OTEC Sites

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Ocean thermal energy conversion (OTEC) is perhaps the most exciting world energy resource for the future-the near future. It promises vast amounts of energy (even ten times the current worldwide human utilization) that is cheap (competitive with $25-per-barrel crude oil), naturally self-renewing, and ecologically friendly. As a beneficial side effect, OTEC can turn vast stretches of starved "ocean deserts" into lush "ocean oases" teeming with sea life.

OTECs can be sited anywhere across about 60 million square kilometers (23 million square miles) of tropical oceans-anywhere there is deep (and, therefore, cold) water lying under warm surface water. This generally means at latitudes within about 20 or 25 degrees of the equator-very roughly between the Tropic of Cancer and the Tropic of Capricorn. (For meteorological reasons this zone is somewhat contracted along the west coasts of continents and expanded along the east coasts.) Surface water in these regions, warmed by the sun, generally stays at 25 degrees Celsius (77 degrees Fahrenheit) or above. Ocean water more than 1,000 meters (0.6 miles) below the surface is generally at about four degrees C (39 degrees F). Since the average ocean depth is about 4,000 meters (2.5 miles), there is a vast reservoir of cold deep water under tropical skies-some 180 million cubic kilometers (43 million cubic miles). And even this inconceivably vast resource is constantly being renewed by deep cold-water flows from the polar regions.

The warmth of the surface water is constantly renewed by the heat of the Sun. The tropical ocean surface functions as an efficient solar collector. Over 90 percent of the radiant energy that falls on it is absorbed and serves to warm the water. The vastness of this energy resource can be appreciated by the realization that the absorbed solar energy per day is equivalent to over 1,000 times the current worldwide human energy consumption.

The OTEC process consists of pumping cold ocean water to the surface and using the temperature differential between this and warm surface water to run a thermal engine to generate electricity. This process, producing electrical energy from a temperature differential, is well known in physics and engineering. In fact, it is the reverse of the

common refrigeration process (which produces a temperature differential using electrical energy).

What are the benefits of OTEC?

1. The energy resources for OTEC are vast.
2. The energy resources for OTEC are naturally self-renewing.
3. OTEC is non-polluting, in fact, it is ecologically positive since it enriches nutrient-poor surface water and tends to "sink" carbon. The nitrogen, phosphorus, silica, and other nutrients raised from the deep are combined via photosynthesis with atomospheric and ocean-dissolved carbon dioxide to produce increased biomass and reduce atmospheric carbon load.
4. OTEC is based on established turbine and refrigeration technologies.
5. OTEC readily produces, as side benefits, considerable quantities of fresh water, sea foods, and marine-life-based industrial products, as well as chill-water for air conditioning* and cold-bed agriculture.**

* *Using the OTEC-byproduct chill-water can save 75% to 85% of air-conditioning costs. For a large commercial complex (e.g., hotel or offices) in a tropical climate this can be a significant factor--savings of the order of a million dollars a year for a large hotel.*

** *Cold-bed agriculture uses chill-water in pipes beneath the surface of the soil to lower the temperature of plant roots. This has two advantages. First, it allows production of temperate-zone crops (such as certain leafy greens, fruits, and legumes) in the tropics which reduces transportation costs in bringing these crops to tropical consumers. Second, one can commonly produce several crops of these temperate-zone plants per year--production rates several times what is possible in temperate climates. This may be because of the high insolation or perhaps because keeping the roots at a significantly lower temperature than the leaves facilitates transpiration or other metabolic processes. In addition to cold-bed agriculture, OTEC can produce abundant fresh water that can be used for irrigation of crops which is often severely limited in tropical regions.*

What are the disadvantages or limitations of OTEC?

1. An OTEC facility requires a substantial initial capital outlay (in the range of $50 to $100 million for a "small" ten-megawatt plant).
2. OTEC has not been demonstrated at full scale over a prolonged period with integrated power, mariculture, fresh-water, and chill-water production.
3. OTEC is only feasible at relatively isolated sites (deep tropical oceans); from such sites, the power and marine products must be transported to market. (In general, the fresh water--and certainly the chill-water--cannot be transported more than a few miles economically.)
4. OTEC is ecologically controversial--at least untested--in large scale and over a long period.

5. The technology for OTEC, once tested and proven, will be applicable across wide geographic (and politically varied) areas; therefore, future profits will not securely inure to the adventurous capitalists who develop OTEC.

What must be done, then, to develop OTEC?

It is technologically easier to build and run an OTEC facility on shore rather than floating on the open ocean. This is because a shore-based facility is not as vulnerable to severe storms or high waves as a floating facility. In addition, siting a facility on shore allows local utilization of OTEC products and byproducts (power, fresh water, mariculture products, and chill-water). This saves on storage, distribution, and marketing expenses.

However, political (and particularly business and ecological constraints) may make it impossible to have initial OTEC sites near or on shore. It may be necessary to have the first few OTECs demonstrating prolonged operational integrity and value afloat on the open tropical oceans. Nevertheless, shore-based OTECs are technologically easier to build and to run. It is therefore an important exercise to try to find a geographically, politically, and economically suitable coastal site for OTEC.

An OTEC facility can only be financed two ways: as a local utility or by venture capital. It should be possible to make a preliminary assessment of the feasibility of each of these financial paths. First, how extensive is the local utility infrastructure (power, water, transportation, etc.) and how is it funded for construction and maintenance? This information might provide some guidance as to whether the political structure of the area is amenable to OTEC development. Second, is there significant venture capital invested in the area? If there is not, it is probably because the effective political and economic forces are not conducive to it.

A careful analysis must be made of possible shore-based sites around the world. This involves several factors.

