POTENTIAL ENERGY RESOURCES OF THE GULF OF CALIFORNIA, NORTHWESTERN MEXICO

by

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Abstract

The Gulf of California in northwestern Mexico is a tropical sea of the northeastern Pacific Ocean. Earthquake activity is common in the region, especially towards the northwest where transform faults are associated with volcanic and geothermal activity, and features such as the San Andreas fault zone. The Gulf contains 132,000 cu km of seawater, with a surface area of 162,000 sq km, and a mean depth of 815 m. Its surface salinity is about 35 ppt. The Gulf is subject to the second highest tides (>10 m in range) in North America. The region is currently undergoing extensive human development and energy exploration. After reviewing the climatic, geologic, soil and vegetation, and oceanographic settings, the potential energy resources of the Gulf are evaluated. These resources include those controlled by climate (solar, wind), geology (hydrocarbon, geothermal), biology (biomass) and oceanography (tidal, wave, hydrothermal). Climatic energy sources (unproven technology) have fair potential for modest-scale, onshore and near-use development. Geologic sources are on-line, and have high potential for large-scale commercial development with export value. Biological sources (unproven technology) have low potential for small-scale, near-use development. Oceanographic sources have high potential for moderate-scale near-use potentially exportable development.

Introduction

The Gulf of California (Sea of Cortes) in northwestern Mexico is a tropical latitude sea of the northeastern Pacific Ocean adjoined by Baja California Norte and Baja California Sur to the west, and Sonora, Sinaloa and Nayarit to the east (Figure 1). The trough-shaped Gulf contains a very irregular base with several basins and has free communication with the Pacific at its entrance above depths of 3,000 m. The Gulf was formed from the plate tectonic spreading center on the East Pacific Rise during Tertiary time and exhibits northwesterly transform faults. Earthquake activity is common, especially towards the northwest where the faults are associated with volcanic and geothermal activity and features such as the San Andreas fault zone of California.

The Gulf contains 132,000 cu km of seawater, with a surface area of 162,000 sq km and a mean depth of 815 m. It receives some recharge from rivers to the southeast, although it is excessive winter cooling and summer evaporation which tend to raise the Gulf's surface salinity. The Gulf is subject to the second highest tides in North America, which is partly why novelist John Steinbeck and his marine biologist friend, Ed Ricketts, called the Gulf "a highly dangerous body of water (39)."

Though the region is among the last to be settled in Mexico, it is currently undergoing extensive urban development (based on fishing, tourism, ranching and farming, and mining) and energy exploration. Small scale solar energy research and geothermal energy exploration, and biomass conversion research began in the 1960's and 1970's, respectively. Petroleum exploration began in earnest in the early 1980's.

The purpose of this report is to review the potential energy resources of the Gulf of California.

Cultural Setting

In 1900, the population of the Gulf states was 716,100, or 5.3 percent of the national total. By 1940 and 1980, the population grew from 1,204,100 to 6,292,000 or 6.1 to 8.8 percent of the national total, respectively.

This growth represented a 43.2, 51.6, 49.5 and 61.0 percent increase in the Gulf states population in 10-year intervals, while the national population increased by only 31.2, 35.4, 41.0 and 49.1 percent for the same time intervals. The Gulf's population doubled in the past 15 years, while the national population has doubled in the past 20 years. Most of this enormous growth occurred in the urban centers. The Gulf states have grown, from fastest to slowest, in this order: Baja California Norte, Baja California Sur, Sinaloa, Sonora and Nayarit. The Baja peninsula is the least densely populated part of Mexico.

Agricultural products from the region include maize, vegetables, cotton and alfalfa (predominantly in the Colorado Delta), wheat, beans, sugarcane and rice (Sinaloa and Nayarit) and coffee (Nayarit). Irrigation is commonly practiced. There are also fruit trees, beehives, cattle, horses, mules, donkeys, sheep, goats, hogs and poultry. Fishery production, especially shrimp, is a major activity, with high tonnage from the Bajas and high value from the Bajas, Sonora and Sinaloa. Limited coal and lignite deposits occur southeast of Hermosillo (Sonora). Copper, salt, sand, gravel and lime are important mineral products. Recent tourism and American recreational and retirement communities have contributed significantly to the Gulf's economy.

The Mexican economy is rapidly expanding and diversifying, while also suffering from the current world-wide recession. Mexico now has an annual five percent growth (1982) in real gross domestic product, though 10 percent was forecast. There is increasing demand for professional and skilled workers. While the annual U. S. inflation rate is falling to less than 10 percent, the Mexican inflation is rising to over 30 percent, and the peso was significantly devalued in early 1982. Inflation in February 1982 reached 53 percent on an annual basis. Mexico, which began exporting energy in the early 1970's, is now the world's fourth-largest producer of oil and gas and the fifth-largest exporter.

