U.S. Army Corps of Engineers
Hydroelectric Power Source Alternative Assessment
State of Hawaii

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Prepared by:
EA/HHF Joint Venture
1221 Kapiolani Boulevard, Suite 1030
Honolulu, HI 96814

For more information or copies of the report, please contact:

Deborah Solis
U.S. Army Corps of Engineers, Honolulu District
Civil and Public Works Branch
Programs and Project Management Building
230 Fort Shafter, HI 96858-5440
(808) 438-0701

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LIST OF ACRONYMS AND ABBREVIATIONS

°C	degrees Celsius
$/kW	dollars per kilowatt
$/kWh	dollars per kilowatt-hour
ADC	Agribusiness Development Corporation
ALOHA	A Long-term Oligotrophic Habitat Assessment
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
CC-OTEC	closed cycle ocean thermal energy conversion
cfs	cubic feet per second
Chong	Cedric D.O. Chong & Associates, Inc.
CZMA	Coastal Zone Management Act
DBEDT	Department of Business, Economic Development and Tourism
DOE	Department of Energy
DOI	Department of the Interior
EIS	Environmental Impact Statement
EPRI	Electric Power Research Institute
F	Floater
ft	feet
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
GAP	Gap Analysis Program
GIS	Geographic Information System
GWh	gigawatt hour
HC&S	Hawaiian Commercial & Sugar Company
HCEI	Hawaii Clean Energy Initiative
HECO	Hawaiian Electric Company
HELCO	Hawaii Electric Light Company
HEI	Hawaii Electric Utilities
HLCC	Hawaiian Lee Counter Current
HOT	Hawaii Ocean Time-series
HYCOM	HYbrid Coordinate Ocean Model
INL	Idaho National Engineering and Environmental Laboratory
kg/s	kilograms per second
KIUC	Kauai Island Utility Cooperative
km	kilometer

kW	kilowatt
kWh	kilowatt hour
L	Land
m	meter
m^3/s	cubic meters per second
MECO	Maui Electric Company, Ltd.
MMS	Minerals Management Service
MW	megawatt
MWh	megawatt hour
NCODA	Naval Research Laboratory Coupled Ocean Data Assimilation
NFIP	National Flood Insurance Program
NDBC	National Data Buoy Center
NEPA	National Environmental Policy Act
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
OC-OTEC	open cycle ocean thermal energy conversion
OCS	Outer-Continental-Shelf
OMR&R	Operations, Management, Repair and Replacement
OREZ	Ocean Renewable Energy Zone
OTEC	ocean thermal energy conversion
OTECA	Ocean Thermal Energy Conversion Act
OWC	oscillating-water-column
SIDS	small island developing states
SWAN	Simulating WAves Nearshore
UH	University of Hawaii
U.S.	United States
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
USBR	United State Bureau of Reclamation
WEC	wave energy conversion
WOA05	World Ocean Atlas, 2005 version
WW3	WaveWatch3 mode

EXECUTIVE SUMMARY

In order to help address the State of Hawaii‟s 2030 Clean Energy Initiative, and meet the State‟s goal of 70% clean energy by 2030, the U.S. Army Corps of Engineers, Honolulu District (USACE) received appropriation from Congress in 2009 to initiate a reconnaissance study. The purpose of this study is to identify and assess potential hydropower and ocean energy projects in the State of Hawaii. The goal of this study is to provide information to help the State of Hawaii reach their Clean Energy Initiative goal of 40% percent renewable energy by 2030.

This study has two main components, the 905b report, and supporting documentation within a Technical Appendix. The 905b report provides a summary of potential sites which have a federal interest and meet the criteria of having comparatively lower economic costs and lower environmental/social impacts. The Technical Appendix (this document) describes the assessment methodologies and contains all of the background information on each of the identified sites. The sites were analyzed in a standardized format to enable direct comparison between potential projects. The review followed the example of a 1981 USACE hydropower study but greatly expanded the scope to include more than 160 hydropower sites and ocean energy areas across the State of Hawaii. Conventional hydropower projects identified in this report include run-of-the-river, run-of-the-ditch, pumped storage, conventional storage and in-line technologies. Ocean energy systems include ocean thermal energy (OTEC) and wave energy conversion (WEC).

Hydropower:
A database was developed in support of the conventional hydropower assessment that included more than 50 site-specific economic and environmental/social criteria. All of the data collected, along with the original source references, is also available as an electronic Excel spreadsheet that can be sorted depending on criteria. This data is cross-referenced as a GIS shapefile, which is available from the Honolulu USACE. The geospatial data allows users to geographically and visually sort projects based on any of the selected fields including island, size, scale, incremental energy cost, location, etc. The information provided allows the USACE, State, County, and private developers to analyze potential hydropower sites based on their needs and interests. This information is available as Appendix A, and provides complete site descriptions, additional caveats, and details about the original documents describing the sites.

Economic and Environmental/Social fields were the primary factors used to screen potential projects. Economic considerations of conventional hydropower projects included a rough order of magnitude comparison of the construction cost of the project with its potential generating capacity. Projects that could produce energy at rates lower than the current utility rates were ranked higher than other sites. Environmental/social considerations include the proximity of sites to critical and pristine habitat, state water classification and land use restrictions, streams of known cultural value, and areas of high recreational use. The environmental/social factors were examined independently from economic considerations for the purposes of screening sites. This approach allows flexibility in screening the projects - for example, if overall infrastructure costs decrease as a result of improved technology, or oil costs increase, more sites could be economically viable.

Combining the results of the independent economic and environmental/social screening processes as described above generated a "shortlist" (Table 5-3) of 75 conventional hydropower projects out of the 166 identified in Appendix A. This included operational plants which could be upgraded or made more efficient. Some of the proposed sites had minimal background information beyond the basic criteria, but more site-specific research can be done on these sites. These proposals should not be discounted without additional research. Sites that did have sufficient background information available were reviewed more closely as cost estimates and potential problems could be more accurately derived.

Certain geographical areas had more interest for conventional hydropower. The Kekaha/Kokee ditch system in Waimea Canyon was identified multiple times for new projects and upgrades to the existing power plants. This region had lower calculated incremental energy costs than many other sites, fewer environmental/social concerns, and is located in an area with USACE flood control projects. Power plants could be placed in an existing irrigation system, linking an additional USACE interest to the project. After further assessment of this shortlist, the conventional hydropower site at Puu Lua-Kitano-Waimea (Site 73, 74) in Waimea/Kekaha in West Kauai was recommended for further study based on consideration of cost, environmental feasibility, and federal interest.

The project falls within a flood control district which needs an improved levee system to meet updated FEMA requirements. The U.S. Bureau of Reclamation plan has also been considered feasible by the local utility, and has interest from land managers at the Agribusiness Development Corporation (under the Department of Agriculture). The Department of Hawaiian Homelands also has a claim for 30% of potential water in the area. This should not limit the project, as run-of-the-river-systems allow water to be used downstream for secondary purposes.

Ocean Energy:
Areas of ocean energy resource potential were identified based on resource availability and then further refined to account for environmental constraints such as marine sanctuaries and sensitive coastal waters. Due to the nature of the resources, WEC is most feasible off the windward and north shores of the islands of Hawaii, Maui, Oahu and Kauai, whereas OTEC has more potential off of the leeward coasts of Hawaii, Oahu, and Kauai. OTEC is feasible where the temperature differential between warm surface waters and cold waters from depth exceed 20 degrees Celsius, typically in waters in excess of 1000 meters. The State of Hawaii has vast WEC and OTEC potential, however environmental and socioeconomic factors may inhibit the development of these resources. Specific environmental problems associated with OTEC and WEC are identified within the Technical Appendix. These factors include marine conservation areas, national marine wildlife sanctuary areas, and areas of high cultural and recreational value to local residents. The areas identified for potential development were further refined taking these factors into account.

Economic considerations for ocean energy are different than conventional hydropower. Ocean energy systems are still in the experimental phase. Costs remain high and proposals focus on expanding potential areas for OTEC development through a streamlined permitting and grid connection system. The recommendation from this study is to work with the State to establish ocean renewable energy zones (OREZ) and pilot projects for both WEC and OTEC. A designated ocean resource energy zone could reduce permitting costs for pre-approved districts that meet land use permitting and infrastructure requirements. This could be taken a step further by establishing an underwater power hub connected to power grid within the OREZ enabling WEC devices to simply plug into the hub to supply power to the grid. This centralized hub for planned energy linkages could reduce costs by consolidating substation and transmission line infrastructure. These proposals are designed to focus funding on ocean energy research and development rather than on permitting requirements.

Potential sites for OTEC and WEC are located within areas of high resource availability, limited public access, and potential for connections to the existing electrical grid (Map 2). Taking OTEC a step further toward contributing to the State"s renewable energy portfolio would involve establishing pilot OTEC plants at Kahe Point on Oahu and/or Keahole Point at the Natural Energy Laboratory Hawaii Authority in Kona, Hawaii. Both sites are located near existing electrical substations, and the Keahole site has access to an existing deep-water intake pipe. The U.S. Navy is developing a WEC site off of Kaneohe Marine Corps Base, Oahu and Oceanlinx, an Australian company, has been pursuing a WEC site off Pauwela, Maui. Preferential areas for OTEC and WEC development based on resource availability and lower environmental/navigational impacts are presented as the product of reconnaissance-level geospatial analyses.

In total, this report provides a valuable resource for the USACE, State, County, and private developers to consider potential conventional hydropower and ocean energy sites around the State. Hawaii has been endowed with substantial natural energy resources that, combined with the highest energy prices in the country, make Hawaii an attractive place to implement renewable energy initiatives. The study represents a key reference to support the State of Hawaii the Clean Energy Initiative goal of 70 percent clean energy by 2030.

1.0 REGIONAL OBJECTIVES

The purpose of this report is to assess and document the current and potential hydropower and ocean energy resources available in the State of Hawaii. This report updates a 1981 USACE regional hydropower study. Currently, the State of Hawaii is almost wholly dependent upon imported petroleum products for generation of power in the public utility system. However, through the Hawaii Clean Energy Initiative formed in 2008, the State of Hawaii and the Department of Energy (DOE) have committed to meeting 40 percent of Hawaii‟s energy needs with renewable energy by 2030. This report does not recommend projects for authorization of construction by the U.S. Army Corps of Engineers. However, this report presents information on those potential hydroelectric projects that should be considered for continued study, consistent with the following objectives:

1. Increase the energy self-sufficiency of the region.

2. Assess the physical potential for increasing hydroelectric power capability and generation.

3. Determine the potential for increasing hydroelectric generating capacity by development of new sites and by adding generating facilities to existing water resource projects.

4. Assess the general environmental and socioeconomic impacts of hydroelectric power development.

5. Provide for maximum feasible utilization of the energy potential derived from the region‟s water resources.

6. Identify and prioritize likely areas to target for permitting.

2.0 EXISTING CONDITIONS

2.1 General Area Description

For the National Hydroelectric Power Study, the Hawaiian Archipelago constitutes the Hawaii Region. The Hawaiian Archipelago extends some 1,523 miles over the northern Pacific Ocean, between the islands of Midway on the west and Hawaii on the east. The archipelago consists of a chain of mountaintop islands, islets, pinnacles and reefs, all rising thousands of feet from the ocean floor. A large part of the Pacific Ocean surrounding the Hawaiian Archipelago has depths ranging from 16,000 to 20,000 feet below sea level. Except for Midway Island, the archipelago is under the jurisdiction of the State of Hawaii, the 50th State admitted to the Union, the 47th in geographic area, and 40th in population. Midway has no potential for hydropower development, so the following study area is comprised of only the State of Hawaii.

The Hawaiian Islands have a total area of 6,470 square miles, consisting of eight principal islands (areas in square miles): Niihau (73), Kauai (553), Oahu (617), Molokai (261), Lanai (141), Kahoolawe (45), Maui (734), and Hawaii, also known as the Big Island (4,035) (Carpenter & Provorse, 1998). These islands form a 400-mile-long arc at the southeastern end of the archipelago and include more than 99 percent of the region‟s land area. The island of Kahoolawe is barren, uninhabited and under reserve status in State control. The island of Niihau is privately owned and has little development. Kahoolawe and Niihau were not considered as part of the principal study area. The island of Lanai has a small population, but the island lacks perennial streams for hydropower, has low rainfall, and has very limited ocean energy resources. Lanai falls within Maui County, but has very limited potential hydropower or ocean energy identified in this report. The island of Oahu, which is the third largest in land area, is the economic, administrative and military center of the State. Oahu, along with the other four main inhabited islands and surrounding waters of Kauai, Molokai, Maui, and Hawaii, therefore constituted the principal study area. The study region is shown on Figure 2-1 on page 2-7 (Macdonald et al., 1983; United States Army Corps of Engineers [USACE], 1981).

2.2 Climatology and Geography

The islands and mountains that constitute the Hawaiian Archipelago have been created almost entirely by volcanic activity. Each island is the top of a volcanic mountain, modified by stream and wave erosion and minor amounts of organic growth. The geology is predominantly igneous, with lava basalts and sporadic occurrences of pyroclastics composed of a variety of rock types. The decomposition of lava and pyroclastics results in residual, lateritic soils which blanket most of the islands.

Constant erosion has changed the topography of the islands from huge, gently sloping volcanoes to dissected and incised cliffs, valleys and basins. The topography of many of the drainage areas is characterized by relatively steep stream courses and steep, rugged basaltic formations. As a result, the streams generally do not meander as they traverse alluvial areas. In areas of the State that are geologically youthful, few if any perennial streams are found. For example, on the island of Hawaii, 710 intermittent streams reach the sea along three-fourths of the coastline, a distance of about 225 miles (Macdonald et al., 1983; USACE, 1981).

2.3 Economics of the Area

The advantages of the State of Hawaii‟s location and climate play a vital role in the State‟s economy. In 2009, the State of Hawaii‟s gross domestic product was $64.1 billion, with tourism, military activities, and agriculture being the largest contributors. During the 1980s, the State of Hawaii experienced a rapid growth in tourism. Tourist arrivals nearly doubled from 3,928,789 in 1980 to 6,723,531 in 1990. However, tourism has steadied since then, with 6,514,000 visitors arriving in 2009. Visitor expenditures amounted to $10.1 billion in 2009, dropping 11.6 percent since the previous year, due to the economic downturn in 2008. However, recent data suggests positive signs of economic recovery in 2010, with modest and gradual economic recovery anticipated over the course of the next several years (Hawaii Department of Business, Economic Development and Tourism [DBEDT], 2010)

The State of Hawaii‟s population has expanded consistently over the course of the last two decades. From 1990 to 2009, the total resident population increased by 16.6 percent, from 1,108,229 to an estimated 1,295,178 (United States Census Bureau, 2010). Population growth is expected to slow to less than 1 percent per year through 2020 (Pacific Business News, 2010). Approximately 70 percent of the State‟s population is located on the Island of Oahu. The island houses most of the major military installations, and depends considerably on the agricultural and food processing industry as well as Waikiki Beach, the region‟s largest tourist destination. The economies of the other islands, sometimes referred to as the “neighbor islands”, historically centered on agriculture and attendant food processing. With the decline of employment in these two sectors, the neighbor islands turned to the tourist industry to stimulate their economies, leaving them with a relatively undiversified economic base.

The State‟s heavy dependence on a few large industries, such as tourism, defense jobs, and plantation agriculture is concerning and has led to vulnerability of unemployment in large numbers. Per capita income (inflation adjusted) has been declining for several decades, and the State has a relatively low wage structure yet a relatively high cost of living. The 2000 Census recorded a labor force of 950,055 of which 612,831 were employed, with 39,036 of the work force in the Armed Forces; 102,254 in educational, health and social services; arts, 86,189 in entertainment, recreation, accommodation and food services; 65,693 retail trade; and 51,039 in professional, scientific, management, administrative, and waste management services. The median household income in 2008 inflation-adjusted dollars was $66,034 (United States Census Bureau, 2008).

For years, the State of Hawaii has sought to balance the State‟s reliance on these large industries by working to initiate growth and development of smaller, more varied economic activities and industries. Much research suggests that a shift to high-tech jobs with titles of scientists, engineers, and technicians will result in more annual growth and will lead to better job opportunities (Hecker, 2005). This evidence has important implications for the Hawaii job market, in that it will be important to increase these types of job opportunities by investing in projects requiring technical professionals. In a recent report conducted by the DBEDT, energy technology services were identified as a key target for future development and investment in the renewable energy may provide economic growth and skilled job opportunities (DBEDT, 2009a).

2.4 Major Energy Users

There are a total of four utility companies servicing the main populated islands (Table 2-1). All of the companies are investor-owned (with the exception of KIUC, a consumer-owned cooperative) but are regulated by the State Public Utility Commission. Each of the islands is served by independent power systems. There is no interconnection of power between the islands.

Table 2-1. Utility Companies.

Island	Company
Oahu	Hawaiian Electric Company (HECO)
Hawaii	Hawaii Electric Light Company (HELCO)
Kauai	Kauai Island Utility Cooperative (KIUC)
Maui-Molokai-Lanai	Maui Electric Company, Ltd. (MECO)

Hawaiian Electric Industries (HEI) produces 95% of the electricity in Hawaii through Hawaiian Electric Company (HECO) on Oahu, MECO on Maui County, and HELCO on the Big Island. The island of Lanai is serviced by MECO, but the generating plant and most of the distribution lines are owned by the privately-owned Castle and Cooke, Inc. The island of Molokai is also serviced by MECO. The top five retailers of electricity in the State are HECO with 72.7 percent of the State‟s total electricity sales, MECO with 11.9 percent, HELCO with 11 percent, and KIUC with 4.4 percent (USACE, 1981; University of Hawaii [UH], 2008).

Combined transportation, including air, water and ground transportation, consumes about 59 percent of the State of Hawaii‟s petroleum energy (Table 2-2). The second highest consumer is the electric power industry, averaging about 30 percent of the State‟s petroleum consumption. In 2008, the power industry consumed 13,407,277 barrels of petroleum for electric power generation. Out of this total, 657,789 barrels of petroleum were used by independent producers for electricity generation.

Table 2-2. State of Hawaii Petroleum Consumption by Basic Industry, 2008.

User Category	Percent of Total
Transportation	59
Electric Power	31
Industrial	7.9
Commercial	1.5
Residential	0.6

Source: DBEDT, 2007

The military is HECO‟s single largest customer, purchasing approximately 15 percent of all kilowatt hours (kWh) produced on Oahu (Cole, 2008). In 2008, about 30 percent of the State‟s electrical energy was consumed by residential users. The other end-sector users consumed the following percentages of the State‟s electrical energy: commercial (33.7 percent), and military/industrial (36.6 percent).

2.5 Future Development

Forecasts of regional demographic and economic growth are taken from the most recent DBEDT Quarterly Statistical and Economic Report (2010) and the longer range DBEDT Series 2035 report *Population and Economic Projections for the State of Hawaii to 2035* (2009b). Both provide detailed regional and national projections of population, employment, and earnings. Projections encompass all of the islands in the State of Hawaii, and are summarized in Table 2-3 and Table 2-4.

The DBEDT population projections indicate an increase in population from 1,277,400 in 2007 to 1,332,000 in 2013 and 1,598,675 by the year 2035. This projection is based on an annual growth rate of 0.7 to 0.8 percent. The projections for earning and income are useful to show the relative magnitude of earnings in various sectors. DBEDT forecasts average annual growth in total personal income from $45,190 in 2015 to $62,130 in 2035. A 0.9 percent annual increase rate in total civilian wage and salary jobs is expected between the years 2007 and 2035, from 661,112 to 834,100 jobs.

As of August 2010, the most jobs in the State are government with 126,350 employees, professional/business with 68,450, and retail trade with 67,050. In 2035, projected employment will be the highest in government, health services, and retail trade, with totals of 159,750; 95,860; and 90,080 respectively (DBEDT, 2010). Health services are expected to grow from the current level of 60,800 jobs due to the rapidly aging population. Tourism is expected to recover steadily from the current recession, growing by 0.7 percent until 2035 and reaching approximately 9 million. This will be an increase of 2.5 million visitors per year if projections hold true.

Table 2-3. DBEDT Projected Population and Visitor Arrivals.

	2008	2009	2010	2011	2012	2013
Economic Indicators	**Actual**		**Forecast**			
Total Population (thousands)	1,287	1,295	1,304	1,314	1,323	1,332
Visitor Arrivals (thousands)	6,823	6,517	6,814	7,074	7,377	7,680

Source: DBEDT, 2010

Table 2-4. Projection of Selected State and County Variables: 2007-2035.

	2015	2020	2025	2030	2035
Total Population (thousands)	1,367	1,432	1,492	1,547	1,598
Total Wage & Salary Jobs	661,112	702,000	736,400	769,800	802,200

Source: DBEDT, 2009b

2.6 References

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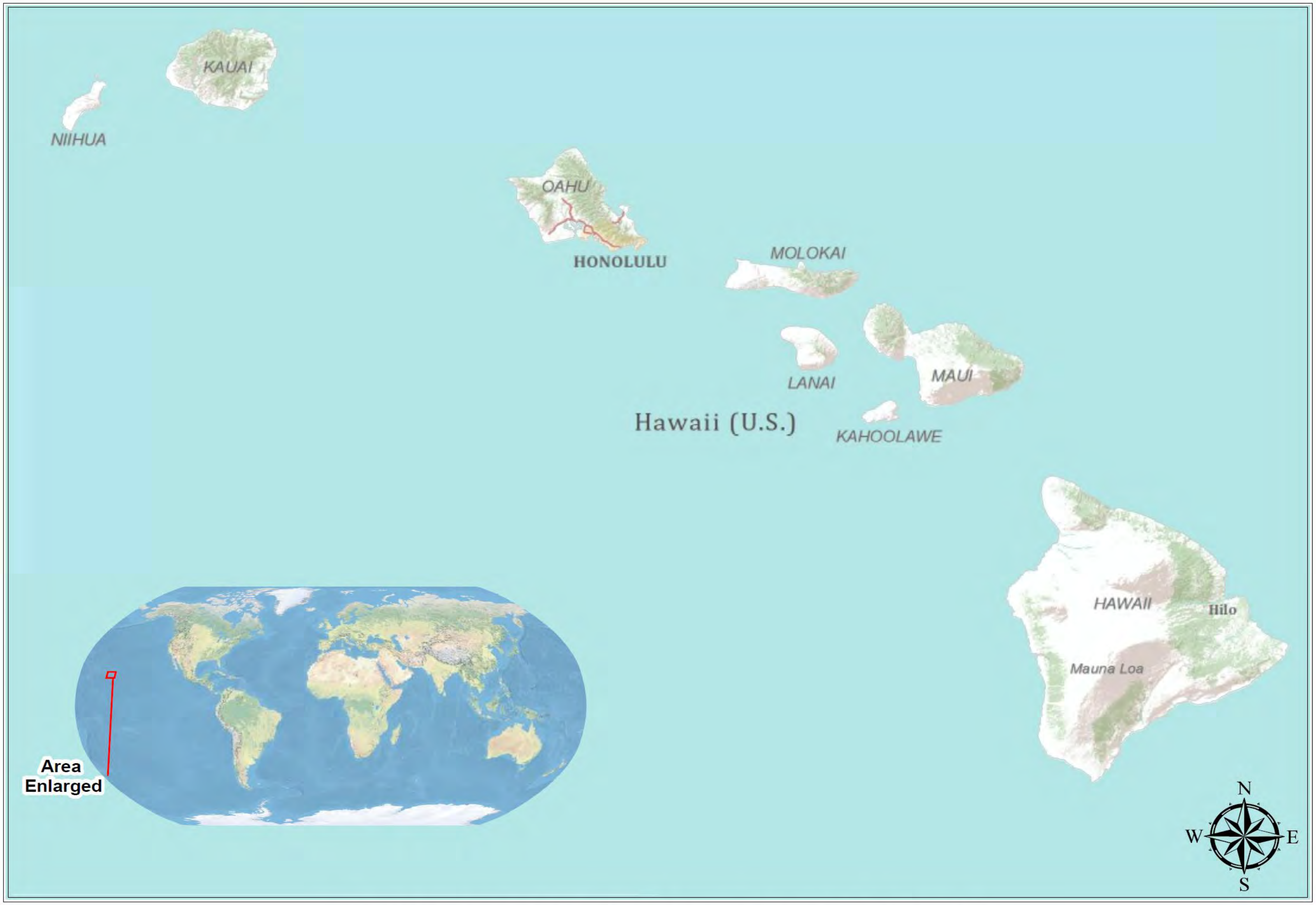
Figure 2-1: Principal Study Area



3.0 DEMAND SUMMARY

Forecasts of electricity demand have been made by DBEDT, HECO, MECO, HELCO, and KIUC.

3.1 Energy

In the State of Hawaii, electric power is generated on the six developed main islands: Oahu, Hawaii, Kauai, Maui, Lanai, and Molokai. Each of the islands has its own electrical system, and there are no interconnections of power transmission lines between the islands. There is currently an on-going feasibility study for an interisland undersea cable running between Oahu and Maui County.

Most of the State‟s power is generated by HEI and KIUC. In 2009, these utilities produced over 10,500 gigawatt hours (GWh), an increase of nearly 500 GWh over the past 20 years. Oahu is by far the largest user and producer of electricity due to the high population density and large tourism and military centers. Kauai, with only five percent of the State‟s population, used approximately 481 GWh in 2007 and 2008. As the smallest islands, Molokai and Lanai only used 33 and 29 GWh respectively in 2008 (DBEDT, 2010; HECO, 2005; HELCO, 2007; MECO, 2007).

As the economy slowed in 2008, electrical demand declined Statewide (Table 3-1). This trend is expected to change as the economy improves. HECO and MECO have projected growth to remain slow over the next 15 years (Table 3-2) (HECO, 2005; HELCO, 2007; MECO, 2007). Kauai‟s average is based on the Base Integrated Resource Plan (Black & Veatch 2008) projected growth scenario.

Table 3-1. Historical Electrical Demand, Islands of Oahu, Hawaii, Maui, and Kauai 2005-2009, GWh.

Year	Utility Company			
	HECO	HELCO	MECO	KIUC
2005	8,104.3	1,217.5	1,262.2	469.5
2006	8,104.9	1,252.8	1,276.9	475.9
2007	8,089.1	1,270.1	1,287.4	489.2
2008	7,950.6	1,244.8	1,247.4	479.1
2009	7,761.6	1,210.0	1,203.5	460.8

Table 3-2. Projected Electrical Demand, Islands of Oahu, Hawaii, Maui and Kauai: 2010-2015.

Year	Oahu		Hawaii		Maui		Kauai	
	Energy	Avg. Ann. Growth Rate	Energy	Avg. Ann. Growth Rate	Energy	Avg. Ann. Growth Rate	Energy	Avg. Ann. Growth Rate*
	GWh	Percent	GWh	Percent	GWh	Percent	GWh	Percent
2010	7,797	-	1,203	-	1,211	-	515	2.3
2011	7,858	0.78	1,216	1.15	1,241	2.48	526	2.3
2012	7,965	1.35	1,232	1.30	1,260	1.57	538	2.3
2013	8,081	1.46	1,253	1.67	1,278	1.41	564	2.3
2014	8,217	1.69	1,279	2.11	1,296	1.43	577	2.3
2015	8,326	1.32	1,307	2.13	1,318	1.70	590	2.3

The State uses imported petroleum for approximately 90 percent of its energy needs. In 2008, about 49 percent was consumed for transportation in the form of jet fuel and gasoline. The State‟s four oil-burning utilities generated 6,701 GWh of electricity in 2008, or 58.9 percent of the State‟s total electric power. The major generating equipment in HECO‟s system is designed to burn residual fuel oil. Other fossil fuels such as coal are more expensive due to shipping costs. One facility on Oahu produces 180 MW of power by burning coal, used tires, and motor oil (Pacific Business News, 2009; Namuo, 2004).

In the past, the State was more self-reliant – for example, in the 1980s, Kauai generated up to 40 percent of their energy from renewable bagasse and hydropower plants (Black and Veatch, 2005; DOE, 2010). Due to the decline of the sugar industry, this waste material is has limited availability for energy production, though it is still in use at Puunene Plant on Maui.

Alternative energy sources including biomass, wind, geothermal energy, refuse, and solar are being used to produce energy (Table 3-3). However, solar and wind are non-firm sources, as their output varies on the wind, clouds or daylight. These intermittent sources need to be balanced with firm sources to ensure that the balance of supply and demand in the power grid is not disrupted, or power surges and outages can occur. Firm sources of power are dispatchable, where output can be increased or decreased in a controlled, planned fashion, and include steam units, combustion turbines and diesel engines (HECO, 2007). The small electrical grids on each island can only handle a small percentage of non-firm energy (MECO, 2010). Once areas of the grid reach a certain threshold of non-firm energy, a reliability study must be performed at the expense of the residential or commercial proponent (Engle, 2011).

In a recent development, Hawaii‟s Public Utilities Commission (PUC) gave final approval in December 2010 for the Hawaiian Electric HECO to implement the rate setting method known as decoupling. Decoupling is a generic term used to describe a variety of methods intended to break the link between sales and revenue (National Action Plan for Energy Efficiency [NAPEE], 2007). Under the new system approved for HECO, the PUC approves a revenue level for the utility based on the services it is expected to provide for customers. This revenue is then adjusted based on actual sales to allow HECO to recover the costs of providing any additional services or a reduced volume of sales, without reaping additional profits from higher sales (HECO, 2010). Excess revenue above the pre-approved amount results in a credit to consumers. This system aims to remove the inherent conflict of interest for utilities to fulfill their responsibilities to shareholders while at the same time encouraging energy efficiency measures to reduce demand (and therefore profit) (NAPEE, 2007). In traditionally regulated energy markets, the more electricity a utility sells, the greater its profit, a concept known as the throughput incentive. This leads to perverse incentives to meet growing consumer demand and expand generation capacity. Decoupling removes the inherent disincentive towards energy efficiency by guaranteeing a fair revenue stream for the utility, regardless of sales. This guaranteed revenue can also allow the utility to pursue capital improvements such as renewable energy generation without worrying about declining revenues (Yonan, 2010).

Table 3-3. Renewable Energy, State of Hawaii 2010.

Energy Source	Hawaii		Kauai		Maui		Molokai		Oahu		Statewide*	
	MW	%	MW	%	MW	%	MW	%	MW	%	MW	%
Solar	4.8	2%	1	1%	1	0.38%	0	0	5.4	0.32%	12.2	1%
Biomass	0	0%	4	3%	16	6%	0	0	57	3%	77	3%
Hydropower	16	6%	8.9	7%	6.3	2%	0	0	0	0%	31.2	1%
Geothermal	30	11%	0	0%	0	0%	0	0	0	0%	30	1%
Wind	31	12%	0	0%	30	12%	0	0	0	0%	61	3%
Total % Renewable	81.8	30%	13.9	11%	53.3	21%	0	0%	62.4	4%	211.4	9%

Notes: Source: Strickler, 2010
*Lanai is not calculated.
MW - megawatt

3.2 Power Capacity

The majority of the State‟s power capacity is generated by the utility companies (Tables 3-4 and 3-5) and the Kauai Island Utility Cooperative. This accounts for 74 percent of capacity on Oahu, 61 percent on Hawaii and 84 percent on Maui. However, not all of this capacity is currently being used, particularly on Hawaii and Oahu. Private sources generate half of the energy on Hawaii and 40 percent on Oahu. Maui is the most reliant on MECO, only 15 percent of their capacity and energy derive from private sources (HECO, 2005; HELCO, 2007; MECO, 2007). As of 2009, Kauai has 114 megawatts (MW) of firm energy capacity, with a peak demand of 78 MW (KIUC, 2010).

Table 3-4. Historical Installed Capacity and Peak Load, Islands of Oahu, Hawaii, and Maui: 2005-2009.

Year	HECO		HELCO		MECO	
	Peak Load	Capacity	Peak Load	Capacity	Peak Load	Capacity

	MW	MW	MW	MW	MW	MW
2005	1,230	1,642.7	197	296.0	202.1	245.2
2006	1,265	1,685.5	201.3	301.5	206.4	290.8
2007	1,216	1,700.2	203.3	318.3	204.4	290.8
2008	1,186	1,700.2	198.2	320.3	194.4	292.8
2009	1,213	1,813.2	194.6	326.0	199.9	292.8

Notes:
Installed capacity includes firm and non-firm generating resources.

Table 3-5. Public Utilities Projected Peak Load and Generating Capacities, Islands of Oahu, Hawaii, and Maui: 2010-2015.

Year	HECO		HELCO		MECO	
	Peak Load	Capacity	Peak Load	Capacity	Peak Load	Capacity
	MW	MW	MW	MW	MW	MW
2010	1242	1783.7	195.0	323.7	197.8	292.8
2011	1249.8	1813.7	197.4	332.9	204.1	292.8
2012	1268.4	1813.7	199.8	354.4	206.5	292.8
2013	1291.4	1820.3	203.4	354.4	209.9	292.8
2014	1325.6	1820.3	207.1	340.0	212.7	292.8
2015	1346.6	1820.3	211.0	340.0	216.1	276.8

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4.0 HYDROPOWER & OCEAN ENERGY SYSTEMS

4.1 Hydropower Resources

Small hydropower systems are feasible in Hawaii, and have been in use for more than a century. Multiple perennial streams flow on the northern and windward side of the islands. Most of these watersheds are narrow, generating short streams with few, if any sizable tributaries. Stream flows are highly variable, and most of the surface runoff comes during the rainy winter months (November through March). These flashy narrow streams are not ideal for large-scale hydropower seen on the continental US. High land costs can also limit available acreage for large reservoirs, but small or mini systems can make good use locally of these resources.

Some of the highest streamflows are found in isolated valleys with limited access. However, many of these upland streams, particularly on Maui and Kauai, have been diverted to the central and coastal fields via extensive irrigation ditches. These systems offer access to potential resources, but the systems require maintenance and are facing legal challenges and changing water-use demands.

