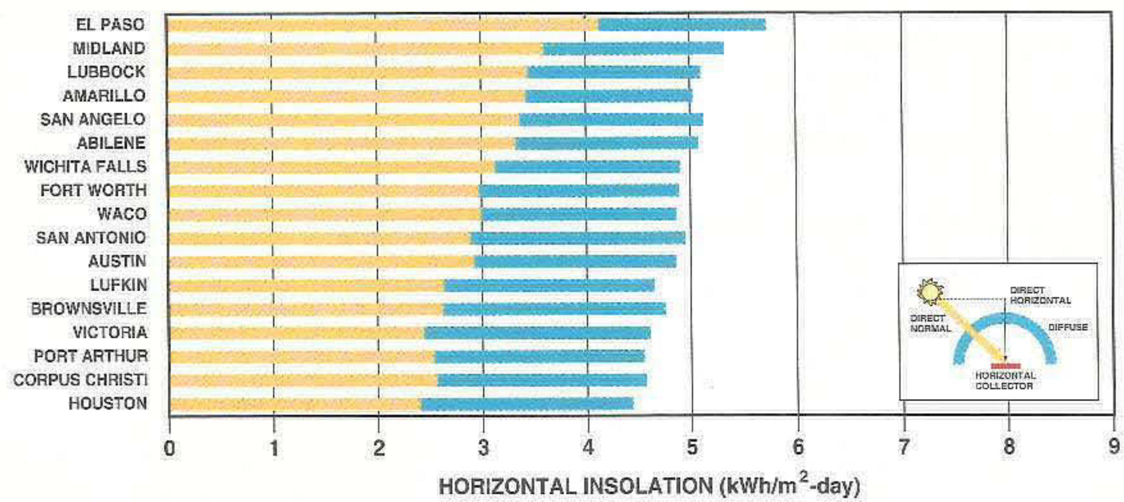
Figure 4.3 illustrates how the three fundamental solar quantities are related. Direct normal insolation is depicted graphically for Texas NSRDB stations as the orange bar segments in Figure 4.3a. On a horizontal surface, only a fraction of the direct radiation is observed (equal to direct normal times the cosine of the solar incidence angle); this is represented as the shorter orange segments of 4.3b. This "direct horizontal" component coupled with the diffuse horizontal produces the total global horizontal insolation shown in Figure 4.3b. In clear climates such as El Paso, the direct normal insolation often exceeds the global horizontal insolation.

El Paso is shown in Figure 4.3 to exhibit the highest direct and total insolation of any NSRDB station in Texas, while Houston and Victoria exhibit the lowest. Clouds, high humidity, and pollution contribute to the relative reduction in direct insolation along the Texas coast. Such obscuring phenomena, while reducing direct insolation by reflection, absorption and scattering, serve to increase diffuse insolation. Not surprisingly, El Paso demonstrates the lowest diffuse insolation, while east Texas sites such as Brownsville, Victoria and Houston exhibit high diffuse insolation (**Figure 4.4**).

General trends in the spatial variability of the average annual solar resource throughout Texas and the conterminous United States are depicted graphically in the maps on pages 48-49 for direct normal insolation (**Figure 4.5**), global horizontal insolation (**Figure 4.6**), and global insolation on a fixed south facing surface tilted from horizontal at an angle equal to the site's latitude (**Figure 4.7**).



a) Solar radiation components on a surface that tracks the sun continuously.



b) Solar radiation components on a horizontal surface.

FIGURE 4.3. Average Annual Insolation for Texas' NSRDB Stations. The direct (orange) and diffuse (blue) components constitute the global (orange + blue) insolation. Shown for a continuous 2-axis tracking surface (a) and a horizontal surface (b).

NREL Solar Resource Maps. The National Renewable Energy Laboratory's Renewable Energy Resource and Information Center developed the maps shown (Figures 4.5-4.7) based on data contained in the National Solar Radiation Data Base. While these maps portray the general national trends in solar radiation, additional measured data and improved modeling techniques are needed to correctly portray the actual complexity of the solar resource. All figures use the common legend provided below. (Labels on maps are in units of kWh/m²-day).

COLOR KEY	AVERAGE SOLAR RADIATION PER DAY (kWh/m²-day)	PER YEAR (MJ/m²)	PER YEAR (quads/100 mi²)
	<3.0	<3,940	<1.0
	3.0 - 3.5	3,940 - 4,600	1.0 - 1.1
	3.5 - 4.0	4,600 - 5,260	1.1 - 1.3
	4.0 - 4.5	5,260 - 5,910	1.3 - 1.5
	4.5 - 5.0	5,910 - 6,570	1.5 - 1.6
	5.0 - 5.5	6,570 - 7,230	1.6 - 1.8
	5.5 - 6.0	7,230 - 7,880	1.8 - 1.9
	6.0 - 6.5	7,880 - 8,540	1.9 - 2.1
	6.5 - 7.0	8,540 - 9,200	2.1 - 2.3
	>7.0	>9,200	>2.3

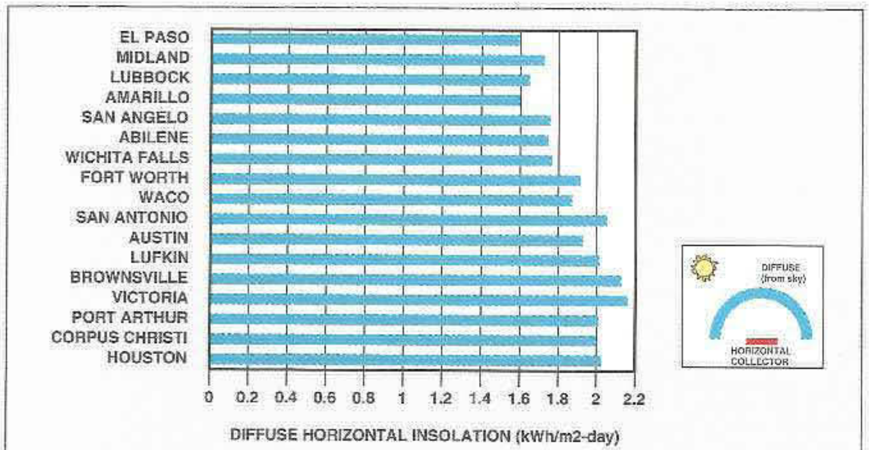


FIGURE 4.4. Diffuse Horizontal Insolation. Solar radiation scattered by the sky (diffuse insolation) varies only modestly across the state, but is slightly higher near the coast.

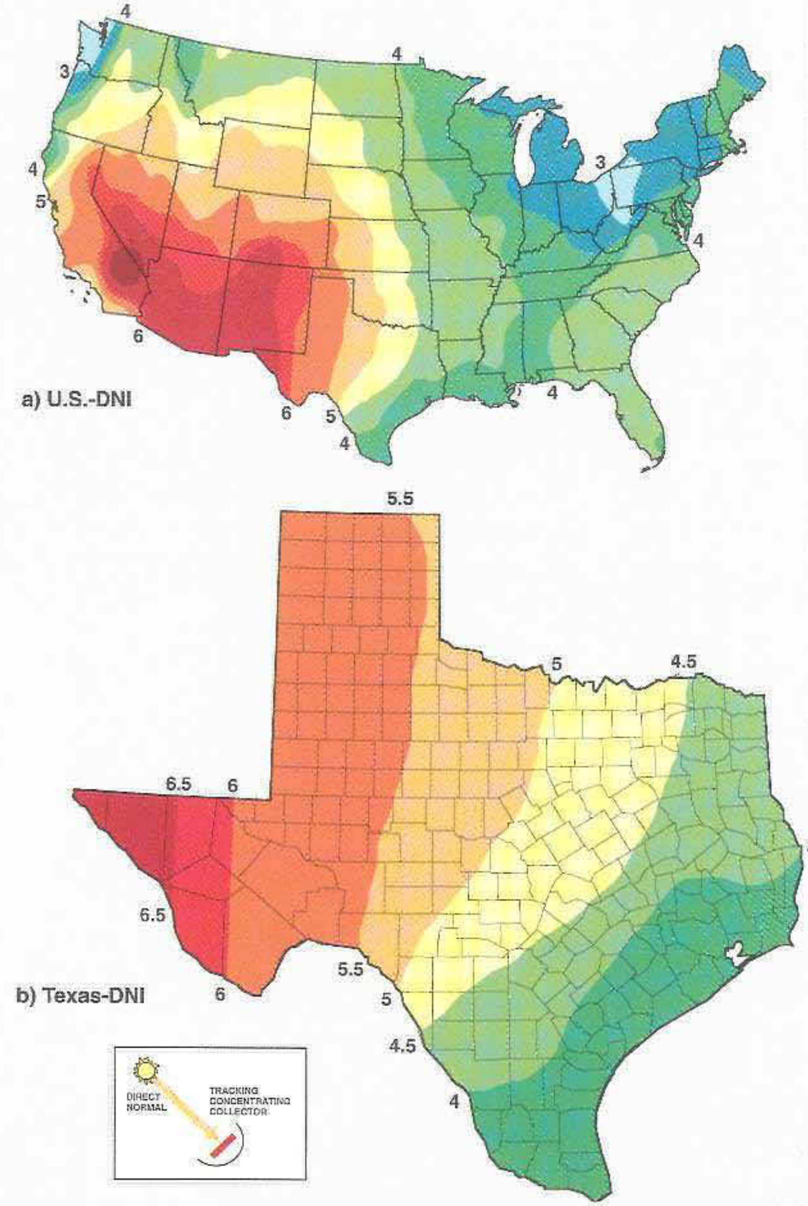


FIGURE 4.5. Direct Normal Insolation (DNI). This fundamental component quantifies the solar resource available to any concentrating solar system.

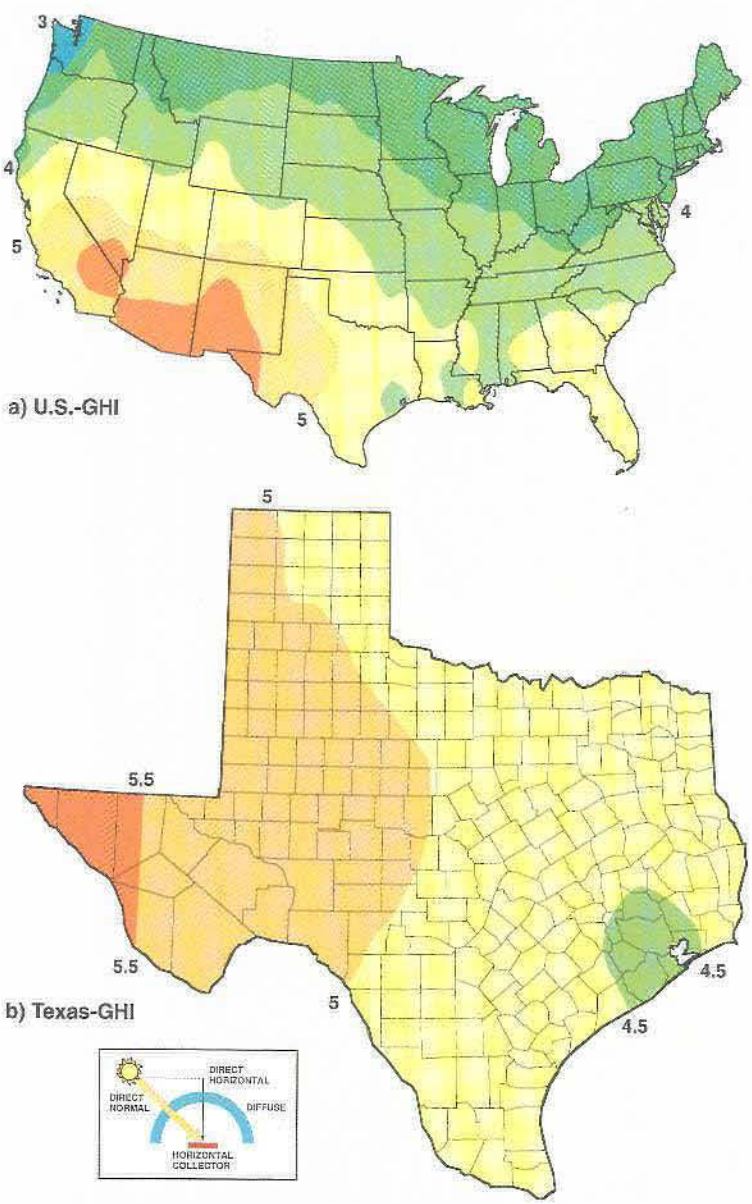


FIGURE 4.6. Global Horizontal Insolation (GHI). This fundamental solar quantity is directly relevant to flat, level surfaces such as crop fields and solar ponds.

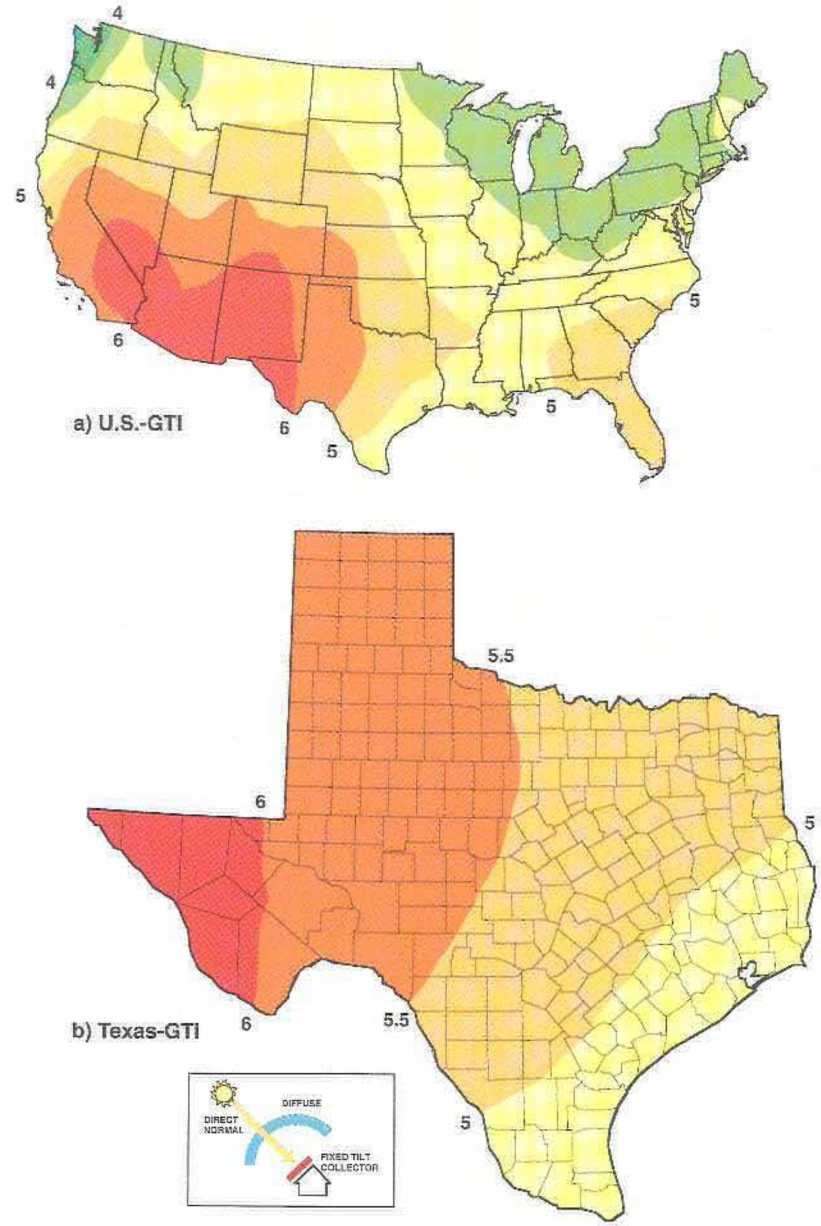


FIGURE 4.7. Global Insolation on a Tilted Surface (GTI). Calculated for a south facing collector with tilt angle = latitude; indicative of total solar radiation available on a well exposed rooftop.

Direct Normal Insolation (Figure 4.5). A quick comparison of Figures 4.5-4.7 illustrates that direct normal insolation is the most variable component of solar radiation. This is logical, since an opaque cloud in front of the sun reduces the direct insolation to zero. In contrast, diffuse insolation is present to some extent every day and does not change drastically with varying weather conditions. Since direct radiation benefits from low cloud cover and low humidity, desert areas exhibit the highest levels of direct solar radiation.

The national direct normal map, Figure 4.5a, shows that the desert Southwest experiences the highest levels of solar radiation in the United States. In particular, the Mojave, Sonoran and Chiahuahuan Deserts exhibit high insolation. Cloudy climates, such as around Seattle and Pittsburg, naturally result in low solar availability.

In Texas, the best average annual direct normal insolation environment exists in the extreme western portion of the state, on the fringes of the Chiahuahuan Desert. Generally the further west, the better the availability of direct insolation. Since cloud patterns can vary significantly in mountainous areas, actual solar conditions are expected to be more complex throughout the Trans-Pecos than indicated in Figure 4.5.

Diffuse Insolation (Figure 4.4). Differences in diffuse insolation are too subtle to meaningfully convey in the common map format used in Figures 4.5-4.7. The similar annual diffuse insolation values for all Texas NSRDB stations are summarized in Figure 4.4. As expected, diffuse insolation is shown to be inversely related to direct insolation, indicating that the cloudy coastal areas of east Texas have higher diffuse insolation than the fair sky regions of West Texas.

Global Horizontal Insolation (Figure 4.6). Since direct is the dominant component of solar radiation, trends in global horizontal are similar to those exhibited for direct normal in Figure 4.5, except that the extent of variability is lessened due to the moderating influence of diffuse insolation.

Insolation on a Tilted Surface (Figure 4.7). Photovoltaic panels and solar water heating collectors are commonly installed on roofs. Figure 4.7 maps the resource that is available to such systems that are ground-mounted or mounted on rooftops that have good exposure to the sun.

Many solar installations are oriented in other configurations, yet the orientations presented above should bracket the insolation available for most applications. Available sources summarize many other configurations.[18] Also, all information presented to this point has ignored reflected radiation. Flat-plate collectors can receive a significant additional contribution of solar radiation that is reflected by the ground, water, or surrounding objects.

Quantification of Resource Base

For an energy resource to make significant and lasting contributions to society, it must be large in size and accessible for use. As summarized in Table 4.3, Texas' solar energy resource base is certainly very large. The total resource is computed by applying the statewide average global horizontal insolation to the entire land area of the state. The resulting sustainable value, 4,300 quads per year, is 250 times larger than the peak historical single year energy production in Texas (17 quads in 1972).[25] Accessible resource, by strict definition, is the subset of the total resource base that can be captured by current and near-term technology. Yet, since the solar energy supply is available and can be taken advantage of everywhere in Texas, some practical limitations are assumed here.

The accessible resource base was estimated by applying "practical" solar utilization factors to certain USGS land classes (identified graphically in Figure 6.4 of the Biomass chapter), determining the total land available, then applying the statewide average insolation. This approach resulted in a 250 quad base of accessible solar radiation, which with the application of an appropriate average conversion efficiency, is converted into usable end-use energy. Existing solar power plants in California have annual efficiencies of about 15% based on collector area, but with spacing between collectors included, drops to a value of 5%.[26] Current roof-mounted photovoltaic systems have efficiencies that currently range from about 3-15%. If solar radiation is to be used for thermal uses such as heating water, average system efficiencies will be considerably higher: up to 30% is representative of current solar thermal technology.

Perhaps the most striking numbers in Table 4.3 pertain to urban lands. Solar technologies integrated into buildings and other urban settings have the potential to satisfy a considerable portion of future energy needs. If photovoltaic systems operating at 10% average efficiency were distributed throughout 5% of urban areas (on building rooftops, over parking lots, along roadways), they would produce more than half a quad of electricity—over half of Texas' current electrical consumption.

The land use mix identified in the accessible solar resource base requires less than 6% of the state's land area and would produce considerably more energy than is consumed by the state today. Alloca-

TABLE 4.3. Quantification of Texas Solar Resource Base. (All values are in quads unless noted otherwise.)

LAND USE*	TOTAL RESOURCE		ACCESSIBLE RESOURCE		ACCESSIBLE END-USE ENERGY				
	PERCENT OF STATE	(quads)	PERCENT USABLE	(quads)	AVERAGE SYSTEM EFFICIENCY 50%	20%	10%	5%	3%
Barren	0.60%	27	30%	8	4.0	1.6	0.8	0.4	0.2
Range	45.30%	1,946	10%	195	97.3	38.9	19.5	9.7	5.8
Urban	2.50%	106	5%	5	2.6	1.1	0.5	0.3	0.2
Agriculture	32.30%	1,390	3%	42	20.9	8.3	4.2	2.1	1.3
Other	19.30%	831	0%	0					
TOTAL	100.00%	4,300	5.8%	250	124.8	49.9	25.0	12.5	7.5

*Based on USGS land use classifications and percentages.

tion of sizable acreage for energy production is not without precedent in Texas. It is noted that during the peak of oil and gas activity, over 40% of the state was under lease and nearly 10% was proven to be productive.[27]

Resource Variability

As with many other renewable energy resources, the intermittent nature of solar radiation is perceived as a limitation to widespread use. The resource does vary but it can be reasonably predicted over short time scales. All of the figures depicting resource variability are based on direct normal insolation—the most variable component of sunshine. As a general rule, variability for global and diffuse insolation will be less than that indicated for direct normal.

Annual Variability

The annual direct normal insolation for each year from 1961 to 1990 is shown for several Texas NSRDB stations in **Figure 4.8.** It is readily observed that annual insolation does not vary much from year to year. Practically all stations exhibit extreme annual insolation (minimum and maximum years) that are within 15% of the long-term average annual value. It is further observed that the data tend to maintain the same order relative to one another. Yet, in some cases, one area can experience higher than average solar conditions, while another area has a downturn in annual sunshine.

Low insolation years will typically occur simultaneously for all of Texas following major volcanic eruptions and during persistent, rainy El Nino events. After a major volcanic eruption, debris spewed high into the atmosphere can linger for years and will tend to reduce direct and total insolation around the entire globe. Such an instance is demonstrated by the Texas data in 1982, the year following the eruption of El Chichon in Mexico. If more recent data were available, a synchronized downdip would also be expected following the 1991 eruption of Mount Pinatubo.

In years dominated by more localized weather systems, relative insolation patterns can be different throughout the state. For example, in 1969, Houston experienced its sunniest year, while in the Panhandle, Amarillo had its third lowest sunshine total in 30 years. Such year-to-year variability, even the seemingly modest levels identified here, is a major operational concern for solar power plants.

Seasonal/Monthly Variability

How solar radiation varies throughout the year is important to the performance of any solar device. If good performance of a solar system is desired during a particular season, it will be important to tailor the system design to solar conditions prevailing during that period. The tables and graphs provided here provide the bare minimum on this topic; additional detail is available from other sources.[18]

Values for average monthly direct normal insolation are plotted in **Figure 4.9** for several locations across Texas. Since the longest day of the year, the summer solstice, occurs during the month of June,

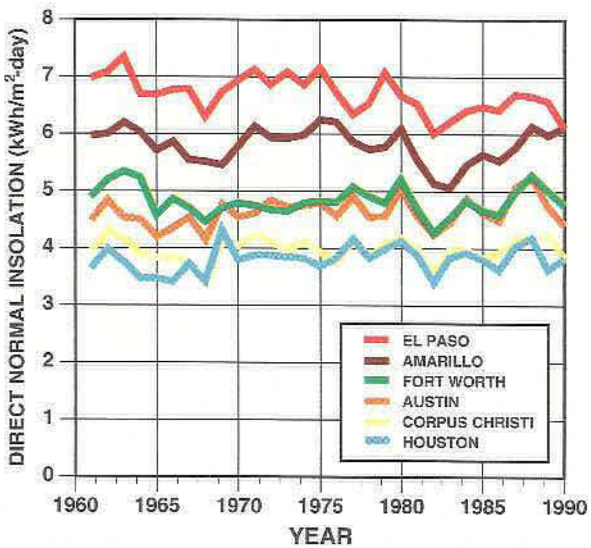


FIGURE 4.8. Average Annual Direct Normal Insolation, 1961-1990.

it can be generally expected that this month will exhibit the greatest monthly insolation. Conversely, the lowest average insolation can be expected during the month of December. Such variations stemming from the orbital cycle of the earth about the sun are reflected in the dashed line in Figure 4.9, which represents a fraction of the extraterrestrial insolation for 30°N latitude. In addition to this first-order influence, local weather conditions determine average solar radiation.

Perhaps the most striking observation made from Figure 4.9 is the sharp drop in insolation during late summer for El Paso. El Paso is exceptionally sunny during much of the year, particularly during spring months but by mid-summer solar radiation drops dramatically. As discussed in Chapter 3, this time marks the onset of the rainy monsoon season in the Desert Southwest. Monthly insolation at El Paso during July and August—the months of highest electric consumption in Texas—is roughly equal to that experienced at Amarillo. This suggests that the summertime performance of concentrating solar power plants may very well be similar throughout much of western Texas.

In contrast, the eastern half of the state experiences relatively high insolation during mid to late summer. Yet, even though these are the sunniest months along the Texas Gulf Coast, the level of direct normal insolation throughout the coastal region is still on the order of 25% lower than that experienced in West Texas. The summer period is bracketed by May and September, two of the heaviest rainfall months for much of Texas. Figure 4.9 indicates these two months have relatively low insolation for most of Texas. By October, generally clear conditions across most of Texas result in relatively high insolation averages.

Table 4.4 lists monthly and annual averages for global horizontal insolation for all NSRDB stations. In addition to their value for solar equipment design, it is noted that the values in Table 4.4 are useful for certain civil engineering calculations, such as calculating the emissions from fuel storage tanks.[28]

Daily (Diurnal) Variability

Plots of average hourly solar radiation are shown for a representative winter day (January) and summer day (August) in **Figure 4.10.** These are not "typical" daily patterns, but rather an average resulting from the mixture of clear, partly cloudy and cloudy conditions that actually occur. Since the sun travels across the Texas sky at about 900 mph (sunrise at El Paso is almost a full hour after sunrise at Orange), there is an apparent shift in the diurnal profiles plotted in the figures. Locating solar power plants west of the load they serve provides a natural shift that tends to enhance afternoon performance.

January data plotted in **Figure 4.10a** indicate a nearly identical shape for all Texas stations. Every diurnal profile, save that for El Paso, indicates somewhat of a bias toward greater afternoon sunshine, stemming from the prevalence of morning cloud cover throughout most of Texas during winter. (See Figure 3.7).

The various August profiles in **Figure 4.10b** show more complexity, stemming from the consistency of several distinct weather patterns that prevail during late summer. These systems include the almost constant flow of moisture and cloud cover flowing out of the southeast from the Gulf, and secondly, the Southwest monsoon that generates after-

TABLE 4.4. NSRDB (1961-1990) Average Daily Global Horizontal Insolation (kWh/m^2-day).[11]

STATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Abilene	3.1	3.9	5.1	6.1	6.5	7.0	7.0	6.3	5.2	4.4	3.3	2.9	5.08
Amarillo	3.0	3.8	4.9	6.1	6.6	7.1	7.0	6.3	5.2	4.4	3.2	2.7	5.03
Austin	3.0	3.8	4.7	5.4	5.9	6.6	6.8	6.3	5.2	4.4	3.3	2.8	4.86
Brownsville	2.9	3.7	4.6	5.3	5.8	6.4	6.5	6.0	5.2	4.5	3.4	2.7	4.75
Corpus Christi	2.8	3.6	4.4	5.0	5.5	6.1	6.3	5.8	5.0	4.3	3.3	2.7	4.57
El Paso	3.5	4.5	5.9	7.1	7.8	8.0	7.4	6.8	5.9	4.9	3.8	3.2	5.73
Fort Worth	2.9	3.7	4.7	5.6	6.2	6.9	7.0	6.4	5.2	4.2	3.1	2.7	4.89
Houston	2.7	3.4	4.2	5.0	5.6	6.0	5.9	5.6	4.9	4.2	3.1	2.5	4.43
Lubbock	3.1	3.9	5.1	6.2	6.7	7.1	7.0	6.3	5.2	4.4	3.3	2.8	5.11
Lufkin	2.7	3.5	4.5	5.3	5.9	6.4	6.4	6.0	5.1	4.3	3.1	2.5	4.65
Midland	3.3	4.2	5.5	6.5	7.0	7.3	7.0	6.5	5.4	4.6	3.6	3.0	5.33
Port Arthur	2.7	3.5	4.3	5.2	5.8	6.3	6.1	5.7	5.0	4.3	3.1	2.6	4.55
San Angelo	3.2	4.1	5.2	6.1	6.5	7.0	6.9	6.4	5.3	4.5	3.5	3.0	5.13
San Antonio	3.1	3.9	4.8	5.5	6.0	6.7	6.9	6.4	5.4	4.5	3.4	2.9	4.95
Victoria	2.8	3.6	4.4	5.1	5.7	6.2	6.2	5.8	5.0	4.3	3.3	2.7	4.61
Waco	2.9	3.7	4.7	5.5	6.0	6.7	6.9	6.4	5.2	4.3	3.2	2.7	4.87
Wichita Falls	2.9	3.7	4.8	5.8	6.4	6.9	7.0	6.3	5.2	4.2	3.1	2.6	4.90

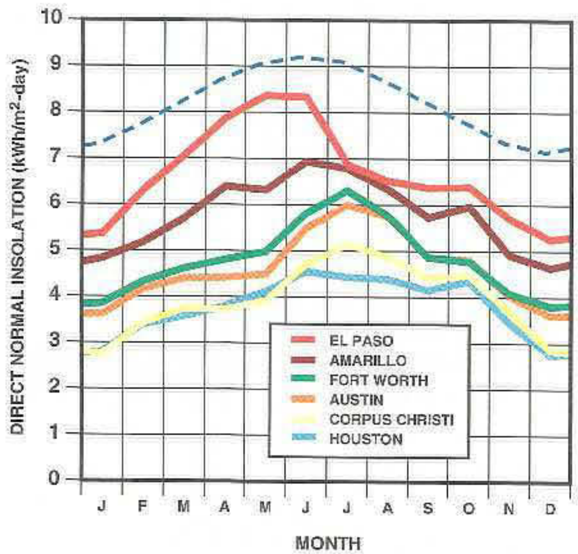


FIGURE 4.9. Average Monthly Direct Normal Insolation. The dashed blue line is indicative of clear conditions.

noon thunderstorms in the Trans-Pecos and drives these systems and their cloud cover eastward. Most cities in Texas exhibit diminished sunshine through the afternoon in summer, yet some coastal areas like Corpus Christi and Brownsville indicate relatively higher sunshine during the afternoon.

A generally accepted rule for installing fixed (non-tracking) solar equipment is to orient the collectors facing due south. In instances where there is imbalanced morning and afternoon insolation (such as Corpus Christi), an orientation other than due south will maximize system output.

Sources for Improved Solar Information

The maps and charts presented to this point are based on the NSRDB. Although useful, this data base nevertheless has two major shortcomings: 1) it includes relatively few stations, and 2) it is based largely on modeled data rather than high quality measurements. Because there are few stations included in this data base, there is no means to achieve a finer resolution needed to discriminate between local microclimates. Fortunately, means are available to improve our knowledge of the solar resource.

Meteorological parameters. Since solar radiation is interrelated with numerous other climatological parameters, it is possible to infer useful information about solar radiation distribution by considering summary information for other weather parameters such as cloud cover, humidity, and temperature. For instance, localized areas of high diurnal temperature variation, mapped in detail in Figure 3.5 of the Texas Climate chapter, may suggest insolation microclimates.[11] The single most useful meteorological source, however, is detailed cloud cover information from weather satellites.

Satellite imagery. Whereas the 239 station NSRDB embodies an average spatial resolution of approximately 200 kilometers, weather satellites such as GOES are capable of spatial resolution on the order of one to ten kilometers.[29] Weather satellite images, like the familiar ones seen on weather reports during the evening news, can be used to develop very high resolution solar maps. At a one kilometer resolution, Texas would contain over half a million pieces of information, contrasted with the mere 17 data points available in the NSRDB. **Figure 4.11** maps global horizontal insolation estimates for 1987 that have been deduced from satellite data.[29] Although this is a coarse satellite grid (about 80

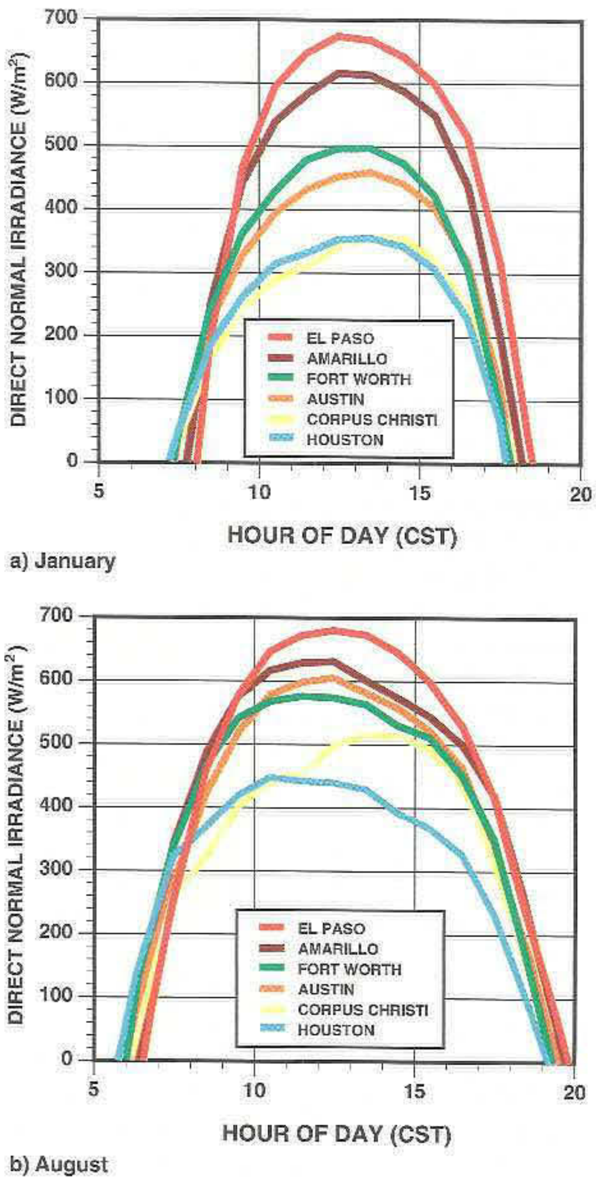


FIGURE 4.10. Average Daily Direct Normal Irradiance during January and August. The middle of the day (mean solar noon) ranges from12:20 at Houston to 13:05 at El Paso.

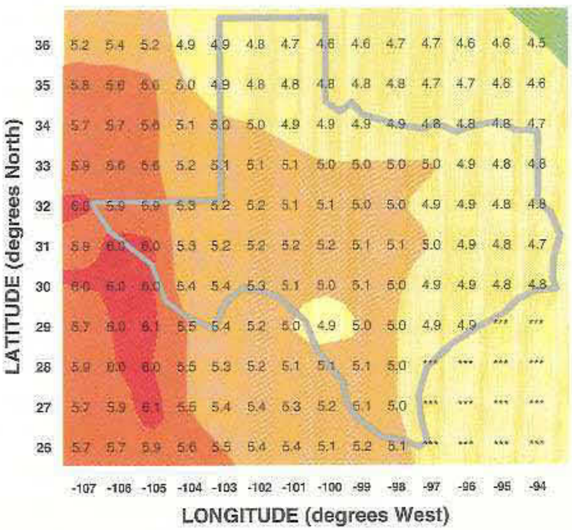


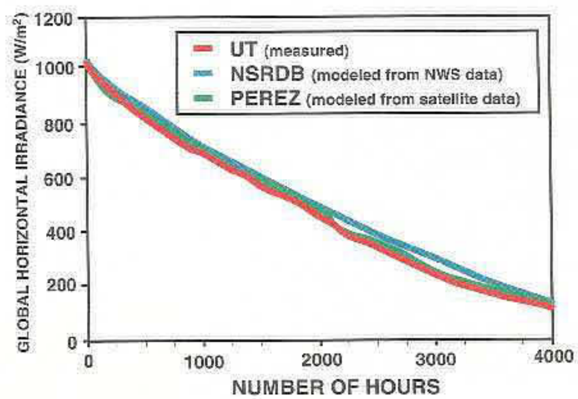
FIGURE 4.11. Average Solar Radiation Map Derived from Satellite Data. Estimated global horizontal insolation (kWh/m2-day) for 1987, on a one degree by one degree latitude-longitude grid.

pixels in Texas), it is able to identify insolation features not evident in Figure 4.6b. Figure 4.11, which generally agrees to within five percent of 1987 annual averages for Texas NSRDB sites, raises concerns regarding the validity of linear interpolation between NSRDB sites and map contours, and also identifies high insolation gradients in mountainous terrain. Although not shown on the map, coastal areas also have high gradients. Due to the nature of summer cloud formation, coastal areas, particularly on the barrier islands, will likely have higher insolation than sites some distance inland (i.e., Galveston is probably sunnier than Houston.

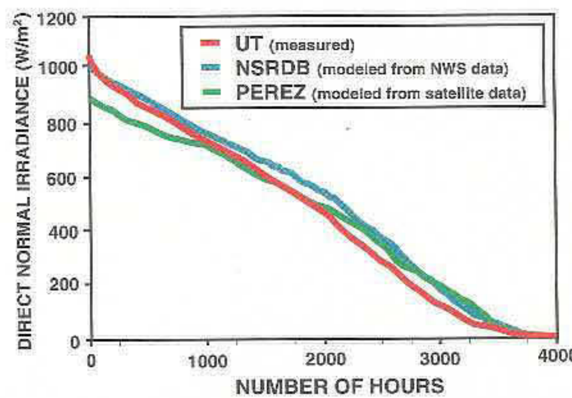
To address the need for better solar maps, NREL has undertaken the Solar Data Grid Mapping project.[30] The study region for this ongoing project, 10°N to 52°N latitude by 60°W to 125°W longitude, is partitioned into a grid comprised of cells spaced approximately 50 kilometers apart. This resolution produces a mesh with nearly 300 pieces of information in Texas. For every grid cell, monthly mean daily-total energy (insolation) for the three fundamental solar radiation elements—global horizontal, direct normal and diffuse horizontal—will be estimated using a modification of the same model used to develop hourly values in the NSRDB. Encouraging preliminary results suggest that much improved, high resolution solar maps covering Texas and other areas of North America may soon be available.[30]

Measured solar radiation. The most desirable source for improving solar information is through long-term, high quality solar measurements. There are many existing data sets, such as those recorded by the University of Texas at Austin and New Mexico State University in Las Cruces, that are available but that have not yet been incorporated into the national solar radiation data archives. Other programs are just starting, such as the solar monitoring efforts of Central and South West Services, that should ultimately improve the solar information base in many areas currently lacking data. Yet, for many of the solar monitoring stations identified in Table 4.2, data are not available. In many cases, an abrupt disruption of funding support prevented proper data archival that has resulted in data becoming unavailable or permanently lost.

High quality measurements provide the foundation of any resource assessment endeavor. They are needed to validate and improve models and also to ground truth satellite-derived insolation maps. Austin is fortunate to have an abundance of solar information currently available. Austin solar data sources were compiled and compared for this project by Leslie Libby of the City of Austin Electric Utility Department.[31] Included from this effort is **Figure 4.12**, which compares measured, modeled and satellite-derived insolation data for Austin for 1987. The good agreement shown in Figure 4.12a



a) Duration Curves of Global Horizontal Irradiance.



b) Duration Curves of Direct Normal Irradiance.

FIGURE 4.12. Comparison of Three Solar Data Sets for Austin, Texas for 1987. The plots show the number of hours that the solar irradiance exceeds any given value.

adds confidence in methods that estimate global horizontal insolation. On the other hand, direct insolation (Figure 4.12b) is much more difficult to model and to measure. With the availability of high quality, measured direct normal insolation data sets, solar models of all types can be improved.

The region west of the Pecos River has been shown to contain the highest levels of solar radiation in Texas. Because of the mountainous terrain in the region, variations in all natural resources, including sunshine, are extreme. **Figure 4.13** compares 1990 insolation data for two sites in the Trans-Pecos that are only 40 miles apart: El Paso (data from NSRDB[12]) and Las Cruces, New Mexico (from the SWTDI[32]). As was seen in Figure 4.12, global horizontal insolation (dashed lines in Figure 4.13) agrees closely, while direct normal values differ. The significant differences in monthly direct insolation, highlighted in the figure, may indicate problems with the data or it could simply point out real differences in the solar environment that occurred over this time period. Real differences of this magnitude would have a major impact on the siting of solar plants. Assuming the insolation differences depicted in Figure 4.13, a 200 MW solar power plant paid $.05/kWh for electricity would have produced almost $3,000,000 more revenue during 1990 located at Las Cruces instead of El Paso. Although unlikely, if this were a consistent, long-term difference, the Las Cruces based solar plant would generate nearly $90 million more during its lifetime than an identical plant sited at El Paso. Such an example illustrates the value and importance of accurate solar information.

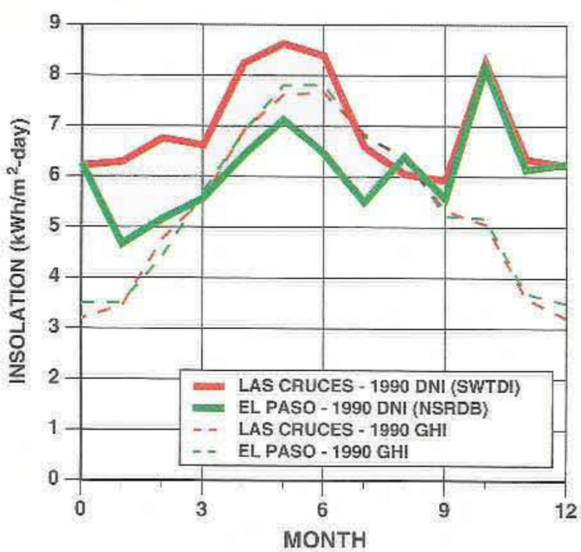


FIGURE 4.13. Comparison of Data Sources Relevant to the Trans-Pecos.

RECOMMENDATIONS

Solar energy represents a practically unlimited energy source for Texas' future. A wide variety of solar technologies are available and many of these are meaningfully contributing in niche energy markets such as off-grid power. Wide scale implementation of solar technology boils down to economics and successful marketing—how much do these energy services cost and how does society value this vast, sustainable energy supply. Better resource information will enhance the competitiveness of solar equipment by facilitating accurate performance projections and the optimization of system designs. The following recommendations prioritize specific resource assessment needs for Texas.

1) ***Establish and maintain a long-term program to measure the solar resource throughout the state.*** Texas sorely needs a network of high quality reference solar monitoring stations supported by a long-term funding commitment to ensure continuous measurements with proper maintenance, quality control, data archival, and information dissemination. Cyclic support for solar resource measurements has undermined efforts to achieve a good understanding of this resource. High quality solar measurements provide the foundation for all resource assessment activities. Importantly, since many years of measured data are required to develop a meaningful period of record, fundamental solar resource monitoring should be initiated many years before the expected time frame to evaluate and deploy solar energy conversion systems.

   Participation in the National Renewable Energy Laboratory's (NREL) CONFRRM project is recommended.[5] Solar radiation measurements, including measurements of direct normal, should be conducted at representative locations throughout the state, but especially in good resource regions lacking data, such as the Trans-Pecos and South Texas.

2) ***Develop high resolution state maps of average solar radiation/cloud cover.*** What is the sunniest place in Texas? How sunny is it? Unfortunately, there simply is not enough information readily available to answer these questions. Sunshine can change significantly over very short distances in mountainous areas such as the Trans-Pecos. Yet, even in the relatively simple terrain of northern Texas, microclimates exist. Such an undertaking is currently a high priority for NREL.

3) ***Develop a better understanding of the correlation between energy use and the availability of solar (and other renewable) resource(s).*** The intermittent nature of solar and wind energy leads many to discount the value of these resources for satisfying future energy demand. Yet fluctuations in the availability of renewable resources do follow regular seasonal and daily patterns. While the resources can indeed change from day to day, these changes can be reasonably predicted over short time scales (several hours). Evaluation of the correlation between renewable energy resources and energy use is needed. Such studies could consider a single site or a broader region (which would lessen the impact of short-time scale influences such as intermittent clouds), consider energy storage, or even methods of modifying energy consumption behavior (for example through variable rate structures) to improve the effective reliability and utilization of solar and other renewable resources.

4) ***Support the development and validation of techniques to model solar data from other information.*** It is highly unlikely that direct measurements of terrestrial solar radiation will ever be of sufficient quality and density to satisfy the needs of the solar energy industry. Therefore the scientific community must diligently pursue improvement in solar modeling techniques. This should consist of validation of models against high quality measured data bases as well as basic model development.

5) ***Measure spectral solar radiation along the industrial areas of the Gulf Coast.*** If spectral solar measurements are contemplated, they should be included along the Gulf Coast for two reasons: 1) marine environments can strongly influence solar spectra, and 2) such data would be valuable for design of solar processes to detoxify waste (needed in industrial areas) and for research related to skin cancer.

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WIND ENERGY

by Vaughn Nelson

INTRODUCTION

Significance of Resource: Historical and Future Uses

The use of wind as an energy source has its roots in antiquity. At one time wind was the major source of power for pumping water, grinding grain and for long distance transportation (sailing ships). A few of the common, present day applications of wind power will be discussed prior to detailing the Texas resource.

Water Pumping

The farm windmill proves that wind power is a valuable commodity. Although the peak use of farm windmills was in the 30s and 40s when over 6 million were in operation, these windmills are still being manufactured and are being used to pump water for livestock and residences. In Texas, there are an estimated 30,000 to 40,000 operating farm windmills. Even though the power output of each is low—0.2 to 0.5 kilowatt (kW)—collectively they provide up to 20 million watts (20 MW) of power. If these windmills for pumping water were instead powered by electricity from the grid, it would require 60 megawatts of thermal power at the generating station, not to mention an extensive investment in transmission lines, electric pumps and other equipment. This says nothing of the energy (and money) saved by not using fossil fuels to satisfy this energy need (equivalent to 80,000 barrels of oil per year).

A very promising development for farm windmills is the wind electric-to-electric water pumping system.[1] The wind turbine is coupled directly to an electric generator, just as in larger systems. The generator is then connected directly to a motor and centrifugal or turbine pump, which is a better match between the characteristics of the rotor and the load. The overall efficiency is 12 to 15%, double the performance of the standard farm windmill. The costs of the two systems are almost the same. However the wind-electric system pumps more water from the same depth. Large systems can pump enough water for small communities or for low volume irrigation. Wind has been and will continue to be a major source of energy for pumping water for livestock in Texas.

Generation of Electricity

During 1993, 3,000 MW of installed wind capacity in the 20,000+ wind turbines dispersed around the globe produced about 4 GWh of electricity—enough to satisfy the annual needs of all households in both Austin and El Paso. The largest concentration of wind turbines are in the mountain passes of California, with many of those machines imported from Europe and Japan. In 1992, 450 MW of wind turbines in Denmark produced nearly 1 GWh, 3% of the total electric consumption in that country.[2]

The installed price of large wind turbines is less than $1,000/kW. Operation and maintenance costs are around $0.01/kWh and availability, the fraction of time each year that the unit is not shut down with problems, approaches 97% at well-maintained facilities. With these cost inputs, wind plants in good to excellent wind regimes are currently producing electricity for $0.05 to 0.08/kWh (see **Table 5.1**). Yet wind power costs are continuing to improve. New wind power projects are now being bid as low as 3 cents per kilowatt-hour, which is competitive with natural gas fired generation and less than the cost of new coal and nuclear power plants.

In Europe, a number of new units are now being installed, with a projection of 4,000 MW in new capacity by the year 2000 and a goal of 25,000 MW by the year 2010. In the U.S., a number of new projects totalling 334 MW were announced in 1994, mostly outside of California in new wind plant locations. The trend in the U.S. points toward 3,500 MW of installed capacity by the year 2000.

Wind Plants in Texas

Utility scale electricity generation from wind is in its infancy in Texas, but already the industry has seen much activity. The Lower Colorado River Authority (LCRA) signed a power purchase agreement with Kenetech, Inc., a major wind power developer, to purchase electricity at less than $0.05/kWh from a wind plant under construction in the high wind region of the Delaware Mountains.[3] The initial 50 MW phase of the project will

TABLE 5.1. Wind Power Classification and Characteristics. Based on wind power classifications of the Pacific Northwest Laboratory.[6] Commercial viability assessments are based on technology expected to be available by the year 2000.

WIND POWER CLASS	WIND CHARACTERISTICS 50 METERS ABOVE GROUND*		
	POWER (W/m^2)	APPROXIMATE SPEED (mph)**	COMMERCIAL VIABILITY
1	0 – 200	0 – 12.5	VERY POOR
2	200 – 300	12.5 – 14.3	POOR
3	300 – 400	14.3 – 15.7	MARGINAL
4	400 – 500	15.7 – 16.8	GOOD
5	500 – 600	16.8 – 17.9	VERY GOOD
6	600 – 800	17.9 – 19.7	EXCELLENT

**Fifty meters (164 feet) is a common tower height for large wind turbines.*

*** Wind speeds based on a Rayleigh distribution at sea level. Higher elevations will require higher wind speeds to achieve the same wind power.*

be operational by mid-1996; an additional 200 MW is expected by the year 2002. The New World Power Corporation was recently awarded a contract by Texas Utilities to build a 40 MW wind plant near Big Springs that is also slated to produce electricity for less than a nickel a kilowatt-hour. A third major wind project, Central and South West Services' 6 MW facility near Fort Davis, is expected to be operational by the fall of 1995. Smaller demonstration projects that are already in place include Southwestern Public Service Company's three Carter 300 wind turbines near Amarillo and Texas Utilities' three Carter 300s located at their Energy Park near the Dallas-Fort Worth airport.

Development Issues: Special Considerations for Large-scale Use

Three main environmental issues may impede wind development. These are: visual impact, noise, and birds. Visual impact is clearly an esthetic matter. Some people do not like to see wind turbines, particularly if they are close to scenic areas such as parks and some coastal zones. There should be little detrimental visual impact in Texas' vast rural areas, but it remains a development issue that wind energy promoters should be aware of.

Noise measurements have shown readings from wind turbines that are generally below ambient levels. However, the repetitive noise from turbine blades stands out and one would not want to live in the middle of a wind plant. The whine from gearboxes on some units is also noticeable.

Avian mortality has become an issue. A major study is under way to find out the effect of rotating blades on raptors and if there are methods to make the turbines stand out to birds, such as color or noise.[4] Truss towers may make natural perches, attracting more birds to the area. One wind plant has stipulated tubular towers as a precaution. A wind plant could not be located next to a wildlife refuge for an endangered bird species, such as the whooping crane. Even though more than 150 million birds die every year in the U.S. as a result of collisions with communication towers, buildings, and cars,[4] environmental groups may oppose wind development if the industry does not adequately address this issue.

Some lands will be excluded from development because of environmental and other considerations: national and state parks, wetlands, and certain wildlife refuges. Environmental impact statements will have to be done as the Environmental Protection Agency has jurisdiction over many aspects. Some states and even counties have regulations concerning the environment that will also have to be met before a wind turbine or a wind plant can be installed.

One non-environmental issue that will have a major impact on wind power projects is the issue of wheeling power (moving electricity) from windy areas to load areas where energy is needed (large urban and industrial centers). Access to transmission lines and upgrade of transmission infrastructure will be part of the large-scale development of wind power. The Lower Colorado River Authority will be wheeling power from the Trans-Pecos to their service territory. Developers are now leasing land in the Panhandle with the idea of transmitting power to the west coast at some future time. These kinds of development scenarios can only take place if the transmission network is there to make it possible. The issue is significant because so many windy regions are sparsely populated and therefore are not serviced with large power lines. It is safe to say that near-term future development will follow the present transmission infrastructure. Texas is better off in this regard than other windy states of the Great Plains, some of which have very limited existing electrical transmission capability due to isolated rural populations.

SURVEY

Wind power (or energy) is proportional to the cube of the wind speed. For this reason, accurate measurement of wind speed is critical to properly assess the wind power potential of the State. Wind speed is influenced locally by wind shear, elevation, complex terrain, vegetation and nearby structures. For assessment of wind power potential, it is important that instruments measuring wind speed (anemometers) be placed at heights representative of commercial wind turbines (40 to 50 meters) at locations that are well exposed to the wind (no obstructions in the area). Unfortunately, the vast majority of available, measured wind information was taken at lower heights and usually in locations that are not windy and/or that are sheltered from the prevailing wind.

FUNDAMENTAL DATA COLLECTION

Wind measurement networks primarily intended to assess wind power potential are identified in **Figure 5.1.** Also shown are the sites of National Weather Service stations that provide readily available, long-term wind speed data.

State/AEI. In 1994, the Alternative Energy Institute, with funding from the State, selected seven (7) stations for long term collection (5 to 10 years) of wind and solar data. Time sequence data (15 minute to one hour) are being collected at heights of 10, 25, and 40 to 50 meters to determine the wind resource and how it will match the load pattern of utilities. Central and South West Services, El Paso Electric, Houston Power and Light, Southwestern Public Service, and Texas Utilities are participating

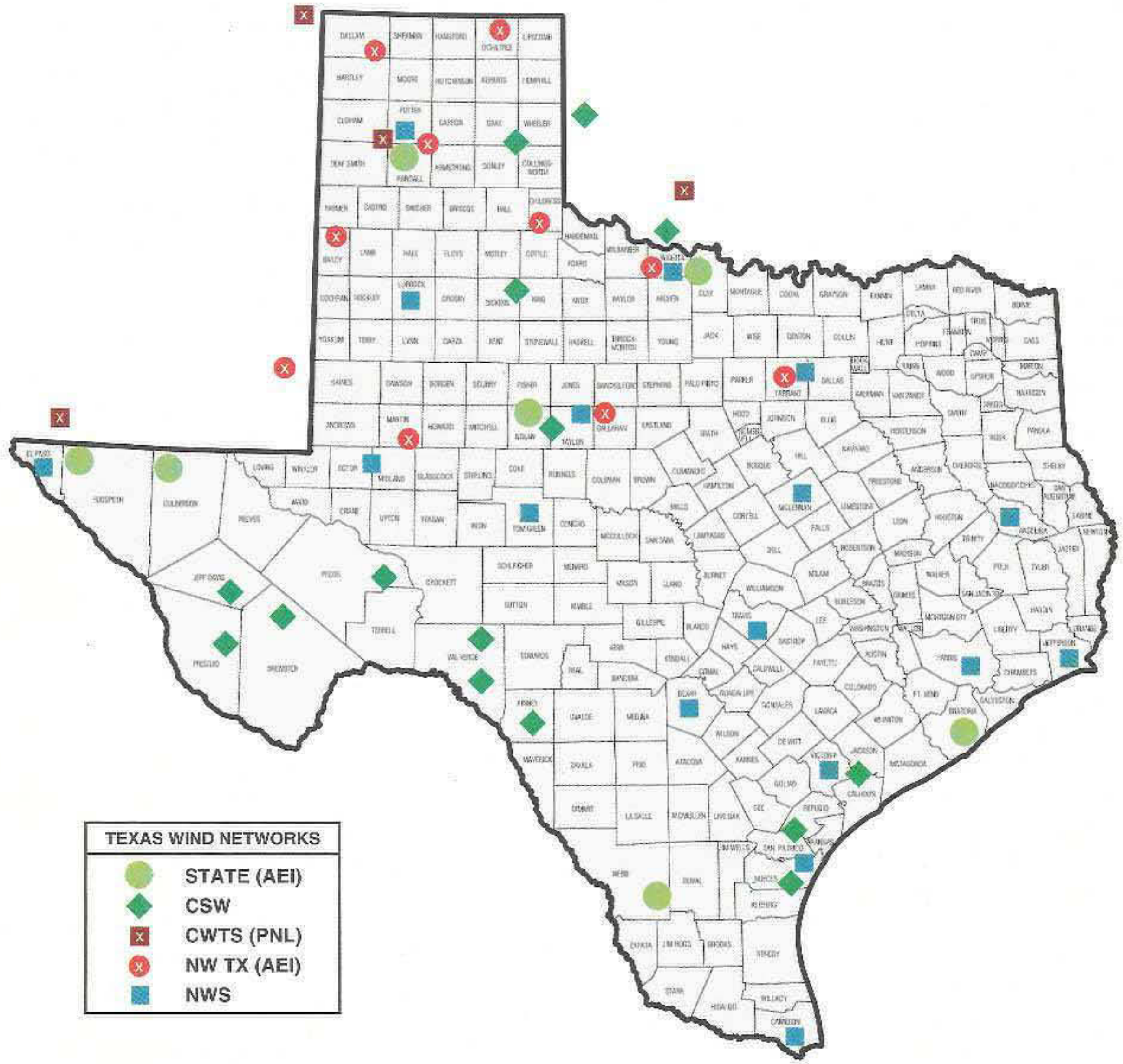

FIGURE 5.1. Location of Wind Monitoring Stations. Other than the National Weather Service stations, all sites shown are or were operated primarily to evaluate wind power potential. The State/AEI and CSW networks are currently active, while the Candidate Wind Turbine Sites and Northwest Texas network are defunct. In all cases, station locations are approximate.

in the program. Other utilities are also expected to participate.