The effects of increasing population, agriculture, tourism and supporting industries and activities, coupled with the social expectations of a rapidly evolving economy, has astronomically increased the demand for energy in the Gulf. Mexico's cultural and economic expectations demand that exportable energy be developed to support growth and security.

Physical Setting

The climate, geology, soil and vegetation, and oceanography of the Gulf of California are the relevant physical components to examine when evaluating the Gulf's potential energy resources.

Climate

The climate of the Gulf region varies from the arid Bajas and Sonora, the semi-arid Sinaloa, and the semi-humid Nayarit (20). The Bajas, most of Sonora and north-coastal Sinaloa have a hot, desert climate; central-coastal Sinaloa and south-coastal Sonora have a hot, steppe climate; and Nayarit and south-coastal Sinaloa both have a dry winter, tropical rainy climate (2).

The mean annual air temperature varies from about 15°C in the mountains of northern Baja to 25°C in coastal Nayarit. Most of the Gulf has an average annual air temperature between 20 to 25°C. The mean annual rainfall varies from less than 250 mm in the northwest, to about 900 mm in the southeast. The area-weighted annual rainfall averages 250 mm, with 25 to 60 percent relative interannual variability. The average annual evaporation rate is on the order of 100 to 200 mm. Winds are generally less than 10 km/hr, but may exceed 100 km/hr during severe storms.

Geology

The geology of the Gulf is structurally controlled by the San Andreas fracture zone which formed the Gulf (17, 28). The thin, western landmass rises abruptly as a coastal plain to the Baja mountain ranges. The broad, eastern landmass rises gently as a coastal plain of buried mountains. The Gulf drains about 668,800 and 432,000 sq km of land from the U. S. and Mexico, respectively. Nearly all the surface water runoff from the U. S., and most of that from Mexico, does not contribute directly to the Gulf, but contributes to numerous, small internal basins. Many of these form sabkeh-like playas, especially on the northeast coast of the Gulf.

The Gulf separates the mountainous peninsula of Baja California to the west (a westward-tilted plateau with a steep eastern side) and the broad coastal Sonora plain to the east (a northern late-Cenozoic desert plains and minor ranges, with central and southern modern deltas, lagoons and twisted and elongated plains). Landward from the eastern coastal plain rises basin and range topography to the high range of the Sierra Madre Occidental. The Colorado River has built a large delta with extensive flanking tidal flats at the northwestern end of the Gulf. The terrain sloping toward the Salton Sea from the Colorado Delta is the Valle de Mexicali (Mexicali Valley), and becomes the Imperial Valley in the U. S. The Gulf occupies a structural depression which embraces the Salton Sea in the U. S.

The eastern coast is straight, low and sandy, with deep water bays at Topolobampo (Sinaloa) and Guaymas (Sonora), and lagoons enclosed by sand bars or sandy spits. The western coast has the natural bay of La Paz (Baja California Sur). Guaymas and Mazatlán (Sinaloa) are principal ports.

The southern Gulf has a relatively thin crust, where the Moho is 10 to 11 km below sea level. The Moho is about 23 to 25 km beneath the Baja peninsula and the mainland. The Gulf is structurally part of the Pacific Ocean. The Gulf floor's topography suggests that it was formed by lateral movements along northwest-southeast trending fractures associated with the San Andreas fault system. Shallow earthquakes are common. The Gulf was formed from the plate tectonic spreading center on the East Pacific Rise during late Tertiary time. The recent rate of motion between the Pacific and North American plates is about 5.5 cm/yr (28).

Soil and Vegetation

The soils of the Gulf region are generally poorly developed, well-drained, calcareous sandy alluvial and aeolian soils, with poorly drained flood plain and estuarine silts and lesser, saline and gypsiferous inland-basin silts and clays. Soils tend to be low in organic matter, alkaline and calcium rich. Soil erosion is slight to moderate. There is a yearly soil moisture deficiency, where potential evapotranspiration exceeds precipitation, except along south-coastal Sinaloa and Nayarit where there is significant soil moisture recharge during summer.

The native vegetation is mostly temperate desert types, except for temperate mesquite grasslands in south-coastal Sonora. There are also tropical decidous and thorn forests along south-coastal Sonora, Sinaloa and Nayarit, and some tropical savannas along south-central Sinaloa and north-coastal Nayarit. Flat coastal marshes support halophytic and estuarine vegetation, especially near the northern Gulf.