4.1.1 Existing Hydroelectric Plants

Hydropower facilities were originally installed in Hawaii a century ago, primarily to supplement the needs of agricultural activities. Several of these systems are still in operation. However, as large-scale plantations have decreased, the management of agricultural land and facilities have been abandoned or replaced by other private companies or public utilities. Based on the best reconnaissance-level information available, there are currently 23 operating hydropower plants located on Maui, Kauai, and Hawaii. However, since this count was based on a literature review, it is possible that small additional systems may be operational on private parcels (Table 4-1 and Figure 4-1). They have the capacity to generate a combined total of approximately 33 MW. Fourteen of the 23 have the capacity to generate less than 1 MW and are classified as “mini” hydropower. The remaining are classified as “small” with 1-10 MW rated output, with the exception of the Wailuku River Hydroelectric Plant (11 MW). As of 2010, hydropower accounted for 1 percent of the State‟s total electric power (Strickler, 2010).

All existing hydropower systems in the State of Hawaii operate as “run-of-the-river” plants, utilizing existing flows for electrical production. Hydraulic turbines do not perform well when actual flow is substantially different from the design flow. Due to the seasonal nature of rainfall existing turbines are not fully used year-round.

HELCO, a subsidiary of HECO, is the utility that serves the island of Hawaii. HELCO operates the Waiau and Puueo hydropower plants, both near Hilo on the Wailuku River. These plants have a combined capacity of 3.65 MW. The Hawaii Department of Water Supply (DWS) also has small generators and small in-line hydro generators at the Waimea Wastewater Treatment Plant, Parker Ranch, Kaloko and the Kahaluu Shaft. These generators use the existing flow to produce energy in order to pump water through their system. The excess energy can be sold to

HELCO. In addition to the HELCO and DWS systems, Hawaii also has privately owned hydropower plants. The Wailuku River Power Plant is managed by a private company and has the capacity to generate 11 MW (HECO, 2010e). Wenko Energy constructed a 7 kilowatt hydroelectric turbine on a stream in the „Ainako neighborhood of Hilo in 1983. Power is used for residential purposes with the excess being sold to HELCO (Pacific International Center for High Technology Research, 1997). The Hawi Agricultural & Energy Corporation provides water to small farmers on the northern tip of Hawaii. The ditch for this water also has a hydroelectric plant with two turbines, each rated at 175 kW, which has been in operation since 1984 (Pacific International Center for High Technology Research, 1997). A parcel of land near Hilo referred to as Hoowaiwai Farms has a 58 kW run-of-the-river hydroelectric generator; a recent search indicates that this land parcel is up for sale.

There are currently four hydropower plants on Maui. Pioneer Mill in Lahaina was recently upgraded and brought online as Makila Hydro. It was reopened in 2006, and can send 0.5 MW into MECO‟s grid as available. HC&S currently operates three small plants on the Wailoa Ditch network in Kaheka, Paia, and Hamakua. The plants have a combined capacity of 5.8 MW when there is available water.

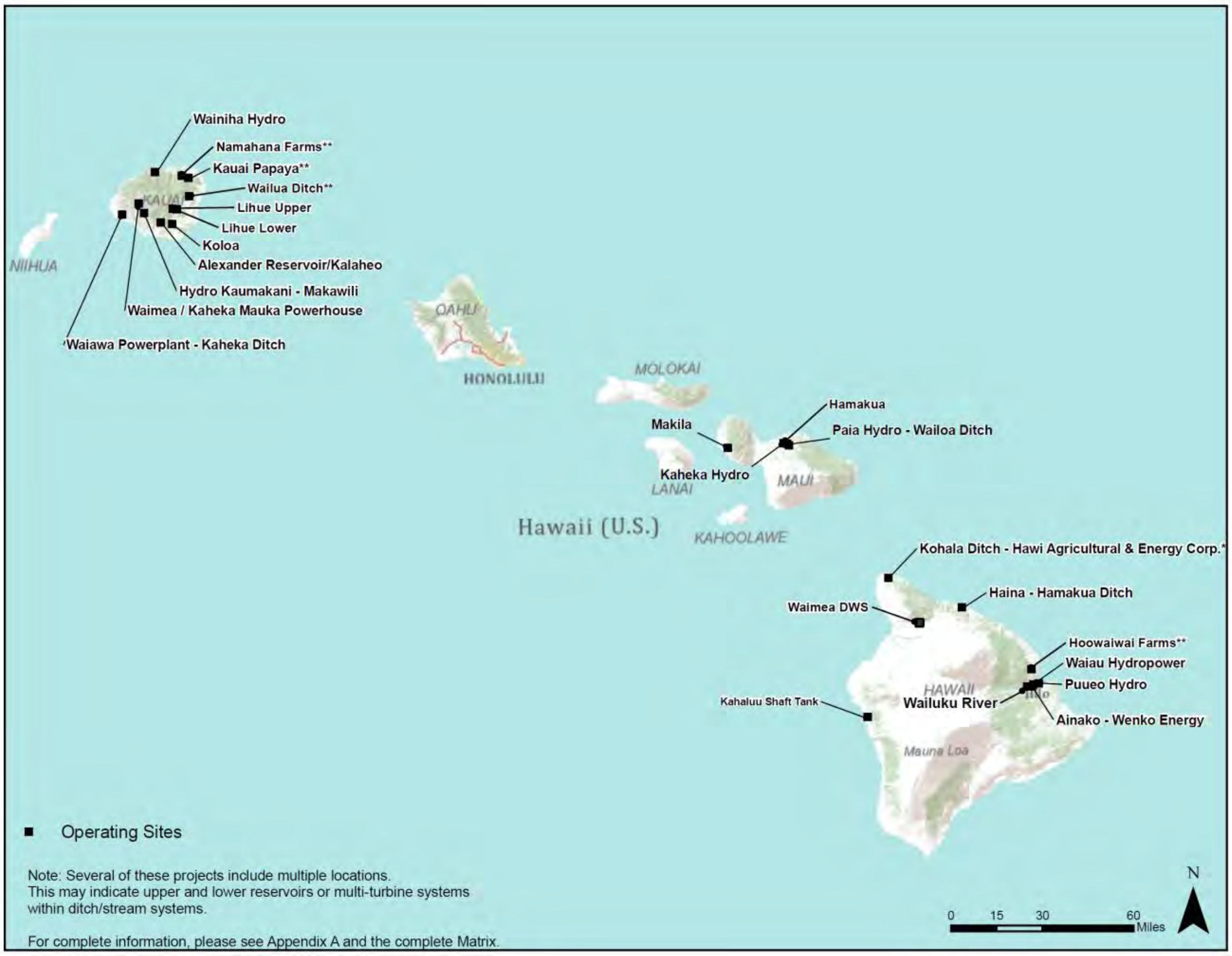
Due to the extensive streams and high rainfall, Kauai has 13 hydropower plants, the most of any island in the State of Hawaii. The island produces 8 percent of its energy from hydropower. Unlike Hawaii, all of Kauai‟s hydropower plants are listed in the “small” to “mini” category. Two of the plants are managed by the KIUC, two by the State Department of Agriculture‟s Agribusiness Development Corporation, and the remainder are privately managed for individual landowners or small developments (Fujimoto, 2010).

Table 4-1. Hydroelectric Power Plants in Operation.

Island	**Site ID**	**Name**	**Owner**	**MW**
Hawaii	160	Ainako**	Wenko Energy	0.007
Hawaii	158	Kohala Ditch**	Hawi Agricultural & Energy Corp	0.35
Hawaii	163	Hoowaiwai Farms**	Unknown	0.058
Hawaii	159	Wailuku River	Wailuku River Hydroelectric Power Co	11.0
Hawaii	143, 144	DWS In-Line Hydro	Hawaii County Department of Water Supply	0.16***
Hawaii	149	Waiau Hydro	HELCO	1.15
Hawaii	148	Puueo Hydro	HELCO	2.5
Kauai	155	Waimea Mauka	State ADC*	1.0
Kauai	150	Waiawa Hydro	State ADC*	0.5
Kauai	145	Lihue Lower	KIUC	0.6
Kauai	146	Lihue Upper	KIUC	0.8
Kauai	151	Wainiha Hydro	Kauai Coffee	4.0
Kauai	162	Kalaheo Hydro	Kauai Coffee	0.85
Kauai	157	Koloa Power	Green Energy Hydro	0.125
Kauai	165	Werheim‟s **	John Werheim	Unknown
Kauai	164	Kauai Papaya**	Kauai Papaya	0.014
Kauai	133	Namahana Farms**	Namahana Farms	0.005
Kauai	161	Wailua Ditch**	AMFAC Sugar-East	1.3
Kauai	156	Hydro Kaumakani	Gay & Robinson	1.25
Maui	147	Makila Hydro	Makila Hydro	0.5
Maui	153	Kaheka	HC & S	4.5
Maui	152	Paia	HC & S	0.9
Maui	154	Hamakua	HC & S	0.4

*State Dept of Agriculture: Agribusiness Development Corporation
** The continued operation of these plants could not be confirmed. See additional notes in Appendix A.
*** Consists of 4 facilities within the DWS distribution system. Only two facilities have sufficient information available for inclusion in Appendix A.

Figure 4-1. Existing Hydropower Plants Hawaii



4.1.1.1 Potential Hydropower in Hawaii

The islands of Hawaii, Maui, Molokai, Oahu, and Kauai have been identified as having potential hydropower resources by utilities, private developers and state and federal agencies. The smaller, drier, island of Lanai and Niihau have not been indentified for hydropower potential in this report. Although the State of Hawaii has abundant rainfall, it has limited resources for large-scale river based hydropower projects. The topography of the Hawaiian Islands lends itself to small streams with flows that fluctuate monthly, and are primarily appropriate for small hydropower plants.

Hydropower is one of the oldest sources of man-made energy, and systems have the benefit of known costs and longevity. Some hydropower systems have been operating for over 100 years in Hawaii. While these systems are no longer considered efficient by today‟s standards, this is a testament to the durability of the resource. Historically, hydropower projects have repeatedly attracted the interest of developers, but restrictions, development costs, and opposition have limited further development. Hydropower can also interfere with native fish spawning, create silted reservoirs, reduce flow to downstream channels, and alter coastlines due to a reduction in sediment loading.

Hydropower can be one of three major systems; 1) impoundment - this includes a dammed river with a reservoir and turbine; 2) diversion - run-of-the-river/ditch; and 3) pumped storage. These systems are also able to be combined. In Hawaii the small, narrow rivers limit large-scale impoundment projects; however, run-of-the river- and pumped storage have potential in Hawaii. Additional criteria and screening methods for determining the most viable options at specific locations are available in Chapter 5.

4.1.1.2 Run-of-the-River/Ditch

Run-of-the-river/ditch systems have the advantage that they can be constructed in small streams and ditches to power individual homes, businesses, and farms. These micro-hydropower plants can be constructed at relatively low cost, and several are already operating in the State. Larger scale run-of-the-river projects, such as Wailua on Kauai, run into considerable opposition due to their potential impacts on aquatic life, recreation, and cultural uses. Smaller scale projects, in particular irrigation ditch systems or existing water supply pipes, may be more acceptable in the State of Hawaii.

A recent law, State of Hawaii House Bill 1351 HD 2 SD1 CD 1 Act 122 (09) Relating to Private Agricultural Parks, allows agricultural users on contiguous State Land Use Agricultural-designated properties to build small-scale power plants and/or share energy costs on their land. The electricity cannot be sold to the utility or consumers outside of the agricultural cooperative. This would benefit farmers who could produce power from fossil fuel or renewable energy sources, including the use of falling water, biomass, wind, and solar energy, reducing their overall costs. Therefore, these small cooperatives would benefit from small run-of-the-river/ditch systems.

4.1.1.3 Potential Hydroelectric: Pumped Storage Generation

Pumped storage hydropower uses a reservoir system to store water upstream for peak demands. During minimum demand (9:00 p.m. to 4:00 a.m.), water from the lower reservoir can be pumped up to the upper reservoir using inexpensive off-peak power and released during peak demands (usually 5:00 a.m. to 9:00 p.m.) This guarantees that energy will be available when it is needed the most. In order to operate, the system needs adequate storage for the reservoirs, and a natural or engineered difference in elevation to generate power.

Pumped storage hydropower can use existing reservoirs and natural depressions for water storage, but transmission line construction and pumping costs must be factored into the plan. One solution for the pumping cost combines wind and stored hydroelectric plants, using wind energy to pump water back to the upper reservoir (Cedric D.O. Chong & Associates, Inc. [Chong], 2004). Pumped storage hydropower can operate as a “battery” for intermittent energy systems.

There are no pumped storage hydroelectric plants in the State of Hawaii. The State has many small reservoirs constructed for the now-waning agricultural industry. It would be feasible to use these sites, but the aging reservoirs would need to be updated/expanded and maintained to prevent flooding. Competition from irrigation users could also limit energy use if stream water needs to be used to replenish reservoirs due to evaporation and system loss. Pumped storage systems could also be combined with new drinking water reservoirs or storage tanks to provide primary or auxiliary water supplies.

4.2 Tidal/Current Power

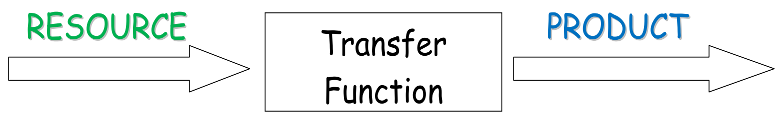
Tidal/current power works best in areas with large tidal swings in constrained areas. Typically, a wide barrage is built across a narrow mouth bay, estuary, or inlets with large tidal fluxes. The water is constrained to flow through a narrow opening which contains a turbine. Tidal fluxes in Hawaii are inadequate for this method. Other methods can install freestanding turbines in areas with 3.6-4.9 knot currents (DOE 2010). Current speeds in the State of Hawaii are below the recommended 2 m/s (4 knots) for energy production and tidal fluxes are too low. Large barrages could be built, but this would effectively serve as a breakwater and could be damaged by high waves, conflict with recreational users, and damage marine habitat. Overall, tidal/current resources in the State of Hawaii are poor (Electric Power Research Institute [EPRI], 2008).

4.3 Ocean Thermal Energy Conversion

OTEC involves technology that exploits the two enormous reservoirs of warm ocean surface water and deeper, colder waters which provide the heat source and the heat sink required for a heat engine to transform thermal energy into electricity. Optimal OTEC conditions require an annual average temperature difference of about 20° C between the warm water source (surface) and the cold water source (typically 1,000 m depth). This band runs roughly between the Tropic of Cancer and Tropic of Capricorn, placing the State of Hawaii in a region of high resource availability. This report provides ocean thermal resource information to assist developers of OTEC systems in site selection and the initiation of engineering designs. As the design progresses beyond the preliminary phase, additional site-specific measurements will likely be required.

As illustrated in the following flow diagram, temperature differences (ΔT) between standard water depths (20 meter [m] and 1000 m) were estimated with currently available high-resolution ocean models to quantify the thermal resource. Information about the transfer functions required to determine electricity production with specific OTEC systems can be found in the available literature (e.g., Vega, 2003).

Ocean Thermal Energy Conversion



RESOURCE	Transfer Function	PRODUCT
$\Delta T_{(°C)} = T_{20m} - T_{1000m}$	Public Domain	kWh; H_2O, AC
Ocean Volume	24/7	

The immense size of the ocean thermal resource and the baseload capability of OTEC systems represent very promising aspects of the technology for many island and coastal communities across tropical latitudes; potential benefits, however, must be weighed against high capital costs and the need for state-of-the-art engineering.

In the State of Hawaii, OTEC electricity generators can supply a large proportion of the electricity consumed throughout the year and at all times of the day. In addition to supplying energy, OTEC has the capability to meet other needs in the State of Hawaii. With the development of electric vehicles, OTEC could also supply electricity required to support land transportation. Domestic water needs can also be satisfied with desalinated water produced with OTEC systems. This renewable ocean resource is vast enough to meet additional electricity demand equivalent to several times present State consumption. OTEC is also attractive to energy utilities as it is considered a firm input to the electrical grid, and can therefore generate additional baseload capacity.

4.3.1 OTEC Background

The vertical temperature distribution in the open ocean can be simplistically described as consisting of two layers separated by an interface. The upper layer is warmed by the sun and mixed to depths of about 100 m by wave motion. The bottom layer consists of colder water formed at high latitudes. The interface or thermocline is sometimes marked by an abrupt change in temperature but more often the change is gradual. The temperature difference between the upper (warm) and bottom (cold) layers ranges from 10 degrees Celsius (°C) to 25 °C, with the higher values found in equatorial waters. This implies that there are two enormous reservoirs providing the heat source and the heat sink required for a heat engine. A practical application is found in a system (heat engine) designed to transform the thermal energy into electricity. This is referred to as OTEC for Ocean Thermal Energy Conversion.

Several techniques have been proposed to use this ocean thermal resource; however, at present it appears that only the closed cycle OTEC (CC-OTEC) and the open cycle OTEC (OC-OTEC) schemes have a solid foundation of theoretical as well as experimental work. In the CC-OTEC system, warm surface seawater and cold seawater are used to vaporize and condense a working fluid, such as anhydrous ammonia, which drives a turbine-generator in a closed loop producing electricity. In the OC-OTEC system seawater is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine-generator. Cold seawater is used to condense the steam after it has passed through the turbine. The OC-OTEC can, therefore, be configured to produce desalinated water as well as electricity (Vega, 2003). See Appendix C for examples of OTEC facilities.

An optimized CC-OTEC Plant with flow rates of 27.7 cubic meters per second [m^3/s] (28,450 kilograms per second [kg/s]), 4.5 °C cold water drawn from a depth of 1,000 m; and, 52.8 m^3/s (54,000 kg/s) 26 °C warm water drawn from a depth of about 20 m, would yield 16 MW at the generator terminals (P_{gross}) with 5.3 MW (P_{loss}) required to pump seawater (93 percent of total in-house electrical load) and the working fluid (e.g., anhydrous ammonia) through the plant. The net output (P_{net}) would, therefore, be 10.7 MW. To keep pumping losses at approximately 30 percent of P_{gross}, an average speed of less than 2 m/s is considered for the seawater flowing through the pipes transporting the seawater resource to the OTEC power block.

Table 4-2 provides P_{net} determined from the optimized heat and mass balance of this plant. The warm water temperature range is representative of conditions measured off Keahole Point in Hawaii with a daily annual average of 26 °C ranging from a 24 °C to 28 °C and the deep ocean water (1,000 m depth) essentially constant at 4.5 °C.

Table 4-2. P_{net} Determined from Optimized Heat and Mass Balance.

Tww /Tcw	**$\Delta T = T_{20m} - T_{1000m}$**	**$P_{net} = P_{gross} - P_{loss}$**
28 °C /4.5 °C	23.5 °C	14.1 MW
26 °C /4.5 °C	21.5 °C	10.7 MW
24 °C /4.5 °C	19.5 °C	7.3 MW

OTEC design parameters can be generalized as follows:

- In-house or parasitic electrical loads P_{loss} represent about 30 percent of P_{gross} , such that the exportable power (P_{net}) is about 70% of P_{gross};
- A cold water flow rate (Q_{cw}) of 2.6 m^3/s is required per MW_{net};
- The optimal warm water flow rate (Q_{ww}) is about 1.9 x Q_{cw}.

P_{gross} is proportional to the square of the temperature differential (ΔT) and the seawater flow rate, such that:

$$P_{net} = P_{gross} - P_{loss} = \beta Q_{cw}(\Delta T)^2 - P_{loss}$$

where, β and P_{loss} are system specific. Considering nominal values it can be shown that a 1 °C change in ΔT leads to a change of approximately 15 percent in P_{net}. This generalization compares favorably with the site specific heat and mass balance tabulated above.

In summary, in the absence of seawater flow rate constraints, extractable power can be characterized, as is done herein, by providing ΔT estimates.

4.3.2 Licensing and Permitting

The proposed location of an OTEC facility determines the various federal, state and county agencies and regulations that apply. In addition to the licenses and permits that must be secured from different agencies, the project must comply with several other applicable laws. The 1980 OTEC Act (OTECA) gives the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce the authority for licensing the construction and operation of commercial OTEC plants. After the promulgation of OTECA in 1981, licensing regulations were developed by NOAA, but in 1996 NOAA rescinded these regulations and eliminated its OTEC office because no applications had been received. NOAA is currently in the process of developing new licensing regulations. Under OTECA, NOAA is required to coordinate with coastal states and the United States Coast Guard as well as other Federal Agencies. An Environmental Impact Statement (EIS) would be required for each license. It is expected that the majority if not all federal, state and local requirements would be handled through the NOAA licensing process.

The original Act gave the Secretary of Energy the authority to exempt Test Plants from NOAA‟s licensing requirements. A Test Plant was defined as *"a test platform which will not operate as an OTEC facility or plantship after conclusion of the testing period"*. An EIS could be required if *"there are other permits to be obtained that are considered a major federal action"*.

4.3.3 Challenges and Barriers

OTEC systems are in the pre-commercial phase with several experimental projects already demonstrating that the technology is viable. Nonetheless, these projects lack the operational records required to attract commercial operators due to unknown potential costs. Adequately sized pilot projects must be implemented to obtain these records. The largest OTEC experimental system was sized at 0.25 MW, however, recent analysis indicates that a pilot plant sized at about 5 MW to 10 MW is required.

Major challenges to OTEC commercialization can be summarized as follows:

- How to overcome the lack of consistent funding that is required for industry to proceed from concept design to the required OTEC pre-commercial demonstration phase;

- While DBEDT is working on coordinating with other State and County agencies, the process of obtaining licenses and permits including the necessary EIS is still cumbersome. The process is project specific, expensive and estimated to require about two years for commercial projects;
- How to evolve into a situation represented by a one-stop-shop (as envisioned in the 1980 OTECA) where industry can process documentation stipulated for licensing and permitting under federal, state, city and county regulations avoiding duplicity, contradictory requirements and interdepartmental jurisdictional disputes.

Perhaps a lesson can be learned from the successful commercialization of wind energy (due to consistent government funding of pilot or pre-commercial projects) that led to appropriate and realistic determination of technical requirements and operational costs in Germany, Denmark, and Spain. In this context, by commercialization it is implied that equipment can be financed under terms that yield cost competitive electricity. This of course depends on specific conditions at each site. Presently, in the State of Hawaii cost competitiveness requires baseload electricity produced at less than about $0.20/ kWh.

4.3.4 Ocean Thermal Resources in the State of Hawaii: Introduction

Ocean thermal resources can be defined by ΔT, the ocean temperature differences between water depths of 20 m and 1000 m. Current methods of resource evaluation utilize high-resolution ocean models. The HYbrid Coordinate Ocean Model (HYCOM) + Naval Research Laboratory (NRL)‟s Coupled Ocean Data Assimilation (NCODA) (1/12°) model can be used, for example, to track changes on a daily basis over a wide area around the Hawaiian islands (e.g., 17°N to 24°N and 153°W to 162°W). An examination of numerical data over a time period of two years reveals interesting geographical patterns. It is found that average OTEC temperature differences are consistently higher (by about 1°C) west of the islands, whereas the amplitude of the yearly cycle globally decreases from north to south as expected. Better OTEC resources in the lee of the islands are attributed to the narrow eastward-flowing Hawaiian Lee Counter Current (HLCC).

Although there is no obvious flow rate constraint for OTEC, ΔT characterizes extractable OTEC power as long as the local thermal structure is preserved. There obviously are many issues that could lead to potential limits on seawater flow rates to prevent a degradation of available thermal resources; these include the avoidance of effluent re-entrainment for a single plant as well as the determination of local, regional and even worldwide power production limits as plant density increases. Such complex issues are beyond the scope of this report, and remain to be settled in spite of a substantial body of work. In what follows, environmentally available values of ΔT only are considered.

The stability of ΔT is an important issue for OTEC plant design and operation. 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 percent in P_{gross}.

Measurements during the operation of an experimental OTEC facility in Hawaii confirmed this point (Vega, 1995). From a net power perspective, matters are even more sensitive since the in-plant power consumption needed to run all pumps is quite large and represents about 30 percent of the reference („design") value of P_{gross}; hence, changes of the order of 10 percent in P_{gross} approximately translate in 15 percent variations in net power output, which is the true basis for the determination of electricity production costs (Nihous, 2007).

Having stressed the importance of ΔT for OTEC systems, this available thermal resource is defined in what follows as the temperature difference between 20 m and 1000 m water depths, with little loss of generality. This choice of depths reflects practical engineering constraints for typical tropical thermoclines and it is understood that more precise values would be the result of site-specific technical and economic optimization. The following section evaluates ΔT around the main Hawaiian Islands using high-resolution computer tools constrained by data assimilation.

The most recent, 2005 version of the World Ocean Atlas (WOA05) compiled by the National Ocean Data Center represents an extremely valuable source of objectively analyzed statistical fields, including ocean temperature (Locarnini et al., 2006). The data includes long-term historical averages of variables that have been determined from 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 4-3 shows a map of the average OTEC thermal resource ΔT from the WOA05 (1/4°) data base plotted with the Ocean Data View software (Schlitzer, 2009). Areas that are shallower than 1000 m are displayed in white to indicate that ΔT is not defined there with our choice of a reference cold-water depth of 1000 m. A restricted color palette, from 15°C to 25°C was used to enhance the practical OTEC range of temperature differences.

As can be seen on Figure 4-3, 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 the State of Hawaii, such as limited land availability, pristine reefs and valuable surf resources, would hardly affect OTEC.

Regarding OTEC thermal resources around the main Hawaiian Islands, a closer look at the WOA05 data shown in Figure 4-4 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. HYCOM, subject to routine data assimilation via the NCODA protocol, allows daily assessments of ocean variables at a spatial resolution of 1/12° latitude by 1/12° longitude across the water column (Chassignet et al., 2009). Although the output from the model is given as a snapshot in time („midnight"), the time resolution for wind forcing is three hours while heat fluxes are input as daily averages; hence, the diurnal cycle is not resolved and model output essentially should be interpreted as daily averages; for numerical stability purposes, however, a time step of four minutes is implemented. This data can be downloaded via public-domain servers such as http://ferret.pmel.noaa.gov/LAS;

ongoing calculations also have a five-day predictive window (providing, in essence, an „ocean forecast").

The development of HYCOM is the result of collaborative efforts among the University of Miami, NRL, and the Los Alamos National Laboratory, as part of the multi-institutional consortium funded in 1999 to develop and evaluate a data assimilative hybrid isopycnal-sigma pressure (generalized) coordinate ocean model. NCODA is an oceanographic version of the multivariate optimum interpolation technique widely used in operational atmospheric forecasting systems. The ocean analysis variables in NCODA are temperature, salinity, dynamic height and velocity. NCODA assimilates available operational sources of ocean observations. This includes along-track satellite altimeter observations, multi-channel sea surface temperature and in situ observations of sea surface temperature and sea surface salinity, subsurface temperature and salinity profiles from bathythermograph profiling floats, and sea ice concentration.

Figure 4-4 shows the average available OTEC thermal resource (ΔT) over a period of two years, from July 1, 2007 through June 30, 2009, for which 731 files of daily data were processed. Although overall geographic variations in the selected area covering 7° of latitude and 9° of longitude are within 2°C, a prominent wedge can be seen; its apex roughly lies at the eastern tip of Hawaii, 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 (Flament et al., 1996). The westward flowing North Equatorial Current forks at Hawaii 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°30'N, with the narrow 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.

The ability of HYCOM + NCODA to resolve the time variability of ΔT on a daily basis is demonstrated in supplementary material (Appendix B). The data is presented in daily-map for the months of August 2008 (31 plots) and February 2009 (28 plots). The performance of the model in tracking fronts and eddies can easily be appreciated. In the lee of Hawaii, for example, mesoscale eddies are frequently spun; the effect of strong cold-core (cyclonic) events are quite visible on the 14^{th} and 18^{th} of August 2008.

Aside from the average value $<\Delta T>$, it is important to have a sense of the long-term time variability of the OTEC thermal resource. One anticipates a dominant yearly periodicity. If the signal is represented as an equivalent sine function, its amplitude A would be equal to the standard deviation of the signal multiplied by $2^{1/2}$. Figure 4-5 shows the distribution of A calculated from the HYCOM data over the same two-year period as in Figure 4-4. The result indicates amplitudes of the order of 2°C with a general decrease from North to South. Hence, the geographic pattern observed for $<\Delta T>$ does not extend to A. It should be noted that by definition, the average of the square of ΔT is equal to the square of $<\Delta T>$ plus the variance of the signal, i.e. $\langle \Delta T^2 \rangle = \langle \Delta T \rangle^2 + 0.5A^2$. Therefore, for given OTEC design and seawater flow rates, the average gross power P_{gross} is known from $\langle \Delta T \rangle$ and A.

Nearly every month since October 1988, data has been collected for the Hawaii Ocean Time-series (HOT) program. These include observations of the hydrography, chemistry and biology of the water column at the deep-water Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22° 45'N, 158° 00'W), 100 km north of Oahu. Other locations are routinely sampled en route to Station ALOHA, such as Station 1 off of Kahe Point, Oahu (21° 20.6'N, 158° 16.4'W). HOT data is readily accessible through the internet-based Hawaii Ocean Time-series Data Organization and Graphical System (Karl and Lucas, 1996). Figures 4-6 and 4-7 display ΔT determined from HOT measurements over a period of 20 years. Expected overall yearly cycles with amplitudes of the order of 2°C are confirmed and no trend is apparent. ΔT at Station 1 is roughly 1°C higher. While the difference in latitude might suggest greater values of ΔT further south, Figure 4-4 reveals that such a perception would be simplistic. Figures 4-8 and 4-9 illustrate the adequacy of the data assimilation protocol NCODA for HYCOM by simultaneously plotting available computed values and HOT data.

4.3.5 Ocean Thermal Resources in the State of Hawaii: Conclusion

Ocean thermal resources have been estimated herein with currently available high-resolution ocean models. Historical averages of the temperature difference ΔT between standard water depths (20 m and 1000 m) were determined from the WOA05 data base at a spatial resolution of one-quarter degree latitude by one-quarter degree longitude. Subsequently, the state-of-the-art HYCOM + NCODA (1/12°) model was used to track changes on a daily basis over a wide area (e.g., 17°N to 24°N and 153°W to 162°W).

An examination of numerical data over a time period of two years revealed that average temperature differences are consistently higher (by about 1°C) west of the islands, whereas the amplitude of the yearly cycle globally decreases from north to south. The existence of a wedge of higher value ocean thermal resources in the lee of the archipelago is attributed to the influence of the narrow eastward flowing HLCC. Long-term measurements taken over two decades for the HOT program at two selected locations were also evaluated to give a longer perspective. This data is used to illustrate the adequacy of the data assimilation protocol NCODA for the high-resolution HYCOM calculations.

The immense size of the ocean thermal resource as well as the baseload capability of OTEC systems remain very promising aspects of the technology for many island and coastal communities across tropical latitudes; potential benefits, however, must be weighed against high capital costs and the need for state-of-the-art engineering. Instead, it was demonstrated here that advanced models can reveal regional variability in OTEC temperature resources that would have a significant long-term impact (of the order of 10 to 15 percent per 1°C) on the cost effectiveness of given OTEC power plants (all other things being equal).

4.3.6 OTEC in the State of Hawaii: Previous Work

The assessment of the ocean thermal resource off the State of Hawaii indicates that OTEC plants could supply a considerable proportion of the electricity and potable water consumed in the State. 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 United States Insular Territories (e.g., American Samoa, Guam, Northern Mariana Islands, Virgin Islands and Puerto Rico).

Over a decade ago, the detailed evaluation of economic feasibility and financial viability of OTEC revealed that in the State of Hawaii plants would have to be sized at about 50 to 100 MW to produce baseload electricity at a price corresponding to the utility‟s avoided cost. Smaller plants were not cost effective in the State of Hawaii. It was also concluded that, although experimental work with relatively small plants had unambiguously demonstrated continuous production of electricity (Steinbach, 1982; Vega, 1995) and desalinated water (Vega, 1995), it would be necessary to build a pre-commercial plant sized around 5 MW to establish the operational record required to secure financing for the commercial size plants. The pre-commercial plant would produce relatively high cost electricity and desalinated water such that support funding was required from the federal and state governments. Unfortunately, development did not proceed beyond experimental plant sized at less than 0.25 MW (Vega, 2003).

