

Ocean Thermal Resources

The vast size of the ocean thermal resource and the baseload capability of OTEC systems remain very promising aspects of the technology for many island and coastal communities across tropical latitudes. For example, OTEC plants could supply all the electricity and potable water consumed in the State of Hawaii throughout the year and at all times of the day. This is an indigenous renewable energy resource that can provide a high degree of energy security and minimize green house gas emissions. This statement is also applicable to all US Insular Territories (e.g., American Samoa, Guam, Northern Mariana Islands, Virgin Islands and Puerto Rico). With the development of electric vehicles, OTEC could also supply all electricity required to support land transportation. The resource is plentiful enough to met additional electricity demand equivalent to several times present consumption.

Thermal resource characteristics are used along with the specific OTEC system transfer function to determine electricity production. Ocean thermal resources are defined by ΔT , the ocean temperature differences between water depths of 20 m and 1000 m. ΔT characterizes extractable OTEC power as long as the local thermal structure is preserved.

The current resource evaluation benefits from high-resolution ocean models. The HYCOM + NCODA (1/12°) model is used by Prof. Gerard Nihous of the University of Hawaii to track changes on a daily basis over a wide area around different locations (nihous@hawaii.edu).

The optimized turbine-generator output P_{gross} varies with the square of ΔT so that for typical values of 20°C, a change of 1°C in ΔT will produce relative fluctuations of about 10% in P_{gross} . Measurements performed during the operation of the *210 kW OC-OTEC Experimental Apparatus* confirmed this point. From a net power perspective, matters are even more sensitive since the in-plant power consumption needed to run all pumps represents about 30% of the reference value of P_{gross} ; hence, changes of the order of 10% in P_{gross} approximately translate in 15% variations in net power output, which is the true basis for the determination of electricity production costs.

In the following discussion the ocean thermal resource off the Hawaiian Islands is considered to illustrate the methodology that can be applied to any region of interest. The most recent, 2005 version of the World Ocean Atlas (WOA05) compiled by the National Ocean Data Center (NODC) represents an extremely valuable source of objectively analyzed statistical fields, including ocean temperature. The data includes long-term historical averages of variables that have been determined from all available

oceanographic measurements. Monthly averages also are available. The data is provided with a resolution of one-quarter degree latitude by one-quarter degree longitude.

Figure 1 shows a map of the average OTEC thermal resource ΔT from the WOA05 data base plotted with the Ocean Data View software (<http://odv.awi.de>).

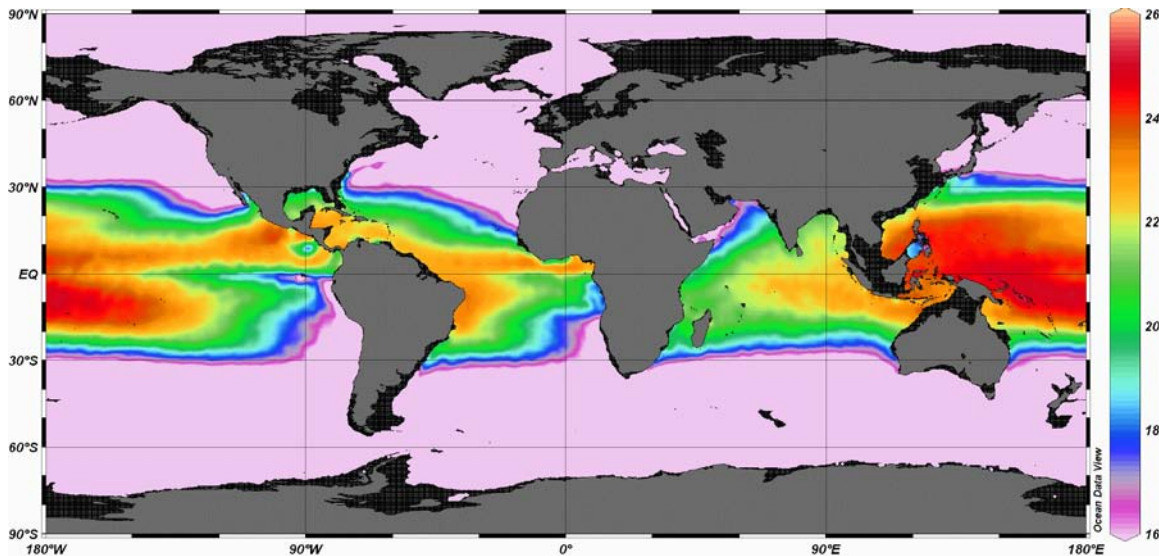


Figure 1.- Average ocean temperature differences (between 20 m and 1000 m water depths) from WOA05 data with color palette from 16°C to 26°C. [Provided by Prof. Nihous.]