Oceanography

The Gulf of California is an arid, tropical latitude sea of the northeastern Pacific Ocean. This elongated, northwest-southeast trough has a very irregular base with ten basins. It has free communication with the Pacific at its entrance above depths of 3,000 m. A central constriction and a group of islands separate the shallow northern section from the deep southern region. The northern section is less than 200 m, while the southern basins are 1,000 to 3,600 m deep. The Gulf contains 132,000 cu km of seawater with a surface area of 162,000 sq km and a mean depth of 815 m. It is 1,500 km long and 100 to 200 km wide.

The Gulf receives some limited flow from the Colorado River and perhaps as much as 18.3×10^9 cu m/yr of recharge and 162×10^6 metric tons/yr of sediment from six eastern rivers. Excessive winter cooling and summer evaporation tend to raise the Gulf's surface salinity. Its surface salinity is about 34 to 36 ppt. No permanent streams exist on the western, or northeastern banks, but there are permanent streams in the southeast. Surface water in the northern Gulf ranges from 16 to 19°C in winter and from 29 to 30°C in summer.

In winter, the northern Gulf's waters are almost isothermal from surface to bottom because of convective mixing. In summer, evaporation produces marked stratification with a warm, slightly more saline surface layer. In the deeper northern basins, strong tidal mixing produces a homogeneous water mass. In the southern Gulf, the water is the Equatorial Pacific.

In the central and southern Gulf, water below the thermocline is identical in salinity and temperature to equatorial Pacific water, with a pronounced oxygen minimum between 400 and 800 m. Above the thermocline, water is modified slightly by evaporation. In the south, water above the thermocline is modified by surface inflow of equatorial Pacific water and water from the California current flowing around Baja.

Surface water circulation is controlled by seasonal wind regimes. Water is driven out of the Gulf by a low-pressure system east of the Gulf and replenished by deeper flow from the Pacific in winter. Water is blown into the Gulf from the Pacific surface by a low-pressure system over the northern peninsula and leaves the Gulf by deeper flow in summer. Upwelling occurs along the eastern bank in winter and along the western bank in summer, resulting in high plankton production.

The mean tidal range in the Gulf increases from about 1 m in the south to 8 m near the mouth of the Colorado, where it exceeds 10 m at spring tides. The northern Gulf is subject to the second highest tides in North America. The tidal wave is a progressive, northward-traveling wave, where tidal current, velocities are high in the northern Gulf and between the large islands of Tiburón (Sonora) and Ángel de la Guarda (Baja California Sur).

Energy Resources

The energy resources of the Gulf of California are controlled by climate, geology, biology and oceanography. These will be either renewable or nonrenewable, and exportable or exclusively domestic. The Appendix presents energy or work, and power unit conversions.

Climatologically Controlled Energy

Solar and wind energy are controlled by climate. These energy sources are renewable, currently exclusively domestic, with fair potential for development in the Gulf. Currently, they are merely research topics. These energy sources are available onshore and near ultimate use.

Solar resources. Solar resources are currently used for desalination, heating and cooling, irrigation pumps, corrosion control of pipelines, and to activate photovoltaic cells which directly convert sunlight into electricity. The estimated total annual energy flux from the sun's radiation is about 10^{41} ergs (26). Photovoltaic power supplies about a million watts world wide for use in remote places such as weather stations, cathodic protection and ocean buoys (6). There are solar villages, solar schools, solar ponds and solar shields (1). Leading research centers and universities in the Middle East and U. S. Southwest, including the University of Arizona, have extensive on-going solar research projects. The Gulf, because of its abundant sunlight, has a fair to good potential for solar energy development.

Wind resources. Wind energy requires a minimum wind speed of 10 to 40 km/hr to be practical (16). The estimated total annual energy flux from near-surface wind is about 10^{29} ergs (26). The Gulf, because of its low to moderate winds, has a poor to fair potential for wind energy development.

Geologically Controlled Energy

Hydrocarbon and geothermal energy are controlled by geology. They are nonrenewable forms of energy which are exportable. There is high potential for geologically controlled energy sources in the Gulf on a commercial scale.

Hydrocarbon resources. Hydrocarbon resources are particularly attractive because their conversion to energy is an established technology, refining produces numerous useful by-products, and such resources have an immediate exportable value. A 42-gallon (159-l) barrel of crude petroleum produces 5 800 x 10^3 BTU (10^{16} ergs) and a dry cu ft (0.0283 cu m) of natural gas produces 1.021 x 10^3 BTU (10^3 ergs).

The geological evidence favorably suggests hydrocarbon accumulation and entrapment in the Sebastian Vizcaíno Embayment, the Eugenia Abrejos Province and the Iray Purísima Region of the Pacific side of Baja California Sur, peripheral to the Gulf (4, 32). The Sebastian Vizcaíno covers about 13,000 sq km and contains 3.0 km or 29,200 cu km of sediments. The Eugenia Abrejos covers about 5,200 sq km and contains 9.1 km or 25,000 cu km of marine and offshore sediments adjoining the Pacific Ocean. The Iray Purísima covers about 12,000 sq km and contains 3.0 km or 45,900 cu km of sediments adjoining the Pacific opposite La Paz (Baja California Sur). Gas strikes in Baja were announced by Pemex in 1978 (24).