CSW.[5] Central and South West Services, Inc., hired a consulting meteorologist who identified 70 potential wind farm sites based on existing wind data, topographical features, and proximity to electric transmission lines. The CSW network, initiated in 1993, consists of fifteen 10 meter met towers and nine 40 meter met towers distributed through the windy areas of their service territories.

Candidate Wind Turbine Sites.[6] The Pacific Northwest Laboratory had a measurement program that recorded up to six years of data (1977-1982) at 26 candidate sites for large wind turbines. Data from this program relevant to Texas includes measurements taken from 30 to 150 foot heights at four sites: Amarillo, Texas, St. Augustine Pass and Clayton, New Mexico, and Fort Sill, Oklahoma.

AEI-Northwest Texas region.[7] The first major wind assessment program in Texas recorded wind data at ten sites in the Northwest Texas region from May 1978 through December 1985. Average wind speed and wind shear information for this network, which took measurements at 10, 20 and 50 meters, are summarized in **Table 5.2**.

National Weather Service. The primary source of historical wind data is from the National Weather Service (NWS) network of first-order weather stations. Most NWS stations are located at airports and have anemometer heights of 10 meters (33 ft); older data from these sites was often taken at about 7 meters (20 ft). The Weather Service is in the process of changing their stations to Automatic Surface Observing Systems (ASOS), which include wind information taken at 10 meters.

NWS stations are not ideally located for wind resource assessment since they are in urban areas at airports that are generally sited to avoid high winds. Wind power plants will tend to be well removed from cities in locations that benefit from terrain enhanced winds. Nevertheless, NWS stations are the best source of long term data for examining wind resource variability across the whole state.

Private sources. Because good wind sites are an economic asset, utilities and private developers consider wind data as proprietary. Developers are now measuring wind in the Delaware and Apache Mountains, near Big Springs, and near Jericho (east of Amarillo). Developers are likely taking data in other locations as well. Because of their proprietary nature, none of these private monitoring efforts are identified on Figure 5.1. For the same reason, CSW sites identified in Figure 5.1 are approximate.

Other sources. Other sources of wind data include additional NWS stations, Federal Aviation Administration (FAA) stations, Air Force and Navy bases, towers at nuclear power plants, and a host of specialized weather station networks such as those monitoring air quality and serving the needs of the agriculture community. Some of these stations contain information that is very valuable for wind power assessment, such as the remote NWS AMOS station at Guadalupe Pass that is used to forecast high wind warnings in the mountains of the Trans-Pecos. It is noted that the FAA, Navy and Air Force are joining the NWS in changing to ASOS, thus establishing uniform standards for future wind measurements taken by these sources.

Useful data may also be available from networks such as the Oklahoma MESONET (for areas near the Oklahoma border), TNRCC's Continuous Air Monitoring Stations (CAMS), the Texas Coastal Observing Network (TCOON), and various agriculture networks operated by the Texas Agricul-

TABLE 5.2. Average Annual Wind Speed and Wind Power Measured at Nine Stations in the Panhandle, 1978-1985.[7] These measurements, taken at heights of 10, 20, and 50 meters, indicate higher wind shear (0.17-0.28) throughout the Panhandle than expected using the 1/7 power law (exponent = 0.14). A tenth station located at Abilene recorded wind speed (5.5 m/s) and wind power (186 W/m^2) at 50 meters, but provided no information on wind shear. Some 10 m data are suspect.

STATION	10m		20m		50m		Wind Shear Exponents	
	Speed (m/s)	Power (W/m^2)	Speed (m/s)	Power (W/m^2)	Speed (m/s)	Power (W/m^2)	50m/ 10m	50m/ 20m
AMARILLO	6.0	217	6.6	279	7.9	450	.17	.20
CHILDRESS	4.4	123	5.1	144	6.4	261	.23	.24
DALHART	5.0	160	6.0	231	7.2	351	.23	.20
FORT WORTH	—	—	4.8	127	6.0	232	—	.26
LOVINGTON, NM	5.1	155	6.1	226	7.6	399	.26	.25
MULESHOE	—	—	6.1	242	7.4	358	—	.21
PERRYTON	5.9	212	6.5	275	7.9	434	.18	.21
STANTON	5.1	150	5.7	189	6.7	277	.17	.28
WICHITA FALLS	3.9	74	4.7	124	6.1	226	.54	.28

ture Experiment Stations, Texas Agriculture Extension Offices, and the USDA. (Many of these weather station sites are identified and described further in the survey section of the solar chapter.) Anemometer height at most agriculture network stations are at typical crop heights, generally 2 meters or less, which is essentially useless for determining wind power potential for wind turbines.

INFORMATION SOURCES

Data Sources

SAMSON CD-ROM.[8] This CD from the National Climatic Data Center includes hourly wind data for 17 NWS stations in Texas. The anemometer heights above ground vary with station and in some cases the height at individual stations changed during the 1961-1990 period of record. AEI has programs that extract wind speed, temperature and pressure data, and calculates the wind power potential normalized to a 10 meter height.

ISMCS CD-ROM.[9] This CD contains summary information (including wind) for 10,000 weather stations worldwide; U.S. stations total nearly 2,000.

In addition to the wind data provided on the CDs listed above, data for scores of additional stations in Texas are available for a fee on an assortment of digital media from the National Climatic Data Center. In Texas, weather data and other digital data are available from TNRIS as well as directly from many of the numerous sources that are recording wind data. (See Appendix B for contact information.) The Alternative Energy Institute archives numerous data sets recorded by Federal, State and private wind assessment projects.

Internet Resources

Several entities maintain wind data on the internet that is accessible by FTP or Mosaic. A few sources are identified below; more detail is provided in Appendix C.

WxNet (cirrus.sprl.umich.edu/wxnet) The University of Michigan's Weather Network, a gateway to numerous weather information sources.

NCAR (http://www.ucar.edu) National Center for Atmospheric Research in Boulder, CO.

NCDC (http://www.ncdc.noaa.gov) National Climatic Data Center in Ashville, NC.

Summary Documents

Wind Energy Resource Atlas of the United States, PNL (Elliott), 1986.[6] Widely regarded as the best comprehensive source on the wind energy resources of the U.S., this report estimates wind power potential at 50 meters above ground from assorted wind measurements available through 1978. Estimates at 50 m are based on an exponential relation (1/7 power law) that calculates the change in wind speed with height from data measured at different height (typically only 6 to 13 m). Due to the lack of data for mountainous regions, wind estimates for passes and crests were derived from atmospheric, upper air wind information. From these wind estimates, seasonal and annual wind power maps of the U.S. were developed by assigning a wind power class value (see Table 5.1) to every cell of a 1/3 degree longitude by 1/4 degree latitude map grid.

Wind Energy Resource Atlas: Volume 7-The South Central Region, PNL (Edwards), 1981.[10] This technical volume provides greater detail on Texas wind regimes than that contained in the national atlas. Of particular interest are summary figures for 52 sites in Texas that cover interannual wind power and speed, diurnal wind speed by season, monthly average wind power and speed, directional frequency and average speed, annual average wind speed frequency, and annual average wind speed and power duration.

Potential for Wind Generated Power in Texas, Nelson and Gilmore, 1974.[11] Analysis of wind power based on 15 NWS stations in Texas ('59-'72) and 7 NWS stations in neighboring states ('64-'72). The average power capturable was estimated at 250,000 MW.

Wind Characteristics, Northwest Texas Region, May 1978-December 1985, AEI (Gilmore), 1987.[7] Monthly histograms of wind speeds were collected from ten stations in the Texas Panhandle region at heights to 50 meters. Average wind speeds and power were calculated for day and night by month and year. Data indicate higher wind shear than would be predicted using the 1/7 power law, particularly at night. Average wind power and resulting wind shear exponents are summarized in Table 5.2.

The CSW System Wind Energy Resource Assessment and Long-Range Wind Farm Development Strategy, Simon and Schroeter, 1994.[5] Outline of the wind monitoring component of a five year project, $17.3 million effort, to learn how wind and solar energy might be applied in the CSW electric utility service area.

An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States, Elliott, 1991.[12] Provides estimates of the wind power potential throughout the U.S.

Gridded State Maps Of Wind Electric Potential, Schwartz, 1992.[13] Digital wind maps and assessments of wind energy potential for the U.S.

Diurnal Variation of Onshore Wind Speed Near a Coastline, Yu and Wagner, 1970.[14] This paper is representative of the extensive research conducted by the meteorology community to characterize Texas' coastal winds.

Wind Turbine Technology, Spera (editor), 1994.[15] Reference text emphasizing fundamental principles covering aerodynamics, structural dynamics and fatigue, wind characteristics, acoustics, electromagnetic emissions, commercial wind power applications, and utility integration.

Wind Characteristics, An Analysis for the Generation of Wind Power, Rohatgi and Nelson, 1994.[16] Technical reference on all aspects of wind characteristics: atmospheric motions, potential flow, atmospheric boundary layer, wind energy conversion, wind measurement, terrain effects, statistics, turbulence, numerical models, and micrositing.

Wind Resource Screening Using GIS

One of the most promising methods to evaluate wind resource potential is with Geographic Information Systems. The following documents were drawn upon to perform the analysis of Texas wind power potential presented later in this chapter.

Applicability Of Digital Terrain Analyses To Wind Energy Prospecting And Siting, Wendell, 1993.[17] The Digital Elevation Model (DEM) data contains terrain elevation values on a latitude-longitude grid with a resolution of 3 arc-seconds (about 90 m) for the United States, Hawaii, and Puerto Rico. The Pacific Northwest Laboratory used this DEM data to create shaded-relief maps for each 1 degree area. PNL emphasized that micrositing and wind flow analyses require finer resolution than 90 meters in complex terrain.

Powering the Midwest, Renewable Electricity for the Economy and the Environment, UCS (Brower), 1993.[18] The Union of Concerned Scientists used the GIS program IDRISI with digital data sets for wind power (PNL), land cover and terrain elevation (USGS), electric transmission lines (DOE), plus political, administrative, and environmental data to estimate the impact of renewable energy on electric power production for the Midwest United States. A power law formula incorporating terrain exposure was used to revise the PNL wind power maps.

Geographical Information Systems for Wind Energy Siting, Bailey, 1992.[19] A siting study using ARC/INFO, a vector-based GIS system, identified attractive wind areas and estimated the development potential of utility-scale wind plants for New York.

Monitoring Site Selection for Wind Resource Evaluation in the Texas Panhandle Using a Geographic Information System, AEI (McCarty), 1994.[20] The wind resource of the Texas Panhandle, defined as all of Texas north of 34 degrees latitude, was examined using the raster-based GIS package IDRISI. Terrain enhancement procedures applied to the PNL wind map resulted in alteration of the wind power class of many areas. A screening based on slope, aspect and proximity to transmission (within 5 miles) identified that class 3 and greater windy lands comprising 37 percent of the Panhandle could produce 205 billion kWh of electricity annually (about 80% of Texas current statewide electric consumption.)

OVERVIEW

Average Annual Summary

The wind power maps developed by the Pacific Northwest Laboratory (PNL) serve as the basis for much of the wind resource assessment work that has been conducted for Texas and the rest of the nation. PNL wind power maps are provided for the contiguous United States and Texas in **Figure 5.2.** To be economically competitive for electricity production, commercial wind power plants require areas with class 3 or higher wind power. As indicated by Figure 5.2, the best wind power potential in Texas occurs in the Great Plains with class 3 and 4 winds, along the Texas coast from Galveston to the Mexican border with class 3 winds, and at site specific areas with class 5 and 6 winds in the mountains of the Trans-Pecos Region. In total, more than a third of the state has winds suitable for wind power production.

Because the estimates for the Trans-Pecos Region are almost all inferred from the terrain, there is much uncertainty associated with these estimates; good wind locations will be very site specific in these mountainous areas. In contrast, large areas of the Panhandle have good wind regimes. Along the Texas coast, the highest average annual wind speeds are expected from the mainland coast up to 30 to 60 km (20 to 40 miles) inland. Average wind power in this segment of the coast may be slightly greater than that observed along the coastal islands (such as Padre Island).

Using the data compiled by PNL, various estimates have been made of the Texas wind resource. The Pacific Northwest Laboratory estimated the land area available for wind energy development under various scenarios of land-use and environmental exclusions. For class 3 and above lands, PNL estimated the developable wind electric potential for Texas was 134,000 MW (4 quads/yr).[12] When restricted to class 4 and above lands, which are primarily in the Panhandle, the total was 28,000 MW (0.84 quads/yr)—still enough to supply 10% of the electrical needs of the entire nation.[12]

An early AEI report estimated the average capturable wind power for Texas at 250,000 MW, which corresponds to over 2 trillion kWh (7.5 quads) annually.[11] The Panhandle and adjacent areas had the highest potential estimated at 100,000 MW (3 quads/yr). These results were based on the analysis of data from 15 National Weather Service stations in Texas and 7 stations in neighboring states.[12]

The Alternative Energy Institute (AEI) had a wind speed monitoring project from May 1978 to December 1985.[7] Ten stations located over a 250,000 km^2 area measured wind speed at 10 m and 50 m heights, and later at 20 m and 50 m on existing radio towers. At some sites, values taken at 10 meters were low due to obstructions and buildings in the vicinity of the wind tower. Data were stored as histograms and collected generally on a monthly basis. Data were further divided into day and night histograms.

Power density (W/m^2) was calculated from the wind speed histograms using monthly average air pressure and temperature taken from the closest National Weather Service station. The results of this study (summarized in Table 5.2) determine a greater area of high wind power potential in the Texas Panhandle than is indicated in the *Wind Energy Resource Atlas of the U.S.* There is a region of peak wind power potential along a 450 kilometer

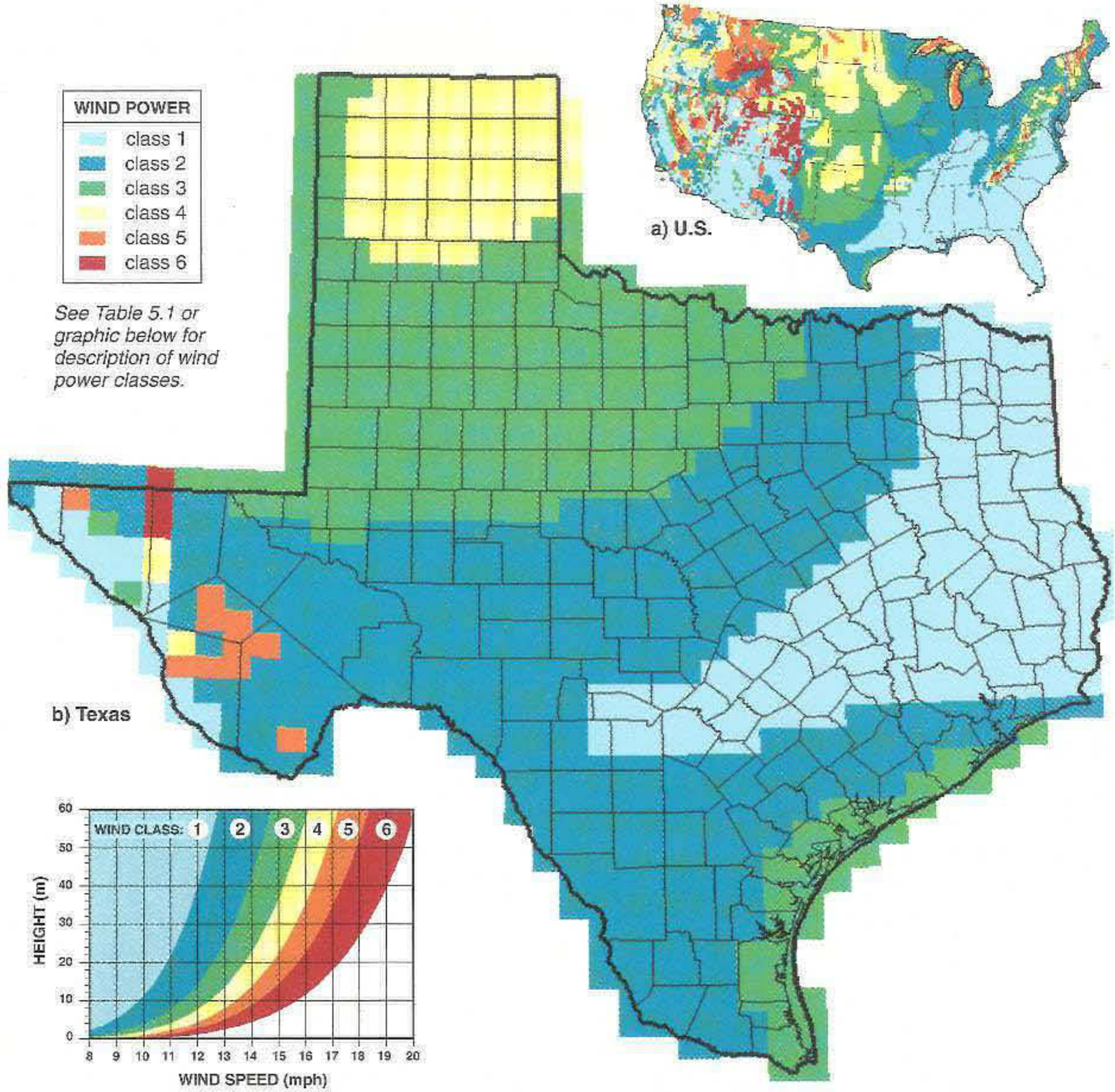

FIGURE 5.2. Wind Power Maps of Texas and the United States.[8] PNL's evaluation technique entailed discrete value assignments to each pixel of the map grid rendering a jagged appearance to (b) Texas after extraction from (a) the U.S. map. Wind speed ranges (in mph) corresponding to each wind power class are also shown as a function of height using the 1/7 power law.

long line from Lovington, NM, through Perryton, TX. At 50 meters above ground, average wind power density ranged from 358 to 450 W/m² along this line. Significantly, this is the only large area wind assessment in Texas that is based on actual, long-term measurements taken at the height of commercial wind turbines.

Importance of Wind Shear

Friction between the earth's surface and the air moving above it results in wind speeds that vary with height above the ground. The effect of increasing wind speed with height, referred to as wind shear, is affected by the local surface roughness of the ground. Smooth surfaces such as flat sandy beaches produce little friction and little wind shear. Areas with high surface roughness, such as a pine forest or urban areas with tall buildings, result in more friction and hence higher wind shear. Formulas such as a power law or logarithmic form (which includes surface roughness) are commonly used to estimate the change in wind speed with height. **Figure 5.3** illustrates a wind shear profile based on the power law with the widely-used exponent of 1/7 (0.14), which has been determined through experimental data to be representative of average wind conditions over open grassy fields. To simplify computations, many wind assessments, including the *Wind Energy Resource Atlas of the U.S.*, assume a 1/7 power law for all surface conditions.

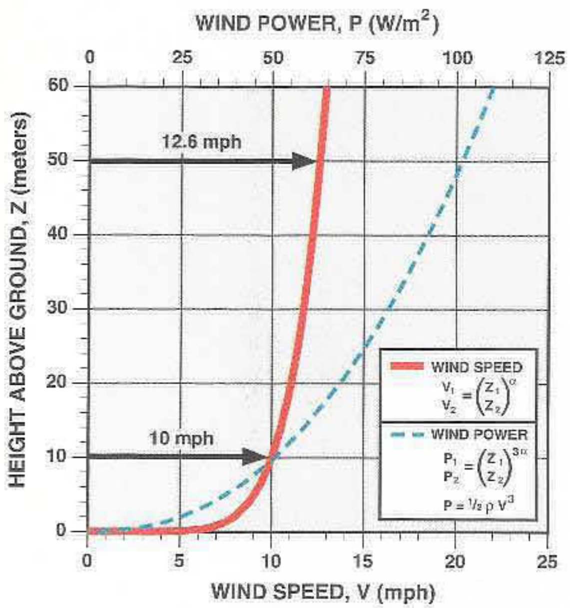

FIGURE 5.3. Typical Wind Shear Profile. The variation of wind speed with height is shown for the power law with exponent of 1/7 ($\alpha = 0.14$). Corresponding instantaneous wind power density is also shown (dashed). Real wind shear profiles can deviate significantly from this empirical relationship.

In the Northwest Texas Study, wind power potential measured at 50 m is larger than that predicted using the 1/7 power law and data measured at 10 m. Wind shear exponents ranged from 0.17-0.28, much higher than the 1/7 (0.14) that is commonly assumed. Also, the large diurnal variation observed at 10 meters height was not as evident at heights of 50 meters, especially during the summer. The Candidate Wind Turbine Site near Amarillo had similar results from 5 years of data, indicating that summer is the season of second highest wind power at 50 m due to high winds at night. In the Great Plains there seems to be a low level jet at night at 50 m that does not reach the 10 m level.

Because of such deviations, it is very important to measure wind data from 10 meters up to 40 to 50 meters to provide information at commercial wind turbine heights and also to determine wind shear so that lower elevation wind measurements can be meaningfully utilized. Long term data stations are needed in regions with good wind power potential to obtain 5 to 10 years of data. Time sequence data should be recorded to determine the diurnal and seasonal variation of wind and how it compares with electric demand.

Estimate of Wind Resource in Texas

An improved assessment of the wind power potential of Texas was achieved by applying GIS techniques similar to those employed in AEI's wind power study of the Texas Panhandle.[20] The general procedure, which involves applying terrain enhancement to revise the PNL wind potential maps (Figure 5.2), is described below.

The base map of elevation, **Figure 5.4**, was developed from the 3 arc second DEM data,[17] however, the number of data points were reduced by a factor of 100 to speed computation. Resulting pixel size is 760 m by 900 m. Estimates of energy production would change some if the resolution were increased to that of the original DEM data (90 m).

Since wind speed generally increases with height, even modest relief may increase the wind power dramatically. IDRISI was used to determine terrain exposure. Terrain exposure is determined by subtracting the average elevation (over a 15 km radius) from the actual elevation of each pixel. Resulting values ranging from a maximum of 1,246 meters to a minimum of -700 meters are plotted in the terrain exposure map (**Figure 5.5**). The different regions of Texas show quite clearly on this map: High Plains and Gulf Coast Plains, the mountains in the Trans-Pecos, and then the hills and valleys associated with Rolling Plains. High positive values indicate good terrain exposure that generally will translate to higher wind speeds than surrounding areas. For the entire state, 28% of the land would be considered sheltered terrain. In the High

Plains around 5% would be considered sheltered terrain and 8% would have very good exposure.

Using the exposure information and knowledge of surface roughness, wind power density can be re-calculated for each pixel of the PNL wind map. The following formula was used and is similar to the one used by the Union of Concerned Scientists.[18]

$$\frac{P}{P_{avg}} = \frac{\ln\left[\frac{H_h+E}{z_o}\right]}{\ln\left[\frac{H_h}{z_o}\right]}$$

Where P equals the corrected power density in W/m²; P_{avg} equals the average power density (from the PNL map, Figure 5.2b), H_h equals the hub height (50 m); E equals the terrain exposure in meters (from Figure 5.5), and z_o equals the roughness length in meters. Surface roughness was estimated from vegetation maps and varied from 0.03 meters for crop and range land to 1.0 meters for forests.

The re-computed wind power map resulting from this technique, presented as **Figure 5.6**, shows that some areas have been increased in wind class due to good terrain exposure (high positive values in Figure 5.5) while other areas decreased due to sheltered terrain. To more clearly discern the results, wind power is shown in Figure 5.6 as "half classes", i.e. there are 2 shades for every full wind power class. While this GIS technique is useful for adding resolution, it is still dependent on the quality and nature of the original wind information, in this case, the PNL wind map. Long-term data still need to be measured across the state to improve the quality of PNL's wind estimates, which in many areas are not based on any measured wind data.

IDRISI was used to estimate the area of each wind class. The area of land with class 3 and higher

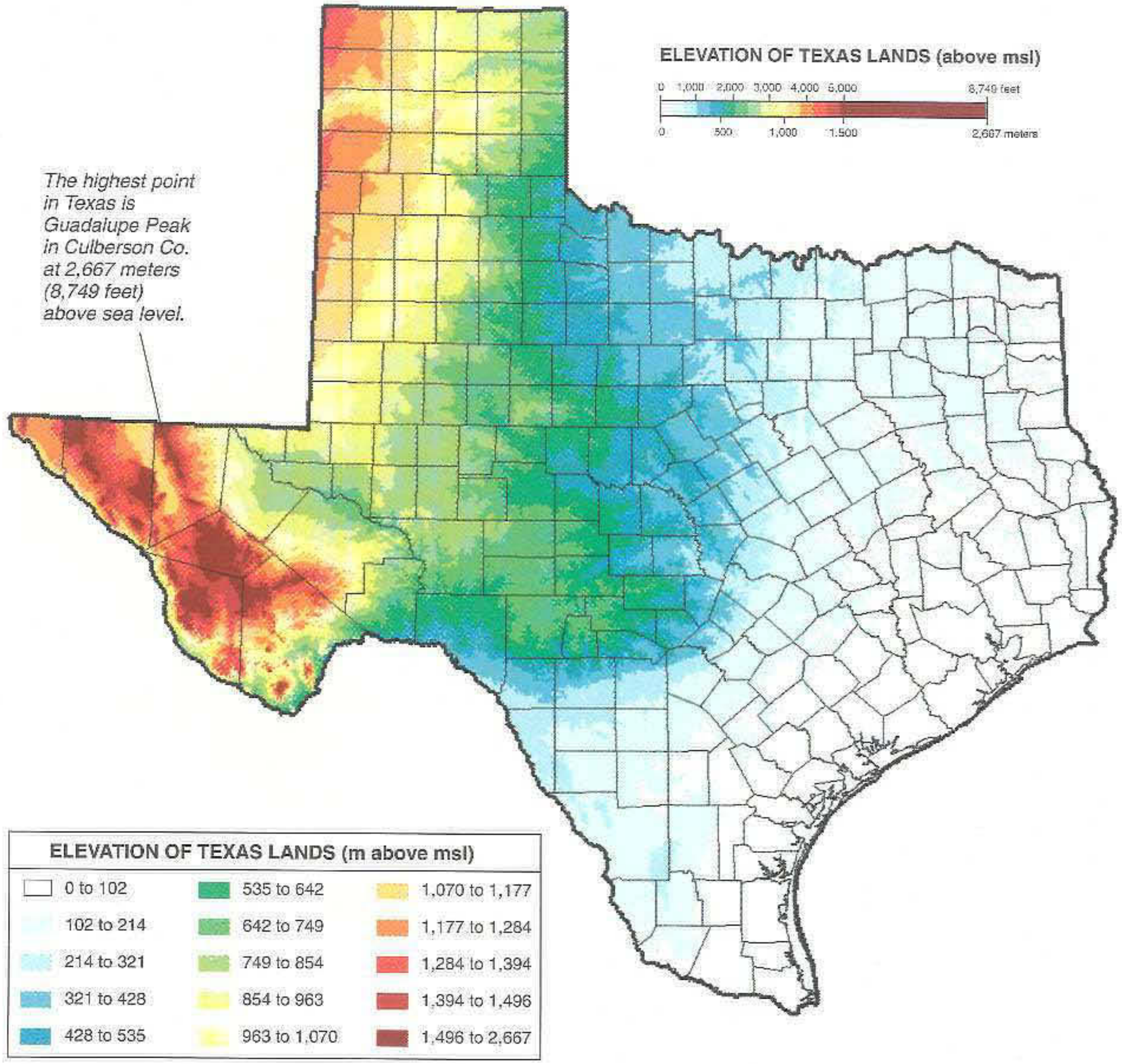

FIGURE 5.4. Elevation Map of Texas. Based on Digital Elevation Model (DEM) data. The legend provides the specific elevation ranges in meters above mean sea level (msl) corresponding to each color, while the color bar (top of page) provides a quick indicator of elevation in both feet and meters.

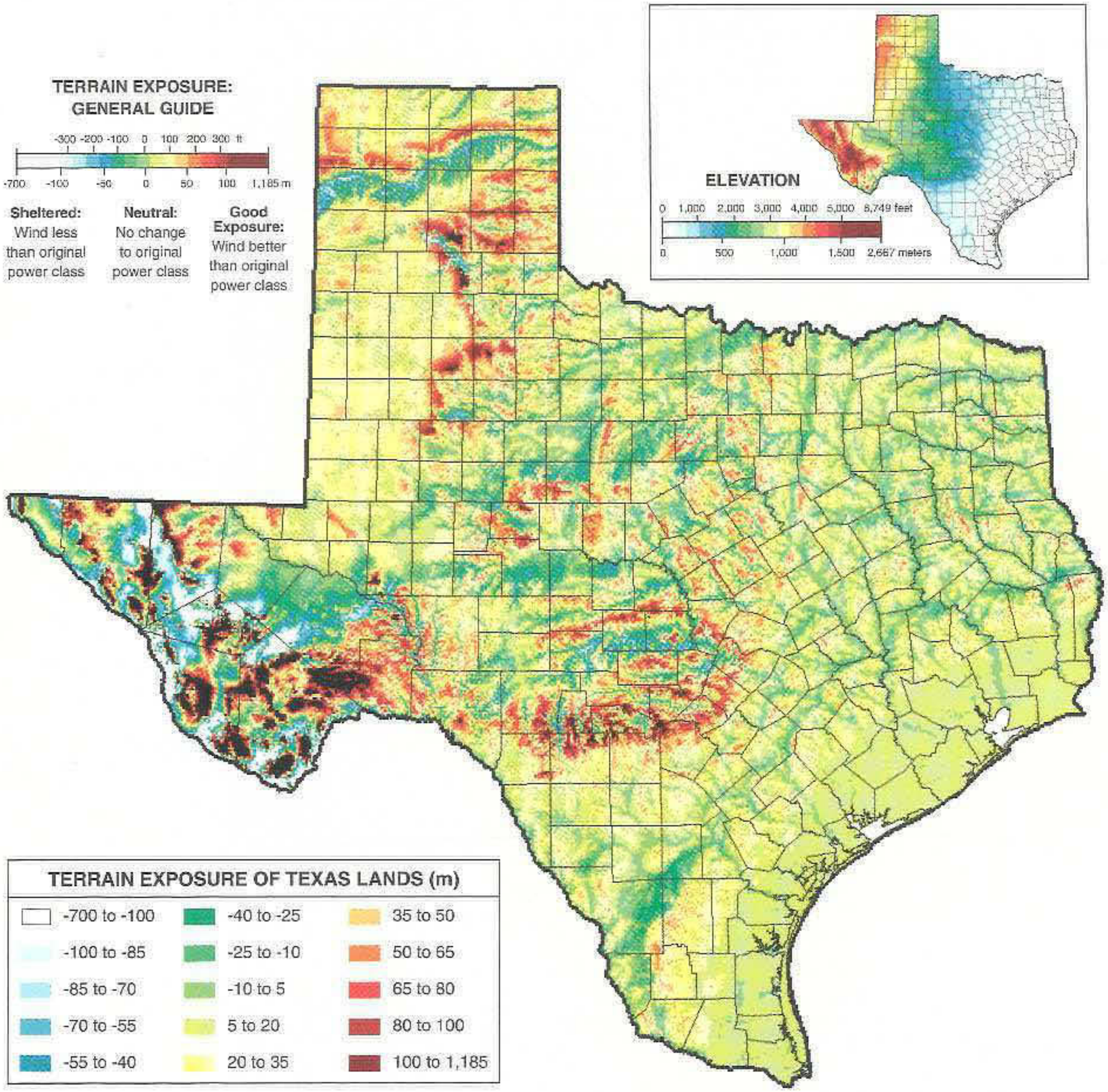

FIGURE 5.5. Exposure of Terrain to the Wind. Terrain exposure (defined in text) influences wind power reclassification as generally indicated in the guide above. Exposure was derived from the DEM-based elevation map (reproduced in the inset above).

wind power totals 250,000 km^2 in Texas. As noted earlier, Texas has an enormous wind resource. Yet not all of this land is suitable for wind power development, so IDRISI was further employed to calculate the capturable wind power.

Selection Criteria for Windy Land Using GIS. Slope is an important consideration in the location of a wind plant. Steeply sloped terrain can change the local wind flow, lead to an increase in undesirable turbulence, and inflate construction costs. Land with slope from 0-3 degrees was selected, resulting in the exclusion of about 5% of Texas.

Aspect describes the orientation of sloped lands. An aspect oriented toward the prevailing wind direction is desirable since the wind is increased over hills and ridges and even modest relief can affect wind flow. Aspect was not considered in this assessment, but it is a recommended screening criterion for smaller blocks of data.[20]

Construction of new 115 kV transmission lines typically cost about $200,000 to $400,000 per mile, depending on the terrain. Since electric transmission lines and substations are quite expensive, land adjacent to existing infrastructure is of higher value for wind plant development.

Texas land suitable for wind power development was determined using the criteria specified in **Table 5.3**. IDRISI selected lands satisfying these screening parameters by overlaying information layers for slope, excluded land, and transmission lines on the reclassified wind map (Figure 5.6). This procedure identified 72% of the class 3 and above lands in the state as being suitable for wind plants. The land areas meeting the screening criteria are shown graphically in **Figure 5.7** and total 178,400 km^2, or about one fourth of the total area of Texas.

TEXAS WIND POWER POTENTIAL				
WIND POWER CLASS	WIND CHARACTERISTICS 50 METERS ABOVE GROUND*			
	POWER (W/m2)	SPEED (mph)	COMMERCIAL VIABILITY	
1	1-	0 – 100	0 – 9.8	VERY POOR
	1+	100 – 200	9.8 – 12.5	
2	2-	200 – 250	12.5 – 13.5	POOR
	2+	250 – 300	13.5 – 14.3	
3	3-	300 – 350	14.3 – 15.0	MARGINAL
	3+	350 – 400	15.0 – 15.7	
4	4-	400 – 450	15.7 – 16.3	GOOD
	4+	450 – 500	16.3 – 16.8	
5	5-	500 – 550	16.8 – 17.4	VERY GOOD
	5+	550 – 600	17.4 – 17.9	
6	6-	600 – 700	17.9 – 18.8	EXCELLENT
	6+	700 – 800	18.8 – 19.7	

** Fifty meters (164 feet) is a common tower height for large wind turbines.*

FIGURE 5.6. Texas Wind Power Potential. The map (right) indicates the prevailing wind environment throughout Texas by wind power class as defined in the legend above.

TABLE 5.3. Selection Criteria for Computing Texas Wind Power Potential. Criteria used to generate Table 5.4.

SELECTION CRITERIA FOR GIS SCREENING
1. Wind class 3 or higher from revised wind map (Figure 5.6).
2. Slope of 0 to 3 degrees.
3. Excluded lands: urban, federal and state parks, lakes, wildlife refuges, federal wetlands.
4. Within 16 km (10 miles) of transmission lines (115 kV or above).

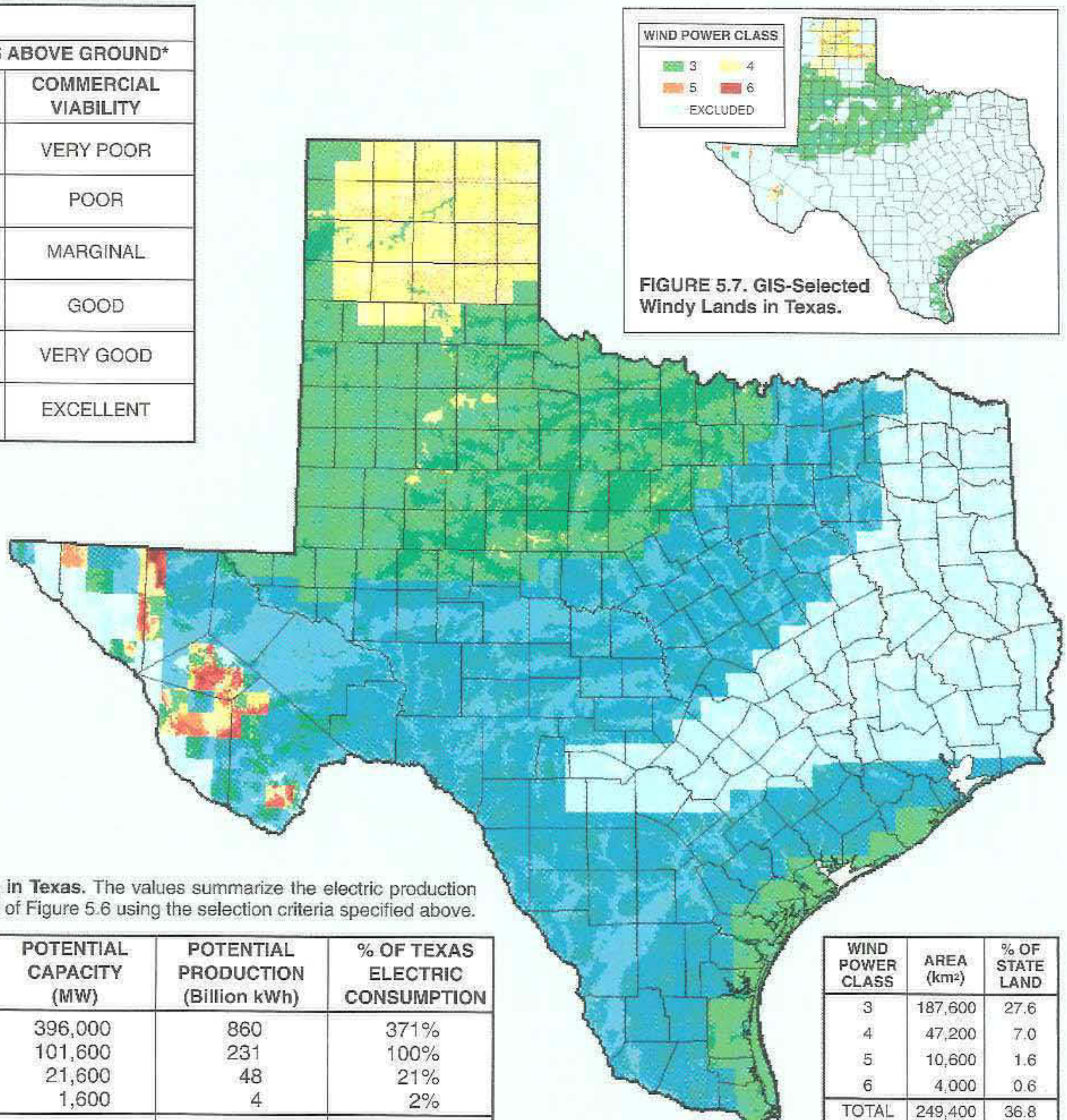

FIGURE 5.7. GIS-Selected Windy Lands in Texas.

WIND POWER CLASS	AREA (km2)	% OF STATE LAND
3	187,600	27.6
4	47,200	7.0
5	10,600	1.6
6	4,000	0.6
TOTAL	249,400	36.8

TABLE 5.4. Potential Electricity Production on Windy Lands in Texas. The values summarize the electric production potential of windy lands identified in Figure 5.7, which is a subset of Figure 5.6 using the selection criteria specified above.

WIND POWER CLASS	AREA (km2)	PERCENT OF STATE LAND	POTENTIAL CAPACITY (MW)	POTENTIAL PRODUCTION (Billion kWh)	% OF TEXAS ELECTRIC CONSUMPTION
3	143,400	21.13%	396,000	860	371%
4	29,700	4.38%	101,600	231	100%
5	5,000	0.74%	21,600	48	21%
6	300	0.04%	1,600	4	2%
Total	178,400	26.29%	524,800	1,143	493%

Quantification of Resource

The total power intercepted over a given land area is a function of the number of wind turbines, the rotor swept area, and the available power in the wind. If the cost of land is high, then spacing between turbines can be decreased, however the output from the wind plant may be reduced due to array effects of wind turbines impacting the wind available to adjacent turbines. In California, some wind plants have turbine spacing of two rotor diameters (2D) within the rows and 7D to the next row. With this spacing there are array losses.

The capturable annual average wind power for Texas summarized in **Table 5.4** was calculated for the following conditions: 50 meter hub height, 10D by 10D spacing, 25% efficiency, and essentially no array losses (reasonable since the spacing is large). Under these assumptions and with the selection criteria outlined in Table 5.3, the annual capturable wind power is 131,200 MW (525,000 MW of wind turbines at 25% capacity factor) with annual energy production of 1,143 billion kWh (4 quads/yr). This amount is nearly five times the 238 billion kWh of electricity energy consumed in Texas in 1990. These results agree very closely with the estimates determined by PNL.[12]

Of course the first wind plants will be sited on the windiest land. Wind development restricted to class 5 and 6 lands could still produce more than 20% of the state's current electric energy needs. Land is both physically and financially available in Texas in the class 5 and 6 categories. These lands, which are located in the Panhandle and the Trans-Pecos, represent less than 1% of the total land area in Texas (5,300 km^2). Furthermore, only 5 to 10% of this amount would be dedicated for use by the wind plant, leaving the rest for traditional uses.

TABLE 5.5. Average Monthly Wind Power Density (W/m^2). Derived from National Weather Service data.

LOCATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
ABILENE	170	186	241	222	190	150	106	86	103	130	158	156	157
AMARILLO	238	262	338	318	269	223	172	137	169	189	223	210	228
AUSTIN	129	137	145	113	85	68	51	47	64	68	98	115	93
BROWNSVILLE	152	187	243	243	202	156	146	131	108	100	145	152	164
CORPUS CHRISTI	197	251	286	285	206	152	152	150	156	138	200	198	197
EL PASO	56	68	116	104	73	49	36	29	28	28	42	48	56
FORT WORTH	162	186	218	195	145	110	84	67	92	108	150	150	139
HOUSTON	100	112	121	114	85	65	47	45	59	60	83	92	82
LUBBOCK	195	222	286	282	239	181	114	83	100	130	163	165	179
LUFKIN	58	67	72	65	47	33	26	27	35	37	50	57	48
MIDLAND	144	169	231	226	196	173	122	107	109	118	139	135	156
PORT ARTHUR	129	143	156	154	113	74	48	44	68	75	110	122	103
SAN ANGELO	135	149	207	174	137	114	82	70	80	97	120	118	123
SAN ANTONIO	91	100	112	100	89	82	70	59	67	68	79	81	83
VICTORIA	161	179	192	174	143	104	84	75	96	97	132	151	131
WACO	169	191	227	196	153	123	103	91	104	114	143	149	146
WICHITA FALLS	194	212	259	254	204	166	125	105	127	151	181	171	178

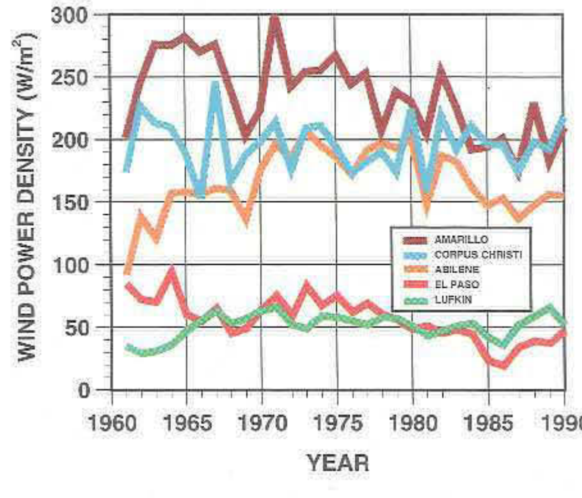

FIGURE 5.8. Annual Variability of Wind Power for Five Representative Texas Stations.

Resource Variability

The average annual, seasonal, and daily patterns of variability of wind power are presented based on data taken from CD-SAMSON[8] for Texas NWS stations and adjusted to a common height of 10 m. More detailed information on wind variability is readily available in sources previously described.[10]

Annual Variability

Annual variability in wind power is shown for select Texas stations in **Figure 5.8.** Over the 30 year period, most stations indicate extreme interannual fluctuations from average conditions on the order of 25-35%. Lufkin (high wind shear due to forests) and El Paso (sheltered terrain) indicate substantially lower wind power than the other sites. Some of the apparent variability likely stems from changes in the anemometer location and height (particularly in the case of El Paso).

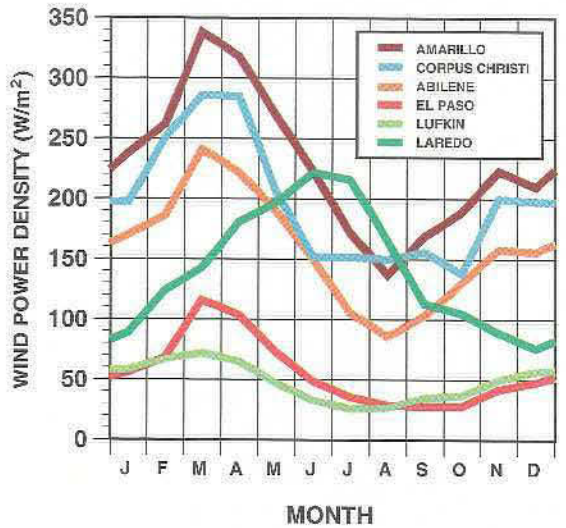

FIGURE 5.9. Average Monthly Patterns of Wind Power.

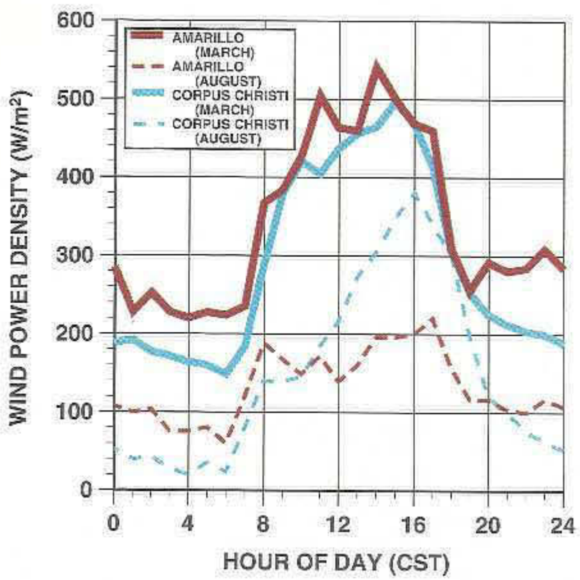

FIGURE 5.10. Average Daily Wind Power Profiles During Spring and Summer for Amarillo and Corpus Christi.

Seasonal/Monthly Variability

As illustrated in **Figure 5.9**, spring is the season of maximum wind power and July and August are the months of lowest wind power for most of the state. Laredo is quite different as it shows a peak in the summer with a value exceeding 200 W/m^2. **Table 5.5** summarizes the average monthly wind power density for all 17 Texas stations contained on the CD-SAMSON. As mentioned earlier, data at 50 meters will probably have less variability (stronger summer winds) than indicated by these exhibits.

Daily (Diurnal) Variability

Figure 5.10, which shows average wind power density profiles for Amarillo and Corpus Christi during March and August, indicates that the wind near the ground (measured at 7-10 m) tends to be much higher during the day than at night. Wind speed measurements at 50 meters in the Northern Plains, however, indicate that the winds continue at night.[7] For most of the state, as determined at Amarillo, the large diurnal variation at 10 m will generally be less pronounced at 50 m.

Wind Direction

Wind direction influences the design and performance of a wind power plant. If the wind almost always comes from the same direction (through a mountain pass for instance), turbines can be spaced close together. If the wind comes from many directions during the year, close spacing will result in major array losses. If the wind shifts regularly during the course of the day, some loss in performance will occur while turbines are tracking the wind.

The prevailing wind direction for most of Texas is out of the south (SE/S/SW). During winter

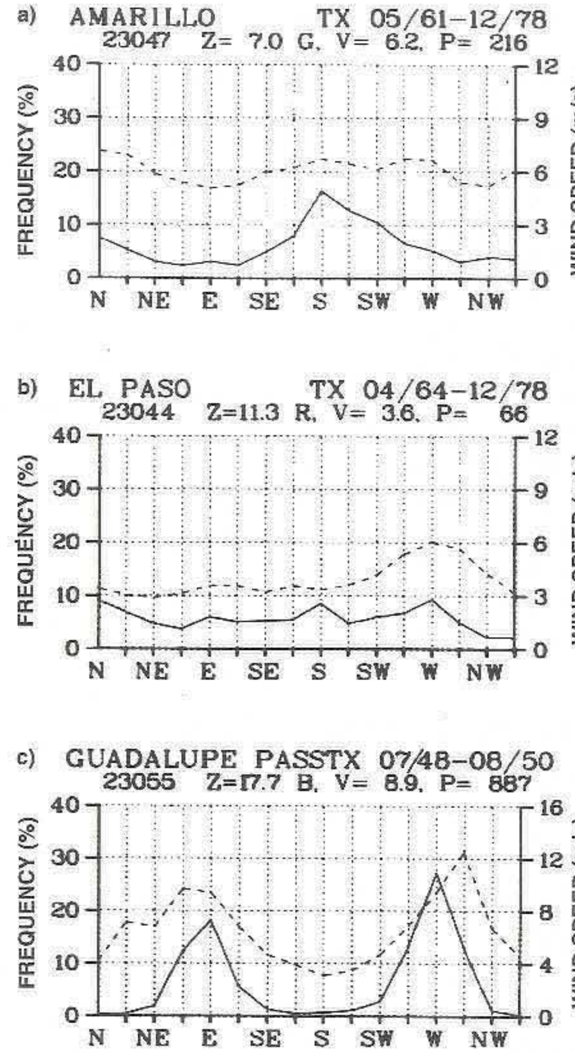

FIGURE 5.11. Wind Direction Plots for a) Amarillo, b) El Paso, and c) Guadalupe Pass (taken directly from the Wind Atlas[10]). Header information for each plot includes the period of record, anemometer height (z, in m), average speed (v, in m/s), and average power (p, in W/m^2). Wind direction frequency is shown as the solid line; corresponding average wind speed for each direction is shown as the dashed line.

"northers" result in a significant presence of winds from the north, particularly in the Plains. **Figure 5.11** summarizes the frequency of wind direction for several Texas locations. In Amarillo, the wind is seen to blow most frequently out of the south-southwest (during spring and summer) yet a significant component of north winds (mainly during the winter) is also evident. El Paso, which is sheltered, does not indicate a dominant wind direction. At Guadalupe Pass, the large mountains north and south of the pass force practically all air movement in either an east or west direction.

RECOMMENDATIONS

The PNL wind map (Figure 5.2) gives the general location of high wind areas in Texas. Wind is fairly site specific, however, so using GIS for wind resource screening will help to determine locations for measurements at possible locations of wind plants. The primary locations are the Panhandle, Gulf Coast, and specific areas of the Trans-Pecos. The revised wind class map (Figure 5.6) shows other locations, and GIS tools can be used for more location-specific wind prospecting and micrositing of wind turbines in these areas.

The objective of the Department of Energy's advanced wind turbine program is to develop turbines suitable for use in regions with class 4 winds. In time even class 3 areas will be feasible for wind energy production. With more than a third of the state experiencing class 3 or higher winds, there is a tremendous wind resource in Texas. The installation of wind plants here will depend primarily on economic and institutional factors, not on the resource base. One institutional factor of primary importance is legislation and regulation to support renewable energy by incentives and by recognition of the externalities of fossil fuels. Wind energy will play a major role in the Climate Change Action Plan. The DOE is looking primarily to wind for the emission reductions from renewables, since wind energy is the most economical source at this time.

With 7 state-funded benchmark stations and data from 3 stations contributed by Central and South West Services, Texas currently has the nucleus of a quality wind resource assessment program. **The State should ensure that the current wind monitoring network remains in place and operational so that a long-term record (5 to 10 years) can be established.** To flesh out remaining voids in the state network, additional reference stations should be added on well-exposed terrain near the following cities: Beaumont, Brownsville, Brownwood, Lubbock, Monahans, Nacogdoches, and Sonoro. **Also, the Texas wind resource map should be updated every year with data from the state wind monitoring network and other available sources.** When possible, proprietary data from the utilities and developers should be used to update the state wind resource map.

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ENERGY FROM BIOMASS

by Richard Faidley

INTRODUCTION

Significance of Resource: Historical and Future Uses

Energy from biomass (plant and animal matter) accounts for approximately 15% of global primary energy consumption.[1] At one time, of course, prior to the industrial revolution and the advent of the use of fossil fuels, biomass accounted for nearly all energy usage. The historical tendency has been for nations to move away from biomass as a fuel source as they advance economically. For example, in developing countries, energy from biomass presently accounts for about 38% of primary energy consumption, while in developed countries this figure stands at only 3%.[1] Because of this trend, biomass has suffered from a perception as a "poor man's fuel".

Furthermore, as Larson points out, "biomass provides a level of energy services that is disproportionately small compared to its contribution to the primary energy mix"[2] because it is used rather inefficiently. For example, the efficiency of conversion of coal to electricity in the U.S. stands at about 35%, while similar numbers for biomass conversion are only 14–18%.[3] While indicative of current practice, these values do not reflect technological barriers. Energy can be extracted from biomass and biofuels at efficiencies typical of fossil fuels with demonstrated technologies. Frequently, however, the biomass feedstock may not be present in sufficient concentration to exploit the economies of scale associated with better technologies, or, in the case of waste feedstocks, efficient energy recovery may play a secondary role to disposal. If anything, the numbers simply emphasize that through improved practices and upgraded technologies biomass can play a much larger role in energy services without significantly altering present production patterns.

As was mentioned in the fundamentals section, biomass is probably the most flexible of renewable energy resources in that it can be readily converted to a variety of fuels as well as used to make electricity. Different biomass feedstocks are appropriate inputs for different energy end products. The connections between feedstock, conversion process, and end product are displayed in **Table 6.1**, adapted from Jones[4]. Conversion processes are employed to make the biomass more useful—that is, to put it in a form that can be easily transported or stored or that can take advantage of specific combustion technologies like gas turbines or diesel engines. A brief discussion of the conversion processes listed in the table will help us understand how biomass is presently used or is likely to be used for energy.

Direct combustion. The most common way of using biomass for energy is to simply burn it. Any biomass—indeed any organic substrate—can be burned, but generally only dry materials lend themselves to direct combustion since otherwise a great deal of combustion energy is consumed in vaporizing water from the fuel. Biomass combustion practices vary widely, ranging from small-scale systems used for cooking or residential space heating to large-scale industrial boilers. The efficiency of these processes will be determined largely by the design of the combustion device. In underdeveloped countries, where cooking with biomass (usually dried animal dung or crop residues) is common, cookstoves are notoriously inefficient and frequently pose a health hazard due to smoke generation. At the other extreme are modern, fluidized-bed furnaces used to fire boilers.

It should be pointed out that direct combustion refers to burning the biomass itself as opposed to first converting it to another fuel. Ultimately, of course, all the fuels described below must be combusted to take advantage of them as an energy source.

Aerobic digestion. Aerobic decomposition is carried out to treat wastes and to make organic fertilizers. Low-grade heat is evolved when micro-organisms decompose biomass into simpler components. Backyard composting is a familiar example of the process. It is also widely used in the treatment of municipal sewage and animal manures. Wet substrates are required, and water may have to be added to some feedstocks, such as straw. In some systems, temperature rises of 50°C can occur,[5] but rarely is the heat captured for other uses.

TABLE 6.1. Biomass Products, Conversion Processes, and Feedstocks.

	PRODUCT	CONVERSION PROCESS	TYPICAL FEEDSTOCK CHARACTERISTICS	COMMON SAMPLE FEEDSTOCK	COMMERCIAL STATUS*
HEAT	High-grade heat	Direct combustion	Dry, ligno-cellulosic	Wood, wood residues	A
HEAT	Low-grade heat	Aerobic decomposition	Wet, ligno-cellulosic	Manure, crop residues	C
GASEOUS	Biogas	Anaerobic digestion	Wet, ligno-cellulosic, or wet waste	Manure, sewage, landfills	A
GASEOUS	Syngas, Producer gas	Thermochemical gasification	Dry, ligno-cellulosic	Wood, grasses	B
LIQUID	Biocrude	Pyrolysis	Dry, ligno-cellulosic	Wood	B
LIQUID	Methanol	Syngas conversion	Dry, ligno-cellulosic	Wood	B
LIQUID	Ethanol	Fermentation	High sugar content	Sugar cane, sweet sorghum	A
LIQUID	Ethanol	+ Weak hydrolysis	Starchy	Feed grains (corn, sorghum)	A
LIQUID	Ethanol	+ Strong hydrolysis	Cellulosic	Waste paper, crop residues	B
LIQUID	Biodiesel	Oil extraction, esterification	High fat or oil content	Oilseed crops, animal tallows	B
SOLID	Charcoal	Pyrolysis	Dry, ligno-cellulosic	Wood	A

**A = Commercialized processes and products. B = Pilot level process demonstrations or infant industry. C = Research level only or limited commercial interest.*

Anaerobic digestion. Bacteria that can break down biomass in the absence of oxygen are referred to as anaerobic. They occur naturally on the bottoms of bogs and swamps. The decomposition itself is commonly called digestion because of the similarity with processes that occur in the digestive tracts of ruminant animals. Since the digesting bacteria are normally active in warm, wet conditions, wet wastes such as manure, sewage, and certain industrial wastes and crop residues are the most common feedstocks for digestors. Millions of small-scale digesters are functioning throughout the world, mainly in India and China where they are used to break down the animal and human wastes of households or villages. Large-scale units used at livestock operations or sewage treatment plants are found in industrialized countries; the City of Austin, for example, operates an anaerobic digester at its sludge treatment facility.