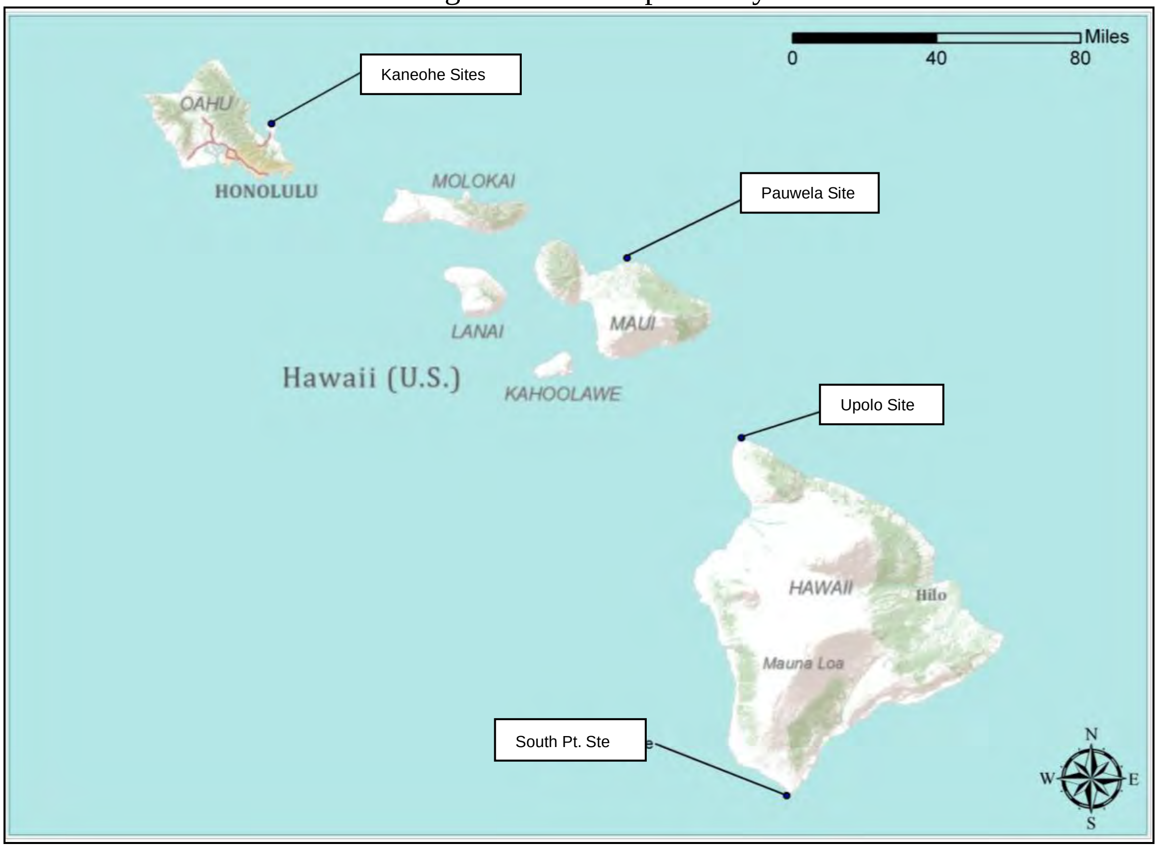
In the mid-1990s an engineering team in the State of Hawaii designed a 5 MW pre-commercial plant and made the information available in the public domain (Vega and Nihous, 1994). However, because the price of petroleum fuels was relatively low and fossil fuels were considered to be abundantly available, government funding for the pre-commercial plant could not be obtained. Direct extrapolation from the experimental plants to commercial sizes, bypassing the pre-commercial stage, would have required a leap of faith with high technical and economic risks that no financial institution was willing to take.

4.3.7 OTEC in the State of Hawaii: Present Status

Given that world oil reserves (almost equal to 1400 billion barrels) can satisfy world-wide demand (greater than 30 billion barrels per year) for at most another 50 years, it seems sensible to envision marine renewable energy resources as additional alternatives to our oil-based economy. It has been postulated that, for example, the United States should begin to implement the first generation of OTEC plantships providing electricity, via submarine power cables, to shore stations, followed, in about 20 years, with OTEC factories deployed along equatorial waters producing, for example, ammonia and hydrogen as the fuels that would support the post-petroleum era (NOAA, 2010).

The resource exploited by OTEC is ample enough to generate a large proportion of the electricity presently consumed in the State of Hawaii. What is pending, however, are realistic determinations of the costs and the potential global environmental impact of OTEC plants and this can only be accomplished by deploying and subsequently monitoring operations with first generation plants.

Figure 4-2: Principal Study Area



4.3.8 OTEC Economics

An analytical model is available to assess scenarios under which OTEC might be competitive with conventional technologies (Vega, 1992). First, the capital cost for OTEC plants, expressed in dollars per kilowatt ($/kW), is estimated. Subsequently, the relative cost of producing electricity ($/kWh) with OTEC, offset by the desalinated water production revenue, is equated to the fuel cost of electricity produced with conventional techniques to determine the scenarios (i.e., fuel cost and cost of fresh water production) under which OTEC could be competitive. For each scenario, the cost of desalinated water produced from seawater via reverse osmosis is estimated to set the upper limit of the OTEC water production credit. No attempt is made at speculating about the future cost of fossil fuels. It is simply stated that if a location is represented by one of the scenarios, OTEC could be competitive.

Two distinct markets were previously identified: (i) industrialized nations; and, (ii) small island developing states (SIDS) with modest needs for power and fresh water. OC-OTEC plants could be sized at 1MW to 10 MW, and 450 thousand to 9.2 million gallons of fresh water per day (1,700 to 35,000 cubic meters per day) to meet the needs of developing communities with populations ranging from 4,500 to 100,000 residents. This range encompasses the majority of SIDS throughout the world.

Floating plants of at least 50 MW capacity would be required for the industrialized nations. These would be moored or dynamically positioned a few kilometers from land, transmitting the electricity to shore via submarine power cables. The moored vessel could also house an OC-OTEC plant and transport the desalinated water produced via flexible pipes. It was noted that the State of Hawaii could be independent; of conventional fuels for the production of electricity, using 50 MW to 100 MW floating plants for the larger communities in Oahu, Kauai, Maui, and the Island of Hawaii.

The 1992 report also provided estimates for land-based 1 MW open cycle plants with and without second-stage desalinated water production as well as a plant with a system including the use of 90 kg/s of 6°C cold seawater as the chiller fluid for a standard air-conditioning unit supporting a 300 ton load (approximately 300 rooms). These plants would be designed utilizing the state-of-the-art, bottom-mounted cold water pipe technology (Nihous et al., 1989). The report also included cost estimates for other plants ranging from 10 to 100 MW. These have been extrapolated to present day costs and are included herein.

It was also established that OTEC–based, mariculture operations and air-conditioning systems could only make use of a small amount of the seawater available; and therefore, could only impact small plants. The use of energy carriers (e.g., hydrogen or ammonia) to transport OTEC energy generated in floating plants, drifting in tropical waters away from land, was determined to be technically feasible but requiring increases in the cost of fossil fuels of at least an order of magnitude (to about $400/barrel) to be cost effective.

Presently, the external costs of energy production and consumption are not included in the determination of the charges to the consumer. Considering all stages of generation, from initial fuel extraction to plant decommissioning, it has been determined that no energy technology is completely environmentally benign. The net social costs of the different methods of energy production continue to be a topic under study. Estimates of costs due to: corrosion, health impacts, crop losses, radioactive waste, military expenditures, employment loss, subsidies (tax credits and research funding for present technologies) are found in the literature. The range of estimates is equivalent to adding from $80/barrel to over $400/barrel. Accounting for these externalities might eventually help the development and expand the applicability of OTEC, but in the interim the scenarios that were identified in the original 1992 report should be considered again.

Industry did not take advantage of OTEC potential because in the 1990"s the prices of oil fuels and coal were such that conventional power plants produced cost-effective electricity (excluding externalities). Moreover, the power industry could only invest in power plants whose designs were based on similar plants with an operational record. It was concluded that before OTEC could be commercialized, a prototypical plant must be built and operated to obtain the information required to design commercial systems and to gain the confidence of the financial community and industry. Conventional power plants pollute the environment more than an OTEC plant would and the fuel for OTEC is vast and free, as long as the sun heats the oceans; however, it is futile to use these arguments to convince the financial community to invest in an OTEC plant without operational records.

4.3.9 OTEC Capital Costs

Capital cost archival information, documented in Economics of Ocean Thermal Energy Conversion in 1992, was converted to present day costs using the USA 20-year average for equipment price-index inflation. In addition, current technical specifications for 10, 50, and 100 MW OTEC plants were used to solicit budgetary quotes. Estimates are summarized in Table 4-3 and in Figure 4-10.

Table 4-3. First Generation OTEC Plant Capital Cost Estimates.

Nominal Plant Size (MW-net)	**Installed Capital Cost ($/kW)**	**Land/Floater (L/F)**	**Source (Extrapolated)**
1.4	41,562	L	Vega, 1992
5	22,812	L	Jim Wenzel, 1995
5.3	35,237	F	Vega et al., 1994
10	24,071	L	Vega, 1992
10	18,600	F	This report
35	12,000	F	This report
50	11,072	F	Vega, 1992
53.5	8,430	F	This report
100	7,900	F	This report

These estimates are applicable for equipment purchased in the United States, Europe or Japan and with installation by USA firms. Deployment and installation costs are included. One might speculate, based on the implementation of similar technologies, that later generation designs will reach cost reductions of as much as 30 percent. However, the premise herein is to indicate that first generation plants can be cost effective under certain scenarios if the cost estimates presented here are met.

Figure 4-10 illustrates that OTEC capital cost ($/kW) is a strong function of plant size (MW). For convenience and future reference a least-squares curve fit is provided:

$$CC\ (\$/kW) = 53{,}000 \times MW^{-0.42}$$

In the State of Hawaii a 100 MW OTEC plant, for example, could be housed in a floating platform[1] stationed less than 10 km offshore, and would have the capability of delivering 800 million kWh to the electrical grid every year. Budgetary quotes from potential equipment suppliers indicate that the installed cost would be $790 million using state-of-the-art components. The annual costs for operations and maintenance are estimated at $40 million such that under realistic financing terms (15 year loan at 8 percent annual interest and 3 percent average annual inflation) electricity could be produced at a levelized cost of less than $0.18/kWh such that a realistic power-purchase-agreement from the utility at around $0.20/kWh would

1Nominal dimensions: 250 m (length) x 60 m (beam) x 28 m (height) with an operating draft of 20 m.

include ample return on investment[2]. It is interesting to note that if the plant could be funded via government bonds at a realistic rate of 4.2 percent over 20 years the cost of energy would be $0.14/kWh (Figure 4-11).

4.4 Wave Energy Conversion

This report provides wave resource information required to select coastal segments (e.g., see Table 4-4 and Figure 4-12) for specific wave-energy-conversion (WEC) technology and to initiate engineering design incorporating production estimates and the wave loading that devices must survive during their life cycle. As the design progresses beyond the preliminary stages, site-specific wave resource measurements will be required.

2 Presently, the electrical utilities in the State of Hawaii purchase baseload capacity for as much as $0.20/kWh.

Table 4-4. Coastal Segments Exposed to Predominant Wave Climates.

Coastal Segment	Description	Length
KAUAI-1	Nahili Point to Makaha Point	12 km
KAUAI-2	Makaha Point to Haena	18 km
KAUAI-3	Haena to Kepuhi Point	23 km
KAUAI-4	Kepuhi Point to Kahala Point	12 km
	Kauai Subtotal	*65 km*
OAHU-1	Kaena Point to Kaiaka Point	18 km
OAHU-2	Kaiaka Point to 4 km southwest of Kahuku Point	17 km
OAHU-3	Kahuku Point vicinity	8 km
OAHU-4	4 km southeast of Kahuku Point to Pyramid Rock	34 km
OAHU-5	Pyramid Rock to Moku Manu Island	4 km
OAHU-6	Moku Manu Island to Makapuu Point	20 km
	Oahu Subtotal	*101 km*
MOLOKAI-1	Ilio Point to 6 km southwest of Kahiu Point	26 km
MOLOKAI-2	West coast of Kalaupapa Peninsula	6 km
MOLOKAI-3	East coast of Kalaupapa Peninsula	6 km
MOLOKAI-4	6 km southeast of Kahiu Point to Lamaloa Head	20 km
	Molokai Subtotal	*58 km*
MAUI-1	Nakalele Point to Kahului	18 km
MAUI-2	Kahului to Opana Point	20 km
MAUI-3	Opana Point to Pukaulua Point	34 km
	Maui Subtotal	*72 km*
HAWAII-1	Upolu Point to Kukuihaele	33 km
HAWAII-2	Kukuihaele to Laupahoehoe Point	36 km
HAWAII-3	Laupahoehoe Point to Pepeekeo Point	23 km
HAWAII-4	Pepeekeo Point to Hilo Bay	12 km
HAWAII-5	Hilo Bay to Leleiwi Point	8 km
HAWAII-6	Leleiwi Point to 3 km northwest of Kaloli Point	12 km
HAWAII-7	3 km northwest of Kaloli Point to Cape Kumukahi	16 km
	Hawaii Subtotal	*140km*
	State Total	436 km

Source: Hagerman, 1992

The wave power flux (P_o), through a vertical plane of unit width perpendicular to the wave propagation direction is used to represent the resource. The spectral parameters tabulated in Appendix B are used to quantify estimates of P_o (kW/m). Designers use their proprietary transfer function (wave power matrix) to estimate daily, monthly and annual electricity production for specific sites. In addition, they incorporate the extreme events into their survivability design.

Discussion of the proprietary transfer functions, required to determine electricity production with specific devices, is beyond the scope of this report.

4.4.1 Background: Wave Power Conversion

This report was conceived as a wave power resource report which would identify potential areas for development. Currently, there are only two operating devices in the world transmitting electricity to distribution lines (i.e., utility interconnected): the 500 kW shore based oscillating-water-column (OWC) Limpet in Islay, Scotland; and, the 40 kW OPT heaving buoy off Kaneohe Bay, Oahu.

There are numerous WEC concepts discussed in the literature. These range from simple sketches to reports of at-sea tests. Some are shoreline based[3] others seabed mounted or moored in depths of less than 70 m. According to their directional characteristics they can be classified as point absorbers, terminators and attenuators. Point absorbers have dimensions that are small relative to ocean wave lengths and are usually axis-symmetric[4]. The principal axis of terminators is aligned perpendicular to the direction of wave propagation and in the case of attenuators[5], parallel to the direction of propagation. These have dimensions in the order of the wave lengths.

WECs currently applicable in the State of Hawaii can be categorized under two operating principles: OWC and wave-activated. The OWC devices use wave action to expand and compress air above a water column, to rotate an air turbine-generator (e.g., the Oceanlinx project, planned for installation off Pauwela, Maui by 2012, sized at less than 2.7 MW). The wave-activated devices oscillate due to wave action relative to a fixed part of the device and use a hydraulic system to turn a motor-generator; or a linear generator that generates electricity by moving a magnetic assembly within a coil; or direct rack and pinion mechanical coupling. See Appendix C for examples of WEC systems.

4.4.2 Licensing and Permitting

The proposed location of the WEC device determines the various agencies and regulations that apply. In general, one must consider the Federal Energy Regulatory Commission (FERC), the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), formerly Minerals Management Service (MMS) of the Department of the Interior (DOI), the USACE, the Environmental Protection Agency, the NOAA of the Department of Commerce, the United States Coast Guard and various state, county and city agencies. In addition to the licenses and permits that must be secured from different agencies, the project must comply with several other applicable laws.

Independent of location, licensing of WEC devices is the responsibility of FERC. In the State of Hawaii, the State Government has jurisdiction up to 3 nautical miles (nm) offshore. The Federal Government has jurisdiction in the Outer-Continental-Shelf (OCS) extending between the outer limits of State waters and the inner boundary of international waters, which begins

3The 500 kW OWC Limpet (Land Installed Marine Powered Energy Transformer) has been operational since 2000.
4 The 40 kW OPT heaving buoy currently under testing in Kaneohe Bay, Oahu, State of Hawaii.
5 The 3rd generation Pelamis (~ 500 kW) is scheduled for deployment at the European Marine Energy Center (EMEC) in 2010.

approximately 200 nm offshore. BOEMRE defines the OCS as including submerged lands, subsoil, and seabed.

For wave energy projects to be located on the OCS, BOEMRE will issue *leases, easements, and rights-of-way* and will conduct any necessary environmental reviews including those under the National Environmental Policy Act (NEPA). FERC has exclusive jurisdiction to issue *licenses* and exemptions for the *construction and operation* of wave energy projects and will conduct any necessary analyses, including those under NEPA, related to those actions. FERC, however, will not issue a license or exemption until the applicant has first obtained a lease, easement, or right-of-way from BOEMRE. Moreover, BOEMRE and FERC can choose to become a cooperating agency in the preparation of any environmental document required under either process. This does not preclude other DOI agencies (e.g., United States Fish and Wildlife Service, the National Park Service, and the Bureau of Indian Affairs) from intervening. This situation could lead to the requirement of two distinct EIS (although similar in content): one for BOEMRE and subsequently another for FERC.

For wave energy projects located in State waters, BOEMRE has no jurisdiction, licenses would still be issued by FERC and all other requirements would be under State, county and city rules.

Renewable energy permitting is being coordinated by DBEDT to streamline the process. DBEDT is in the process of implementing, fast-tracked, online permitting for renewable energy projects.

4.4.3 Challenges and Barriers

WEC systems are in the pre-commercial phase with several experimental projects having already demonstrated ability to convert wave energy into electrical energy but lacking the operational records required to proceed into commercialization. Adequately sized pilot or pre-commercial projects must be implemented to obtain these long-term operational records. In addition, validation of the performance and survivability of specific WECs under harsh ocean conditions is required to gain commercial acceptance.

There are some WEC designs with appropriate operational records although they are only cost competitive under limited conditions. A validated concept is given by, for example, incorporating the OWC LIMPET into new breakwaters. This concept may become practical if breakwaters in suitable locations were upgraded or constructed.

Major challenges can be summarized as follows:

- No first generation WEC system exists that would be cost competitive in the State of Hawaii;
- How to overcome the lack of consistent funding that is required for industry to proceed from concept design to the required pre-commercial demonstration phase;
- DBEDT, DLNR, and the Counties are currently working on streamlining the burdensome, although necessary, process of obtaining licenses and permits including the

necessary EIS, though a joint system has not been finalized. Cooperation between these groups is important as the process is project specific, expensive and requiring about three years for commercial projects;

- How to evolve into a situation represented by a one-stop-shop where industry can process all documentation stipulated for licensing & permitting under federal, State, city and county regulations avoiding duplicity, contradictory requirements and interdepartmental jurisdictional disputes.

- The issues of resource seasonal variability, siting considerations and the corresponding nearshore ocean area requirements pose a daunting challenge to the implementation of wave farms in the State of Hawaii

Wave energy commercialization would require the same inputs as specified for OTEC above. Commercialization would require financing under terms that yield cost competitive electricity, dependent upon site-specific conditions. Present cost-competitiveness for intermittent resources, non dispatchable electricity in the State of Hawaii is less than t $0.12/kWh.

4.4.4 Wave Power Resources: Previous Work

The useful references available at the onset of this project were:

1. *Ocean Wave Energy: Current Status and Future Perspectives* (Cruz, 2008). Although not state specific, this book provides the most comprehensive reference for aspects of wave energy conversion.

2. *Wave Energy Resources and Economic Assessment for the State of Hawaii* (Hagerman, 1992). The main conclusion can be stated as follows: *"Except for Oahu, where electricity demand is comparable to 2/3 of the resource base, wave energy can be withdrawn at very low levels and still make a <u>reasonable contribution</u> to energy needs in the State of Hawaii".* This is a seminal report and remains the main reference for estimates of the wave resource as well as the identification of the coastal segments exposed to the relatively highest resource. Unfortunately, the author did not address siting issues and resource seasonal variability.

   In the report, the average wave power fluxes (kW/m) along coastal segments (Table 4-4) of the islands of Kauai, Oahu, Molokai, Maui and Hawaii (Big Island) were estimated using ocean data available as of 1991 (Figure 4-12). Hagerman estimated that annual averages of wave power flux along the 80 m depth ranged from 10 to 15 kW/m. However, because the island shelves are so narrow, even this outer shelf depth contour can be closely sheltered by adjacent headlands or peninsulas, which is the case at Kailua, Oahu, and in the vicinity of Hilo. At these locations, wave power density along the 80 m depth contour ranges from 7 to 9 kW/m. Refraction and shoaling, however, significantly reduce wave power densities in shallow water. For example, along the 5 m depth contour, they were assumed to be roughly 20 percent lower than along the 80 m contour (Figure 4-12).

3. *E2I EPRI Survey and Characterization of Potential Offshore Wave Energy Sites in Hawaii* (EPRI, 2004). This is one of several useful reports prepared by EPRI and available at http://oceanenergy.epri.com/. The information about WEC devices provided in this report remains current. The wave power resources discussed are from the 1992 Hagerman Report. The main conclusion is: *"In an annual basis, WEC devices could generate more than 30% of the electricity presently consumed in the State."* Unfortunately, although the estimate is theoretically correct, this report does not address siting and seasonal variability issues.

4.4.5 Wave Farms: Siting and Ocean Area Requirements

A wave farm would consist of arrays of WEC devices spaced such that interactions between components are minimized. For example, about 7 km^2 of ocean area would be required[6] for 100 x 1 MW or 200 x 0.5 MW WECs arranged into a 100 MW wave farm. For comparison consider that a 100 MW offshore wind farm would require about 12 km^2.

Multiplying the average wave power flux along the 80 m depth contour (Figure 4-12) by the length of each coastal segment (Table 4-4) and by the number of hours in a year, and summing the results for all segments, gives an estimate of the annual wave energy resource for a particular island. Estimated wave energy resources (GWh/year) from the 1992 Hagerman report are given in Table 4-5.

Table 4-5. Theoretical Wave Power Contribution for the Generation of Electricity.

Island	**Wave Energy Resource (GWh/year)**	**Extractable Energy with a Wave-to-Electricity Converter (GWh/year) CF:15%**	**Required Wave Farm Name Plate (MW) / Wave Farm Ocean Area Requirement (km^2)**	**2007 Electricity Consumption (GWh/year)**	**Potential Wave Energy Contribution to Electricity Consumption**
Hawaii	12,900	1,940	1476 MW/103 km^2	1,259	150%
Maui	8,200	1,230	936/66	1,385	90%
Oahu	9,600	1,440	1096/77	8,293	17%
Kauai	7,200	1,080	822/58	266	400%
Molokai	6,800	1,020	776/54	39	2,600%
Totals		6,710		11,242	60%

Given the Hawaiian wave resource and efficiencies achieved with viable WEC devices, an all-encompassing global capacity factor[7] of about 15 percent is assumed. As tabulated in the third column of Table 4-5, this factor is used to estimate the amount of electricity that could be generated in an annual basis. The cumulative nameplate (MW) and the ocean area that would be required to accommodate the arrays are given in the fourth column. It must be emphasized that

6 Say 11 km (6.7 miles) along the coastline x 0.6 km (0.4 miles) away from coastline or other equivalent rectangular area.

7 Number of hours per year, expressed as percent of 8760 hours, which a WEC array operates at the rated power capacity (nameplate).

this analysis ignores seasonal resource variability and assumes that all coastal segments are utilized. This is not feasible because of conflicting ocean uses and because some of these segments would be off limits for the installation of WECs.

As indicated in Table 4-5, the 2007 electricity demand in the islands of Hawaii, Kauai and Molokai could have been generated with WEC farms deployed in all coastal segments. In the case of Maui the analysis indicates as much as 90 percent of the demand could have been generated and for Oahu less than 17 percent. This is done on an annual basis without matching the resource to the demand assuming that all electricity generated can be used when produced or somehow stored for later use. As shown in later sections of this report, the resource seasonal variability is such that during winter months, electricity generation could be as much as six to seven times more than in the summer months.

Given the limited availability of unpopulated coastlines, siting of WEC devices would be challenging. In addition, WECs are currently designed to operate in waters shallower than about 70 m and because of the relatively narrow insular shelf surrounding the islands, wave farms would have to be deployed within 1 to 3 kilometers from the shoreline in full public view.

4.4.6 Offshore Wave Power Resources: Present Status

Wave power resources off the State of Hawaii consist of three main climate patterns: north swell; south swell; and, wind waves (Figure 4-13). The Hawaiian Islands are exposed to swells from distant storms as well as seas generated by trade winds. The island chain creates a localized weather system that modifies the wave energy resources from the far field. UH researchers working for the Hawaii National Marine Renewable Energy Center (http://hinmrec.hnei.hawaii.edu/) implemented a nested computational grid across the major Hawaiian Islands in the global WaveWatch3 (WW3) model and utilized the Weather Research Forecast model to provide high-resolution mesoscale wind forcing. The resulting winds and deep water ocean waves estimated in this fashion compare favorably with satellite and buoy measurements.

The validated model reveals that under deep water conditions (greater than 150 m depths), in the winter months northwest swells have relatively large amounts of wave power of upwards of 60 kW/m (power per wave-crest unit length). However, in the summer months the wave power flux (also referred to as wave power density) due to northwest swells is less than 10 percent of the winter values. South swells, prevalent in the summer months, have lower power levels of less than 15 kW/m. The wind waves are the most consistent throughout the year and yield offshore power levels in the range of 5 to 25 kW/m. Significant seasonal variations are present at all island sites between winter and summer months.

The consistency of the wave climate and the proximity to shore play an important role in the selection of optimal locations for deployment of wave energy devices. While the north and south facing shores would capture swell energy, the most favorable sites are in areas exposed to the direction of the wind waves (Figure 4-13). This indicates the soundness of the selection of coastal segments shown in Figure 4-12 from the Hagerman 1992 report.

This deep water model, however, is not applicable to shallow water conditions (e.g., water depths less than 100 m) and the WEC devices, under development, are to be installed in depths of at most 70 m such that the wave resource must be evaluated for shallow water conditions as is done in the following Section.

4.4.7 Shallow Water Wave Power Resources: Present Status

To estimate the shallow water resource, the Simulating WAves Nearshore (SWAN) model was used with spectral wave data hindcasted from WW3 to obtain ten years (January 2000-December 2009) of the parametric wave data required by designers of WEC devices (SWAN Team, 2006). This project, considered five representative sites (see Figure 4-14): (i and ii) North Beach in Kaneohe at two water depths; (iii) Pauwela in Maui; (iv) shallow water site off South Point (Big Island); and (v) shallow water site in the Alenuihaha Channel off Upolo Airport (Big Island). The model was evaluated using archival data available from the stations listed in Table 4-6 (further discussed in Appendix B).

Table 4-6. Station Locations.

Station	**Location**	**Latitude (N)**	**Longitude (W)**	**Water Depth (m)**	**Data Availability**	**System**
51201	Waimea Bay	21.673	158.116	198	Sep 2004-Current	Waverider Buoy recording wave parameters and water temperature.
51202	Mokapu Point	21.417	157.668	100	Sep 2004-Current	Waverider Buoy recording wave parameters and water temperature.

For reference, the water depth (from LiDAR data with a resolution of approximately 3 m) and latitude and longitude coordinates of each site are presented in Table 4-7.

These five locations were chosen to be in water depths of less than about 70 m to coincide with the upper limit of WEC devices currently under design by reputable developers. The Kaneohe II site was selected as a possible location for an additional WEC in deeper waters (58 m versus 27 m). The Pauwela site was selected off the north shore of Maui at 73 m depth. The other two sites off Hawaii were deemed to be interesting because of their exposure to trade wind waves (Upolo at 47 m) and both trade wind waves and southern swell (South Point at 40 m).

The wave power flux (P_o), through a vertical plane of unit width perpendicular to the wave propagation direction is used to represent the resource. Daily, monthly and annual averaged P_o (kW/m) over the ten-year period are presented herein. For future reference daily values for the ten-year period are tabulated in Appendix B.

Table 4-7. Location of Sites Selected for SWAN Analysis.

Site	Location	Latitude (N)	Longitude (W)	Water Depth (m)
Kaneohe	Kaneohe, Oahu	21.465	157.752	27
Kaneohe II	Kaneohe, Oahu	21.472	157.747	58
Pauwela	Pauwela, Maui	20.958	156.322	73
Upolu	Upolu, Hawaii	20.275	155.863	47
South Point	South Point, Hawaii	18.910	155.681	40

The wave power flux for each site was estimated as described below (Eq. 1). Monthly and annual averaged estimates over the ten-year period are given in Tables 4-8 and 4-9. Monthly averages are plotted in Figure 4-14 along with values derived from NOAA/National Data Buoy Center (NDBC) Buoy 51202 (Mokapu) (NDBC, 2010). These show that the site selected by Oceanlinx in Pauwela represents a relatively high resource. The graphical representation in Figure 4-14 is indicative of the relatively high seasonal resource variability with summer months showing power levels of 1/7 the winter values in Pauwela and 1/3 in Kaneohe. In the case of the sites exposed to southern swell (see South Point and Mokapu) the seasonal difference is less pronounced.

The averaged daily and monthly values are shown in Figures 4-15 through 4-24. Significant seasonal variations between winter and summer months are clearly shown. The average approximate monthly wave power flux between May and September show similar values for the Upolu and Kaneohe sites (5 to 7 kW/m), and slightly higher values at the Pauwela (6 to 9 kW/m) and South Point (13 kW/m) sites. Between October-April, significantly higher values (approximately 17 to 43 kW/m) are shown at the Pauwela site. The daily variability is also pronounced indicating relatively large swings that would be expected in the power output from any WEC device.

$$P_o = \rho g \int_{\omega=0}^{\omega=\infty} Cg(\omega,h)\left(\int_{\theta=0}^{\theta=2\pi} S(\omega,\theta,h)\,d\theta\right)d\omega \quad (\text{W}/m) \qquad (1)$$

where,

- $S(\omega,\theta,h)$ = site specific wave spectrum
- θ = wave direction
- ω = wave frequency
- h = water depth
- Cg = site specific group speed
- g = gravitational acceleration, ~ 9.81 m/s²
- ρ = density of sea water, ~ 1025 kg/m³

P_o can be expressed as:

$$P_o = c_G E_{tot} = \frac{\rho g^2}{64\pi} T_e H_s^2 \quad (Watts/m) \tag{2}$$

indicating that, P_o is proportional to the wave period and to the square of the wave height.

The Energy-Period, T_e, and the significant wave height are defined as:

$$H_s = 4\sqrt{\iint (S(\omega,\theta,h) d\omega d\theta} \tag{3}$$

$$T_e = 2\pi \left(\frac{\iint \{(S(\omega,\theta,h)/\omega) \tanh(kh)[1 + 2kh/\sinh(2kh)]\} d\omega d\theta}{\iint S(\omega,\theta,h) d\omega d\theta} \right) \tag{4}$$

It must be noted that P_o, as properly defined above, applies to any water depth. The approximation for deep water conditions (not applicable herein) is found to be used incorrectly throughout the open literature even when discussing shallow water waves.

Table 4-8. Monthly Average Wave Power Flux.

	Power Flux (kW/m)											
Site	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Kaneohe	15.5	13.1	13.2	11.1	5.9	4.9	4.8	5.0	6.3	9.7	16.2	16.6
Kaneohe II	15.7	13.1	13.0	10.9	5.8	4.8	4.6	4.8	6.2	9.7	16.3	17.1
Pauwela	41.8	33.0	26.1	18.1	8.8	6.4	5.9	6.4	8.9	16.6	30.4	43.3
Upolu	15.2	12.8	13.2	11.3	6.5	6.0	6.1	6.6	6.8	9.6	14.9	15.6
South Point	17.0	15.3	14.2	14.2	12.7	13.1	12.7	12.5	12.4	11.8	12.8	15.5
Mokapu Buoy	22.2	20.2	16.7	16.7	12.2	10.2	10.7	10.2	8.7	12.7	20.7	21.7

Table 4-9. Annual Average Wave Power Flux.

Site	**Power Flux (kW/m)**
Kaneohe (27 m)	10.2
Kaneohe II (58 m)	10.2
Pauwela (73 m)	20.5
Upolu (47 m)	10.4
South Point (40 m)	13.7
Mokapu Buoy (100 m)	15.2

Comparing annual average estimates obtained herein (Table 4-10) with the 1992 estimates (Figure 4-12) indicates that, with the exception of the Pauwela site, the original estimates are useable for initial evaluation. However, monthly and daily estimates, as presented in this report, are required to proceed beyond a simple site evaluation.

Table 4-10. Annual Average Estimate Comparison.

Site	Annual Average	Coastal Segment (See Figure 4-12)	Annual Average
Kaneohe (27 m)	10.2 kW/m		
Kaneohe II (56 m)	10.2 kW/m	OA-5 (80 m)	12.0 kW/m
Pauwela (73 m)	20.5 kW/m	MA-3 (80 m)	13.5 kW/m
Upolu (47 m)	10.4 kW/m	HA-1 (80 m)	10.0 kW/m
South Point (40 m)	13.7 kW/m		

4.5 Marketing and Regulations

FERC is an independent agency that is charged with the authorization and regulation of the nation‟s non-federal hydropower resources. There are no hydropower plants in the State licensed by FERC at this time. Filing a Declaration of Intention with FERC will determine if a proposed project requires licensing, or a project owner may carry on filing a hydropower license application. Owners of small hydropower projects may apply for the 5-MW Exemption if the project is located at an existing dam or if the project uses a natural water feature, and the owner owns the lands and facilities aside from federal lands. A 2.7-MW plant off the north coast of Maui, developed by Oceanlinx became the first project in the State of Hawaii to receive a preliminary permit from FERC in 2009.

Licensing and Permitting Process under FERC:

1. Consult with relevant Federal, state, and interstate resource agencies, Native tribes, and non-governmental agencies.
2. Apply for preliminary Permit
3. Follow the Integrated Licensing Process

    - Projects must be in compliance with applicable laws, including but not limited to:

        - Section 401 of the Clean Water Act
        - Endangered Species Act
        - Coastal Zone Management Act (CZMA)
        - Federal Power Act
        - Magnuson-Stevens Fishery Conservation and Management Act
        - Marine Mammal Protection Act
        - National Energy Act
        - NEPA
        - National Marine Fisheries Service regulations
        - NOAA regulations
        - Rivers and Harbors Act
        - Outer Continental Shelf Act
        - MMS Final Rule on Renewable Energy and Alternative Uses of Existing Facilities on the Outer Continental Shelf

- MMS regulations
- Submerged Lands Act

The State of Hawaii, and the individual counties each have their own environmental permits, reviews, and county plans under which each project must have compliance.