Hydrocarbon shows were reported in the Huichol wildcat drilled by Pemex in the Pacific waters off Nayarit and east of Islas Marias in 1979 (25). Pemex studies found sedimentary basins covering 77,700 sq km in waters off Sinaloa, Nayarit and Jalisco in 1979. In 1979, Pemex completed Jalisco #1 as an oil discovery on the Pacific Coast (9). The Danwood Ice drillship was used to drill Totoaba #1 (dry and abandoned) off the Pacific coast. The Zapata Trader drillship (renamed Cora) drilled Huichol #2, which reported gas shows. In 1980, Pemex explored the Gulf and found no shows (9), though researches have found petroleum in offshore geysers (40). Pemex began a seven-well advanced exploration program both on and offshore from the Gulf and past the tip of Baja to Manzanillo. A wildcat 21 km offshore from Nayarit found gas in producible amounts (42).

Guzman (21) reviewed the petroleum possibilities in the Altar Desert of northwestern Sonora, northeast of the Gulf. Gravity, magnetic and seismic surveys indicate that the Altar Basin has good prospects for petroleum production. The basin covers about 15,500 sq km and contains 4.0 km or 46,500 cu km of continental and marine sediments. The Basin, which extends south to Tiburón Island (Sonora), has a very close relationship to the San Andreas fault system to the southwest. Since about 90 percent of California's basin petroleum production is from similar Miocene to Pliocene sediments, Altar's marine sediments are likely to be productive. Drag folds due to movement of the San Andreas fault produced structural traps. Displacement along the fault system is about 350 km. Should the rocks be returned to their original position, the Altar Basin would be opposite the productive Los Angeles Basin. Drilling near Hermosillo (Sonora) indicated oil shows in Eocene Rocks.

In early May 1981, Pemex announced that it plans a stepout from its indicated commercial gas strike in the Gulf off the mouth of the Colorado River (35). It reported that its Extremeño #1 flowed 5.7 MMcfd (0.16 MMcmd) of gas plus some condensate through a 1/4-in. (0.64 mm) choke from an interval of 13,510 to 13,543 ft (4,118 to 4,128 m). The total depth of the well was 15 746 ft (4,799 m). The strike was drilled by the Reforma drillship in 130 feet (40 m) of water, 80 km south of Mexicali (Baja California Norte) and north of Montage Island.

The Extremeño #1 strike was from a Pleistocene sand at 16 km offshore from the mouth of the Colorado River, from a structure thought to cover 60 sq km (42). The strike was the first to establish commercial gas production in Mexico's western offshore area. According to World Oil (42), Pemex has been looking for production in this horizon since 1948 and has drilled about 40 wells in the past seven years. Fourteen of these had shows. In 1975, Pemex found subcommercial gas at Catrina I and II onshore near Guerro Negro. Exploration picked up in 1978 when Pemex brought three floating rigs to the Sea of Cortes, in the Pacific, and west and south of the Baja peninsula.

The Extremeño #1 strike sparked land leasing for petroleum rights in the Imperial Valley of California (36). The Oil & Gas Journal (36) noted that "geothermal hot waters probably have been flushing the hydrocarbons up dip along the flanks" of the Valley, where a number of noncommercial gas shows have been found at 600 to 1 200 m.

Hydrocarbon discoveries are expected in Baja California, Chihuahua, the Gulf of California and offshore Mazatlán in the medium term in northwestern Mexico (42). However, World Oil (43) projects a 13.6 percent decline in the number of wells to be drilled in 1982 over 1981, which may delay new discoveries and encourage cautious production in proven fields in and near the Gulf of Mexico where Mexico's production is secured. Two factors contribute to the projected decline: 1) Mexico's "cardinal sin of borrowing heavily against resources in the ground" at the same time that there is a world-wide decline in demand or unexpected softness of the world crude market; and 2) Mexico's political climate, in which drilling traditionally declines in an election year. Mexico lost at least five billion dollars in anticipated revenues as a result of the 1981 - 1982 world oil glut. However, world-wide market or supply changes, such as a new Middle East war or a world-wide economic recovery, would increase the value of Mexican oil.

Mexico became an oil exporting country in the early 1970's. From 1976 to 1981, Mexico annually produced about 1.5, 1.6, 2.0, 2.3, 3.3 and perhaps 4.5 to 5.0 percent of the world's crude oil. It's anticipated that this percentage will increase in the mid term, with increasing production from existing and new fields, including those yet to be developed in the Gulf. Mexico's proven reserves are estimated to be about twenty percent of those of the U. S.