The gas generated as a product of the decomposition is termed biogas. A well-known example of biogas is the landfill gas evolved naturally from municipal dumps. Biogas is roughly equal parts of carbon dioxide and methane, but also includes small amounts of hydrogen sulfide and other trace gases. It is the methane that is captured and burned in energy recovery applications that include electricity generation. The exact biogas makeup varies depending on the composition of the feedstock and completeness of the reaction. Reaction rates are heavily influenced by digester temperature, which dictates the type of bacteria used to breakdown the biomass. Effluent from a digester contains undigestible solids, and dissolved minerals and nitrogen, the last of which makes it valuable as a fertilizer. Several sources offer good reviews of the process.[2,6]

Pyrolysis and gasification. When biomass is heated at relatively high temperatures and in the absence of air, the volatile components vaporize. This process is called pyrolysis, or sometimes, destructive distillation. Dry, ligno-cellulosic feedstocks such as wood are the normal inputs for the reaction. The products of pyrolysis can be solid residues (char and ash), liquids (condensed tars and oils), or a variety of gases.

If the goal is to retrieve the solids, then the pyrolytic reaction is an end in itself; liquids and gases are not recovered and the remaining uncombusted char is made up of about 75-85% carbon.[7] When wood is the feedstock, char is simply charcoal; coal char is called coke. Liquid pyrolysis oils, sometimes called "biocrude," can be condensed from the vapors of pyrolyzed biomass. These include tars like pitch and creosote, and a mixture of other liquids, primarily acetic acid. The reactor type, operating parameters, and feedstock source will greatly influence condensate characteristics. Biocrude can be burned directly as a fuel or used as a refining feedstock much like crude petroleum.

If the goal is to maximize the gaseous output for later combustion, pyrolysis is the first stage of an overall gasification process. The final reaction, called char conversion, entails the burning of some of the solid char. This provides heat to gasify the remaining char and to sustain the pyrolysis of fresh fuel. The gaseous product is known as "syngas" or sometimes "producer gas." Ash is the only solid left after gasification. The composition of the gas can vary widely, but will typically consist of about 25% carbon monoxide, 10% hydrogen and small amounts of other constituents. The remainder, as much as 70%, is inert gases, carbon dioxide and nitrogen. After cleanup, the hot syngas can be burned immediately in a combustor or gas turbine that is close to the gasifier, or it can be cooled, removing any condensed tars and oils, and piped for distribution. A catalytic reaction can be used to convert syngas into methanol. See Twidell and Weir for more details of pyrolysis and gasification.[7]

Gasification is not a new concept and is not limited to biomass. The first coal gas was produced over 200 years ago. This was the so-called "town gas" used in local distribution systems in the U.S. and Europe to provide heating and street lighting from the mid-19th to early 20th centuries. After the second World War, natural gas displaced town gas as the fuel of choice when extensive pipelines and distribution systems were constructed.[2]

Gasified fuels are often classified according to their energy content as low-, medium-, or high-Joule (Btu), with corresponding energy values of about 5MJ/m^3, 12 MJ/m^3, and 25 MJ/m^3.[8] The fraction of inert gas in the fuel greatly impacts this value. Natural gas, in contrast, has an energy value of about 37 MJ/m^3.

Gasification technology is important to future biomass utilization mainly because it will allow biomass combustion to take advantage of gas turbine technology. Integrated gasification/gas turbine systems should greatly improve biomass combustion efficiencies and allow utilization of some of the high alkali plant feedstocks inappropriate for direct combustion. To date, several pilot-scale systems have been demonstrated.

Fermentation. Under proper conditions, certain yeasts are able to act upon sugars to naturally produce ethanol, C_2H_5OH. The process, called fermentation, is the same one used to produce alcoholic beverages. The fermented product is normally distilled to eliminate water and raise the alcohol content to about 95%. The resulting fuel ethanol has, in the United States, traditionally been blended with gasoline at about a 10% fraction; in other places, notably Brazil, ethanol is commonly used as a neat fuel (unblended).

Feedstock composition is an important issue in ethanol production. Any carbohydrate can be used to make it, but ferments can only act upon simple sugars—mono or disaccharides. The more complex polysaccharides—starches, hemi-cellulose, and cellulose—must first be broken down in a process called hydrolysis. Aqueous solutions of acids or enzymes are used to break these materials into their simple constituents. Starches require a relatively weak hydrolysis to be broken apart, while cellulosic materials require stronger treatment. Also, the lignin that encrusts cellulose in cell walls tends to inhibit hydrolysis.

Presently, all ethanol production in the U.S. (about 1 billion gallons in 1992) is made from starch in the form of surplus feed grains—mostly corn and some grain sorghum. It is probable that in order for ethanol to acquire a substantial fraction of the transportation fuel market, production will have to take advantage of cellulosic feedstocks. These materials are lower in cost and much more abundant than storage starches. Recent research and development at government labs have resulted in processes that may make ethanol derived from cellulose a near-term reality. Several private companies are working on commercial-level production of ethanol from agricultural residues and waste paper.

Extraction. Exudates in the form of oils and hydrocarbons can be extracted from some plants and animals and used with little further processing as liquid fuels. Chief among these are storage lipids, the fats and oils of plants and animals. Extraction of plant oils consists of pressing and dissolving oils from oilseed crops—soybeans, cottonseed, peanuts, sunflower, rapeseed, etc.—or from seeds of trees, palm and coconut, for example. Extraction of animal fats refers to the rendering process by which fats are separated from other tissues.

These products are the familiar lards and oils used in cooking. They can be burned directly in a diesel engine, but will foul engine parts and coke injectors.[9] For this reason, the fats are dissolved in alcohol (methanol or ethanol) in the presence of a catalyst to yield esters of the original fatty acids. The product, called biodiesel, can be blended with petroleum-based diesels in any fraction and with no engine modifications. A valuable co-product of the reaction, glycerin, has a number of industrial applications.

Complex hydrocarbons found in certain other plants can also be extracted for use as a fuel or an industrial chemical. These exudates belong to a class of chemicals known as terpenoids. Pine resin is a well-known example of a lightweight terpenoid while latex tapped from tropical rubber trees is an example of a heavier terpenoid. Tapping, pressing, and removal with solvents are common methods of terpenoid extraction. Terpenoids possess a high energy content, but historically have been used as industrial chemicals rather than as fuel.[10]

Finally, in comparing the various forms of biomass and biofuels to their fossil fuel counterparts, it is instructive to look at the energy densities of these potential fuels. **Figure 6.1** shows the gravimetric energy density of a variety of fuels ranging from raw plant matter to pure methane gas. Biomass energy densities were based on dry matter weights. A lower energy density means that more material must be burned to release the same amount of heat—and in turn, that more material must be transported and stored to achieve the same level of energy service. The high energy densities of many fossil fuels is one reason our economy has evolved around them.

Development Issues: Special Considerations for Large-scale Use

As with other renewables, many arguments favor the expansion of energy production from biomass. Certain issues could, however, slow the pathway to development. Most evolve from the fact that, as detailed in Chapter 2, growing biomass is a land-intensive form of energy production. Large-scale development could entail major changes in land-use patterns and concomitant impacts that may be difficult to predict. These impacts are largely determined by the base state of the land selected for biomass production. For example, destruction of a native forest to develop an energy plantation has much graver environmental implications than the institution of the same plantation on degraded or denuded forest lands. The nature of these impacts is diverse, but all may be said to fall under the rubric of sustainability, or more precisely, the burgeoning fields of sustainable agriculture and forestry. A few will be introduced here.

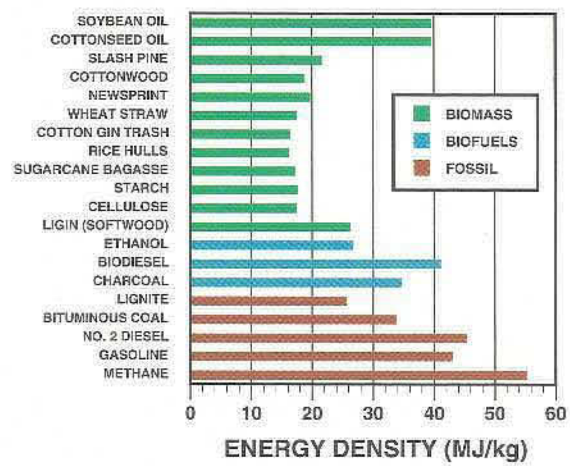


FIGURE 6.1. Energy Densities (Higher Heating Values) of Some Common Biomass Feedstocks, Biofuels, and Fossil Fuels. Note that gaseous fuels, such as methane, while exhibiting very high gravimetric energy densities, will compare poorly on a volumetric basis.

Effects on soil erosion. On any given soil, the establishment of perennial grasses or trees will always have benefits with respect to erosion over a similar establishment of annual crops. Likewise, established perennials require relatively low-input management practices. For these reasons, perennial crops—both herbaceous and woody species—have been targeted for dedicated energy crop production by the Department of Energy (DOE). Perennial energy crop production may yield positive benefits with respect to soil erosion, particularly if established on croplands that are presently eroded or have a high potential for erosion.

Besides dedicated energy crops, the proposed collection and utilization of harvest residues could also impact soil erosion, although in a negative manner. Residues offer protection to otherwise exposed soils from the impacts of raindrops and act like a mulch to retain moisture, thereby mitigating the erosive potential of winds. However, in many regions crop productivity is great enough to safely allow the removal of considerable residues. Soil scientists can predict the amount of residue that should be left behind to guard against soil loss with surprising accuracy. Although these comments are geared toward agricultural residues, similar statements hold for logging residues left behind after forest harvests.

Effects on soil nutrients. In addition to erosion, removal of harvest residues may have adverse impacts with respect to soil nutrients. When they are decomposed by reducer species, residues have great value in replenishing nutrients. This is true regardless of whether the residue is forest slash, wheat stubble, or yard clippings. As with the impact on soil erosion, however, residues can be sustainably removed at rates that do not degrade soil quality. This statement is particularly true of modern, developed world agriculture in which a sizable portion of nutrients are supplied externally as fertilizers.

A positive, overlooked role for dedicated energy crop production lies in the removal of nutrients from nutrient-saturated regions. These would be principally livestock or dairy cattle production areas in which the long-term, large-scale import of feed grains has resulted in soils saturated with phosphorous and potassium, since these nutrients pass through the animal unused and are left on the land in the form of manure. A dual-use perennial grass could provide some forage while at the same time fixing nutrients for export out of the region as a fuel feedstock.

Air-quality effects. As a somewhat gross generalization, it may be stated that emissions from burning biomass are generally lower both in degree and in toxicity than their fossil fuel counterparts. Indeed, biofuels are often blended with fossil fuels precisely because they afford some enhancement in air quality. Biomass burning generates no net carbon dioxide emissions since carbon released in combustion is fixed during plant growth. However, the picture of the carbon-cycle is considerably more complex than this statement suggests. Tilling earth volatilizes carbon that is trapped in the soil. Some researchers have looked towards fallowing lands as an effective carbon sequestration method.[11] The point here is simply that placing new lands under the plow impacts carbon levels; low-impact perennial production may still be consistent with soil carbon sequestration.

Effects on biodiversity. Managed ecosystems offer significantly less diversity in plant and animal species than natural ones. The history of the westward expansion and settlement of the United States is also the history of the extirpation of many animal species from previously expansive ranges and the replacement of unbroken and enormously complex forests and prairies in favor of the familiar patchwork quilt of farms that produce a very few, economically important species. From a biodiversity perspective, the dedicated growth of biomass for fuel is similar to other agricultural practices in that it will rely on standard monocultural production techniques. Cook offers a good review of this complex topic[12] and points out that conversion, as is widely suggested, of idled lands to energy crop production is a negative impact as these lands may support a diverse range of plant and animal species. Nonetheless, production of perennial energy crops on these lands is preferable to their returning to other crops requiring more intensive management.

Land availability. Clearly, sustainable, large-scale biomass development is dependent upon the availability of large amounts of land that possesses at least some agronomic potential. The Texas resource will be detailed later, but it is worthwhile to note that nationally, major grain yields have increased dramatically since World War II, and according to the USDA, this trend will continue: model results suggest that 2030 yields may be twice those of 1982.[13] The same assessment projects a possible 130 million acres (52 million ha) of cropland (nearly 37% of the projected available, or an area equivalent to about 75% of the size of Texas) not needed for food production. The high productivity of the American agricultural sector is the producer's own worst enemy, leading to chronically depressed prices and large government subsidies. Farmers and forest owners would welcome new outlets for their products, as would government officials keen on lowering budget deficits.

Some Comments on the Term "Biomass"

In ecological circles, the word "biomass" retains a fairly precise meaning: as defined in the glossary, it is the dry mass of living organisms within a particular region at a particular time, and will be expressed in units of mass per unit area or sometimes mass of carbon per unit area. Phytomass is plant biomass, and zoomass is animal biomass. The vast majority of global biomass is phytomass, averaging about 10-12 kg/m^2 globally, while total zoomass is around 0.1 kg/m^2.[14]

In the energy community, biomass is used less rigorously, referring generally to any material, excluding fossil fuels, that was or is a living organism and can potentially be used as fuel.[15] This includes a variety of wastes from industrial and agricultural practices as well as living plants. A fair measure of imprecision follows actual usage. Sometimes agronomists may speak of a plant's biomass when referring to the bulk of its ligno-cellulosic structure as opposed to the grains or fruits that presently have value as food and feed.

For completeness, the Energy Security Act(PL 96-294) of 1980 defines biomass as any organic matter that is available on a renewable basis, including agricultural crops and agricultural wastes and residues, wood and wood wastes and residues, animal wastes, municipal wastes, and aquatic plants.

SURVEY

Fundamental Data Collection

Natural Resource Surveys

A number of ongoing survey instruments that are critical to the evaluation of our nation's natural resources form the backbone of information from which biomass related studies can be performed. These are summarized below.

National Cooperative Soil Survey (NCSS). The Soil Conservation Service (SCS) of the United States Department of Agriculture (USDA) began surveying soils throughout the country in the 1930's in response to concerns about erosion losses and sustainability of agricultural practices. Today soil scientists, using a combination of aerial and field observations, maintain an extensive data base of more than 25 soil attributes for each of over 18,000 recognized soil series in the United States. This includes information such as soil chemistry, particle size distribution, water retaining capability, salinity, water table, subsidence characteristics, erosion potential, and land management.[16] County surveys are continually being revised and republished, with agricultural areas reviewed more frequently than forest or range lands. Most Texas surveys have been updated in the last 20 years.

National Resources Inventory (NRI). Also prepared by the SCS, the NRI is carried out every 5 years in accordance with the Rural Development Act of 1972. The purpose of the NRI is to provide support for developing policies and programs affecting agriculture and the environment. For example, information from the NRI was extensively used in formulating the Farm Bills of 1985 and 1990, and in assessing potential impacts of the Conservation Reserve Program (CRP). The inventory process consists of gathering information at sites throughout the United States referred to as primary sample units (PSUs). Each PSU is an area of about 160 acres. In the latest (1992) inventory, there were 21,990 PSU's in Texas and over 250,000 nationwide.[17] Within each PSU, conditions are assessed at 3 points. A combination of field visits and remote sensing are used to evaluate resource parameters. The data collected varies slightly from inventory to inventory to reflect current concerns. The 1992 data can be categorized as follows: soil characteristics, earth cover, land cover and use, erosion, land treatment, vegetative conditions, conservation treatment needs, potential for cropland conversion, extent of urban land, habitat diversity, and cover maintained under the CRP.

Because many of the same sample sites are used in inventories of different years, the NRI is useful not just as a snapshot of conditions in the year of the inventory, but also as a trending tool. However, unlike the NCSS, NRI sampling is not dense enough to be statistically reliable at the county level. Results should be interpreted only at regional levels—such as SCS-defined Major Land Resource Areas (MLRA's)—or at state levels.

U. S. Forest Service forest inventories. The U. S. Forest Service (USFS), part of the USDA, conducts periodic, multi-resource inventories of major forested regions of the United States. Originally authorized in the late 1920's, forest surveys are now carried out principally under the Forest and Rangeland Renewable Resources Planning Act of 1974. Forty-three forested counties of East Texas are included in the Forest Service's Southern Region. Surveys in the Southern region rotate on roughly a seven year basis. The most recent survey for East Texas was completed in 1992. The survey comprised three components: a review of aerial photographs to classify lands as forested or nonforested, an adjustment to these estimates based on ground observations, and finally, field measurements of tree variables at 2056 forested sample plots.[18] Like the NRI, statistics are valid at the state or survey region level, but county-level inferences may not be reliable.

Meteorological networks. All climatic variables have some bearing on plant productivity, but temperature and availability of water and sunshine predominate. The various networks of the National Weather Service (NWS) and other government agencies that record this information have been discussed in Chapters 3 and 4 of this document and will not be discussed here. In general, it may be stated that very good historical and spatial records exist for precipitation and temperature (or growing season) through NWS weather stations and the cooperative users weather network. However, the resolution and record of solar radiation data is comparatively poor.

Remote Sensing Activities

Over the last twenty years, remote sensing has become an increasingly powerful and popular method for examining climate, land cover, and land use. Coupled with strides in computational speed, it has afforded researchers and policy analysts the ability to quickly discriminate major land use patterns on a gross scale, with the trade-off being a loss of detail relative to ground observations. With time, interpretative models verified in the field have become more sophisticated.

Remote sensing technology is either airborne or spaceborne. The methodology may be passive, relying on radiation reflected from the earth's surface, or may employ an active system in which the sensing instrument also supplies the illumination source (radar, for example).

Remote sensing activities are myriad. Most of the fundamental surveys already mentioned rely on remote sensing in some measure. The following discussion covers activities or surveys of most interest to agriculture and ecology. Wickland[19] gives a comprehensive review of this topic.

Satellites. **Table 6.2** summarizes major ongoing satellite sensing efforts. The most widely used instruments to survey detailed land cover are the Landsat Thematic Mapper (TM) and the French SPOT. AVHRR (Advanced Very High Resolution Radiometer) scanners are used more commonly to evaluate weather patterns and gross regional land characteristics due to poorer spatial resolution.

For spaceborne sensing, a distinct division of labor exists: responsibilities for fundamental data collection are generally severed from data interpretation, which may be carried out at hundreds of government agencies and universities around the world.

Aerial surveys. Aerial photography has been used since the earliest days of aviation to give humans a "bird's eye view" of their world. Soil surveys have relied on it for years, and aerial maps or photographs of major urban areas are available from aerial photography services or local tax appraisal districts. Two airborne surveys of interest to Texans are the USGS Land-Use/Land Cover map and USDA remote sensing activities.

The United States Geological Survey (USGS) has developed a data base of land use and land cover that divides all lands in the conterminous United States into 8 major areas as well as many minor ones.[20] The 9 major zones are: wetlands, forested lands, agricultural lands, urban lands, rangeland, barren land, tundra, perennial snow or ice, and water. Examples of minor classifications would be, for agricultural lands, pasture, cropland, feeding operations, etc. The data base was developed from aerial photographs taken from approximately 1975-1983, and has not been updated. It is the most highly resolved land cover information available, and hence is still widely used.

The USDA's remote sensing research unit located at the Sub-tropical Agricultural Research Laboratory of the Agricultural Research Service (ARS) in Weslaco, Texas, carries out aerial photography and aerial videography as part of a broader remote sensing mission. This effort involves the incorporation of remote sensing, geographic information systems, and global positioning systems with mathematical models to evaluate and predict the behavior of agricultural ecosystems.[21]

Surveys of Commercial Activity

Many commercial activities that produce biomass or biomass derived wastes are inventoried by government agencies or trade associations. It should be pointed out that for most of these surveys, data is known in more detail than is reported. Government agencies are bound to aggregate information in such a way that competitively relevant data is not disclosed. Often this means that county-level information is not published.

Some of the principal data gathering organizations and their efforts are described below. This

TABLE 6.2. Spaceborne Remote Sensing Activities of Interest to the Ecological and Agricultural Communities.

SATELLITE NAME	SPONSORING AGENCY	PERIOD ON RECORD	RESOLUTION	
			SPATIAL	TEMPORAL
Landsat MSS	NASA	1972-present	80m	N/A
Landsat TM	NASA	1982-present	30m	16 days
AVHRR	NOAA	1981-present	1100m	12 hrs.
SPOT	French government	1986-present	20m	6 days

summary undoubtedly does not capture all survey efforts of interest to the biomass community; the USDA alone has over 500 independent primary data collection efforts, most of which are not publicly available and in any case are not relevant to the present discussion. All primary data collection carried out by the federal government must be approved by the Office of Management and Budget which produces topically arranged monthly inventories of data collection efforts that can be consulted for more detail.

USDA: National Agricultural Statistic Service/ Texas Agricultural Statistics Service (NASS/TASS). The NASS is an agency of the USDA. Information collected by each state branch is compiled into the NASS database. (In Texas, the TASS is cooperatively funded by the USDA and the Texas Department of Agriculture (TDA)). Primary information is collected by surveys of individual producers—farmers and ranchers. In Texas, annual mail-in surveys of up to 40,000 producers yield information accurate to the county level. Smaller summer phone surveys of current harvest information influence commodity markets. Typical collected data includes acreage planted and harvested, irrigation practices, yields, and average market prices. In addition to about 15 major annual crops, orchard output (essentially pecans and citrus in Texas) and livestock, poultry, and dairy production are surveyed.

U.S Department of Commerce, Bureau of the Census. The Bureau of the Census of the U.S. Department of Commerce conducts censuses periodically to examine a wide variety of information and trends. Two that are relevant to biomass are the Census of Agriculture and the Economic Census, both now taken every five years (like the NRI, in years ending in 2 or 7). The agriculture census, first taken in 1840, is carried out by polling farmers about their practices and profits in the previous year. It has more of a commercial perspective to it than the production figures compiled by the NASS and aims at 100% participation. Fundamental definitions of things such as farms, woodlands, or rangeland are not necessarily identical between the two agencies. Typical census information includes number of farms, land in farms, irrigation, agricultural chemicals used, value of farm products, crop production, labor statistics, and operator characteristics. Census information is usually aggregated at the county level.

The Economic Census is really a series of seven censuses. One of these, the Census of Manufactures, covers a number of agricultural processing ventures and forest products industries that bear significance for biomass. Besides the periodic censuses, the Census Bureau continually canvasses certain commercial activities for inter-census publications. Again, information is aggregated at a level that does not disclose proprietary information—typically a state or census bureau region.

The Bureau of the Census also gathers fundamental population and demographic information in the familiar ten-year census taken in years ending in 0. Population numbers are of interest to biomass researchers since oftentimes the amount and distribution of certain wastes is simply scaled from population figures.

Texas Forest Service. The Texas Forest Service performs an annual canvass of primary mills of the East Texas timber industry. Primary mills are those such as sawmills, plywood mills, and pulp mills, that process the raw logs rather than secondary operations such as furniture manufacturers. The survey reviews harvest volume, timber products output, and harvest value. Harvest information is aggregated at the county level.

Texas Natural Resources Conservation Commission (TNRCC). The TNRCC maintains data on certain wastestreams as part of its charge to safeguard the state's air and water. Landfills, for example, are surveyed annually to determine waste intake, changes in capacity, and other operating parameters. Waste to energy facilities and other waste recovery or processing centers are also canvassed. Likewise, discharge of sewage effluent and sludge disposal or transport are monitored by the commission.

Trade associations. Certain trade groups such as the National Bioenergy Industry Association or the American Forest Products Association maintain energy related statistics about their industry that may interest biomass researchers.

Field Trials

The use of test plots to scientifically evaluate crop performance has been well established in this country since the establishment of land-grant colleges via the Morrill Act in 1862. The entry of the DOE into this arena is much more recent, but in the last 10 years field trials of woody and herbaceous species have contributed much to our knowledge of their potential as energy crops. In Texas, switchgrass field trials have been carried out since 1992 at six locations, summarized in **Figure 6.2.** Results will be discussed in the overview section that follows.

Information Sources

Survey Data Bases

All of the major survey instruments discussed above generate electronic data bases or summary documents. In fact, both the USDA and Census Bureau generate such a bewildering array of publications, disks, CDs, and electronic files that any attempt to summarize it would be quickly eclipsed by new product announcements. Much smaller but equally useful data bases such as those collected by the Texas Forest Service are generally summarized in a single document. The interested reader is advised to contact the appropriate agency directly; contact information is provided in an appendix to this report.

Research and Educational Organizations

Figure 6.2 is an attempt to summarize the various state and regional institutions of importance to the biomass/natural resources community. Several organizations on the map not previously mentioned for a role in primary data collection may nonetheless be significant contributors to resource assessment efforts and are described below.

The Texas Agricultural Experiment Station (TAES) —Texas A&M University. The agricultural experiment station system was established in 1887 under the Hatch Act to be the primary agricultural research arm of the recently formed land-grant colleges and universities. Today, the TAES and the parent Texas A&M University conduct a broad spectrum of research activities encompassing areas such as food health and safety, agro-environmental impacts, crop productivity and management, and biotechnology. Of particular interest to biomass resource assessment are crop modeling capabilities. Two models, EPIC (Erosion Productivity Impact Calculator) and SWAT (Soil and Water Assessment Tool), developed by the TAES' Blackland Research Center and co-located USDA-ARS facility in Temple, simulate crop yields and long-term environmental impacts of agricultural practices. EPIC is a detailed field-level model while SWAT allows broader assessments of crop performance and impacts at a regional level. Both models have seen extensive use and verification.

The DOE Regional Biomass Energy Program—Western Regional Program. In 1983, the Department of Energy established the regional biomass energy program to tailor biomass energy development to regional resources. Texas lies in the Western Region, which comprises the following states: Texas, Oklahoma, Kansas, Nebraska, South Dakota, North Dakota, New Mexico, Colorado, Wyoming, Arizona, Utah, Nevada, and California. WRBEP (Western Regional Biomass Energy Program) has sponsored a number of biomass resource studies including statewide inventories and industry-specific assessments. Four that cover Texas resources are studies of agricultural wastes and paper residues, cotton gin trash utilization, manure resources, and waste to energy conversion. A comprehensive publication list is available from WRBEP. Periodic newsletters and bulletins are also available.

A comparable program in the southeastern U.S., SRBEP (Southeastern Regional Biomass Energy Program), has performed studies of timber resources that are pertinent to East Texas. Other SRBEP publications and newsletters may likewise be of interest.

Other Summary Documents

Ultimately, the biomass resource is about plant production—about which plants grow where, how much they yield, and what residues are left. The sciences of agronomy and forestry comprise an almost inexhaustible stream of literature. An extensive literature search was conducted in major agricultural and engineering databases to identify

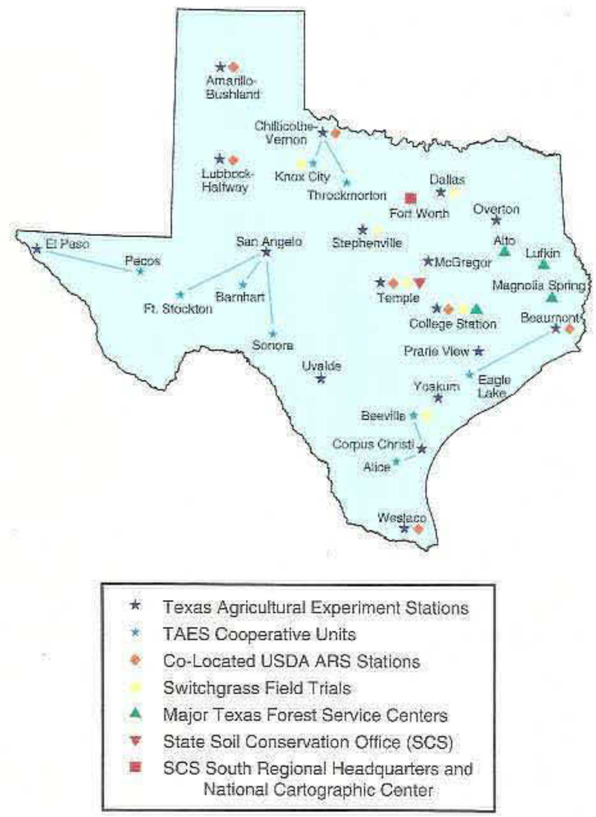


FIGURE 6.2. Texas Biomass Research and Information Centers.

studies pertinent to the Texas biomass resource, which, undoubtedly, did not capture many worthy documents. The search strategy and the bibliography generated from it are included in a separate appendix to this report. The bibliography comprises 348 references.

OVERVIEW

ANNUAL AVERAGE SUMMARY

LAND RESOURCES

As has already been mentioned, biomass development is land intensive. It is appropriate then, in a review of biomass resources, to review the land resource and its availability.

In ecological terms, Texas is truly a state in transition. Precipitation varies from over 50 inches per year along the Sabine River valley to under 10 inches per year in the Trans-Pecos. As a result of this variation in climate and also owing to its enormity, Texas has perhaps the most diverse ecology of any mainland state, ranging from sub-tropical savannahs along the Gulf coast to the arid Chihuahuan desert in the west. The Soil Conservation Service aggregates regions by similarities in soil, climate, water resources, land use, and farming patterns. Using these definitions, Texas has more Land Resource Regions (LRRs) and Major Land Resource Areas (MLRAs) than any other state except Alaska.[22] From the perspective of the biomass developer (and reviewer), this diversity represents both challenge and opportunity.

Several different types of maps are useful when examining the state's land resources. The first, **Figure 6.3**, identifies ten major ecological regions of Texas. Drawn from MLRA definitions and vegetative cover information[23], this map describes areas of broadly similar physical characteristics in the state. Reference will be made to the specific map regions throughout the remainder of this chapter. The figure also gives descriptions of the major vegetation and land use of each region in the map.

ECOLOGICAL REGION	MAJOR VEGETATION TYPES OR LAND COVER *In approximate order of coverage*
East Texas Forests	Pine or pine/hardwood forests
Gulf Coast Prairies and Marshes	Crops, grassland, and marsh
Post Oak Savannah	Post oak woods/forest, grasslands
Blackland Prairie	Cropland, native or introduced grasses
South Texas Plains	Mesquite rangeland, crops
Edwards Plateau	Live oak, juniper, and mesquite woods/parks, mesquite/juniper brush
Central Prairie and Cross Timbers	Grasslands, oak/juniper woods, crops
Rolling Plains	Mesquite range or grasslands, crops
High Plains	Croplands, mesquite or shortgrass range
Trans-Pecos	Shortgrass range, desert shrub

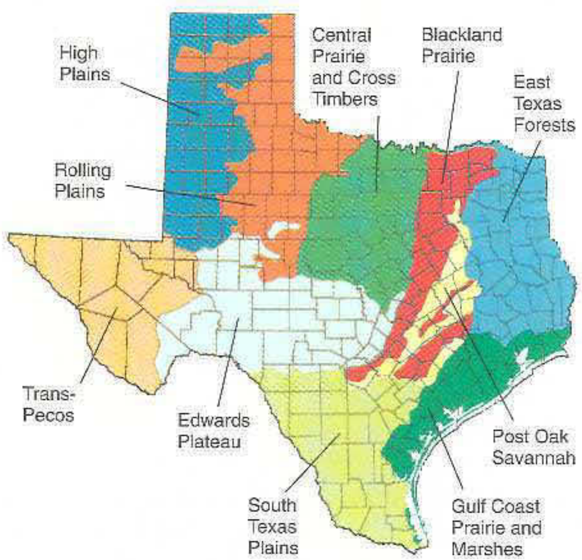


FIGURE 6.3. Ecological Regions of Texas. The areas identified here are regions of broadly similar physiography and vegetative cover.

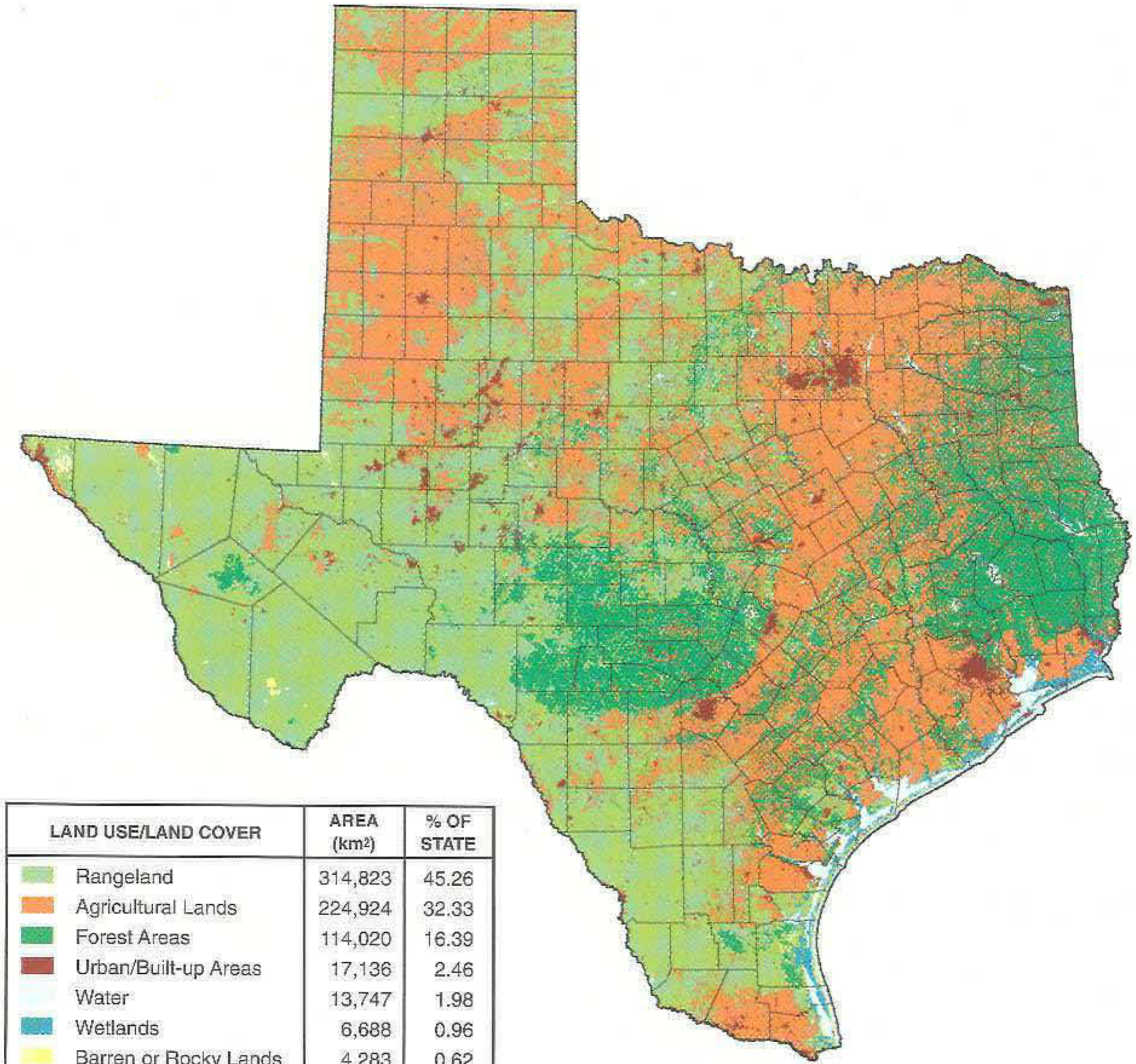
Another descriptive tool is the USGS land use/land cover map. As discussed previously, this map offers primary and secondary interpretations of how land is used and what cover is on it, regardless of the region it is in. **Figure 6.4** shows the state by major land use/land cover categories: agriculture, rangeland, forested lands, barren or rocky lands (including beaches and strip mines), wetlands, urban areas, and water. For the purposes of this map, agricultural areas include row crops, idled farmland, and pastures as distinct from rangeland. The major agricultural belts in the High Plains and Blackland and Gulf Coast Prairies, the forests of East Texas, and rangeland in the Trans-Pecos and South Texas are all evident in Figure 6.4. Total area of each type is tabulated with the figure. These definitions were used as inputs to a biomass production model that will be described later.

Land quality is one of the primary determinants in how land is used and what its economic value is. For example, farmland with rich soil that drains easily is clearly worth more than rangeland or other farmland that requires intensive culture for the same production. Land quality is important to the discussion of biomass production for energy because it is widely assumed that such production will take place on lower quality or even degraded lands. One measure of land quality is mapped in

Figure 6.5, the distribution of prime farmland in Texas. Prime farmland is a soil interpretation developed by the SCS that takes into account many factors that combine to make the land ideal for growing crops. Factors such as soil quality, growing season, moisture supply, and susceptibility to erosion are incorporated into the designation.[24] Figure 6.5, developed from the STATSGO soil survey database, shows the percentage of lands that are classified as "prime" within a particular region. Expanded definitions of prime lands that incorporate management practices—for example, "prime, if irrigated", or "prime, if properly drained"—have also been developed by the SCS, but Figure 6.5 relies upon the strictest definition as it is assumed that energy crops will not warrant intensive inputs.

A final measure of the state's land resource is its availability. Lands presently enrolled in the Conservation Reserve Program (CRP) have been frequently mentioned as candidates for energy crop production. Established via the Food Security Act of 1985, the CRP pays farmers in exchange for retiring cropland for a period of ten years. Land eligibility requirements have varied slightly from one sign-up period to the next, 12 of which have been carried out since 1986. In general, however, the main program objective has been the reduction of soil erosion on highly erodible lands, with a host of secondary goals that have included items such as reducing sedimentation, improving water quality, curbing surplus commodity production, and providing farm income support.[25] Since 1990, the CRP has been coupled with the protection of wetlands.

Texas has more CRP lands than any other state, approximately 4.15 million acres (1.65 million ha) as of the latest (1993) sign-up. Figure 6.6 shows



LAND USE/LAND COVER	AREA (km^2)	% OF STATE
Rangeland	314,823	45.26
Agricultural Lands	224,924	32.33
Forest Areas	114,020	16.39
Urban/Built-up Areas	17,136	2.46
Water	13,747	1.98
Wetlands	6,688	0.96
Barren or Rocky Lands	4,283	0.62
TOTAL	695,624	100.00

FIGURE 6.4. USGS Land Use/Land Cover. As identified by aerial survey, the map shows seven distinct categories of land use or cover and the percentage of the state in each one.

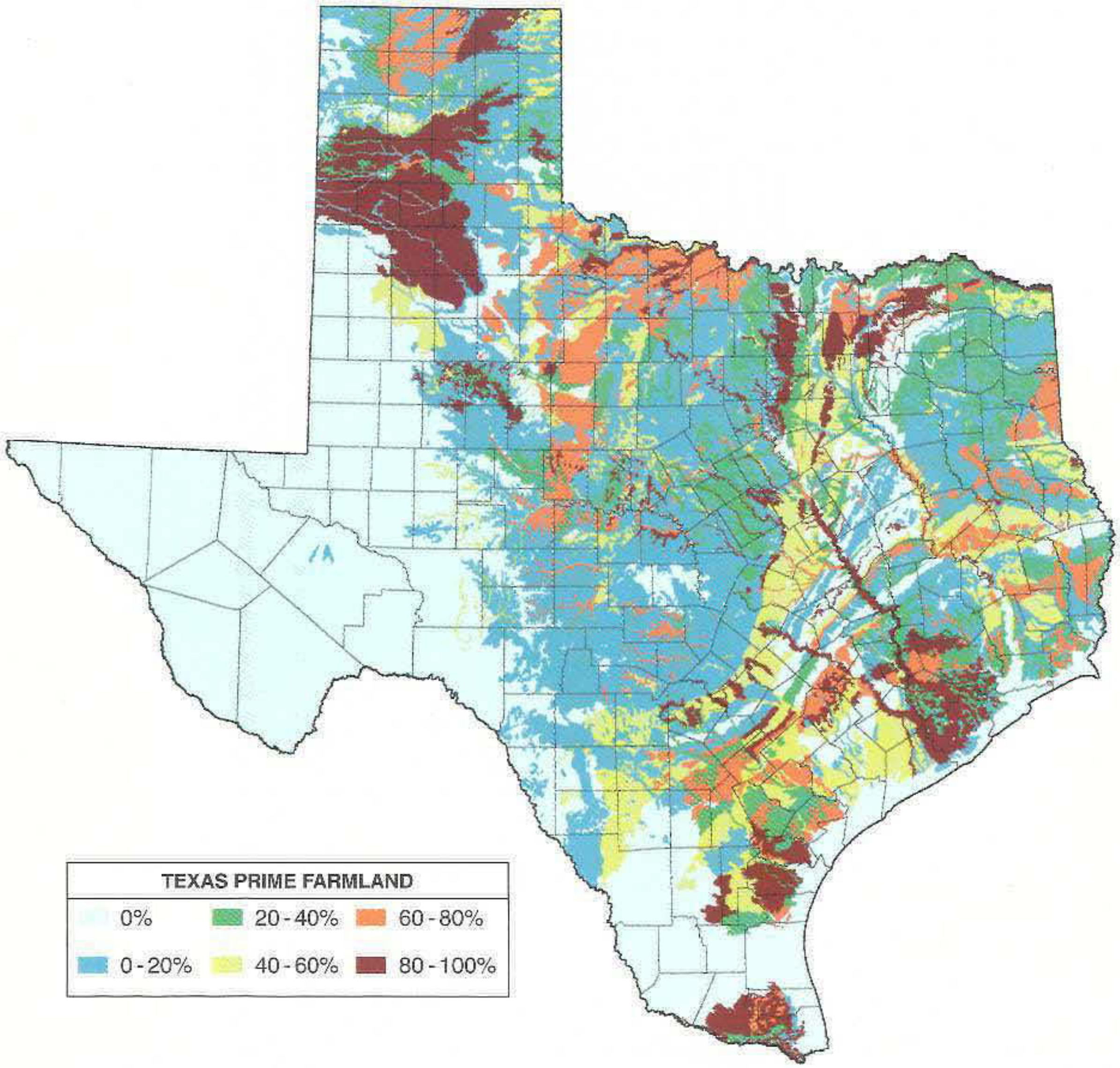


FIGURE 6.5. Texas Prime Farmland. Prime farmland, a soil grouping developed by the SCS, designates land "that has the best combination of physical and chemical characteristics for producing...crops." The map shows the percent of land within particular mapping units that are designated as prime and hence displays a gradation of land quality from poor to excellent.

CRP acreage for the top ten states and the distribution of Texas lands by county. Texas' highest concentrations of CRP enrollment have been in the High Plains region of the panhandle. A few counties in this region have over 20% of the entire county set aside (program limits set an upper bound of 25%). Susceptibility of these lands to wind erosion is the one of the main reasons for such high enrollments. The first lands to come out the program—and potentially back into production—will be in 1996.

The marginal character of lands enrolled in the CRP is made clearer by comparing Figures 6.5 and 6.6. Prime farmland in the Blackland and Gulf Coast prairies are not enrolled in the program and prime lands in the panhandle are enrolled at lower levels than other, poorer lands in this region. Texas' position atop the CRP heap is therefore a rather dubious honor. From the standpoint of energy crop production, however, it suggests that there are sizable excess lands of at least some agronomic potential available for future development.

BIOMASS RESOURCES

There are many ways to taxonomize biomass energy sources, such as by production sector or end-fuel type. In the discussion that follows, we will broadly group the biomass resource into functional categories based on the plant material of interest, since this will often dictate or even limit how the resource can be converted and used. Different economic groupings—dedicated production in energy crops versus production from surpluses, co-products and wastes—will then be discussed within each broad category. The distinction between a dedicated energy crop and other crops is sometimes fuzzy, since even fuel crops will generally have some non-fuel uses. We use the phrase in reference to any crop presently grown or likely to be grown foremost for its energy content. The purpose for this commonly used distinction is that the economics of biomass utilization are dramatically different for the two categories. We make no attempt in the present study to quantify this difference, but only recognize its importance to future biomass energy development.

Without immersing ourselves in biochemistry, it will be useful to first describe the major categories of plant or animal matter that are of most interest to bioenergy development. They are: non-structural carbohydrates (starches and sugars), lignocellulose, and lipids (fats and oils).

Lignocellulose, a fibrous plant tissue, is far and away the most common living matter on the planet. It forms the cell walls of the major structural components of plants, the stems and stalks of crops and the trunks and limbs of trees. Lignocellulose comprises three components: lignin, cellulose, and hemicellulose. Cellulose and hemicellulose are carbohydrates; that is, they are built up of simpler sugar units. In cellulose, these sugars (glucose) are linked in a very regular, linear manner. Cotton fibers are an example of almost pure cellulose. In hemicellulose, the pattern is more random and in fact, the term actually refers to any structural carbohydrate that is not cellulose. In any case, these carbohydrates can be broken down (hydrolyzed) into simple sugars, while lignin, a complex, three-dimensional hydrocarbon, cannot. Also, the energy density of lignin is higher than the carbohydrates. Hence, the lignin fraction of lignocellulose is significant. In wood, it stands at about 22 to 29%,[26] while for crop stalks and grasses it is much lower, about 7 to 11% (dry basis).[27] This difference is what makes trees much stiffer than grasses.

The water content of lignocellulosic feedstocks can vary dramatically and impacts how the material is likely to be used. Hence, in the discussion that follows, we will separate the sources into dry and wet categories. This somewhat imperfect delineation will be made at moisture contents of about 70%.

Although the great bulk of plant matter is composed of lignocellulose, it would be wrong to suggest that this is the only component that can economically be used as fuel. Many plants store energy in reserves such as sugars and starches (non-structural carbohydrates or NSCs) or oils (storage lipids). Since humans cannot digest fibrous, cellulosic tissues, centuries of effort have been invested in cultivating and breeding plants to increase yields of digestible reserves. Genetic manipulation has now joined traditional breeding techniques in earnest to further advance plant productivity. These two classes of plant material, storage lipids (fats and oils) and non-structural carbohydrates (sugar and starch) will therefore be covered in addition to lignocellulose. Both of these materials are presently being used as biofuels.

Sources of Sugars and Starches (Non-Structural Carbohydrates)

for fermentative conversion to ethanol

Dedicated Energy Crops

In Brazil, over half of all sugarcane production is dedicated to the making of ethanol—a total of 12 billion liters (3.2 billion gal.) in 1989, with the heat evolved from burning bagasse used for both distillation and electricity generation.[28] This has not been the model for development in the U.S., where the 4.6 billion liters (1.2 billion gal.) consumed in

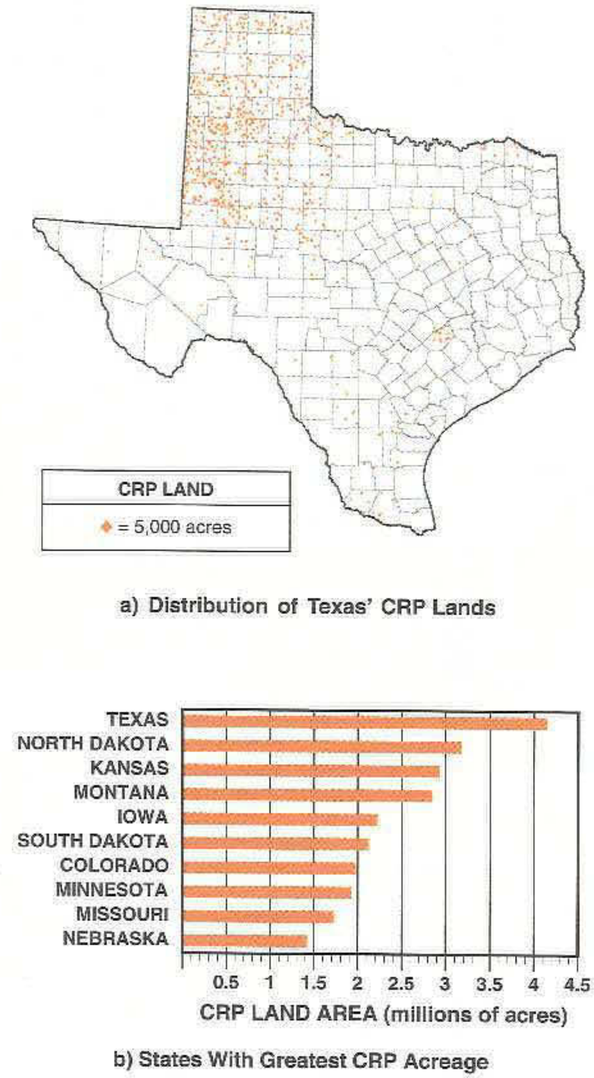


FIGURE 6.6. Lands Enrolled in the Conservation Reserve Program. (a) Distribution of lands in the state with each dot representing 5,000 acres, and (b) ranking of the top ten states. All data are taken through the 12th signup (1993). Position of dots within counties is random.

1990[29] (slightly less than 1% of the energy consumed in gasoline[30]) were fermented exclusively from surplus grain feedstocks. These starch crops (mainly corn) are clearly not dedicated to energy production. By one estimate,[31] about one third of the cost of present ethanol production is recouped in the value of non-energy co-products—corn oil and gluten meal, for example. Actual fractions fluctuate widely with grain prices.

One sugar and starch crop widely cultivated in Texas is frequently cited for its potential energy yield: sorghum.[32,33] Sorghum (*Sorghum bicolor*) possesses several qualities that recommend it for production as an energy crop. Among the most important of these is the great variety within the sorghum genus (over 30,000 distinct cultivars in present collections) and its responsiveness to genetic improvement demonstrated over the last 40 years of hybrid production.[34] As a C_4 crop originating in northeast Africa, it is an efficient light user and biomass producer, and has proven productive in both the tropics and dry, hot temperate regions of the world. The crop appears to be especially well-adapted to Texas, the nation's leading grain sorghum producer, and is grown in all major agricultural regions of the state. Johnson grass (*Sorghum halepense*) is an example of a pernicious form of the genus that unfortunately also grows well throughout the state.

Domesticated sorghums are divided into three types: grain, forage, and sweet. Sweet varieties, used to make syrups and molasses, have generated the most interest from the biomass energy community. In sweet sorghums, the plant partitions its energy and about 70% of its dry weight into a stem that possesses a sugary pith like sugarcane, as opposed to grain sorghums which may deposit as much as 60% of dry weight in panicles (grain heads).[35] As a result, sweet sorghums can grow very tall, upwards of 3 m (10 ft.). Extensive research on the energy yield of sweet sorghums has been conducted at Texas A&M by Miller, McBee, and others. They demonstrated ethanol yields of sweet varieties of about 3400 l/ha (360 gal./ac.), based on NSCs only.[36] More recently, sweet sorghum demonstrations conducted in California as part of that state's Industrial Crops Demonstration Program showed almost identical potential ethanol yields.[37] This is higher than an average yield from corn of 2500 l/ha (270 gal./ac.) (based on ethanol yields of 440 l/Mg (110 gal./ton) and Texas corn yields of 105.4 bu./ac. (5.6 Mg/ha)), but less than the average 1989 Brazilian sugar cane yield of 5200 l/ha (560 gal./ac.).[28] Earlier research suggested, however, that high energy sorghums grown in Texas that are hybrids of grain and sweet varieties may demonstrate yields of 5000 l/ha (540 gal./ac.) if grain starches are also converted; yields of this magnitude have been reported from Brazilian sorghums.[35]

As a dedicated energy crop, temperate climate sorghums possess the disadvantage of being an annual and thereby requiring energy inputs typical of present agricultural practice. According to Miller, sweet sorghums can be cultivated in any part of the state that grain sorghums presently are, with the caveat that, due to their greater height, lodging (collapsing of the plant) may become a problem in the presence of high winds or intense thunderstorms.[38]

As a point of reference, to displace 10 % of Texas' 1992 gasoline consumption (a typical gasohol blend) would require 4.6 billion liters (1.2 billion gal.) of ethanol, and, in turn, 1.3 million ha (3.3 million acres) of sweet sorghum at demonstrated yields. This amounts to about 72% of land harvested in grain sorghum for the same year, or about 2% of total state land. As with sugar cane, sweet sorghum bagasse (cellulosic stalk residue left after pressing) burned or otherwise converted would contribute significantly to the overall energy production from the process.

A starchy root crop native to the Southwestern U.S. that has been explored as a potential energy source is the buffalo gourd (*Cucurbita foetidissima*). This root fuel is being examined as a cleaner burning alternative to the wood and coal presently used for winter heating in the Navajo Nation.[39] Test plots in New Mexico have demonstrated high yields and low water requirements which, coupled with the gourd's starchy character, make it an interesting candidate ethanol feedstock. In Texas, the plant is native to the High Plains and other high range areas in the western reaches of the state.[40]

Surplus, Co-product and Waste Sources

Nationally, expanded production of ethanol from surplus commodity grains or sugar crops is presently unlikely due to production economics and investor uncertainty about tax incentives. Nonetheless, it is worth mentioning that Texas, in spite of not being considered a part of the corn belt, is a significant producer of the feedstocks presently employed in fuel ethanol production. Starch fractions of corn and grain sorghum are nearly the same at around 72% of the grain.[27] **Figure 6.7** shows the top twenty states in production of corn and sorghum, where Texas ranks eighth.

Fuel ethanol is presently not blended in Texas. It is interesting, however, to note the similarities of feed grain production between Texas and Kansas. Production of corn and sorghum in Kansas mirrors Texas numbers almost identically (Figure 6.7). There, four facilities annually make about 30 million gallons (110 million l.) of fuel ethanol from both feed grains, about 2.5% of national production.[41]

Food staples such as wheat and rice also possess high fractions of NSCs, but they are not presently used for fuel ethanol and hence were not included in Figure 6.7. Some of these grains are, however, fermented into beverage alcohols. Likewise, sugar sources such as sugar cane and sugar beets were excluded from Figure 6.7 for the same reason. Texas sugar production is minor compared to other states and not likely to expand due to climatic limitations. Production of sugar cane, for example, is limited to the southernmost parts of the state and is presently grown in three counties, Cameron, Hidalgo, and Willacy. Sugar beets are grown in a smattering of counties in the central High Plains that probably represent the southernmost extent of this cool weather crop.

Sugar Wastes. There are several potential waste sources of sugars. The beverage industry produces sugary effluents suitable as fermentation feedstocks. In southern California, Parallel Products, Inc. collects about 250,000 kg daily of fermentable wastes from the region's major breweries, bottlers, and food and drink distributors.[42] Most is spilled or lost fluids from brewers and bottlers; a smaller fraction is dated case goods and sugar-rich foodstuffs such as syrups or marshmallows. Fruit processing industries are another potential source for such an operation, but their relative efficiency at handling wastes in-house has limited their use in the California operation. The company is paid for the disposal service at a discount to local sewerage rates, and generates about 9 million liters of fuel alcohol for sale each year.[43] Substantial amounts of protein concentrate and brewer's yeast are also produced in the process. Texas has the urban base and several of the very large breweries necessary to make a similar recovery operation viable.

Dry, Ligno-cellulosic Feedstocks

for conversion to a variety of fuels and electricity

As mentioned above, ligno-cellulose is far and away the most common tissue in plants. Lignin, cellulose, and hemi-cellulose fractions are frequently of interest for biochemical conversion schemes. In general, wood is about 50% cellulose, 25% lignin, 20% hemicellulose and 5% other constituents, with softwoods showing slightly higher lignin and lower hemicellulose fractions than hardwoods. Hays and grasses, on the other hand, are only about 7% lignin. Higher lignin fractions give trees a higher combustion energy density relative to grasses. Roughly, lignin will have an energy density of 25 MJ/kg compared to about 17 MJ/kg for most carbohydrates, with lignin energy densities being much more variable owing to its variable composition.[44]

Dedicated Energy Crops

Energy crop production is generally separated into two categories: herbaceous crops (grasses) and short rotation woody crops (SRWC). An extensive species screening performed at the Oak Ridge National Laboratory (ORNL) as part of the DOE's Biofuels Feedstock Development Program has reduced the candidate energy crops to just a few. Wright has recently reviewed the program's status and results.[45]

Herbaceous crops. Switchgrass (*Panicum virgatum*), a native warm-season perennial grass (WSPG), was identified at ORNL from among 35 species as the single best potential herbaceous energy crop for the eastern half of the U.S. A tall grass ranging from Canada to Central America, switchgrass growth is limited in the West by water availability. McLaughlin has summarized the characteristics that recommend it for biomass production.[46] These include: consistently high biomass yields across a wide range of soils and conditions, drought tolerance, low requirements of nutrients and other agricultural inputs, anaerobic capacity (flood tolerance), and excellent soil erosion control characteristics. Many of these qualities stem from the plant's perennial nature. The deep root structure of perennials stabilize soils and enable them to tolerate extended periods of low rainfall or inundation. Furthermore, farmer familiarity with production techniques—it can be mowed, baled,

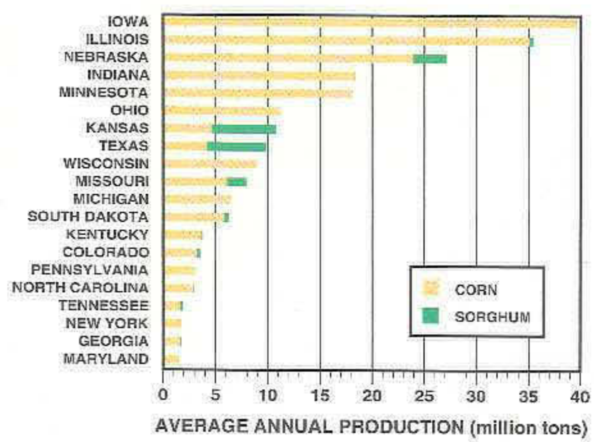


FIGURE 6.7. U.S. Production of Corn and Grain Sorghum, Top 20 States. Although Texas is not normally thought of as part of the corn belt, it ranks 8th in the nation in production of the feed grains presently used to make fuel ethanol.

or foraged like other grasses or hays—is an enormous plus.

