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Hawaii Ocean Current Resources and Tidal Turbine Assessment

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1018027

Final Report, September 2008

Cosponsor
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CITATIONS

This report was prepared by

Sea Engineering, Inc.
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Waimanalo, Hawaii 96795

This report describes research sponsored by the Electric Power Research Institute (EPRI) and Hawaiian Electric Company, Inc.

The report is a corporate document that should be cited in the literature in the following manner:

Hawaii Ocean Current Resources and Tidal Turbine Assessment. EPRI, Palo Alto, CA and Hawaiian Electric Company, Inc.: 2008. 1018027.

REPORT SUMMARY

Interest in converting the kinetic energy of ocean current and tidal flow into electrical power has increased in recent years. This report focuses on the ocean current resource in Hawaii, which includes tidal flows as well as uni-directional oceanic current flows around the main Hawaiian Islands, with the exception of Kauai, from the shoreline to approximately the 2000-m depth contour.

Results & Findings

The report introduces the topic of ocean current resources in Hawaii with a review of available information from past studies. Because there are large sectors where no circulation information is available and a more comprehensive assessment of tidal current resources is needed, a numerical model was applied to the Hawaiian Islands and validated using existing available current data. The report details the tidal results from this model for potential ocean current power generation. Complementing this resource evaluation, the report describes the present state of underwater turbine technology and discusses the applicability of TISEC (Tidal In-Stream Energy Conversion) technology to Hawaii.

Challenges & Objective(s)

The study's objectives were to evaluate ocean current resources around the main Hawaiian Islands, assess the present state of underwater turbine development, and determine the potential applicability of that technology to the resource in Hawaii. Preliminary literature reviews indicated that technology presently under development would probably not be applicable to Hawaii due to insufficient current flow speeds. Consequently, particular care was taken to identify technologies that might be applicable to relatively low current speeds.

Applications, Values & Use

Many firms have plans for relatively ambitious future tidal power projects. Although the number of these projects indicates a high degree of interest in tidal power, commercial application of underwater turbine technology is still in the development stage.

EPRI Perspective

A comparison of the required speeds for efficient turbine operation with the available resource in Hawaii leads to the conclusion that, given the present technology, generation of electrical power with underwater turbines is not feasible at the present time. A significant, and at this point unforeseen, technological advance will be necessary to make the generation of electrical power by underwater turbines feasible in Hawaii.

Approach

The project team's assessment of the ocean current resource includes a discussion of the driving forces for currents in the Hawaiian Islands and the factors that result in localized variations in the currents. A state of the art circulation model developed by the University of Hawaii that simulates tide-driven currents around the Hawaiian Islands was used to develop contour plots of the ocean current resource. Available information from past current studies was used to validate the model results.

Underwater turbine technology was evaluated based on an extensive literature search that included both written reports and Internet sources. This search was supplemented by follow-on contact with technology developers identified in the search. A primary objective of the literature search was to find evidence of promising technologies that might make generation of electrical power by underwater turbines feasible in Hawaii.

Keywords

Ocean current resource
Tidal current resource
Hydrokinetic energy conversion
Hydrokinetic turbines

EXECUTIVE SUMMARY

Sea Engineering, Inc. (SEI) was contracted by Hawaiian Electric Company, Inc. (HECO) to assess the feasibility of utilizing the ocean currents around the Hawaiian Islands as a renewable energy resource. The work included an evaluation of the ocean current resources, assessment of the present state of underwater turbine development, and determination of the potential applicability of that technology to the resource in Hawaii. The geographic area covered included the waters around the main Hawaiian Islands, with the exception of Kauai, from the shoreline to approximately the 2,000 m depth contour.

The primary driving forces for currents in the Hawaiian Islands are tidal currents which result from the passage of the semi-diurnal and diurnal tide waves, the North Pacific Equatorial Current which flows in a generally westerly direction through the islands, the sporadic influence of offshore eddy development on the leeward side of the islands, particularly the island of Hawaii, and wind stress on the surface water layers. The resultant currents are modified by coastal configuration and bathymetry and can be complex. In most areas of Hawaii, the tides are the predominant influence, and the currents typically reverse with the semi-diurnal tide, flowing parallel to the depth contours.