1. One must identify tropical sites where there is deep ocean water very near shore (within, say, ten kilometers or six miles). This is because the huge OTEC intake pipes are a major portion of the initial capital expense. It is important to make them as short as possible. This paper considers a maximum possible length to be ten kilometers (six miles). However, some authorities consider the practical maximum cold-water-pipe length to be much shorter than this, perhaps at most two or three kilometers (one or two miles).
2. One must then determine which of these sites have accommodating governments (for permitting, proprietary ownership, construction, labor, taxes, marketing products, etc.). George Lockwood points out (in a personal communication) that political risk insurance is available from the World Bank and the U.S. Overseas Investment Corporation at modest costs. He reports that there are very few countries where risks of expropriation or appropriation cannot be mitigated.
3. In addition, one must establish which of these sites have adequate local infrastructure to absorb an additional five or ten megawatts of power and several

million gallons of fresh water per day. (Note that some authorities project practical OTEC facilities as small as one megawatt with a half-million gallons of fresh water produced per day.) In fact, one of the most critical factors affecting the feasibility of a shoreline OTEC site turns out to be availability of a willing buyer for the power. Furthermore, many power system engineers and financiers will not look much beyond diesel generation for power to remote locations since they consider diesel power to be proven and reliable. Calculation and projection of power and water needs can also be difficult. Socioculturally advanced communities use up to one megawatt of electricity and 400,000 liters (100,000 gallons) of water per day per 1,000 people. In less developed areas, people may use half as much water (though several times this amount may be needed in agricultural regions) and one-tenth as much electricity. Bearing in mind these complexities, as a rule of thumb, for OTEC development one is looking for a minimum population of at least 10,000 but, optimally, a population in excess of 50,000.

In 1987 the Pacific International Center for High Technology Research (PICHTR) investigated shore-based sites in the Pacific region for OTEC. This analysis of thirty islands and Asian locations covered:

- populations
- economies
- internal policies
- energy demands and projections
- OTEC-related cashcrop potential

An analysis of distance to deep water of potential shoreline OTEC sites “near the U.S.” by William Gale (First Millennial Foundation, September 1996) concluded that the following were “most worthwhile to learn more about”:

- the island of Hawaii
- Providence Island in the Bahamas (Nassau)
- St. Croix in the Virgin Islands
- Grand Cayman

In addition, Gale listed “other places that just might work” (that is, what would be needed next would be “tourist information”):

- Belize
- Bahamas, other islands
- Caicos
- Martinique
- Jamaica
- Guadeloupe

- Grenada
- Colombia

A book by Takahashi and Trenka titled *Ocean Thermal Energy Conversion* (John Wiley, 1996) lists 99 nations and territories with access to OTEC thermal resources. This was based on a study performed for the U.S. Department of State in 1981.

- There are 15 listed as "Americas--Mainland"
- 23 as "Americas--Island"
- 18 as "Africa--Mainland"
- 5 as "Africa--Island"
- 11 as "Indian/Pacific Ocean--Mainland"
- 27 as "Indian/Pacific Ocean--Island"

This list of 99 is longer than the PICHTR and Gale lists because geographically it has worldwide scope, and also because it considers ocean depths out to the full 200-nautical-mile EEZ (Exclusive Economic Zone) of each country. This would include possible floating OTEC facilities in addition to shore-based facilities which require that there be deep ocean within ten kilometers (six miles) of shore. In addition, this extensive list does not eliminate sites based on political and economic feasibility.

This list of 99 can be reduced to 61 by eliminating areas that, although they have deep ocean within their EEZs, do not appear to have access to deep ocean within ten kilometers (six miles) of shore (based on charts in the *Rand McNally Atlas of the Oceans,* 1994, and the *National Geographic Atlas of the World,* 1995, as well as data provided on the World Wide Web by the National Oceanic and Atmospheric Administration [NOAA]). Further reduction of the list to 29 is possible by eliminating those that are too small or have unstable or unreceptive political or business climates. (Much of the information on geography, politics, and economics summarized below was derived from the *World Reference Almanac* published by Dorling Kindersly, 1996; this was supplemented by guide books and other reference materials including the Web pages of the 1996 World Factbook.) The remaining 29 are as follows:

- 15 listed as "Americas--Mainland" reduces to one, Mexico
- 23 listed as "Americas--Island" reduces to 12
- 18 listed as "Africa--Mainland" reduces to one, Tanzania
- 5 listed as "Africa--Island" reduces to one, Madagascar
- 11 listed as "Indian/Pacific Ocean--Mainland" reduces to one, India
- 27 listed as "Indian/Pacific Ocean--Island" reduces to 13

Americas--Mainland (reduces from 15 to one, Mexico)

Mexico should probably be considered a relatively fertile field for foreign investment as well as ripe for extensive development of municipally funded infrastructure. However, there is endemic corruption at the national and state levels, a weak economy, chronically high inflation, and poverty-level wage scales. There was a severe debt crisis during the

1980s leading to Mexico defaulting on its international loans, and a bailout provided and financial restructuring required by the International Monetary Fund (IMF). The advent of the North American Free Trade Agreement (NAFTA) in 1994 linked the economies of the U.S., Canada, and Mexico causing difficult political consequences, but probably with long-term positive and stabilizing effects on the Mexican economy. There was a devaluation of the Mexican peso in 1994 with a $20-billion bailout loan from the U.S. The Mexican stock market experienced some recovery in 1996. Mexico is known to have OTEC-accessible shoreline sites at the extreme southern tip of the Baja California peninsula (23°N, 110°W). It also appears, on bathymetric charts, to have three other possible sites: at Puerto Vallarta in Jalisco (20°30' N, 105°30' W), at Puerto Angel in Oxaca (16°N, 97°W), and along about 120 kilometers (75 miles) of the east coast of the Yucatan Peninsula from Punta Herrero to Xcalak in Quintana Roo (19°N, 88°W). .