In general, switchgrass production would be limited in Texas to areas identified in Figure 6.3 as the prairie regions (Gulf Coast, Blackland, or Central) or in East Texas; production in the plains regions would be limited by water availability.[47] Native short grasses of this region do not possess the above-ground biomass productivity to make them attractive as an energy crop.

As mentioned previously, field trials of switchgrass are being carried out at six locations in the state (Figure 6.2). In Texas, investigators are examining management practices and cultivars as part of an overall program of evaluating the crop's suitability in the Southern U.S. Plots were established in 1992 and data collection began in 1993. Preliminary studies at Stephenville showed dry matter yields of about 9.0 mg/ha (4.0 tons/acre), and evaluated response to fertilizers.[48] The Alamo cultivar appears to be the best adapted for many regions of the state. Research into the stability and quality of baled switchgrass during storage has shown losses in dry matter of about 13 and 19% over a period of six months in two different years.[49] Covering bales would mitigate these losses. Feedstock storage is an important issue for biomass energy developers. The ability to conveniently bale and store switchgrass like a hay gives it an advantage over certain thick-stemmed grasses that must be silaged.

For this report, switchgrass production was modeled on Texas agricultural lands using the SWAT model discussed previously. Parameters for the switchgrass plant—such as leaf area index, biomass to energy ratio, root to shoot ratio, etc.—were developed at the Blacklands Research Center of the Texas Agricultural Experiment Station based on field trials. GIS input layers to SWAT comprised the STATSGO soil survey data base and the USGS land use/land cover data base from which the definition of agricultural land was taken. The results are displayed graphically in **Figure 6.8.** This map presents a generalized portrait of potential biomass production in the state. It is important to remember that switchgrass is only modeled on agricultural lands. Non-agricultural lands were modeled with the vegetative cover listed in the figure. All forested areas were assumed to be pine, as this is the only woody species for which modeling parameters are presently available. The results showed statewide average switchgrass yields of 11.8 dry Mg/ha/yr (5.2 tons/acre) with no irrigation. This value compares favorably to a previous study by Graham, which estimated switchgrass yields nationally. Her results showed yields of approximately 11-15 Mg/ha/yr (5-7 tons/acre) for the regions of Texas included in her study.[50]

It is important to examine potential switchgrass yields in the context of probable production scenarios. Since the most likely dedicated energy crop production will occur on marginal agricultural lands, the results from Figure 6.8 were overlaid with those of Figure 6.5, Texas Prime Farmland, to examine yields on less productive lands. These results are summarized in **Table 6.3**, which, interestingly, shows that yields are not dependent on the prime land designation. Graham used 11.2 Mg/ha (5.0 tons/acre) as a cutoff value below which production is likely to be uneconomic. This would suggest that all but the very poorest agricultural lands can sustain switchgrass production.

Other productive perennial grasses reviewed by ORNL included eastern gama, bluestem (big and little), reed-canary, and lovegrass. Some may prove locally better adapted than switchgrass. Switchgrass is presently grown for forage in some locations; seed availability and price favor it over many other WSPGs, some of which are simply not readily available.

ORNL has focused on switchgrass for sound agronomic reasons, not the least of which is its expansive range. Certain thick-stemmed grasses, however, will out-produce switchgrass under proper (mainly sub-tropical) conditions. Thick-stemmed species reviewed by ORNL included a high biomass producing variant of sugar cane (*Saccharum species*) known as energy cane, napiergrass (often called elephant grass, *Pennisetum purpureum*), and some forage sorghums (sudangrass-sorghum hybrids). The first two are perennials and share the advantageous attributes associated with other perennial grasses. They are not very frost tolerant, however, and would be limited in Texas to regions of the Gulf Coast Prairie and the sugar cane producing counties of South Texas. Prine's field trials of thick-stemmed grasses in Central Florida

TABLE 6.3. Potential Switchgrass Yields as a Function of Land Quality.

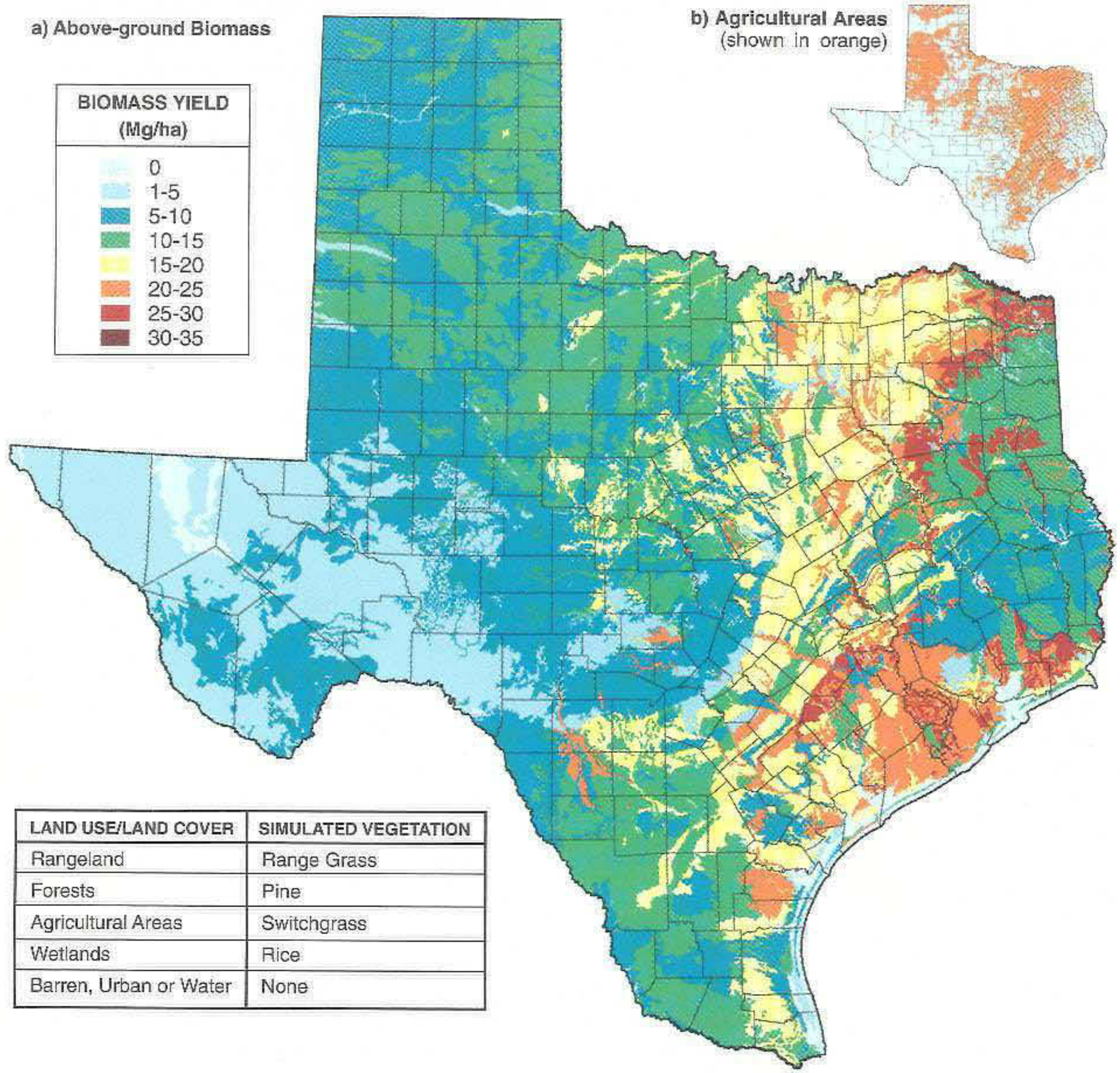
LAND QUALITY: PRIME LAND IN MAP UNIT	SIMULATED SWITCHGRASS YIELD	
	(Mg/ha)	(Tons/acre)
0%	9.2	4.1
0–20%	11.6	5.1
20–40%	14.0	6.2
40–60%	13.1	5.8
60–80%	12.4	5.5
80–100%	11.7	5.2

demonstrated 4-yr annual average yields ranging from 36-56 Mg/ha (16-25 tons/acre) for a number of canes and elephant grasses.[51] These yields are higher than the very best switchgrass yields and were measured in a part of Florida in the same USDA hardiness zone as the Texas Gulf Coast.

ORNL's review of thick-stemmed annuals considered for cellulosic energy crops centered on forage sorghums. In general, interest in annuals is limited for the agronomic reasons already discussed. Sanderson gives a good comparison of sorghums to switchgrass in relation to their suitability as energy crops.[52]

Woody crops. ORNL's screening of over 150 woody species identified several that are of interest for their biomass producing capability, including hybrid poplar, hybrid willow, silver maple, and American sycamore. Poplar and sycamore are the most appropriate species for the Southeastern U.S., including East Texas, with poplar being the first choice.[53] The southern variant of this species is the familiar cottonwood tree (*Populus deltoides*). Cottonwoods would typically be crossed with other faster growing varieties to yield a hybrid that is conditioned to Southern climates.

Cottonwood was not modeled in Figure 6.8 because input parameters for the species have not been developed. However, annual dry matter yields of SRWCs grown in field trials throughout the U.S. have been on the order of 10-17 Mg/ha (4.5-7.5 tons/acre) with maximum yields over 20 Mg/ha (9 tons/acre).[45] Upcoming poplar field trials in the Southeast should initially yield less, perhaps 9 Mg/ha (4 tons/acre), due to a lack of hybrids optimized around the region's poorer soils.[53] Properly adapted hybrids may greatly improve



LAND USE/LAND COVER	SIMULATED VEGETATION
Rangeland	Range Grass
Forests	Pine
Agricultural Areas	Switchgrass
Wetlands	Rice
Barren, Urban or Water	None

FIGURE 6.8. Texas Biomass Potential. (a) Annual above-ground biomass yields for monocultural production of species typical of local land cover. Agricultural areas are modeled with switchgrass. Typical management practices are assumed with no irrigation. Agricultural regions are identified in (b) above right.

upon this number. For comparison, a typical dry matter growth rate for loblolly pine is about 3.4 Mg/ha (1.5 tons/acre). Efforts are presently underway to incorporate poplar—and more tree species in general—into the EPIC and SWAT models.

Surplus, Co-product, or Waste Sources

Agricultural Sources

Harvest residues. Residues left in the field after the harvest of farm crops can form a significant energy resource. **Table 6.4** shows widely used harvest residue ratios generated by Heid.[54]

Tyson reviewed agricultural harvest residues generated in the Western U.S. in a 1990 WRBEP sponsored study.[55] Her results were based on 1987-88 production numbers of the following crops: wheat, corn, sorghum, sunflower, barley, oats, rye, cotton, and orchard trimmings; wetter harvest residues such as those from soybean and rice were excluded due to the relative difficulty of collection. Although these values are now seven years old, they are representative of Texas agricultural production and have been reproduced here. The numbers for collectable residues were based on the following assumptions: a minimum of 1 ton per acre (2.2 Mg/ha) must be left behind for soil conservation, 20% of the residues will be lost in collection, and a yield of less than 0.5 ton per acre (1.1 Mg/ha) after allowing for soil conservation and collection losses was assumed to be uneconomic. These inputs lead to the numbers of "collectable agricultural residues" summarized in **Figure 6.9.** This map is essentially a representation of the heavy agricultural regions of the state.

TABLE 6.4. Harvest Residue Ratios of Some Common Texas Crops.[54]

CROP	HARVEST RESIDUE RATIO*
Corn (yield < 95 bu. /acre)	1.0
Corn (yield > 95 bu. /acre)	1.5
Spring wheat	1.3
Winter wheat	1.7
Oats	1.4
Grain sorghum	1.0
Rice	1.5
Cotton	1.5
Sunflower (yield < 500 lb. /acre)	1.0
Sunflower (yield > 500 lb. /acre)	1.5

**Field residue weight/collected harvest weight*

The highest concentration of collectable residues in Texas is in the Gulf Coast counties of Wharton, Jackson, and Matagorda. The intensity of collectable residues generated in this region compares favorably to the highest residue producing regions of the western U. S., second, in fact, only to the high corn-producing counties of south central and southeastern Nebraska. Wharton county's total of 490,000 tons (445,000 Mg) ranked eighth in the WRBEP territory. Statewide, agricultural residues sum to over 5.3 million tons (4.9 million Mg). This amounts to an energy potential of 0.085 EJ (0.081 quad), or about 7.1 billion kWh of electricity (30 % conversion efficiency).

Figure 6.9 is useful in that it points out the regions of the state in which agricultural residues may play a role in energy production. However, a more detailed feasibility analysis that would entail modeling of long-term soil conservation impacts and production variability would be a necessary next step prior to site-specific implementation. For example, even though panhandle residue generation is high, the erosive character of these lands would probably dictate that more harvest residues be left in the field. This impact could be assessed on a region-wide basis using the SWAT model.

Processing wastes. Residues from the commercial refining and milling of foods and grains are an attractive potential energy resource because, unlike field residues, they are generated at a central source. Sometimes, existing competition for resi-

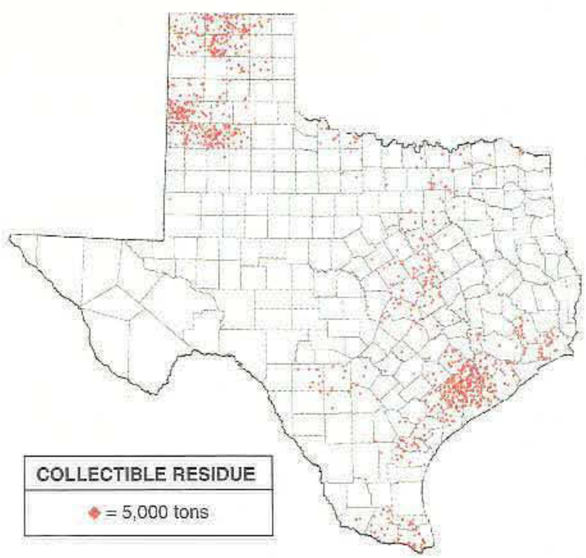


FIGURE 6.9. Collectible Agricultural Residues. The data assume 1 ton per acre of residues is left behind to protect soils from erosion. Intense resource areas along the Gulf Coast are among the highest in the WRBEP territory.

dues for use as fertilizers, soil conditioners or other products may outbid their use for energy purposes.

In general, surveys of waste generated from commercial activities are much more difficult to come by than similar assessments of primary resources, due to the proprietary nature of such information. Since a canvassing of individual mills is beyond the scope of this report, the summary presented here will focus on information from published sources or estimates that are accepted as generally valid. Major Texas agricultural residues include cotton gin trash, rice hulls, sugar cane bagasse, and peanut shells.

Cotton gin trash is the leaves, burs, stems, and soil stuck to the cotton fiber after harvest and separated at the gin. A 1993 WRBEP-sponsored assessment of gin trash showed Texas to be the leading producer among western states with a 10-year average generation rate (1981-1991) of about 1 million tons per year.[56] The leading counties in gin trash production are concentrated in the southern High Plains; the actual geographic distribution is shown in **Figure 6.10.** Cotton gin trash has a higher heating value of 16.4 MJ/kg,[44] which means that the 1.4 million tons (1.3 million Mg) produced in 1991 represented a primary energy source of 0.021 EJ (0.020 quad), or about 1.7 billion kWh of electricity if converted at 30 % efficiency.

Present practice in Texas is to spread gin trash on farm soils close to the gin. Gin trash is not perceived as a disposal problem, but neither is it a revenue-producing co-product. Some trash is mixed with livestock feed for roughage. It should be pointed out that actual Texas gin trash production is probably somewhat higher than that indicated by the WRBEP numbers in Figure 6.10. This is because, for consistency across the entire WRBEP

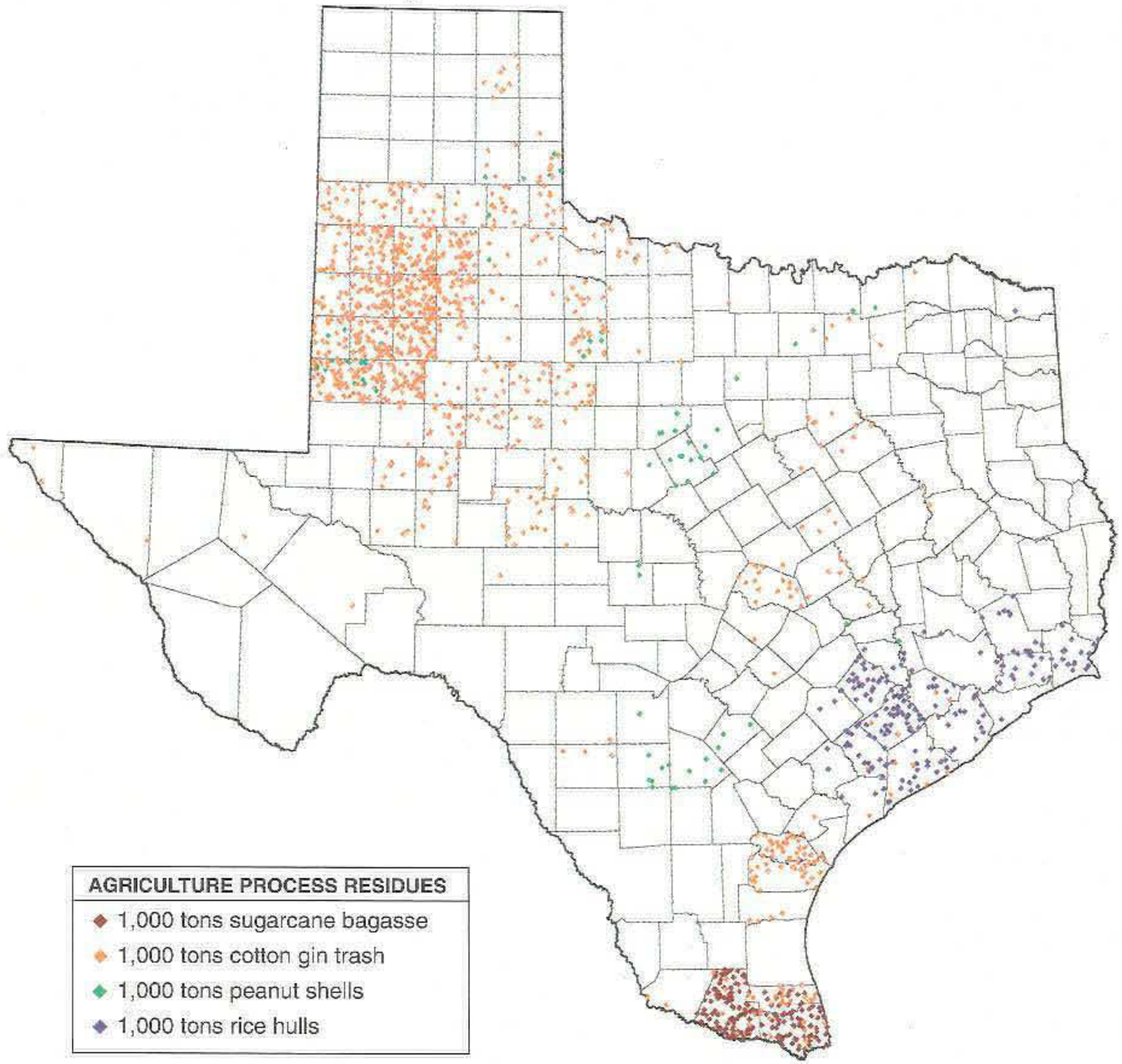


FIGURE 6.10. Agriculture Process Residues. The amount and distribution of four major agricultural process residues as taken from county-level production data. Cotton gin trash dominates this resource type and is found throughout the state. Location of dots within counties is random.

territory, the study used a constant value of 609 dry lbs. (275 kg) trash per bale of cotton that is conservative for Texas production techniques (stripper harvesting). For a given harvester, gin trash "yields" may be as much as twice this number.

Besides trash generated at gins, cotton residues are also produced at oilseed mills in the form of cottonseed hulls. Hulls are a better animal feed than is gin trash and have been incorporated into other products as well, such as certain plastics and drilling muds. Historically, however, they have low market value and hence could become an energy feedstock. Hulls typically represent 25% of cottonseed weight. The WRBEP report did not survey cottonseed hull production in comparable detail to gin trash generation due to the lower volume of hulls and their superior economic standing. However, it can be estimated that about 450,000 tons (410,000 Mg) are generated in Texas annually, concentrated at oilseed mill locations in the High Plains.

Texas accounts for about 12% of domestic rice production and ranks fourth nationally behind Arkansas, California, and Louisiana. Rice hulls have been burned in both California and Louisiana to generate electricity. Other disposal practices include composting to make an organic soil conditioner or incorporation into livestock feed. Hulls represent about 20% of total dry weight of the harvested grain.[57] A typical Texas production year of 950,000 tons (860,000 Mg) yields around 195,000 tons (177,000 Mg) of hulls concentrated at mills in the region.

Bagasse is the fibrous stalk and leaves left over when sugar is pressed from the cane. It is burned to supply process heat at most sugar mills; sometimes electricity is generated and exported from the mill. Texas is a minor sugarcane producer, ranking last among the country's four cane producing states. However, owing to the productivity of sugarcane and the fact that bagasse represents nearly 30% of its dry weight,[58] even small amounts of sugar production can result in large residue accumulations. In Texas it averages about 190,000 tons (170,000 Mg) of bagasse per year. The state has only one mill, which utilizes its bagasse for energy on-site.

Texas' average annual peanut production of 250,000 tons (230,000 Mg) ranks it second only to Georgia. Peanut shells account for almost 30% of the harvested weight and in Georgia have been co-fired to generate electricity.

The size and distribution of these various agricultural process wastes is summarized by Figure 6.10. Clearly, the gin trash resource dwarfs all others. It is also one which has minimal competing uses. The dots shown in Figure 6.10 are derived from NASS county production numbers for each commodity, and hence do not represent the locations of mills. Of course, mills will typically be located in major producing regions.

Forest Sources

Standing biomass. The above-ground woody biomass of East Texas, as derived from the U.S. Forest Service's 1992 survey,[59] is shown in **Figure 6.11.** Total biomass in the region is estimated at 455 million dry tons (413 million Mg), with 190 million tons of softwood and 265 million tons of hardwood (173 and 240 million Mg). The energy content of this immense resource is nearly 8.7 EJ (8.2 quads). The wood does not represent a long-term asset, of course, unless it is harvested sustainably. Presently growth of growing stock trees matches removals fairly closely. A reduction in demand, however, might free up more forest resources for energy production. Successful recycling efforts, for example, might create a surplus in the pulp wood market.

Outside of East Texas, substantial woody biomass in the form of brush species occupies much of the remainder of the state. The SCS assesses brush and range conditions based on data taken from the NRI. The assessment is in terms of three broad groupings of canopy cover (light, moderate, and dense) and hence does not contain the detail necessary for an accurate biomass estimate. However, a detailed inventory of 25 major brush species compiled from the 1982 NRI revealed that "dense" brush infestations (greater than 30% canopy cover) occurred on over 33.7 million Texas acres (13.6 million ha), or about 20 % of the state's land area, and that some degree of brush canopy is present in nearly 60% of the state.[60] Mesquite is easily the most common brush species, abundant in all range areas of the state (see figure 6.4). Based on the abundance, density, and perniciousness of certain brush species, brush clearing may appear to represent a substantial new source of woody biomass. However, certain root-sprouting species, including mesquite, may reach even thicker infestations after top removal; clearly, brush harvesting must coincide with sound range management practices.[61]

Logging residues. Logging residues are the unused portions of trees cut or killed by logging and left in the woods. In East Texas, they could represent a significant energy resource. Logging residues are not captured directly in the Forest Service's assessment, but, like agricultural residues, can be estimated as a percentage of total harvest

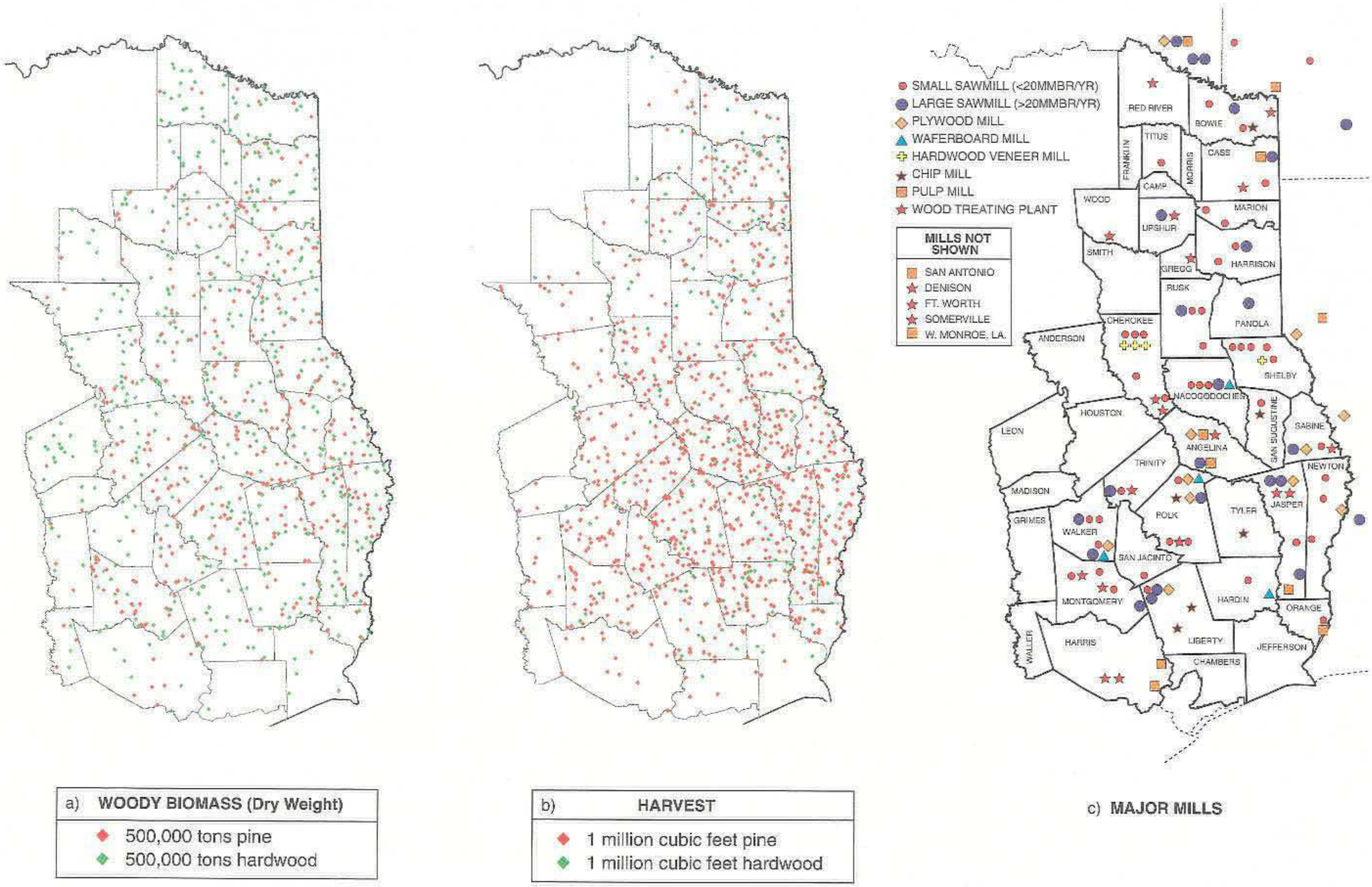


FIGURE 6.11. The East Texas Forest Resource. (a) Above-ground biomass, 1992;[59] (b) Average annual harvest, 1986-1992;[62, 64] and (c) Locations and sizes of major mills canvassed in the annual harvest survey.[62]

based on common field practices. Values are therefore subject to uncertainty as local practice and conditions vary. Based on values of 14% of hardwood harvest and 6% of pine harvest, the Texas Forest Service's annual survey of harvest trends puts logging residues for 1992 at the following level: 29.8 million cubic feet of pine and 15.6 million cubic feet of hardwood.[62] These are estimates of the residues of growing stock trees—basically those trees of commercial species that meet specific standards of dimension and merchantability. Additionally, other sources of logging residues include cull trees and non-commercial species that are killed during logging operations. The US Forest Service's South Region Forest Inventory Analysis group has estimated these residues for 1990 at 32.0 and 63.4 million cubic feet for Texas pines and hardwoods, respectively.[63] From these numbers, a total annual energy content from logging residues can be estimated at 0.089 EJ (0.084 quad) over the 43 county East Texas area. In this number, no effort has been made to account for residue collectability or soil erosion characteristics.

The distribution of logging residues will follow the harvest. Figure 6.11 shows the average annual pine and hardwood harvest over the years 1986-1992 for counties in East Texas. Texas' average total harvest of 685 million cubic feet ranks 5th among the seven states in the Forest Service Southern region, slightly less than both Arkansas and Louisiana.[63, 64].

Mill residues. In the forest products industry, sawmills and pulp and paper mills are the major waste producers, while secondary operations such as furniture manufacturers make relatively minor contributions to the biomass waste stream. Nationally, primary biomass energy consumption at forest mills amounted to nearly 1.7 quads (1.8 EJ) in 1990[29], making it easily the largest category of biofuel consumption. Further, inventories of energy consumption maintained by the American Forest & Paper Association (AFPA) show that self-sufficiency (per cent of energy generated on site) of the pulp and paper industry has increased from 40.3 % in 1972 to 56.2% in 1992.[65]

Estimates of mill residues and the degree to which they are used as fuel are not routinely maintained by any governmental agency, again owing to the proprietary nature of these statistics. Energy consumption numbers of the AFPA and the EIA are likewise not available at the state level. However, estimates from the U.S. Forest Service Southern Experiment Station puts total 1990 Texas softwood and hardwood mill residue generation at 2.925 and 0.766 million dry tons respectively. Of this, approximately 33% of softwood residues and 30% of hardwood residues were estimated to have been used for fuel, including almost all bark residues. The vast majority of remaining residues were used in fiber products; less than 2% of total mill residues were thought to have gone unused.[63] The annual survey of mills by the state Forest Service gives a general picture of the distribution of the industry and hence of mill residues. This is shown in Figure 6.11.

Urban Sources

Municipal biomass derived wastes. Ligno-cellulosic feedstocks, mainly in the form of paper, make up a considerable portion of urban wastes. Municipal solid waste (MSW) includes items such as durable and nondurable goods, containers, packaging, food wastes, and yard trimmings—all items that are commonly landfilled. Other non-hazardous wastes that may be landfilled, such as agricultural wastes, demolition wastes, or sewage sludge, are not defined as MSW, but may have a substantial biomass component. The best estimates of the composition of MSW are characterization studies conducted every two to three years under contract to the EPA. These studies use a materials flow methodology that relies on production data and product life to characterize MSW rather than site specific wastestream sampling. Values generated are average numbers for the entire U.S. and show that for 1992 about 70% by weight of discarded MSW was derived from biomass, with paper and paperboard alone accounting for 31%. Yard trimmings (18%), food wastes (8.4%) and wood (7.3%) are other major biomass contributors. The total organic fraction (biomass plus plastics) stood at nearly 83%.[66]

Applying these numbers to landfill data collected by the TNRCC suggests that approximately 13.5 million tons (12.3 million Mg) of biomass were discarded by Texans in 1992, or about 4.25 lbs. (1.93 kg) per person per day.[67] Note that these weights are on an "as received" basis; certain biomass wastes, such as yard trimmings or food wastes, will possess a significant moisture content. Furthermore, it should be kept in mind these values only represent discards. Actual waste generation is higher due to recycling and energy recovery practices. Nationally, over 20% of MSW was recycled or composed and an additional 16% combusted in 1992.[66] Recycling fractions have increased dramatically in recent years as both municipal and homeowner disposal practices change. These efforts will compete with recovery for energy.

The distribution of biomass wasted is portrayed by **Figure 6.12**, Texas Population. Each 1000 per-sons in Texas discards approximately 775 tons (705 Mg) of biomass derived wastes per year. This map reasonably represents concentrations of wastes across the state, but since it is based on state and national averages, local variations in the waste stream will not be captured. For example, yard trimmings will be greater in eastern parts of the state than in the Trans-Pecos. Likewise wooden pallets and crates, an important urban wood source, are likely more abundant around ports than elsewhere.

The total annual energy content of Texas' municipal biomass wastes can be estimated at approximately 0.16 EJ (0.15 quad). For energy recovery from combustion, the distinction of whether or not the waste is biomass-derived is not so vital as its organic/inorganic makeup. Including petroleum-based products (plastics and tires) in this assessment raises the annual energy content to 0.20 EJ (0.19 quad). The biomass fraction is important, however, for other energy recovery methods, such as the production of fuel ethanol from cellulosic feedstocks.

Wet Feedstocks and Wet Wastes

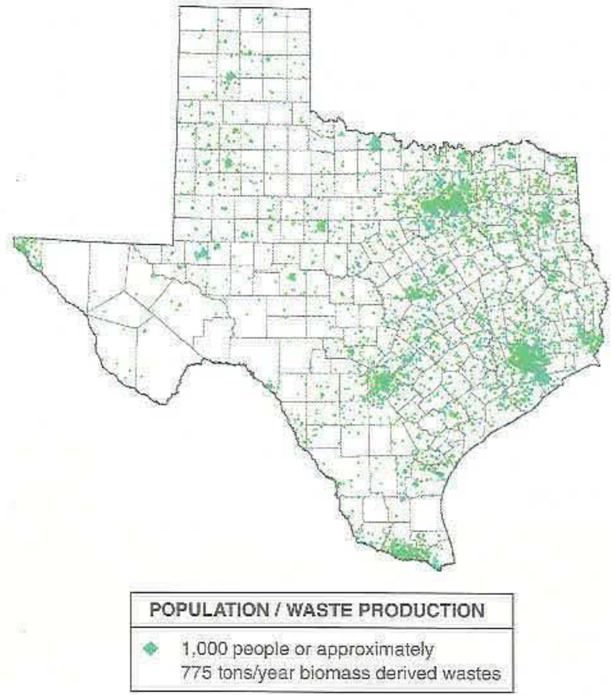
appropriate for anaerobic digestion

The high water content of certain types of biomass may end up dictating how they are used. For example, direct combustion of wet materials is normally impractical, and drying them may prove uneconomical. We group these materials together, therefore, with the notion that anaerobic digestion to evolve biogas will often be the most practical method of utilizing them for energy. **Table 6.5** shows the approximate moisture content of several forms of biomass. For the purposes of the following discussion, our definition of wet will begin at moisture contents of about 70%.

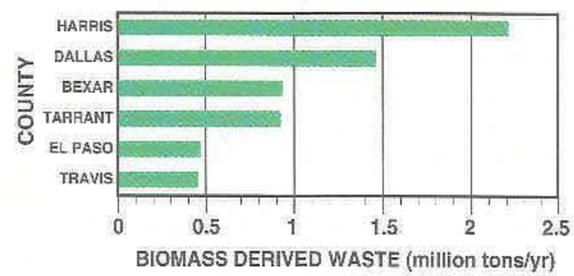
Dedicated Energy Crops

Many aquatic plant species have been mentioned as possible energy crops because of their profuse growth rates. These include phytoplankton, micro-algaes, macro-algaes (seaweeds), floating or emergent species such as water hyacinths, and marsh plants.[68] Both fresh and salt-water species have been examined. Development scenarios frequently envision utilization of unarable lands or near off-shore areas of sunny coastal regions similar to the South Texas Plains. Nutrient limitation is an important siting and cultivation issue. In order for these species to achieve their impressive potential productivities, intensive fertilizer inputs may be required. For this reason, another common production scenario is to grow aquatic plants in the effluent from sewage treatment facilities.

In spite of the large potential yields from these aquatic plants, significant barriers exist that will limit their near-term introduction. The greatest of these is simply the relative immaturity of the field of aquaculture in contrast to its agricultural and silvicultural cousins. A few of these species, like giant kelp, have been grown in significant quantities in Asia and other parts of the world. In general, however, a lack of experience in species domestication and breeding, management techniques, and harvest methodologies—as well as a lack of the necessary infrastructure to study these problems—will retard aquacultural development. Because of this, a more likely development path will be the continued and growing exploitation of these plants as industrial crops rather than as energy crops—that is, as highly value-added pharmaceu-



a) Texas Population / Biomass Waste Production



b) Five Top Texas Counties

FIGURE 6.12. Texas Population and Population-Derived Statistics. Population numbers are based on the 1990 Census. Each dot represents 1,000 people. Compact cities such as Austin and Corpus Christi may appear smaller than they really are.

tical, cosmetic, or prized foods rather than as fuel.

In Texas, land-based aquaculture development would be best suited to regions of high insolation and abundant water supply, either fresh or saline. Coastal counties of the South Texas Plains such as Kenedy or Kleberg would be promising candidates. West Texas counties with saline water resources would also be appropriate.

Microalgal strains that are capable of partitioning large amounts of their total mass into lipids are presently the only area actively being researched under the DOE's aquatic plants program. The potential of these algae will be discussed in more detail in the next section on fats and oils.

TABLE 6.5. Typical Initial Moisture Contents of Selected Biomass. Adapted from Jenkins.[69]

TYPE	MATERIAL	MOISTURE CONTENT (%wet basis)
Crop Residues	Corn cobs	25–45
	Corn stalks	40–60
	Cotton stalks	40–50
	Rice straw	50–80
Processing Residues	Cotton gin trash	7–12
	Rice hulls	7–10
Tree Sources	Bark	30–60
	Wood	35–60
	Shavings	8–19
Animal Manures	Beef cattle	86
	Chickens	75
Municipal Solid Wastes	Food wastes	70
	Paper	8
	Refuse derived fuel pellets	25–35
Aquatic Biomass	Water hyacinth	95
	Kelp	88

Waste Sources

Animal wastes. Texas is a major producer of animal manures from the state's immense livestock industry. A 1994 WRBEP inventory of animal wastes showed that Texas ranked second overall among thirteen western states in manure production. (See **Figure 6.13.**) The generation of collectible manure solids totaled 4.4 million tons (4.0 million Mg) per year with a potential biogas energy content estimated at 0.026 quad (0.028 EJ).[70] As in the case of crop residues, only Nebraska showed higher figures. Texas was first in manure production from poultry broilers, and second in generation from poultry layers, dairy cows, and feedlot cattle.

From the perspective of utilizing these wastes for energy, total state production is not so important as the concentration of the resource. Large concentrations of feedlot cattle in the High Plains and of poultry broilers in East Texas may yield economic manure energy projects, particularly if the waste presently represents a disposal problem. To date, however, most successful manure digestors have involved swine or dairy operations, as existing manure management practices of these facilities can more readily incorporate digester technologies.

Municipal sewage. Population statistics provide an easy and reliable method to examine sewage production. The Texas population distribution shown previously (Figure 6.12) can be interpreted as production of total volatile solids/year if each dot is taken to represent 188 tons (170 Mg). Harris county alone generates approximately 760,000 tons (690,000 Mg) of total volatile solids per year. From these values it can be estimated that Texas' annual sewage biogas energy potential is roughly 0.027 EJ (0.025 quad).

Elimination of pathogens and environmentally safe sludge and effluent disposal are the primary goals of sewage treatment. Energy recovery will only be adopted where it meshes with broader treatment goals. Anaerobic units are somewhat more expensive than traditional aerobic techniques because they require covering of sewage to capture biogas, but some studies indicate that they may provide superior pathogen reduction, and, of course, the evolved gas represents an economic co-product.[6] A few units are in operation in Texas, including one at the city of Austin's sludge treatment facility. Given the existence of an extensive installed capacity, anaerobic digestion of sewage

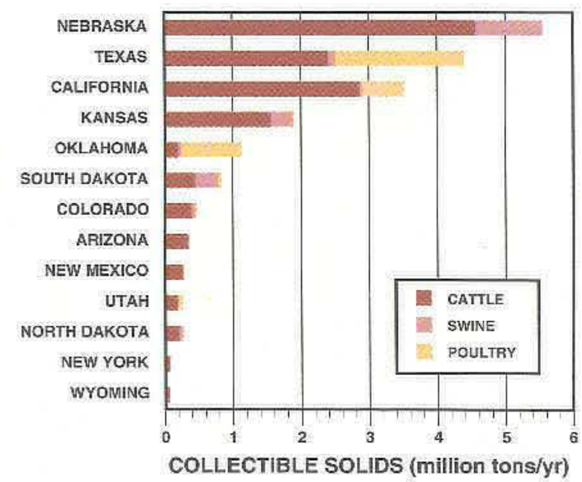


FIGURE 6.13. Manure Resources of the Thirteen WRBEP States. California's surprisingly large cattle component is largely dairy cows while Texas' is primarily feedlot cattle.

wastes may be largely limited to new units.

Landfill gas. Estimates of biogas evolved from landfills vary. Gas generation is governed by the fraction of landfilled material that is biodegradable and by air infiltration which limits the anaerobic process (materials consumed aerobically will not be digested anaerobically). A 1992 study funded by EPRI used a number of 100 m^3 of methane generated per Mg (3880 scf/ton) of landfilled waste.[71] This value incorporated digestion and collection efficiencies. Applying this to the 21.7 million tons (19.7 million Mg) of waste landfilled in Texas in 1992[67] suggests a potential annual resource of 1.97 billion m^3 (69.5 billion scf) of methane with a corresponding energy content of 0.071 EJ (0.067 quad).

The methane generated in landfills is released slowly, over a period of years. Reaction rates are influenced by a number of factors such as landfill pH, moisture content, and temperature. Hence, the energy value cited here represents the statewide annual resource in steady state conditions—that is, new materials are being landfilled at the same rate for years. More practically, gas generation rates of individual facilities can be estimated by consulting TNRCC landfill capacity statistics.[67] Finally, it should be stressed that the landfill gas resource calculated in this manner is not additive with previous assessments of MSW. Wastes can be landfilled and energy recovered as biogas or they can be burned directly, but obviously not both.

To summarize, biogas from waste sources, if entirely captured, could account for approximately 0.13 EJ (0.12 quad) of primary energy, enough to supply 6% of Texas' electricity production. This is summarized in **Table 6.6.**

Sources of Fats and Oils (Storage Lipids)

for conversion to biodiesel

Storage lipids are commonly referred to as fats when solid at room temperature and oils when liquid. They may be derived from animal sources (lards and tallows) or derived from plants. Lipids are the source for biodiesel.

Dedicated Production

Lipid-bearing algae. When stressed, certain strains of microalgae accumulate a large proportion of their total biomass in storage lipids. The algae exhibit high growth rates and tolerance to fluctuations in both temperature and water salinity. In production scenarios envisioned by researchers at the NREL, salt water algal ponds would be built in regions of high insolation and preferably close to an existing fossil-fueled power plant or other source of carbon dioxide. The ponds would then be fertilized with nutrients including greatly enhanced levels of CO_2 sparged into the water from the waste source. After harvest, lipids are pressed out of the algae and the solid residue used as an animal feed or fed back to the power plant boiler. In research conducted over the last 12 years, biomass yields of 0.28 Mg/ha-day (0.12 ton/acre-day) have been demonstrated with lipids representing as much as 40% of total biomass.[72] For comparison, these biomass production rates are roughly 3-5 times the best biomass yields of terrestrial crops and approach limits of photosynthetic efficiency.

Texas has all of the necessary ingredients for this production scheme. A 1985 initial resource evaluation by SERI identified regions in the southwestern U.S. most appropriate for microalgae production based on climate suitability and land and water availability. The largest contiguous area in the Southwest identified as being most suitable was in eastern New Mexico and adjacent regions of the Texas High Plains. Other large areas of Texas classified as most suitable included parts of the southeastern panhandle, the Pecos river basin, and the Rio Grande basin close to El Paso. Interestingly, the study did not include south Texas or anywhere east of approximately Abilene.[73]

TABLE 6.6. Annual Potential Texas Biogas Production from Waste Sources.

SOURCE	ENERGY CONTENT	
	(EJ)	(Quads)
Animal wastes	0.028	0.026
Municipal sewage	0.027	0.025
Landfills	0.071	0.067
Total	0.13	0.12

It should suffice to say that microalgal production in Texas would not be limited by land, sunshine, or saline water resources. A much more limiting factor would be the presence of a significant source of CO_2, if indeed this were requisite for production. Algae production at atmospheric levels of CO_2 can certainly generate biomass yields higher than most terrestial farming, but not near the values cited above. As a point of reference, for Texas to displace 20% of its 1992 diesel consumption at demonstrated algae biomass and lipid yields would require a total pond area of approximately 90,000 ha (224,000 acres) or a square about 30 km (18.7 mi.) on a side.

Other sources. Shay reviews a number of potential sources for biodiesel fuel.[74] One of these is the Chinese tallow tree, a fast-growing species common to Texas coastal savannahs. Oils make up approximately 45% of the weight of the tree's seeds. It has been estimated that, grown in a plantation, oil yields as high as 5.8 Mg/ha-yr (2.2 ton/acre) might be attainable.

Co-product and Waste Production

Oilseed crops. Worldwide, oilseed crops are the largest source of commercially exploited fats and oils. In the U.S., oilseed crops are classified as either major or minor, with major crops comprising soybean, cottonseed, and peanut (groundnut), while minor crops include sunflower, safflower, flax, and rapeseed (canola). The soybean, an Asian native, is far and away the largest contributor to the national and world vegetable oil market, accounting for over 70% of U.S. vegetable oil production and 30% globally.[74,75] Like peanuts, it is a legume, and is frequently rotated with corn in midwestern states for its nitrogen-fixing capabilities. Rape, a member of the mustard family, has the highest oil yield of common oilseed crops but is grown mainly in northern latitudes such as Europe, Canada, and northern border states of the U.S. Great Plains. It is the prime candidate for European biodiesel production and, like soybeans, yields a substantial protein meal co-product used in animal feeds. At least one study has examined cultivars appropriate for adoption in the southern U.S.[76]

All of the major oilseed crops barring rapeseed are presently grown commercially in Texas. For 1992, Texas ranked first in cottonseed production, second in peanuts, sixth in sunflower seed, and twenty-third in soybeans among the fifty states.[77] Oil is the most profitable component of cottonseed, accounting for over 40% of total seed revenues, and about 8% of total cotton revenues.[56]

With the exception of sunflower, none of the major oilseed crops mentioned above are grown specifically or even foremost for their oil. Increased agricultural production of oilseeds will therefore depend on the complex economics of a variety of seed, bean, and fiber co-products. Export policy and crop subsidies will also greatly influence oilseed production. Biodiesel may represent a much needed secondary market for these products. Texas land, climate, and soil characteristics are not fundamental limitations for expanded oilseed output, with the caveat that panhandle oilseed production, like most agricultural activity of the region, depends upon irrigation.

Animal fats. Lards and tallows from animal sources are another potential biodiesel feedstock. They possess a distinct price advantage over vegetable oils, but may be limited to use in a summer biodiesel blend as they are more viscous (higher levels of saturation) and will increase both the diesel's cloud and pour point. Other differences are negligible.

Unlike plants, animals will never be raised specifically for their fats. In fact, consumer trends toward leaner meats and unsaturated cooking oils have resulted in a depressed market for edible tallows. Inedible products are added to pet foods and animal feeds to increase palatability, but in general fats must be viewed a low value added co-product of packing operations. For this reason, present production is viewed as a decent indicator of the resource. Texas is one of the nation's leading livestock producers, ranking first in cattle production, first in sheep and goats, sixth in broilers and hens, and thirteenth in hogs among all 50 states.[78]

For the purposes of this assessment, average production levels of all fats and oils were tallied to give a snapshot of the state's resource. These are shown in **Figure 6.14**, which displays the average annual production of fats and oils from both animal and vegetable sources from 1988-1993. Texas ranks sixth in this tally, behind the major soybean states of Iowa, Illinois, Minnesota, Indiana and Nebraska. Note that the animal fat resource was apportioned according to the location of the animal crop rather than the slaughter; considerable interstate movement of beasts occurs prior to butchering. The energy content of all fats and oils produced in the state is 0.023 EJ (0.022 quad), an amount equal to 4.1% of Texas' 1992 diesel consumption.

Fish oils have also been proposed as a source for

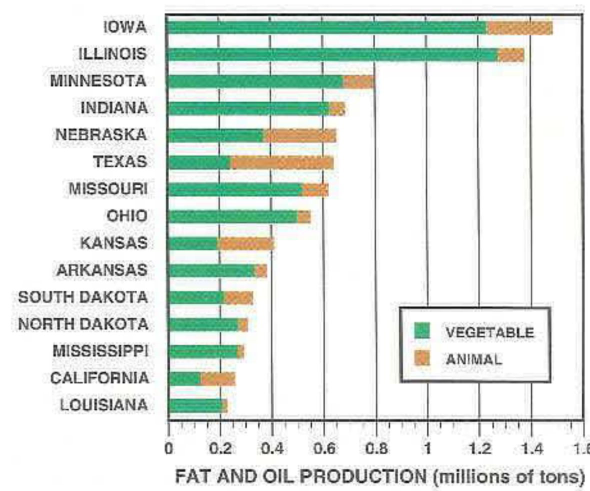


FIGURE 6.14. U.S. Primary Production of Fats and Oils, Top Fifteen States. Values are averaged over five years. Texas ranks 6th in this series, well behind the top soybean producers, but still with significant resource. Secondary sources such as restaurant greases are not included.

biodiesel. Fish oils currently are used in food processing and as lubricants. A lack of state data precluded their inclusion in Figure 6.14, but national production is minute compared to other oils.

Used cooking oils. Because of its low price, used cooking oil collected from restaurants is one the most promising feedstocks for biodiesel. Production schemes utilizing restaurant oils are presently being implemented in Austria.[79] In the United States, normal practice is for local independent renderers to recover oils from restaurant collection bins. Oil usage and potential recovery vary greatly with type of restaurant and volume; fast-food establishments or any restaurant relying on deep fat fryers are generally large waste oil producers. After collection, renderers re-cook the product to form yellow grease, which, like inedible tallow, finds its way into the animal feed and export markets.

From Commerce Department figures average annual national grease production (1988-1993) is approximately 2.1 billion pounds (950 million kg.), or 8.4 lbs. (3.8 kg.) per person per year.[73] The 1993 value increased to 2.7 billion lbs. (1.2 billion kg.). This number means that recovered greases are about 10% of the primary production of fats and oils.

A potential waste feedstock not included in the these numbers is the trap grease that restaurants wash down sinks and floor drains. In present practice, a contract service periodically empties the grease trap for disposal; the high water and particulate content of trap fluid makes it unattractive to renderers. It is difficult to estimate the amount of used oil in grease traps, but in certain operations it could represent as much as recovered oils.[80] Disposal of grease trap waste has become more costly for most restaurants in recent years. Disposal practices are monitored by the TNRCC.

Summary

The data used to model switchgrass production and embodied in Figure 6.8 is useful in that it allows quantification of the state's biomass potential. Even though numbers derived from it are not indicative of economic production capability, they at least offer an upper bound on the resource that allows comparison with other resources. These numbers are summarized in **Table 6.7**. The total annual resource of 14 EJ (13 quads) is slightly larger than Texas' annual total energy consumption of about 10.5 EJ (10.0 quads). An "accessible" resource value was taken as a somewhat arbitrary 15 % of the upper bound. The total resource represents an annualized photosynthetic efficiency of 0.3%.

In **Table 6.8** the energy content from a number of the waste or co-product sources discussed above is summarized. Urban refers only to landfilled biomass derived wastes. This is probably the single largest category of untapped potential. Logging and harvest residues suffer from constraints associated with their economic collection and transportation. Forest mill residues, while large, are already highly utilized. Biogas resources include municipal sewage and animal manures, but exclude land fill gas as this resource is already accounted for in urban waste. In total, these waste resources possess a potential of 0.45 EJ (0.43 quad), although the economically viable fraction of this resource is probably less than half this amount. At this rate, the numbers suggest that waste resources alone could account for over 10% of the energy consumed in Texas electricity production.

TABLE 6.7. Quantification of Total and Accessible Texas Biomass Resource.

TOTAL ANNUAL RESOURCE		ACCESSIBLE ANNUAL RESOURCE	
(EJ)	(Quads)	(EJ)	(Quads)
14	13	2.1	2.0

TABLE 6.8. Annual Texas Biomass Waste Resources.

WASTE SOURCES	TYPE	ENERGY RESOURCE	
		(EJ)	(Quads)
Agricultural Residues	Harvest	0.085	0.081
	Processing	0.030	0.028
Woody Wastes	Logging Residues	0.089	0.084
	Mill Residues	0.070	0.066
Biogas	Manure, Sewage	0.055	0.052
Urban	Landfill Biomass	0.16	0.15
TOTAL		0.45	0.43

Resource Variability

One of the central strengths of biomass as a renewable energy resource is that it does not suffer from the intermittence associated with wind and solar resources. However, biomass resources do exhibit annual and seasonal variations that can impact their commercial viability. Feedstock source and type dictate the range and nature of these temporal variations.

Dedicated energy crops. As has been stated earlier, perennial trees and grasses offer superior insurance against variations in yield over annuals. Trees will show the least variation because, even in short-rotation systems of 6-12 years, their growth is integrated over multiple growing seasons; year-to-year extremes in climate are averaged out so that, barring catastrophic events such as fire, net biomass production is reasonably predictable. Perennial herbaceous crops should also demonstrate fairly consistent yields beyond the first year of establishment. As an example, Wright notes that during the dry year of 1988, switchgrass and sorghum yields at multiple test plots in Indiana were about the same at 8.0 and 8.9 Mg/ha (3.6 and 4.0 tons/ acre) respectively. However, yields of the perennial switchgrass ranged from only 7.3 to 9.9 Mg/ha (3.2-4.4 tons/acre), while the sorghum, a thick-stemmed annual, showed yields ranging from 1.7 to 21.0 Mg/ha (0.76-9.3 tons/acre).[45] Such risks, along with the higher energy and nutrient inputs noted previously, may preclude the adoption of annuals in dedicated biomass energy schemes.

Waste and co-product sources. Waste biomass sources will also exhibit annual or seasonal variability, but some sources are far more stable than others. Ironically, urban biomass wastes such as landfilled materials and municipal sewage will be among the most stable of all biomass resources. Per capita production of landfilled biomass materials has only increased over the last 40 years.[64] Generation of landfill gas is likewise quite predictable based on models that incorporate landfill size, fill rate, and biomass digestion rate. Other waste sources show much more variability. Agricultural process residues in particular follow production swings that can range from bumper harvests to complete crop failures. Furthermore, many agricultural processing units are only seasonally operational. Texas cotton gins, for example, will typically run about 1000 hours per year in the fall and winter. Gin trash would therefore have to be stockpiled to take advantage of baseload electricity production. Wastes from many biomass processing facilities, such as forest products mills, animal feeding operations and meat packing plants, will not suffer greatly from seasonal variability or crop failures, but commodity price fluctuations will impact overall production and therefore waste generation.

It is important to remember that production of a biomass waste or co-product does not ensure that it will be used in energy recovery. Competition frequently exists for biomass wastes that may diminish their availability as a fuel. Manures have value as fertilizers; waste paper can be recycled; cottonseed hulls find their way into oil drilling muds, wood chips into landscape mulches, restaurant greases into pet food. Recognition of this fact is vital to understanding the resource availability, as fuel is a very low value-added use of biomass. Real resource variability is frequently dictated as much by competing market demands as by the natural variations imposed by soil and weather; this situation is common to other commodities but rather unique among renewable energies.

RECOMMENDATIONS

Fundamental Assessments of Natural Resources

The land resources of North America in the region occupied by the conterminous United States are among the most studied, best known, and most thoroughly mapped on the planet. **This report sees no need for further assessments beyond the ongoing surveys carried out at the federal level.**

The case for further meteorological data has been made in other chapters. The resource that most impacts biomass and for which information is deficient is the solar radiation data base. By contrast, both the temporal and spatial record for precipitation and temperature are well-known.

Energy Crop Assessments

Extensive crop test plots are the norm in the agricultural community, generally carried out through the agricultural experiment station system. Likewise, the DOE has sponsored test plots for energy crop production in various parts of the country, as witnessed by the successful switchgrass program in Texas. Upcoming woody species (cottonwood hybrids) field trials sponsored by ORNL are planned for neighboring states, but presently not for Texas. **Texas should participate in this program through the state Forest Service or the forestry schools at Stephen F. Austin and Texas A&M. Assessments of other species, particularly of thick-stemmed perennial grasses, should also be carried out. Results from these trials should be used to develop parameters for incorporating more energy crops into present crop growth models.**

Assessments of Commercial and Municipal Activities

Unlike other renewables, utilization of biomass for fuel often centers around a commercial co-product or waste. Surveys of commercial activities can sometimes be difficult: they must yield enough information to be of value and at the same time results must be fashioned discretely enough as to avoid the disclosure of proprietary information.

Because businesses may be reluctant to participate in such surveys, it is recommended that only industries with high potential for biomass energy production be canvassed. The present assessment has only provided a sense of the overall state biomass resource. **A scoping study may therefore be appropriate to help define which of the commercial or municipal activities outlined above hold the greatest promise for increased biomass energy development.** A survey could be developed from the results of such a study that examines the interests and needs of the targeted industries.

Other Recommendations

Two other recommendations which do not fall neatly into the category of "resource assessment" are also suggested as a result of this report.