Ocean energy has different requirements than terrestrial hydropower. NOAA specifically has licensing and administrative authority over commercial OTEC plants (EPRI, 2005). Test plants do not require a NOAA license. NOAA is currently in the process of developing new licensing regulations. NOAA is required to coordinate with Coastal States and the US Coast Guard as well as other Federal Agencies. An EIS would be required for each license. It is expected that the majority if not all federal, state and local requirements would be handled through the NOAA licensing process. The State has jurisdiction out to three nautical miles under the CZMA and the Submerged Lands Act. These sites fall under the OCCL and State EIS permitting. The USACE has permitting jurisdiction beyond three nautical miles (nm) to the outer continental shelf, or the 200 nm of the exclusive economic zone. In the State of Hawaii, the exclusive economic zone is roughly 890,000 square kilometers (Wilder, 1998). The USACE works with MMS for permitting. Under the guidance of the 1952 Outer Continental Shelf Act, the BOEMRE Offshore Energy and Minerals Management program manages offshore renewable energy development. BOEMRE is responsible for inspection and oversight of energy companies to ensure that renewable energy projects that occur on the OCS meet applicable laws and safety regulations. The OCS begins three to nine nautical miles (nm) from shore and extends 200 nm outward. BOEMRE issues commercial leases and limited leases. Right-of-way, right-of-use and easement grants are issued in support of renewable energy activities (Table 4-11).

Table 4-11. Types of BOEMRE Access Rights.

Type	Years of Issuance	Description
Commercial Lease	30	Access and operational rights to produce, sell, and deliver power on a commercial scale through spot market transactions or a long-term power purchase agreement
Limited Lease	5	Access rights to conduct activities, like site assessment and technology testing that support production of renewable energy, and may provide the right to produce and sell power within limits set by the terms and conditions of the lease.
Right-of-way	N/A	Allow for the construction or use of a cable or pipeline for the purposes of gathering, transmitting, distributing, or otherwise transporting electricity or other energy product generated or produced from renewable energy not generated on a lease issued under BOEMRE
Right-of-use and easement	N/A	Authorize the use of a designated portion of the OCS to support renewable energy on a lease or approval not issued under BOEMRE (e.g. State-issued lease)
Alternate Use RUE	N/A	Authorize energy or marine-related use of an existing OCS facility activities not otherwise authorized by BOEMRE or other applicable law.

If new power plants will be connected to the existing grid for public use they will be regulated by the Public Utilities Commission of the State of Hawaii, under the Department of Budget and Finance. Electric rates must be approved by the Public Utilities Commission. Any potential Federal power marketing activities will be performed by the U.S. Department of Energy.

As part of the Hawaii Clean Energy Initiative (HCEI), DBEDT, with assistance from various Hawaii state and county agencies, federal agencies, the U.S. Department of Energy (National Renewable Energy Laboratory), and private stakeholders, is developing A Guide to Renewable Energy Facility Permits in the State of Hawaii. This guide provides the first comprehensive overview of the renewable energy permitting process in the State of Hawaii. Until the Guide is complete in early 2011, existing drafts are available on the HCEI website. Resource-specific sections have been created to provide federal and state approvals for hydroelectric and marine/ocean thermal energy conversion, while four other sections provide county-specific information. At the end of each draft guidebook currently available to the public, there is a checklist to determine which permits/approvals may be required for a specific project. To compliment the Guide, DBEDT and PB Americas are developing an online Permit Wizard linked to the HCEI website, also expected to be complete in early 2011, which will enable users to generate a permit plan for any project based on project-specific information provided by the developer/user. DBEDT is also assisting other state agencies to provide online permitting ability. While these resources are a good starting place for developers, laws, legislation, and procedures for executing these permits and approvals are constantly changing. Currently the State is developing a streamlined process for fulfilling permitting requirements as set forth under HRS 201N. To help meet Hawaii's aggressive clean energy goals, county, state, and federal agencies in Hawaii are working to expedite permit processing for renewable energy and energy efficiency projects.

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Figure 4-3: Worldwide average ocean temperature differences (between 20 m and 1000 m water depths)

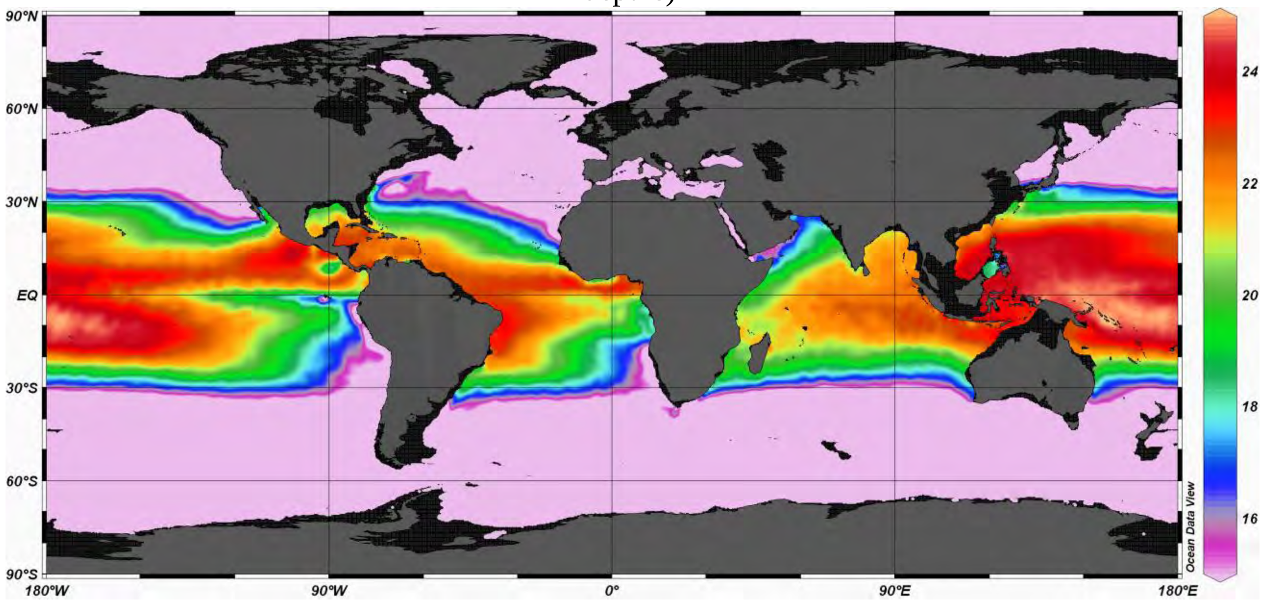


Figure 4-4: Average ocean temperature differences (between 20 m and 1000 m water depths) around the main Hawaiian Islands from HYCOM + NCODA (1/12°) data for the period July 1, 2007 through June 30, 2009 (the color palette is from 18°C to 24°C)

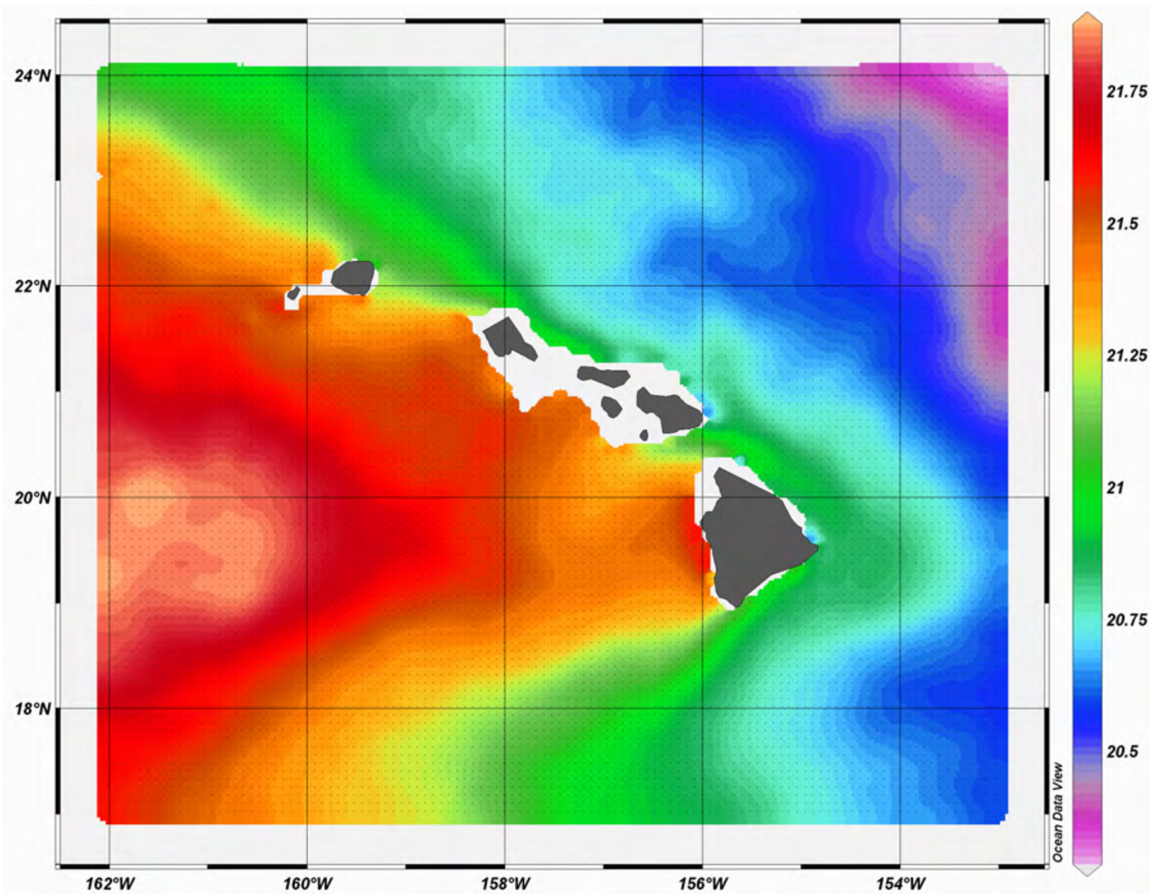


Figure 4-5: Yearly amplitudes of ocean temperature differences (between 20 m and 1000 m water depths) around the main Hawaiian Islands from HYCOM + NCODA (1/12°) data for the period July 1, 2007 through June 30, 2009 (the color palette is from 0°C to 2°C)

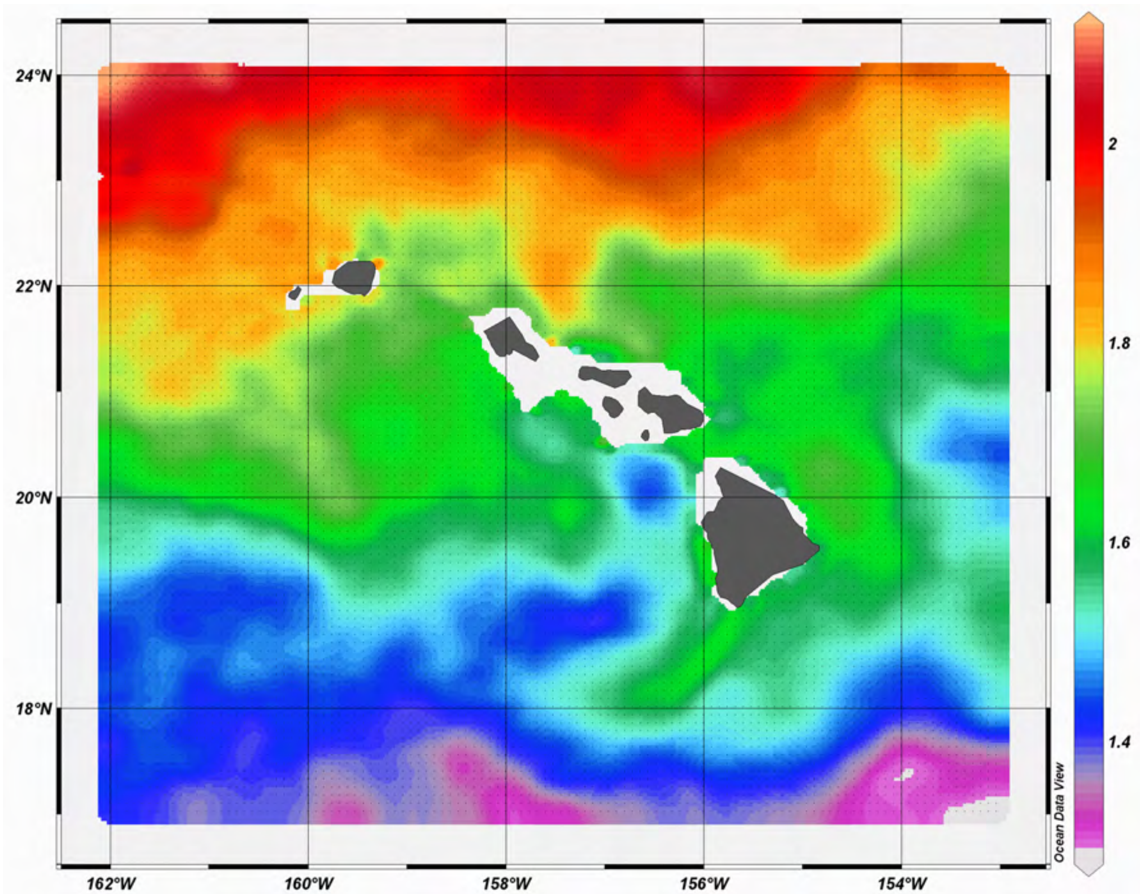


Figure 4-6: Measured ocean temperature differences (between water depths closest to 0 m and 1000 m) at HOT Station 1 („Kahe Point‟: 21°20.6‟N, 158°16.4‟W) from November 1988 through 2009

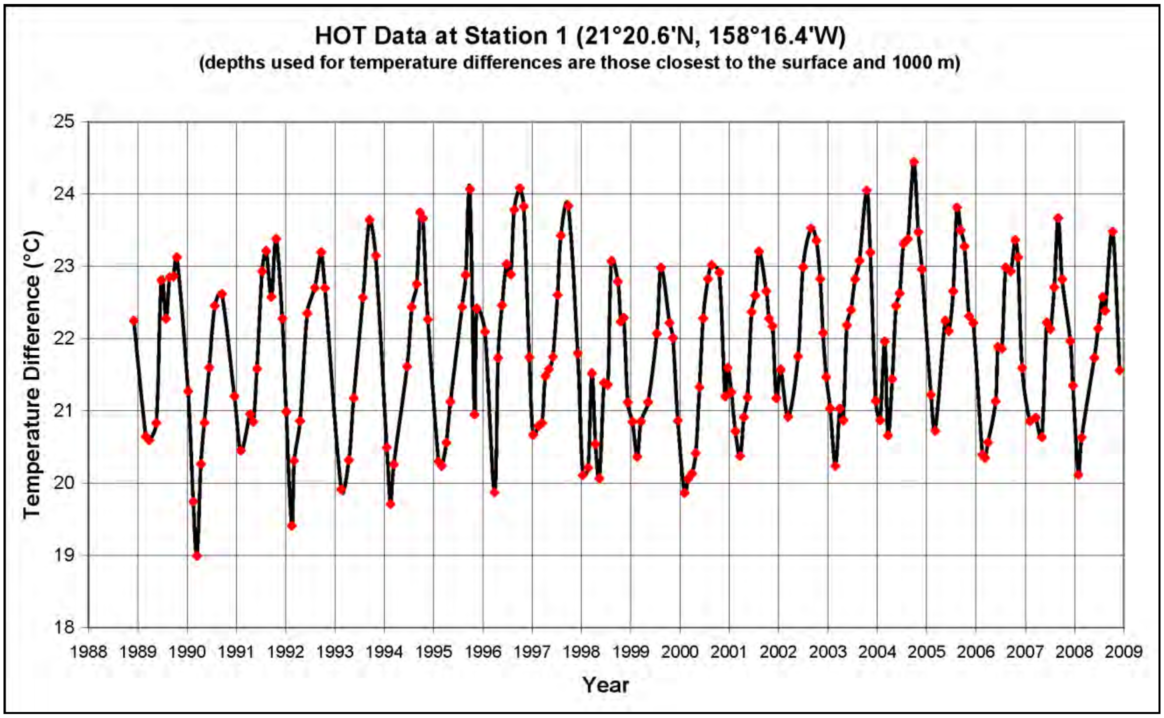


Figure 4-7: Measured ocean temperature differences (between 20 m and 1000 m water depths) at HOT Station ALOHA (22°45‘N, 158°W) from November 1988 through 2009

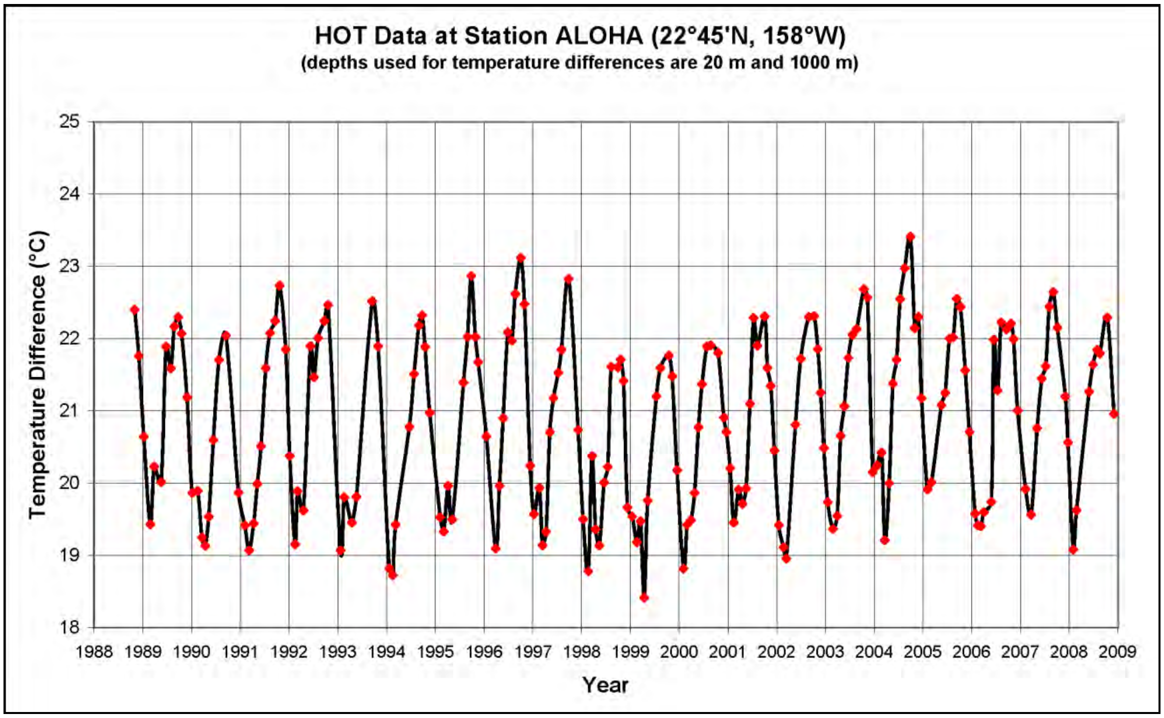


Figure 4-8: Comparison between HYCOM + NCODA and HOT data sets at HOT Station 1 („Kahe Point‟)

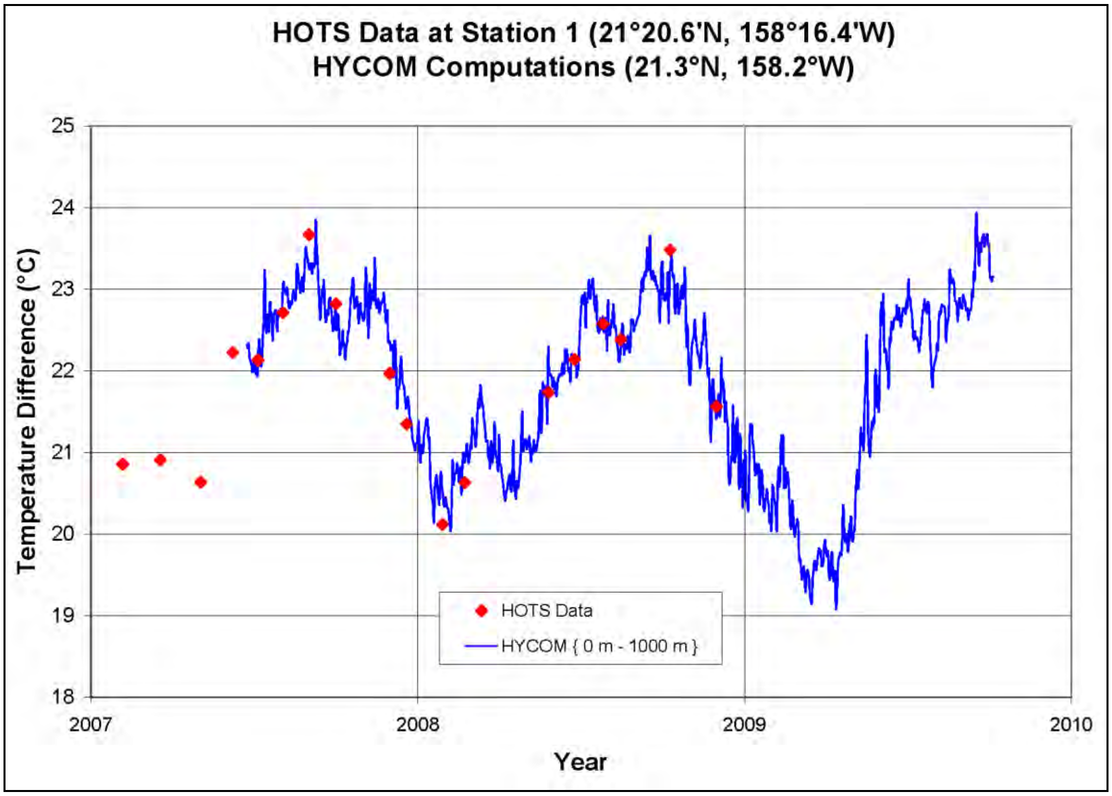


Figure 4-9: Comparison between HYCOM + NCODA and HOT data sets at HOT Station ALOHA

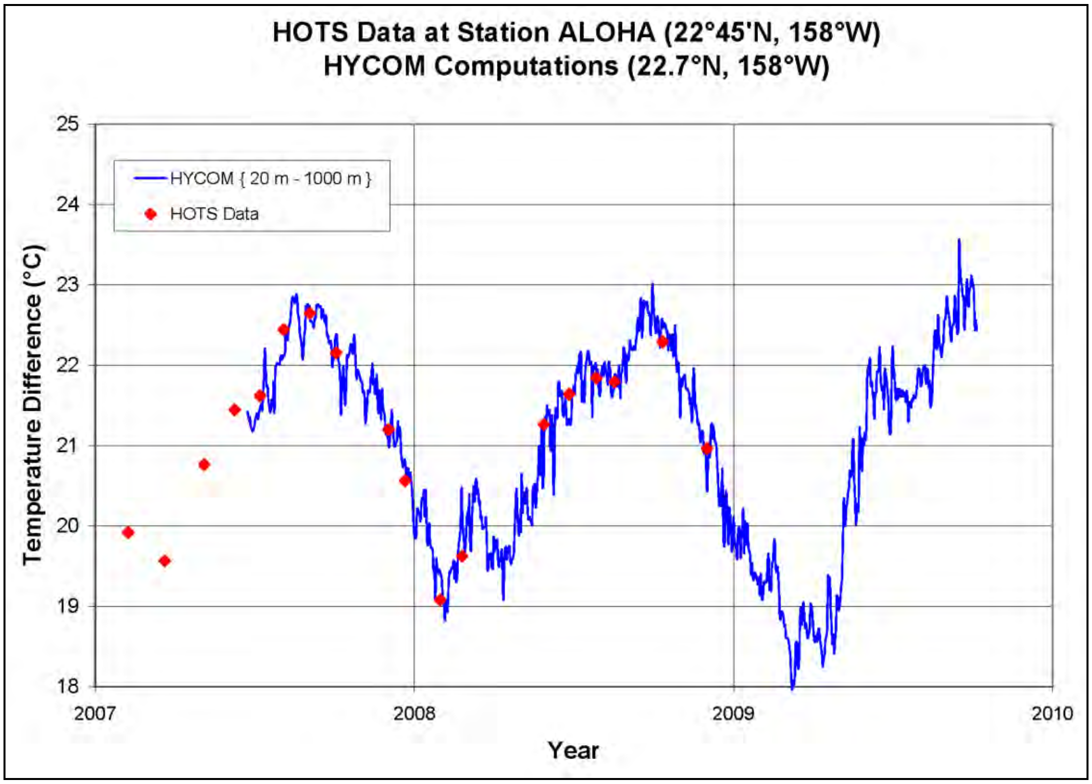


Figure 4-10: Capital Cost Estimated for First Generation OTEC Plants

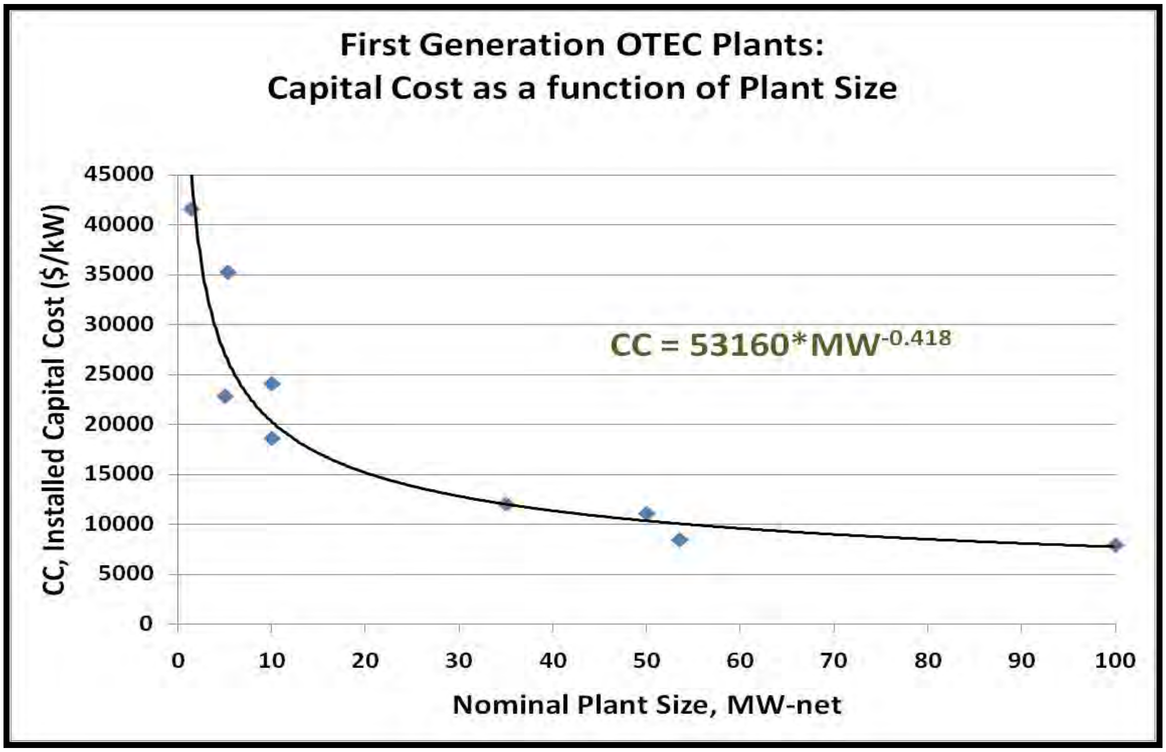


Figure 4-11: Cost of Electricity (*Capital Cost Amortization + OMR&R Levelized Cost*) Production for First Generation OTEC Plants as a function of Plant Size with Loan Terms (*interest and term*) as Parameter

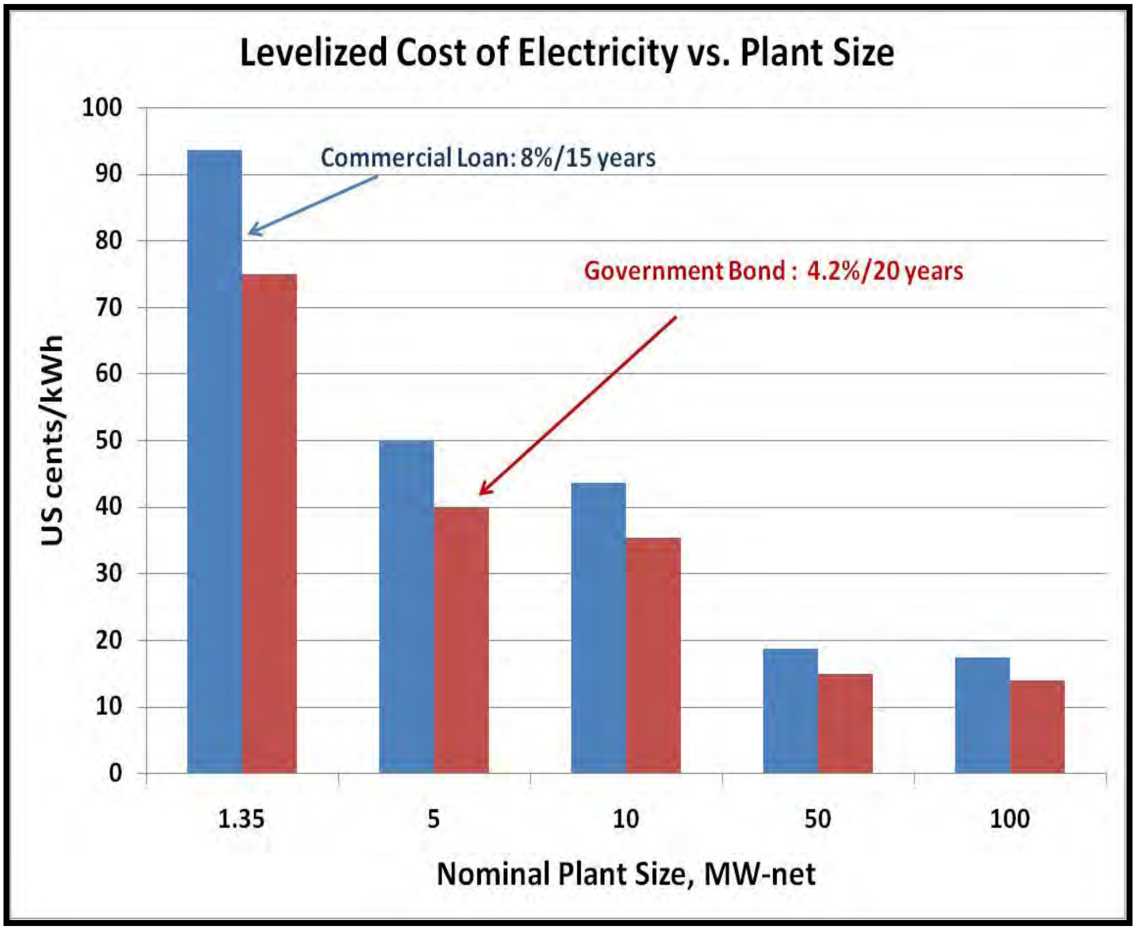


Figure 4-12: Wave Power Flux (kW/m) along coastline segments identified in the George Hagerman 1992 Report

Average Wave Power (kW/m) Along Selected Coastal Segments and Potential Constraints

	Coastal Segment	5 m Water Depth	80 m Water Depth
KAUAI	KA-1	6	9
	KA-2	10	13
	KA-3	12	15
	KA-4	9	12
OAHU	OA-1	10	11
	OA-2	8	12
	OA-3	12	14.5
	OA-4	8	11
	OA-5	10	12
	OA-6	7	9
MOLOKAI	MO-1	12	14
	MO-2	8	10.5
	MO-3	8	11
	MO-4	12	14
MAUI	MA-1	9	12
	MA-2	10.5	13.5
	MA-3	10.5	13.5
HAWAII	HA-1	9	10
	HA-2	11	13
	HA-3	10	12.5
	HA-4	5	7
	HA-5	6.5	8
	HA-6	6	8
	HA-7	10	11

Data Sources:
Hagerman (1992)
Kauai Coastal Resource Atlas, USACE (1984)