Mexico's prospective areas of major hydrocarbon fields include 60,000 sq km offshore from Sinaloa and Nayarit, 68,000 sq km in western Baja California Sur, 84,000 sq km offshore at the mouth of the Gulf, and 245,000 sq km in northwestern Sonora (3).

Geothermal resources. Geothermal energy is extracted from superheated underground steam or water with temperatures often greater than 300°C. The estimated total annual energy flux from the thermal gradient is about 10^{28} ergs (26). At least 22 countries are developing geothermal resources to produce electricity.

The Oil & Gas Journal (34) reported the beginning of a five-year study of the hot-brine geothermal resources of the Cerro Prieto area, 32 km southeast of Mexicali and the California-Mexico border in Baja California Norte. At that time, the area was the site of a geothermal plant with an electric generating capacity of 75 MW and an ultimately planned annual production capacity of 440 MW. The Cerro Prieto Geothermal Field in Mexico's Mexicali Valley had its first wells drilled in 1959 and 1961 as a result of hot springs, geysers, mud pots and fumaroles observed near Laguna Volcano about 8 km southeast of the volcanic Cerro Prieto. The Cerro Prieto Geothermal Field is a hot-water dominated system. Underground hot brines contain pressured water that "flashes" into steam at the earth's surface. Water and steam from the Cerro Prieto system is reported to be as hot as 330°C.

The Geological Society of America led a November 1979 field trip to the Salton Trough, and reported that the Cerro Prieto Field completed its 75-MW power plant in 1973, and increased production to 150 MW in April 1979 (12). By November 1979, 65 deep geothermal wells were completed in the field.

Several geothermal anomalies which lack surface expression have been discovered in the Imperial Valley and the Mexicali Valley. By 1979, 63 geothermal production wells were drilled in the Imperial Valley for a 10-MW plant, and several additional power plants are planned. These include Republic Geothermal's 50-MW dual-flash power plant at East Mesa, Southern California Edison's 10-MW plant near Brawley, Southern California Edison/Union Oil's 10-MW plant and Southern California Edison's 55-MW plant near Red Hill Volcano at the Salton Sea Geothermal Field, and Southern California Edison/Chevron Resources' 50-MW unit at the Heber Geothermal Field near El Centro.

According to the U. S. Geological Survey, six identified geothermal fields in the Imperial Valley with reservoir temperatures greater than 150°C could produce a total of 6,800 MW for 30 years, or 225 MW/yr (5). Additionally, there are numerous smaller experimental geothermal plants in the Imperial and Mexicali Valleys. Western Services, Inc. estimates that the Imperial Valley could provide up to 10,000 MW of power over the next 30 years (16).

There are 350°C-hot springs on the 2,650-m deep sea floor on a mid-ocean ridge in a small region along the crest of the East Pacific Rise near the entrance to the Gulf of California (29).

Additionally, 315°C-hot geysers have been found in petroleum-seeping mounds at 2 000-m depths along transform faults offshore Baja California Sur in the Gulf (40). Numerous indications of hydrothermal activity suggest that productive geothermal fields may be present beneath the Gulf.

Biologically Controlled Energy

Biomass energy is controlled by biology in the Gulf. This is a renewable resource which is currently exclusively domestic. The estimated total annual energy flux from marine biomass is about 10^{28} ergs (26). Currently, the biomass energy source is merely a research topic, where conversion of fiber to energy is a promise.

Though forest and wood products are scarce, there is an abundance of natural salt-tolerant or halophytic plants which may be irrigated with sea water to produce a locally available, biomass energy source. Cooperative research studies in this regard have been conducted by the University of Arizona's Environmental Research Laboratory and the Universidad de Sonora near Puerto Peñasco (Sonora) since 1978. More recently, the University of Arizona's College of Agriculture and the Office of Arid Lands Studies have entered this research area (33).

Mature Atriplex (salt bush) and Salicornia (pickleweed) contain about 35 and 20 percent of crude fiber, and about 35 and 40 percent ash, respectively (22). Soaking the ground product in 10 volumes of fresh water for 16 hours can reduce the ash content in saltbush and pickleweed to about 15 and 7 percent, respectively, to make a more energy-rich product. These leached plant products could provide a limited, near-site energy supplement.

There are arid-land plants, such as Simmondsia (jojoba) and Euphorbia (gopher plant), which have naturally high hydrocarbon contents (27). Jojoba data are sparse, but gopher plant data from California indicate production of 10 to 25 barrels of crude oil/ha/yr (10^4/ergs ha/yr). Additionally, Salsola (common Russian thistle, or tumbleweed) have a high energy content and could yield about 3, 500 cal/g or about 32 billion cal/ha/yr (10^{15} ergs/ha/yr) from fertilized and irrigated land (19). Unfortunately, jojoba, gopher and tumbleweed plants require fresh water.