Of the other 14 areas listed under "Americas--Mainland," 11 do not appear to have deep ocean water within ten kilometers (six miles) of shore: Belize, Costa Rica, El Slavador, French Guiana, Guatamala, Guyana, Honduras, Nicaragua, Panama, Suriname, and the United States. The other three are Brazil, Colombia, and Venezuela.

Brazil appears to have OTEC-accessible shoreline sites along the eastern coast on a 1,100-kilometer (700-mile) stretch from north of Natal to south of Salvadore. However, foreign investment is deterred by corruption and xenophobic favoritism, and municipal infrastructural development is limited by chaotic, politicized financing.

Colombia appears to have suitable sites for shore-based OTEC along the Pacific coast, but corruption and narcotics-related violence discourage foreign investment and infrastructural development.

Venezuela is a major oil producer (one of the original OPEC countries). There is, therefore, little political/economic motivation for developing OTEC or other energy resources.

Americas--Island (reduces from 23 to 12)

(1) Antigua is the largest of the Leeward Islands in the West Indies, about 280 square kilometers (108 square miles) with lush, tropical vegetation, a varied terrain, and some 365 beautiful beaches--all public. The resident population is small (about 65,000) but the island is visited by over a half-million tourists each year. Nealy half the resident population clusters near the city of St. John's. Antigua is economically limited, relying mainly on tourism. There are a few large resorts and casinos and many small hotels. Most hotels do not have air conditioning; temperatures are usually between 27 and 32 degrees C (in the 80s F) but occasionally reach 35 degrees C (the mid 90s F); low humidity and year-round trade winds keep the ambient conditions comfortable. There is little rainfall, generally limited to rare, brief, heavy showers; water shortages occur frequently. The total electrical capacity is 52 megawatts. At present all energy needs depend on importation. There appear to be suitable sites for shore-based OTEC on the south coast by Cape Shirley (17° N, 61°45' W).

(2) The Bahamas comprise an archipelago stretching 1,200 kilometers (750 miles) from near the Atlantic coast of Florida to the Caribbean Sea. There are 700 islands and 2,400 cays of which 30 are inhabited (total population under 300,000). There are two urban centers with most of the population: Nassau on New Republic Island and Freeport on Grand Bahama. The climate is subtropical with occasional hurricanes from July to December. The Bahamas are stable politically with a developing economy with considerable tourism and international banking and ship registry. Infrastructure is quite limited. The total electrical capacity is 424 megawatts. All energy requirements are currently met by importation. There appear to be sites suitable for shore-based OTEC on New Providence Island along a 20-kilometer (13-mile) stretch of the north and west coasts from Nassau to Adelaide (25° N, 78°30' W).

(3) The Cayman Islands* are located in the Caribbean Sea some 150 kilometers (100 miles) south of Cuba. There are three Cayman Islands: Grand Cayman (200 square kilometers or 76 square miles, half of which is swamp) and two small islands, Little Cayman (25 square kilometers or 10 square miles) and the slightly larger Cayman Brac. Nearly all the population of 30,000 is on Grand Cayman (one-fourth in George Town). The Caymans are a politically stable British territory with a high standard of living and little crime, economically dependent on tourism (one million per year) and on providing international financial services. The climate is pleasant year-round with an average temperature of 26 degrees C (79 degrees F). Because of the porous rock base, there are no rivers or streams. Water is collected in home cisterns and also provided at $14.32 per 1,000 gallons by a municipal utility that uses reverse osmosis. Business licenses are granted to foreigners on elaborate application, and are good for 12 years (renewable). There are 10,000 foreigners living in the Caymans on "work permits" which are for three years (renewable). The greatest need is for professional and management staff; natives are given preference. There appear to be suitable sites for shore-based OTEC on Grand Cayman (19° 30' N, 81° 30' W) which presently has a total power grid of 70 megawatts (Cayman Brac and Little Cayman have an additional four megawatts).

***** *Note: Much of the information on the Cayman Islands was provided by Gary W. Frame.*

(4) Dominica (population of 71,000) is one of the Windward Islands in the West Indies. It is 47 kilometers (29 miles) by 26 kilometers (16 miles) of rough, varied terrain including tropical rain forests and mountains as high as 1,400 meters (4,700 feet). The political system is democratic, an independent republic within the British Commonwealth. The economy is very limited, based largely on bananas. Tourism, though being promoted, is limited by a rugged coastline and the absence of a large airport. Annual rainfall of 1,000 centimeters (400 inches) provides adequate water; in fact, Dominica exports water. Total electrical capacity is seven megawatts. Energy needs are currently met by importation. Dominica appears to have suitable sites for shore-based OTEC along the west shore (15° 30' N, 61° 30' W).

(5) The Dominican Republic (population of 7.8 million) shares the island of Hispaniola with Haiti, lying between Cuba and Puerto Rico in the Greater Antilles portion of the

West Indies. The economy is based mainly on tourism (two million tourists per year), mining nickel and gold, and production of sugar and tobacco (as well as transshipment of narcotics). The historical political control by rich white landowners and the military has recently been democratizing. However, the Dominican Republic probably does not present an attractive business investment environment. Although the government officially welcomes foreign investment and has enacted facilitating legislation, there are significant barriers. The business climate is highly centralized and tends to be bureaucratic, unstable, and confusing. The government has weak economic policies with a tendency to resort to monetary expansion to finance public expenditures. The government owns most public utilities and a variety of other enterprises such as insurance companies, banks, and factories, most of which lose money routinely. The banking system is not well regulated; loans are expensive; there is no deposit insurance. The government-owned electric power company does not have sufficient capacity. Power outages are frequent. Most industrial enterprises have their own back-up (or entirely independent) power. Two new dams are being built to provide hydroelectric power. Considerable oil (two million tons per year) is imported from Venezuela and Mexico. The Dominican Republic appears to have OTEC-feasible shoreline sites along the north (Atlantic) coast (20° N, 70° 30' W), but it seems unlikely that these can be developed in the present political and business climate.