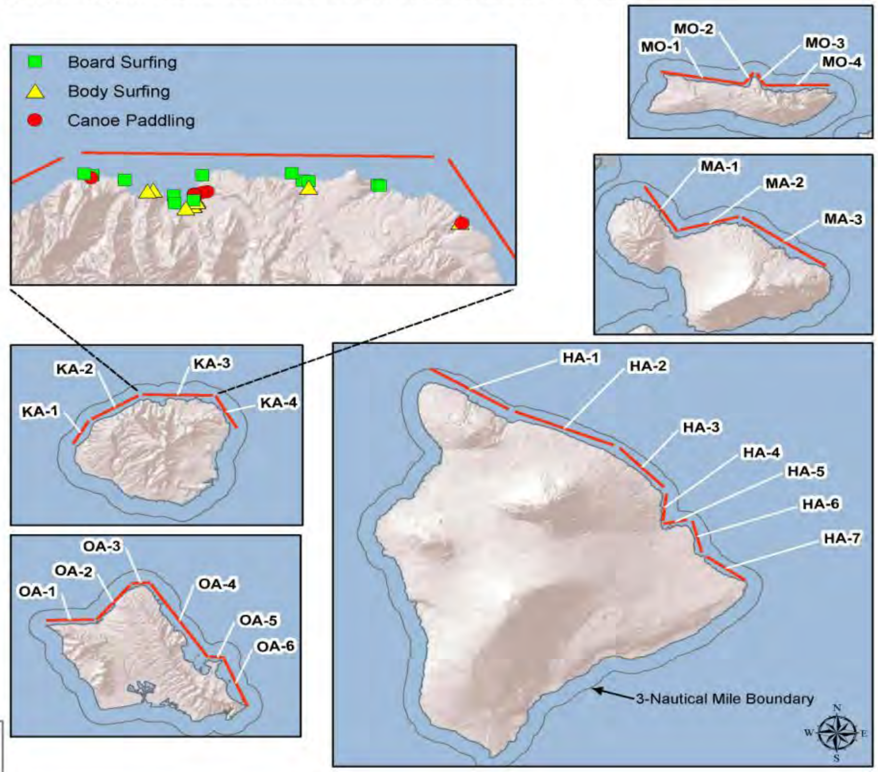


Figure 4-13: Hawaii Wave Power Climate Patterns

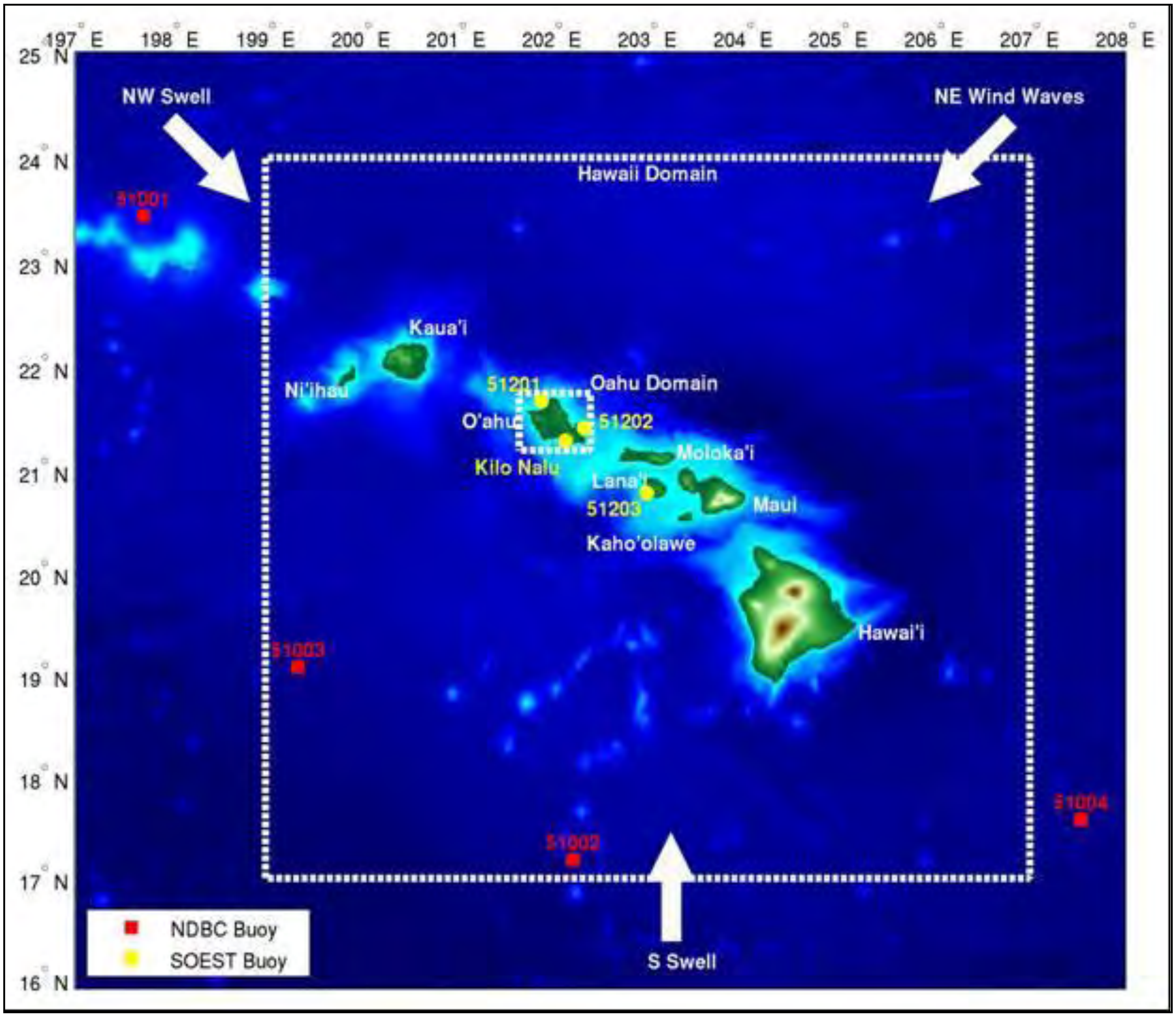


Figure 4-14: Monthly Average of Wave Power Flux at all Sites

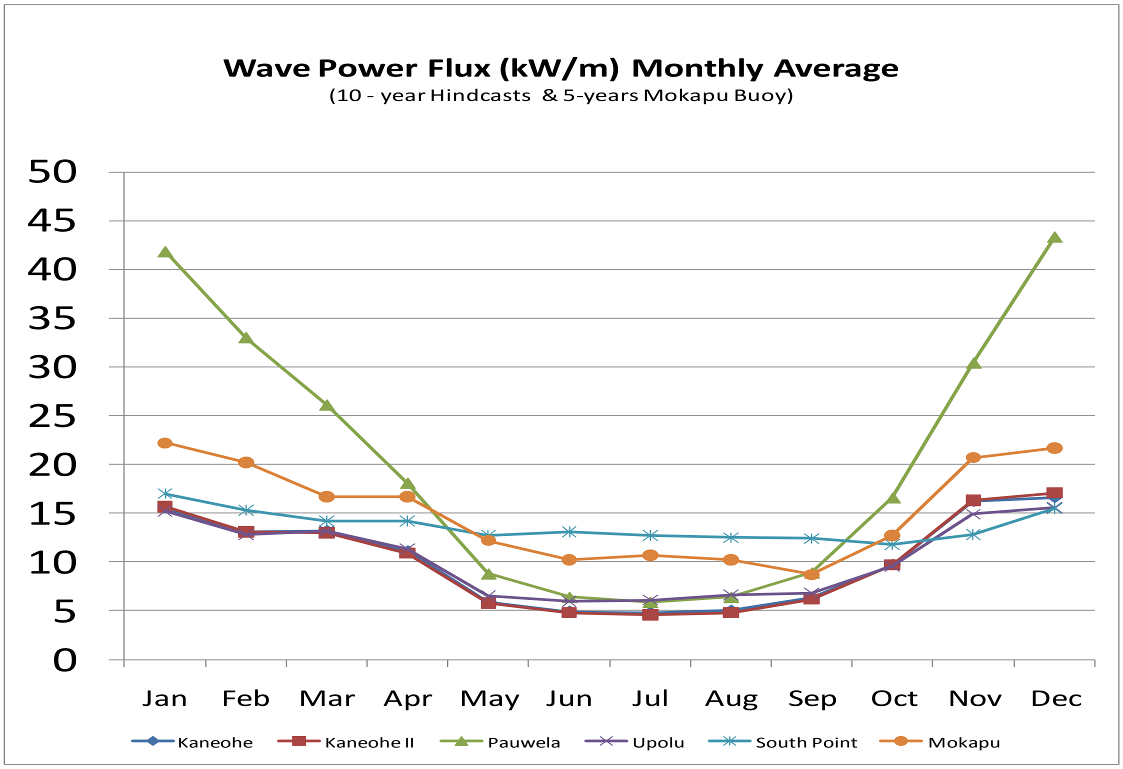


Figure 4-15: Daily Average Wave Power Flux for Kaneohe Site (27 m)

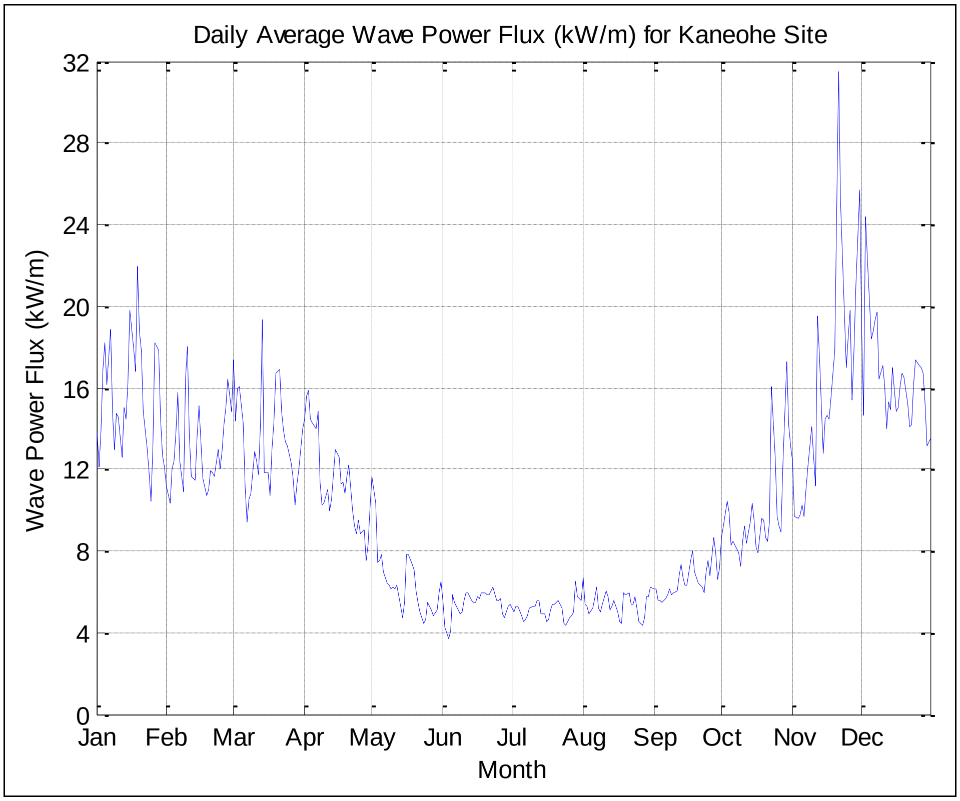


Figure 4-16: Monthly Average Wave Power Flux for Kaneohe Site (27 m)

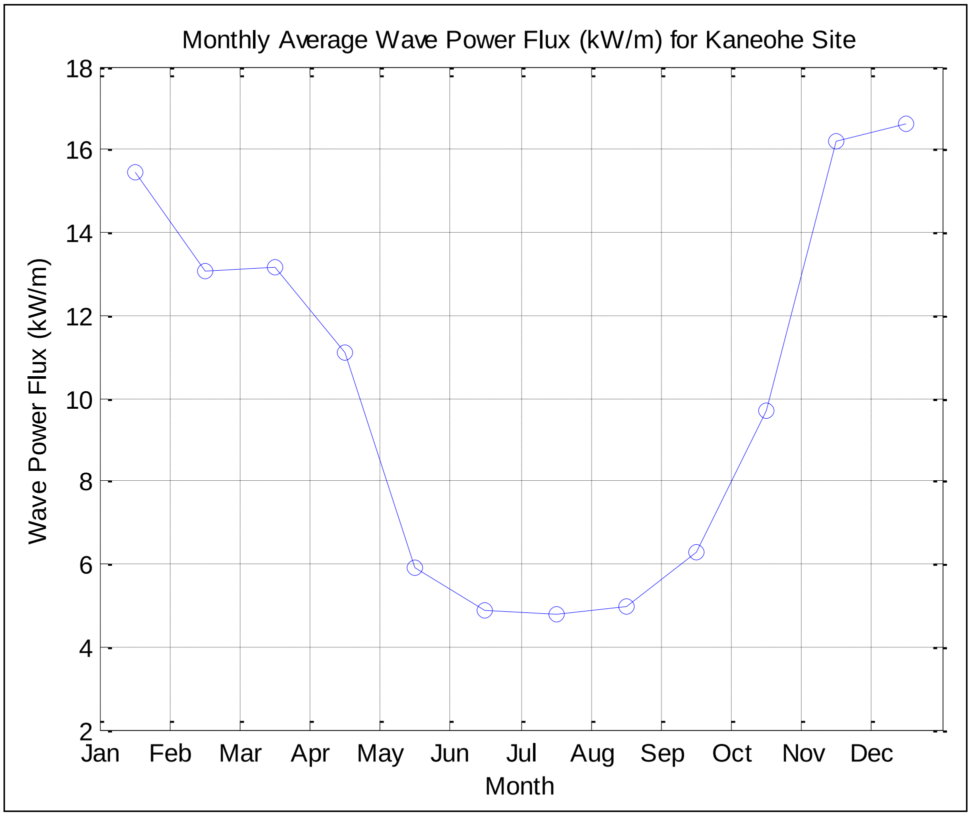


Figure 4-17: Daily Average Wave Power Flux for Kaneohe II Site (58 m)

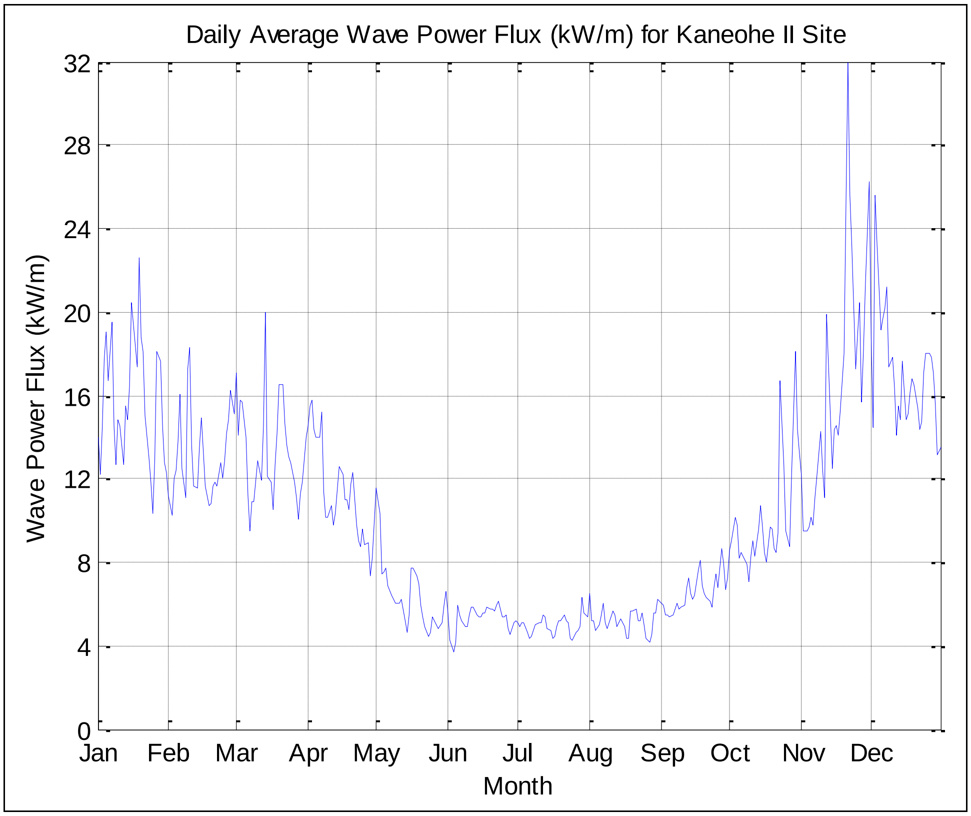


Figure 4-18: Monthly Average Wave Power Flux for Kaneohe II Site (58m)

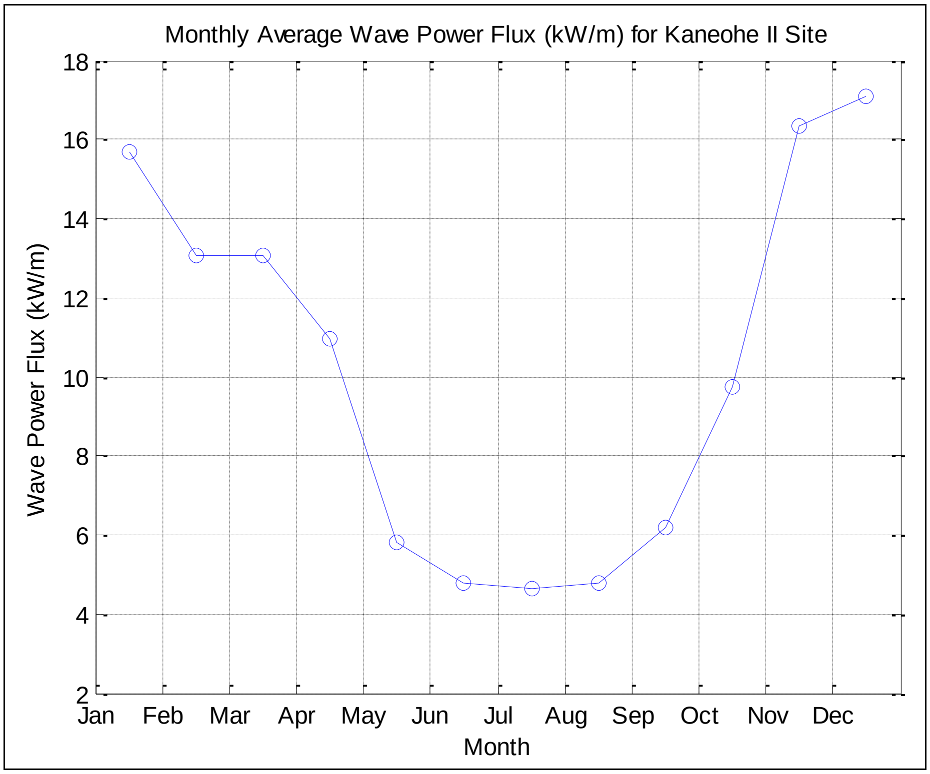


Figure 4-19: Daily Average Wave Power Flux for Pauwela Site (73 m)

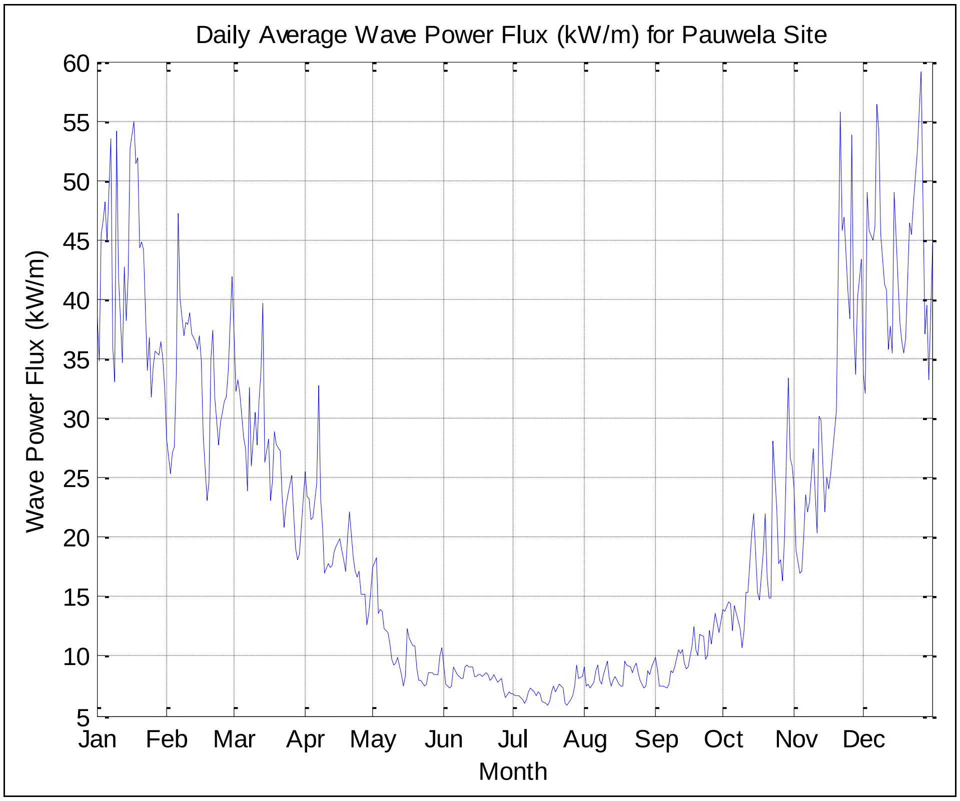


Figure 4-20: Monthly Average Wave Power Flux for Pauwela Site (73 m)

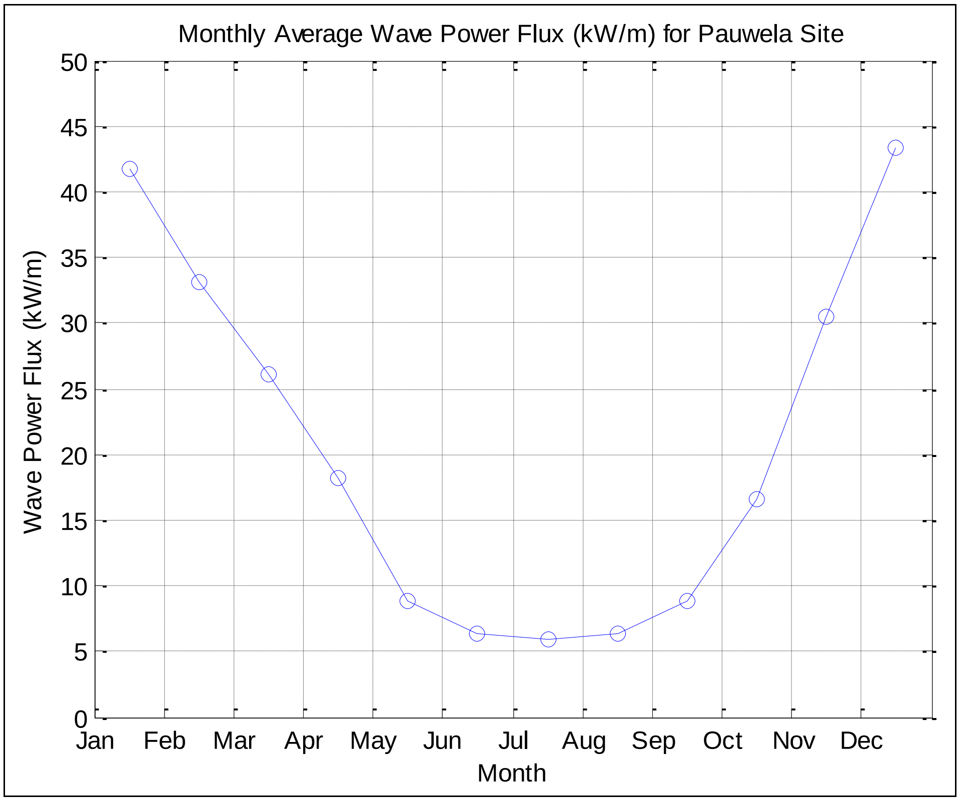


Figure 4-21: Daily Average Wave Power Flux for Upolu Site (47 m)

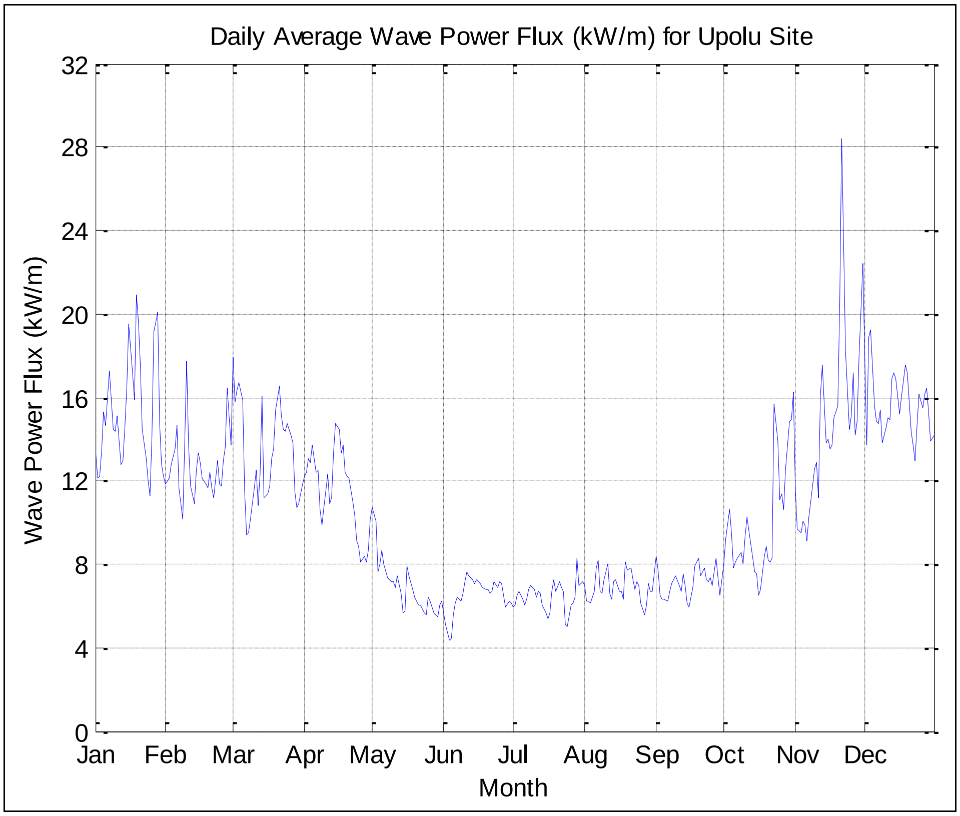


Figure 4-22: Monthly Average Wave Power Flux for Upolu Site (47 m)

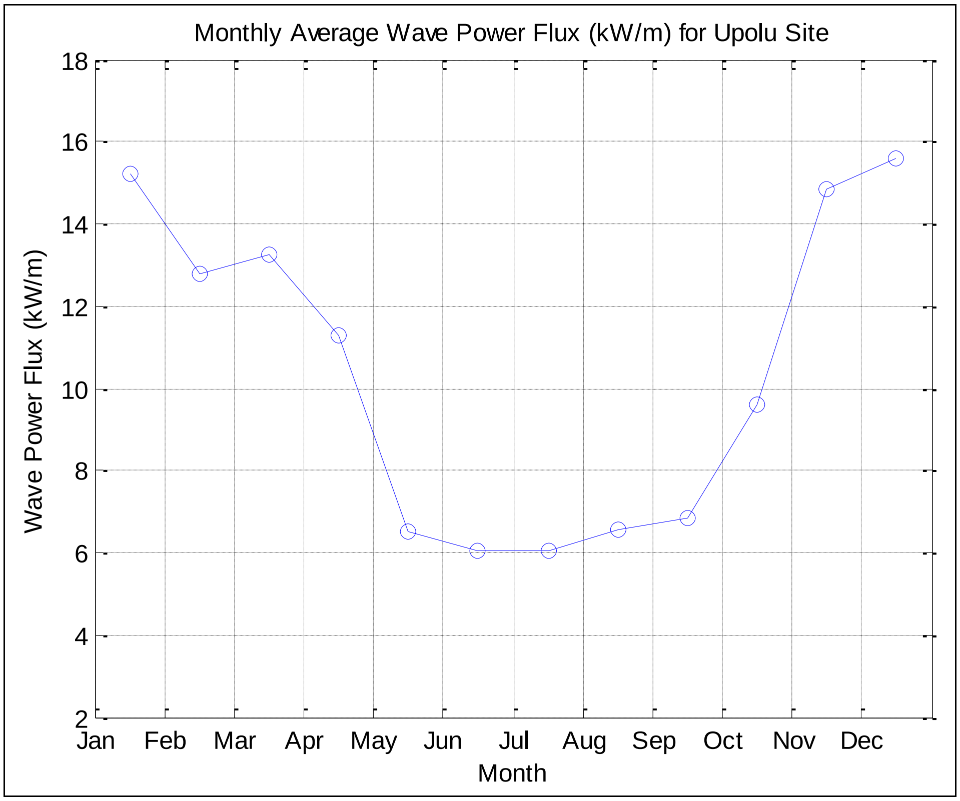


Figure 4-23: Daily Average Wave Power Flux for South Point Site (40 m)

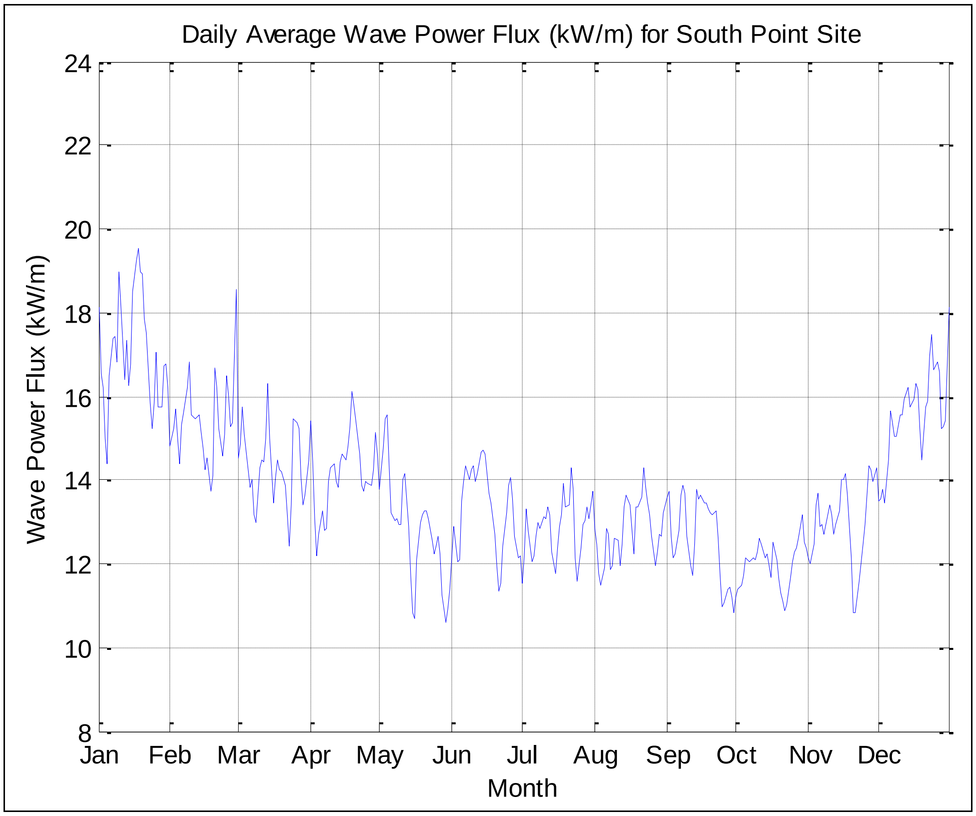
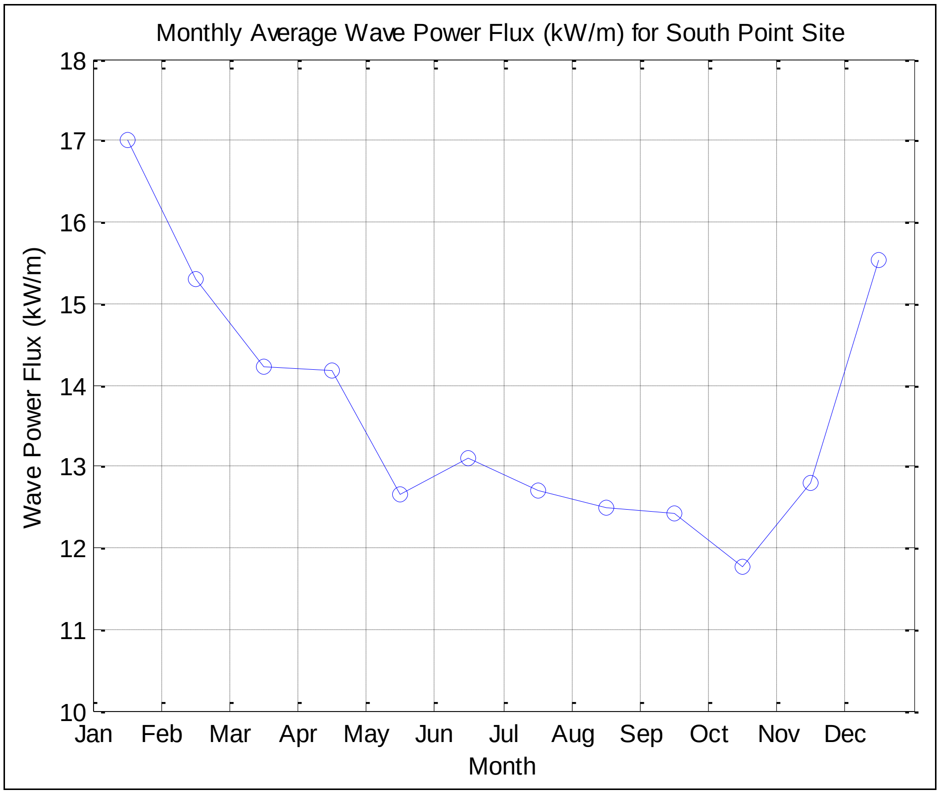


Figure 4-24: Monthly Average Wave Power Flux for South Point Site (40 m)



5.0 EVALUATION OF CONVENTIONAL HYDROPOWER SITES

5.1 Conventional Hydropower Screening Criteria

5.1.1 Data Collection

An inventory of existing dams, hydropower facilities, and undeveloped sites having the physical potential to generate hydropower were compiled into a database to allow for these sites to be screened based on the following information, including but not limited to, location, streamflow, owners, and size of project. The database provides complete site descriptions based on these parameters as well as the original source of where this information was found.

The database for potential hydropower sites was established from more than fifty sources ranging from state, national, utility and private-sector reports. Island-specific reports produced by the local utility companies frequently provided the most useful data on hydropower at a county level. The database standardizes the data collected from over 160 sites through the State. Projects identified in this database include existing/operating hydropower plants, those that were active at one time but have since fallen into disuse, and those that were proposed but never built. Sites presented in the database are linked with geospatial coordinates referencing their location in the State, and integrated into a geospatial information system (GIS) that will be available from the USACE. In addition to the data collected in the literature review, data fields are also populated with geospatial and economic analyses. Therefore, this database, found in Appendix A, provides a wealth of interactive information in which users can discover which sites provide the greatest energy development potential based on whichever parameters are most important to the user.