Combined agricultural production and biomass energy conversion may be feasible in the Gulf if an agronomic crop, with high energy conversion, could be cultivated. On the big island of Hawaii, for example, over 40 percent of all energy needs are met from biomass energy conversion of sugarcane wastes. Additionally, marine biomass power could be developed in shallow water through eelgrasses and kelps which are efficient producers of organic material and are easily harvested (26).

Oceanographically Controlled Energy

Tidal, wave and hydrothermal energy are controlled by oceanography in the Gulf. These energy sources are renewable and potentially exportable. These energy forms generally require no storage systems. Isaacs and Schmitt (26) discussed the nature and distribution of non-petroleum power sources of the sea, including waves, tides, currents, salinity and temperature gradients, as well as submarine geothermal sources, salt domes, ice and other marine-associated concentrations.

Tidal resources. Tidal energy uses the oscillatory flow of water in the filling and emptying of partially enclosed coastal basins during the semidiurnal rise and fall of the tides (11). This energy may be partially converted into renewable tidal electric power by damming such basins to create a difference in water level between the ocean and the basin, and then using the water flow while the basin is filling or emptying to drive hydraulic turbines to propel electric generators. The hydraulic head for power generation can generally be available for 6 to 12 hrs daily.

The estimated total annual energy flux from major ocean currents and feasible tidal power is 10^{25} ergs each (26). Globally, near-shore areas with a great tidal range and potential for tidal power development are widely distributed; they include the coasts of Alaska and British Columbia, the Gulf of California, the Bay of Biscay, the White Sea, the central Indian Ocean, and the coasts of Maine and eastern Canada. Existing installations are in the French Rance River estuary (producing 240 MW) and at Kislaya Bay in the Soviet Union (producing 440 kW).

The energy, E, produced between high water and low water (10) amounts to:

$$E = mgh = 8\ g\rho As^2 / T$$

where m is the mass of water, g is the gravitational acceleration, h is the tidal range, ρ is the water density, A is the cross-sectional area, s is the wave amplitude, and T is the tidal period. The mean tidal range is 2s, and the water volume flowing through a bay during half a tidal period is 2sA. Theoretical power output, TPO (kW), from a hydromechanical device can be calculated from the following equation (30):

$$TPO = \frac{Q\ (cfm) \times H\ (ft)}{708} = \frac{Q\ (cfs) \times H\ (ft)}{11.8} = \frac{Q\ (lps) \times H\ (m)}{102}$$

where Q is the flow of water through the perfect power generating system, and H is the hydraulic head. If variable head drives the device, the energy produced is about 90 percent of what is calculated. In practice, head losses from pipe flow and fittings must be subtracted from the hydraulic head, and the overall efficiency must be multiplied by the TPO to derive the operating power output. Actual power output, APO (kW), can be calculated from APO = OE x TPO, where OE is the overall efficiency of the system (usually 0.50 to 0.80). The electrical output, EPO (kW), from a turbine can be calculated from the following equation (30):

$$EPO = \frac{D\ (ft) \times C\ (cf) \times N \times R \times F}{708} = \frac{D\ (m) \times C\ (l) \times N \times R \times F}{102}$$

where D is the diameter of the turbine, C is the working volumetric capacity of each cell, N is the number of cells in the turbine, R is the rotational speed in rpm, and F is the turbine efficiency (usually 0.60 to 0.80).

Based on a review of published figures for one existing and six planned power stations (7, 11, 13-15, 38), it appears that the tidal power plant with 1-m tidal range and 15 000-m barrage length produces about 1 000-MW power output, or power output (MW) equals 15 times tidal range (m) times dam or barrage length (m). The Gulf has good to high potential for tidal energy development.

Wave resources. Wave energy uses the up and down motion of the waves to drive air turbines to propel electric alternators (38). This renewable energy source is still in early experimental stages. The estimated total annual energy flux from waves is about 10^{27} ergs (26). Waves could produce about 50 kW per meter of wave, assuming 50 percent efficiency for generation and 50 percent efficiency for transmission losses (37). About 1,000 km of devices could produce 12 kW in sites off the coast of the United Kingdom. The Gulf has fair to good potential for wave energy development.

Hydrothermal resources. Hydrothermal energy uses warm currents from tropical waters to heat a fluid, such as ammonia, and turn it into vapor which drives a turbine to produce electricity. Cooler seawater from depths of about 900 m cools the vapor and condenses it to form water needed to repeat the cycle. Hydrothermal energy could theoretically be harvested by ocean thermal energy conversion (OTEC) plants (6), where a 64°-F (36°-C) range of water temperature is available. The Gulf has a high potential for hydrothermal energy development.