(6) Guadeloupe is the most northerly of the Windward Islands group in the Lesser Antilles portion of the West Indies. It consists mainly of two large islands, Grande-Terre and Basse-Terre, each about 770 square kilometers (300 square miles). These two islands are joined by a 6.5 kilometer (four-mile) bridge. There are also several smaller islands bringing the total land area to 1,700 square kilometers (660 square miles). The climate is humid subtropical, modified by trade winds. There are periodic water shortages and occasional severe droughts; hurricanes occur between June and October. Guadeloupe has a total population of 413,000. The government is an overseas department of France. There is high unemployment and an economy largely limited to bananas, sugar production, and tourism (there are 160,000 tourists per year, mainly from Europe). There is little industrialization. The total electrical capacity is 320 megawatts. Most fuel is imported. The Gardel factory which does all sugar manufacturing on the island has an attached electric power plant that burns coal and bagasse (crushed sugar cane). There appear to be suitable sites for shore-based OTEC along the west coast of Basse-Terre (16° N, 61°45' W).

(7) Jamaica* (18° N, 77° W), at 11,400 square kilometers (4,400 square miles), is the third largest island in the West Indies. It is south of Cuba. It has a population of 2.5 million with 250,000 tourists per year. The largest metropolitan area is Kingston with 850,000 residents. It has political and economic life formerly influenced by family favoritism and narcotics trafficking and characterized by violence. However, in recent years it has developed quite a salutary democratic government, and it has a broad-based economy including mining and refining bauxite for aluminum (a very energy-intensive process), tourism, and significant agricultural production of sugar, bananas, rum, and coffee. Zoning and environmental regulations do not appear significantly restrictive although bureaucratic delays are common. Water supplies are a problem because of silt

from deforestation and poor upkeep of treatment plants. There are occasional droughts although periodic water shortages can be attributed more to limited infrastructure andplanning. Utility prices tend to be high. Foreign ownership of businesses is allowed although joint ventures are preferred. There are tax incentives for companies that earn foreign exchange, use Jamaican raw materials, create employment opportunities for Jamaicans, or introduce new technologies. The tax incentives can be relief from all taxes for up to ten years; for horticulture and fish farming, the tax relief can be up to fifteen years. Both political parties support deregulation, liberalization of the economy, reducing tariffs, and ending import restrictions. The government is working on antitrust legislation to reduce constraints on the economy from monopolies. Jamaica is known to have suitable sites for shore-based OTEC. Preliminary designs for a one-megawatt land-based OTEC pilot plant were completed in the early 1980s. There are also negotiations currently under way in conjunction with Kaiser Aluminum for a shore-based OTEC in Jamaica to provide power for bauxite refineries.

***** *Note: Much of the information on Jamaica was provided by William Gale.*

(8) Martinique is one of the Windward Islands in the Lesser Antilles portion of the West Indies. It is 1,100 square kilometers (425 square miles), mostly mountains but with varied terrain-and with an active volcano. The climate is tropical and humid, moderated by trade winds. It is vulnerable to hurricanes and flooding (the rainy season is June to October). Martinique has a population of 371,000 about half of whom live in the capital, Fort-de-France. Legally it is a French "overseas department." The economy is based on tourism and on growing sugarcane and bananas (there is some transshipment of narcotics bound for the U.S. and Europe). Economic power resides with a wealthy white landowning minority. There is a high standard of living despite high unemployment. Martinique has minimal industry; the total electrical capacity is 113 megawatts. Crude oil is imported; there is some export of refined petroleum products. There appear to be sites suitable for shore-based OTEC along the west and south coasts (14° 30' N, 61° W).

(9) Puerto Rico is a large island, 177 kilometers (110 miles) by 56 kilometers (35 miles), one of the Greater Antilles of the West Indies, roughly at 18° N, 66° W. It has a population of 3.6 million (plus four million tourists per year). It is a commonwealth territory of the U.S. with stable politics and a strong financial and industrial base, especially in apparel manufacturing, electronics, and petrochemicals. There are government incentives for manufacturing including tax exemptions, loans, and research assistance. There has been considerable influx of capital, technology, and entrepreneurship from mainland U.S. Agriculture is of two sorts, small subsistence farms and large export farms. Coffee is the most valuable crop followed by vegetables, sugar cane, bananas, pineapple, tobacco, and rice; dairy products, poultry, and beef are also important. Mineral extraction exceeds $160 million per year; this is mainly cement, sand, gravel, and stone, plus less significant amounts of clay, graphite, lime, and salt. Puerto Rico has a high standard of living, but also a high crime rate. Fresh-water demand is around 200 cubic meters (60 million cubic feet) per day at $0.32 per cubic meter ($9 per thousand cubic feet). There are summer water shortages. Peak electricity demand in 1983

was 1,878 MWe at 10.42 cents per kilowatt-hour; this cost was expected to triple by the year 2000. Most (98%) of the electricity is generated by petroleum-burning plants.

The University of Puerto Rico campus at Mayaguez on the west coast has a graduate department of Marine Science. This department offers academic specialization in aquaculture as well as in several branches of oceanography and marine biology. Much of the teaching and research is carried out at a marine center 35 kilometers (22 miles) south of Mayaguez.