The Idaho National Engineering and Environmental Laboratory (INL) performed a nationwide analysis of streamflow energy resources and their gross power potential as described in two reports and available through an online GIS interface at
http://hydropower.inel.gov/prospector/index.shtml (INL, 2004; INL, 2006)

The 2006 report identified 2,230 MW of annual mean power as the resource available in the State of Hawaii, as generated by 884 resource sites. Of these totals, 414 resources sites were considered „feasible‟ based on a generalized review of land use and environmental sensitivities, prior development, site access, and load and transmission proximity. These resource sites were estimated to generate up to 280 MW of annual mean power. For the purposes of this report, contacts were established with the authors of these INL reports and sites considered feasible in these studies were reviewed. While these studies provide a comprehensive national-scale review of the State‟s water resource potential, the focus of this study remained centered on better-developed project proposals that existed in the literature. While the INL study placed water resource projects around the State based on national-level stream characteristics and limited constraints on development, the projects reviewed for this study have been conceived of and proposed by federal, state and private developers. As such it is anticipated that these individual projects have been studied and reviewed more carefully on a site-specific basis than those identified in INL‟s national-level study. The INL reports are acknowledged, however, as important references in understanding the State‟s overall streamflow energy resource potential.

5.1.2 General Screening Criteria

Potential hydropower projects in the State of Hawaii were screened according to physical, economic, environmental, and federal interest considerations.

Economic reviews of conventional hydropower projects included a rough order of magnitude comparison of the construction cost of the project with its potential generating capacity. Projects that could produce energy at rates lower than the current utility rates were ranked higher than other sites. Sites in more accessible locations were ranked higher than ones in isolated valleys with little to no infrastructure or access. Although some sites may have not been feasible when initially planned, it is possible that advanced technology and economic changes could allow for potential sites to be constructed in the present or at a later date.

One of the main environmental/social considerations was the proximity of sites to U.S. Fish and Wildlife critical and pristine habitat. Critical habitat is defined as a specific geographic area(s) that contains features that are essential for the conservation of threatened or endangered species and that may require special management or protection (USFWS, 2010). Hydropower projects have the potential to alter critical and pristine habitat and therefore the siting of projects within close proximity to these areas may subject to Federal regulation or face public opposition. Additional environmental/social factors that were considered included sites within Conservation Districts[8], streams of known cultural value, and areas of high recreational use. Environmental/social factors were examined independently from economic considerations for the purposes of screening sites. This approach allows flexibility in screening the projects - for example, if overall infrastructure costs decrease as a result of improved technology, or oil costs increase, alternative sites may be economically viable.

Of the sites which passed the economic and environmental/social screening, some had applicable federal interest. Several fell into the USACE primary interest in flood control, but many would fall into secondary interests of hydropower or irrigation. Some pumped storage systems could be combined with existing water tanks or systems to provide power within the drinking water supply.

Some of the sites had minimal background information beyond the basic criteria, but this does not mean they should be discounted. Sites which did have sufficient background information were reviewed more closely as cost estimates and potential problems could be more accurately derived.

The results of these independent screening processes are presented as a stand-alone Appendix A that is also available as an electronic, sortable Excel spreadsheet and as fields in the GIS

8 Conservation Districts are administered by the State of Hawaii‟s Department of Land and Natural Resources Office of Conservation and Coastal Lands.

shapefiles. A more in-depth explanation of the screening criteria follows. The information provided allows the USACE, State and local decision makers, and private developers to analyze potential sites that have been considered in the past 30 years.

5.2 Economic Criteria & Evaluation: Conventional Hydropower

All existing dams, hydropower facilities, and undeveloped sites with reasonable hydropower development potential were considered to be possible sites for new or incremental hydropower development. Data on the location, ownership, available power head, and potential flow were collected for each site. This was used to calculate potential output and costs.

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5.2.1 Incremental Energy Costs

Additional site-specific data from published and unpublished reports, United States Geological Survey (USGS) streamflow and GIS data was collected during this stage. Hydropower potential of the sites in the database was assessed by determining the incremental energy cost for developing a power facility at each site. Incremental energy cost was defined as the undeveloped power potential of a site using the following equation:

$$Incremental\ Energy\ Cost = \frac{Total\ Levelized\ Annual\ Cost}{Incremental\ Annual\ Energy}$$

Available data was reviewed to establish parameters needed to determine the potential incremental energy cost of the one hundred and sixty six (166) sites found in the literature reviewed. Thirty-two (32) sites did not have sufficient information to define the location needed to estimate potential stream flow available for power generation and calculate the potential incremental energy cost of the site. Of the remaining 134 sites, thirty (31) sites had data available to define the total levelized annual cost and incremental annual energy values from the source material. One-hundred and three (103) sites had sufficient data to calculate the incremental energy costs from the calculations below.

In addition, a sensitivity analysis was conducted for the sites estimating the cost variations resulting from environmental/cultural complications and/or project development/transmission line construction uncertainties that could impact licensing effort and project economics.

5.2.1.1 Total Levelized Annual Costs

Total levelized annual cost was defined as the sum of the debt payment for design, licensing, and construction of the project components and the annual operating and maintenance cost estimated for the generating facilities. Source documents for many of the sites had estimates for capital and/or operation and maintenance costs that were used in the incremental energy cost calculation. For sites with no published cost data, estimation formulas published by the Idaho National Engineering and Environmental Laboratory (INL) were used to prepare cost estimates for the hydropower projects (INL, 2004, 2006).

The INL formulas approximated individual licensing, construction, water quality monitoring, and various mitigation costs such as fish and wildlife, recreation, fish passage, historical, and archaeological. These costs were summed to estimate the total capital cost. Levelized capital costs were computed using engineering economics factor tables for a project life of 50 years and the Army Corps interest rate of 4.125 percent. The INL equations were also used to estimate fixed and variable O&M costs. Levelized capital costs were summed with the O&M costs to obtain the total levelized annual cost for the site. For those sites that INL equations were used to estimate cost, an inflation rate of 1.37 percent was applied to update the INL 2004 costs to 2011 (USACE 2010).

5.2.1.2 Incremental Annual Energy

Sites in the database were grouped into five (5) categories reflecting the extent of information available to determine the incremental annual energy. The categories were:

1. Defined incremental annual energy
2. Defined incremental power capacity
3. Defined hydraulic head (feet [ft]) and average flow (cubic feet per second [cfs])
4. Undefined sites having coordinates allowing GIS analysis to determine head, flow, power, and energy
5. Undefined sites with no defined location, head, flow, power, and/or energy.

Table 5-1 shows the calculation process for each of these categories.

Table 5-1. Summary of Available Data.

Category	Incremental Annual Energy	Incremental Power Capacity	Hydraulic Head and Average Flow	Site Coordinates
1	Database	Not Needed	Not Needed	Not Needed
2	Calculated	Database	Not Needed	Not Needed
3	Calculated	Calculated	Database	Not Needed
4	Calculated	Calculated	Calculated	Database
5	Unknown	Unknown	Unknown	Unknown

Sites with an estimate for incremental annual energy (Category 1) in the source documents required no further analysis and the source document values were incorporated in the database.

For Category 2 sites for which an incremental power capacity was provided in the source document, incremental annual energy was estimated using the assumption that the turbines would operate at rated capacity of approximately 6,000 hours per year, or 68 percent of the time. Therefore, incremental annual energy was calculated as the incremental power capacity (kW) times 6,000 hours/year. This number is used a relative ranking category, fewer hours per year using the same operational basis may over or underestimate the value.

For Category 3 sites with no incremental power provided in the source document, the turbines were sized at 1.5 times the average flow and the turbine power was calculated using the following equation:

$$P = 0.746e\frac{\rho_w Q_T H}{550}$$

where: e = turbine efficiency (assumed 80 percent)
Q_T = turbine design flow ($Q_T = 1.5Q_{avg}$, cfs)
γ_w = density of water (62.4 lb/ft^3)
H = hydraulic head (ft)
P = power output (kW)

The head available for power generation at each of these Category 3 sites was based on data in the source documents relative to dam heights or river slope. Incremental annual energy was calculated using the estimated power output and the same method described for Category 2 sites.

For Category 4 sites, GIS was used to locate the specific site on a river reach such that the watershed and river slope could be defined. A 2,000 ft long penstock (600 m) was assumed for these sites and the hydraulic head over this stream reach was used as the turbine head to calculate power. USGS stream gage data for gages in the State of Hawaii with quality controlled, daily flow data was used to calculate an average flow per square mile (cfs per square mile) and average flow at sites near the gage. The average gage flow was multiplied by the watershed area of each potential hydropower site to obtain the average flow for that site. The USGS gages were selected for each of the potential hydropower sites based on their proximity to the gage and/or similarities in watershed characteristics and size. If a site was more than 5 miles from a USGS gage with a similar watershed, the average cfs per square mile for all of the gages on the island was used to estimate the average flow.

The incremental power capacity for the Category 4 sites was estimated using the calculated head and average flow with the same method described for Category 3 sites, and the incremental annual energy with the method described for the Category 2 sites.

The final type of potential hydropower sites were those that could not be defined, or were eliminated from the analysis for various reasons (Category 5). Some sites had no latitude/longitude coordinates, and as such the necessary GIS data for the cost analysis could not be obtained. Other sites were located on hazardous dams or otherwise poor conditions for hydropower development. Run-of-the-ditch sites with existing hydropower were assumed to be irrigation sites with no additional hydropower potential. Pumped storage sites without incremental capacity or annual energy defined in the source document were not analyzed because of the uncertainty of the flow available for power generation.

5.2.1.3 Outputs and Assumptions

As described above, incremental energy costs were calculated for 134 sites using standardized formulas, but if incremental energy costs were established in the source literature, these values were updated to 2010 costs based on USACE Civil Works Construction Cost Index System and used in place of the calculated incremental energy costs (USACE 2010). It was assumed that incremental energy costs calculated in the source literature (often in-depth engineering reports) were more reliable than the costs as calculated as described above for all 134 sites. All discussion of incremental energy costs hereafter refers to the best available estimates, which represent a mix of values calculated and found in the source literature, where available.

Incremental energy costs for the sites in the database range from $0.03/kWh to $1.72/kWh. For this study, the power potential of the sites has been characterized as Excellent, Good, or Poor. An Excellent designation was assigned if the incremental energy cost was less than $0.10/kWh. If the incremental energy cost was greater than $0.10/kWh but less than $0.25/kWh, the site was considered to be a Good site. Sites with incremental energy costs greater than $0.25/kWh were considered to be Poor sites and did not pass the screening.

5.2.1.4 Sensitivity Analysis

Licensing and transmission line costs are the two greatest issues that would influence the economic feasibility of hydropower development. In order to evaluate the impacts of added costs associated with these issues on a project incremental energy costs, an additional $500,000 and $1,000,000 were added to capital costs for developing the potential hydropower sites. For this study, $500,000 was selected as additional licensing costs that would be required for a site with significant recreational, cultural, and/or environmental issues. In addition, $500,000 was selected to represent additional transmission line costs that may be associated with any of the projects. A review of GIS data indicated that all of the proposed sites are less than 10 miles from a population center. Construction industry cost data indicates that transmission line installation costs would be approximately $50,000 per mile (RS Means, 2007). Therefore, adding $500,000 to each of the project costs would represent a reasonable approximation of licensing costs for a cultural or environmentally sensitive site or a site needing transmission line improvements. An additional $1,000,000 would represent additional costs for a site that has licensing and transmission line issues.

5.2.2 Environmental/Social Screening Criteria: Conventional Hydropower

Developing conventional hydropower resources in the State of Hawaii may impact natural resources and be subject to considerable community scrutiny due to social/cultural concerns. Additional coordination with DBEDT may help in identifying likely resource areas and assistance with renewable energy development.

For this study, all potential sites identified in the literature review were assessed on a rough scale of low to high environmental/social concerns. These potential projects would require in-depth research prior to development which could result in a ranking change. Boundaries could also change over time, resulting in new critical habitat, conservation zones, or land-use restrictions.

For this study, sites were ranked as having high environmental/social concerns if they were located in Class 1a or 1b waters. These classes are specified in the State of Hawaii HAR 11-54 as inland surfaces waters with limited uses based on their locations. These classifications limit allowable land uses and provide specific habitat for protected or endangered species. Hydropower proposals located in Class 1a or 1b waters would result in conflict with the State Department of Health over appropriate use of these waters.

- Class 1a waters are limited to "scientific and educational purposes, protection of native breeding stock, baseline references from which human-caused changes can be measured, compatible recreation, aesthetic enjoyment, and other non-degrading uses which are compatible with the protection of the ecosystems associated with waters of this class." Class 1a waters includes all waters within state and national parks, federal and state fish and wildlife preserves, sanctuaries, refuges, and U.S. Fish and Wildlife Service unique/critical habitat areas. Sites located within Class 1a waters were considered to have high environmental concerns due to land use conflicts.

- Class 1b uses are "domestic water supplies, food processing, protection of native breeding stock, the support and propagation of aquatic life, baseline references from which human-caused changes can be measured, scientific and educational purposes, compatible recreation, and aesthetic enjoyment. Public access to these waters may be restricted to protect drinking water supplies." Class 1b waters are located within the State Land Use Conservation District Protective Subzone. Sites located in Class 1b waters were ranked as having high environmental concerns due to land use restrictions and allowable water uses.

- In some instances, ditch systems fall within the Conservation District Protective Subzone. Ditch systems which do not discharge into other waters of the state are considered agricultural waters, and are separate from the HAR classifications. However, due to the Protective Subzone development restrictions in the surrounding land, these sites were ranked as having medium environmental concerns.

All remaining waters within the State are listed as Class 2 waters. Uses include industrial and agricultural, which can include hydropower.

Site locations were ranked as having high environmental/social concerns if they were located along a stream of cultural importance based on the 1990 Hawaii Stream Assessment. Not all streams were part of this survey. This assessment was considered to be an indicator of cultural significance.

Sites were also ranked as having high environmental/social concerns if they were within a native forest as based on Gap Analysis Program (GAP) satellite data. The goal of University of Idaho/USGS GAP data is to identify land coverages in order to protect and identify whole ecosystems rather than a single species-by-species approach. The coverages are corrected to be state-specific based on satellite imagery and known vegetative surveys. In the State of Hawaii, this includes 39 different land covers, including strawberry guava dominant forests to open ohia forest with uluhe fern.

Sites were ranked as having medium environmental/social concerns if they were part of a previous hydropower location. These sites may have environmental/social challenges today, but the existing infrastructure is already in place. Medium sites frequently refer to irrigation ditch and reservoir systems that are currently in operation as opposed to stream-based hydropower systems. More site-specific information should be obtained for these locations.

Sites were ranked as having low environmental/social concerns if they were currently operating hydropower locations. Pumped storage facilities were listed as having low concerns if existing reservoirs could be used, or if existing reservoirs did not need to be greatly expanded. Locations with low opposition/impacts listed in their original documents were ranked as such if these factors have not changed significantly since the time of publication. Sites may become less feasible due to changes in critical habitat boundaries, water class, public opposition, and land use.

Many of the reports referenced are basic engineering reports that only calculated the potential energy at the various locations, and did not perform environmental/cultural assessments or public outreach. Each stream and site is unique and has a multitude of potential issues that may impede development. Water rights and usage is a hotly contested issue in the State of Hawaii, and citizen groups are active and vocal in this regard. For example, several plans to develop the hydroelectric capacity of the Wailua River on Kauai have been met with strong local opposition over the past four decades. Maui will be implementing new instream flow standards that could alter the feasibility for some irrigation ditch hydropower systems due to decreased flows.

5.2.3 Federal Interest in Hydropower:

Developing renewable energy sources is an output with a high budget priority, and promoting energy independence is the primary output of the alternatives to be evaluated in the feasibility phase, there is a strong federal interest in conducting the feasibility study. There is also a federal interest in other related outputs of the alternatives including flood control, irrigation, drinking water and navigation that could be developed within existing policy. Based on the preliminary screening of alternatives, there appears to be potential project alternatives that would be consistent with Army policies, costs, benefits, and environmental impacts. These alternatives have the potential to increase State energy security. A stronger flexible electrical grid could help the State during natural disasters and oil shortages or cost fluctuations. Energy expenditures will also be kept in-state rather than exported. New technologies can be developed for export to other states. Updated hydropower infrastructure can benefit agriculture and drinking water supplies by keeping water systems maintained and in operation. Renewable energy systems can be combined with flood control projects and sediment management projects.

USACE Island Specific Reports:

- Hawaii: Flood Control: The Keaiwa-Meyer Reservoir project site is within the Paauau, Hawaii, flood control project area. This includes a levee, hardened walls, floodplain easements and management areas constructed in 1984. This report does not specifically identify potential hydropower sites, but does highlight potential flooding hazards within the area.

- Maui: Maui has a variety of USACE reports which covered geographic areas of interest for hydropower. Many potential hydropower projects in Maui called for the use of existing irrigation ditches and/or streams on West Maui for run-of-the-river/run-of-the-ditch systems. Changes and alterations in stream and irrigation flow could have an impact on estimated capacity and costs of these hydropower plants.

  - Kahoma Stream Flood Control, Maui
  - Reconnaissance Study: Hawaii Water Management: Pioneer Mill, Kokee Kekaha, East Kauai, Waiahole, Upper and Lower Kula, Kauai, 2005
  - Reconnaissance Study: West Maui Watershed Project (includes all of the West Maui drainages from the south at Mā‚alaea, west at Lahaina, north at Honokōhau, and east at Wailuku), 2009.

- Oahu: One project fell within the USACE 1980 Kaneohe-Kailua flood control project area. This includes the Kamooalii-Kaneohe drainage basin, which is bounded on the west and south by the Koolau Mountain Range, on the east by the remnants of Kaneohe volcanic cone, and on the north by Kaneohe Bay. This report provides general background information on location for a proposed site, but no data specifically for hydropower. The Reconnaissance West Honolulu Watershed Study (2003) provided excellent background information that could be used for sites in the Waikele area, but did not specifically address hydropower topics. Changes and alterations in stream and irrigation flow in this area could have an impact on estimated capacity and costs of these hydropower plants.

- Kauai: The USBR report identified the Puu Lua Kitano Kekaha area specifically with maps and data identifying the location of projects, potential capacity, and possible linkages using existing irrigation systems. The USACE flood control project at Waimea River provides background information on the general location, and highlights the problems associated with flooding and sediment deposition within the Waimea River.

  - USACE Flood Control: Waimea River, Kauai, 1984
  - USBR. 2004. Small Hydropower Potential on East Kauai Water User Cooperative Lands and Other Kauai Agricultural Water Delivery Systems. U.S. Department of the Interior, Lower Colorado Region. November.

5.3 Conventional Hydropower Evaluation Results

This report identified 166 conventional hydropower sites. Appendix A is a consolidation of information in an Excel format which provides a complete listing of the sites considered in this study, as well as the information gathered for each site. Site-specific data were collected from state, national, utility, and private sector reports, as well as contacts in the local hydropower community. Additional engineering and technical studies were not performed specifically for this report. The results of the study, therefore, are preliminary estimates of developable hydropower within the foreseeable future.

Each site was sorted into a database with more than thirty fields, including original or calculated cost per kilowatt hour, environmental/social constraints, and capacity. The complete listing of sites can be found in Appendix A. This document allows users to focus on any of the potential sites, their sources, and to sort by specific requirements. The sites should be used as a general ranking, to compare one to another, and not necessarily as a precise numerical hierarchy. All of these sites could have additional environmental/economic costs that are not immediately apparent from the data and literature review. As presented in Figure 5-1, of the 166 sites identified, 32 did not have their economic costs calculated based on the standardized format due to lack of source information or alternative sources of information. Of the remaining 134 sites assessed, 99 offered excellent energy costs calculated at less than $0.10/kWh, 27 had good energy costs between $0.10 and $0.25/kWh, and 8 sites had poor energy costs over $0.25/kWh.

Potential sites were identified through the screening processes described earlier in this report. Sites with excellent economic values, but high environmental/social concerns were dropped, as were sites with low environmental/social concerns but poor economic value.

In general, most of the potential hydropower sites were not sensitive to cost increases considered in the sensitivity analysis. The results of the sensitivity analysis indicate that adding $500,000 to $1,000,000 to the capital cost of all projects considered did not significantly change the cost per kWh breakdown as presented in Figure 5-1. Electric costs in the State of Hawaii are significantly higher than the mainland United States, thus projects that would seem too expensive could be feasible at a breakeven price, or cheaper than the current diesel power plants.

The sites with good to excellent incremental energy costs were cross-checked against sites with low to medium environmental/social concerns and extracted. This resulted in 75 sites with acceptable economic and environmental/social characteristics. A complete listing is available on the following page. Some of these may be different proposals at the same location.

The majority, though not all, of the screened potential sites are located in Hawaii (25 sites), Kauai (24), and Maui (16) (Tables 5-2, 5-3, Figures 5-3, 5-4, 5-5, 5-7). Identified projects on the island of Molokai are presented in Figure 5-2 to visually present the screening process. Some of these projects are duplicates or slightly different layouts on the same resources, so the actual unique count would vary depending on the projects selected. Some projects were located within the watershed, but lack longitude and latitude coordinates for exact locations. See Appendix A, complete matrix for details. Calculated capacity varies from less than 100 kW to over 50 MW, with an average of 6 MW. The majority of the sites, in particular run-of-the-river plants, are projected to produce less than 5 MW due to the small, variable nature of Hawaiian streams. The larger capacity plants (10 MW and greater) are typically pumped storage with larger reservoirs, some in excess of 15 acres. A large, firm source of hydropower is more appealing to the utilities.

Table 5-2. Number of Hydropower Projects with Acceptable Environmental/Social/Economic Characteristics.

		Identified/Inactive						
	Operating	**Pumped Storage**	**Run of river/ditch**	**Unknown**	**Storage**	**Total**	**Federal Interest**	**Total Identified & Inactive MW****
Hawaii	4	10	8	2	1	25	1	144.8
Maui	1	11	2	0	2	16	13	230.7
Molokai	0	5	0	0	1	6	0	14.9
Oahu	0	2	1	0	2	5	3	25.7
Kauai	8	1	10	0	4	23	16*	40.2
Total	13	29	21	2	10	75	33	456.3

*Three are United States Bureau of Reclamation (USBR) projects
** Multiple projects may be proposed for the same site, and as such this is likely an overestimate of identified development potential

The Big Island has four existing hydropower plants that passed the screening and could be expanded and upgraded (Figure 5-4). The majority of the new proposed projects are pumped storage, but there are several plans for reopening inactive projects, or using run-of-the-river. The Big Island could also combine wind and hydropower as described above. The northern and southern tips of Hawaii have excellent potential wind energy sites, but only the northern area has significant wind and rainfall.

On Maui, there is the potential to add additional power plants to existing ditches. Pumped storage could also provide additional firm energy backup (Figure 5-5). The currently operating Makila Hydro Plant (formerly Pioneer Mill) could be upgraded to 14.6 MW with an additional pumped storage system. Five large-scale 30 MW pumped storage sites have also been proposed for West Maui and Kula. This area offers good potential for hydropower based on environmental/social and economic considerations and should be examined for private development. However, the area does not have a primary federal interest, though sites do have federal interest due to hydropower, water supply, and irrigation projects.

All environmentally/economically feasible projects on Molokai are pumped storage (Figures 5-2, 5-5). Molokai has fast-flowing streams with a high head, but they are within the steep valleys along the north shore. Constructing power plants in these locations would be technically challenging and environmentally degrading. The least expensive scenario would expand one reservoir by 10 milling gallons and have the capacity to generate 3 MW (Molokai currently uses 5 MW). The largest potential site could generate 8.6 MW, but would require a large new reservoir (Chong, 2007).

Oahu had five potential sites (at several duplicate locations), but the projects were fairly small compared to the size of Oahu‟s energy usage (Figure 5-6). A lack of suitable streams and existing reservoirs limits hydropower possibilities. Oahu uses the largest amount of electricity, and should consider alternative sources of energy including solar, wind, biomass, and OTEC.

Kauai has fewer economically/environmentally feasible projects, but the ones that exist have strong potential, and use existing irrigation reservoirs and ditches (Figure 5-7). A number of proposed sites on the Kekaha/Kokee ditch system appeared multiple times on the shortlist. These projects had acceptable costs and lower environment/social concerns than other projects on the island. In addition, the Waimea Canyon area has an existing USACE flood control project that requires updating to meet the revised FEMA standards.

The Puu-Lua-Kitano-Waimea project near Waimea/Kekaha is recommended as an example project (Figure 5-8). It would boost hydropower on Kauai from 9 to 18 MW. This project is currently under review by a local company, and was recommended for development by KIUC. It combines hydropower with an active irrigation system. The project uses existing reservoirs and ditches, minimizing new construction. The system is on the century-old Kokee and Kekaha ditches. The Kokee Ditch primarily serves the upland areas along the west side of Waimea Canyon. This upper elevation ditch originally pulled water from five streams beginning at the Waimea headwaters within the Alakai Swamp, Mohili, Waiakoali, Kawaikoi, Kauaikinana, and Kokee Streams (Wilcox, 1996; DOA, 2003). The Alakai and Mohili intakes have since been abandoned. The system ran for 18 miles, and included the Puu Lua, Puu Opae, and Kitano storage reservoirs. The irrigation system was built by the now-closed Kekaha Sugar plantation. Today, the semi-public Agribusiness Development Corporation (ADC), under the Department of Agriculture, owns the infrastructure. The ADC leases the system to the Kekaha Agricultural Association, who maintains the system. The Department of Hawaiian Homelands has claims to water within the system, but run-of-the-ditch systems have the benefit of allowing water to be used downstream. The ditches have two small operating hydropower systems. The ditches and reservoirs need repairs, but improvements to this area would pay off not only for hydropower, but to allow for food and biofuels to be grown in the districts.

The Kekaha area has an existing flood control project built by the county in 1951 to prevent widespread flooding in the town of Waimea. The levee was rebuilt in 1984 by the USACE. During the past 20 years, over 5,000 cubic yards of sediment were added annually. The Kauai Department of Public Works did not have the funding to remove it. In 2004, the Waimea project was inspected by the USACE and listed as unacceptable and inactive due to lack of maintenance. In 2009, a USACE study found that the levee was below new Federal Emergency Management Agency (FEMA) requirements by two to three feet. Over 300 parcels in Waimea are no longer considered protected and now require flood insurance. The State has requested funding to build the levee up to the new FEMA guidelines (Hirono, 2010). Better sediment management upstream could reduce loading downstream to minimize flooding and siltation. This siltation is also filling the Kikiaola Small Draft Harbor causing coastal water quality problems currently being investigated by the USACE.

5.4 References

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Figure 5-1: Estimated Cost per kWh for the 166 Sites Identified

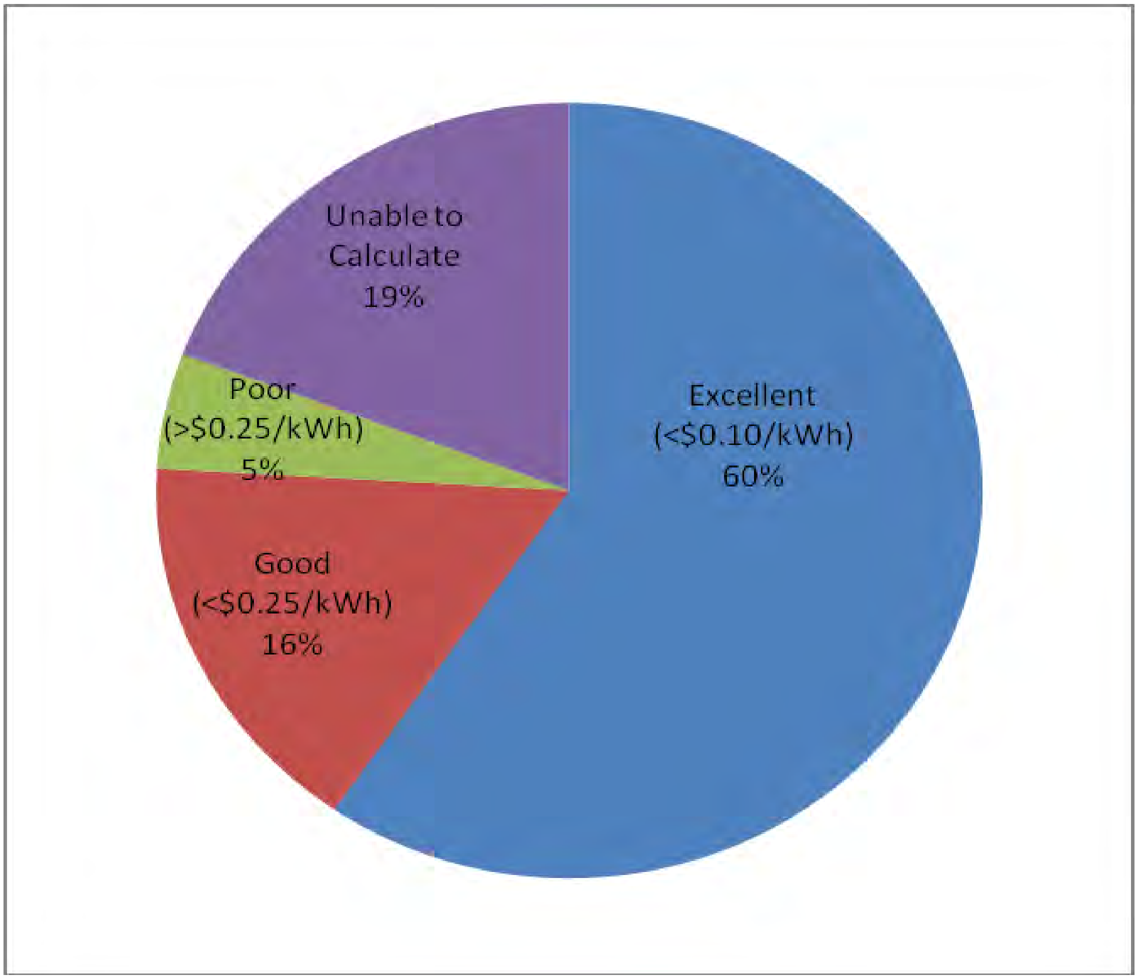
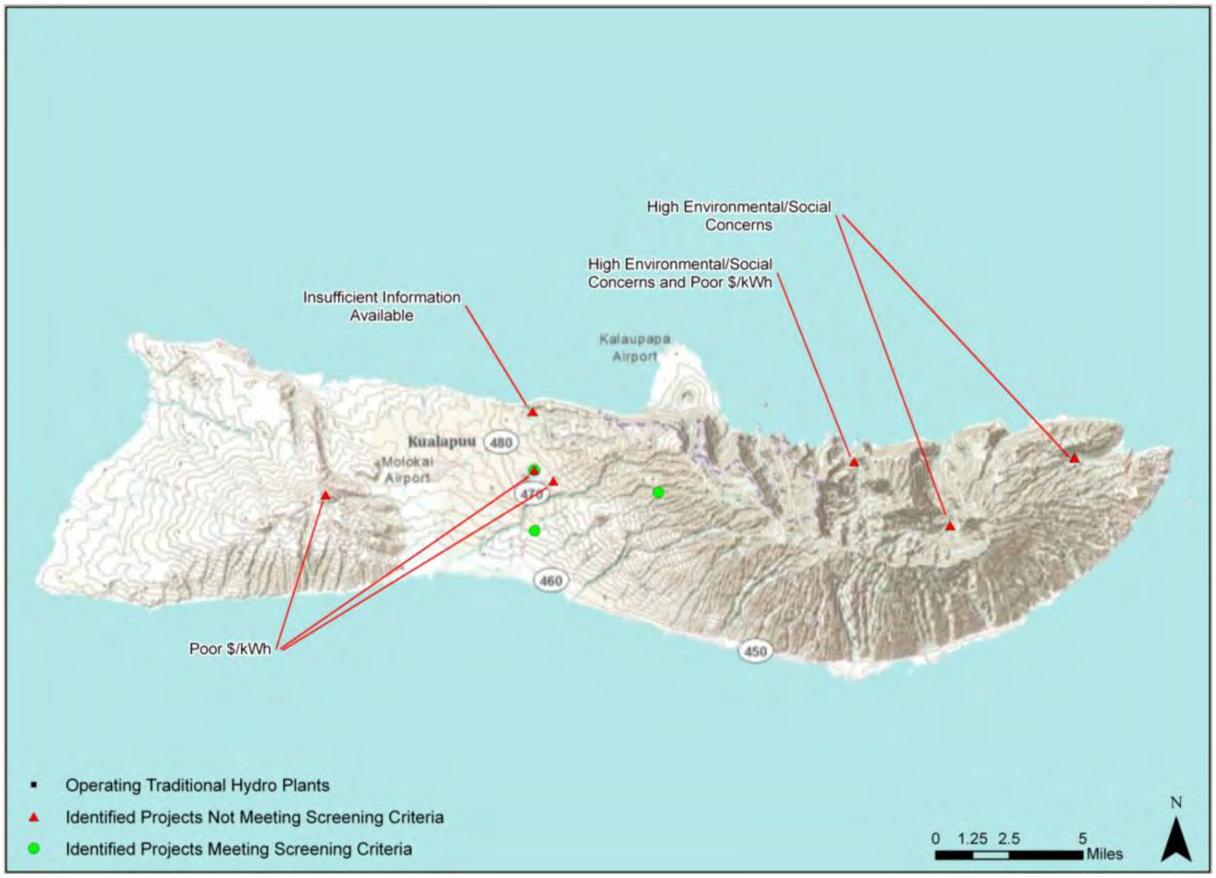