First, in terms of climate, physiography, and even culture, East Texas is much more a part of the Southeast than of the West or Southwest. In general, biomass energy utilization by the paper, pulp, and timber industry is probably as mature in the Southeast as anywhere in the nation. Certainly Texas mill operators are familiar with practices within their company outside of the state, but nonetheless many **foresters, community planners, and development groups interested in exploiting the East Texas biomass resource would do well to stay apprised of activities in the Southeast.** A mechanism should be in place for this to happen.

Finally, biomass is the only renewable energy resource capable of making significant contributions to the transportation sector without a complete restructuring of the present industry. Nationally, transportation accounts for 42% of total energy consumption (1992) and has the most adverse impact on balance of payments of any energy sector due to its heavy reliance on oil imports. The greatest potential for biomass may therefore lie in the arena of liquid biofuels. Texas, through the efforts the General Land Office, has been the unrivaled leader in promoting natural gas as an alternative transportation fuel. Likewise, the state Railroad Commission has made significant strides in promoting propane. Given the state's immense agricultural wealth and heritage, **an effort should be made to incorporate biofuels into Texas' alternative fuels umbrella.**

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ENERGY FROM WATER RESOURCES

by Alan Propp

INTRODUCTION

Water and energy are two of the most fundamental and interrelated elements of an industrial economy. In fact, the number one use of water in Texas is for cooling water used by thermoelectric power plants.[1] Although very little of the water is actually consumed, this use accounts for 41% of all water withdrawals in the state—roughly 40 gallons for every kWh generated. While availability of dependable water supplies for cooling, makeup and plant maintenance is critically important to many types of emerging renewable as well as traditional fossil generating sources, this chapter will be restricted to the review of energy derived directly from Texas' renewable surface water resources. These are comprised of hydroelectric power from lakes and rivers; ocean energy in the form of temperature gradients, waves, currents and tides; and energy from salinity gradients. Each of these is introduced below and is summarized in **Table 7.1**.

SIGNIFICANCE OF RESOURCE: HISTORICAL AND FUTURE USES

Hydroelectric Power (Hydropower)

Hydropower is among the most efficient means of producing electricity.[2] From its primitive beginning as mechanical power in grist mills to today's hydroelectric power plants, efficiencies have increased to almost 90 percent. Hydropower plants convert the kinetic energy of water as it flows from a higher to a lower elevation into electrical energy through the use of turbines and generators. In this report, hydropower plants that use water from a lake, river, or reservoir in a single pass through turbines will be termed "conventional" hydropower plants. Hydropower plants that take advantage of the difference in cost of electricity between peak and off-peak consumption times to economically recycle water between two reservoirs for multiple turbine passes are known as "pumped storage" plants. Pumped storage plants do not produce new power; rather, they merely act as batteries for power generated by other means.

Hydroelectric power development began with the electrical age. On July 24, 1880 the Grand Rapids (Michigan) Electric Light and Power Company demonstrated the generation of electricity by a dynamo belted to a water turbine at the Wolverine Chair Factory.[2] From that modest beginning hydropower production progressed rapidly and by 1907 accounted for 15% of the electric generating capacity of the U.S. By the 1930's hydropower provided 40% of the nation's electric energy. While hydropower capacity has continued to grow, its share of the total electric generation has steadily declined. Hydropower capacity leveled at about 74,000 MW, and now accounts for about 10% of the nation's electrical energy generation. Texas currently has 643 MW of hydropower generating capacity which represents only one percent of the state total and only half a percent of the electricity generated.[3]

Ocean Energy

Oceans cover more than two thirds of the earth's surface. For energy generation schemes to be practical, however, they will typically be located close to shore. Four types of ocean energy resources are reviewed here: energy from ocean temperature differentials (ocean thermal energy conversion, or OTEC), wave energy, currents, and tidal energy.

OTEC. Because sea water is translucent to a large proportion of the incident sunlight, the oceans act as a huge solar collector. The sunlight only penetrates about 65 meters of the ocean surface so most of the sun's thermal energy is trapped in its uppermost layers. Beyond about 100 meters depth, the oceans remain perpetually dark and cold. The basic premise of OTEC is the utilization of the difference in temperature between the surface water and that at depth to drive a heat engine (such as a Rankine engine).

The concept of harnessing the power available due to the temperature difference between the surface water and that at depth was first proposed by d'Arsonval in the late 19th century.[4] In 1929 an open cycle pilot power plant was built and operated in Cuba by Georges Claude. Claude's plant delivered only a very small power output and ceased to operate when the cold water pipe was

TABLE 7.1. Summary Characteristics of Water Resources Used for Energy.

	TYPE	SOURCE/CHARACTERISTICS	USES*	STATUS**
HYDRO	Hydroelectric	Rivers, with or without reservoirs	Electricity, but primarily flood control and water supply	A
OCEAN RESOURCES	Thermal Gradients	Deep ocean (>1,000 meters with gradient >20°C/km)	Electricity, process heat	B
	Waves	Large waves, preferably near shore	Electricity	B
	Tides	Coastal water impounded at high tide; needs high tidal range	Electricity	B
	Currents	Fast moving water	Electricity	C
SALT GRADIENT	Salinity Gradient Solar	Natural or man-made salt lakes/ponds with high temperature gradient	Electricity, process heat, fish farming	B
	Salinity Gradient Osmotic Pressure	Rivers entering ocean–salinity gradient induces pressure differential	Electricity	C

*Hydrogen can also be produced by electrolysis of water.
**A=Commercialized processes and products. B=Pilot level process demonstrations or infant industry. C=Research level only or limited commercial interest.

destroyed. In the 1950's, the French government partly sponsored a company called "Energie de Mers" which began construction of an open cycle plant near Abidjan, Nigeria. This plant was never finished although several of the subsystems were demonstrated. Othmer and Roels[5] have proposed a plant which would overcome many of these difficulties, but such a plant was never constructed. A closed cycle OTEC design, which was first proposed in the early 1900's, uses a secondary working fluid, such as propane, that possesses a relatively high vapor pressure.

Many significant attempts at demonstration of OTEC systems were made in the 1970's (e.g. McGowan and Heronemus)[6] and led to U.S. government sponsorship of research and development in this area. Funded activities included Mini-OTEC, artificial upwelling activities, materials research, and research and development on critical aspects of OTEC plant designs such as the heat exchangers.[7] The U.S. government stopped its sponsorship of OTEC research in 1984, but the state of Hawaii and private industry have continued research and development activities at a substantial level. Hawaii is currently operating a 210 kW open-cycle OTEC plant and has plans for a second one. A shore-based 5 MW, closed-cycle facility has been proposed for the Marshall Islands as has a commercial project in St. Croix, Virgin Islands. A variety of deep ocean water application (DOWA) activities are also ongoing (fresh water production, mariculture, air conditioning, etc.).

Wave energy. Oceans receive energy from the wind in the form of waves through friction between the moving air and the water. Because water is very dense the energy it absorbs from the air is stored in a concentrated form.

Interest in extracting energy from ocean surface waves began in the United States in the 1800's. The earliest patents on wave energy machines were issued in the 1880's, and patents continue to be issued on them today.[8] These devices vary widely in scale and sophistication, from small, wave-driven pumps[9] to large, hydroelectric power generation units.[10] A device currently being prototyped by Eberle et al[11] uses wave power to produce high pressure gas, which can then be piped to on-shore generators or used in a variety of other ways. According to the inventor, a demonstration site of this technology will soon be under construction in Korea. If this technology proves successful it could possibly have local applications at sites in Texas where remote power generation is needed. Other wave energy devices are also under development.

Currents. The kinetic energy embodied in the natural patterns of sea water circulation represent an energy resource analogous to wind energy. While ocean currents move much slower than typical breezes, the density of water is about 1,000 times the density of air, resulting in significantly higher power density for brisk ocean currents than for windy land areas. The corrosive underwater environment, however, poses significant challenges that have limited the practicality of this energy resource. Due to its limited potential, currents will not be considered further in this chapter.

Tidal energy. Tidal energy has fascinated geographers and engineers since the time of the ancient Greeks, and the existence of tidal mills in England and Wales was documented as early as 1066.[4] In the 1700's Belidor of the French Military Academy taught the importance of harnessing tidal energy. Ocean powered mills have been employed in Europe and until the early 1900's were in use in the northeastern U.S. as well. Over the past two centuries numerous patents have been issued dealing with tides. Several tidal power plants have been constructed to date: La Rance (France), Kislaya Guba (Former Soviet Union), Jiangxia (China), Annapolis (Canada), and several small plants in People's Republic of China.

Any geographic location that provides a basin that can be enclosed to capture and hold rising tides could possibly be utilized to generate tidal power. Extraction of tidal energy is considered practical only when the tides are large however.[12] Typically, a barrage is constructed across the opening of an estuary. As the tide rises, water enters the basin through sluices in the barrage. As the tide ebbs, water is retained in the basin while seas outside the barrage reach low levels. The water is then released through turbines into the surrounding seas, generating electrical power. Variations such as bidirectional turbines have been proposed as an improvement over the sluice-turbine scheme. Many high tidal areas are being analyzed for future power plant construction.

Energy Production From Salinity Gradients

There are two approaches to using salt gradients to produce useful energy. The first utilizes the differential osmotic pressure that exists at the interface between fresh river water and salty sea water. This is salinity gradient osmotic pressure technology. The second approach employs a man-made salinity gradient, usually in a man-made reservoir. Fresh water is injected into salt brine such that a salinity gradient is formed that suppresses natural convection and allows heating of the bottom zone of the reservoir by solar thermal input. This approach is known as salinity gradient solar technology. These two technologies are discussed individually below.

Salinity gradient osmotic pressure technology. The history of the use of salinity gradients for the production of useful power generation dates to only 1939.[13] Pattle suggested the use of the osmotic pressure differential between river water and sea water to generate power and actually constructed an apparatus in 1954 that produced power. Loeb et al[14] constructed and tested a system which proved some of the technology but was not economically viable. Although interesting from a physics point of view, osmotic pressure salinity gradient power generation has proven impractical to engineer. The drawback is that a workable semi-permeable membrane has yet to be produced. Virtually no work is being done in this area, so there is little hope for meaningful power generation from natural salinity gradients.[15] As such, this topic will not be given further coverage in the sections that follow.

Salinity gradient solar technology (SGST). SGST was not invented, it was discovered. Naturally occurring salinity gradient solar lakes are found in many places on earth. The phenomenon was first observed in Transylvania in the early 1900's where natural salinity gradient lakes formed when fresh water from melting snow flowed onto salt brine lakes and mixed to create a salinity gradient allowing the sun to heat the bottom layers of the lake.

The capability of salinity-gradient solar technologies to capture and store solar thermal energy is unique. One of their main advantages over other solar technologies is that this energy is available on demand, decoupled from short-term variations in solar input, which is an important factor in examining potential applications for this technology. Another advantage is that these technologies can utilize what is often considered a waste product, namely reject brine, as a basis to build the salinity gradient. This is an important point when considering using solar ponds for inland desalting and fresh-water production, or for brine concentration in salinity control and environmental cleanup applications.

SGST applications include using the salinity gradient to protect fish from cold kill in aquaculture applications; to control crystallization in certain mining operations; and to attain higher temperatures in salinity gradient solar ponds for water desalination, process heat, or electricity production. Solar ponds have been the focus of considerable research over the past several decades. Extensive technology descriptions for salinity gradient solar ponds are contained in numerous published sources.[16,17,18,19,20]

Development Issues: Special Considerations for Large-scale Use

Hydropower

Although hydropower does not emit air pollution, there are environmental concerns associated with its development. Streamflow alterations can adversely affect aquatic life and can alter components of water quality such as oxygen content and temperature.[21] Dam diversions and damming streams also impede the upstream and downstream movement of fish. Finally, the potential impact of flooding from a hydropower facility on upland areas requires assessment. These concerns must be addressed on a case-by-case basis.

Legal and regulatory impediments to hydropower development are significant. Local, state, and federal governments, Indian tribes, and public interest groups have become involved in the regulation process. Disagreement can exist over who should develop the resource and how to compensate existing landowners where a hydropower facility would require a dam and reservoir to be built. Environmental protection, economic regulation of water and electricity, safety, and land use are the major regulatory categories. Frequently, solutions to these societal problems are more difficult and expensive to solve than those imposed by nature.

Ocean Energy

OTEC. The U.S. Department of Energy has funded a number of studies into the environmental impact of OTEC plants. Some of these potential impacts are: (1) disturbance of the seabed due to construction, especially areas of ecological importance such as coral reefs; (2) attraction of marine organisms to the structure and lighting which can then become trapped in the warm water intakes; and (3) perturbance of the natural thermal and salinity gradients and levels of dissolved gases, nutrients, trace metals, and carbonates. Current evidence suggests that these impacts are minimal. Leaks of the working fluid, however, could have a much more serious environmental impact. An ammonia spill from a 40 MW plant could destroy marine life over an area as large as $4km^2$.[22]

Waves. Because of the low magnitude of the resource, wave energy systems would require large installations along the shoreline for bulk power generation. It is easy to imagine many regulatory hurdles for such development. An exception to this might be installation of wave energy equipment on a local basis, such as supplying power to a remotely-sited hotel. Wave buoys might be an eyesore but would be relatively environmentally innocuous. A more significant near-term stumbling block is simply the demonstration of an economically feasible wave energy machine capable of withstanding the rigors of ocean conditions, a goal that has eluded many researchers and entrepreneurs.

Tides. In addition to potential interference with tourism and fishing, adverse environmental impact on the estuarine ecosystem is a primary drawback of tidal energy development. Barrages can however provide protection from coastal flooding. A site specific environmental impact study would be required for any proposed plant. The output of a tidal power plant is proportional to the square of the tidal range. Because tides throughout Texas are so small, a tidal facility with meaningful output would require a barrage of such length that the environmental impact alone would exclude its use.

Energy from Salinity Gradients

Salinity gradient solar technology (SGST). SGST has moved forward significantly over the last several decades and may be poised to make sizable contributions as a near-term renewable energy technology. Impediments to the technology center around the salt water resource. For large-scale development,the salt water resource must be abundant in regions of good solar radiation and inexpensive land. More importantly, salt water cannot be allowed to leach into ground water. For this reason, solar ponds should not be built above moving ground water that is close to the surface. In many cases, a liner may be necessary to contain the brine.

Salt and brine are typically considered to be environmentally harmful products rather than resources. Inland desalination for surface water cleanup, chloride control projects, or disposal of "produced water" pumped coincidentally with petroleum from oil wells yield concentrated brines that pose a disposal problem. Solar ponds can utilize these waste brines. Near-term SGST development may therefore follow such desalting programs where the economic and environmental synergism between application and technology gives them a competitive edge.

SURVEY

Fundamental Data Collection

Hydropower

The U.S. Army Corps of Engineers completed a comprehensive study of U.S. hydropower resources in 1981.[23] This 23 volume study entitled the *National Hydroelectric Power Resources Study*

(NHS) includes all 50 states and Puerto Rico. Its purpose was to evaluate the potential for additional U.S. hydropower sites and to prepare a plan for future development under the jurisdiction of the Secretary of the Army. It included analysis of all physical aspects of hydropower development including economic, social, environmental and institutional factors. The study focused on conventional hydropower potential. Run-of-river, storage, and diversion projects were included in the inventory, and all sites, both Federal and non-Federal, were assessed. Although this resource is somewhat dated it does serve as a good source of comparison of the Texas hydropower resource with other regions of the U.S.

Two more recent studies were conducted by the Federal Energy Regulatory Commission (1992) and the U.S. DOE (1993). These studies are entitled *Hydroelectric Power Resources of the United States* [2] and *U.S. Hydropower Resource Assessment: Texas*[24] The U.S. Bureau of Reclamation also conducted an earlier study. An evaluation of regional pumped storage potential can be found in Volume 10 of the NHS .[23]

Ocean Energy

OTEC. The natural resource for OTEC plants is the temperature difference between the surface water and the colder water at depth. OTEC plants operate on a relatively small temperature difference, so an accurate knowledge of this temperature difference is imperative in determining their economic feasibility. The primary sources of thermal data for the Gulf of Mexico are NOAA's National Oceanographic Data Center and the U.S. Navy's Fleet Numerical Weather Center.

Waves. Both visual observations and gauge measurements have been collected to document wave height in the Gulf of Mexico. Visual surf observations were performed by the Coast Guard from 1954 to 1964, but are too far from Texas to be of use in this study. In addition, it appears that much error was incorporated into the observations, so use of this data is considered problematic.[25] Deep water visual shipboard Summary of Synoptic Meteorological Observations (SSMO) data have been collected in coastal areas, including the Texas coast.[26] Visual shipboard observations are also collected by the U.S. National Weather Service through its Cooperative Ship and Nearshore Observation program. These observations are relayed by radio from ship to shore at synoptic times (0000, 0600, 0120, and 1800 Greenwich Mean Time). The visually estimated wave height and period of both sea and swell are recorded.[27]

Accurate visual estimates of wave height and period from a moving ship are difficult. Comparisons with buoy measurements indicate errors of up to one meter in wave height and 2 seconds in wave period.[28] Also, because data is collected only along ship routes and at irregular intervals, it is not a statistically valid sample.[29] Finally, the data tends to be biased toward fair weather conditions since ships avoid storms whenever possible.

Gauge measurements of shallow water wave heights were conducted by the Coastal Engineering Research Center (CERC) using the pier gauge at Galveston in the 1960's and 1970's.[30] NOAA also operates four buoys in the central Gulf of Mexico.

Tides. The Texas Coastal Ocean Observation Network (TCOON) contains more than 40 tide gauges located along the Texas Gulf Coast (see Figure 7.1).[31] The network is sponsored by the Texas General Land Office, the Texas Water Development Board, Texas A&M University's Conrad Blucher Institute for Surveying and Science in Corpus Christi, and Lamar University. The primary function of the TCOON network is to precisely determine mean tide levels for boundary delineation between state and private lands. The National Oceanic and Atmospheric Administration (NOAA) also cooperates in the endeavor.

Salinity gradients

The Texas Water Development Board commissioned an assessment of saline water (>3,000 ppm of total dissolved solids or TDS) that was published in 1972. Utilizing geologic well records, the study detailed the distribution and chemical composition of surface and subsurface saline water throughout the state. The Water Development Board continually adds to its knowledge of water resources, saline or otherwise, through monitoring of water chemistry in the streams, reservoirs, and aquifers that feed into municipal water supply systems.

Information Sources

The Texas Water Development Board periodically publishes *Water for Texas*, a comprehensive plan for satisfying the State's future water needs. Commonly referred to as the Texas Water Plan, this series of documents contain detailed information on a host of Texas water issues and related planning issues such as population and economic growth. Major Water Plans have been published in 1968, 1977, and 1984.[32,33,34] Numerous plan updates have also been completed, including updates in 1990 and 1992.[35,36] A major effort is currently un-

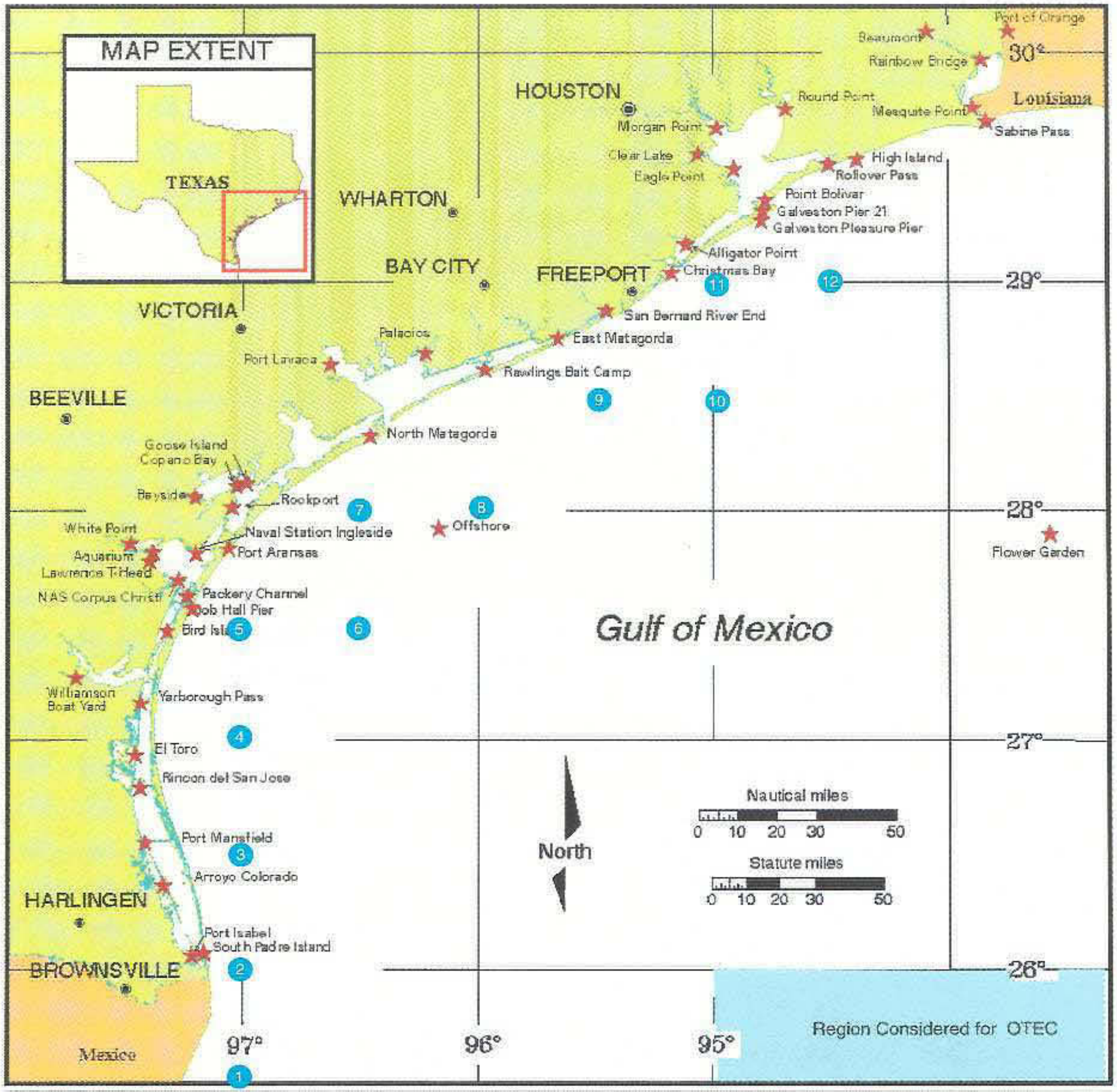

FIGURE 7.1. Texas Coastal Ocean Observation Network (TCOON) Tide Measurement Sites.[31] TCOON sites are indicated by red stars. Also shown are the locations of the wave hindcast stations used by the Army Corps of Engineers (blue dots with numbers) and the ocean area nearest to Texas evaluated for OTEC potential (due east of Brownsville).

derway at the TWDB, with input from the Texas Natural Resource Conservation Commission and Texas Parks and Wildlife Department, to produce a new *Water for Texas* to be published in 1996.

Hydropower

Portions of the Army Corps of Engineers' National Hydroelectric Power Resources Study of particular interest to Texans include *Volume 10, An Assessment of Hydroelectric Pumped Storage,* and *Volume 21, Regional Assessment: Electric Reliability Council of Texas.*[23] An inventory of Texas' low-head hydroelectric resources (hydraulic head less than 20 meters) was also produced from the NHS, and is available in the western states inventory of low-head hydroelectric sites.[37]

The Federal Energy Regulatory Commission has compiled a hydropower resource assessment for most sites in the United States based on reports of federal agencies, states, federal-state entities, and others.[2] These estimates were based on natural stream flow, regulation of stream flow by storage, and available head at power sites. Although the report claimed that the sites evaluated had shown "indications of engineering feasibility," it did not include environmental or economic feasibility assessments of most of the sites. The report is intended to provide the upper limit of the conventional U.S. (and Texas) hydropower potential.

The DOE's Idaho National Engineering Laboratory (INEL) developed a computer model to evaluate the hydropower potential of a given site called the Hydropower Evaluation Software (HES). It was used to measure the potential hydropower resources in the United States using uniform criteria for measurement. The Texas resource assessment has been compiled in a booklet entitled *U.S. Hy-*

dropower Resource Assessment: Texas.[23] Information on the Hydropower Evaluation Software can be obtained directly from INEL.

Ocean Energy

OTEC. The National Oceanographic Data Center maintains the information it collects regarding ocean surface temperatures, temperature differences, seasonal variations, etc. The Department of Energy also has extensive OTEC resource data. Under contract to the DOE, Ocean Data Systems Inc. (ODSI) developed a computer data base of temperature soundings for OTEC areas of interest based on NOAA and Navy data. Temperature profiles were compiled for 1 degree longitudinal and latitudinal squares. ODSI published reports for six geographical OTEC regions, including one for the western Gulf of Mexico.[38] This data base is the best source available for analyzing ocean thermal resources.

Waves. The Coast Guard wave observations discussed above are available on CD from the National Climatic Data Center (NCDC). Likewise, the NCDC archives the shipboard observations collected through the NWS cooperative program.[27] SSMO data has been published by the U.S. Naval Weather Service Command.[27] Gage data for four central Gulf locations is available from the National Oceanographic Data Center, in Riverdale, Maryland.

Rather than relying solely on visual observations, wave intensities are commonly estimated by the use of a "hindcast" model. Hindcast data predicts wave characteristics by using measured wind fields as inputs to a computer model. Its accuracy has been verified against actual data.[39] Herbitz[40] also used 1988 data from buoys operated by NOAA in the Gulf to calibrate the hindcast model. Comparison of data from nearby buoys to hindcast estimates made for the same time period showed very good agreement most of the time. The authors advise that users of hindcast data interpret significant wave height to be low in the mean by 0.1 m.[41]

The U.S. Army Corps of Engineers computed twenty years of hindcast wave data at three hour intervals for 56 stations along the Gulf Coast. Eleven of these are off the Texas coast (identified in Figure 7.1). This hindcast data includes direction, period, and height of the waves. The mean and largest wave heights for each year have also been tabulated at each station. Hindcast estimates produce reasonable accuracy and are the most extensive estimation of wave information available.

Tide tables. Tide tables have been published by the National Ocean Service since 1853. For a number of years these tables consisted of detailed instructions, enabling mariners to make their own predictions of tides as the occasion arose.[42] The first tables to give predictions for each day were published in 1867. Tidal tables are now issued for much of the world. They are computed using a computer program that relates tide levels to relative positions of the sun, moon and the earth as well as to harmonic components of the earth's surface at each location.

Tide tables contain daily high and low tide height and time predictions for 198 reference ports. Galveston is Texas' reference port. **Table 7.2** shows the tidal predictions for a portion of July 1995 at Galveston. Tide predictions for 6,500 other locations called "subordinate stations" can be predicted by applying differences to the predictions for the reference ports. Tidal heights and times can be predicted for twenty-six additional Texas sites using this method. Weather conditions can modify actual tides to some extent.

Tide tables, tidal current tables and charts, and nautical charts are all available from NOAA. Likewise, for those requiring an even more detailed dose of Texas tidal information, time series tide gauge readings are available from the TCOON network and from NOAA.

Salinity gradients

The Texas Water Development Board's survey of the state's saline water resource was published in 1972 in a multi-volume set that is available from the Board.[43,44,45,46] The *1968 Water Plan* also included information on the chloride characteristics of Texas' surface waters.[32]

TABLE 7.2. Tidal Predictions for Galveston for July 1995. Reproduced directly from *Tide Tables.*[42]

July							
	Time	Height			Time	Height	
	h m	ft	cm		h m	ft	cm
1 Sa	0729	1.3	40	16 Su	0024	0.0	0
	1257	0.9	27		0735	1.2	37
	1558	1.0	30		1348	0.5	15
	2352	0.1	3		1916	1.0	30
2 Su	0756	1.3	40	17 M	0109	0.3	9
	1342	0.8	24		0804	1.2	37
	1720	0.9	27		1450	0.4	12
					2054	0.9	27
3 M	0027	0.2	6	18 Tu	0152	0.6	18
	0819	1.3	40		0831	1.2	37
	1427	0.7	21		1552	0.2	6
	1917	0.9	27		2246	0.9	27
4 Tu	0105	0.4	12	19 W	0237	0.8	24
	0839	1.2	37		0857	1.1	34
	1513	0.5	15		1650	0.1	3
	2121	0.8	24	◑			
5 W	0148	0.6	18	20 Th	0059	1.0	30
	0855	1.2	37		0348	0.9	27
	1602	0.3	9		0920	1.1	34
◐	2318	0.9	27		1743	0.0	0

OVERVIEW

Average Annual Summary

Hydropower

Texas currently has 643 MW of conventional hydroelectric power generating capacity, which represents about 1% of the state's total electric capacity.[3] **Table 7.4** lists the individual facilities and their capacities by river basin. Texas' undeveloped hydropower potential at 89 sites identified in the DOE's recent assessment is estimated to be about 1000 MW.[24] Of this total, about 200 MW is undeveloped potential at existing facilities and 800 MW is at undeveloped sites. **Table 7.5** shows the developed and undeveloped capacities for each of the Texas river basins.

Texas' undeveloped potential of 1,000 MW represents about 1.4 percent of the undeveloped U.S. potential.[2] Texas utilities presently generate about one percent of the U.S. hydropower total. Washington, Oregon, and California generate about half of U.S. hydropower. These states, along with the Rocky Mountain region also have the largest amount of undeveloped hydropower, estimated to be over 40,000 MW, or about 55 percent of the U.S. total.

Existing sites without hydroelectric generating facilities would require retrofitting and re-permitting. Additionally, most of the undeveloped sites referred to in this study may not be built for many decades, if at all. Due to economic and environmental constraints, much of the estimated 1000 MW of additional hydropower identified in Texas may never be developed.[47]

The capacity, or power rating, of a hydropower facility is only one aspect of its potential contribution to the state's energy mix. To determine the total annual energy derived from hydropower, we must examine the capacity factors of various facilities. An annual capacity factor is a fraction given by the amount of energy a facility generates in a year divided by the total possible energy it could generate if it ran at full power all year long. Capacity factors for representative Texas hydro systems are shown in Table 7.5. Because Texas has limited water supplies, water systems are managed first for water supply and flood control needs and secondarily for power production. Accordingly, capacity

TABLE 7.4. Existing Hydroelectric Power Plants in Texas.[3]

BASIN	DAM	RESERVOIR	CAPACITY (MW)	TOTALS (MW)
Red	Denison	Lake Texoma	89.0	89.0
Sabine	Toledo Bend	Toledo Bend	80.0	80.0
Neches	Sam Rayburn	Sam Rayburn	52.0	52.0
Brazos	Morris Sheppard Whitney	Possum Kingdom Whitney	22.6 30.0	52.6
Colorado	Buchanan Roy Inks Alvin Wirtz Max Starke Mansfield Tom Miller	Buchanan Inks LBJ Marble Falls Travis Austin	37.5 11.5 52.0 32.0 93.0 15.0	241.0
Guadalupe	TP-1 Abbot (TP-3) TP-5 H-4 H-5 Seguin Canyon City of Gonzales City of New Braunfels	Dunlap McQueeny Nolte H-4 H-5 TP-4 Canyon	3.6 2.4 2.0 1.9 2.1 2.4 6.0 1.1 0.5	22.0
Rio Grande	Amistad Eagle Pass Falcon	Amistad* Canal Falcon*	66.0 9.0 31.5	106.5

**Mexico has matching generation capacity at these sites: 66 MW at Amistad and 31.5 MW at Falcon.*

factors for Texas hydropower systems are relatively low. This fact lowers the potential impact of developing hydropower as an energy resource.

Texas has no operating pumped storage facilities. The Lower Colorado River Authority operated one between Inks Lake and Lake Buchanan in the past but the current difference between peak and off-peak power rates is not great enough to make its operation economically feasible at this time. Texas total potential pumped storage capacity is estimated to be 1,300 MW.[24] This number represents about two percent of the estimated U.S. pumped storage potential. It should be noted that although Texas' pumped storage potential capacity is relatively small, it could be a valuable resource in that it represents a renewable source of peaking capacity.

Ocean Energy

OTEC. For several hundred miles off the Texas coast, the ocean depth in the Gulf of Mexico is less than the 1,000 meters suggested for OTEC development. The closest point to Texas analyzed by Ocean Data Systems, Inc. in their assessment of the OTEC resource (identified in Figure 7.1) is more than 100 miles offshore. These facts point to the difficulty in classifying any energy conversion from this source as a Texas resource. Furthermore, average annual temperature differentials at the sites closest to Texas are in the 18° to 20°C range. This is considered a very marginal temperature difference for OTEC development.

Worldwide, the best OTEC resource areas will be in equatorial regions with sufficient depth and ocean temperature differentials as high as 25°C. The best U.S. OTEC resources are off the coasts of Hawaii and Puerto Rico. The Texas coast has never been seriously considered as an OTEC resource area and the possibility of developing OTEC here in the near future is remote.

Waves. **Table 7.6** displays the mean significant wave height for the twenty years 1956 through 1975 for the eleven Texas Gulf locations shown in Figure 7.4. These values were predicted using hindcasting techniques.[39] The potential power from the waves was then calculated using standard methods.[48]

The greatest mean significant wave height is found at Station 2 located off the southernmost tip of Texas and is approximately 1.4 meters. The mean significant wave heights of the eleven locations off the Texas Coast range between 0.9 and 1.4 meters. These figures compare favorably with wave heights charted along the U.S. Atlantic Coast but are somewhat smaller than those charted along the U.S. Pacific Coast.

For those who have been to all three coastal areas, this statement regarding the relative size of Gulf waves may seem curious. It is important to remember that the wave estimates are made for locations miles off shore. The Texas Gulf Coast is much more shallow than along the Atlantic and Pacific coasts and as a result tends to dissipate waves to a greater degree. Shoreline observers will witness greater waves reaching the beaches in California and Florida than in Texas.

This phenomenon is relevant when proposing wave energy plants in Texas in that waves would have to be harnessed while they still have a reasonable amount of energy, many miles off the shore. In fact, the major thrust of Windle's[49] promotion of his wave harnessing technology is the utilization of abandoned drilling platforms of which he claims there are thousands. Such generated electricity would be utilized to produce liquid or gaseous hydrogen locally which would be shipped or

TABLE 7.5. Number of Sites and Associated Hydroelectric Potential of Texas Rivers.[3,24]

RIVER BASIN	EXISTING		UNDEVELOPED POTENTIAL			
	NUMBER OF SITES	RATED CAPACITY (MW)	NUMBER OF SITES	RATED CAPACITY (MW)	ANNUAL ENERGY (GWh)	CAPACITY FACTOR
Red	1	89	13	371	1,028	32%
Neches-Sabine	2	132	10	20	43	25%
Trinity	0	0	16	180	569	36%
Brazos	2	53	12	52	83	18%
Colorado	6	241	14	368	874	27%
Guadalupe	8	22	18	21	50	26%
Nueces	0	0	2	4	11	29%
Rio Grande	3	107	4	2	1	7%
Total	22	643	89	1,019	2,659	30%

pumped to shore. Conduction of electrical power from a remote location into a transmission network would be cost prohibitive.

The United Kingdom has some of the most powerful wave activity in the world. Even with this large wave energy potential, no commercial systems have been constructed to satisfy energy demand. In fact, the UK has stopped funding further wave energy development and the U.S. has in turn followed this lead.[15]

Tides. Mean tidal ranges in Texas vary from a minimum of 0.5 feet at Port O'Connor, Matagorda Bay to a maximum of 2.8 feet at Sabine Bank Lighthouse. Median predicted diurnal tide range for the 27 Texas locations is 1.3 feet.[42]

Texas' largest mean tidal range at Sabine Bank Lighthouse of 2.8 feet is dwarfed when compared to Passamquoddy Bay's (Maine) mean tidal range of 18 feet. Because tidal power generation varies as the square of the mean tidal range, the available tidal power at Passamquoddy is 40 times that of Sabine Bank. This comparison becomes especially meaningful when one considers that the development at Passamquoddy was abandoned due to its marginal economic feasibility! While other factors impact site viability, the relatively minute amount of available tidal energy in Texas helps explain why the Texas coast has never been seriously considered for tidal power development.

While mean tidal range is an important criterion in site analysis, other factors will affect a site's feasibility. For instance, even if an area experiences great tidal fluctuations, it may not be suitable if it has limited available basin area or if its required barrage would be prohibitively big and expensive. Conversely, a site with marginal available energy may be viable if its geographic features offer great storage and an opportunity to construct a relatively inexpensive barrage. Techniques have been developed and are available for site parametric analysis.[50,51]

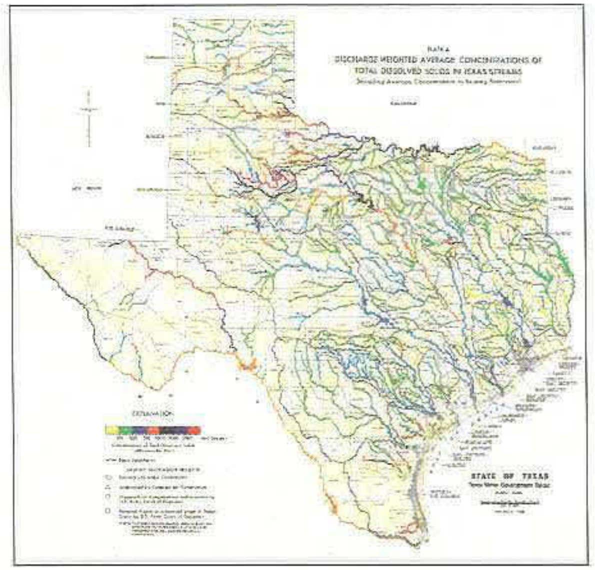

FIGURE 7.2. Salinity of Texas Surface Waters (Reproduced from 1968 Water Plan).[32] The high salinity levels in western Texas (shown in red on map) hamper fresh water quality but are an asset for salinity gradient solar technology.

Table 7.6. Mean Significant Wave Height and Wave Power for Wave Stations Adjacent to Texas.

STATION NUMBER	MEAN WAVE HEIGHT (meters)	ADJUSTED MEAN WAVE HEIGHT (meters)	MEAN PERIOD (seconds)	POTENTIAL POWER (kW/m)	RECOVERABLE POWER* (kW/m)
2	1.5	1.4	6.8	6.4	1.9
3	1.4	1.3	6.6	5.4	1.6
4	1.4	1.3	6.6	5.4	1.6
5	1.4	1.3	6.1	4.9	1.5
6	1.5	1.4	6.5	6.1	1.8
7	1.3	1.2	5.9	4.1	1.2
8	1.3	1.2	6.2	4.3	1.3
9	1.0	0.9	5.7	2.2	0.7
10	1.0	0.9	5.9	2.3	0.7
11	1.1	1.0	5.6	2.7	0.8

**Estimated by assuming 30% of potential can be realized.*

Salinity-Gradient Solar Technology

Salinity-gradient solar applications require a unique combination of sunshine, salt, and brackish water to be a viable energy source. Texas has an abundance of these resources. Underground brine occurs throughout much of the state. As indicated in **Figure 7.2**, the extremely saline surface waters of West Texas, which include literally thousands of natural saline lakes and surface deposits, could provide sites for solar pond development. Land resources in this region are abundant since much of the land is arid and of limited use except for some ranching and oil development. Although high

TABLE 7.7. Energy Resource Base from Texas Water Sources.

	RESOURCE TYPE	TOTAL (quads)	ACCESSIBLE (quads)	COMMENTS
HYDRO	Developed	.022*	.0055	Already highly developed, some future additions possible.
	Undeveloped	.039	.0074	
OCEAN	OTEC	.022	0	Texas resources are relatively poor and far from shore.
	Waves	.041	0	
	Tides	.017	0	
SALT	Salinity gradient solar ponds	1**	1	Perhaps best potential for major contributions.

** If operated as pumped storage systems, could deliver up to an additional 0.01 quad previously generated by conventional or renewable sources.*

*** Assumes only natural saline lakes are used; with man-made structures, potential is much higher.*

quality fresh water is in scarce supply in much of the Southwest, brackish water supplies (suitable for use in solar ponds) are abundant in many areas.

Summary

The estimated total and accessible energy potential of Texas water resources is summarized in **Table 7.7**. Hydropower is the most mature resource and the best sites have already been tapped. All existing and potential hydroelectric sites considered by the DOE's recent assessment are identified in the map in **Figure 7.3** and summarized by river basin in **Figure 7.3b**. Even with aggressive development of all potential sites, the resource is still minor, with an ultimate capability that is still less than 1% of state's current energy consumption

Ocean resources are also quite modest, particularly in light of the relative immaturity of ocean energy conversion systems. Salinity gradient solar technology represent the largest potential contributor. At least one quad is estimated to be available in existing natural saline lakes; a large fraction of this

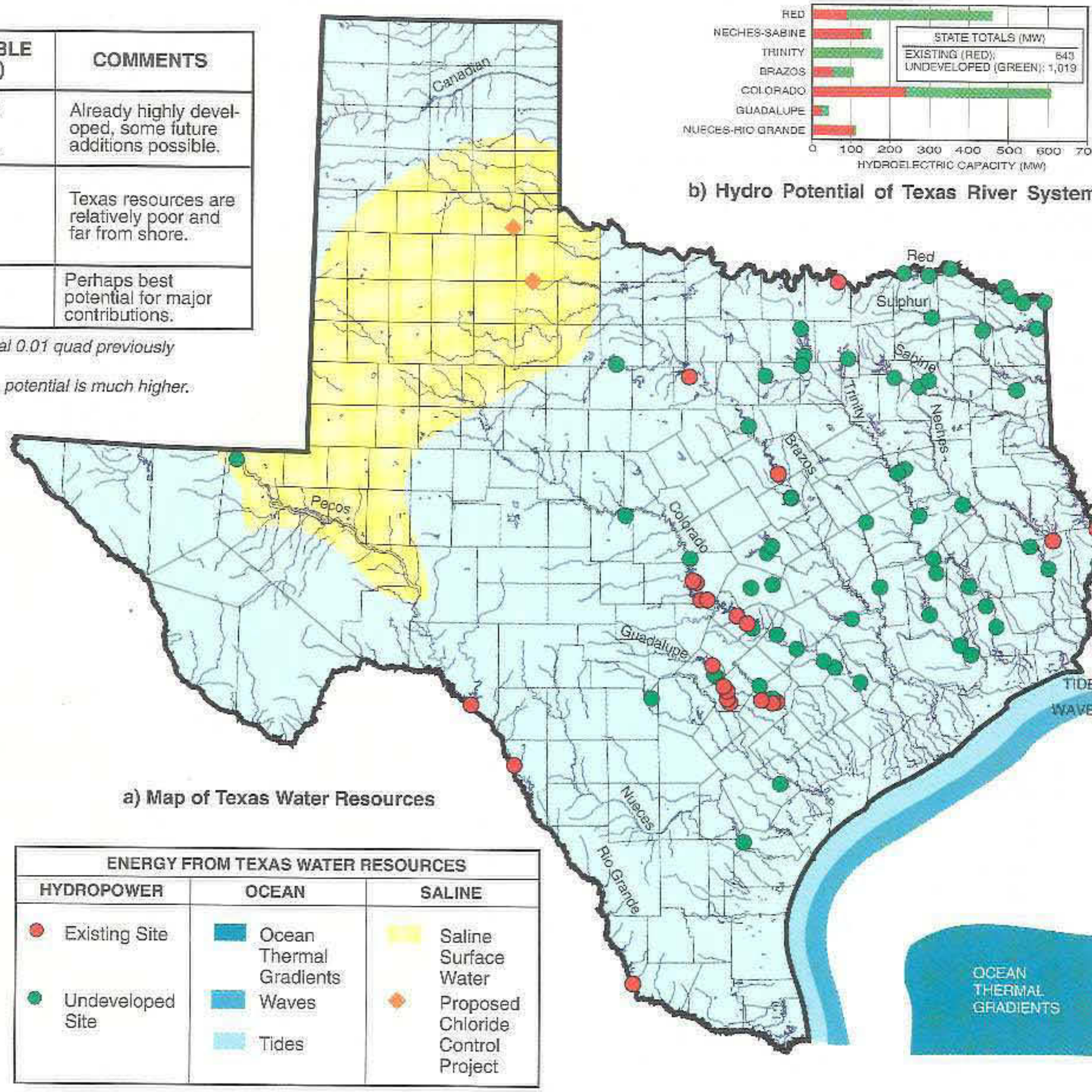

FIGURE 7.3. Summary of Energy From Texas Water Resources. The map (a) shows the location of all existing and undeveloped hydropower sites. These are summarized by river basin in (b) above. Ocean and salinity resources are also shown.

total could be utilized as low grade process heat. With man-made structures, the potential for salinity gradient solar technologies is far greater. Outside the realm of natural salt lake conversion or use at chloride control structures, solar ponds should be considered foremost as a solar energy conversion device, which are already considered in the solar chapter.

Resource Variability

Hydropower

Rainfall in Texas varies significantly from season to season and from year to year. In addition, the primary purpose of most Texas reservoirs is for flood control and/or water supply. Hydroelectric production at these installations is a desirable by-product of normal operation, but seldom does it influence the daily operation of the facilities.

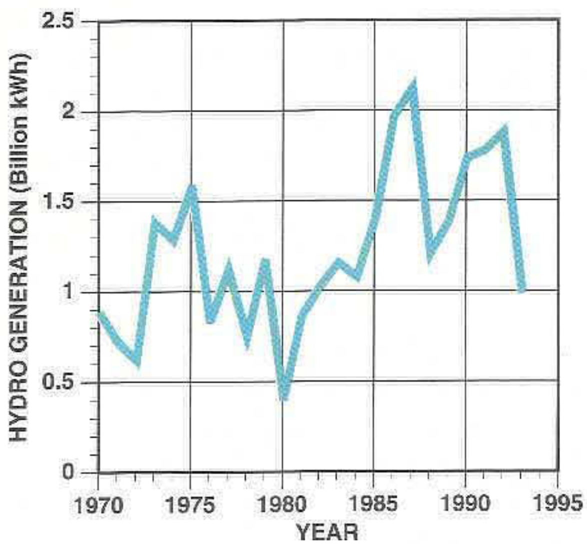

FIGURE 7.4 Total Annual Electric Generation by Texas Hydroelectric Facilities, 1970-1993.[52]

The extent of variability in the State's hydroelectric resource is demonstrated in **Figure 7.4**, which totals annual electric production from all hydroelectric facilities in Texas between 1970 and 1993.[52] Even though the state has had relatively steady hydroelectric capacity over this period, aggregate annual output is shown to vary by more than a factor of five from lowest (1980) to highest (1987) years. These values translate to annualized capacity factors of less than 10% to about 40%. It is noted that aggregating generators together and averaging over a long time scale (yearly) will serve to lessen the peaks and lows experienced at individual sites. Accordingly, typical variability for shorter time scales (months, daily profiles) and for individual hydroelectric facilities can generally be expected to be even more extreme than that indicated in Figure 7.4.

Ocean Energy

OTEC. The temperature difference between the ocean surface off the Texas coast and at OTEC depth varies significantly with season. During the winter months, the temperature difference can fall below 17°C. Also, cold core eddies and hurricanes can dramatically affect the surface temperature, making the economics of an OTEC plant in this region very difficult to predict. ODSI has published a report on OTEC that details the variability of this resource.[53]

Waves. Waves vary almost continuously in height, direction, and period. There is also significant variability in day-to-day, month-to-month, and year-to-year average wave characteristics. Since waves are driven by winds, variability in the wave resource will follow variations in the wind. Hindcast data, which relies on inputs of wind data, can be used to examine wave variability.

Tides. Tides vary with the rising and setting of the moon. Therefore the times at which the maximum and minimum tidal heights occur changes from day to day, but, as shown in Table 7.2, can be predicted quite precisely. Within any given month the height of the high tide on a given day may be 25% or more above or below the average tide for that month. There is also seasonal variability in the tidal range, with the highest tides generally occurring in the spring and fall and the lowest tides occurring in the fall and summer.

Salinity-Gradient Solar Technology

An important advantage of salinity-gradient solar technology is its inherent energy storage capacity that provides independence from short-term solar fluctuations and diurnal cycles. Even impacts from multi-day weather patterns are small. Energy from solar ponds is dispatchable.

Performance does, however, vary seasonally. More solar radiation can be collected by the horizontal surface of a solar pond in the summer when the sun is higher in the sky. Winter ambient temperatures also contribute to higher heat loss from the pond. Neither of these conditions prevent salinity gradient solar applications from being viable in the colder periods of the year or in colder regions of the state. It does mean that performance will peak in spring, summer, and fall months. The difference between summer peak and winter performance could be as great as a factor of three.

RECOMMENDATIONS

Hydropower

Two federal agencies identified all possible sites for conventional hydropower development in Texas and estimated the total available output from these sites. **The authors see no need for further resource assessment for conventional hydropower.**

Neither of the two Federal Hydropower studies included pumped storage potential in their estimates. While current economic conditions do not bode favorably for pumped storage hydropower, future conditions might. Therefore **we recommend that the pumped storage potential of Texas be studied.** By conducting such a study now the State will be in a better position to act if and when the economics of such systems become favorable.

Ocean Energy

OTEC. As discussed in the overview, the nearest potential OTEC sites are located several hundred miles from the Texas coast and do not possess first-rate thermal gradients. The transport of electric power from such sites is fraught with difficulties. Because a working commercial OTEC power plant has yet to be constructed, even at those sites with extremely favorable conditions, we think it unlikely that OTEC-generated electric power will be feasible for Texas in the foreseeable future. Because of this, **we recommend no further resource assessment for OTEC.**

Waves. The wave energy resource off the Texas coast varies from energetic to almost nonexistent. The waves vary dramatically with season, especially during tropical depressions and hurricanes.[14] Even in locations throughout the world with more consistent and favorable wave conditions, no commercially viable wave energy plants are yet in operation. In addition, the current generation of wave energy generating equipment has yet to be proven able to withstand the rigors of even favorable sea conditions, much less the extreme conditions occasionally encountered off the Texas coast. For these reasons, it would appear that knowledge of the wave resource derived from hindcast data is presently adequate and **we recommend no further resource assessment efforts.** However, should significant wind resource assessments be conducted along the Texas coast, it may be possible to incorporate this data into hindcast estimates to improve their resolution. Estimating significant wave height for the Northwestern Gulf of Mexico has techniques for estimating wave height for future use or site specific studies.

Tides. The tidal ranges have been well documented along the Texas shores. Because they are negligible when compared with those locations where tidal power is marginally feasible **we recommend that no further resource assessment effort be expended in this area.**

Salinity Gradient Technologies

The State of Texas has significant potential for the use of salinity gradient solar technologies due to its large land area, high levels of insolation, numerous natural salt and playa lakes, large salt deposits and abundant brine sources, both natural and man-made (such as produced water from oil wells). It is likely that Texas has the best resource base for SGST applications of any state in the U.S., but to date no statewide resource evaluation has been conducted. Since the resource base for these technologies is regional, the Department of Energy and other federal agencies are unlikely to invest in the necessary assessments required to capitalize on these natural resources for salinity gradient solar technologies. Thus, state programs are essential to accomplish this task.

Although some preliminary regional studies have been completed,[54,55] they are inadequate to determine the potential of these technologies throughout the state. If proper assessments were available, and several demonstration projects were operating successfully, salinity gradient solar technology applications could advance rapidly in the state.

In summary, an SGST specific resource assessment is needed to identify where the required resources (land, salt, brine water, insolation) are co-located with a specific local need for the energy that could be supplied. Such a study must consider both the resources and the application since the technology is not only dependent on local resources, but is also highly dependent on the load to be met (e.g. heat for oil brine separation versus energy for electrical production). Thus, a useful resource assessment would need to be categorized by end-use and matched with the natural resources available statewide.

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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.

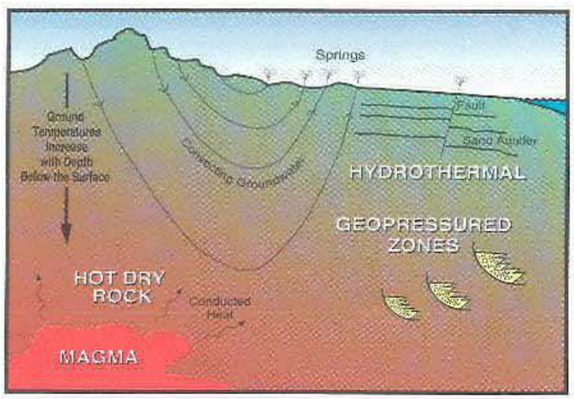


FIGURE 8.1. Portrait of the Four Geothermal Resources.

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.

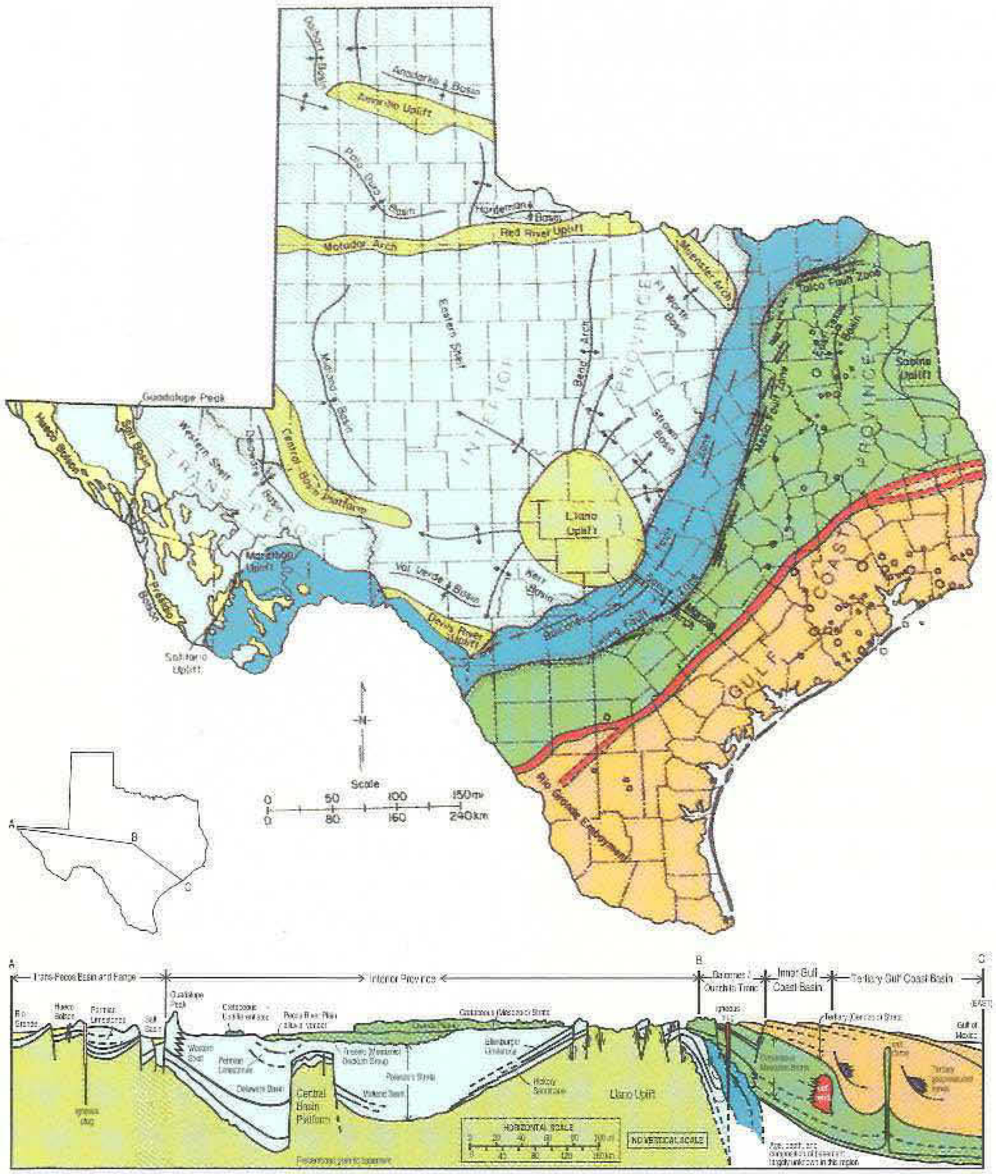
Geopressured Geothermal Energy: Proceedings of the Sixth U.S. Gulf Coast Geopressured Geothermal Energy Conference. Dorfman and Morton, 1985.[13] This compendium of papers presented to a 1985 geopressured/geothermal conference held in Austin, Texas, included topics on the production characteristics of 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



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.