Puerto Rico is known to have a site suitable for shoreline-OTEC on the southeast coast near Maunabo (65° 53' W). The Puerto Rico Power Authority proposed, in 1981, a 40-MWe (net) closed-cycle OTEC that was to be constructed on a tower 200 meters (one-eighth mile) off Punta Tuna near Maunabo (Avery and Wu, Oxford, 1994). Close inspection of coastal bathymetric data provided by the U.S. Army (available at http://bigfoot.wes.army.mil/b502.html) shows no other location along the Puerto Rican shoreline that has 1,000-meter (3,000-foot) deep ocean within ten kilometers (six miles) of the coast.

(10) Saint Lucia is one of the Windward Islands in the Lesser Antilles portion of the West Indies. The climate is tropical moderated by trade winds; the rainy season from May to August includes hurricanes. Saint Lucia has a population of 145,000. It has a multiparty democracy and an economy which is growing although it is weak, largely based on bananas and foreign-owned tourist facilities with some developing industry and information processing. The total electrical capacity is 20 megawatts. At present most energy is imported; there are plans to develop geothermal resources. It appears to have suitable sites for shore-based OTEC along the southern part of the west coast (13° 45' N, 61° W).

(11) Saint Vincent, one of the Windward Islands in the Lesser Antilles portion of the West Indies, is about 345 square kilometers (133 square miles) and has a population of about 100,000. The climate is tropical with little seasonal variation in temperature. The rainy season is May to November and includes hurricanes. There is a very limited economic base (based largely on bananas) but adequate political stability and growing infrastructure and industrialization. The total electrical capacity is 17 megawatts. There is a hydroelectric plant, but most energy needs are met by importation. There appear to be sites suitable for shore-based OTEC along the north and west coasts (15° 30' N, 61° 15' W).

(12) The U.S. Virgin Islands are located just east of Puerto Rico at the north end of the Leeward Islands in the Lesser Antilles portion of the West Indies. Politically this is a U.S. territory with non-voting representation in the U.S. Congress. It has stable political structure and good financial services, infrastructure, and industrial base on the largest islands, Saint Thomas and Saint Croix. Tourism amounts for more than 70% of the GNP. The total population of 104,000 is 80% on St. Thomas. The climate is subtropical and not overly humid. There are limited fresh-water resources, impacted by frequent and severe droughts and floods. The rainy season is May to November. Total electrical capacity is

320 megawatts. Saint Croix is known to have suitable sites for shore-based OTEC along the north and northwest coasts (17°45' N, 64°50' W); Saint Thomas does not appear to have suitable sites. Saint Croix has one of the world's largest oil refineries. Historical research on deep-sea nutrients for OTEC-associated mariculture was done on Saint Croix by O. A. Roels (1976).

Six island areas listed in the State Department report do not appear to have deep ocean within ten kilometers of shore: Aruba, Barbados, Grenedines, Saint Kitts and Nevis, Trinidad and Tobago, and Montserrat. The other five are Barbuda, Cuba, Curacao, Grenada, and Haiti.

Barbuda, a political dependency of Antigua, is listed separately from Antigua in the 1981 U.S. State Department survey. Although it does appear to have possible shoreline OTEC sites, it has a very small resident population (about 1,500).

Cuba is a communist dictatorship under U.S. trade embargo.

Curacao, part of the Netherlands Antilles, has been politically unstable with financial difficulties (including drug trafficking).

Grenada has been politically unstable and economically weak.

Haiti is politically corrupt and unstable with a weak economic base.

Africa--Mainland (reduces from 18 to one, Tanzania)

Tanzania on the east coast of Africa (5° to 10° S, 40° E) has a population of 29.7 million). Though it is perhaps the best candidate for OTEC development on the African continent, Tanzania is a very poor country with an economy heavily dependent on agriculture (58% of GNP, 85% of exports, 90% of the workforce). There is very limited industrial development, mainly consisting of processing of agricultural products with some mining and oil refining. Natural resources awaiting more extensive development include tin, phosphates, iron, diamonds, gemstones, gold, and nickel. Tanzania has a multiparty democracy and state commitment to reforms that have cut inflation and budget deficits. There is limited foreign investment, but a receptive political and economic climate. Currently more than 90% of energy demand is met from wood and charcoal; hydropower provides 70% of electricity and is being expanded. The total electrical capacity is 440 megawatts. Oil imports are substantial; there are new oil discoveries and some development of offshore gas resources. There appear to be suitable sites for shore-based OTEC at five locations: on the north coast just south of Tanga, at Dar Es Salam, along the south coast around Lindi, and on the islands of Zanzibar and Pemba.

Eleven of the countries on the African mainland with OTEC-feasible ocean within their EEZs do not appear to have deep ocean water within ten kilometers (six miles) of shore: Angola, Cameroon, Congo, Gabon, Guinea, Ivory Coast, Kenya, Liberia, Nigeria, Togo, and Zaire. An additional five can be eliminated from the list because of political and

financial instability: Benin, Equatorial Guinea, Mozambique, Sierra Leone, and Somalia. Finally, Ghana has surplus hydroelectric power from the Volta Dam.

Africa--lsland (reduces from 5 to one, Madagascar)

Madagascar is a large island off the east coast of Africa with a population of 14.8 million. Although Madagascar is perhaps the most favorable African island for development of OTEC, it is a very poor country with chronic malnutrition and underfunded health and education resources. It has a new multiparty democracy which replaced a stifling socialistic regime in 1993, but continues to be plagued by corruption, instability, and erratic commitment to economic reforms. The weak economy has a varied agricultural base with exports of vanilla, coffee, and cloves, as well as prawns. The country has commercialization of off-shore oil and gas resources, and significant tourism. There is limited infrastructure with an extensive domestic air network but poor road and rail systems. There is widespread soil erosion from deforestation and overgrazing. Surface waters are often contaminated with raw sewage and other organic wastes. The island is often hit by cyclones and plagued by severe flooding. The total electrical capacity is 220 megawatts. Madagascar imports petroleum. It appears to have suitable sites for shore-based OTEC at the northern tip near Antsiranana (12° S, 49° E).