Figure 5-2: Example of Screening Rationale for Molokai



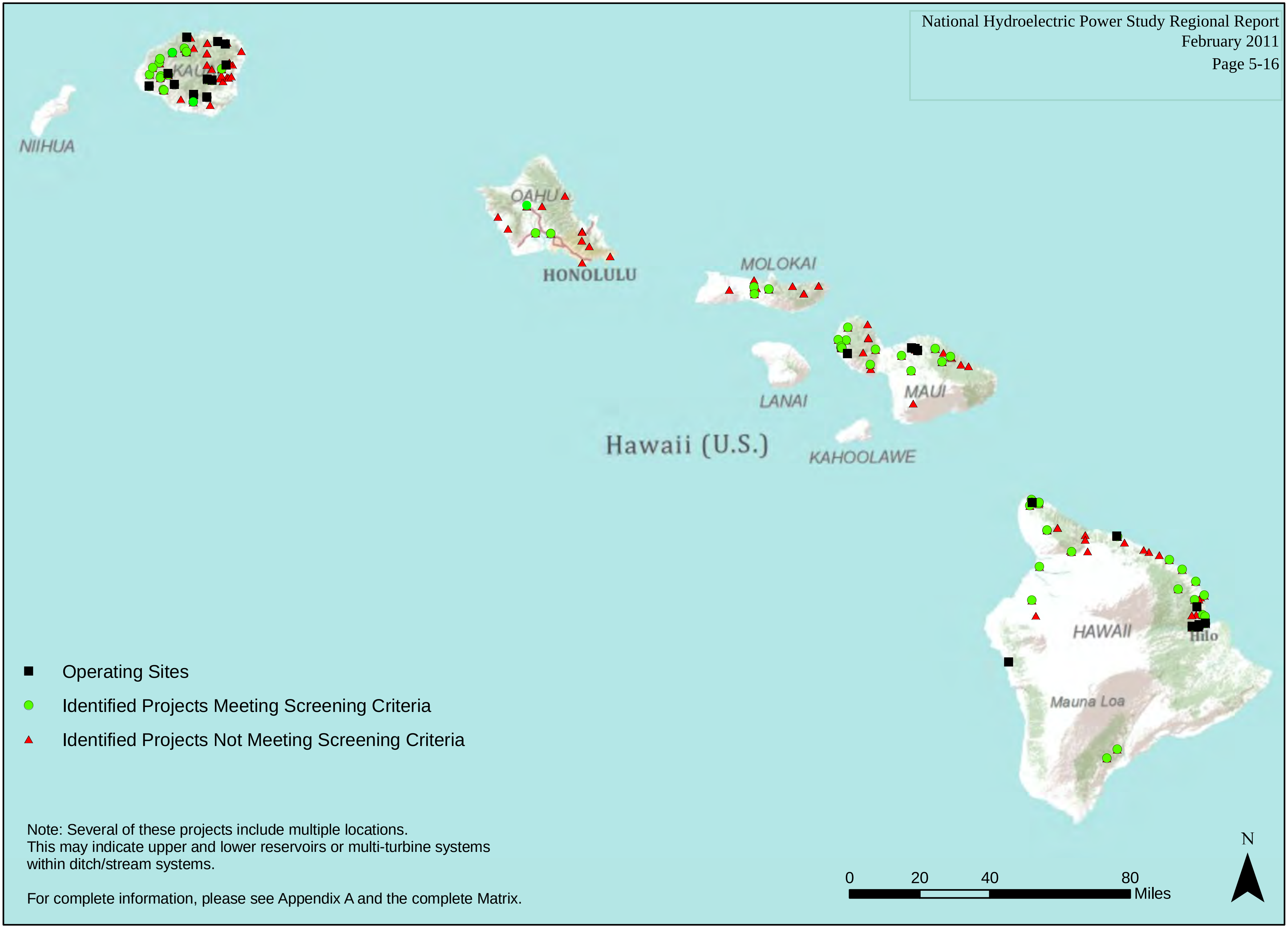


Figure 5-3: Operating and Potential Hydropower Projects: State of Hawaii

Prepared by EA Honolulu. Data from State of Hawaii GIS Oct. 2010 & EA Engineering

Figure 5-4: Operating and Potential Hydropower Projects: Hawaii County

Prepared by EA Honolulu. Data from State of Hawaii GIS Oct. 2010 & EA Engineering

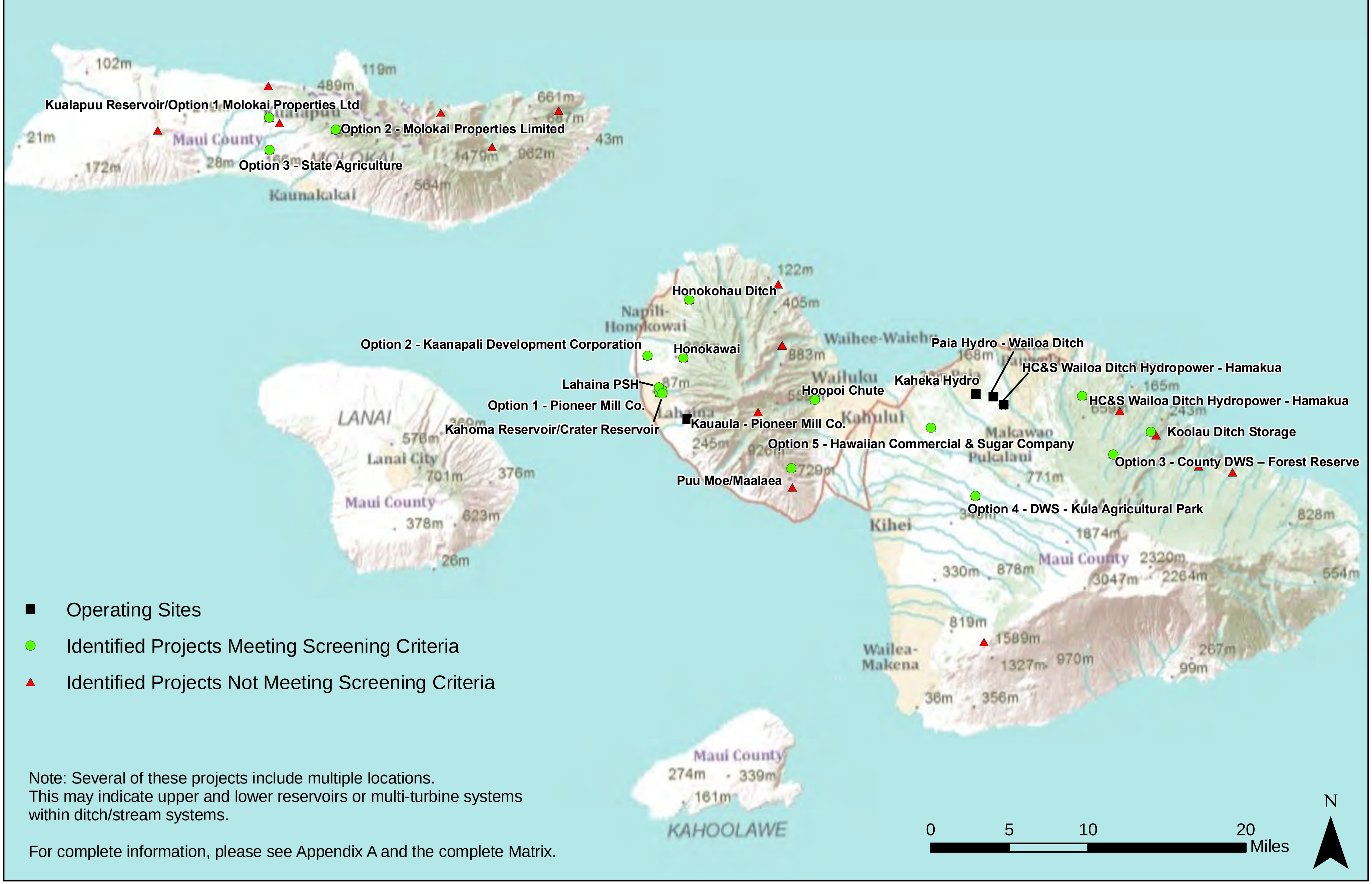


Figure 5-5: Operating and Potential Hydropower Projects: Maui County

Prepared by EA Honolulu. Data from State of Hawaii GIS Oct. 2010 & EA Engineering

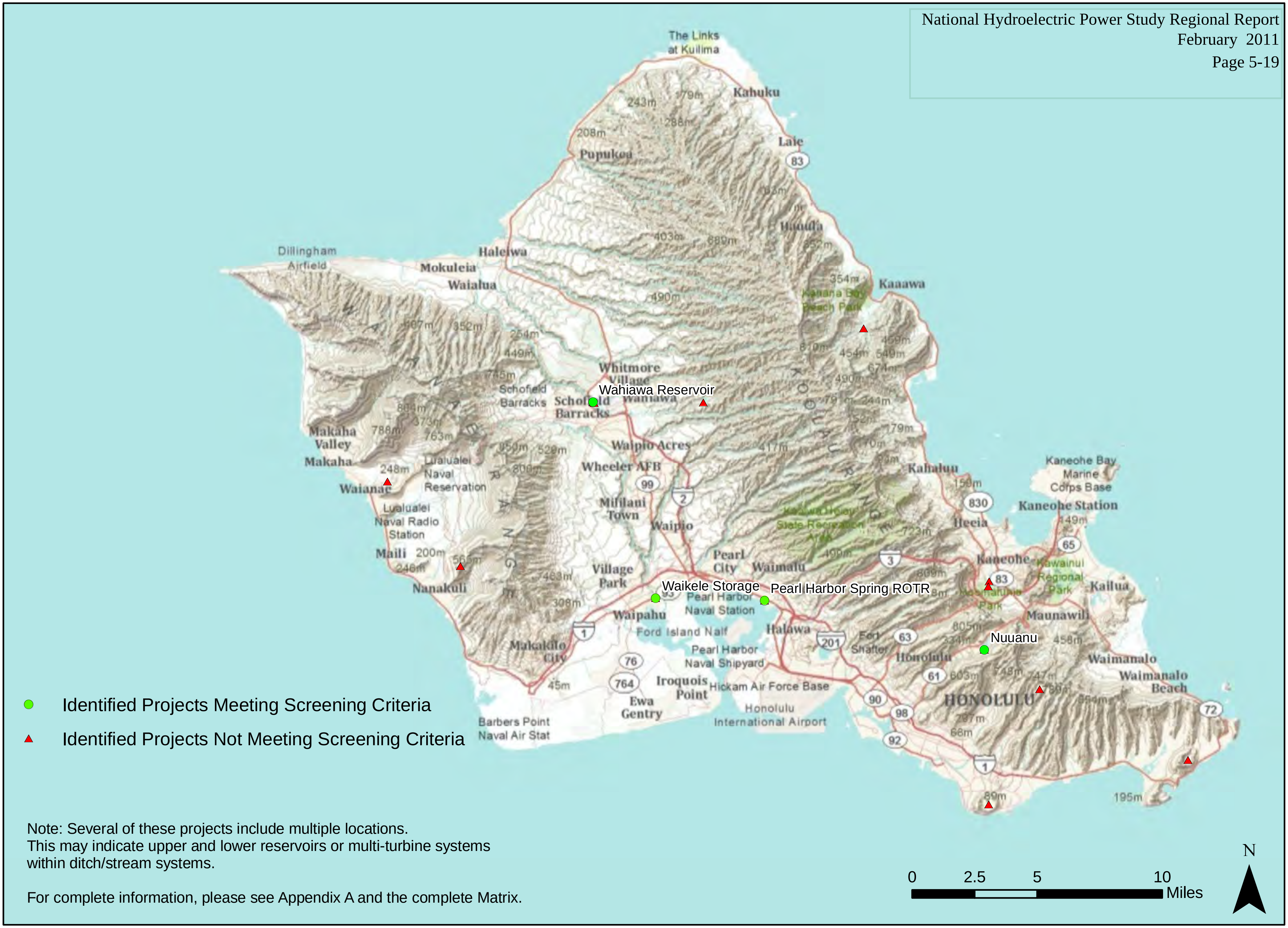


Figure 5-6: Operating and Potential Hydropower Projects: City & County of Honolulu

Prepared by EA Honolulu. Data from State of Hawaii GIS Oct. 2010 & EA Engineering

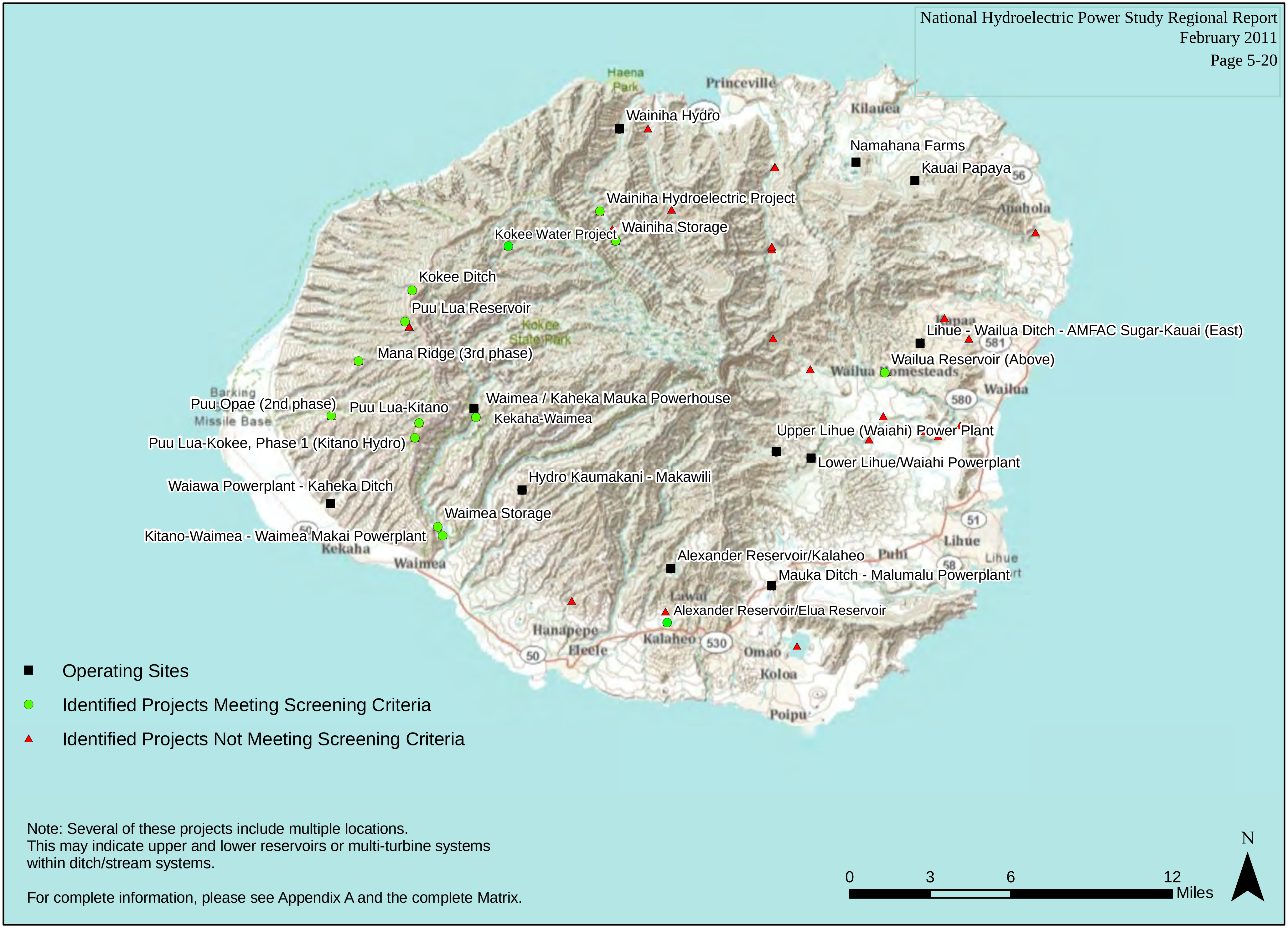
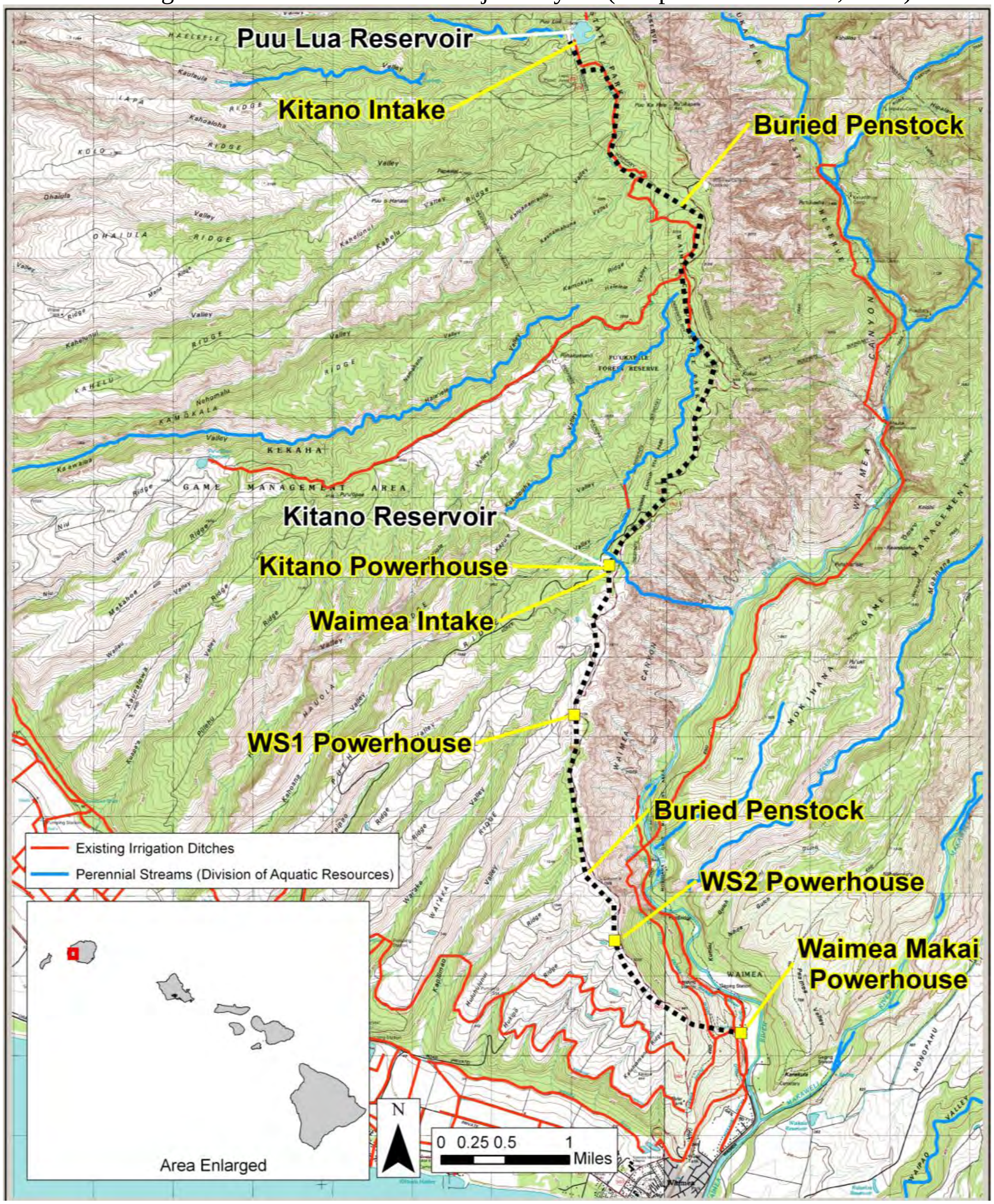


Figure 5-7: Operating and Potential Hydropower Projects: Kauai County

Prepared by EA Honolulu. Data from State of Hawaii GIS Oct. 2010 & EA Engineering

Figure 5-8. Puu-Lua Kitano Project Layout (Adapted from USBR, 2004)



6.0 EVALUATION OF OCEAN ENERGY OPTIONS

6.1 Ocean Energy Concerns

Ocean and wave energy production involves new technologies whose long-term effects require further study from test sites. Much of the State of Hawaii"s shore is heavily used and highly visible. The lack of a large continental shelf on the islands restricts wave energy sites to areas within three nautical miles. These near shore construction projects would likely face opposition on the grounds of viewshed or user conflicts. Projects would need to be situated far off-shore, as in the case of OTEC, at a low-profile, or away from close public access.

6.2 Data Collection and Screening Criteria

Geospatial analysis was utilized to delineate areas of high resource availability and low permitting and technical constraints for OTEC and WEC (Figures 6-1, 6-2, and 6-3). Potential OTEC development areas were approximated using the following approach:

- OTEC must be sited deeper than the 1000 m bathymetric as the systems require an annual average temperature difference of about 20° C between the warm water source (surface) and the cold water source (typically 1,000 m depth) as gross power output is proportional to the square of this temperature differential (ΔT).

- OTEC should generally be sited within 10-20 nautical miles of the coastline to minimize costs associated with transmission to electricity demand centers, construction and maintenance.

Potential WEC development areas were approximated using the following approach:

- Most current WEC devices are designed to operate within 70 m of water depth.

- WEC should be sited outside of known protected areas such as marine life sanctuaries and outside of known sensitive areas such as Class AA marine waters.

- WEC should generally not be sited in close proximity to boating facilities, fish-aggregating devices, harbors, major surf spots, and impediments to navigation.

- WEC should be sited in areas with high wave energy resource potential, as defined in Hagerman (1992) and depicted in Figure 6-1. These figures indicate priority areas, and additional locations should not be discounted.

As shown in Figure 6-1, areas of potential OTEC development are found off the southwest coasts of Kauai, Oahu, and Hawaii. This distribution is based mostly on the presence of high temperature differential values found in these areas. Areas of potential WEC development are generally found on the north shores of Kauai, Oahu, Maui and Hawaii. No WEC development areas were delineated on the north shore of Molokai due to low electricity demand and considerable construction difficulties due to the rugged terrain found there. The distribution of potential WEC development areas is based mostly on the various constraints found in the near-shore zone, particularly protected and sensitive waters. The approximate area of each zone is shown in Table 6-1. It should be stressed that the areas shown in the Figures are approximate, based only on the considerations listed above, and meant solely for the purposes of state-level reconnaissance. More detailed siting studies will be required during the feasibility study stage.

Table 6-1. Approximate Area of OTEC and WEC Resource Zones.

Zone	Area (Square Miles)
Hawaii WEC 1	209
Hawaii WEC 2	27
Hawaii OTEC	995
Oahu WEC 1	12
Oahu WEC 2	9
Oahu WEC 3	36
Oahu OTEC	717
Maui WEC 1	6
Maui WEC 2	38
Kauai WEC 1	15
Kauai WEC 2	19
Kauai OTEC	733

In order to limit potential impacts and reduce permitting needs due to NOAA regulations, ocean energy sites were not considered within the Hawaiian Islands Humpback Whale National Marine Sanctuary or within Class AA Marine Waters as defined by the State of Hawaii HAR 11-54-3 and State of Hawaii GIS:

> It is the objective of class AA waters that these waters remain in their natural pristine state as nearly as possible with an absolute minimum of pollution or alteration of water quality from any human-caused source or actions. To the extent practicable, the wilderness character of these areas shall be protected. No zones of mixing shall be permitted in this class. The uses to be protected in this class of waters are oceanographic research, the support and propagation of shellfish and other marine life, conservation of coral reefs and wilderness areas, compatible recreation, and aesthetic enjoyment.

The State of Hawaii has unique marine life, and construction near existing reefs would create conflict even in places that are not officially recognized as marine life sanctuaries. While not explicitly considered in this report, site-specific habitat concerns could be identified through the NOAA Center for Coastal Monitoring and Assessment mapping program. This geospatial dataset identifies near shore marine cover, structure, and zones. This data was derived from IKONOS imagery and fact-checked in problem areas.

The areas of high wave energy resources could also overlap with popular surfing locations. (Hawaii State Office of Planning, 1994). Consistent waves offer more WEC potential that areas with large seasonal swells, but this new technology should have good public outreach to ensure that accurate information is shared. Waves can bypass or pass through WEC devices to re-form in shallower areas. However, any large item in the ocean will reduce waves immediately behind it. A 2005 report on wave energy (EPRI, 2005) acknowledged that there could be a 12 percent reduction in waves directly behind WEC devices, with a 5 to 10 percent reduction in overall wave heights. Wave height variances due to construction would require site-specific study.

6.3 Evaluation Results

Ocean energy is a newer technology with fewer site-specific studies. Ocean energy technology project areas can be much larger in scope, as the technology is not limited to a single river or irrigation ditch. Proposals focused on pilot projects, with an interest in expanding potential sites through a streamlined permitting and grid connection system. A designated ocean renewable energy zone could reduce permitting costs for pre-approved districts throughout the State of Hawaii. Infrastructure costs could be leveraged by establishing energy hubs where multiple pilot and commercial devices could be linked to the existing energy grid, sharing costs for substations, transmission lines, and permitting.

Ocean thermal energy exists where there is at least a 20 °C temperature differential between the surface and cold water source, typically at 1000 m depth. This primarily occurs on the leeward coasts of the islands, in particular Oahu, Kauai, and Hawaii. The boundary runs from the 1000 m depth to 20 nautical miles offshore due to undersea connection costs. Hawaii has roughly 1,000 square miles of potential OTEC waters. Maui does not offer good OTEC resources due to a shallow coastal shelf and marine sanctuaries. Oahu and Kauai have approximately 700 square miles of OTEC resources (Figures 6-1 to 6-5). The 20 nautical mile limit is not the definitive boundaries; this report does not eliminate potential sites, but identifies sites with greater potential. The most feasible locations are at Kahe Point on Oahu and Keahole Point at the Natural Energy Laboratory Hawaii Authority in Kona, Hawaii. Both sites are located near existing electrical substations, and the Keahole site has access to an existing deepwater intake pipe.

Wave energy resource potential is found on the northern and windward coasts. Current WEC systems operate within 70 m depth due to the State of Hawaii‟s narrow coastal shelf; this restricts wave energy development within 3 nautical miles of shore. It is possible that WEC construction could reduce sediment transport, effecting shoreline widths. WEC resource sites in this report are limited by marine sanctuaries and harbor shipping lanes. These factors were not taken into consideration in the 1992 Hagerman report. The majority of wave resources are found on Hawaii with 78 square miles, Oahu with 58 square miles, Maui with 44 square miles, and Kauai with 35 square miles (Figures 6-2 to 6-5) of potential sites. The United States Navy is developing the Kaneohe wave energy construction site. Oceanlinx, an Australian company, has been pursuing the Pauwela, Maui location.

6.4 References

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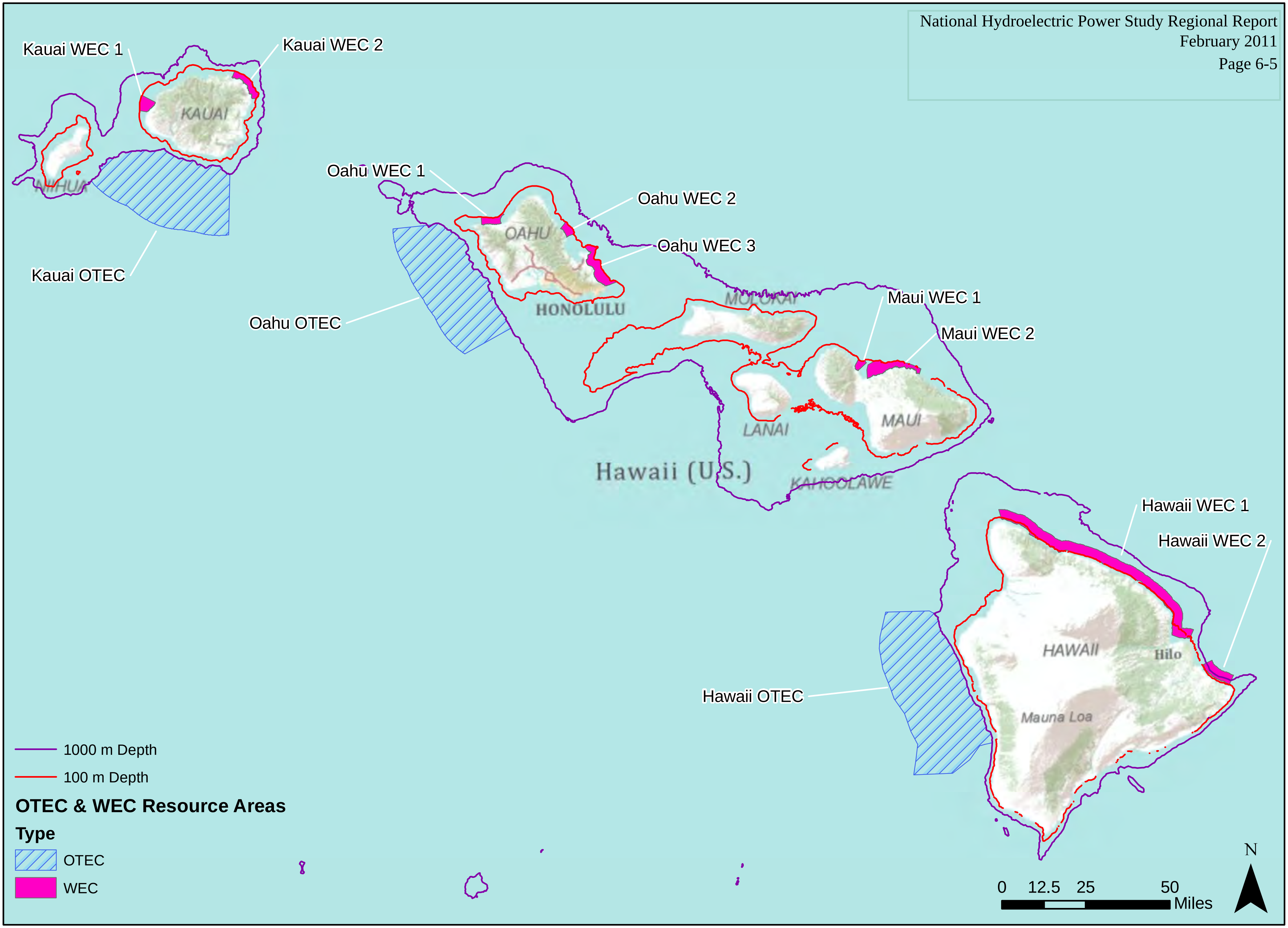


Figure 6-1: OTEC & WEC Resource Areas: State of Hawaii

Prepared by EA Honolulu. Data from State of Hawaii GIS Oct. 2010 & EA Engineering

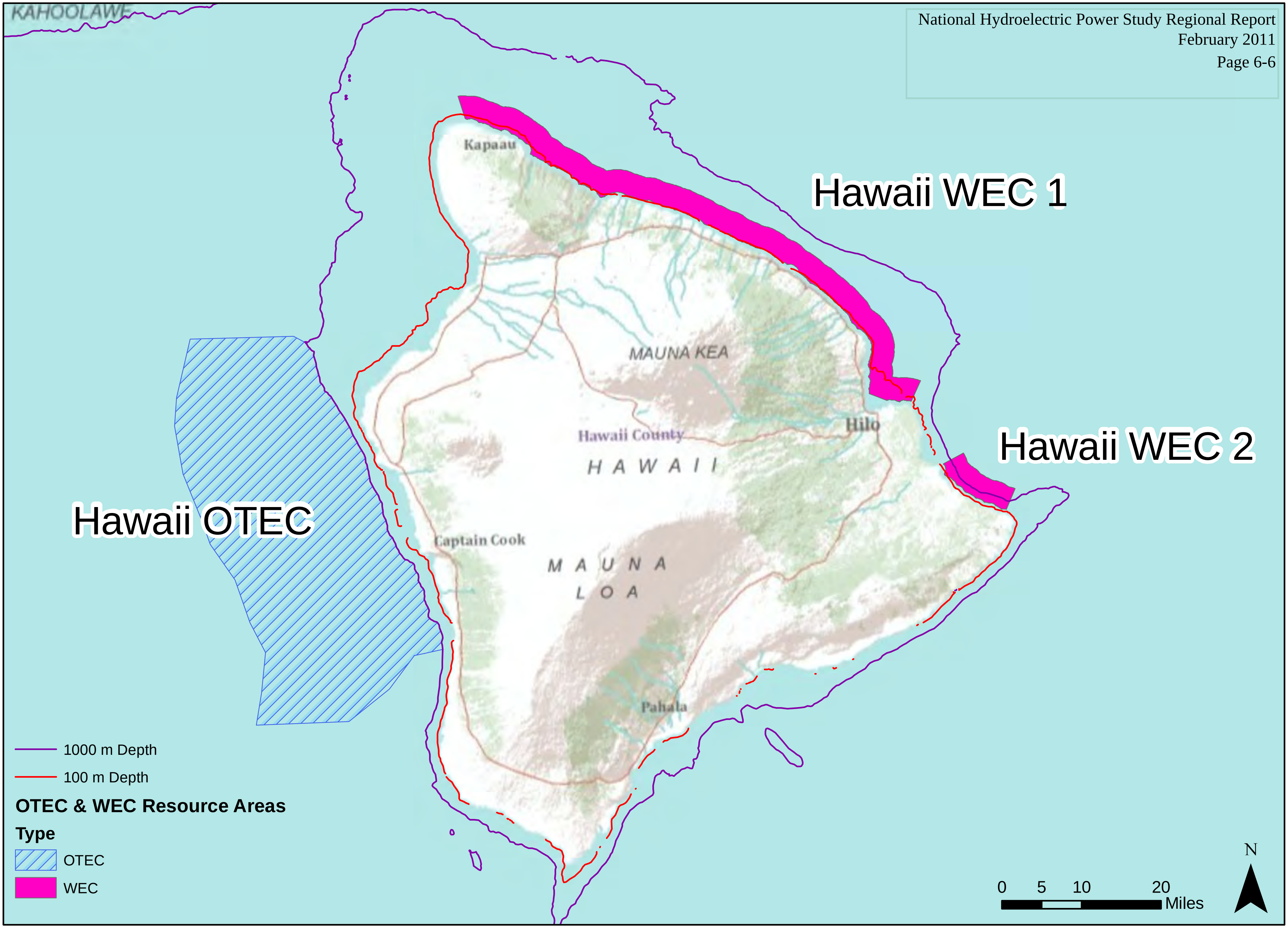


Figure 6-2: OTEC & WEC Resource Areas: Hawaii County

Prepared by EA Honolulu. Data from State of Hawaii GIS Oct. 2010 & EA Engineering