As can be seen in Figure 1, the Hawaiian Archipelago is very well located from a thermal resource perspective. The volcanic islands have a steep bathymetry that affords good access to deep water. Their isolation and nearly complete dependence on fossil fuels today make any local baseload power production technology particularly attractive. Additional factors that would hamper other renewable energy technologies in Hawaii, such as limited land availability, pristine reefs and valuable surf resources, would hardly affect OTEC.

A closer look at the WOA05 data in Figure 1, suggests that such resources are not enhanced from North to South, as would be intuitive, but roughly from Northeast to Southwest. Recently available predictive tools afford a much more detailed analysis. An ocean model called HYCOM (HYbrid Coordinate Ocean Model), subject to routine data assimilation via the Naval Research Laboratory (NRL)'s Coupled Ocean Data Assimilation (NCODA) protocol, allows daily assessments of ocean variables at a spatial resolution of 1/12 degree latitude by 1/12 degree longitude across the water column. NCODA assimilates all available operational sources of ocean observations. The model output essentially should be interpreted as daily averages. These data can be downloaded via public-domain servers such as <http://ferret.pmel.noaa.gov/LAS>.

Figure 2 shows the average available OTEC thermal resource ΔT over a period of three years, from July 1, 2007 through June 30, 2010. Areas that are shallower than 1000 m are displayed in white to indicate that ΔT is not defined there. Although overall geographic variations in the selected area covering 7 degrees of latitude and 9 degrees of longitude are within 2°C , a prominent wedge can be seen; its apex roughly lies at the eastern tip of the Big Island, and the feature is somewhat symmetric across the latitude of that point; from the apex, a line running along the northeast (windward) coasts of the islands defines the angular overture of the wedge. The emergence of such a feature is likely to be the result of the strong influence the islands exert on large-scale ocean currents. The westward flowing North Equatorial Current (NEC) forks at the Big Island and gives rise to a branch that follows a northwesterly direction (North Hawaiian Ridge Current). West of the islands, the vorticity of the wind-stress curl associated with the wake of the islands causes a clockwise circulation centered at 19°N and a counter-clockwise circulation centered at $20^{\circ}30'\text{N}$, with the narrow Hawaiian Lee Counter Current (HLCC) extending between them from 170°W (or from as far as the Dateline) to 158°W . The eastward flowing HLCC is responsible for the advection of warm water toward the lee of the Hawaiian archipelago.