The other four African island areas can be dropped from the list for political/financial reasons: Aldabra [UK], Ascension [UK], Comoros (total power grid under one megawatt), and Sao Tome and Principe.

Indian/Pacific Ocean--Mainland (reduces from 11 to one, India)

India has a multiparty democracy and commitment to free-market economic development. On the other hand, there is high unemployment, poor infrastructure, high inflation, and huge budget deficits. In addition, although there is both a large foreign-investment establishment and an influx of multinational investment capital, there is also widespread hostility to foreign investment. Sea Solar Power of York, Pennsylvania negotiated, in the mid 1990s, for the construction of OTEC facilities off the coast of Tamil Nadu in southern India; contracts were not finalized due to disagreements about financial risk management and power sales on the local utility grid (according to a private communication from Phil Kopitske). India appears to have a very limited stretch of suitable sites for shore-based OTEC along the Bay of Bengal near Amalapuram (16° 30' N, 82° 30' E).

Japan can be dropped from consideration for new OTEC because it is at the forefront of OTEC research and development (as are the U.S. and Taiwan).

Australia can be dropped from consideration because it does not appear to have deep ocean within ten kilometers of shore along the northern half of the continent, whereas the southern half does not have warm enough surface water. In addition, Australia imposes paralyzing ecological constraints on any unusual development.

Seven additional nations and territories can be dropped from the “Indian/Pacific Ocean--Mainland” list because they do not appear to have deep ocean water within ten kilometers of shore: Bangladesh, Brunei, Burma, China, Hong Kong [listed in 1981 as separate from China], Malaysia, and Thailand. In addition, Vietnam can be dropped because of political/financial instability.

Indian/Pacific Ocean--lsland (reduces from 27 to 13)

(1) American Samoa in the South Pacific Ocean is a U.S. territory consisting of the island of Tutuila (137 square kilometers or 53 square miles) and six smaller islands. The population is only 60,000 (with 95% on Tutuila). The economy is based largely on government service (one-third of the workforce), tuna processing (another third), plus minimal light industry and tourism (a few thousand visitors per year). The climate is hot and humid year-round. Typhoons are common from December to March. Tourist accommodations are relatively expensive. Pollution has been a problem. Water resources are limited, much depending on roof catchments. The total electrical capacity is 30 megawatts. Petroleum products are imported. There appear to be suitable sites for shore-based OTEC on Tutuila (15° S, 170° W).

(2) French Polynesia, some 130 islands in the southeast Pacific Ocean, has adequate population only on the main island of Tahiti (about 150,000). The economy is thin, largely based on tourism. The climate is tropical but moderate. There are occasional cyclonic storms in January. The total electrical capacity is 75 megawatts. Fuels are imported. Tahiti (17° 30' S, 149° 30' W) is known to have deep ocean water close enough off shore to make shore-based OTEC feasible. The French did a feasibility study for five-to-twenty-megawatt open-cycle and closed-cycle OTEC in Tahiti in 1978-80. Construction on a five-megawatt plant was begun near Papeete (17° 32' S, 149° 35' W). It was scheduled for completion in 1985, but not brought to operational status. There also appear to be other possible shoreline-OTEC sites on Tahiti.

(3) Guam is in the North Pacific Ocean roughly 2,500 kilometers (1,500 miles) from Japan to the north, from The Philippines to the west, and from Australia to the south (13° N, 145° E). The climate is tropical marine, generally warm and humid, though moderated by northeast trade winds; there is little seasonal temperature variation. The rainy season runs from July to December with occasional typhoons in August. Guam has adequate population (157,000) and infrastructure. Its politics are dominated by the indigenous Chamorro people. It boasts a high standard of living and thriving economy but these are based largely on tourism and an enormous U.S. military base. The total electrical capacity is 300 megawatts. Petroleum products are imported. Guam appears to have suitable sites for shore-based OTEC at two locations: along the northeast coast from Pati Point to Catalina Point and along the west coast from Asan to Meriza.

(4) Indonesia, in southeast Asia, is the world's largest archipelago. There are five main islands (Sumatra, Java, Kilimantan [mainly Borneo], Irian Java, and Sulawesi), but a total of 13,677 islands spread across 5,000 kilometers (3,100 miles) between the Indian Ocean to the west and the South China Sea and Philippine Sea of the Pacific Ocean to the east.

Indonesia is the fourth most populous nation in the world with 200 million people. The population is very divergent; there are some 300 ethnic groups with more than 350 languages and dialects. Religion is predominantly Muslim (87%). There has been international concern about human-rights abuses and persecution of ethnic minorities. Politics is quasi-democratic, dominated by the largest ethnic group, the Javanese (45% of the population) and by the military (General Suharto has been president for 30 years). However, there is a generally favorable economic and business climate. Big business is largely dominated by the Chinese ethnic groups. Bureaucratic delays and political corruption tend to impede business. Environmentally, Indonesia has been rather ineffective at stopping logging destruction of the world's second-largest tropical rain forest (the largest is in Brazil); some experts estimate that Indonesian rain forests will be gone in the next thirty years. Indonesia is rich in energy resources; for example, it is one of the world's leading exporters of liquefied natural gas. Other significant resources are oil, coal, bauxite, nickel, and agricultural products such as rubber and palm oil in addition to considerable lumber from logging forests (which cover 75% of the land area). Despite Indonesia's abundance of energy resources, with ultimately limited fossil-fuel production and growing domestic energy demands, the government is considering development of geothermal and nuclear energy over the next few decades. In addition, there appear to be feasible shoreline sites for OTEC at numerous locations throughout the Indonesian archipelago.