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

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

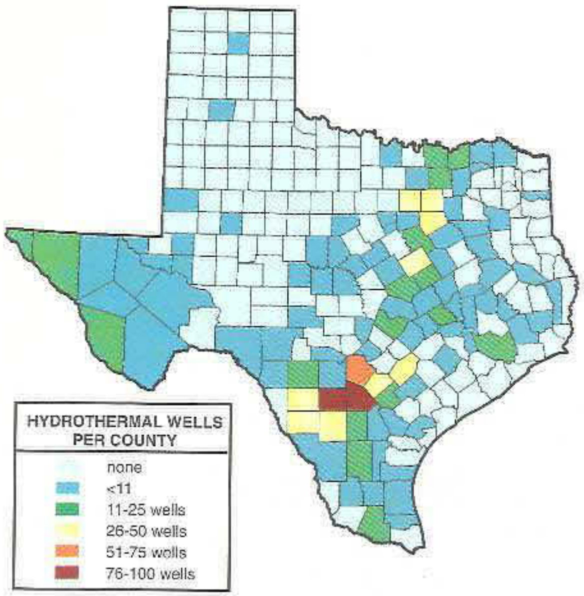


FIGURE 8.3. Texas Hydrothermal Wells and Springs.[17]

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

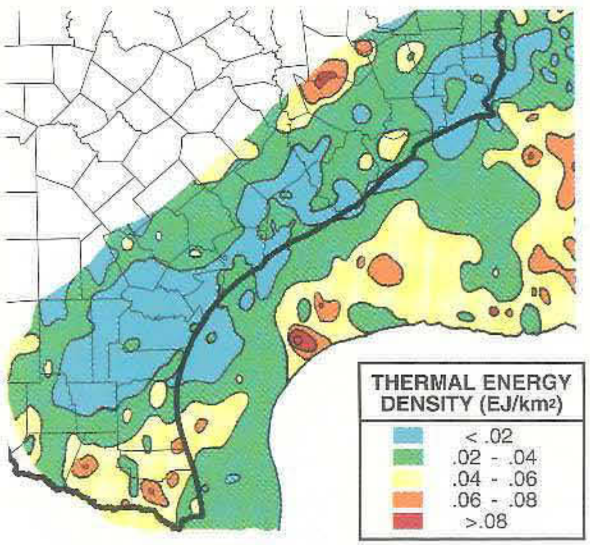


FIGURE 8.4. Distribution of Thermal Energy in the Geopressured Zones Along the Texas Gulf Coast.[17] Identifies total thermal energy contained down to a depth of 22,500 feet.

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-

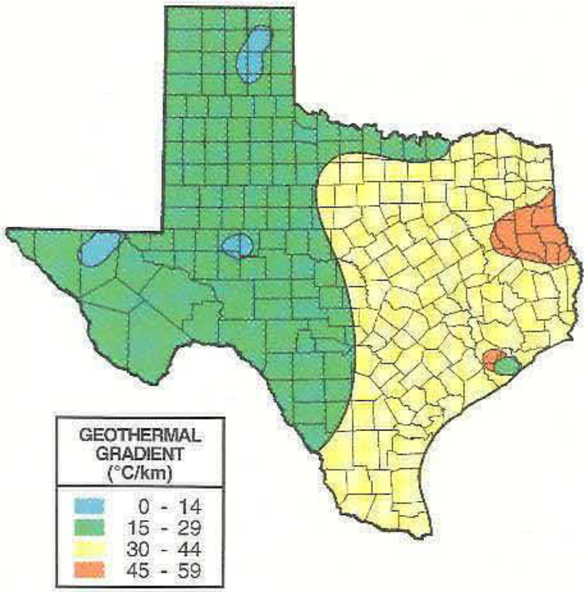


FIGURE 8.5. Typical Geothermal Gradients in Texas.[25] Texas does not have any major regions of high-grade (>60°C/km) resource for Hot Dry Rock technology.

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.

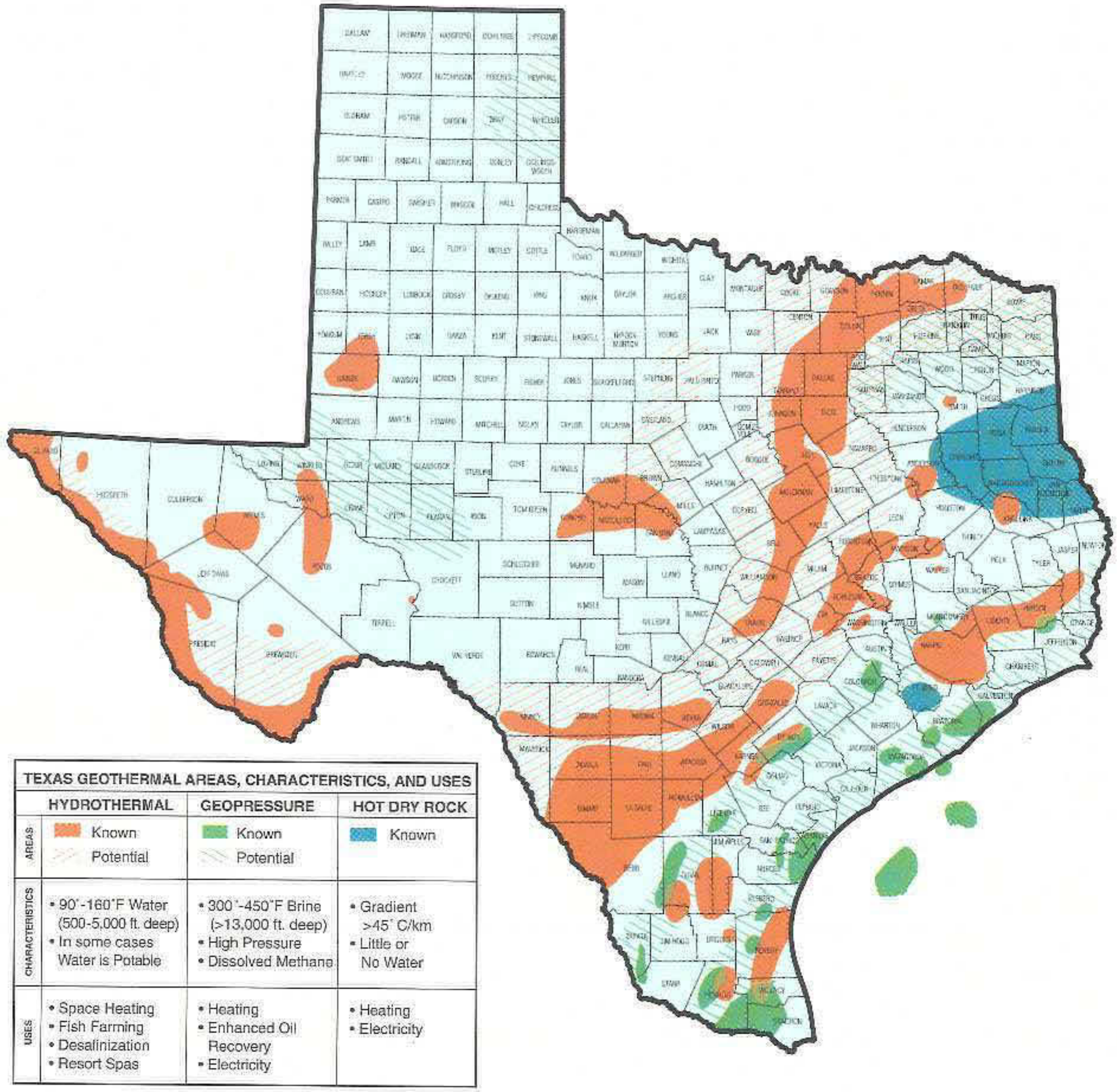
Support for hot dry rock and magma development has yet to be determined, but they hold promise as abundant and perpetual sources of energy.

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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BUILDING CLIMATOLOGY

by Leonard Bachman

INTRODUCTION

Significance of Resource: Historical and Future Uses

Building climatology refers to the study of climate as it impacts human comfort and, more specifically, to architectural strategies that exploit the climatic resource to minimize the energy demands of buildings. It is a passive approach to meeting energy requirements that requires careful tailoring of a building to its climate, site, and occupancy. In this perspective, regional climate characteristics and the microclimatic influences of the building site are viewed as the "resource" and buildings are designed and operated in the manner of a "conversion technology." Rather than constructing buildings to be visual edifices and mere containers of their intended use, passive design philosophy mandates that the building serve as prime provider of environmental conditions for comfort and activity. Those demands of environmental control that cannot be met by passive means are served by active, backup systems.

By necessity, the premises of building climatology have been incorporated into architecture throughout most of human history. Indeed, a survey of indigenous peoples around the world will illustrate the genius with which human shelter has been adapted to the character of regional climates. In hot-arid climates, the design invariably utilizes thick wall, high thermal mass structures with small openings and compact shapes. Hot-humid region builders always use large parasol roofs with open walls and raised floors built of lightweight materials. Cold climate strategies are much like hot-arid buildings in their defensive compactness and sheltered openings. In temperate climates of course, a less significant, even nomadic type structure suffices. Using American Indian examples of regional adaptation, one can compare the pueblo, the Seminole hut, the igloo, and the teepee to their native climates.

Eventually, people's building habits began to reflect cultural influences as much as physical ones. This gave rise to regional flavor and an ascendance of vernacular architectural style. Adaptation to climate was melded with the functional requirements of a non-primitive lifestyle. Eventually, specialization and standardized building methods played a role in the changing shape of buildings. One factor that did not change was the dependence on a climatic orientation for comfort. Although wood or coal was burned for heating and cooking, ventilation, shading, insulation, and thermal mass were still important considerations in building design. The traditional styles that evolved along climate responsive lines include the Cape Cod salt box, the southern Plantation, the western Mission or Santa Fe style, and the Texas "dog trot" houses.

Regional architectural styles continued to be influenced by climatic character for as long as occupant comfort was dependent on non-mechanical means. The demand for artificial means of providing comfort began with urban density. Urban living patterns began to place people in densely packed dwelling units in which the availability of light and air to every room was blocked. As radiant heating, electrical lighting, fan-forced ventilation, and eventually electrical cooling were progressively employed to facilitate occupant comfort, the density of living and working conditions could constantly be increased. For modern cities to be possible, these inventions had to be realized. The high-rise office building we know today would probably not be viable without the cool and efficient fluorescent lamp.

Mechanical space conditioning—coupled with inexpensive and seemingly abundant electrical generating resources—made reliance on passive design unnecessary. Ranch houses went to New York and Cape Cods came to Houston. Glass boxes were everywhere. Architectural design, for a time, was liberated from the influence (and inspiration) of regional context. The efficiency and appropriateness of building envelopes was replaced by inexpensive heating and cooling systems. It seemed like the best of both worlds, comfort and stylistic expression.

Since the advent of oil shortages and the growth of environmental awareness, however, passive design has begun to re-establish itself as a sensible and practical alternative to more energy-intensive practices. Employing the vast, benign, and renewable energies of the climate to meet building energy needs seems somehow wiser than dependence on depletable and polluting energy sources. And with rising energy prices, investment in efficient buildings becomes more attractive. Among designers, there seems to be a longer-range and more realistic attitude concerning the viability of our building stock and the well-being of their inhabitants. This attitude is evident both in the actions of builders and their clients as well as the regulatory environment.

Development Issues: Special Considerations for Large-scale Use

Several key factors may slow the adoption of passive building strategies in Texas. Chief among these is a traditional first-cost orientation in the building trades industry combined with a history of inexpensive energy costs and building codes that require only minimum levels of energy efficiency. Until very recently, construction budgets have been dominated by first cost targets. This tended to de-emphasize long-term savings and environmental benefits in favor of efficiency of material and labor investment. This attitude may, however, be changing. Concern for building operating costs and the continually growing public consciousness of environmental issues indicate a willingness to pay extra "up front" for less consumptive—yet comfortable—buildings. Energy Efficiency Mortgages (EEM), that allow buyers to afford slightly more expensive, energy-efficient homes, is one way of addressing the problem. The pending implementation of energy codes, such as ASHRAE 90 and state and local building codes, will also hasten this transition.

Another obstacle confronting wide scale implementation of passive techniques is essentially institutional—that is, a generally incomplete understanding of Texas building climatology. Since the air conditioner was adopted as the panacea of environmental solutions in the 1950s, the awareness and practice of passive heating and cooling techniques have fallen into general disuse. This will change only as professional architectural practice begins to re-embrace regionally appropriate construction strategies. In the meantime, Texas, like all other states, is now dominated by an inventory of buildings that were intentionally designed to utilize inexpensive electricity and be fully serviced by mechanical air conditioning. These buildings have a posture towards the climate that is defensive at best (witness the construction of windowless schools built in the name of energy efficiency). In many cases, building shells can be upgraded and comfort equipment retrofitted with passive or hybrid passive/mechanical systems. But because building climatology begins with orientation, siting and massing decisions, few buildings in today's inventory will ever realize the full potential of designing with the climate.

SURVEY

Fundamental Data Collection

The relationship between climate and architecture can be fundamentally described by measures of those climatic elements which are most significant to building energy performance. The governing standard is human comfort. More technical classifications of climate exist for meteorological purposes such as those of Koppen (1922) and of Thornwaith (1931, 1948), both of which are based on seasonal patterns of temperature and rainfall.[1] Other classifications would include continentality, altitude, vegetation type and other indicators. These scientific descriptions are often useful in determining the boundaries of distinct climate types, but are less helpful in prioritizing and designing the appropriate building response.

The particular measures that are significant to buildings would be:

- Solar radiation on horizontal surfaces, direct and diffuse components
- Global solar radiation of a vertical south facing surface
- Wind speed, direction, and variability
- Normal degree days heating and cooling
- Daily variation in dry bulb temperature, also called diurnal flux
- Dry bulb temperature frequency distribution and mean coincident wet bulb temperature.

Solar radiation measurements have been compiled by the National Renewable Energy Laboratory from a variety of historical surveys that are summarized in a previous chapter (chapter 4). Most of the other factors are standard meteorological readings collected by the National Weather Service (see chapter 3). Dry bulb temperature frequency distribution and mean coincident wet bulb temperature is a non-standard data set collected at military bases or derivable from NWS records.

As important as all of these factors are, two other parameters determine whether or not the climate is a resource, a benign event, or a liability. First is the correlation of climate factors themselves—that is, is there sunshine when the weather is cold, does the wind blow from a predictable direction when ventilation is useful, and is humidity low when temperatures are high. These and many other relationships are required to determine the value of a particular climate's assets. These correlations are not surveyed directly, but can be largely determined from existing meteorological records of sufficient temporal resolution.

Secondly is the question of the building type as a candidate for the climatic resource. Buildings each have their own thermal metabolism, just as humans do. Buildings produce heat inside by use of lights and equipment, and even from the occupants' own metabolisms. Simultaneously a building is constantly exchanging heat with the outdoor environment through the dynamics of conduction, convection, solar radiation, ventilation, and moisture exchanges. Some entire buildings and zones of many others are perpetually overheated and so must air condition year round. The ability of such structures to tap the climate as a resource is limited. To date, only the most preliminary assessments of the Texas building stock and the degree to which it can be meshed with passive strategies have been conducted.[2] No ongoing surveys were identified. Accordingly, estimates—including those provided later in this chapter—of the potential energy reductions achievable through adopting building climatology principles inherently reflect a high degree of uncertainty.

Information Sources

The following documents include information on climate and climate-responsive architecture most essential for understanding the Texas resource.

Armed Forces Weather Engineering Manual, DOD.[3] Contains frequency distribution by hourly occurrence of dry bulb temperatures in 5°F temperature bins with the mean coincident wet bulb temperature for each temperature bin. The armed forces maintained and published this manual for military stations around the world. Fourteen Texas stations are listed including the major population centers of the state and at least one station for each of the Texas climate regions categorized in this report. This data is used in determining the potential of passive strategies in a particular climate region and prioritizing the architectural response. Its greatest attributes are the correlation of wet bulb and dry bulb temperatures and the hourly frequency distributions. Data is presented in 8 hour increments by month and year and by total monthly and annual observations.

Comparative Climate Data of the United States, NOAA.[4] Contains tables of 30 year average weather conditions for some 300 locations across the United States including 17 Texas cities. These long-term or "normal" readings are used to determine the character of a climate but not to predict events of a "typical" year.

Climates of the United States, NOAA.[5] A map-based graphic representation of U.S. data.

Local Climatological Summaries, NOAA.[6] Long-term records and averages for many stations.

Annual Degree Days to Selected Bases, NOAA.[7] Degree days heating from 40 to 65°F reference temperatures and degree days cooling referenced from 45 to 70°F. Includes more than 160 Texas stations.

Passive Solar Design Handbook, J. Douglas Balcomb, 1980.[8] A standard in passive solar heating design, this manual contains monthly insolation data and degree day heating referenced from 50°F to 70°F for 20 Texas cities. It also features empirically determined tables of solar savings fractions based on the Load Collector Ratio method for standard passive heating strategies in the same climates.

Passive/Hybrid Cooling in Humid American Climates, Gene Clark, 1982.[9] This is a good source for information about passive cooling alternatives. There are some especially good maps on nocturnal cooling rates for cooling by night sky re-radiation.

Comparative Climatology, Griffiths and Driscoll, 1982.[10] This excellent primer on climatology was published by two faculty members at Texas A&M University. Beyond the fundamentals, it contains chapters on regional climates, climate classification, small scale climates, architecture, transportation, and energy.

Climatic Building Design, Watson and Labs, 1983.[11] This is a how-to manual with strategy and implementation sections for many fundamental and some less conventional passive techniques. The book also includes an analysis of many U.S. cities and an extensive bibliography.

Design with Climate, Victor Olgyay.[12] The classic text for assessing climates and building to the natural order of architecture.

Man, Climate and Architecture, Baruch Givoni, 1976.[13] This is a diverse treatise on climate and buildings.

Spreadsheets for Architects, Bachman and Thaddeus.[14] Computerized methodologies on companion disk for climate analysis, sun angles, building heat loss, daylighting, etc.

Regional Guidelines for Building Passive Energy Conserving Homes, The American Institute of Architects.[15] An overview of U.S. climates and appropriate strategies.

Solar Radiation Manuals, NREL.[16,17] Provide insolation data and weather statistics for 17 cities in Texas. The resource is available in printed format, from NREL, as well as electronically on the World Wide Web (http://solstice.crest.org/renewables/solrad/index.html) in a downloadable format.

OVERVIEW

METHODOLOGY

Bioclimatic analysis of normal weather data was championed in Victor Olgyay's book *Design with Climate* in the early 1960s.[12] Further refinement and a psychrometric basis for the analysis was later developed by Baruch Givoni and Murray Milne.[18] The methodology used in this inventory of Texas climates is based on the tools developed by the formative thinking of those studies.

Passive strategies can be employed to satisfy or greatly reduce the need for mechanical systems for lighting and climate control. In most situations ambient natural lighting can be utilized to satisfy the daytime lighting needs of structures. Perhaps less obvious, passive strategies utililizing the natural conditions offered by the outdoor climate can also provide thermal comfort within dwellings. Several simple measures of climate coupled with the psychrometric chart form the basis for understanding the interaction of climate and comfort. These are described below.

Degree Days Heating and Degree Days Cooling [4,5,7]

Degree days, defined in the glossary, measure monthly and annual temperature severity. As such, they are not directly employed as a passive resource, but are indicators of a climate's character. The monthly and seasonal pattern of degree days serves as a "first glance" analytical tool. Use degree days to quickly summarize a climate and to compare one climate to another.

As a developed statistic, degree days are generally published on an assumption of a 65°F balance point. This is a somewhat antiquated basis considering the improved thermal envelope techniques of modern construction and the simultaneous increase of internal loads from artificial lighting, appliance, and office automation. Most modern buildings and residences will have a balance point well below 65°F.

Average Daily Solar Insolation on Vertical South Facing Surfaces [8]

South walls are most ideally suited for collection of the low winter sun in Texas latitudes. Because the sun is very high during the mid day hours of summer months, south walls are also readily shaded by overhangs or other horizontal shading devices.

Daily Temperature Range, (Diurnal Variation) [6]

Difference between day and night temperatures are reflected in the daily average high and low temperature recordings. This in turn is a key indicator of the potential for several passive cooling techniques. To a lesser extent, diurnal variation is also an indicator of the amount of thermal storage required for a passive heating system.

For summer data, high daily temperature swings indicates either a dry climate or a high altitude climate or both. In Texas, it is predominately dryness which contributes to diurnal variation. With little atmospheric moisture or cloud cover, there is less absorption and reflection of solar radiation by day and also less of a barrier to re-radiation to the night sky.

Psychrometric Data—Hourly Dry Bulb Bin Data and Mean Coincident Wet Bulb Temperatures [3,18]

Psychrometric charts, like the one shown in **Figure 9.1**, are used to examine the thermodynamic properties of air. Examination of chart data provides the single best analytical indicator of passive priorities for building climatology. While it is beyond the scope of this study to develop a full explanation of its use, a few of the principles involved should be mentioned. First, the chart is composed of a grid of vertical lines of constant dry bulb temperature (°F) and horizontal lines of constant absolute humidity (#H_20/#air). Since warmer air can carry more moisture, lines of constant relative humidity are drawn in sweeping curves across the chart. The upper boundary is formed by the saturation curve or 100% relative humidity line. Other values are found on most psychrometric charts, like diagonal lines of constant wet bulb temperature.

For bioclimatic purposes, the chart has been divided into areas where the properties of outside air represent known environmental conditions. Human thermal comfort, for example, is identified as a band of dry bulb temperatures from 67.5°F to about 78°F and from about 20% to 80% relative humidity. Within that zone of the chart, all weather conditions which occur are said to be conducive to thermal comfort assuming that occupants are in full shade, lightly clothed, and only moderately active. All climate data that are plotted at lower dry bulb temperatures (to the left of the comfort zone) are indicative of times when solar radiation (passive heating) could be utilized to restore comfort. All hours of dry bulb occurrences which are above 67.5°F therefore require shading.

Other definitions outline the zones of the psychrometric chart where conditions are favorable to various passive cooling strategies. Evaporative cooling, for example, is generally effective below the 71.5°F wet bulb temperature line, at dry bulb temperatures less than 104.5°F, and above the 78°F effective temperature upper limit of comfort. By plotting annual hours of occurrence at dry bulb and wet bulb coordinates on the chart, the appropriate passive strategy is determined and the relative priority of each strategy can be sorted by summing the hours suggested for each method. Six passive strategies are identified and, along with comfort, may be defined as follows.

Comfort. Under these temperature and humidity conditions, most people would feel comfortable if they were engaged in little activity, in the shade, in normal office attire, and in the presence of slight air movement. As long as internal heat loads from people, lighting and equipment do not dominate the interior environment, many buildings can be maintained with natural or fan assisted ventilation under these conditions.

Solar Gain. Whenever temperatures are below comfort levels, solar radiation should be promoted and excessive air movement beyond that required for fresh air ventilation should be restricted. Since the sun stays low in the southern sky during winter months, south facing windows receive the most useful solar radiation and are easiest to shade in comfortable and overheated months. Unlike active solar technologies, building climatology focuses on solar energy incident on vertical south facing surfaces. A 60% saving fraction is reasonable in most Texas localities.

Shade. At temperatures which are comfortable or

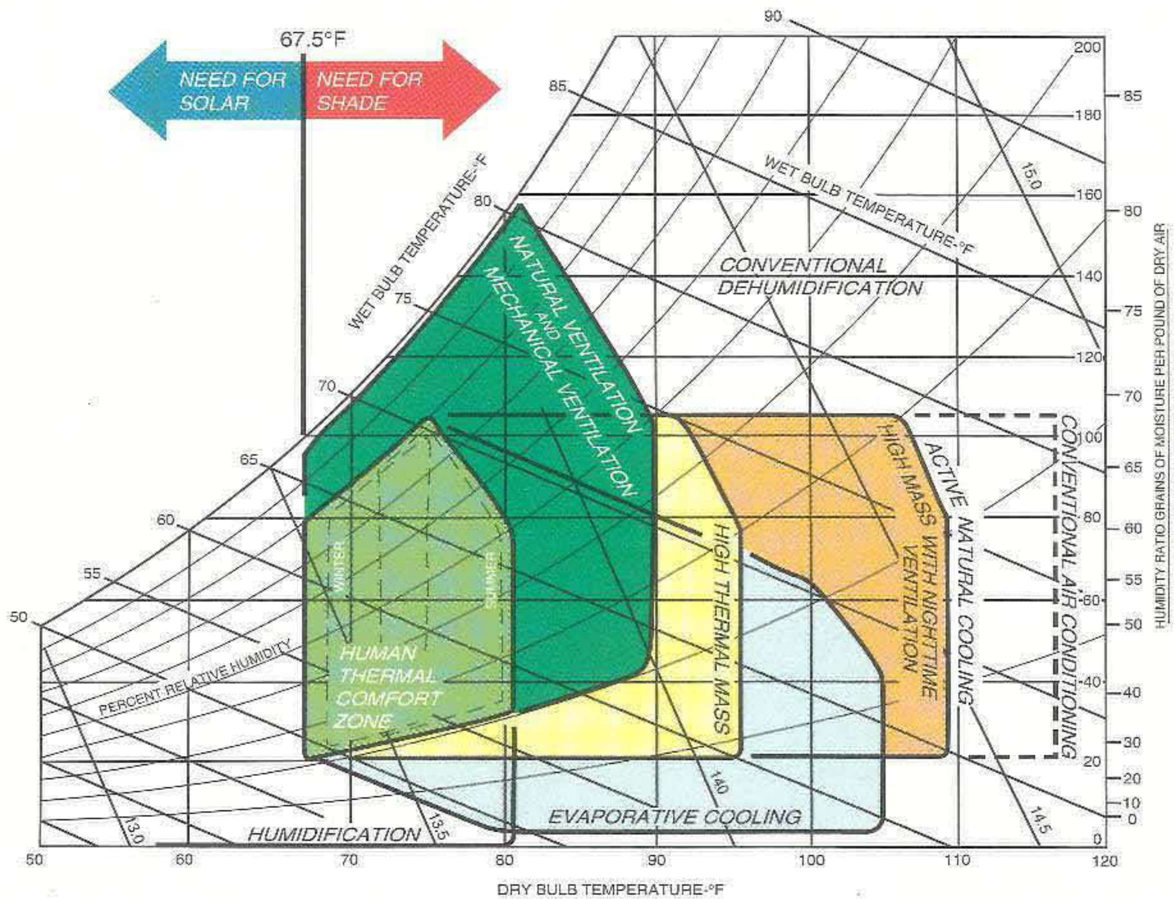

FIGURE 9.1. Summary of Cooling Design Strategies as a Function of Ambient Conditions in Overheated Periods.[18]

higher, shade should be provided. External shading of windows by fixed overhangings and vertical fins are the most common method of tuning a window's exposure to the needs of sun-in and sun-out periods of the year. Since the sun changes path across the sky every day from solstice to solstice, the design of fixed devices, the placement of vegetation on the site, and even the orientation to surrounding structures need to be considered. Solar geometry relative to a particular window is determined by day of year, hour of day, latitude, and longitude.

Ventilation. During warm and humid conditions, natural ventilation, fan forced air flow, or solar induced ventilation can maintain a feeling of comfort. Naturally, as conditions are less comfortable, air velocity has to increase to compensate. The useful hours of ventilation potential identified here do not in any way assure that sufficient breezes will be available. Adequate ventilation velocity and effective air "washing" of heat from interiors can however be affected by appropriate site design and room arrangement. Ventilation is critical to Coastal and Southern Texas climates.

Thermal Mass. Envelope construction with high thermal energy storage capability, or heat capacity, is referred to as thermal mass. It is used in floors and walls in dryer climates to act as a thermal flywheel, moderating the characteristic extreme heat of summer days with the sudden coolness of night and providing a heat sink for solar gain in winter that releases heat after sundown. Additional cooling is obtained by re-radiation of heat to the clear night sky. Diurnal variations in temperature in excess of 25°F are the best clue as to the applicability of external thermal mass. As seen in Figure 3.3 (chapter 3), the Trans-Pecos, Northwest Plains, and Edwards Plateau regions are good candidates for utilizing thermal mass.

Night Ventilation. As a companion strategy to thermal mass in floors and walls, the flushing of high heat capacity internal mass with cool nighttime air is used to moderate cooling requirements in dry climates. Once cooled by night air, this internal mass (often the structure of the building) acts to absorb heat from interior spaces during the next day. The cycle is then repeated the next night. Generally, night ventilation works well in tandem with massive envelopes in arid climates.

Evaporation. Whenever dry and overheated conditions are encountered (generally below 71.5°F wet bulb temperatures), water can be evaporated directly into the air stream of the occupied space to produce cooling. Sensible heat (temperature) is traded for latent heat (phase change related to evaporation of moisture). Since the latent heat of evaporation of water is about 8,000 Btu per gallon, each gallon evaporated will provide roughly two-thirds of a ton-hour of air-conditioning. Evaporation is generally accomplished by the use of fan powered "swamp coolers" but might also entail fountains, pools, or bodies of water on the site. A large diurnal temperature variation indicates a potential for evaporative cooling. Evaporative cooling can extend the range of comfort to areas where the maximum outdoor wet bulb temperature is 74°F.

In addition to the six passive approaches, daylighting and energy efficiency measures are strategies that work in all climatological regions of Texas. Daylighting substitutes sunlight for artificial light through windows and skylights. At a given light level, sunlight adds less heat to buildings than any artificial light source and may also contribute to worker productivity. Energy efficiency encompasses improvements to building shells (insulation, caulking) that reduce demand or the selection and maintenance of energy-efficient appliances and other equipment. Building a structure that utilizes passive strategies while ignoring daylighting and efficiency measures is ill-advised and counterproductive. The skillful blending of all of these elements for a given climate is the basis of enlightened design.

Regional Synopsis

Architectural classification of climate is made according to the dominant comfort characteristic, with the four general varieties being: warm-arid, warm-humid, cold, and temperate. Texas is composed of seven very distinct but generally temperate climatic regions. These regions and their major population centers are:

1. Trans-Pecos—El Paso
2. Northwest Plains—Lubbock, Amarillo, Midland
3. Northeast—Dallas, Ft. Worth
4. Coastal Plains—Houston, Galveston, Port Arthur, Corpus Christi
5. South—Brownsville
6. Edwards Plateau—San Angelo, Del Rio
7. South Central—Austin, San Antonio

The serendipitous spacing of the state's major population centers, the presence of first order weather stations, and local collection of specialized data all serve to facilitate this classification. The exact boundaries between the regions is unimportant architecturally, since most of the energy resource opportunities for passive architecture occur in the greater metropolitan area of the listed cities.

For reference, comparative data for the seven climates of Texas are presented on the following pages. **Figure 9.2** shows net degree days per month. Heating degree days are represented as a negative and cooling degree days positive so as to reduce the data to one parameter. Texas climates are generally temperate, that is, they have both significant heating and cooling seasons and both are of moderate severity. It is unusual to have large numbers of degree days heating and cooling in the same month as the mild spring and fall seasons act as transitional periods.

In **Figure 9.3**, appropriate passive strategies for each Texas climate have been inventoried and prioritized by hours of effectiveness. Again, these data were generated via the bioclimatic methodologies outlined above—that is, by examining the frequency distribution of dry bulb and mean coincident wet bulb temperatures on a psychrometric chart divided into zones of applicability for each passive strategy. A description of each climatic region follows.

Trans-Pecos

The driest region of Texas is characterized by intense diurnal temperature swings and abundant insolation year round. Heating and cooling degree days are moderate and reasonably balanced at 2677 DDH and 2097 DDC at 65°F. Solar heating is appropriate for 47% of the year (including night hours)

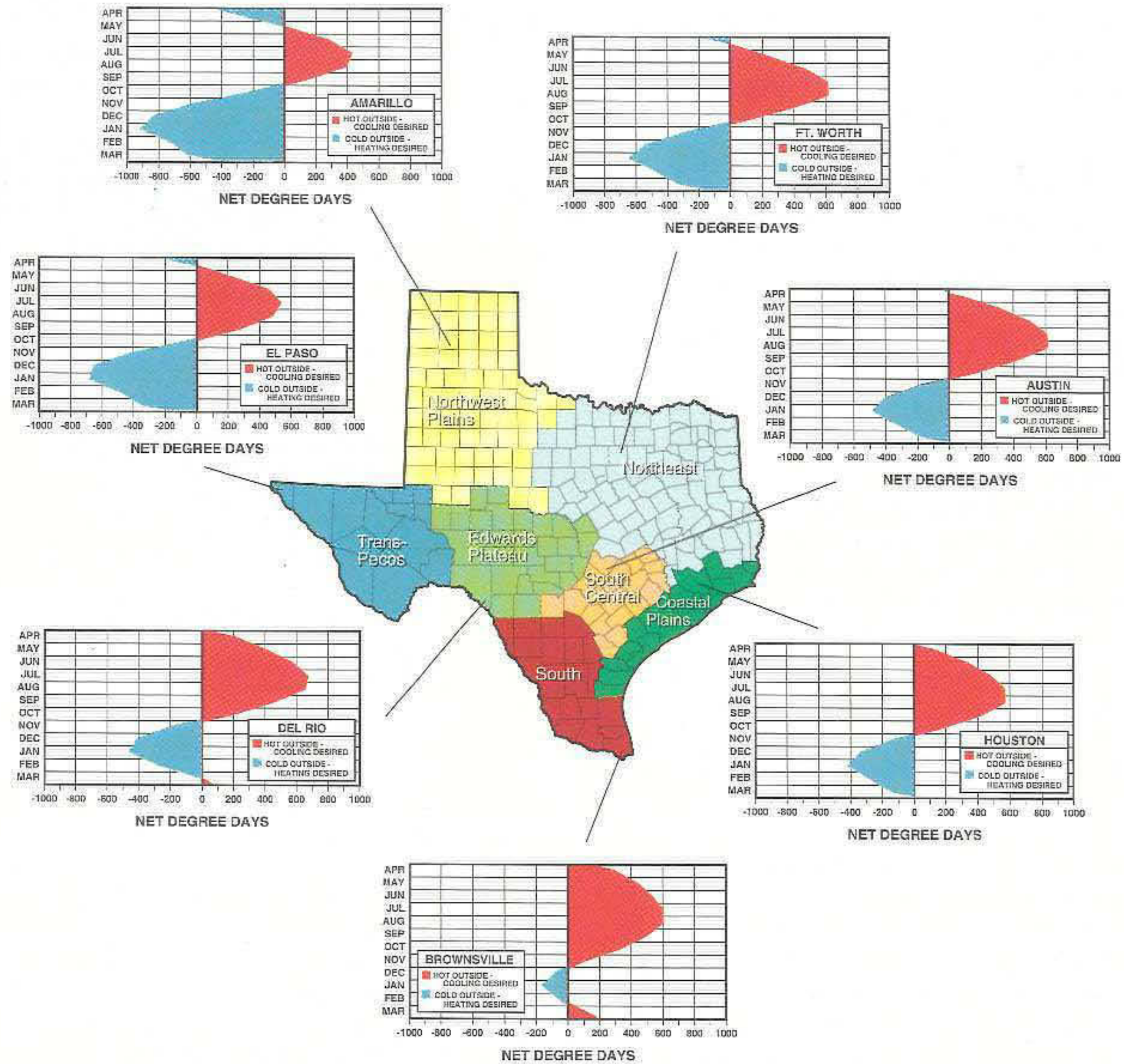

FIGURE 9.2. Monthly Net Degree Days for Representative Texas Cities. Net degree days (degree day's cooling minus degree days heating; 65°F basis) provide an indicator of whether a structure will generally require more heating or cooling to maintain comfort during each month of the year. Note that South Texas has very little cold weather producing a need for heating (indicated by the small blue portion of the Brownsville figure) whereas the Northwest Plains (Amarillo) have a large heating requirement.

and matches very well with an abundant resource of vertical south facing solar energy. Passive cooling can provide all of the energy required for summer space conditioning. El Paso weather is normally 30% overheated (2596 hours per year), 34% comfortable (2793 hours), and 36% underheated (3191 hours).

Northwest Plains

The region encompassing the Panhandle is the coolest part of the state with heating degree days outnumbering cooling degree days by almost 3 to 1 (4181 DDH to 1433 DDC at 65°F). Amarillo weather is characteristically 14% overheated (1225 hours per year), 25% comfortable (224 hours), and 61% underheated (5311 hours). Passive heating is the number one priority here. Fortunately, due to the dryness of the climate, the Northwest Plains receive almost as much winter sun (vertical south facing surface insolation) as does the Trans-Pecos. Passive cooling of envelope dominated buildings is facilitated by the same dryness in summer when diurnal temperature variation generally exceeds 25°F. Evaporative cooling and adequate thermal envelope mass provide the needed resource for summer comfort.

Northeast

The Dallas-Ft. Worth area and surrounding population centers, including Waco, are more moderate than the dry west Texas climates. In Dallas, cooling degree days slightly outnumber heating degree days by 2754 DDC to 2290 DDH at 65°F. A respectable 32% of the year (2766 hours) is comfortable. The passive heating requirement still covers more hours of the year than passive cooling at 3934 hours to only 2060 overheated hours. Winter sun is

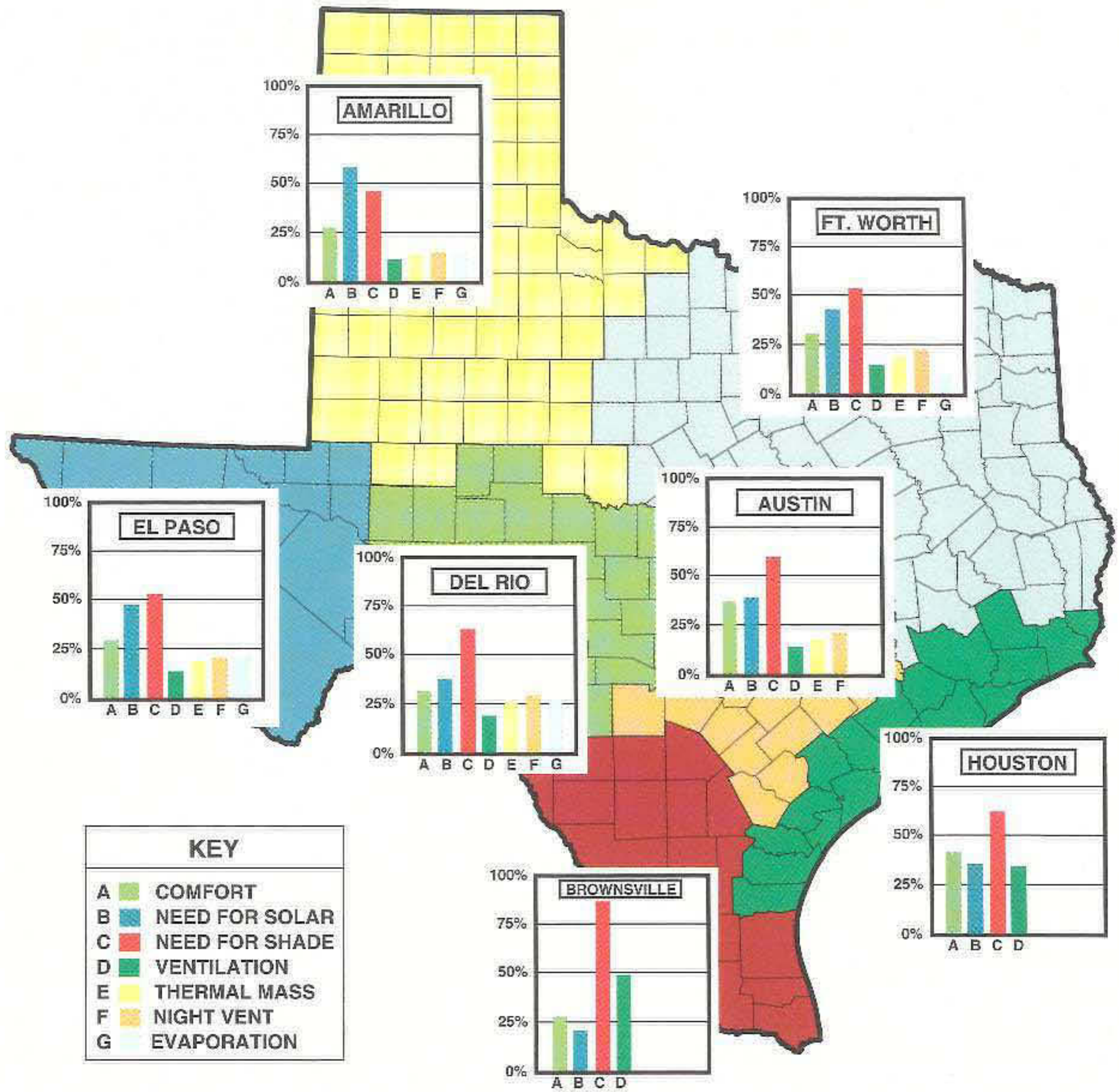

FIGURE 9.3. Percentage of Annual Hours That Passive Strategies Would Be Useful. Each bar corresponds to a specific passive strategy as identified in the key. More precisely, each bar represents the percentage of the year that mean coincident wet bulb and dry bulb temperatures fall in specific psychrometric ranges for passive strategies identified in Figure 9.1.

however, less abundant. Like much of Texas, clear skies in the Northeast region come and go with cool fronts or "Northers". In the final analysis, the resource is adequate for much of the heating needs here. Shading is needed for more than 50% of the year so heating and cooling strategies must be carefully balanced. Passive cooling here will rely more on ventilation (natural or solar induced). Mass and evaporation are marginal strategies.

Coastal Plains

Houston is the definitive Coastal Plains climate of Texas. The proximity to the Gulf of Mexico keeps temperatures in moderation and humidity very high. With a two to one degree day ratio of 2889 DDC and 1433 DDH @ 65°F the cooling priority is clear. By an hourly count of hours however, about 43% of the year (4517 hours) are comfortable if somewhat humid. Some 36% of the year (3124 hours) is underheated and 21% (1863 hours) is overheated. Ventilation is the most important passive cooling strategy here and should be promoted along with shading for most of the year. About 400 hours per year are beyond conventional passive cooling means and another 600 or so are marginally addressable. Solar heating is needed 36% of the year (3124 hours) even though winter temperatures are seldom severe. Winter sun from Corpus Christi to Port Arthur is diminished by the ever-present moisture and cloudiness. But again, the resource seems to be proportional to the need.

South

The lower valley in the South region of Texas is best exemplified by the climate of Brownsville. This is the most temperate of all Texas climates with constant warmth and humidity. It is the virtual lack of a winter season that most distinguishes the South from the Coastal Plains climatic region. Only 26% of the year in Brownsville is, strictly speaking, comfortable; but 64% (5623 hours) of the time is tolerably situated between 65° and 85°F. Like the Coastal Plains, shade and ventilation are the dominate considerations. Cooling degree days outnumber heating degree days by six to one (3874 DDC to 650 DDH at 65°F). Ventilation is required even during comfortable temperatures due to the humidity. Mass and evaporative cooling strategies are not appropriate here. Passive heating is not likely to be required often enough to be worthy of much expenditure beyond well shaded south facing glass incorporated into the ventilation scheme. There are normally less than 200 hours per year below 45°F.

Edwards Plateau

East of the Pecos River and centered around San Angelo lies the climate of the Edwards Plateau. In the central parts of the region, degree days cooling and heating run 2702 DDC and 2239 DDH at 65°F. Further south, in Del Rio, the ratio is more like 3362 DDC to 1523 DDH at 65°F. The two cities do receive almost identical distribution of solar radiation throughout the year with San Angelo perhaps the more sunny of the two. Bin data from Del Rio, which is on the cusp of the Coastal Plains climatically speaking, suggest that about 34% of the year (2973 hours) is comfortable. Roughly another third (36% or 3191 hours) in underheated and about 30% (2596 hours) is overheated. Abundant winter sunshine is adequate for most passive heating requirements. In the summer, mass, evaporative cooling and some night ventilation should be promoted. Ventilation may also be a contributing cooling strategy, depending on humidity conditions.

South Central

The center of the state is typified by the Austin and San Antonio climates. The degree day indication of climate severity in Austin is 2907 DDC and 1737 DDH or a ratio of 1.7 to 1.0 in favor of cooling. These climates are slightly too moist for mass and evaporative cooling strategies. Diurnal temperature variation seldom exceeds 25°F in summer months. Ventilation and shading are to be highly promoted here most of the year. On an hourly basis, the region is comfortable about 37% of the time, though humidity makes some of those hours marginal. In winter, Austin and San Antonio are considerably sunnier than coastal Houston and comparable to the Dallas-Ft. Worth area. The 39% of the year (3244 hours) that this region is normally underheated benefit accordingly. Overheating prevails about 24% of the year (2144 hours).

Caveats

These capsule views of passive strategies are directed toward envelope-dominated buildings such as single family residences. Internal-load dominated buildings will be overheated a much longer part of the year than outdoor conditions dictate. In these larger buildings, cooling strategies should be emphasized and integrated with the mechanical systems for the purposes of outdoor air ventilation and night time flush ventilation when conditions permit. More importantly, the utilization of daylight should be made a priority in internal load dominated buildings in order to reduce internal waste heat generation and save on attendant lighting and cooling energy. The degree days heating and cooling are expressed here for a 65°F base balance point and also reflect the thermal character of a surface load dominated building. Degree days to other temperature bases are available or may be determined from normal weather data.[7]

Secondly, the potential to utilize a strategy does not always mean that the requisite climate asset will be present. For example, all temperatures below 65°F would indicate the potential for solar gain. This does not mean that adequate sunshine is characteristically present. What determines "adequate" is a function of the building design and the sizing of its passive components, like aperture size for solar collection. Ventilation cooling fits the same need/resource scenario. Thermal mass, night ventilation, and evaporation on the other hand, are strategies where the indication of potential is sufficient to assure some success with its application.

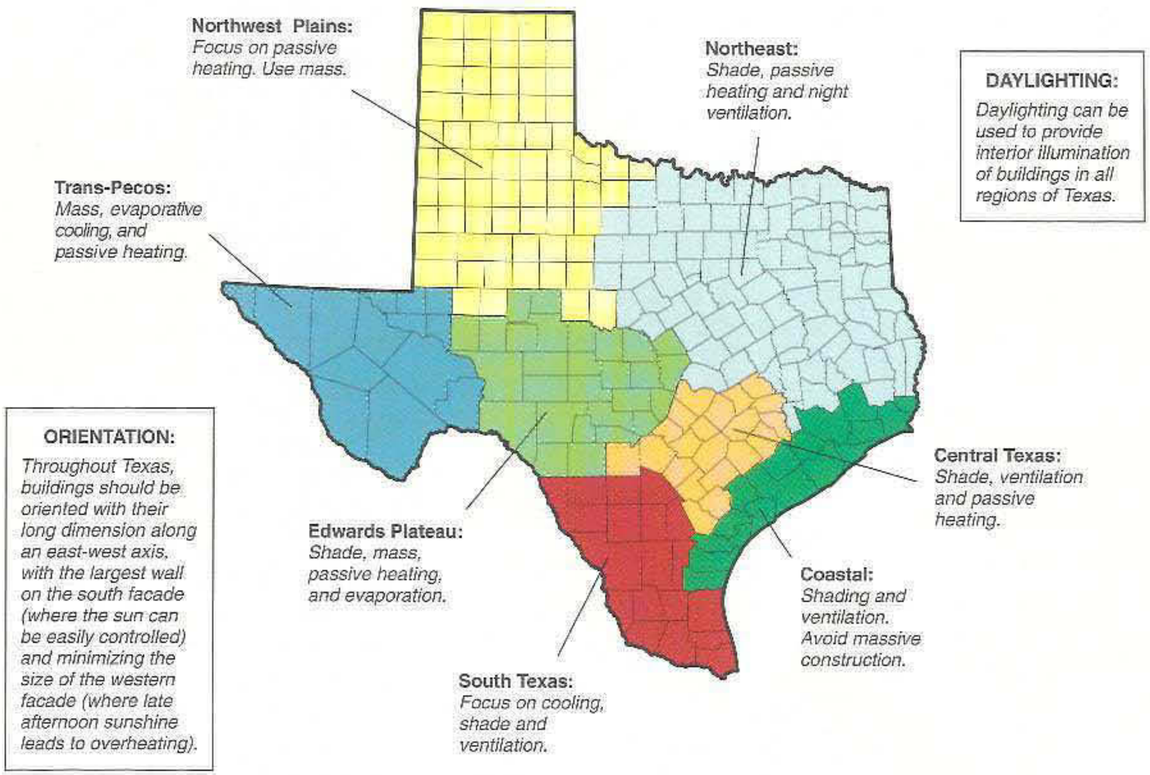

FIGURE 9.4. Primary Passive Strategies Suitable for the Seven Climatic Regions of Texas. The strategies above can often be incorporated to reduce energy demands and to improve comfort in buildings. In west Texas, practically all passive strategies can be used effectively. Of course, actual recommendations are specific to the characteristics of the building site.

Quantification of Resource

The combined potential of all strategies to provide comfortable conditions ranges from 60 to 70% of annual hours for the representative climates of Texas. Since another 30 to 40% of annual hours are within the comfort zone, all but the most severe weather seems to be within the reach of passive strategies.

To quantify the ability of passive strategies to minimize building energy demands, we have estimated the potential energy savings by end use. **Table 9.1** summarizes the results. These values were constructed by first partitioning total building energy consumption into the state's seven climatic regions based on each region's population and heating and cooling degree-day demands. Using the bioclimatic methods embodied in Figure 3, the fraction of each region's heating and cooling needs that could be met by passive strategies was estimated and total energy savings calculated. Daylighting was assumed to meet 25% of commercial lighting needs.

The "accessible potential" listed in Table 9.1 assumes market penetrations of 70% in new construction and only 20% in the existing building stock. Further, energy savings are for end use consumption, typically gas for heating and electricity for cooling and lighting. No attempt has been made to translate electrical energy savings into an accompanying reduction in primary consumption.

Clearly these results represent only a very rough assessment of the potential of building climatology in Texas. No analysis of the present building stock has been conducted to evaluate the appropriateness of retrofitting passive strategies. As mentioned previously, the real potential of these methods will be limited in structures already out of tune with the climate.

VARIABILITY

Most passive design decisions are based on long term meteorological averages because they are readily available and give a good reading on the climatic character of a region. The shortcoming of this is that long term averages disguise the real texture and sequences of related events which occur in "typical" years. Further, the siting of a building greatly modifies the microclimate to which it is exposed by geography, topography, vegetation, bodies of water, and surrounding features. Designing with climate means understanding this microclimatic character and the seasonal climatic perturbations of specific locales. In practical architecture this is culled from the experience of regional designers.

Since building climatology is fundamentally linked with more traditional interpretations of climate, a more quantifiable approach to climatic variability would be to examine extremes in long-term meteorological records. Chapter 3 of this report offers insights into the variability of Texas climate and sources for more detailed study.

RECOMMENDATIONS

The climate data as analyzed here agree with the experience of passive solar buildings across the state. (See **Figure 9.4**) The near term value of designing with the climate is clear and obvious. Passive strategies rely on simple physics and are effective, economical, simple, and environmentally benign. They can be tuned to the thermal character of any building and can replace significant needs for energy and power in all regions of the state. However, the true potential of incorporating building climatology principles into practice is unknown; the values presented above (Table 9.1) represent only the grossest effort to quantify potential energy savings. The numbers are problematic because they are not constructed from any data relating to the present building stock and its receptiveness to retrofitting with passive strategies. This is because no such data exists. Because of this shortcoming, **it is strongly urged that a comprehensive review of the Texas building stock be undertaken with an eye to assessing opportunities for reducing building energy demands.**

Such a study would begin with the modeling of prototypical buildings—in each climactic region of the state. Building stock of several different eras might be analyzed. The analysis would lead to accurate assessments of potential energy savings and, importantly, detail the specific strategies and costs with which these savings could be achieved. Such information could be an invaluable aid to local architects, contractors, or anyone interested in lowering their energy bill. Furthermore, opportunities for energy efficiency extend beyond those human comfort needs that can be impacted by climate. A study of building energy demands could be naturally extended to examine loads such as cooking, refrigeration, hot water, and office equipment as well as the potential gains that could be had by efficiency investments. These loads would be modeled (to the extent possible) to determine their impact on space conditioning demands.

Beyond the critical hole in our understanding of the Texas building stock, several other information needs present themselves. As for data that can be derived directly from climate records, a few items that would assist designers in selecting and sizing passive systems include:

- characterization of weather phenomena, such as "Northers" and their effect on buildings

TABLE 9.1. Texas End-Use Building Energy Consumption and Potential Savings with Passive Strategies.[19]

End Use	TOTAL RESOURCE	ACCESSIBLE RESOURCE	
	Consumption in Buildings	Accessible Potential Reduction	
	(quads)	%	(quads)
Heating	0.12	50	0.059
Cooling	0.35	50	0.17
Lighting	0.11	25	0.027
Total	0.57	45	0.26

- degree hour data as a refinement of degree days that use average daily temperature
- wind data by speed and direction for night and day time periods
- sky luminance in foot-candles for different orientations and various sky conditions
- published Test Reference Year (TRY) data.

Aside from these new first order data sets, the temporal nature of each climate needs to be explored in a way that reveals the useful coincidence of data. When ventilation is needed, for example, where do breezes come from and how strong are they? How coincident is solar radiation with the requirements of passive heating? These correlations could be constructed from TRY data and presented as 3-D surface plots of hours of occurrence (Z-axis) versus the data in question (X-axis and Y-axis) for:

- temperature versus wind direction
- temperature versus wind speed
- temperature versus relative humidity
- temperature versus sunshine
- wet bulb versus dry bulb temperature (this is the "bin" data used here)
- wet bulb temperature versus wind speed.

Also, the effectiveness of certain passive strategies needs further, regional validation. City or region specific performance could be determined by empirical methods (experiments on site), translated to analytical procedures (such as computer models or simplified algorithms), extrapolated to other Texas climate data sets, validated, and published as tables. Some systems that merit study would include:

- nocturnal radiation rates from dry and wetted roof surfaces [9,20]
- direct evaporative cooling performance
- indirect evaporative spray roof cooling
- night flush ventilation rates
- solar induced (stack effect) ventilation performance.

In addition to these second order climate/performance statistics, some guidelines on daylight savings versus unwanted solar gain are needed. Additional clarification on fenestration and shading strategies for each region might encourage appropriate integration of solar heating with passive cooling strategies. Regional design tables quantifying effectiveness of all measures discussed in this chapter would assist local builders and, with the validation of experience, might eventually form the basis for updated local building codes.

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RESOURCE TRANSPORTATION ISSUES

by Mike Sloan and Charles Freeman

INTRODUCTION

This project has endeavored to characterize all renewable energy resources throughout Texas. Where good resources exist, there lies the possibility to develop renewables to provide useful energy services for Texans. Of course, issues such as potential environmental and social impacts, public acceptance, and a host of technical issues will dictate whether a site is acceptable for large-scale development. One significant technical issue—resource transportation—relates to the economical movement of energy from a good resource area to a location where it can be used.

Basics of Energy Use

Utilization of energy to power human activities requires that energy be available at the point of consumption. Often times, exploitable energy resources are concentrated in relatively small areas and must be transported over long distances to markets. Fossil fuels invariably must be extracted from the ground and transported to the point of consumption. Yet, even in the case of renewable energy resources that are available everywhere (such as solar radiation and wind), the quality of the resource may differ such that it is most cost effective to "harvest" it in a good area and transport it to areas of ultimate use.

In such cases, several intermediate processes or steps may be required. Potential intermediate steps include gathering, transportation, storage, and distribution **(Figure 10.1)**. Each of these steps incurs a cost. Processes that supply energy services without each of these intermediate steps obviously recognize a cost advantage compared to processes that do require them. Also, one (or more) energy conversion processes is almost always required at some point prior to end use. The sum of all cost inputs determines the overall cost. This accounting may include "external" costs such as health, social, and environmental costs as well as traditional direct costs. To determine whether it is justifiable, the economic feasibility of transporting renewable resources must be considered within the context of all other costs and benefits.

At this time, renewables are a very minor player in the fossil fuel dominated energy markets in Texas. Through decades of optimization, these traditional energy supply systems have lowered costs through central-ization, increases in size (economies of scale), and the use of efficient, high-volume transportation systems. How renewable energy sources adapt to and perhaps utilize the billions of dollars worth of energy infrastructure already in place in Texas will play an important role in determining their future success.

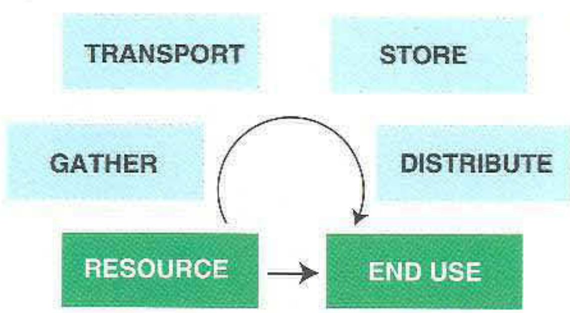


FIGURE 10.1. Intermediate Steps Often Involved in the Use of Energy Resources. Intermediate steps may occur in a different order than indicated. Conversion processes may be required between any given steps.

A review of information pertinent to the State's existing energy infrastructure is the primary focus of this chapter. Since all renewable energy sources can be used to generate electricity, a characterization of Texas' electric system and an assessment of its transmission grid receive particular attention.

Importantly, the spectrum of renewable energy options will likely adapt to current energy markets in different ways. Many renewable energy options, such as landfill gas plants and rooftop photovoltaics, are well suited to small, distributed installations. Rather than requiring access to transmission, such installations may offset centralized generation and thereby effectively increase capacity in the existing transmission system. Many of the small, distributed renewable energy systems are also capable of providing energy services directly to end-use customers at retail rates. Although such systems effectively bypass traditional transmission systems, they represent a major potential for renewable energy and will receive some consideration here.

SURVEY

A vast array of information is available from public and private sources on the topic of energy and energy transportation systems. This section identifies but a few of the major institutions maintaining information relevant to energy derived from renewable resources in Texas.

Texas agencies and groups that maintain basic data and publish documents and other products that characterize energy use and energy transportation systems in Texas include the Texas Railroad Commission and Texas Public Utility Commission (PUC). Primary national institutions maintaining energy-related information include the Department of Energy/Energy Information Administration (DOE/EIA), Federal Energy Regulatory Commission (FERC) and industry organizations such as the Electric Power Research Institute (EPRI), Gas Research Institute (GRI), and North American Electric Reliability Council (NERC).