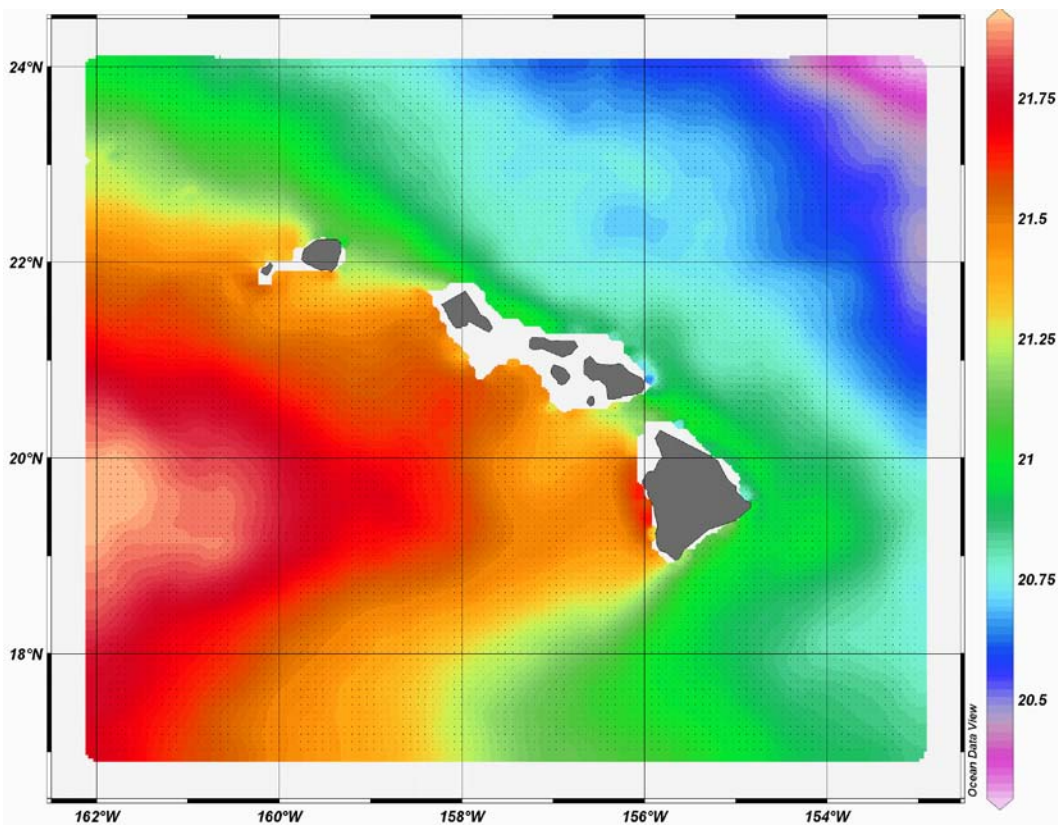


Figure 2.- Average ocean temperature differences (between 20 m and 1000 m water depths) around the main Hawaiian Islands from HYCOM + NCODA ($1/12^{\circ}$) data for the period July 1, 2007 through June 30, 2010. [Provided by Prof. Nihous.]

Site Selection Criteria for OTEC Plants

As stated above, the search for renewable energy resources has resulted in OTEC's second revival. As it is well known the concept utilizes the differences in temperature, ΔT , between the warm tropical surface waters, and the cold deep ocean waters available at depths of about 1000 m, as the source of the thermal energy required.

The historical monthly averages of ΔT for February and August are depicted in Figures 3 and 4 respectively. Values are color coded as indicated in the right-hand-side of the Figures. The values were obtained by Prof. Nihous from the National Ocean Data Center's World Ocean Atlas. Deep seawater flows from the Polar Regions. These polar water, which represents up to 60% of all seawater, originates mainly from the Arctic for the Atlantic and North Pacific Oceans, and from the Antarctic (Weddell Sea) for all other major oceans. Therefore, T_{CW} at a given depth, approximately below 500 m, does not vary much throughout all regions of interest for OTEC. It is also a weak function of depth, with a typical gradient of 1°C per 150 m between 500 m and 1000 m. These considerations may lead to regard T_{CW} as nearly constant, with a value of 4°C to 5°C at 1000 m.

A desirable OTEC thermal resource of about 20°C requires typical values of T_{WW} of the order of 25°C . Globally speaking, regions between latitudes 20°N and 20°S are adequate. Some definite exceptions exist due to strong cold currents: along the West Coast of South America and to a lesser extent for the West Coast of Southern Africa. Moreover, T_{WW} varies throughout the year, and sometimes exhibits a significant seasonal drop due to the upwelling of deeper water induced by the action of the wind: such are the cases of the West Coast of Northern Africa in the southern hemisphere winter (Figure 4).

The following summarizes the availability of the OTEC thermal resource throughout the World:

- Equatorial waters, defined as lying between 10°N and 10°S are adequate except for the West Coasts of South America and Southern Africa;
- Tropical waters, defined as extending from the equatorial region boundary to, respectively, 20°N and 20°S , are adequate, except for the West Coasts of South America and of Southern Africa; moreover, seasonal upwelling phenomena would require significant temperature enhancement for the West Coast of Northern Africa, the Horn of Africa, and off the Arabian Peninsula.

The accessibility of deep cold seawater represents the most important physical criterion for OTEC site selection, once the existence of an adequate thermal resource has been established. In the case of a floating plant, the issue of cold seawater accessibility is only relevant inasmuch as submarine power cables, and, maybe, a desalinated water hose, are needed to transfer the OTEC products to shore. For the grazing plantship, with energy intensive products like hydrogen or ammonia as the product, the distance is important from the perspective of the transit time for the vessels that would transport the product to shore.

Many other points must be considered when evaluating potential OTEC sites, from logistics to socioeconomic and political factors. One argument in favor of OTEC lies in its renewable character: it may be seen as a means to provide remote and isolated communities with some degree of energy independence, and to offer them a potential for safe economic development. Such operational advantages, however, are often accompanied by serious logistical problems during the plant construction and installation phases: if an island is under development, it is likely to lack the infrastructure desirable for this type of project, including harbors, airports, good roads and communication systems. Moreover, the population base should be compatible with the OTEC plant size: adequate manpower must be supplied to operate the plant; and, the electricity and fresh water plant outputs should match local consumption in orders of magnitude.