(5) The Maldives* are in the Indian Ocean roughly 800 kilometers (500 miles) off the southern tip of India. There is a total population of 300,000. The Maldives comprise nearly 1,200 low coral islands of which 200 are populated, but there is only one significant population center, the capitol city of Male with 65,000. The culture is Islamic. Political power is organized around a few families. The economy is limited, dominated by tourism but including tuna fishing, coconut production, clothing industries, and shipping; fish export is the second largest industry (after tourism). Foreign investment has recently been encouraged by liberalizing regulations; it is now possible to have companies in the Maldives that are wholly owned by foreign parties. In addition, the Maldivian government is supposedly keen on projects that go beyond the usual tourist attractions and amenities. Manufacturing and infrastructural support in general are very limited. Drinking water for tourists and all oil products are imported. The total power grid is about five megawatts. The Maldives have a huge foreign (e.g., 17,000 Sri Lankans) "guest" workforce to make up for local workforce shortage. Bathymetric charts indicate there are feasible sites for shore-based OTEC near Male (5° N, 73° E).

Note: much of the information on the Maldives was provided by Thomas Bjelkeman-Pettersson.

(6) The Marshall Islands comprise a group of 30 atolls and 1,152 islands located between 4° and 14° N, and between 160° and 173° E, in the North Pacific Ocean about halfway between the Hawaiian Islands and Papua New Guinea (about 3,500 kilometers or 2,000 miles from each). The population amounts to about 60,000, half of whom live in the capital, Majuro. The Republic of the Marshall Islands has a constitutional government. Politics is based on the power of local chiefs. The official languages are English and

Marshallese. There is a close association with and marked economic dependence on the U.S. which provides two-thirds of the gross national product as foreign aid. The Marshalls, particularly Bikini Atoll, have received considerable historical notoriety for U.S. nuclear bomb testing. The economy is very weak, based on small farms, limited tourism, and handicrafts produced from shells, wood, and pearls. Untapped resources appear to be limited to low-grade phosphate deposits and marine products. Attempts are being made to establish the Marshall Islands as an international offshore banking resource. The weather is tropical with occasional monsoons from May to November. Potable water is in short supply. The total electrical capacity is 42 megawatts, largely produced by small diesel generators using imported oil. There appear to be feasible shoreline OTEC sites. Majuro has reportedly been intensively studied for OTEC.

(7) New Caledonia (20° to 23° S, 164° to 168° E) is in the South Pacific Ocean roughly 900 kilometers (1,450 miles) east of Australia. The climate is frankly tropical--hot and humid. It is a French overseas territory with a population of 188,000. The political climate has been quite unstable, at times violent, but there has been reasonable calm since reforms in 1988 with a referendum on independence promised for 1998. The economy is limited to tourism, agriculture, and nickel mining. In addition to nickel there are natural resources of chrome, iron, cobalt, manganese, silver, gold, lead, and copper. The total electrical power capacity is 250 megawatts. Fuels are imported, as are foods and machinery. There appear to be suitable sites for shore-based OTEC.

(8) The Northern Marianas (15° N, 145° E), a commonwealth territory of the U.S., lie in the North Pacific Ocean just north of Guam. The climate is tropical marine moderated by northeast trade winds with little seasonal temperature variation. The rainy season from July to October includes typhoons. Groundwater is contaminated in some places by raw sewage. The total electrical power capacity is 105 megawatts. Petroleum products and foods are imported. There are known to be suitable sites for shore-based OTEC. However, the population is small (53,000) and the economy limited to tourism and subsistence farming.

(9) The Philippines (10° to 20° N, 120° to 125° E), with a total population over 67 million, is known to have suitable sites for shore-based OTEC. There is a democratic government and growing, though agriculturally based, economy. Infrastructure is weak; there are often power outages. Foreign investment is welcome. There is extensive oil production and use of geothermal power.

(10) The Seychelles (5° S, 55° E) have a total population of 73,000 on 115 islands. There is a total land area of 455 square kilometers (175 square miles). About half the islands are granitic--rocky and hilly with a narrow strip of coast; half are coralline--flat with elevated reefs. The climate is tropical marine: humid with temperatures year-round rarely dropping below 24 degrees C (75 degrees F). The Seychelles lie outside the cyclone belt so severe storms are rare. There are no natural fresh-water resources; catchements collect rain water; there are occasional short droughts. There is multiparty democracy. The economy is based on tourism, fishing (shrimp and tuna), and export of tuna, copra, cinnamon, and tea. There are significant trade and budget deficits, but a generally high

standard of living with no slums and very little crime. Infrastructure is limited; there are airstrips on nine of the islands and power is generated by imported fuel on the three islands that have electricity supply systems. There appear to be suitable sites for shore-based OTEC.

(11) The Solomon Islands (7° to 12° S, 156° to 163° E) have a total population of 400,000. They comprise several hundred islands with most of the population on the six largest (Guadalcanal, Malaita, New Georgia, Makira, Santa Isabel, and Choiseul). The climate is tropical monsoon with moderate temperatures. Political power resides in a multiparty parliament which is dominated by prominent figures from the villages. The economy is limited, based on copra and timber with subsistence agriculture. Infrastructure is limited. There is one major airport (on Guadalcanal). The total electrical capacity is 21 megawatts. Energy needs are currently met by importation. There appear to be suitable sites for shore-based OTEC.

(12) Tonga (20° S, 173° W), with a total population of 106,000, consists of an archipelago of 170 islands in the South Pacific Ocean a few hundred kilometers south of Samoa. The climate is tropical, modified by trade winds. Politics is dominated by the king, nobles, and wealthy landowners. There is subsistence agriculture with commercial production of coconut, cassava, and passion fruit. At present all energy needs are met by importation, transported in uneconomical 166-liter (44-gallon) units. The total electrical grid throughout Tonga is about six megawatts. There appear to be suitable sites for shoreline OTEC but their proximity to population centers is not known.