Summary Documents

ELECTRIC TRANSMISSION

Load Flow Modeling Study of the Texas Electric Grid, Electric Power Engineers, 1994.[1] This study, summarized later in this chapter, performed "ball park" calculations of the capacity limitations of the state's electric grid at numerous (29) potential renewable energy generation sites in Texas.

SEDC Renewable Resource Regional Studies. SEDC Transmission Subcommittee, 1994.[2] Examined the costs associated with electric transmission upgrades required at five sites installing up to 2,000 MW of renewable energy generation for delivery to major load centers in Texas.

DOE Electric Transmission Studies in Texas, Oak Ridge National Laboratory, 1995.[3] Includes analyzes performed by Texas Utilities Electric Company and the Lower Colorado River Authority to examine several regions in West Texas and the Panhandle.

US/Mexico Electric Trade Study, DOE, 1991.[4] Investigates opportunities for expanding electricity transfers between the two countries. **Table 10.1**, adapted from this report, identifies all the current electrical interconnection points currently existing between the U.S. and Mexico.

Bulk Load Modeling Study, PUC, 1988.[5] Although somewhat dated, it is a major source of transmission system information throughout the state.

ELECTRIC SYSTEM CHARACTERIZATION

Generating Unit Inventory, PUC.[6] Maintained as an ongoing database and in hard copy form.

ERCOT OE-411.[7] Annual publication containing information on ERCOT members' power plants and transmission systems.

Electricity Annual, EIA.[8] Annual EIA publication detailing many aspects of the electric industry.

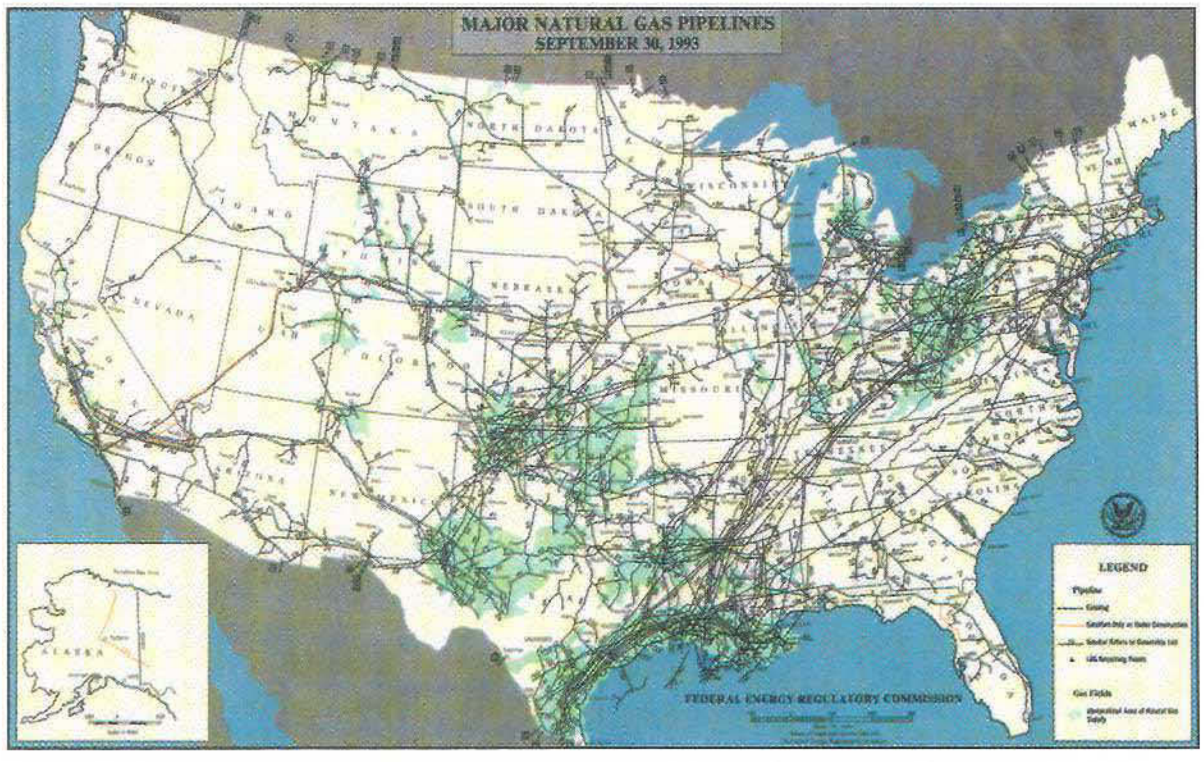


FIGURE 10.2. Natural Gas Pipeline Map of the United States (from FERC[11]). Note the intensity of pipelines in Texas.

TABLE 10.1. Major Existing U.S.-Mexico Electric Grid Interconnections.[4]

ORDER	U.S. TERMINAL	MEXICAN TERMINAL	VOLTAGE (KV)	CAPACITY (MW)
1	Brownsville, TX (ERCOT)	Matamoros, Tamaulipas	69	20
2	Falcon Dam, TX (ERCOT)	Falcon Tamaulipas	138	150
3	Laredo, TX (ERCOT)	Nuevo Laredo, Tamaulipas	138	150
4	Eagle Pass, TX (ERCOT)	Piedras Negras, Coahuila	138	150
5	Presidio, TX (ERCOT)	Ojinaga, Chihuahua	12	4
6	El Paso, TX (WSCC)	Ciudad Juarez, Chihuahua	69	80
7	Nogales, AZ (WSCC)	Nogales, Sonora	14	10
8	Imperial Valley, CA (WSCC)	La Rosita, Baja California	230	408
9	Miguel, CA (WSCC)	Tijuana, Baja California	230	408
10	San Ysidro, CA (WSCC)	Tijuana, Baja California (2)	69	20

Solid Fuel Transportation

Coal Industry Annual, EIA.[9]

Liquid Fuel Transportation

Petroleum Supply Annual, EIA.[10]

Gas Transportation

Natural Gas Pipeline (Map), FERC.[11] Shown in **Figure 10.2**, this map conveys the intensity of gas gathering and transmission in and near Texas.

Natural Gas Annual, EIA.[12]

OVERVIEW

For the purposes of the remainder of this chapter, energy sources are categorized by their physical form, that is, 1) solid, 2) liquid, 3) gas, or 4) electric. The following discussion is intended to provide basic information on the state's energy infrastructure, with particular focus on the state's electric system. It consists primarily of numerous maps and tables with brief accompanying narrative.

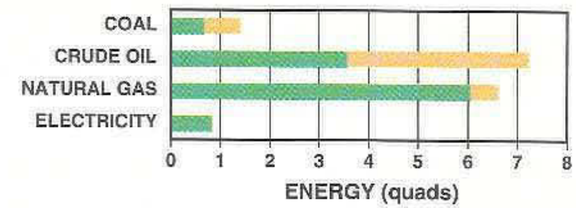
Relative Size of Energy Sources

The supply and disposition of several major energy commodities in Texas are summarized in **Figure 10.3**. While this is not a comprehensive accounting, it does provide a general indicator of the relative size (in equivalent energy terms) of these energy industries. Secondly, Figure 10.3 suggests the relative size of the respective energy transportation systems, both within the state and for export.

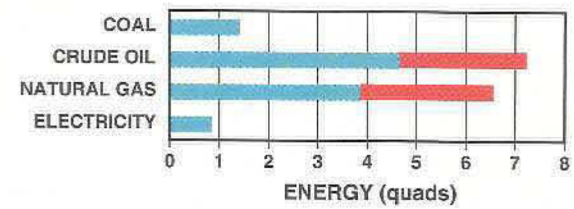
Both graphics tally 1993 data reported by the EIA,[8,9,10,11,13] for Texas' principle solid fuel (coal), liquid fuel (crude oil), gaseous fuel (natural gas) and electricity. The disposition bar labeled crude oil actually represents petroleum products derived from crude oil. It is noted that Texas refineries handle an additional 1.5 quads of non-crude feedstocks (mainly unfinished oils) that are not reflected in the supply and disposition accounting of Figure 10.3.

Most renewable energy sources can be feasibl converted into electricity. In some regions of the country—for instance, between Southern California and the Pacific Northwest—large net transfers of electricity do take place. Here in Texas, however, existing infrastructure can support only minor interstate transfers of electricity and, as Table 10.1 attests, international electricity transfer capability is also quite small. While renewable energy can realistically serve in-state electric markets, sizable bulk transfers of electricity to out-of-state markets by renewables (or conventional generating sources) would represent a major change from current practice. This is not to say that it could not happen, but it would likely entail very significant additions to the interstate electric transmission system in this part of the country.

In comparison to electricity, Texas primary fuels demonstrate very large export potential: at least 4 quads of petroleum products and at least 2.7 quads of natural gas. Renewable resources suitable for

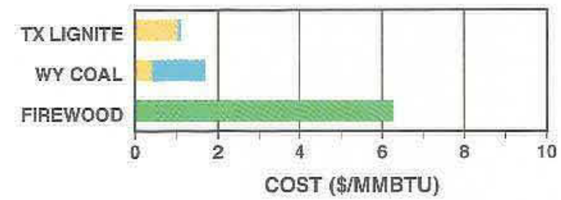


a) Texas Energy Supply (partial)

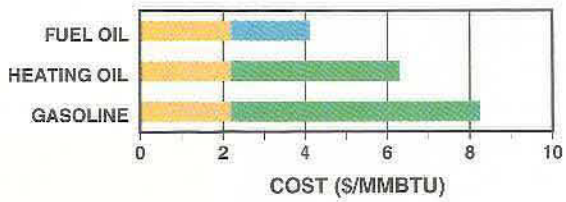


b) Texas Energy Disposition (partial)

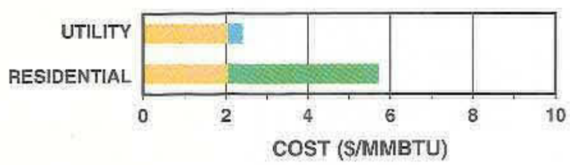
FIGURE 10.3. Texas Energy Supply and Disposition. The supply chart (a) is comprised of domestic production (green bar) and imports (orange). The disposition chart (b) includes in-state consumption (blue) as well as exports (red).



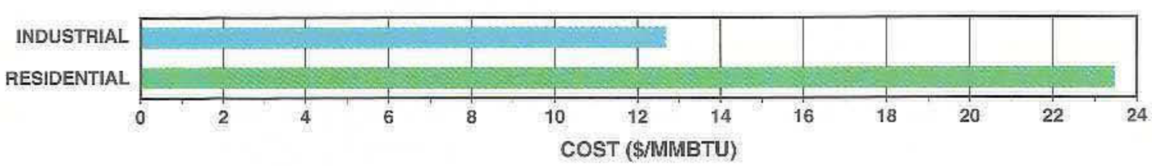
a) Solid Fuel (Coal and Wood). Texas lignite is consumed near or at the mine while the delivered cost of Wyoming coal is predominantly railroad freight charges.



b) Liquid Fuel (Petroleum Products). Unlike the others, the cost of gasoline includes almost $2/MMBTU of taxes.



c) Gaseous Fuel (Natural Gas). The charges for pipeline transportation of natural gas are relatively modest for large consumers; distribution to retail customers is more costly.



d) Electricity. Even though it is considerably more expensive per unit of energy, versatile electricity has continued to expand sales. The values above equate to $.0432/kWh for industrial sales and $.08/kWh for residential.

KEY - FIGURE 10.4 a,b,c

- Cost at Source (Minemouth/Refinery/Wellhead)
- Additional Cost (above Source Cost) for Industrial Use
- Additional Cost (above Source Cost) for Residential Use

FIGURE 10.4. Relative Cost of Texas Energy Commodities for Industrial and Residential Uses. Representative costs ($/MMBTU) for industrial uses (blue) and retail uses (green) for a) solid fuel, b) liquid fuel, c) gaseous fuel and d) electricity are provided based on 1993 data.[8,9,10,11,13] The meaning of bar segments in a, b, and c are defined in the key above. It is noted that crude oil and natural gas source costs may vary dramatically from year to year.

these transportation systems (biomass-derived fuels and eventually hythane/hydrogen) should have no problems accessing large export markets.

Relative Cost of Energy Sources

As with any business venture, clear definition of a target market is of great importance to renewable energy industries. Wholesale energy markets tend to reduce to competition based solely on price. Retail markets, on the other hand, can be influenced by other factors. **Figure 10.4** presents the various Texas energy commodities on an equivalent cost per unit of energy basis (from 1993 EIA data [8,9,10,12]). The blue bar segments of Figure 10.4 a/b/c, which represent the portion of the delivered costs in excess of the respective source costs, provides a general indicator of the relative transportation costs incurred in these primary fuel sectors (where transportation is a major cost component). For instance, it can be seen that the majority of the delivered cost of Wyoming coal stems from transportation (railroad freight) charges while large natural gas customers in Texas incur relatively low transportation charges. Figure 10.4 also underscores that retail uses command higher prices than industrial or wholesale uses. Even though additional transportation, distribution and marketing charges are generally required to serve residential customers, direct sales to end-use customers may be desirable for certain renewable energy industries.

Added value/co-products. Some end-use customers may place added value on the use of a renewable resource. Polls indicate a willingness among consumers to pay more for renewables than for conventional energy sources. Since wholesale ener-gy markets do not capture this sentiment, end-use customers may need to be targeted directly to capture this added value. Particularly when the renewable application helps achieve other objectives of an end-use customer—for instance, an anaerobic digestor installed at a dairy solves a manure disposal problem and offsets electricity purchased at retail rates—the overall project becomes more attractive.

To enhance competitiveness, renewable energy companies should be attentive to opportunities for "co-products" in addition to the sale of energy or energy services. Ethenol manufactured for use in motor vehicle fuels would not be cost effective if it were not for the additional revenue generated by sales of the other products (high-protein gluten feed and brewers yeast) derived from the ethenol-making process. Building-integrated photovoltaic systems (PV shingles, translucent glazing, and structural panels) can satisfy valued architectural needs of a building while also generating electricity.

Transport of Renewable Resources

Distributed Resources

The most efficient and lowest cost resource transportation option is when transportation is not needed at all. Many technologies using renewable energy sources are well-suited to small-scale distributed applications located where the energy service is needed. Examples include daylighting of structures, properly designed roof overhangs (to reduce cooling requirements), rooftop solar panels, ranch and farm wind turbines, and space heating from firewood or geothermal sources.

As electricity travels from a power plant to a house, business, or other destination, about one tenth of the electricity is lost along the way. Because of this, distributed generation lessens the need for additional power lines or lowers the demand on existing ones. Use of distributed generation can free up capacity of resource transportation systems, thereby providing upstream benefits for transportation infrastructure. As such, some electric utility Demand-Side Management programs include small renewable energy generation systems, such as solar water heaters and photovoltaic generation.

Efficiency/conservation. In the Texas electric sector, transportation and distribution (T&D) facilities (power lines and related equipment) represent roughly half of the investment of electric utilities. In primary energy as well, sidestepping the need for T&D systems saves investment in new infrastructure and circumvents energy losses incurred during the transportation of energy (once again, in the electric sector about 10%). Efficiency and conservation do not require these systems and thereby enhance capacity of existing T&D systems.

Process heat. Producing heat represents the largest energy use in Texas. Many renewable sources (biomass, geothermal, solar, and salinity gradients) provide thermal energy that can be utilized in appropriate temperature ranges and can prove a better value than burning fossil fuel. For instance saw, paper, and pulp mills generally meet their sizable process heat requirements through biomass. Other renewable sources generally serve lower temperature heating, although concentrating solar equipment can provide heat at very high temperatures.

Mechanical energy. Kinetic energy sources such as moving water and air (wind) have historically been tapped to pump water, grind grain, and perform other mechanical services. These uses, however, have generally given way to electric counterparts. When these loads (remote water pumping, for example) stay "off-grid", it still circumvents the need for transportation.

Fuels Suitable for Transportation

Only two types of systems are presently feasible for long distance power transmission: electrical power transmitted through electrical conductors, and chemical energy transmitted via pipelines or freight systems.

From an energy standpoint, the transportation sector is almost three times the size of the electric end use market. Biofuels derived from the chemical energy stored in biomass are the only renewable option for participation in the transportation market through traditional liquid fuels. Any renewable suitable for electric production could obviously participate if electric vehicles were to gain significant market share for transportation services.

Renewable solid and liquid fuels will be derived from biomass. Vehicles powered by gaseous fuels could utilize methane or other hydrocarbon gases derived from biomass feedstocks, or ultimately, hydrogen manufactured from water electrolysis using renewable derived electricity.

Solid fuels. Solid fuels tend to be relatively expensive to transport and handle. Solid biomass will typically not be transported very far prior to being converted into electricity or another biofuel because its energy density and spatial concentration are too low to justify the cost of long-distance transport. Biomass usage makes most sense where resources are already concentrated. Biomass processing facilities will not generally handle materials from outside of about a 50 to 100 mile radius from the plant due to transportation costs. Solid charcoal derived from biomass is a higher value-added form that may be transported very long distances via standard freight systems.

Liquid fuels. Liquid biofuels derived from biomass refer mainly to ethanol or biodiesel. These fuels can be transmitted in pipelines just as finished petroleum products can, or can be transported via standard freight systems—barge, railroad tank car, or fuel truck. The higher value of these products as transportation fuels means that they can be cost-effectively shipped long distances. Furthermore, in the case of ethanol, a substantial and growing market may soon exist in additives used to make reformulated gasoline (RFG). Under the Clear Air Act, RFG will soon be mandated in many of the metropolitan areas with ozone pollution problems. The main oxygenates proposed for blending into RFG are two ethers: methyl tertiary butyl ether (MTBE), derived from non-renewable methanol, and ethyl tertiary butyl ether (ETBE), manufactured from renewable ethanol. If ETBE captured 30% of this market, it would create a need for an additional 500 million gallons (roughly) of ethanol, increasing the size of the present ethanol market by about 50%. This large market is the energy equivalent of over 5,000 MW of wind power (at 25% capacity factor). Ethanol is not presently distilled in Texas, but Texas will nonetheless be a major participant in any renewable oxygenate development as the vast majority of the oxygenates will be blended at refineries along the Texas/Louisiana Gulf Coast. The single largest facility in the U.S. with ETBE capacity is in fact at ARCO Chemical in Corpus Christi.

Gaseous fuels. Gaseous chemical energy derived from renewables can be biogas evolved from anaerobic digestion of wet biomass, syngas generated in thermochemical biomass gasification schemes, or renewable hydrogen manufactured by electrolytically splitting water into its elemental components. The first two will likely be used close to the source biomass conversion facility because they are not of the quality (energy content, and cleanliness) to warrant pipeline transportation. Renewable hydrogen has been the source of much interest, but is not likely to be technically or economically viable for some time. It is fabricated with an expensive, high quality fuel in electricity, and electrochemical conversion technologies are not mature. Furthermore, hydrogen can not be immediately substituted into existing pipelines because of a phenomenon called "hydrogen embrittlement"—metals lose their ductility due to elemental hydrogen diffusing into the metallic lattice. Hydrogen can, however, be blended in low concentrations with natural gas in a mixture called "hythane" with no apparent pipeline degradation. Should the hydrogen economy ever become a reality, Texas should be well-positioned to export renewable hydrogen due to an immense existing pipeline infrastructure—that is, pipeline right-of-ways are in place, even if the proper pipelines are not.

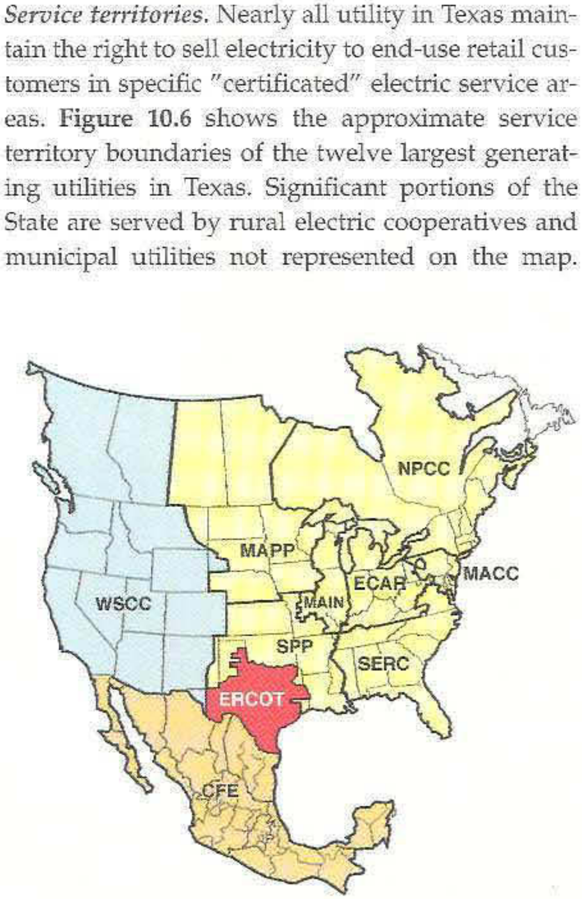
ELECTRICITY

Organization of Electric System

Power pools. By interconnecting individual utilities together, operating problems at one utility can be compensated for by the generation of another, thereby providing uninterrupted electric service to the end-use customer. Over the years, four distinct systems have evolved in North America to enhance system reliability: Western States Coordinating Council (WSCC), The Eastern Interconnection, Electric Reliability Council of Texas (ERCOT), and the Comision Federal de Electricidad (CFE). As shown in **Figure 10.5**, the fringes of all four systems come together in the remote expanses of West Texas.

Types of utilities. Texas, the nation's number one electric producer and consumer, has numerous providers of electric energy services. These include investor-owned utilities, municipal (city-owned) utilities, electric cooperatives (owned by the customers themselves), government authorities, self-generators and co-generators (entities that produce electricity and heat for their own needs and sell the excess). These utilities range in size from Texas Utilities Electric Company (one of the largest utilities in the country) to numerous small electric cooperatives. Summary statistics for the major utilities in Texas are shown in **Table 10.2.**

Service territories. Nearly all utility in Texas maintain the right to sell electricity to end-use retail customers in specific "certificated" electric service areas. **Figure 10.6** shows the approximate service territory boundaries of the twelve largest generating utilities in Texas. Significant portions of the State are served by rural electric cooperatives and municipal utilities not represented on the map.



WSCC - Western Systems Coordinating Council
ERCOT - Electric Reliability Council of Texas
EASTERN INTERCONNECTION:
ECAR - East Central Area Reliability Coordination Agreement
MAAC - Mid-Atlantic Area Council
MAIN - Mid-America Interconnected Network
MAPP - Mid-Continent Area Power Pool
NPCC - Northeast Power Coordinating Council
SERC - Southeastern Electric Reliability Council
SPP - Southwest Power Pool
CFE - Comision Federal de Electricidad

FIGURE 10.5. Electric Power Pools of North America.[4]

TABLE 10.2. 1993 Summary Statistics for Electric Utilities in Texas.[14]

UTILITY	TOTAL GENERATION (TWH)	PEAK DEMAND (GW)	SYSTEM CAPACITY (GW)	RESERVE MARGIN (%)	DEMAND GROWTH RATE (%)	RESIDENTIAL RATE (cents/kWh)
TU	84.6	17.9	21.7	22	1.9	8.2
HLP	60.8	11.4	14.6	28	1.6	9.0
GSU	29.8	5.5	6.7	21	0.9	7.7
CPL	17.4	3.2	4.3	36	2.9	8.5
SPS	17.2	3.2	3.9	24	1.3	6.3
SWEPCO	15.5	3.2	4.4	36	2.7	6.5
CPS	12.6	2.9	4.4	52	3.6	6.5
LCRA	8.1	1.8	2.1	19	0.1	n/a
COA	7.2	1.6	2.4	52	2.5	6.9
WTU	5.9	1.2	1.4	19	0.8	8.0
EPE	5.0	1.0	1.2	21	1.6	10.1
TNP	4.9	1.0	1.0	0	2.2	9.1
TEXAS	249.4	50.8	65.0	28	—	—

Such entities often purchase their electricity from wholesale suppliers (generally from the large generating utilities identified on the map) and then in turn sell power to their customers or members. While most electric ratepayers in Texas have only one source for purchasing electricity, some regions of the state have four or more retail providers.

Transmission system. A network of electric transmission lines connect the State's electric generation plants to large electric load centers like refineries, factories and cities (**Figure 10.7**). Fanning out from this primary transmission system is a secondary system that functions to distribute electricity to smaller electric users such as houses and farms. Large, new power plants in areas not already serviced by major transmission lines require new lines to be installed at a significant additional expense to the project. Distributed generation sources smaller than about 5 MW can usually interconnect successfully on distribution feeders for modest cost.

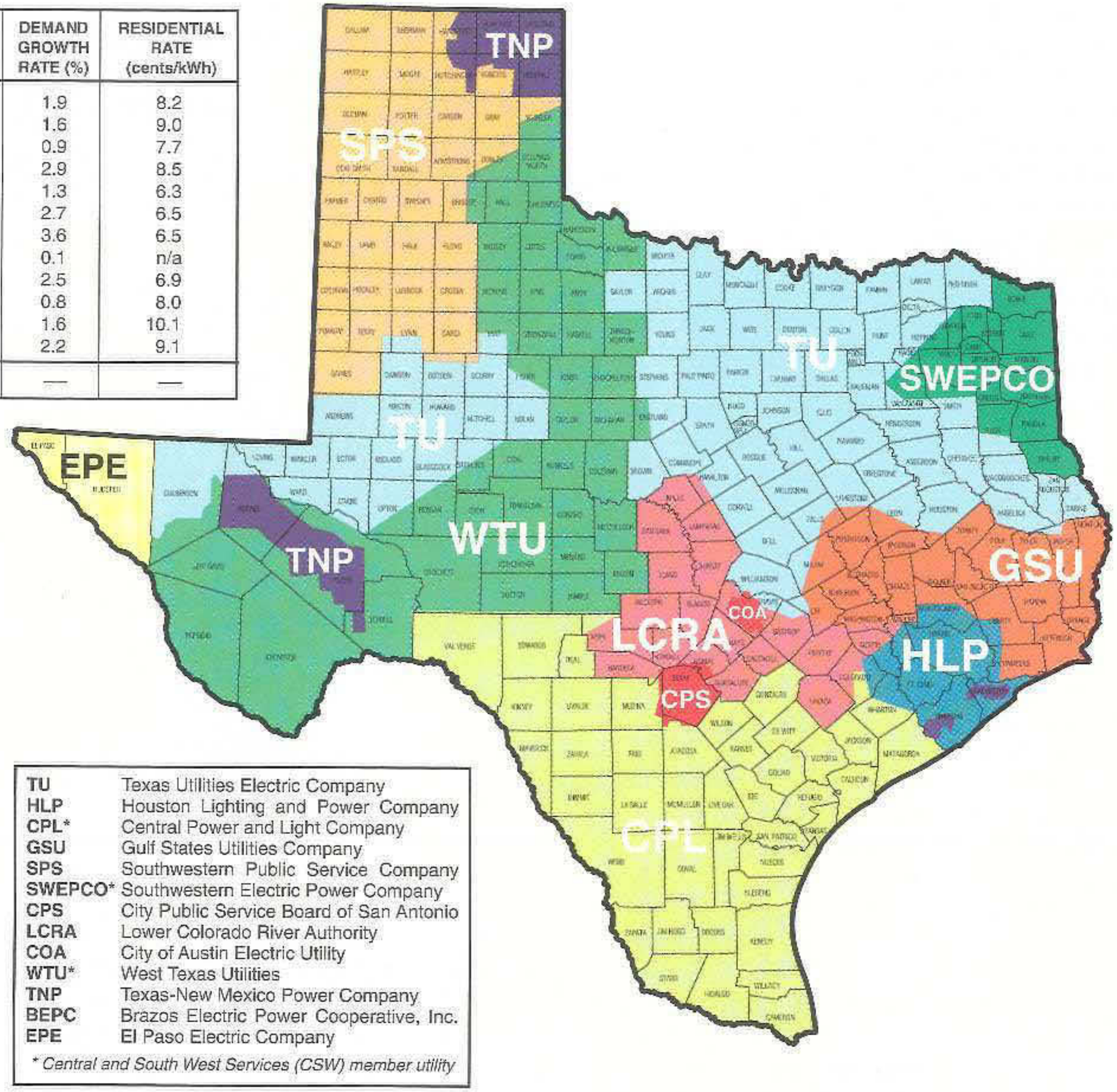


FIGURE 10.6. Electric Service Territories of the Major Generating Utilities in Texas. Adapted from PUC sources.[6]

Electric Transmission Studies

Physical proximity to electric transmission lines is often used for preliminary site screening; however, often times the available capacity on lines in fully committed. The SEDC supported two independent efforts to examine the relative transmission requirements that would be needed in different renewable energy resource areas of the state. These studies are briefly summarized below.

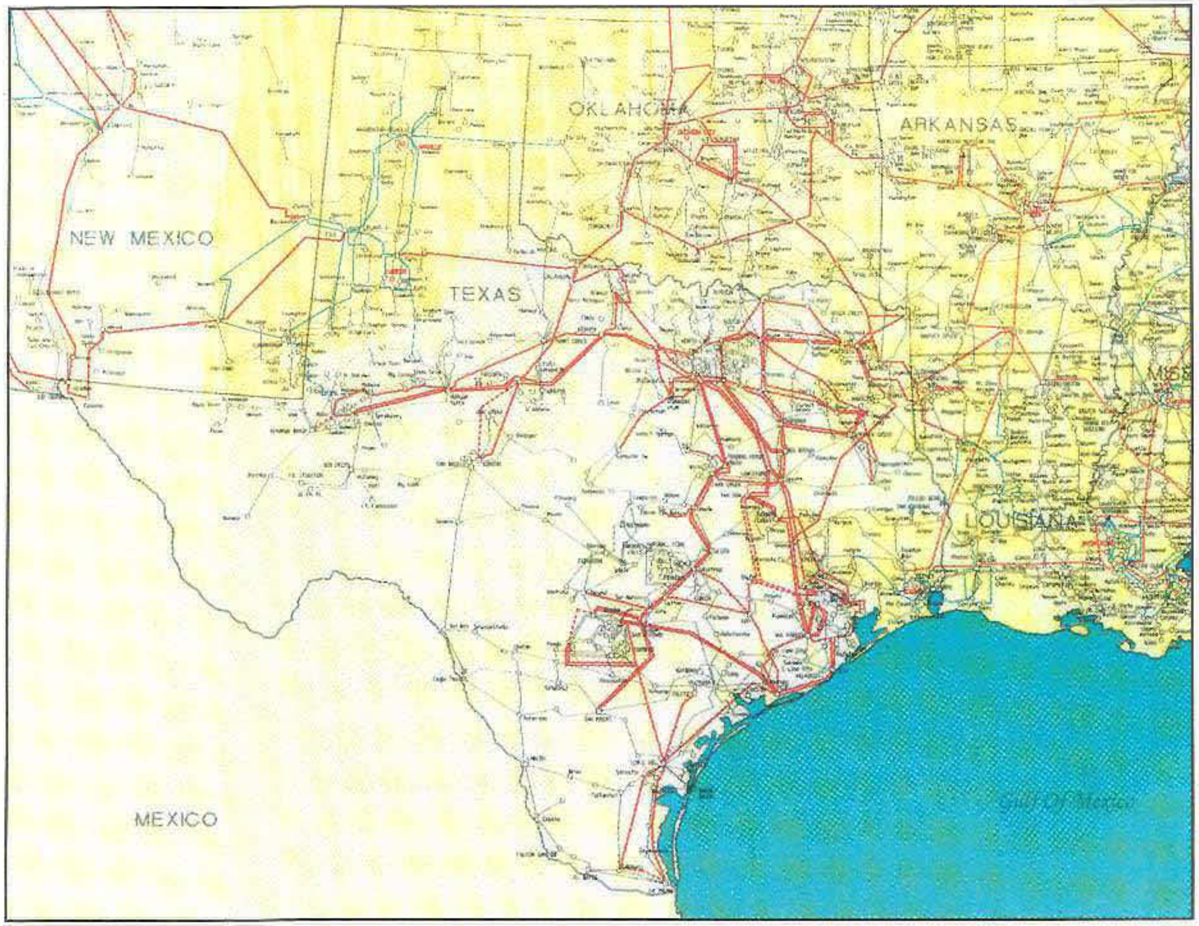


FIGURE 10.7. Map of Electric Transmission Lines In and Near Texas (Southwest Power Pool Map[12]). The numerous 345 kilovolt circuits (red) connecting the States major population centers and industrial areas in the Permian Basin form the backbone of Texas' electric grid. The Southwest Power Pool (yellow areas) and the Western Systems Coordinating Council (around El Paso) cannot easily transfer electric power to the vast majority of loads in the rest of Texas (which are in ERCOT).

SEDC Transmission Subcommittee Report

Several of the state's major electric utilities (LCRA, Texas Utilities, and West Texas Utilities), pooled their resources to evaluate the cost of electric transmission facilities that would be required to transport electricity from five good renewable energy resource areas to major population centers such as Dallas, Houston and San Antonio. Their analyzes entailed the full initial evaluation procedures that would be conducted for transmission projects actually intended to be built.

The results from this study, summarized in **Figure 10.8**, indicate that renewable energy developments at different locations in Texas can incur significantly different transmission costs. For instance, transmission needed to carry electricity out of some areas of West Texas may add 25% or more to the total price tag for a new wind power plant (assumed cost of $750 per kilowatt). Yet, if this same wind plant were to be located near Kleberg in

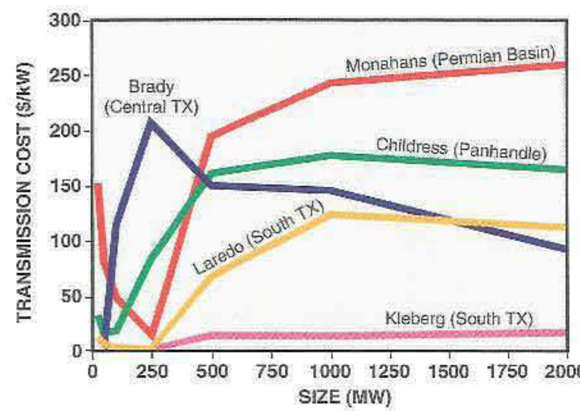


FIGURE 10.8. Electric Transmission Costs.[2] Summarizes improvements required at five prospective power plant sites.

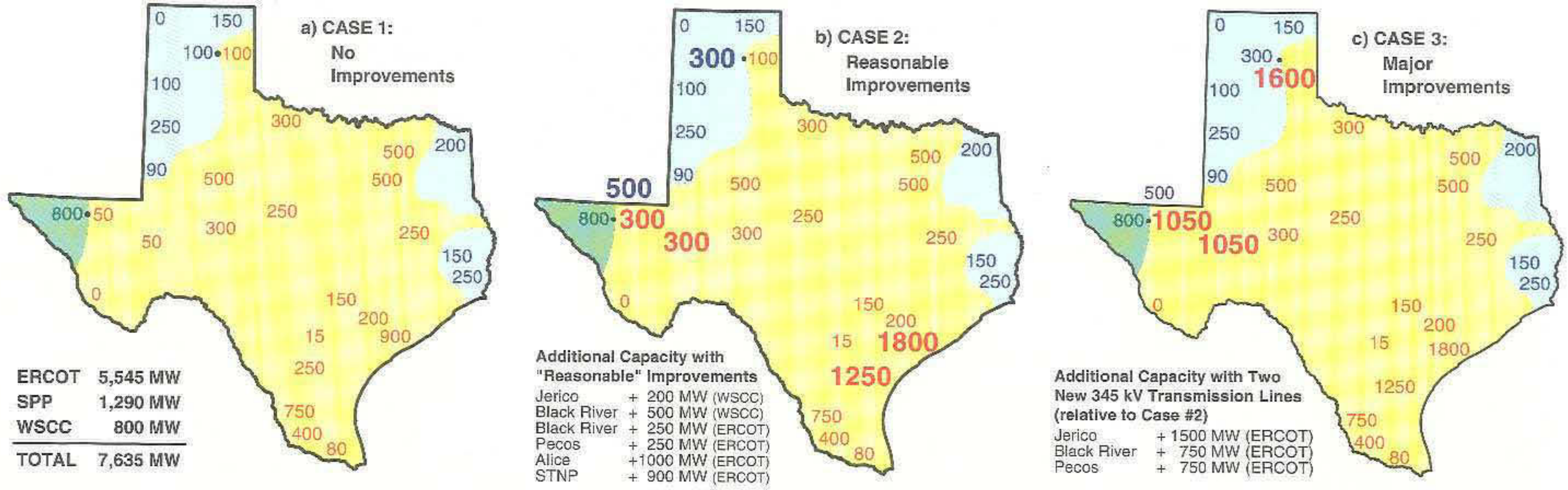


FIGURE 10.9. Summary of Results of Load Flow Modeling Study. Each value is an estimate of the maximum generation potential (MW) at that site assuming (a) no grid improvements, (b) minor improvements, and (c) with major upgrades (two new 345 kV circuits) to two areas.

South Texas, transmission costs would amount to less than 5% of the total wind project cost.

Load Flow Modeling Study of the Texas Electric Grid

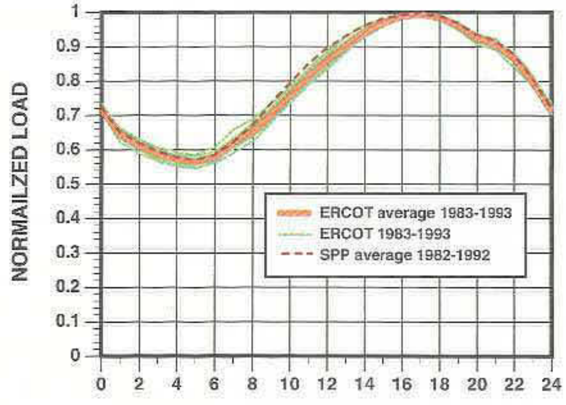
A second recent study that examined the Texas electric grid was performed by Electric Power Engineers (EPE) in conjunction with this resource assessment project. Their goal was to project limits of the electric grid within and adjacent to Texas in distributing electric power generated from renewable resources. Twenty-nine prospective renewable energy generation sites distributed throughout the state were considered.

Incremental generation blocks were specified for each resource type consistent with anticipated optimum unit sizes. Each increment of generation at each site was prioritized to specify an order in which the potential generators would be added to the grid. Generation was incrementally increased at each site, in priority order, until overload conditions were achieved. Generation was attributed to ERCOT load growth, and when practical, exported to adjoining power pools (SPP and WSCC).

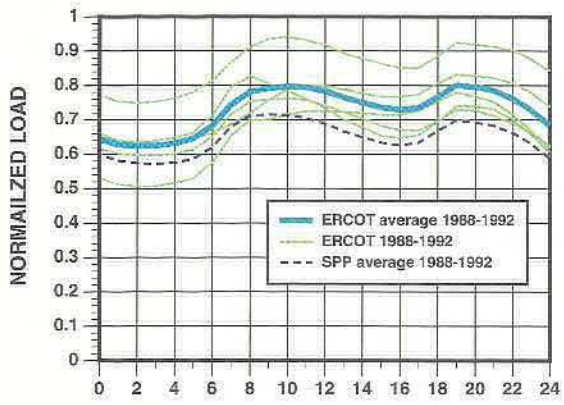
Three scenarios were considered to determine the limit of the 1999 Texas' transmission grid to absorb the output of the 29 renewable resource generation sites. The scenarios considered: Case 1) no system improvements; Case 2) minor line improvements; and Case 3) two, new, 345 kV, double-circuit transmission lines linking far west Texas (Wink area) and the Panhandle (Clarendon area) to load centers in Dallas/Houston/San Antonio.

The load flow analysis results, summarized in **Figure 10.9**, suggest that many large renewable energy power plants could be added to the grid even with no new power lines (Case 1). The small Case 1 numbers in the Panhandle and Trans-Pecos, suggest that new transmission lines will be required to fully tap these good resource areas (as in Case 3).

The EPE study is intended to be used as a starting point and guide for additional studies of complex issues concerning the incorporation of relatively large amounts of renewable resource generation into the Texas transmission grid. Such issues include establishing renewable resource unit availability by type, resource, and site location; establishing the effects of new technology transmission enhancements; identifying and quantifying the effects of energy storage; and addressing transmission access.



a) Summer Electric Peak Load Profiles



b) Winter Electric Peak Load Profiles

FIGURE 10.10. Average Electric Peak Load Profiles for ERCOT. Profiles for (a) summer are extremely consistent while (b) winter profiles show some modest deviations.

Peak loads profiles. Reliable generation during peak load periods is more valuable than electricity generated during all other times. **Figure 10.10** shows historical summer and winter peak load profiles for the ERCOT system.

RECOMMENDATIONS

This chapter has considered transportation issues relating to renewable energy resources going from source to end-use. The following recommendations and observations from this investigation are offered:

1) **A better understanding of the correlation between energy use and the availability of renewable resources is needed.** A wide range of issues need to be examined to determine the value of renewable energy sources and their ability to be successfully incorporated into the state's energy mix. Significant, unresolved issues include the appropriate capacity value and firmness of renewable resources, whether existing conventional capacity can be used to firm renewable generation, and the impact of new technology, energy storage and methods of modifying energy consumption behavior to facilitate improved utilization of renewable energy resources.

2) **The state's existing electric transmission system can support large renewable energy development, but is constrained in some of the best renewable resource regions of Texas.**

3) **Implementation of energy efficiency, conservation, and small-scale renewable energy generation will offset demand on current energy transportation infrastructure.**

4) **Renewable-derived oxygenates for reformulated gasolines (RFG) may represent opportunity for Texas biomass.** A large portion of RFG will be blended here in Texas, and certainly could use Texas biomass feedstocks to manufacture the blending ether ETBE.

5) **Hydrogen derived from renewable sources is a long-term opportunity for Texas.** If the nation eventually transitions to a Hydrogen based economy, it will likely occur through the gradual conversion of natural gas systems to hythane and eventually hydrogen. Existing pipeline infrastructure and pipeline right-of-way throughout Texas may prove to be a valuable, long-term asset.

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3 Lower Colorado River Authority. *West Texas Renewable Resource Integration Studies.* (Draft) Austin, TX, 1994.
4 U.S. Department of Energy. *United States/Mexico Electricity Trade Study.* Springfield, VA : National Technical Information Service, March 1991.
5 Public Utility Commission of Texas. *Bulk Load Modeling Study.* Austin, TX, 1988.
6 Public Utility Commission of Texas. *Electric Generating Unit Inventory.* (Draft) Austin, TX, 1993.
7 Electric Reliability Council of Texas. *Coordinated Bulk Power Supply Program, OE-411.* Austin, TX, 1994.
8 Energy Information Administration. *Electric Power Annual 1993.* Washington, D.C. : U.S. Government Printing Office, 1994.
9 Energy Information Administration. *Coal Production 1993*, Washington, D.C. : U.S. Government Printing Office, 1994.
10 Energy Information Administration. *Petroleum Supply Annual 1993, Vol. 1.* Washington, D.C. : U.S. Government Printing Office, 1994.
11 Federal Energy Regulatory Commission. Major natural gas pipelines (map), September 30, 1993, Washington, D.C.
12 Energy Information Administration. *Natural Gas Annual 1993, Vol. 1.* Washington, D.C. : U.S. Government Printing Office, 1994.
13 Energy Information Administration. *State Energy Data Report 1993: Consumption Estimates.* Washington, D.C. : U.S. Government Printing Office, 1995 (pending).
14 Public Utility Commission of Texas. *1994 Statewide Electrical Energy Plan.* Austin, TX, 1995.

RECOMMENDATIONS

Texas is blessed with abundant renewable energy resources. In fact, Texas' solar, wind, and biomass potential rank among the very best in the nation. As summarized in **Figure 11.1** below, many areas of the state have sufficient "commercial quality" resources to support large investments such as electric power production, cogeneration, and alcohol manufacturing, as well as multitudes of distributed, small-scale projects. Texas' excellent endowment suggests that renewable energy offers exceptional potential to help meet the state's future energy needs.

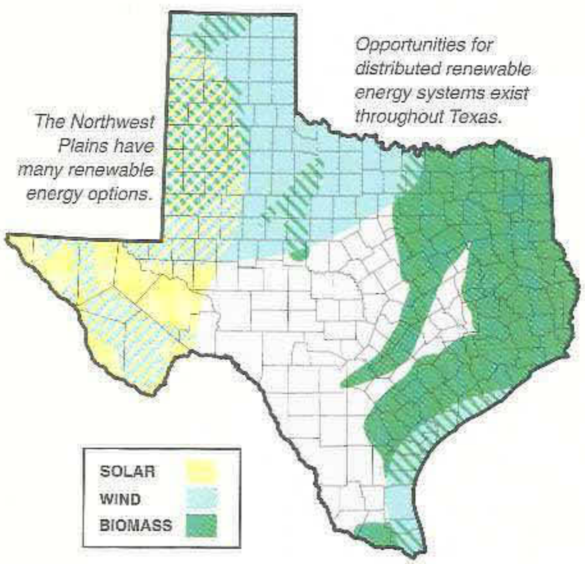


FIGURE 11.1. Areas of High Solar, Wind, and Biomass Potential. Striped areas indicate the presence of more than one good resource. Grey areas can use distributed sources.

Development of the state's renewable energy resources could provide meaningful employment opportunities and stimulate local economies. The Northwest Plains, with sizable wind, solar, and biomass potential, is well positioned to reap rural economic benefits associated with the growth of renewables. In the urban areas of East and Central Texas, distributed renewable energy systems such as rooftop solar collectors can satisfy a large portion of local energy needs. In addition, many renewable energy systems mesh synergistically with efforts to control various wastes. Examples include distributed electric generation facilities fueled by landfill gas and other urban wastes, and solar ponds constructed in conjunction with facilities that prevent saline water from contaminating fresh water supplies.

This project has gathered information from a wide variety of sources. In total, these sources determine that Texas has plentiful renewable resources. But in order to optimally utilize the renewable energy resource base of the state, additional information will be required. The recommendations which follow are designed to provide a better understanding of resources that have the potential to make significant near-term contributions towards the state's energy needs.

Specific Resource Assessment Needs

Future investments in renewable energy resource assessment should be focused in areas where they are expected to have the greatest near-term impact, and secondly when and where opportunities present themselves to participate in other ongoing resource assessment activities.

1) **Building Climatology:** **(a)** *Characterize the state's building stock and examine the potential impact of passive strategies.* Building structures that are more in tune with their environmental surroundings makes sense economically. However, passive strategies do not operate independent of one another; additional validation of optimal strategies for structures built in Texas climates is warranted.

   (b) *Examine the coincidence of renewable energy resources with building energy loads.* Many resources may not be available at the times when they are needed. For example, summer winds may be low during electricity consumption peaks, or winter peak demand periods may not coincide with the presence of sunshine. This critical aspect of resource planning should be studied in more detail to facilitate the adoption of renewable energy strategies.

2) **Wind:** **(a)** *Ensure the long-term operation of the state's newly established wind monitoring network.* Accurate assessment of the state's wind resource hinges on long-term quality measurements taken at heights representative of commercial wind turbines on windy, well exposed terrain suitable for wind farm

development. Texas currently has such a program in place but, after this year, funding is uncertain. Given the modest financial commitment needed to maintain the program and the relative near-term competitiveness of wind electric power plants, steps should be taken to ensure vitality of this wind monitoring program in order to build a continuous record of at least five (5) years.

(b) *Consolidate and evaluate existing wind data.* A lack of resources precluded the incorporation of numerous existing wind data in previous assessments of the state's wind resource. Support should be provided for bringing together and analyzing as much existing wind information as possible.

3) **Solar:** **(a)** *Establish more solar monitoring stations throughout the state, particularly in the Trans-Pecos and along the Rio Grande.* The best solar resource areas of Texas have almost no measured solar data available. The long-term maintenance of such monitoring stations is critical to ensure continuous measurements and quality data; cyclic support for solar measurements has undermined efforts to reasonably understand the resource. Major solar development will require substantially improved resource information to optimally design facilities.

(b) *Support the development of high resolution state maps of average solar radiation/cloud cover.* Determination of the sunniest spot in a local region is obviously of interest to entities siting solar facilities. Unfortunately, there simply is not enough information readily available to determine such solar microclimates. High resolution maps derived from existing satellite data bases would be extremely valuable in addressing this issue.

(c) *Support the development and validation of techniques to model solar data from other information.* Since direct measurements of terrestrial solar radiation will likely never be of sufficient density to satisfy industry needs, it is important to pursue modeling techniques that infer the solar resource from other data such as satellite-measured cloud cover and other meteorological parameters.

4) **Resource Transportation Issues:** *Develop a better understanding of the correlation between energy use and the availability of renewable resources.* The intermittent nature of solar and wind energy leads many to discount the value of these resources for satisfying future energy demand. Yet fluctuations in the availability of these resources do follow regular seasonal patterns and furthermore they can be reasonably predicted over short time scales of several hours. A wide range of issues need to be examined to determine the true value of wind and solar energy and their ability to be successfully incorporated into the state's energy mix. Significant, unresolved issues include the appropriate capacity value and firmness of renewable resources, whether existing conventional capacity can be used to firm renewable generation, and the impact of new technology, energy storage and methods of modifying energy consumption behavior to facilitate improved utilization of renewable energy resources.

5) **Biomass:** **(a)** *Fully participate in federally sponsored programs.* Although active in certain areas such as switchgrass field trials, Texas researchers have been absent from other assessment opportunities relevant to the state's biomass resource. Participation in reviews of potential energy crops is particularly important since the state's widely varying physiography and climate may make it difficult to accurately extend results from other regions of the country.

(b) *Support a scoping study to determine which biomass resources hold the greatest near-term promise.* The present study has outlined the state's various biomass resources, but has not attempted to rank them according to their economic viability. This is a reasonable next step to efficiently promote the biomass resource, given its diversity and complexity.

6) **Water:** *Examine opportunities to develop solar ponds in conjunction with planned chloride control projects.* If water agencies construct new chloride control lakes to improve water quality in the western parts of the state, this may present an opportunity for solar pond development. This potential should be investigated.

7) **Geothermal:** *Update the State's hydrothermal and geopressured data bases.* At some existing wells there are current opportunities to utilize geothermal heat. More current information would help facilitate action on such opportunities.

In addition to the recommendations above, organizations that are considering investments in assessment of renewable energy resources should be attentive to special opportunities for co-funding projects with entities with related interests. For instance, the Texas Natural Resource Conservation Commission is leading an effort to establish a Texas mesoscale weather observing network (MESONET). Such a network would prove extremely valuable to many elements of Texas' renewable energy community.

SUPPLEMENTAL DOCUMENTATION

PROJECT SUMMARY

by Virtus Energy Research Associates
February, 1995; 17 pages.

Summarizing the highlights of Texas Renewable Energy Resource Assessment: Survey, Overview, and Recommendations, this full color booklet is identical to the Project Summary included as the first 16 pages of this Final Report.

LOAD FLOW MODELING STUDY OF THE TEXAS ELECTRIC GRID

by Charles Freeman (Electric Power Engineers)
December, 1994; 50 pages.

Limitations to the 1999 electric transmission grid, within and adjacent to Texas, in distributing electric power generated by renewable energy resources are examined. The study considers 29 potential renewable energy generation sites and finds that supplying electric load growth expected to occur in Texas beyond the year 1999 is a futuristic yet achievable scenario. Many significant issues pertaining to transmission of renewables are raised.

SOUTH TEXAS WIND INFORMATION

by Mike Sloan (Virtus Energy Research Associates)
December, 1994; 18 pages.

The wind resources along the Texas Gulf Coast and in South Texas have received less attention from electric utilities and developers than the high wind resource areas of the Panhandle or the mountain ranges in the Trans-Pecos. Available information is summarized that suggests South Texas may produce the strongest and most reliable winds coincident with electric system peak in Texas.

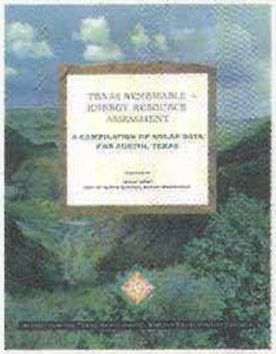
Through the course of the Texas renewable energy resource assessment project several additional reports and related information products have been produced. This appendix outlines the major supplemental documentation and products resulting from this project and reviews the various survey methods employed to identify and gather additional documents and information products.

Supplemental Project Documentation

In addition to this final report, the following documents have been produced:

- *Texas Renewable Energy Resource Assessment: Survey, Overview and Recommendations - Project Summary.* (Identical to the first 16 pages of the final report, this short booklet is available under separate cover.)
- *Texas Renewable Energy Resource Assessment Bibliography*
- *Load Flow Modeling Study of the Texas Electric Grid*
- *A Compilation of Solar Data for Austin, Texas*
- *A White Paper on Cloud Cover Climatologies*
- *South Texas Wind Information*

These documents are described in the sidebars on pages 151 and 152. The Bibliography, which was one of the primary survey methods utilized for this project, is described more thoroughly later in this appendix.



A Compilation of Solar Data for Austin, Texas

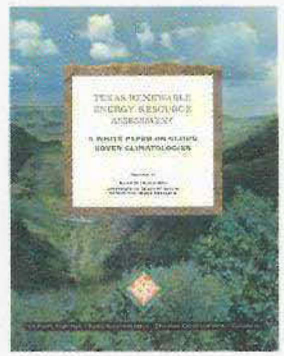
by Leslie Libby (City of Austin Electric Utility Department)
December, 1994; 78 pages.

Austin is fortunate to have several measured and modeled solar data bases readily available. This document tabulates monthly averages of solar radiation and ambient temperature from seven different sources in the Austin area. Also included are duration curves of direct normal and global horizontal irradiance (number of hours exceeding any given threshold). This novel tool graphically portrays discrepancy among different data sets.

A White Paper on Cloud Cover Climatologies

by Keith D. Hutchison (University of Texas, Center for Space Research)
December, 1994; 10 pages.

One of the most promising methods of improving the resolution of solar radiation maps is through the use of satellite image data bases. The author of this white paper has extensive experience in the development of such data bases (including the Air Force's Real Time Nephanalysis data base). This expert offers his opinions for the best methods and data available for developing high quality solar radiation contour maps of Texas.



Texas Renewable Energy Resource Assessment Bibliography

by Paula Knesel (Virtus Energy Research Associates)
December, 1994; 264 pages.

One of the major activities of the survey component of this project was a thorough search of literature for sources pertaining to Texas renewable resources. This was conducted through a search of the DIALOG online service. Almost 4,000 records were retrieved and examined; about 30% of these were retained. The retained records appear by subject in this abstracted bibliography.

Related Information Products

Over the course of the project, various additional renewable energy resource maps, Geographic Information System (GIS) data layers, computer programs/spreadsheets and data files were developed and archived. Such items were shared with SEDC vendors and interested parties for use in other renewable energy-related projects. Some of the products that were developed are identified below.

Resource Maps and Presentation Graphics. Renewable energy resource information from a wide array of sources and formats (digital GIS map files, paper maps, tabular data, hardcopy reports, etc.) were retrieved during the project. Invariably, the original information pieces required additional manipulation to produce graphic images that were compatible with desktop publishing standards.

In addition to "re-packaging" existing information sources, some new resource assessment products were created specifically for the project, such as the revised wind maps produced by AEI, the temperature and precipitation maps developed by George Bomar of the TNRCC, and the numerous Texas biomass maps generated by the Blackland Research Center. Not all of these maps appear in the final report, although they have been developed and have been used for related projects and functions, such as the Texas Bioenergy Conference.

GIS data layers. This project worked closely with a SEDC-funded project to establish and archive GIS-compatible renewable energy information layers through TNRIS. (This is described in more detail in Appendix C.) Members of the resource assessment project team supplied TNRIS with information to facilitate the creation of GIS layers on temperature, rainfall, wind, solar radiation, and water resources.

Data Files. Numerous computer files and data bases were acquired that may prove useful for future studies involving the renewable energy resources of Texas. Such files include renewable energy resource contact data bases; load flow data for ERCOT, WSCC, and SPP; hourly system load data for ERCOT and SPP; Geothermal well records (Geotherm data base); Texas hydroelectric site inventory (HES software); and numerous hourly and monthly averaged data files of wind, solar, temperature, and/or other natural resource parameters for many sites in Texas.

Acquiring Project Information Products

By contract, all deliverables from the Texas Renewable Energy Resource Assessment Project were to be delivered to the Texas Sustainable Energy Development Council. However, the SEDC is concluding its business and disbanding after August 31, 1995, and it has not yet been determined what State agency or other entity will assume responsibility for dissemination of information from this project and other SEDC-sponsored activities.

As of press time for this document, it is unclear how to direct inquiries requesting project documents and information after August, 1995. The most likely candidates to assume official responsibility for SEDC-related activities are the General Land Office, State Energy Conservation Office, or the Public Utility Commission. In lieu of an official contact, it is recommended that inquires for information be directed to the SEDC's Internet homepage (expected to remain active at least into 1996) or to the project contractor, Virtus Energy Research Associates. More specific recommendations and contact information are summarized on the sidebar on this page.

SURVEY

This section reviews the various methods that were used to acquire information for the resource assessment project. These consist of: 1) direct solicitation, 2) written survey, and 3) literature review. The literature review technique that resulted in the project's survey component deliverable (the Bibliography) is described in detail.