Technical Feasibility

The technical feasibility of an energy resource may improve with time due to of technical advances and economic demand.

Climatic energy sources are currently an unproven technology with storage, transmission efficiency, electronic and structural problems. Solar energy generally requires an energy storage system, and wind energy demands fatigueless metals or ceramics. These sources are currently research areas with fair potential for modest-scale development in the Gulf. Geologic energy sources have a proven technology with technical limits. Hydrocarbon energy has safety and air quality problems, and geothermal energy has turbine efficiency, structural and fatigue, and corrosion problems. Offshore development has unique structural and corrosion problems. These sources are currently on-line with high potential for large-scale commercial development in the Gulf. Biological energy sources are an unproven technology riddled with biological uncertainties, corrosion and air quality problems. These sources are currently research topics with low potential for small-scale development in the Gulf. Oceanographic energy sources have turbine and transmission efficiency, and corrosion problems. Tidal energy has a proven technology, though most plants are research plants. Wave and hydrothermal energy production are currently research projects. These sources have a high potential for moderate-scale development in the Gulf.

Environmental Impacts

The environmental impacts of energy exploration, development and transmission can be considered in terms of air, water, soil and biota.

Climatic energy has a low impact on air, water, soil and biota. There is no air pollution. Development would require consideration of drainage and erosion impacts. Geologic energy has moderate, high, moderate and fair impact on air, water, soil and biota, respectively. Development of geologic energy would require consideration of brine disposal, spills and water demand. FERTIMEX is currently building a potassium chloride recovery unit for geothermal plants in Cerro Prieto, indicating that waste recovery is feasible. Biological energy has a fair, moderate, fair and small impact on air, water, soil and biota, respectively. Development would require consideration of saltwater agriculture, drainage, soil salinity and water demand. Oceanographic energy has a low impact on air, water, soil and biota. There is no air pollution. Development would benefit by water storage, which would reduce operating costs and prolong operating hours.

Any offshore and nearshore energy development in the Gulf must consider the impact of seismic activity. The eastern Pacific Shelf off southern California near Baja has had 24 earthquakes in the past 60 years of a local magnitude 6 (Richter scale) or larger (23). The Pacific and the Gulf coasts are subject to earthquakes, tsunamis (seismic sea waves), and slumps and slides.

Mid-1980's Production Costs

Assuming a 15 percent annual inflation, it will cost about $350/kW and $2,000/kW in capital for a natural gas/oil-fired steam plant and a nuclear power plant, respectively (38). Currently designed and nearly completed coal-fired steam plants are costing about $800/kW and $1,600/kW, respectively in the Texas gulf coast. The following costs are projected in the Gulf for comparative purposes only.

Climatic energy would cost about $40,000 to $50,000/kW for solar (6) and wind forms, while geologic energy would cost about $350 to $3,500/kW for hydrocarbon (38) and geothermal (6, 16) forms in the mid-1980's. Biological energy would cost more than $50,000/kW. Oceanographic energy would cost about $7,600, $35,000 and $1,200/kW for tidal (8, 13-15, 38), wave (38) and hydrothermal (6, 38).

These cost estimates could be reduced with technical solutions to engineering problems. For example, turbine and metal fatigue problems caused by brine in geothermal power units has recently forced redesign for a second 10-MW plant operated by Southern California Edison. This has doubled capital costs in the Imperial Valley to $3,000/kW (16). Technical solutions could reduce this cost in future plants.

Energy Investment Strategies

There are four general methods used for selecting alternative energy investment projects (31, 41). These include accounting (average rate of return, payback) and discounted cash flow (internal rate of return, net present value) methods. Data are unavailable to allow comparison of investment strategies between climatic, geologic, biological and oceanographic energy.

In Mexico, the federal government determines and implements the country's energy policy through Pemex (Petróleos Mexicanos) for hydrocarbons and the Comisión Federal del Electricidad (CFE) for electric power at the operating level. On March 18, 1938, Mexican President Lazaro Cárdenas nationalized the oil industry, and established Mexican control. More recently, however, Brown & Root, a division of Halliburton, Inc., has become the prime contractor for Pemex, responsible for organizing the engineering, purchasing, building and managing of Mexico's major fields (18).

Mexico's energy program for the 1980's, announced in November 1981, is that export sales will be guided by the need to finance intrastructural improvements and to achieve national security goals (3). Mexico in the early 1980's plans to conduct exploratory drilling activities in only about 10 percent of the areas which are likely to contain hydrocarbons.