Another important point to consider is the preservation of the environment in the area of the selected site, inasmuch as preservation of the environment anywhere is bound to have positive effects elsewhere. OTEC is one of the most benign power production technology, since the handling of hazardous substances is limited to the working fluid (e.g.: ammonia), and no noxious by-products are generated; OTEC merely requires the pumping and return of various seawater masses, which, according to preliminary studies, can be accomplished with virtually no adverse impact. This argument should be very attractive, for pristine island ecosystems, as well as for already polluted and overburdened environments. For example, the amount of CO_2 released from electricity-producing plants (expressed in gr of CO_2 per kWh) ranges from 1000, for coal fired plants, to 700, for fuel-oil plants, while for OC-OTEC plants it is at most $\sim 1\%$ of the amount released by fuel oil plants. The value is much lower in the case of a CC-OTEC plant.

Ninety-eight nations and territories with access to the OTEC thermal resource within their 200 nautical mile exclusive economic zone (EEZ) were identified in the 1980's. A partial list is provided in Table 1. For the majority of these locations, the OTEC resource is applicable only to floating plants. Unfortunately, now as then, there is no OTEC plant with an operational record available. This still remains the impediment to OTEC commercialization.

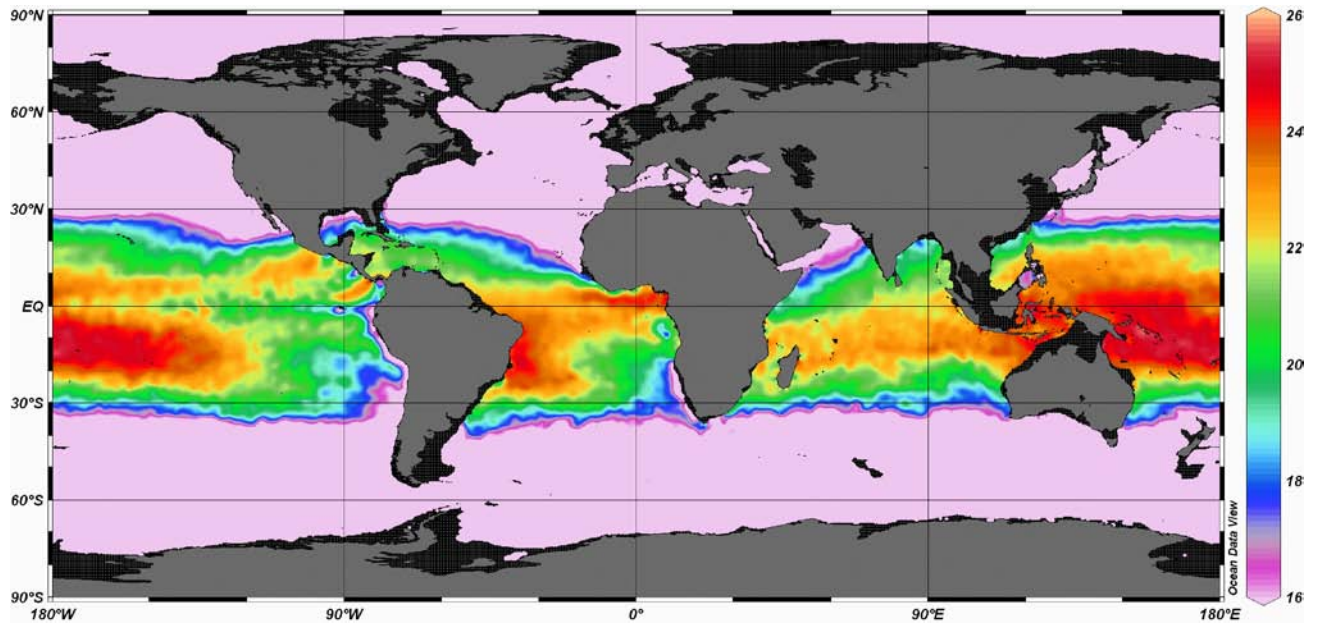


Figure 3.- Historical Monthly average of ΔT during February from WOA05.