Direct Solicitation

As expected, direct solicitation of knowledgeable contacts proved to be the most productive means of acquiring pertinent resource information. Each chapter author pursued contacts in their subject area, mainly by telephone. In a few cases, project management traveled to meet face-to-face with groups expected to be particularly helpful (NREL and Blackland Research Center). Many of the sources that contributed to the project through direct solicitation are identified in Appendix B (Sources of Information).

Written Survey

A one page questionnaire was developed and mailed to about 480 individuals. The distribution list was achieved by eliminating names from a compilation of several renewable energy data bases (TX-SES, TREIA, WRBEP, etc.) until those that remained were considered to have a reasonable chance of maintaining information useful to the project. A second mailing was targeted at "minor" academic institutions that otherwise did not appear on the distribution lists.

About 20% of the distribution list responded to the survey. In many cases, one representative of an institution would respond on behalf of all that had

ACQUIRING PROJECT INFORMATION

At this time, it is not certain what entity will assume responsibility for dissemination of SEDC-related information. Inquiries regarding documents and other information products from the Texas Renewable Energy Resource Assessment Project can be made as follows:

1) **SEDC Internet Homepage**
URL = **http://sedc.twdb.texas.gov**

TNRIS expects to maintain this internet node for some time into the future. If the homepage does not contain the needed information, an inquiry can be posted with the system webmaster.

or contact:

2) **Virtus Energy Research Associates**

contact: **Mike Sloan**, Project Manager
phone: **(512) 476-9899**
e-mail: **sloan@vera.com**

3) **Direct Inquiries to Document Authors**

Charles Freeman,	EPE,	(817) 755-7272
Keith Hutchison,	UT,	(512) 471-3434
Leslie Libby,	COA,	(512) 322-6290

received a survey. Also, many individuals who had already been cooperating with the project did not return the survey. While telephone follow-up is mandatory to achieve a high survey response rate, the project team opted to focus on direct solicitation and the computerized literature search.

Literature Review

An online search of DIALOG Information Retrieval Service, from Dialog Information Services, Inc., was chosen as the method for conducting the literature search. DIALOG is a commercial database provider made up of more than 450 individual databases, many of which cover scientific and technical literature. These databases provide bibliographic references to journals, books, government reports, conference proceedings and other related literature. Many of these references also include an abstract summarizing the coverage of the actual document.

The literature search was broken down into the following seven sub-topics: renewable energy—general; solar energy; wind energy; biomass energy; geothermal energy; water energy (ocean and hydro); and building climatology.

A list of relevant keywords and their variations was generated for each of the sub-topics. These keywords and related terms were used as the primary mechanism of the online search. Due to the broad nature of many of these keywords, a list of limiting terms was created to be combined with the keywords. Some of the limiting terms included energy, power, resource, assessment, potential, estimation, and others as relevant to the specific topic. Finally, these results were combined with a set of geographical terms, such as United States, Texas, and Southwest.

TABLE A.1 Summary of DIALOG Records Retrieved.

SUBJECT	RECORDS RETRIEVED	RECORDS RETAINED	PERCENT RETAINED
Renewable Energy	132	46	35%
Solar	916	238	26%
Wind	733	175	24%
Biomass	428	348	81%
Water (Hydro & Ocean)	166	56	34%
Geothermal	526	226	42%
Building Climatology	908	69	8%
Total	3809	1158	30%

In order to ensure relevancy, these keywords were searched in the title, descriptor, and major descriptor fields. A descriptor is a word or phrase assigned to a record to describe the subject matter of the document. There may be several descriptors assigned to individual records, making the major descriptor field more useful at times. A major descriptor is applied when there is one aspect of the document that is covered more thoroughly than any other sub-topics.

As summarized in **Table A.1**, this strategy yielded 3,809 records for all seven topics. Of these 3,809 records, 1,158 were determined to be relevant to this specific project and were included in the 264 page bibliography document.

Data Base Descriptions

Inspec. Provides indexing of journals, conference proceedings, books, and dissertations since 1969. It is strong in the area of physical sciences and contains more than 4 million records.

National Technical Information Service (NTIS). Consists of summaries of government-sponsored research, development, and engineering projects. It contains more than 2 million records from 1969 to the present.

Compendex Plus. Covers major scientific and engineering literature and contains more than 3 million records from 1970 forward.

Energy Science and Technology. A multidisciplinary file of worldwide references to basic and applied scientific and technical research literature, sponsored by the Department of Energy. It was started in 1974 and contains more than 3 million records.

Georef. The database of the American Geological Institute, providing coverage of worldwide technical literature on geology and geophysics. It provides coverage dating to 1785 and contains more than 2.5 million records.

Oceanic Abstracts. indexes world wide technical literature on all aspects of the oceans. It contains more than 500,000 records, dating from 1964.

Meteorological and Geoastrophysical Abstracts. provides current citations for the most important meteorological and geoastrophysical research published in worldwide literature sources. From 1970 to present, more than 200,000 records have been added.

Inspec, Compendex Plus, Energy Science and Technology and NTIS were used in all seven searches. The remaining databases were added to the searches of specific sub-topics when applicable.

SOURCES OF INFORMATION

AREA	NAME	AFFILIATION	PHONE	COMPANY	ADDRESS	CITY	STATE	ZIP
RENEWABLES GENERAL	Drew Decker	TNRIS	(512) 463-8338	Texas Natural Resource Information System	P.O. Box 13231	Austin	TX	78711-3231
	Edward Gastineau	Consultant	(214) 931-1676	Sustainable Energy Economics, Inc.	1532 Chesapeake	Plano	TX	75093
	Gary Jones	US/ECRE	(202) 383-2607	Energy Conservation and Renewable Energy	122 C Street N.W. 4th Floor	Washington	DC	20001-2109
	Tom Ross	NCDC	(704) 271-4994	National Climatic Data Center	P.O. Box 743	Marshall	NC	28753
	Stephen Rubin	NREL	(303) 275-4065	National Renewable Energy Laboratory	1617 Cole Blvd.	Golden	CO	80401
	Russel Smith	TREIA	(512) 345-5446	Texas Renewable Energy Industries Assoc.	P.O. Box 43101	Austin	TX	78745-0003
SOLAR								
	Jim Augustyn	Consultant	(510) 525-0464	Augustyn + Company	1029 Solano Ave.	Albany	CA	94706
	Ray Bahm	Consultant	(505) 831-3911	Ray Bahm and Associates	2513 Kimberly Court NW	Albuquerque	NM	87120
	John Bigger	UPVG	(202) 857-0898	Utility Photo Voltaic Group	1800 M St., NW, Suite 300	Washington	DC	20036-5802
	Michael Ewert	NASA	(713) 483-4134	NASA Johnson Space Center	2101 NASA Rd. 1	Houston	TX	77058
	Robert Foster	SWTDI	(505) 646-3948	Southwest Technology Development Inst.	Box 30001, Dep. 3SOLAR	Las Cruces	NM	88003-8001
	Leslie Libby	COA	(512) 322-6290	City of Austin Electric Utility Dept.	721 Barton Springs Rd.	Austin	TX	78704
	Eugene Maxwell	NREL	(303) 275-4688	National Renewable Energy Laboratory	1617 Cole Blvd.	Golden	CO	80401
	Richard Perez	ASRC	(518) 442-3808	Atmospheric Sciences Rsrch. Ctr, SUNY	100 Fuller Rd.	Albany	NY	12205
	David Renne	NREL	(303) 275-4648	National Renewable Energy Laboratory	1617 Cole Boulevard	Golden	CO	80401-3393
	Andy Rosenthal	SWTDI	(505) 646-1049	SW Technology Dev. Institute, NMSU	Box 30001, Dept. 3SOLAR	Las Cruces	NM	88003-8001
	Mike Sloan	VERA	(512) 476-9899	Virtus Energy Research Associates	906 1/2 Congress Avenue	Austin	TX	78701
	Tom Stoffel	NREL	(303) 275-4690	National Renewable Energy Laboratory	1617 Cole Boulevard	Golden	CO	80401-3393
	Lorin Vant-Hull	UH	(713) 743-9126	University of Houston	4800 Cullen	Houston	TX	77204-5506
	Gary Vliet	UT Austin	(512) 471-3120	University of Texas at Austin	Dept. of Mech. Eng. ETC 7.142	Austin	TX	78712
	Bob Walters	ENTECH	(214) 456-0900	ENTECH, Inc.	P.O. Box 612246	DFW Airport	TX	75261
WIND								
	Nolan Clark	USDA	(806) 356-5734	USDA Agriculture Research Service.	P.O. Drawer 10	Bushland	TX	79012-0010
	Earl Davis	EPRI	(360) 681-8096	Electric Power Research Institute	P.O. Box 10412	Palo Alto	CA	94304
	David Eggleston	Consultant	(915) 683-5735	DME Engineering	1605 W. Tennessee	Midland	TX	79701
	Dennis Elliott	NREL	(303) 384-6935	National Renewable Energy Laboratory	1617 Cole Blvd., NWTC	Golden	CO	80401
	Walter Hornaday	TWP	(512) 320-0305	Texas Wind Power Company	707 West Avenue #209	Austin	TX	78703
	Vaughn Nelson	AEI	(806) 656-2296	Alternative Energy Institute	WTAMU Box 248	Canyon	TX	79016
	Richard Simon	Consultant	(415) 381-2245	Consulting Meteorologist	80 Alta Vista Avenue	Mill Valley	CA	94941
	Andrew Swift	UTEP	(915) 747-5450	University of Texas at El Paso	Mechanical Engineering	El Paso	TX	79968
BIOMASS								
	Philip Badger	TVA	(205) 386-3086	Tennessee Valley Authority CEN3A	P.O. Box 1010	Muscle Shoals	AL	35662-1010
	John Bean	BFI	(713) 870-7450	Browning Ferris Gas Services, Inc.	757 N. Eldridge	Houston	TX	77079
	Scott Beasley	SFA	(409) 468-3304	Stephen F. Austin, College of Forestry	P.O. Box 6109 SFA	Nacogdoches	TX	75962
	Mark Downing	ORNL	(615) 576-8140	Oak Ridge National Laboratory	P.O. Box 2008	Oak Ridge	TN	37831-6226
	Richard Faidley	VERA	(512) 476-9899	Virtus Energy Research Associates	906 1/2 Congress Avenue	Austin	TX	78701
	Peter Felker	TX A&M	(512) 595-3966	CKWRI TAMU	Campus Box 218	Kingsville	TX	78363
	Robin Graham	ORNL	(615) 576-5454	Oak Ridge National Laboratory	P.O. Box 2008	Oak Ridge	TN	37831-6036
	Wayne LePori	TX A&M	(409) 845-3931	Texas A&M University	AERL Rt. 4 West Campus	College Station	TX	77843
	Roger Lord	TFS	(409) 845-2641	Texas Forest Service	John Connally Bldg. RM 361	College Station	TX	77843-2136
	Bill Ocumpaugh	TX A&M	(512) 358-6390	Texas Ag. Experiment Station	HCR-2, Box 43-C	Beeville	TX	78102
	Ken Rogers	TFS	(409) 639-8180	Texas Forest Service, FPL	P.O. Box 310	Lufkin	TX	75902-0310
	Matt Sanderson	TX A&M	(817) 968-4144	Texas Ag. Experiment Station	Rt. 2, Box 00	Stephenville	TX	76401

	Max Shauk	BU	(817) 755-3563	Baylor University, Aviation Sciences Dept.	Box 97413	Waco	TX	76798-7413
	Raghavan Srinivasan	TAES	(817) 770-6600	TAES, Blacklands Research Ctr.	808 E. Blackland Road	Temple	TX	76502
	Noni Strawn	NREL	(303) 275-4347	National Renewable Energy Laboratory	1617 Cole Blvd.	Golden	CO	80401
	David Swanson	WRBEP	(303) 231-1615	Western Regional Biomass Energy Pgm.	P.O. Box 3402 (A) 450	Golden	CO	80401
	John Sweeten	TX A&M	(409) 845-7451	Texas A&M University Agriculture Engineering	303 Scoates Hall	College Station	TX	77843-2121
	Charlie Tischler	USDA-ARS	(817) 770-6600	USDA-ARS	808 E. Blackland Rd.	Temple	TX	76502
	Shaine Tyson	NREL	(303) 275-4616	National Renewable Energy Laboratory	1617 Cole Blvd.	Golden	CO	80401
	John Vissage	USDA	(601) 324-1611	Southern Research Station, Forestry Sciences	P.O. Box 928	Starkville	MS	39760-0928
	Dewayne Weldon	TFS	(409) 639-8180	Texas Forest Service, FPL	P.O. Box 310	Lufkin	TX	75902-0310
	Art Wiselogel	NREL	(303) 275-4466	National Renewable Energy Laboratory	1617 Cole Blvd.	Golden	CO	80401
	Lyn Wright	ORNL	(615) 574-7378	Oak Ridge National Laboratory	P.O. Box 2008	Oak Ridge	TN	37831-6226
	Micki Yoder	USDA-NRCS	(817) 774-1255	USDA-NRCS	101 S. Main St.	Temple	TX	76501-7682
WATER								
	W. Eberle	Consultant	(214) 630-6751	Eberle Energy Enterprises, Inc.	2777 Irving Blvd., #112	Dallas	TX	75207
	Jim Francfort	INEL	(208) 526-6787	Idaho National Engineering Laboratory	P.O. Box 1625	Idaho Falls	ID	83415-3875
	Bill Hoffman	TWDB	(512) 463-7932	Texas Water Development Board	P.O. Box 13231	Austin	TX	78711
	Nick Krause	TCOON	(512) 994-2646	Blucher Institute, TX A&M University	6300 Ocean Dr.	Corpus Christi	TX	78412-5503
	Quentin Martin	LCRA	(512) 473-4064	Lower Colorado River Authority	P.O. Box 220	Austin	TX	78767-0220
	Alan Propp	VERA	(214) 824-4915	Virtus Energy Research Associates	5636 Winton St.	Dallas	TX	75206
GEOTHERMAL								
	David Blackwell	SMU	(214) 768-2745	Southern Methodist University	Dept. of Geological Sciences	Dallas	TX	75275
	Dave Duchane	LANL	(505) 667-6722	Los Alamos National Laboratory	MSD460	Las Alamos	NM	87545
	Gregory Nunz	LANL	(505) 667-6722	Los Alamos National Laboratory	MSD460	Las Alamos	NM	87545
	Steve Seni	BEG	(512) 471-7721	University of Texas at Austin (BEG)	10100 Burnet Rd.	Austin	TX	78758
	Janet Valenza	Consultant	(512) 327-8573	Consultant	6101 Cape Coral	Austin	TX	78746
	Charles Woodruff	Consultant	(512) 480-0355	Consulting Geologist	711 West 14th St.	Austin	TX	78701
BUILDING CLIMATOLOGY	Leonard Bachman	UH	(713) 743-2372	University of Houston	945 Rutland Rd.	Houston	TX	77008
	Gene Clark	Trinity	(210) 736-7504	Trinity University	715 Stadium Dr.	San Antonio	TX	78212
	Steve Cook	UTEP	(915) 747-6646	University of Texas at El Paso	1300 Likins Dr.	El Paso	TX	79925-2506
	Larry Degelman	TX A&M	(409) 845-1221	Texas A&M University	Department of Architecture	College Station	TX	77843-3137
	Mac Holder	Consultant	(512) 345-8817	L.M. Holder III , AIA	4202 Spicewood Spgs. Rd., #214	Austin	TX	78759
	Bruce Hunn	CES	(512) 471-3104	University of Texas at Austin	ETC 5.160	Austin	TX	78722
	Doug Seiter	COA	(512) 499-3506	City of Austin	206 E. 9th St., STE. 17.102	Austin	TX	78701
CLIMATE								
	George Bomar	TNRCC	(512) 239-0770	TX Natural Resource Conservation Commission	P.O. Box 13087, Capitol Station	Austin	TX	78711-3087
	Bruce Gammon	TX A&M	(409) 862-1580	Texas A&M University	Dept. of Meteorology	College Station	TX	77843-3150
	John Griffiths	TX A&M	(409) 845-8076	Office of the State Climatologist	Dept. of Meteorology	College Station	TX	77843-3150
	Keith D. Hutchison	UT Austin	(512) 471-5573	UT at Austin Center for Space Research	2901 North IH35, Ste. 300	Austin	TX	78712-1085
	Juan Landivar	TX A&M	(512) 265-9201	Texas A&M University	Hwy 44 W Rt 2, Box 589	Corpus Christi	TX	78406-9704
	Dan White	TNRCC	(512) 239-1324	TX Natural Resource Conservation Commission	P.O. Box 13087 Capitol Station	Austin	TX	78711-3087
UTILITY								
	Steve Collier	Cap Rock	(512) 476-0844	Cap Rock Electric Cooperative	807 Brazon St., Ste. 700	Austin	TX	78701
	Thomas Foreman	LCRA	(512) 473-3387	Lower Colorado River Authority	P.O. Box 220	Austin	TX	78767
	J. B. Headrick	TU	(214) 812-8412	Texas Utilities Electric	400 N. Olive St., L.B. 81	Dallas	TX	75201
	John Hoffner	COA	(512) 322-6284	Electric Utility Department	721 Barton Springs Rd.	Austin	TX	78704
	Steve Jones	SPS	(806) 378-2799	Southwestern Public Service Co.	P.O. Box 1261	Amarillo	TX	79170
	Deb Lewis	LCRA	(512) 473-3200	Lower Colorado River Authority	P.O. Box 220	Austin	TX	78767
	Ward Marshall	CSW	(214) 777-1374	Central & South West Services	P.O. Box 660164	Dallas	TX	75266
	Bill Sumners	HL&P	(713) 229-7117	Houston Lighting & Power	P.O. Box 1700	Houston	TX	77251
ELECTRIC TRANSMISSION	Ed Ethridge	PUC	(512) 458-0398	Public Utility Commission of Texas	7800 Shoal Creek Blvd.	Austin	TX	78757
	Charles Freeman	EPE	(817) 755-7272	Electric Power Engineers	2002 Alico Bldg.	Waco	TX	76701
	Stuart Nelson	LCRA	(512) 473-3257	Lower Colorado River Authority	P.O. Box 220	Austin	TX	78767

SEDC INFORMATION THROUGH TNRIS

by Drew Decker

INTRODUCTION

This appendix will provide SEDC users with a brief guide to obtaining data. The SEDC has collected a set of statewide digital data files that can be used for renewable energy-related research as well as other projects. Why make all these files easily available? The intent of supplying SEDC data is to educate the public and foster further research into the possibilities of renewable energy in Texas.

These data are stored at the Texas Natural Resources Information Systems (TNRIS) in Austin, TX and are intended to be used for illustrative purposes as well as analysis. Most of the data are shown as color maps that illustrate various data useful in sustainable energy analysis. These include weather, transportation, and cultural phenomena. These maps can be viewed via the Internet as well as through basic graphics programs. Other data may be utilized for more detailed sustainable energy analysis when used with geographical information system (GIS) software. TNRIS also houses collections of non-digital data including USGS maps, aerial photographs, and US Census data.

TNRIS Background

The Texas Natural Resources Information System (TNRIS) is the state's clearinghouse and referral center for natural resources data. Its primary purpose is to make data available to users quickly and reliably. TNRIS was originally established by the Legislature in 1968 as the Texas Water Oriented Data Bank. In 1972, after four years of growth and diversification, it was designated the Texas Natural Resources Information System. The mission of TNRIS is to provide a "centralized information system incorporating all Texas natural resource data, socioeconomic data related to natural resources, and indexes related to that data that are collected by state agencies or other entities."[1]

TNRIS Data and Other Services

The TNRIS natural resource data collection contains the following digital and nonautomated data:

- Weather data
- U.S. Geological Survey (USGS) Maps
- Black and White Prints (More than 800,000 prints with varying sources, data, and scale.)
- Satellite imagery (over 400 Landsat images)
- Texas Water Development Board publications
- Texas Water Well Database
- National Wetlands Inventory Maps
- GIS data
- USGS Topographic Maps
- U.S. Fish and Wildlife Wetland Maps
- USGS Land Use Maps
- Geodetic Data
- Mexican (INEGI) Topographic Maps
- State of Texas Base Maps
- U.S. Census data and maps (1970, 1980, and 1990).

SEDC data have been added to TNRIS' GIS data collection. The SEDC data were collected from different sources or modified from existing TNRIS data. All TNRIS digital data are available on many different forms of media. These include disks, tapes, CD-ROM, and the Internet. All TNRIS data are considered public domain and no restrictions are placed TNRIS customers on usage of the data. TNRIS does charge for both computer and staff time required for some requests, however, in addition to the cost of the media.

Computer data exist both as databases and as computer map files. The computer map data are utilized by hardware and software called geographical information systems (GIS).

GIS AND THE INTERNET

Defintion and Uses of GIS

GIS is a graphical term that is being heard more frequently in business and information services. It is probably best described as "a decision support system involving the integration of spatially referenced data in a problem solving environment."[2] Several features distinguish GIS from more conventional mapping systems such as computer aided drafting (CAD). First, a GIS can create new information by combining different data sets of the same area. Operations that do this include overlays

SEDC Data via the Internet

SEDC data can be accessed through the internet in several ways.Two software packages that may be used are Mosaic and Netscape.

Mosaic and Netscape

1) Properly secure Internet connections.
2) Start Windows software and start Mosaic or Netscape.
3) In Mosaic, select the **File** button and choose **Open URL**. In Netscape, select the **Open** button.
4) Enter TNRIS Navigator homepage address: **http://tnris.twdb.state.tx.us.**
5) After the Navigator homepage appears, select the **Special Projects** button.

FTP

1) Properly secure Internet connections.
2) Type **ftp tnris.twdb.state.tx.us** or **ftp www.twdb.state.tx.us**
3) For user name, type **anonymous**
4) For password, type your full e-mail address. (i.e., "smith@commerce.state.tx.us").
5) Change directory to **/pub**.
6) Search for data of interest. Use **Get** command to retrieve the information. Most data will be found under the **/pub/GIS** directory.

HELP!

If you have trouble with the TNRIS or SEDC Internet connection, please get in touch with TNRIS by phone or email at (512) 463-8337 or **tnris@twdb.state.tx.us**.

and buffers. Second, GIS allows ancillary information to be tied to geographic features. A road, for instance, may be tied to a database that can list road width, age, and surface material just by selecting the road on one's computer screen.

A GIS can be used to help solve many spatial problems. For example, a GIS can help in routing problems. If one wanted to determine the best street route(s) to use for deliveries, a GIS can determine an optimal solution, minimizing fuel consumption and delivery time. Another common GIS use is site selection. In choosing the best site for locating a structure or planning for a particular land use, many aerial factors must be addressed. These could include distances to roads, depth to groundwater, ground slope, access to electrical power, and many more. GIS allows users to combine data on each pertinent factor to eliminate undesirable areas and help select a "best fit" site that can then be studied further. GIS also can also incorporate a third dimension, such as elevation, and arrive at a spatial model. A drainage basin could be shown by having the GIS construct a model based on differences in elevations between adjacent locations. The result is a model showing valleys and ridges and the direction of potential flow down slopes and into the valleys.

Obtaining Data: The Internet and More

The significance of the Internet in distribution and interconnection of information sources cannot be overstated. In the last year, large levels of growth have caused Internet awareness and usage to surge. TNRIS has joined in by allowing users to view TNRIS data sets, communicate with staff, order data, link up with other data sites, and even download digital data to their own computers.

The Internet can be best described as a network of networks allowing seamless, easy communication between local computer networks to networks in other counties. Its operation among linked computers appears similar to that of long distance telephone networks, allowing one phone to communicate with others.

Accessing TNRIS Data via the Internet

TNRIS can be reached through the Internet in several ways. Users can use a graphical or non-graphical interface to view Internet nodes. Graphical interfaces offer "point and click" operations with a computer mouse. Highlighted words, phrases, and images can be selected to obtain more information. Pictures and logos appear as images (color or black and white) that can be queried for more information or downloaded. Two examples of these interfaces (also known as browsers) are Mosaic and Netscape. Non-graphical interfaces appear much like operating system command lines. No pictures or graphics are shown on the screen. Data can still be accessed and downloaded. File Transfer Protocol (FTP) is a common means of allowing data retrieval through the Internet.

The main TNRIS homepage is called the "TNRIS Navigator," which can be accessed as shown in the sidebar "SEDC Data via the Internet." On this page are links to services provided by TNRIS, including the SEDC homepage.

Other Related Internet Sites

A number of other sources are accessible for SEDC-related data. The SEDC Internet homepage has links to these sources. These other Internet nodes include the state and federal government, universities, and private companies. The current nodes are described below. Please note that these node links may change as Internet resources are created and discontinued. Users may also search for sites if the address is unknown or has been changed. Keywords such as "DOE" or "NCAR" will help find the site. Several helpful nodes are identified below.

NREL (http://www.nrel.doe.gov) The National Renewable Energy Laboratory is a federal source associated with the U.S. Department of Energy (DOE) and is located in Denver, Colorado. NREL specializes in renewable energy research and has a very informative Internet node. It discusses current research, available data sets, news events at NREL, staff news and jobs, and provides further links to other sources.

ORNL (http://www.ornl.doe.gov) The Oak Ridge National Laboratory is a major component of the Department of Energy's research laboratories. Beyond its description of ORNL activities, the node provides links to about 20 other Department of Energy facilities.

EREN (http://www.eren.doe.gov) The Energy Efficiency and Renewable Energy Network specializes in locating and organizing qualitative information about renewable energy and energy efficiency technologies. There are sections on technological applications (building, industrial, transportation, utilities, technical/financial assistance), locating other energy information resources (keyword search), and renewable news/events.

TELRC (http://riceinfo.rice.edu/projects/TELRC/TELRC.html) The Texas Environmental Library and Resource Center site is sponsored by Rice University and offers Texas natural resource information to all users with current maps, agency and book listings.

ES-NET (http://www.es.net) Energy Sciences Network is an energy research community of DOE and US university energy research scientific facilities. This Internet site caters to academic research and provides a means of information exchange between academia and government.

Desktop Publishing and GIS

Using GIS data layers in desktop publishing applications is not a straightforward task. Most of the renewable energy resource maps appearing in this book were developed by GIS packages such as IDRISI, ARC-INFO, MAP INFO, and GRASS and then placed in Quark Express on a MacIntosh computer. In all cases, numerous problems were encountered (such as file compatibility, file size, color, and resolution) that had to be labored through to achieve maps suitable for publication. While desktop publishing and GIS are continually moving closer together, the following suggestions are offered to anyone contemplating the near-term union of GIS images and desktop publishing.

1) **Use TIF (raster) images whenever possible**
2) **Keep EPS files as simple as possible**
3) **Investigate the latest available conversion software for GIS files.**

PNL (http://www.pnl.gov/2080) Pacific Northwest Laboratory is a component of DOE that specializes in environmental and health issues. Current research involves sustainable energy technology and global environmental changes.

NEPA (http://www.eh.doe.gov/nepa/) The National Environmental Policy Act. This is another DOE sponsored homepage that lists the latest DOE energy policies.

DOE (http://www.doe.gov) The Department of Energy's site is a must for finding other energy-related Internet nodes. From here, other DOE and energy-related topics can be located relatively easily.

SEDC DATA LAYERS

A number of digital data sets are located at TNRIS. that are available to the public. These SEDC data layers may be downloaded from the Internet or may be obtained through conventional means on diskette or tape. Additional data layers may be added to the SEDC collection identified here

County Outlines. A 1:250,000 scale map of the Texas state and county outlines has been obtained through the USGS. County outlines at 1:24,000 and 1:2,000,000 are also available.

Hydrographic Layers. Texas rivers, lakes, major and minor aquifers, and dams are available as separate layers. The data were collected from several sources including USGS and the Texas Water Development Board (TWDB). Texas rivers and lakes are available at 1:250,000 and 1:2,000,000 scales.

The dams are at 1:2,000,000. The aquifer data were collected by the TWDB at 1:250,000.

Electrical Transmission Grid. Major Texas electrical lines in three categories (69 kV, 230 kV, and 345 kV) are shown. These data were collected from the Lower Colorado River Authority (LCRA). Several local and state government agencies and utilities contributed to this layer.

Seasonal Rainfall. 30 year averages for the four seasons are available. The Texas weather data were collected through a dense network of monitoring stations managed by the National Weather Service. Data from 1961 through 1990 were assimilated to obtain seasonal averages in inches. These maps and the other weather maps have a scale of approximately 1:2,000,000.

Diurnal Temperatures. 30 year average diurnal temperature ranges (Fahrenheit degree) were collected both monthly and annually and drawn as isolines. Diurnal temperatures ranges refer to the difference between the average daily maximum and minimum. Higher diurnal values reveal the wide temperature differential that is indicative of arid regions with higher solar energy potential.

Maximum and Minimum Temperatures. 30 year averages based on daily high and low temperatures. Two coverages are available. Isolines are used to show values in degrees Fahrenheit.

Annual Precipitation. The average annual precipitation over 30 years. This simple coverage shows annual rainfall in inches. Isolines show the wide variation over the state with rainfall.

Average Mean Temperature. This coverage shows the average temperature for sites over the last 30 years, regardless of season or time of day.

Land use and Land cover. These 1:250,000 scale maps were obtained from the USGS and converted into ARC/INFO format. These files show general land uses throughout Texas and divide the state into classes. These classes include industrial, residential, commercial, rangeland, and other land uses/covers.

Elevations. USGS 1:250,000 scale Digital Elevation Models (DEMs) converted to ARC/INFO format. Statewide coverage. DEMs are a lattice of positional coordinates with elevations. Three dimensional models can be created from DEMs for evaluations of drainage, slope, and topography. At 1:250,000, these points are approximately 90 meters apart.

Elevation Map. A 1:2,000,000 scale map showing Texas elevations divided into 15 categories. The data provide a very good illustration of general Texas topography. The Texas General Land Office (GLO) provided the data.

Roads. TNRIS has road maps at 1:24,000 and 1:100,000 scales indicating major highways down to small roads. These data were supplied by the Texas Department of Transportation (TxDOT).

Gas Pipelines. Some digital gas pipeline data have been gathered for Texas from Texas Power, Inc. in Houston, TX. A national pipeline map has also been scanned. Texas has additional pipeline data available on paper maps.

Population. A dot-density map of Texas population was provided by the Blacklands Research Center. The dot-density format is well-adapted for showing populated areas at a glance.

Texas Parklands. Texas parklands were collected by TNRIS from the TxDOT county highway maps. The result is a large scale map at 1:24,000. National parks, state parks, wildlife refuges, protected areas, national parks, and some larger city parks are included. This layer effectively serves as a "public lands" data layer.

Endangered Species. Data on Texas' endangered species of plants and animals have been gathered by the Texas Parks and Wildlife Department. Data are available by county and show the species and number of sightings within each county.

Pollution Data. Data have been collected from TNRCC on major atmospheric pollutants within Texas. Data are available by county and show attainment or non-attainment status. Carbon monoxide, ozone, and particulate matter data have been collected. More detailed data are only available for selected urban areas where relatively high densities of testing stations have been established.

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1 *Texas Water Code, 16.021.*
2 Cowen, D. *GIS Versus CAD Versus DBMS: What Are the Differences?* Photogrammetric Engineering and Remote Sensing, 1988.
3 Krol, E. *The Whole Internet User's Guide.* Sebastopol, CA: O'Reilly and Associates, Inc., 1994.

GLOSSARY

Glossary definitions appear under the heading of the resource to which they are applicable. Energy terminology common to all resources is defined in the last section labeled "Energy."

◆ SOLAR [1,2]

Air mass—Effective mass of air that direct beam radiation penetrates relative to the air mass in the vertical direction.

Altitude, solar—Angular elevation of the sun above the horizon.

Azimuth angle (solar)—Angular direction of the sun relative to the direction of the equator.

Concentrator—Lens (refractor) or mirror (reflector) which directs the intercepted solar radiation onto an absorber area that is smaller than the aperature.

Diffuse insolation—Portion of the global insolation reaching a collector or building surface after scattering from clouds, atmospheric particles or any other materials (i.e., that portion whose direction is not from the sun).

Direct radiation, Direct insolation—That portion of the insolation that comes directly from the sun without scattering by the atmosphere or clouds.

Emissivity, emittance—Property of a surface that determines its ability to emit radiant energy. The ratio of the radiation emitted by a surface at a particular temperature to that emitted by a blackbody at the same temperature.

Equinox—One of two dates in the year when the sun's declination is zero. Spring equinox occurs on March 21 and autumn equinox occurs on September 21.

Global insolation—The insolation striking a surface from all directions, including the diffuse plus the beam insolation.

Incidence, angle of—The angle relative to the surface normal at which insolation strikes a surface.

Insolation—Amount of solar energy reaching a surface per unit of time, typically over a day (kWh/m^2-day).

Nocturnal radiation—Loss of energy by radiation to the sky at night when the surface (collector) is warmer than the effective sky temperature.

Photochemical conversion—Conversion of photoenergy directly to a chemical energy form in a material. Plants use such reactions in photosynthesis.

Pyranometer—Measuring device used to determine local values of global (direct and diffuse) insolation.

Pyrheliometer—Measuring device used to determine local values of direct (beam) insolation.

Reflected radiation—Portion of the incident radiation on a surface (window, wall, collector) reflected by the surface.

Reflectivity—Property of a material that specifies the fraction of incident radiant energy reflected. Ranges between 0 and 1.

Selective surface—Surface that responds differently to different wavelengths of radiation (i.e., having wavelength-dependent properties.) in solar energy applications. Refers to a surface with a large value of absorptivity for solar energy and a small value of emissivity for infrared wavelengths. A solar collector with such a surface absorbs energy well, but has low radiation energy losses.

Solar constant—Insolation on a surface in space at the earth's mean distance from the sun. Presently accepted value is 1367 W/m^2 (World Radiation Center, Davos-Dorf, Switzerland, 1985).

Solar spectrum—Distribution of the sun's energy with wavelength. About 40 percent of solar energy is in the visible wavelengths, with most of the remainder in the long-wavelength (infrared) portion of the spectrum and a small fraction in the ultraviolet portion.

Solar time—Hour of the day as reckoned by the apparent position of the sun. Solar noon is that time on any day that the sun reaches its highest altitude angle.

Solstice—One of the two dates during the year (summer solstice on June 21 and winter solstice on December 21) when the sun's declination to the plane of the equator is a maximum (23.5 degrees and -23.5 degrees, respectively).

Spectral distribution—Distribution of some quantity (such as solar energy, emissivity, or absorptivity) with wavelength.

Transmissivity, transmittance—Property of a material that specifies the fraction of incident radiation that is transmitted through a given thickness; reduction in transmittance is due both to absorption and reflection. Varies between 0 and 1.

Ultraviolet radiation—Short-wavelength portion of the solar spectrum (< 400 nanometers) which is largely absorbed by the atmosphere.

Visible radiation—Portion of the solar spectrum sensed by the human eye (about 400-700 nm) accounting for about 40 percent of solar radiation.

WIND

Anemometer—device for measuring wind speed; cup, propeller, or vanes.

Exposure—open plains, ridges, passes, and mountains ridges exposed to wind.

GIS—geographic information system; computerized mapping/analytical tool.

Rayleigh distribution—probability determined mathematically from the average wind speed.

Sheltered—valleys, river bottoms, urban areas which are sheltered from the wind; down wind side from natural (trees) or man made obstructions.

Surface roughness—small (short grass) to large (tall forest), affects the wind shear; friction from the type of surface.

Weibull distribution—probability determined mathematically from two parameters, scale factor and shape factor.

Wheeling—transmission of electricity from one service territory to another.

Wind power class—range of wind power, scale defined by Pacific Northwest Laboratory, small numbers correspind to low wind power, high numbers correspond to higher wind power.

Wind power plant—number of wind turbines at one location for generation of electricity, connected to the utility grid; also called wind farm or wind park.

Wind shear—change in wind speed with height above the ground, commonly modeled with a power law.

Wind turbine—machine for converting wind energy into other forms, primarily mechanical and electrical.

1/7 power law—used to calculate the change in wind speed with height, where the exponent is 1/7 (from experimental measurements).

BIOMASS

The following terms, phrases, and abbreviations are commonly used in the fields of ecology and biomass energy. Definitions were adapted from several sources.[3,4,5,6,7]

Aerobic—living or active only in the presence of free oxygen.

Anaerobic—living or active in an environment with no air or free oxygen.

Anaerobic digestion—degradation of organic materials by microbes in the absence of oxygen to produce biogas (carbon dioxide and methane).

Anthropogenic—caused or produced through the agency of man.

Aquaculture—cultivation of fish, algae, water plants, and other waterborne organisms.

Autotrophic—capable of synthesizing complex organic substances from simple inorganic substrates, as, for example, of a green plant in photosynthesis. cf. heterotrophic.

Bagasse—residue remaining after extraction of sugar from sugar cane.

Biodiesel—a diesel fuel consisting of methyl or ethyl esters of the energy storage lipids of plants and animals.

Bioenergy—energy derived from the conversion of biomass.

Biofuel—solid, liquid, or gaseous fuels derived from the conversion of biomass.

Biogas—a gaseous mixture of carbon dioxide and methane yielded by the anaerobic digestion of organic matter.

Biogenic—produced by the activity of living organisms.

Biomass—plant or animal matter; strictly, a quantitative estimate of the total mass of organisms (plants and animals) within a given area, measured in units of mass, volume, or energy.

C3 plant—a plant employing the pentose phosphate pathway (the Calvin or Calvin-Bensen cycle) of carbon dioxide assimilation during photosynthesis; most green plants belong to this group.

C4 plant—a plant employing the dicarboxylic acid pathway for carbon dioxide assimilation during photosynthesis and capable of utilizing lower carbon dioxide concentrations than C3 species.

Carbohydrate—any of a group of organic compounds having the approximate formula of $(CH_2O)n$ and including, in order of increasing complexity, sugars, starches, hemi-cellulose and cellulose.

Cellulose—a complex polymeric carbohydrate that is the chief structural component of plant tissue, found in cell walls or fibers.

Char—the solid, carbonaceous residue resulting from incomplete combustion of organic materials.

Consumer—an organism that feeds on another organism or on existing organic matter; examples include herbivores, carnivores, parasites, and all other heterotrophs.

Coppice system—silvicultural systems in which trees regenerate from the shoots of stumps and roots left after harvest.

Cultivar—a variety of a plant species in cultivation.

Digester—the biochemical reactor in which organic matter is decomposed via anaerobic digestion.

Effluent—liquid or gas discharged after processing activities, usually containing residues from such use.

Enzymes—a class of proteins that catalyze biochemical reactions.

Ethanol—ethyl alcohol ("grain" alcohol) produced by fermentation and distillation; chemically, C_2H_5OH.

Fats—triglycerides which are solid at room temperature; the solidity or high viscosity owing to a comparatively high proportion of saturation among component fatty acids.

Fatty acids—any of a number of saturated or unsaturated organic acids such as acetic, stearic, propionic, etc.

Fermentation—the decomposition of complex organic compounds into relatively simpler ones under the action of a ferment—typically a yeast, bacteria, or other micro-organism.

Fixed carbon—carbon remaining after heating in a prescribed manner to distill volatiles.

Forest land—land that is a minimum of 1 acre in size and is at least 10% stocked by forest trees of any size, including land formerly possessing such cover that will be regenerated.

Forest residues—unused wood in the forest including logging residues, cull trees, dead trees, and annual mortality.

Gasification—a chemical or heat process used to convert a feedstock to gaseous form.

Gasifier—a device that converts solid fuel to gas.

Glucose—the six-carbon sugar, $C_6H_{12}O_6$, that is the primary product of photosynthesis and forms the building block for more complex starches and cellulose.

Gross primary productivity (GPP)—the total assimilation of organic matter or energy by an autotrophic individual or population per unit time per unit area; the growth rate of plants excluding plant respiration.

Hardwood—a dicotyledonous tree, usually broad-leaved and deciduous.

Hemicellulose—a class of non-cellulosic polysaccharides of cell walls that are more readily hydrolyzed than cellulose to yield simple sugars; includes xylan.

Heterotrophic—pertaining to organisms, such as animals, that are unable to synthesize organic compounds from inorganic substrates.

Hydrolysis—decomposition of a chemical compound by reaction with water.

Landfill gas—naturally occurring biogas produced from the decay of organic materials in landfills.

Lard—animal fat with a melting point below 40°C.

Legume—any of a large family of plants including beans, peas, clovers, etc. noted for their nitrogen-fixing abilities.

Lignin—the non-carbohydrate, structural constituent of wood and some other plant tissues that encrusts cell walls and cements cells together.

Lignocellulose—plant materials made up primarily of lignin, cellulose, and hemi-cellulose that form the structural portion of plants.

Lipids—any of a group of water-insoluble organic compounds consisting of fats, oils, and other substances of similar properties.

Logging residues—the unused portion of growing stock trees cut or killed in harvest and left in the woods.

Macroalgae—multi-cellular, photosynthetic aquatic plants such as kelp or seaweed.

Microalgae—unicellular, photosynthetic aquatic plants.

Methanol—methyl alcohol ("wood" alcohol) usually manufactured by steam reforming of natural gas, but also by the destructive distillation of wood; chemically, CH_3OH.

Moisture content—the amount of water contained in biomass, expressed as a percentage of the total mass of dried material (dry basis) or of the original wet material (wet basis).

Monosaccharide—a simple sugar unit, such as glucose, not decomposable by hydrolysis.

Municipal solid waste (MSW)—urban refuse collected for landfilling including paper, organic matter, metals, plastic, etc., but not certain agricultural or industrial wastes.

Net primary productivity (NPP)—the net rate of assimilation of organic matter or energy by autotrophic individuals or populations per unit time per unit area; the growth rate of plants including plant respiration.

Oils—triglycerides that are liquid at room temperature, owing to a comparatively lower proportion of saturated fatty acids than in fats.

Pasture—land that is currently improved by cultivation, seeding, or irrigation for grazing.

Photosynthesis—the biochemical process that utilizes radiant energy from sunlight to synthesize carbohydrates from carbon dioxide and water in the presence of chlorophyll.

Photosynthetically active radiation (PAR)—radiation in the wavelength range of 380-710nm that is capable of driving photosynthesis.

Phytomass—plant biomass.

Polysaccharide—any of a group of complex carbohydrates, such as starch or cellulose, that can be decomposed by hydrolysis into monosaccharides.

Primary productivity—the productivity of autotrophic organisms.

Producer—an organism that synthesizes complex organic substance from simple inorganic substrates.

Protein—a class of nitrogenous molecules composed of a complex union of up to several hundred amino acids and functioning as catalysts in plant and animal metabolism.

Pulp—a mixture of ground-up, moistened cellulosic material obtained from a variety of mechanical, chemical, and thermal treatments and used to make paper.

Pulpwood—wood cut or prepared primarily for the production of pulp.

Pyrolysis—the breaking apart of complex molecules by heat alone, without oxidation, to yield a variety of solids, liquids, and gases; often referred to as destructive distillation.

Rangeland—large, open areas of land distinguished by natural vegetative cover that is predominantly grasses, forbs, and shrubs, and generally used for grazing livestock.

Reducer—any heterotrophic organism responsible for degrading or mineralizing organic matter; a decomposer.

Refuse-derived fuel (RDF)—the combustible portion of solid waste that has been processed to remove heavier, noncombustible materials.

Saccharification—any conversion process in which long-chain carbohydrates are broken down into fermentable sugars.

Silviculture—forestry; the theory and practice of forest management.

Slash—the unmerchantable material left on site after harvesting or thinning, or resulting from storms, fires, etc.

Sludge—a non-pumpable mixture of solids and liquids, frequently referring to the residue of sewage treatment.

Softwood—a coniferous tree, usually evergreen, having needles or scale-like leaves.

Starch—a reserve polysaccharide molecule consisting of long chains of glucose bonded together.

Tallow—animal fat with a melting point above 40°C.

Volatile solids—all matter that will oxidize and be driven off as gas at 550°C.

Zoomass—animal biomass.

WATER

Salinity Gradient—a change in salinity between bodies of water or layers within a body of water.

Salinity Gradient Osmotic Pressure Technology (SGOPT)—technology that uses the osmotic pressure difference between saline and fresh bodies of water.

Salinity Gradient Solar Pond (SGSP)—salinity gradient solar technology that uses a reservoir of brine with a one to two meter salinity gradient that captures and stores solar energy at temperatures up to 100°C for a variety of applications.

Salinity Gradient Solar Technology (SGST)—technology that uses the effect of a salinity gradient within a body of water to suppress convection and allow solar heating of the bottom zone of the reservoir for collection and storage of useful heat energy.

Sluice gate—an opening in the tidal barrage which permits water flow in or out of the basin.

Tidal range—The vertical distance between the high and low tide Tidal barrage. The dam-like structure used to enclose a natural bay or estuary to form a basin.

Wave Hindcasts—wave conditions predicted using numerical models with wind data as input

GEOTHERMAL

Accessible fluid resource base—energy in geopressured water in sandstones and shales reachable by production drilling without regard to the amount recoverable or cost of recovery.

Accessible resource base (HDR)—that part of the resource base at temperatures above 25°C down to current routinely drillable depth (approximately 7 km) or the depth at which the critical temperature of water (374°C) is reached, whichever is less.

Accessible resource base (hydrothermal)—limited to permeable reservoirs that can produce water to a maximum depth of 3.2 km to bring thermal energy to the surface.

Aquifer—subsurface rock unit from which water is produced.

Basin—segment of the crust that has been downwarped. Sediments in basin increase in thickness toward the center.

Bolson—a basin with no drainage outlet.

Beneficial heat—the part of the resource that is usable in a specific application.

Binary cycle technology—the preferred alternative for developing liquid-dominated reservoirs

Brine—a highly saline solution.

Depocenter—site of maximum deposition.

Drawdown—the reduction in temperature of an HDR unit due to extraction of its heat energy at a rate greater than its natural reheating.

Fairway—also called a prospect (in Louisiana)— a localized, prospective geothermal resource.

Fault—a plane of weakness within a rock body along which separation and differential movement occurs.

Geopressured—type of geothermal resource occurring in deep basins in which fluid is under high pressure.

Geothermal energy—heat transferred from the earth's interior to underground rocks or water located relatively close to the earth's surface.

Geothermal gradient—the change in temperature of the earth with depth, expressed in degrees per unit depth, or in units of depth per degree.

Heat Flow—a measure of geothermal heat transfer involving the interrelationship between the geothermal gradient and thermal conductivity of rocks; one Heat Flow Unit (HFU) = .0418 W/m^2.

Heavy metal—metallic elements with high molecular weights, generally toxic in low concentrations to plant and animal life. Mercury, chromium, cadmium, arsenic, and lead are examples.

Hot dry rock (HDR)—heat energy residing in impermeable crystalline rock. Fracturing creates permeability to allow the circulation of water to facilitate removal of the heat.

Hydrothermal—hot water. The systems can be either a hydrothermal convection system in which upward circulation of water transports thermal energy to reservoirs at shallow depths or to the surface or a conduction-dominated system involving the existence of high vertical temperature gradients in rocks that include aquifers of significant lateral extent.

Igneous rock—rocks whose origin is the cooling and solidification of magma, molten rock material.

Injection well—well into which water or gas is pumped to promote secondary recovery of fluids or to maintain subsurface pressure.

Intrusion—a body of rock that has invaded the earth's crust from deeper depths in a molten state.

Magma—molten rock, generated within the earth, from which igneous rocks are thought to have been derived through solidification and related processes.

Mantle, crust, core—the core is the central region of the earth. Outside the core is the mantle, extending from about 19 miles underground in the continental areas to 1,790 miles where the core begins.

Methane—a major component of natural gas.

Permeability—a measure of the capacity of a rock for transmitting fluid.

Potentially useful resource base (for HDR assessments)—that part of the accessible resource base that could potentially be used for either electricity generation or direct heat applications, assuming a minimum process rejection temperature of 40°C. This assessment is dependent upon the then-current drilling and energy conversion technology and its economics.

Recoverable Resource (hydrothermal)—that part of accessible resource base that is producible at the wellhead under reasonable assumptions of future economics and technology.

Reserve—portion of identified resources that can be produced legally at a cost competitive with other commercial energy sources.

Reservoir—natural underground container of liquids, such as oil, water or gas. May be formed by local deformation of strata, by faulting, by intrusions, and by changes of porosity.

Resource—fraction of accessible fluid resource base that can be extracted for use at costs competitive with other forms of energy at a foreseeable time, under reasonable assumptions of technological improvement and economic favorability.

Rio Grande Rift—a province extending from New Mexico into Texas has a high heat flow and thermal springs.

Seismic activity—the likelihood of an area being subject to earthquakes.

Subsidence—movement in the earth's crust in which surface material is displaced vertically downward with little or no horizontal component.

Total resource base (for HDR assessments)[8]—all the heat energy contained in the rock units underlying the specified area or region (exclusive of hydrothermal and geopressured systems) to a depth of 10 km at temperatures above a reference of 15°C. If all the requisite temperature and rock property data were available to accurately and incontrovertibly calculate the resource base's value, it would be a fixed and relatively "immortal" number, independent of technology and economics.

Undiscovered resources—the presence of geothermal energy that has been estimated on the basis of geologic inference.

Vapor-dominated geothermal system—a conceptual model of a hydrothermal system where steam pervades the rock and is the pressure-controlling fluid phase.

BUILDING CLIMATOLOGY

Measures of Climate [9,10,11]

Btu/ft²/yr—annual square foot energy requirements for heating, cooling and lighting.

Degree days—the difference between the average daily temperature and the building's balance point, usually assumed to be 65°F. This measure is used to estimate building energy needs. It is also a quick way to compare the severity and character of two climates.

Design data—outdoor dry bulb and wet bulb temperatures used in sizing heating and cooling systems.

Diurnal temperature variation—daily high and low dry bulb temperatures.

Insolation—the amount of radiant energy from the sun incident on a surface, Btu/ft–hr.

Normals—long term averages of actual weather record or reconstructed data.

Percent possible sunshine—the percentage of time that sunshine is received compared to clear day sunshine cloudiness- measured in days of clear, partly cloudy and cloudy weather.

Relative humidity—the percent saturation of a moist air mixture at given conditions.

Wet bulb temperature—the temperature to which a moist air mixture could be cooled if it was saturated by evaporation.

Wind direction—published as the seasonal prevailing direction from which the wind blew.

Wind speed—the average wind speed regardless of direction.

Measures of Buildings [12,13]

Balance point—the outdoor temperature at which a building's heat loss to the environment is equal to internal heat gains from people, lights and equipment. Surface load dominated buildings such as single family detached residences will have balance points in the 55 to 65°F range. Internally load dominated structures, like office buildings, may have balance points so low that the climate never overcomes their internal heat gain.

Building loss coefficient, Btu/degree day—heat transfer through a building skin due to temperature difference.

Modified loss coefficient, Btu/degree day—building loss coefficient exclusive of south facing glass used as solar collector.

Peak load—the required capacity of heating and cooling equipment to meet thermal loads at design conditions.

ENERGY

British thermal unit (BTU)—a unit of energy equal to the amount of heat required to raise the temperature of one pound of water 1°F.

Capacity—the maximum power that a machine such as an electrical generator or a system such as a transmission line can safely produce or handle.

Capacity factor—the amount of energy a facility generates in one year divided by the total amount it could generate if it ran at full capacity. A capacity factor of unity implies that the system ran at full capacity the entire year; a typical wind farm will operate at 0.25 capacity factor, or 25%.

Heat rate—the amount of chemical energy required by a given fossil-fueled power plant to produce 1 kWh of electricity, expressed in Btu's. Heat rate is actually the inverse of the plant's thermal efficiency but expressed in inconsistent units (both Btu's and kWh are energy units).

Heating value, higher and lower—the potential combustion energy of any material, referred to as higher heating value (HHV) when water in the combustion products is condensed into liquid, and lower heating value (LHV) when the water remains a vapor.

Joule (J)—a standard international unit of energy; 1055 Joules is equal to 1 BTU.

Kilowatt (kW)—one thousand Watts; the power requirement of ten 100 W light bulbs or about that of a hair dryer.

Kilowatt-hour (kWh)—a unit of energy equal to one kW applied for one hour; running a 1 kW hair dryer for one hour would dissipate one 1 kWh of electrical energy as heat.

Megawatt (MW)—one million Watts; a modern coal plant will have a capacity of about 1000 MW.

Megajoule (MJ)—one million Joules.

Quad—a very large unit of energy equal to one quadrillion (10^{15}) BTU.

Thermal efficiency—the ratio of the useful work out to the energy in for a given thermodynamic process. Efficiencies are less than one or may be expressed as a percent.

Watt (W)—a standard unit of power defined as one Joule of energy transferred or dissipated in one second.

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UNITS ABBREVIATIONS

acre:	ac	inch:	in
British thermal unit:	Btu	Joule:	J
foot or feet:	ft.	meter:	m
gram:	g	mile:	mi
hectare:	ha	pound:	lb
hour:	hr.	second:	s
horsepower:	hp	Watt:	W

SI (SYSTEME INTERNATIONAL) PREFIXES:

Prefix	Abbreviation	Value
exa	E	1 000 000 000 000 000 000
peta	P	1 000 000 000 000 000
tera	T	1 000 000 000 000
giga	G	1 000 000 000
mega	M	1 000 000
kilo	k	1 000
hecto*	h	100
deka*	da	10
deci*	d	0.1
centi*	c	0.01
milli	m	0.001
micro	µ	0.000 001
nano	n	0.000 000 001
pico	p	0.000 000 000 001
femto	f	0.000 000 000 000 001
atto	a	0.000 000 000 000 000 001

**to be avoided where possible*

Note: *In some circles it is common to denote one million Btu's as one MMBtu. This notation is derived from the Roman numeral "M" for one thousand, and should not be confused with the SI prefix M for mega or one million.*

UNIT CONVERSION FACTORS

Area units

1 ha = 10,000 square meters = 2.47 acres

1 square mile = 640 acres = 2.59 square kilometers

1 square kilometer = 100 hectare

1 square meter = 10.76 square feet

Mass units:

1 kg = 2.2 lbs.

1 metric ton = 1 Mg = 1000 kg = 1.10 ton (short) = 2205 lbs.

Length units:

1 mi. = 5280 ft. = 1.61 km = 1609 m

1 m = 3.28 ft. = 39.37 in.

Temperature units:

Celsius and Fahrenheit conversion: $C = (F-32)/1.8$

Celsius and Kelvin conversion: $K = C + 273.16$

Energy units:

1 Btu = 1055 J

1 kWh = 3,600,000 J = 3412 BTU

1 quad = 1quadrillion BTU = 1.055 EJ

Power units:

1 hp = 746 W

1 W = 1 J/s

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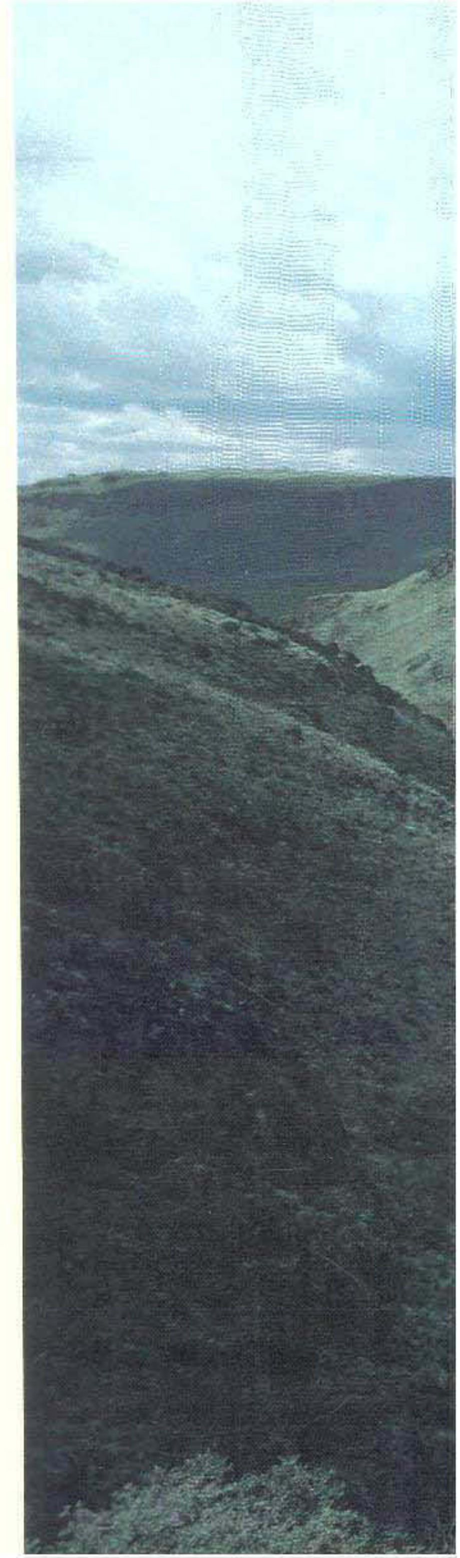
MAILING ADDRESS
1700 North Congress Avenue, Room 850
Austin, Texas 78701-1495
(512) 463-1745 • Fax 305-8953

STREET ADDRESS
201 East Fourteenth Street, Suite 104
Sam Houston State Office Building
Austin, Texas 78711



SEDC VISION STATEMENT

The Texas Sustainable Energy Development Council envisions a Texas responsibly powered by its sustainable energy resource base and serving as a model to others in equitable prosperity, environmental health, advanced technology, innovative government and respect for future generations.