(13) Vanuatu (14° to 20° S, 166° to 170° E) is in the South Pacific Ocean. It was formerly called New Hebrides (UK/FR). Vanuatu consists of 82 islands, 12 of which are of significant size. The climate is tropical, moderated by southeast trade winds. There is a total population of 178,000. Politics is democratic but volatile. The economy is dominated by tourism and offshore financial services. There is subsistence farming and small-scale cash cropping. Copra and cocoa are exported. The total electrical power capacity is 17 megawatts. Nuclear power development has been banned by legislation. There appear to be suitable sites for shore-based OTEC.

Three island areas (Hawaii, Okinawa [part of Japan], and Taiwan) can be dropped from further consideration for new OTEC because they are already at the forefront of OTEC research and development. However, OTEC has been developed on Hawaii only at the Natural Energy Laboratory at Keahole Point on the westernmost point of the "Big Island" of Hawaii. According to bathymetric data posted on the Web by the U.S. Army (http://bigfoot.wes.army.mil/b512.html), there are other possible sites on the southwest and southeast coasts of the island of Hawaii (19° to 19° 30' N, 154° 50' to 156° 5' W) and on two other of the Hawaiian Islands: on the south coast of Kahoolawe (20° 30' N, 156° 40'W) and on the southeast coast of Maui (20° 40' N, 156° to 156° 20' W). Mauritius and Western Samoa can be dropped from the list because they do not appear to have deep ocean water within ten kilometers (six miles) of shore. In addition, eleven island areas can be dropped because they are too small or have other political/financial limitations:

Cook Islands, Indonesia, Fiji, Kiribati including Christmas Island, Nauru*, Palau, Papua New Guinea, Sri Lanka, Tuvalu, Wake Island, and Wallis and Futuna Islands.

** Note that Nauru (0°30′ S, 166°55′ E) was the site of the first successful net-power generation by a land-based OTEC facility. According to Avery and Wu (Oxford, 1994) and an NOAA report (1986), the Tokyo Electric Power Company and Toshiba Corporation began plans in 1973 that projected a ten-megawatt prototype. The plant finally constructed and run in 1980-1982 was located on the southwest coast of Nauru by Yaren near the international airport. It was closed-cycle design using Freon as the working fluid and produced 100-120 kilowatts gross power (15-30 kilowatts net) which was successfully integrated with the local power grid. However, Nauru may not present a practical site for further OTEC development. It is a very small island (population of 10,000) which has been 80% destroyed by phosphate mining. The population tends to be wealthy as a result of the phosphate mines, but phosphate deposits are expected to be exhausted by the year 2000. The island is supported by overseas investments and by an international fund established in compensation for exploitation of the phosphate deposits. The total electrical capacity of Nauru is 14 megawatts.*

The next step in finding feasible shoreline OTEC sites would be confirm on finer-scale regional depth charts which of these 29 nations and territories quite certainly have sites for shore-based OTEC. After that, one would do a more thorough survey of political and economic situations within each of these 29 nations and territories to identify restrictive business, ecological, or other constraints that would make shoreline OTEC impossible. These two processes should distill out a few that warrant further evaluation. The criteria for further evaluation are listed below.

OTEC Site Criteria

In assessing a potential shoreline site for development of an OTEC (ocean thermal energy conversion) facility, there are quite a number of factors that must be evaluated. After assuring that the geographic characteristics make OTEC feasible (tropical climate with near deep ocean), the most important considerations are political and infrastructural.

- Is there a tropical climate? (What are the average monthly ambient temperatures through the year?)
- What are the average monthly surface-water temperatures through the year?
- Are there severe storms (typhoons, tornadoes, monsoons, high surf)?
- What is the distance off shore to 1,000-meter ocean depth?
- What is the shoreline construction base (sand, lava, bedrock, etc.)?
- Is the political climate supportive of large infrastructural development?
- Is it supportive of foreign investment from the standpoints of taxation, permitting, and emigration (or working visas) for foreigners?
- Who are the local authorities (by names and positions)?
- Are there prohibitive ecological constraints?
- Are there local building-code constraints? (Is there large hotel construction in the area?)

- What is the area population (and population density in the local 100-to-500-square-mile area)?
- What is the local per-capita income?
- What is the minimum hourly wage and the minimum (or average) construction and clerical hourly wages?
- What is the local utilization of electricity, for example, the per-capita use? How does demand vary with daily or seasonal cycles?
- How is electricity currently generated (diesel, hydroelectric, nuclear, wind, etc.), and are there currently specific power-generation development plans?
- What is the total capacity of the local power grid?
- Is there a willing buyer for power that would be produced by OTEC?
- What is the population of transients (tourists) through the year?
- What is the local tourist infrastructure (hotels, transportation, interesting sites)?
- How densely is shoreline developed (how expensive and available are shoreline sites)?
- What are present sources of fresh water (rivers, run-off, desalination, importation, etc.)?
- What is the local market for fresh water (volume, cost per 1,000 gallons, per-capita use)?
- Is there significant local fishing (commercial, tourist)?
- What are the local markets for fish and marine-life products (prices, varieties, volumes)?
- What is the local infrastructure for transport of products (fish, industrial products, water, etc.--highways, railways, seaport facilities, airports)?
- Is there local demand for air-conditioning (or other uses of chill-water)?
- Is there local industry (perhaps with significant power utilization)?
- Is there local agriculture?
- Would there be local interest, markets, competition regarding cold-bed agriculture (i.e., temperate-zone fruits and vegetables)?
- Is there local aquaculture (perhaps even mariculture)?