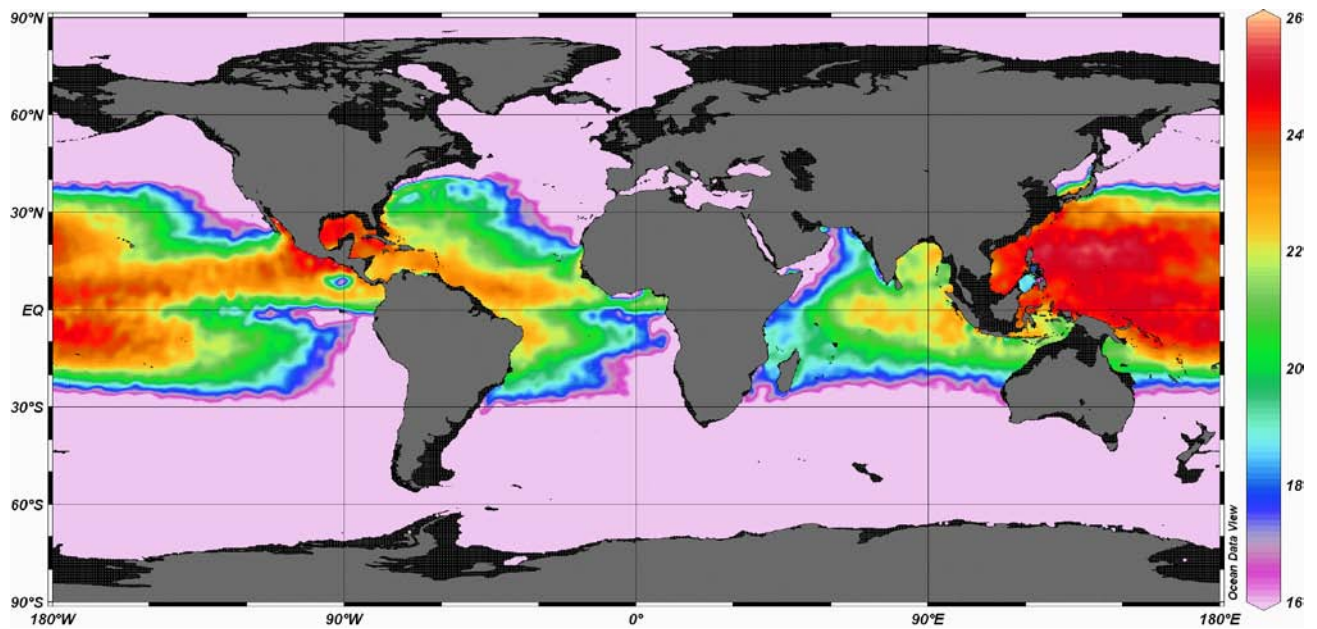


Figure 4.- Historical Monthly average of ΔT during August from WOA05.

GEOGRAPHICAL AREA	MAINLAND		ISLAND		
AMERICAS	Mexico	Guyana	Cuba	Guadeloupe	
	Brazil	Suriname	Haiti	Martinique	
	Colombia	French Guiana	Dominican Rep.	Barbados	
	Costa Rica	Nicaragua	Jamaica	Dominica	
	Guatemala	El Salvador	Virgin Is.	St. Lucia	
	Honduras	Belize	Grenada	St. Kitts	
	Panama	United States	St. Vincent	Barbuda	
	Venezuela		Grand Cayman	Montserrat	
			Antigua	The Grenadines	
			Puerto Rico	Curacao	
			Trinidad & Tobago	Aruba	
			Bahamas		
	AFRICA	Nigeria	Gabon	Sao Tome & Principe	
		Ghana	Benin	Ascension	
Ivory Coast		Zaire	Comoros		
Kenya		Angola	Aldabra		
Tanzania		Cameroon	Madagascar		
Congo		Mozambique			
Guinea		Eq. Guinea			
Sierra Leone		Togo			
Liberia		Somalia			
INDIAN/PACIFIC OCEAN		India	Australia	Indonesia	American Samoa
	Burma	Japan	Philippines	Northern Marianas	
	China	Thailand	Sri Lanka	Guam	
	Vietnam	Hong Kong	Papua New Guinea	Kiribati	
	Bangladesh	Brunei	Taiwan	French Polynesia	
	Malaysia		Fiji	New Caledonia	
			Nauru	Diego Garcia	
			Seychelles	Tuvalu	
			Maldives	Wake Is.	
			Vanuatu	Solomon Is.	
			Samoa	Mauritius	
			Tonga	Okinawa	
			Cook Is.	Hawaii	
			Wallis & Futuna Is.		

Table 1.- List of Nations with Appropriate Ocean Thermal Resource within their 200 nautical miles Exclusive Economic Zone.