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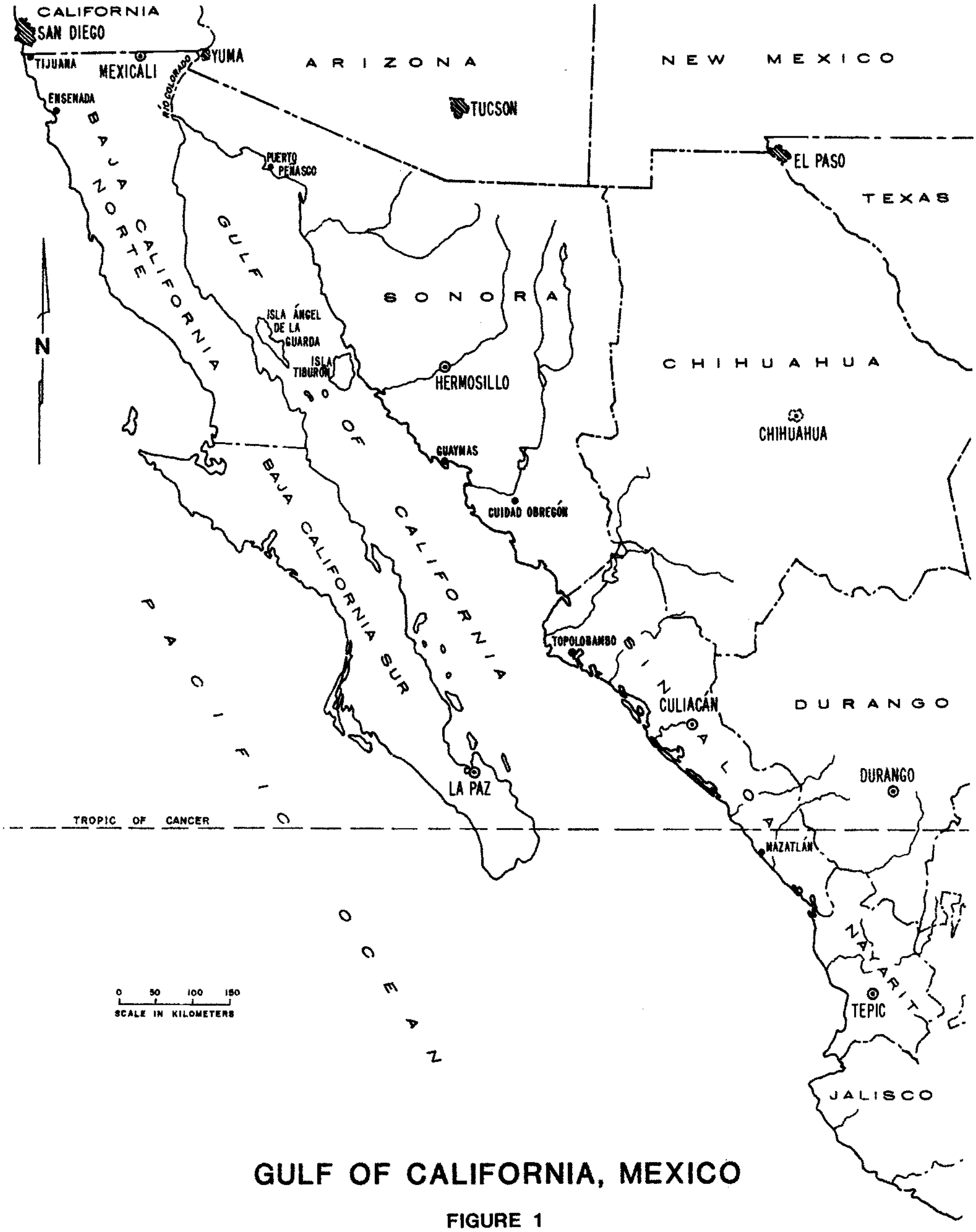
Appendix

Energy or Work

One British thermal unit (BTU) equals 1.0548 x 10^{10} ergs or dyne-centimeters (dyne-cm), 777.97 foot-pounds (ft-lb), 3.9292 x 10^{-4} horse power-hour (hp-hr), 1054.8 joules (J) or newton-meters (N-m), 0.25198 kilogram-calorie (kg-cal) or 2.930 x 10^{-4} kilowatt-hour (kW-hr).

Power

One horse power (hp) equals 42.418 British thermal units per minute (Btu/min), 7.4560 x 10^{9} ergs per second (erg/sec) or dyne-centimeters per second (dyne-cm/sec), 550 foot-pounds per second (ft-lb/sec), 10.688 kilogram-calories per minute (kg-cal/min), 0.74570 kilowatt (kW), or 745.70 watts (W) or joules per second (J/sec).



GULF OF CALIFORNIA, MEXICO

FIGURE 1