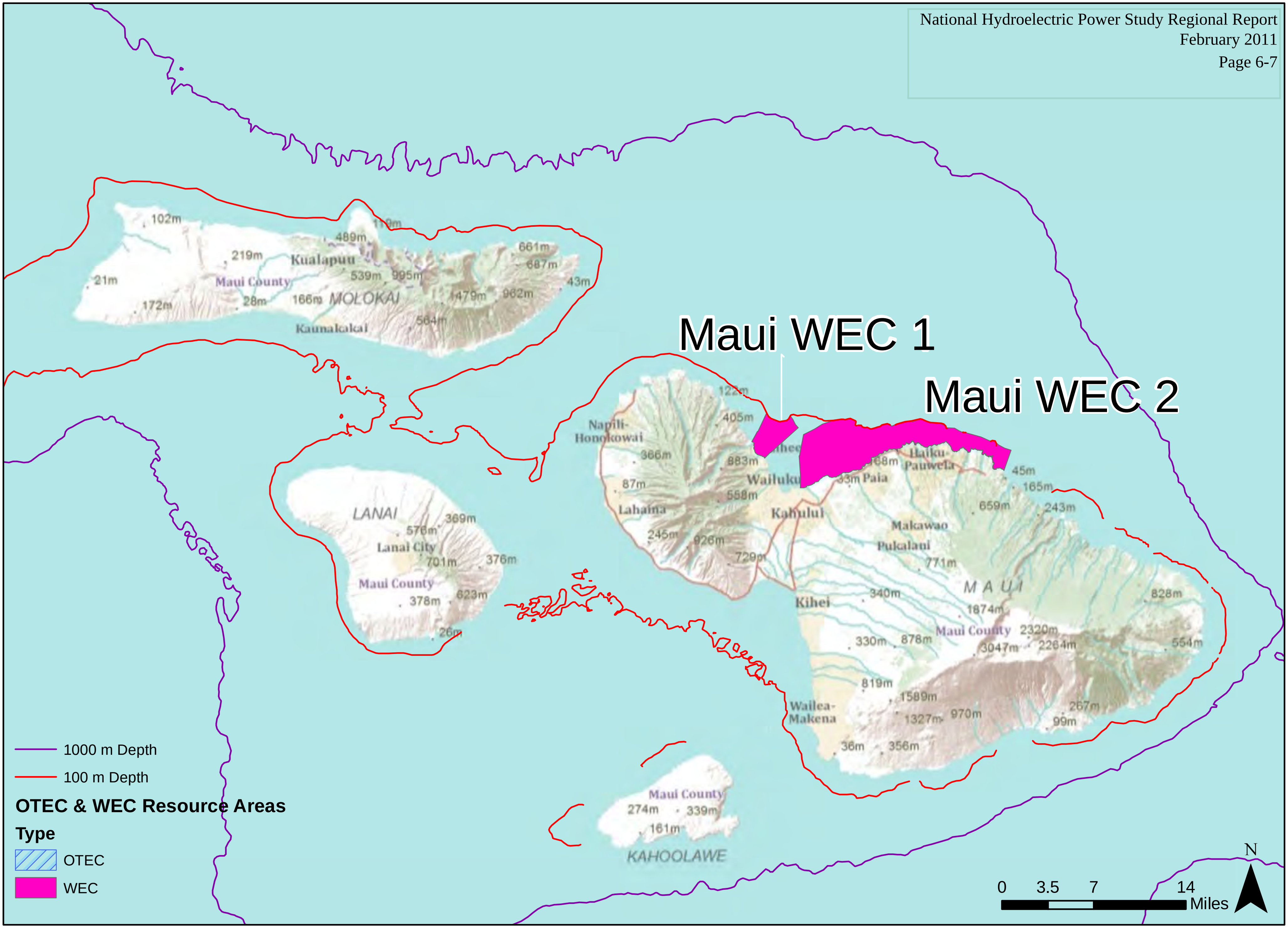


Figure 6-3: OTEC and WEC Resource Areas: Maui County

Prepared by EA Honolulu. Data from State of Hawaii GIS Oct. 2010 & EA Engineering

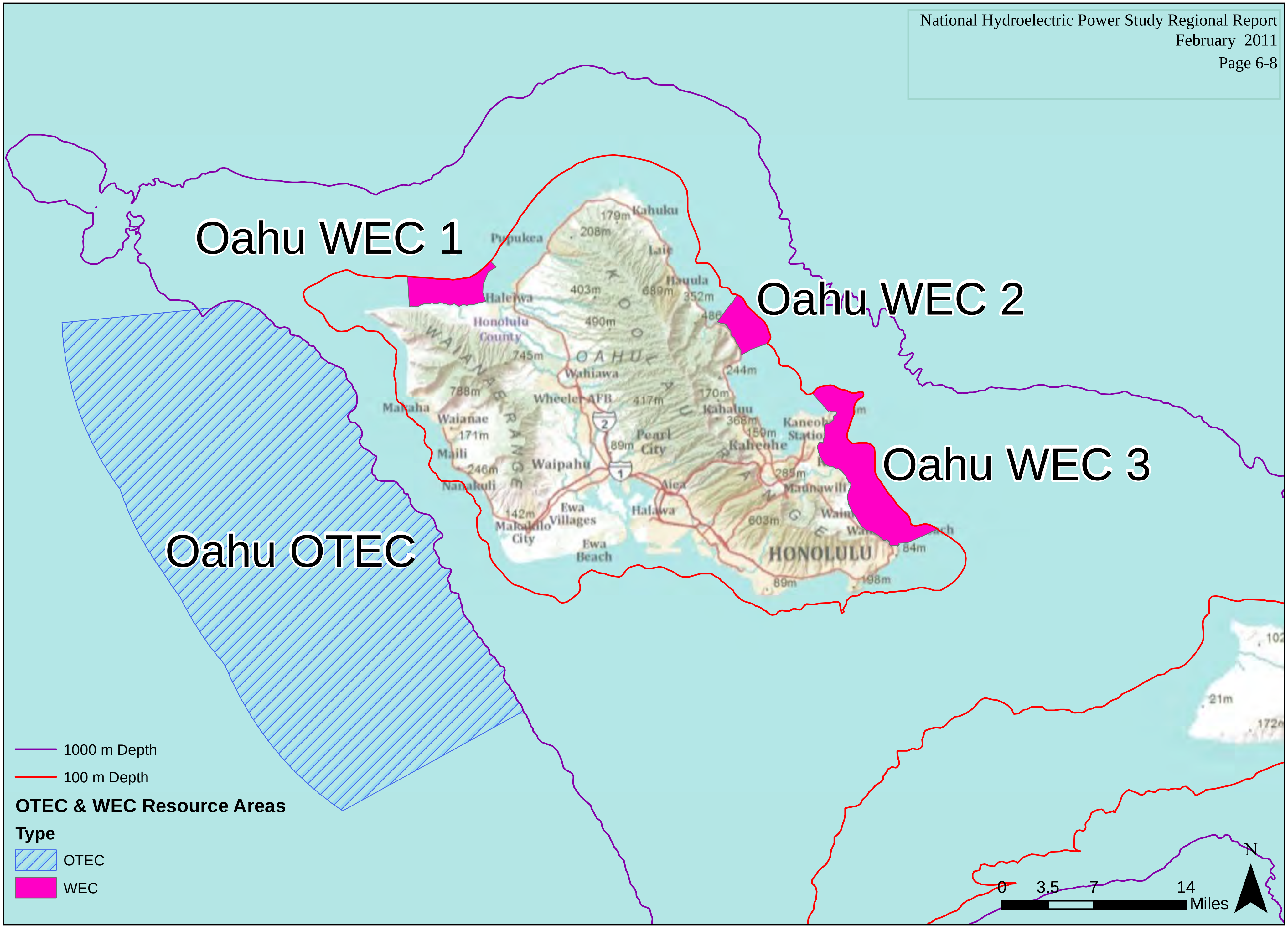


Figure 6-4: OTEC and WEC Resource Areas: City & County of Honolulu

Prepared by EA Honolulu. Data from State of Hawaii GIS Oct. 2010 & EA Engineering

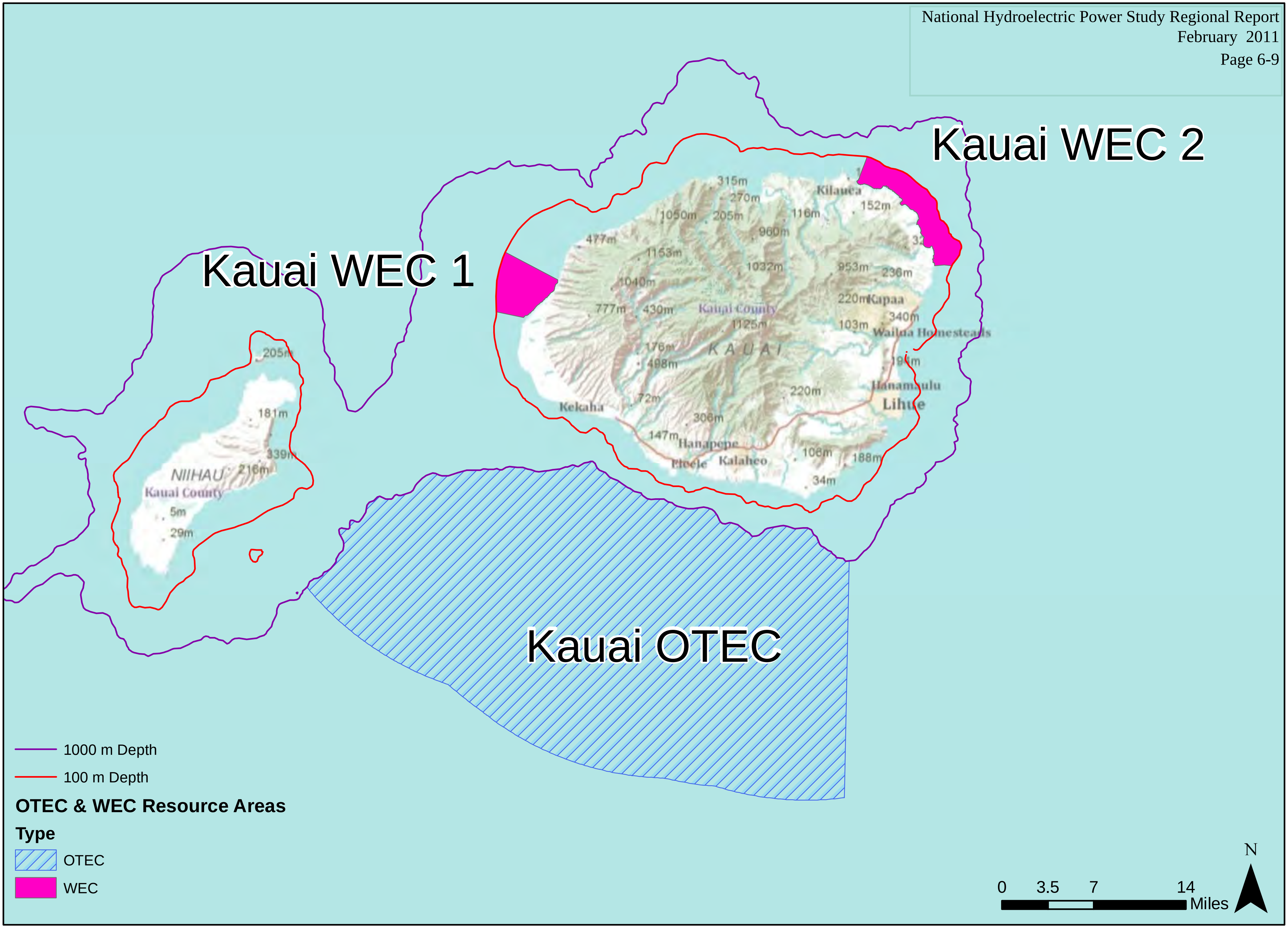


Figure 6-5: OTEC & WEC Resource Areas: Kauai County

Prepared by EA Honolulu. Data from State of Hawaii GIS Oct. 2010 & EA Engineering

APPENDIX A. IDENTIFIED CONVENTIONAL HYDROPOWER PROJECTS IN THE STATE OF HAWAII

A complete electronic listing (Microsoft Office Excel) is available. Please contact:

Deborah Solis
U.S. Army Corps of Engineers, Honolulu District
Civil and Public Works Branch
Programs and Project Management
Building 230
Fort Shafter, HI 96858-5440
(808) 438-0701

APPENDIX B. SWAN CALIBRATION

Appendix B

SWAN Calibration

Archival data available for the NOAA/NDBC Buoy 51201 and Buoy 51202 includes estimates of significant wave height (Hs) for the period September 2004 to December 2009. Buoy location and water depth are given in Table B1. To assess the accuracy of parameters obtained with SWAN over the same period, scatter plots of computed and measured Hs were obtained as shown in Figure B1 and Figure B2 at both locations.

While analysis based on all available buoy data indicates that SWAN appears to underpredict Hs at the shallower buoy site (Mokapu Pt.), the correlation value at both locations is 0.9. Scatter plots were also derived for the more energetic period of November-April, and the May - October period (Figure B3 through Figure B6) with results indicating that SWAN underpredicts Hs values ($\leq$ 1 m) during the energetic period. The correlation values are included in the Figures. NOAA/NDBC reports an accuracy of $\pm$ 0.2 m in their estimates of wave height.

It must be noted that the wave power flux, as defined by equation 1, can be expressed as

$$P_o = c_G E_{tot} = \frac{\rho g^2}{64\pi} \mathrm{T_e} H_s^2 \quad (Watts/m) \qquad (2)$$

such that, the wave power flux is proportional to the wave period and to the square of the wave height.

The Energy-Period, T_e, and the significant wave height are defined as:

$$H_s = 4\sqrt{\iint (S(\omega,\theta,h) d\omega d\theta} \qquad (3)$$

$$T_e = 2\pi \left(\frac{\iint \{(S(\omega,\theta,h)/\omega) \tanh(kh)[1 + 2kh/\sinh(2kh)]\} d\omega d\theta}{\iint S(\omega,\theta,h) d\omega d\theta} \right) \qquad (4)$$

Table B1 - NOAA/NDBC Buoy Locations

Station	**Location**	**Latitude (N)**	**Longitude (W)**	**Water Depth (m)**	**Data Availability**
51201	Waimea Bay	21.673	158.116	198	Sep 2004-Dec 2009
51202	Mokapu Point	21.417	157.668	100	Sep 2004-Dec 2009

Figure B1 - Hs Scatter Plot for Buoy 51201 (198 m)

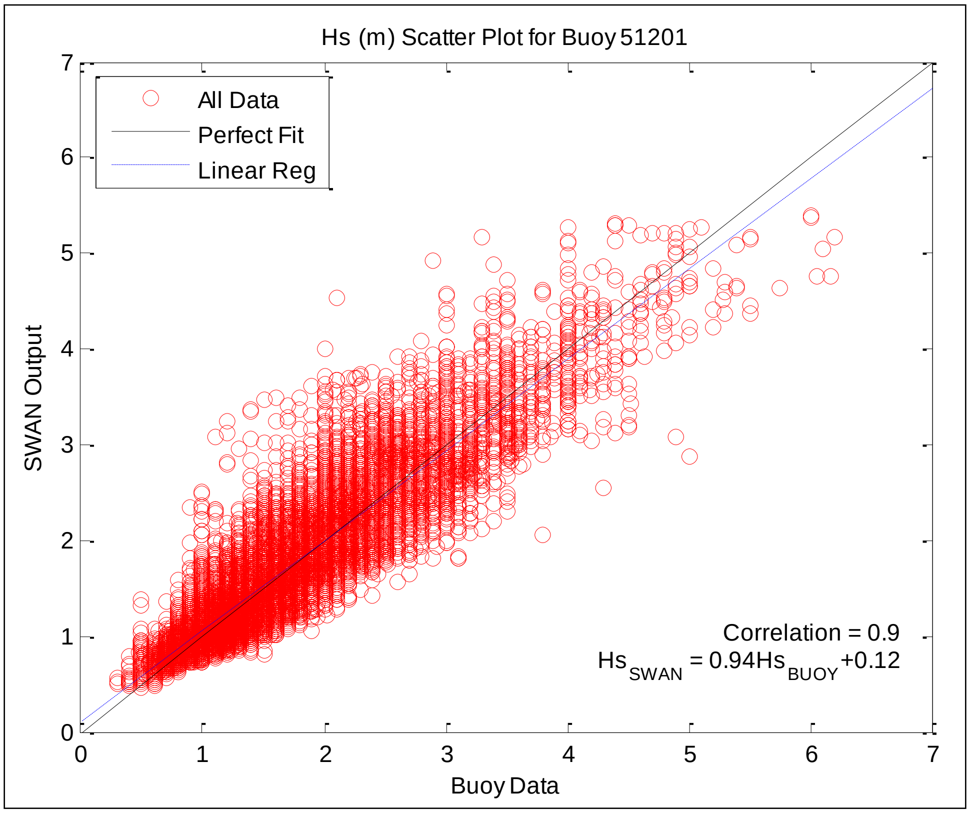


Figure B2 - Hs Scatter Plot for Buoy 51202 (100 m)

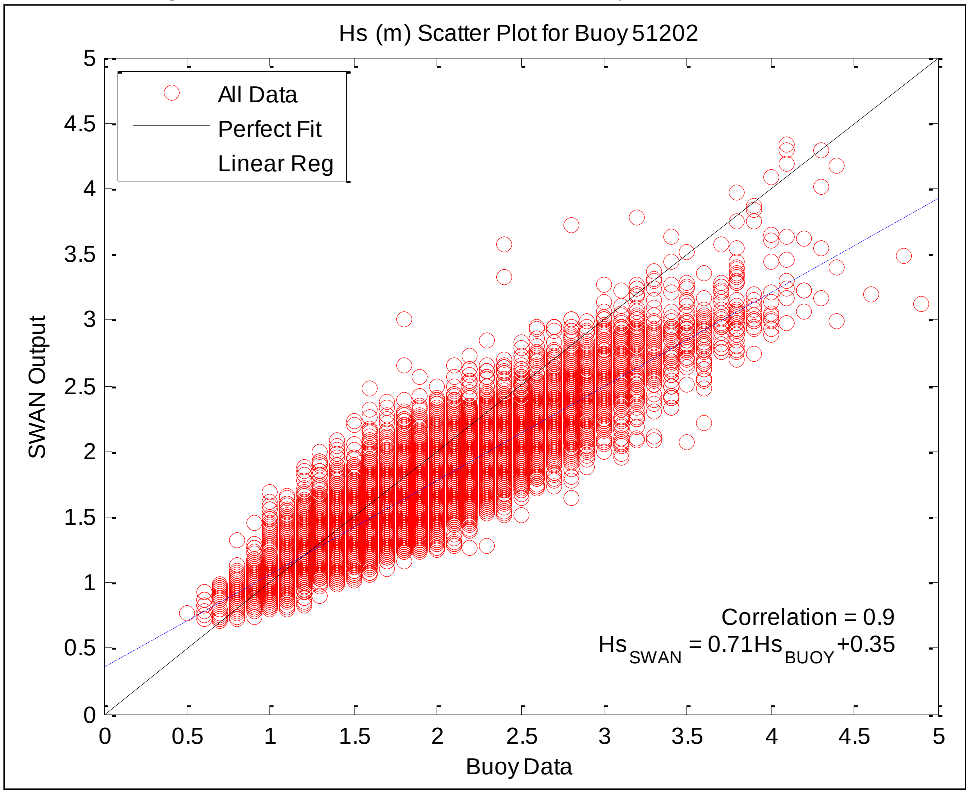


Figure B3 - Hs Scatter Plot for Buoy 51201(198 m), November – April

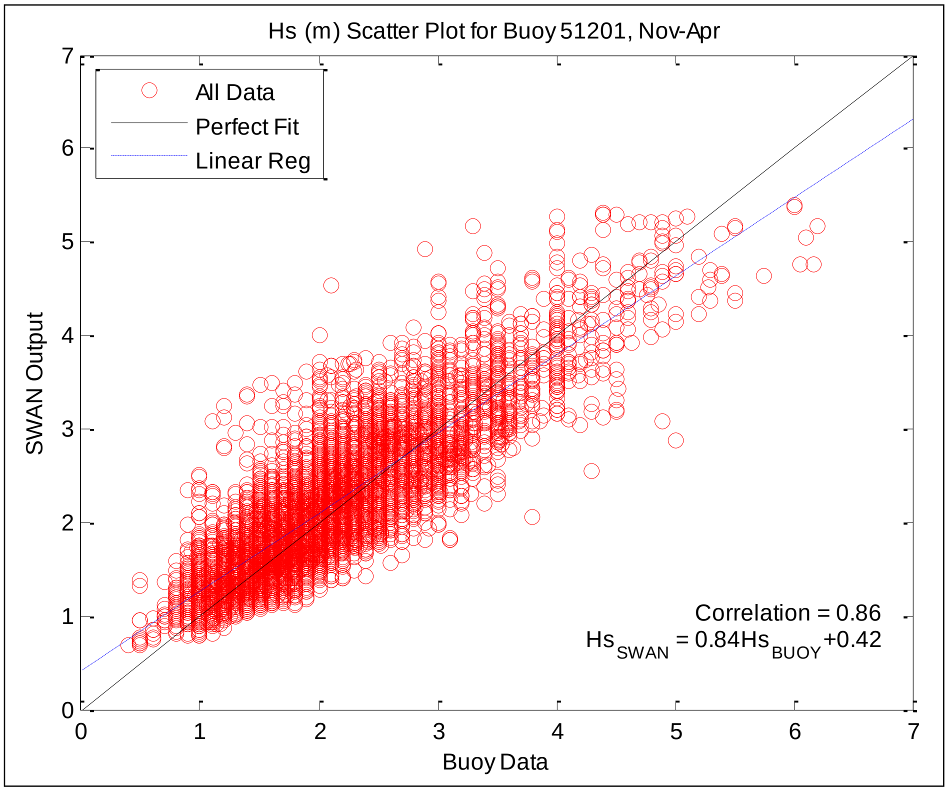


Figure B4 - Hs Scatter Plot for Buoy 51201 (198 m), May-October

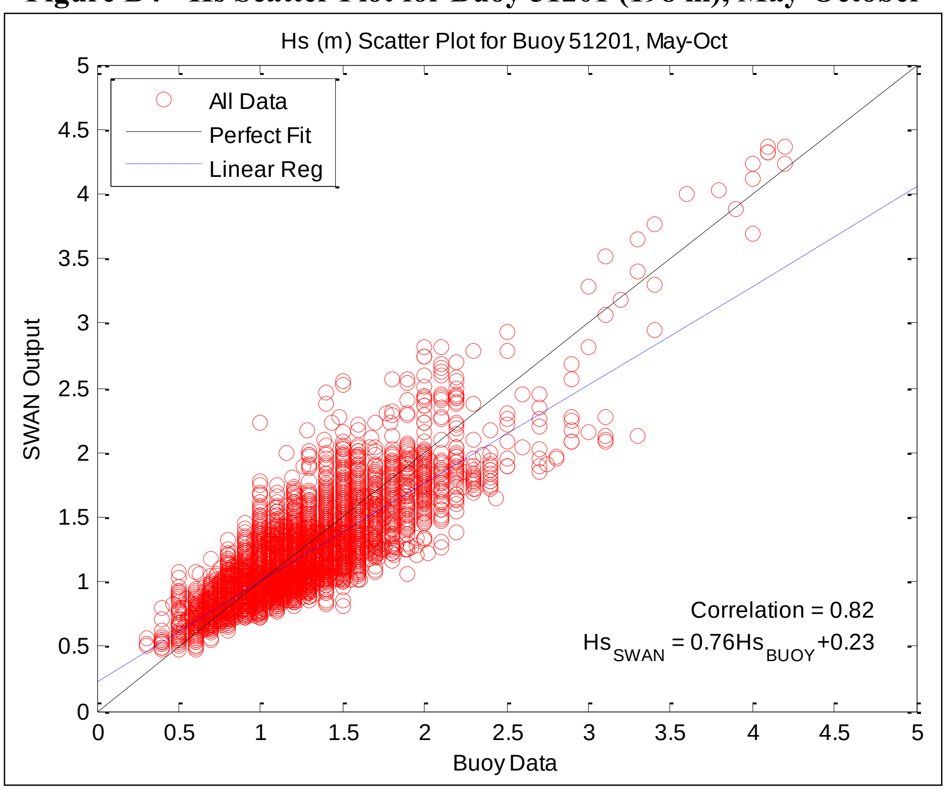


Figure B5 - Hs Scatter Plot for Buoy 51202 (100 m), November-April

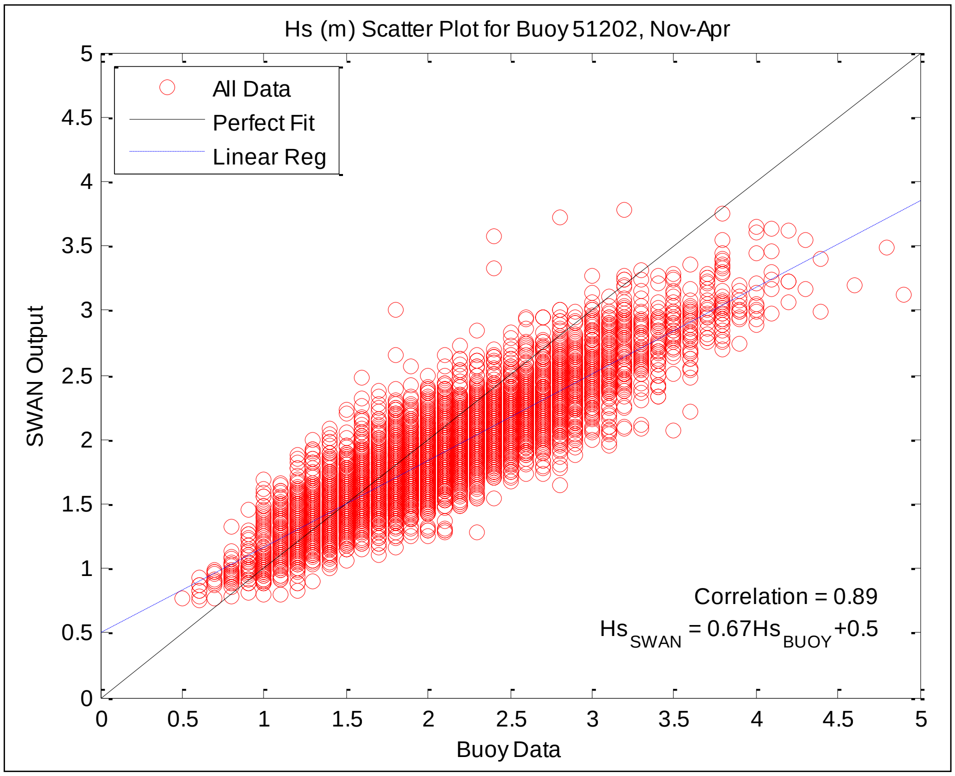
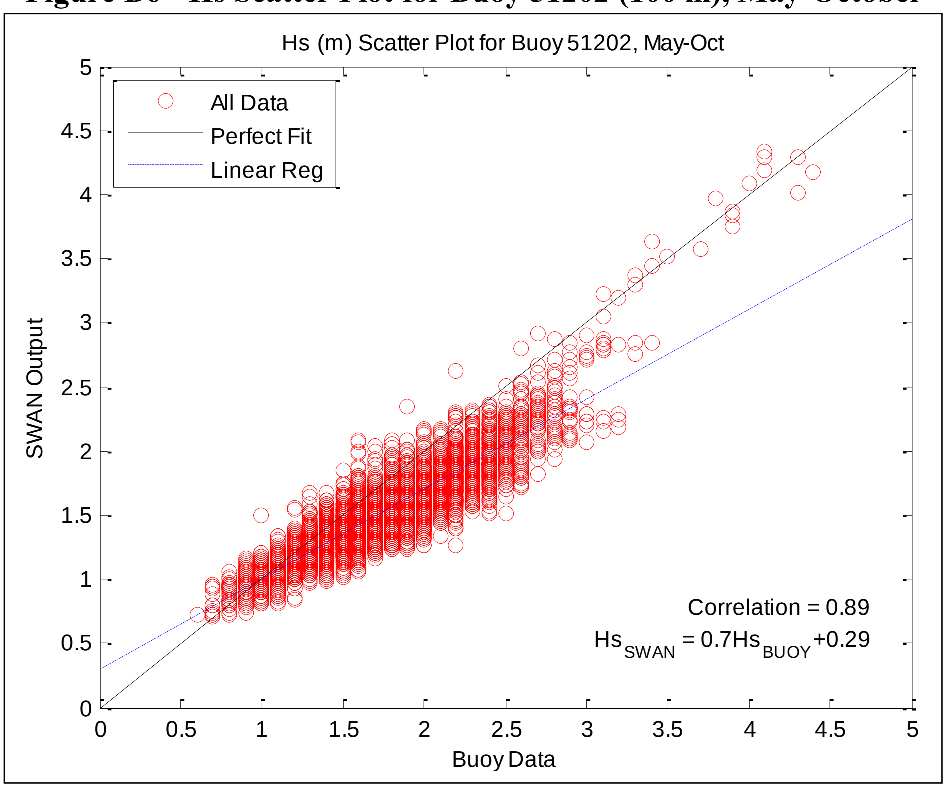


Figure B6 - Hs Scatter Plot for Buoy 51202 (100 m), May-October

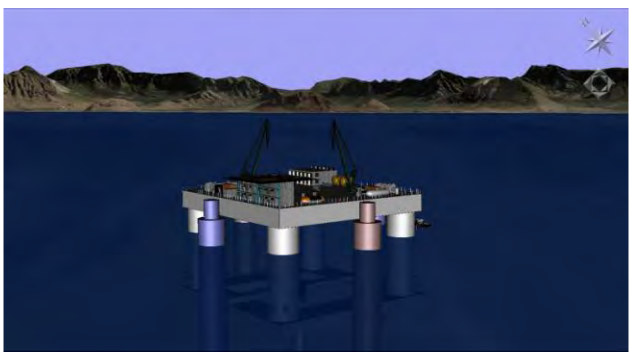


APPENDIX C. WAVE AND OTEC EXAMPLES

Appendix C - Wave and OTEC Examples

210 kW Open Cycle OTEC Experimental Plant operated by Vega et al 1993-1998 (Photo: HNMREC)

Heaving Buoy Wave Energy Conversion Device in Kaneohe Bay, Oahu (Photo: Ocean Power Technologies)



Conceptual Visualization of OTEC Facility (Photo: Lockheed Martin)

Oscillating Water Column Wave Energy Conversion Device (Photo: Hawaii’s Energy Future)

APPENDIX D. MARINE PROECTED SPECIES OF THE HAWAIIAN ISLANDS

MARINE PROTECTED SPECIES of the HAWAIIAN ISLANDS

National Marine Fisheries Service, Pacific Islands Regional Office

MARINE MAMMALS

All marine mammals are protected under the Marine Mammal Protection Act. Those identified under the ESA Listing are also protected under the Endangered Species Act.

Common Name	Scientific Name	ESA Listing
Blue Whale	*Balaenoptera musculus*	Endangered
Blainville's Beaked Whale	*Mesoplodon densirostris*	
Bryde's Whale	*Balaenoptera edeni*	
Cuvier's Beaked Whale	*Ziphius cavirostris*	
Dwarf Sperm Whale	*Kogia simus*	
False Killer Whale	*Pseudorca crassidens*	
Fin Whale	*Balaenoptera physalus*	Endangered
Humpback Whale	*Megaptera novaeangliae*	Endangered
Killer Whale	*Orcinus orca*	
Longman's Beaked Whale	*Indopacetus pacificus*	
Melon-headed Whale	*Peponocephala electra*	
Minke Whale	*Balaenoptera acutorostrata*	
North Pacific Right Whale	*Eubalaena japonica*	Endangered
Pygmy Killer Whale	*Feresa attenuata*	
Pygmy Sperm Whale	*Kogia breviceps*	
Sei Whale	*Balaenoptera borealis*	Endangered
Short-finned Pilot Whale	*Globicephala macrorhynchus*	
Sperm Whale	*Physeter macrocephalus*	Endangered
Bottlenose Dolphin	*Tursiops truncatus*	
Common Dolphin	*Delphinus delphis*	
Fraser’s Dolphin	*Lagenodelphis hosei*	
Pantropical Spotted Dolphin	*Stenella attenuata*	
Risso's Dolphin	*Grampus griseus*	
Rough-toothed Dolphin	*Steno bredanensis*	
Spinner Dolphin	*Stenella longirostris*	
Striped Dolphin	*Stenella coeruleoalba*	
Hawaiian Monk Seal	*Monachus schauinslandi*	Endangered
Northern Elephant Seal	*Mirounga angustirostris*	

SEA TURTLES

All sea turtles are protected under the Endangered Species Act.

Common Name	Scientific Name	ESA Listing
Green Turtle	*Chelonia mydas*	Threatened
Hawksbill Turtle	*Eretmochelys imbricata*	Endangered
Leatherback Turtle	*Dermochelys coriacea*	Endangered
Loggerhead Turtle	*Caretta caretta*	Threatened
Olive Ridley Turtle	*Lepidochelys olivacea*	Threatened

Last updated May 2010