Although there is an extensive amount of available information from past current studies in the Hawaiian Islands, there are large coastal sectors where no circulation information is available. To provide a comprehensive assessment of the tidal current resource, a state-of-the-art tidal circulation model developed by the University of Hawaii (UH) was utilized for this study. The model is based on the Princeton Ocean Model, one of the most widely used and verified ocean circulation models. Researchers at the University of Hawaii have developed, improved, applied and verified the model over the past several years to simulate tidal currents around the Hawaiian Islands.

The model is based upon the tidal currents, so it does not take into account large or small-scale eddy formation, wind driven currents, or the effect of the North Pacific Equatorial Current. However, in most areas around the island, tidally driven flow comprises most of the flow and this component is predictable over the long term. Predicted tidal flows therefore provide the most logical basis for determining the location of turbine systems and the model limitations are acceptable for the purposes of this study. The influence of the North Equatorial Current is relatively small in most coastal areas and its presence is often difficult to detect within the dominant tidal flows. Prevailing winds influence approximately the top 5 m of the water column only.

The model output has been verified by UH researchers by comparing the predictions with measurements from two current meter moorings between Oahu and Kauai. The good agreement between the UH computations and the field observations indicates that the model reproduces the dynamics of the major tidal forcing of currents in the Hawaiian Islands with reasonable accuracy. SEI further validated the model for this project by comparing our model results with existing current meter data from various locations around Oahu, Maui, Molokai and Hawaii, including most of the headlands and points known for strong currents. Agreement was generally very good, with measured mean current speeds ranging from 0.1 to 0.6 m/s, while the model computed mean speeds ranged from 0.2 to 0.7 m/s. Both the model and the observed measurements indicated that the strongest mean and maximum currents occurred offshore of Laau Point, Molokai. Analysis of the difference between the observed and modeled mean speeds indicates that the model generally over-predicted mean speeds by 0.08 m/s, but there is no indication of a bias to over or under predict peak current speeds.

Model results indicated that mean and maximum current speeds in most of the study area are typically less than 0.3 m/s and 1.0 m/s, respectively. The strongest currents occur off headlands and points. Three areas had the highest predicted current speeds: Laau Point, Molokai (Penguin Bank); Kaena Point, Oahu; and Makapu'u Point, Oahu. Mean speeds in these areas were approximately 0.6 to 0.8 m/s and peak speeds were 1.9 to 2.2 m/s. The table below summarizes several areas around the islands with relatively strong currents.

Table ES-1
Model Predicted Peak and Mean Current Speeds

Location	Velocity Magnitude (m/s)	
	Peak	Mean
Penguin Bank	2.2	0.8
Kaena Point, Oahu	2.1	0.7
Makapuu Point, Oahu	1.9	0.6
Lahaina, Maui	1.4	0.5
Upolu Point, Hawaii	1.4	0.6
Kahuku Point, Oahu	1.4	0.5
Barbers Point, Oahu	1.3	0.4
Diamond Head, Oahu	1.2	0.4
Kikoa Point, Lanai	1.2	0.4
South Point, Hawaii	0.9	0.3
Hana, Maui	0.9	0.4
Cape Kumukahi, Hawaii	0.6	0.2

The one exception to good agreement between predicted and measured currents was the Kona Coast of the Big Island, with the measurements indicating that model results significantly under predicted current speeds. This is consistent with the numerous observations and studies that have shown that this coastal region is unique in the islands due to the prevalence of regional eddies that drive the currents. These eddies can result in extended periods of uni-directional flow superimposed on the tidal currents. The resultant flow can be strongly to the north or to the south for extended periods of time depending on the location of the offshore eddy. Mean current velocities are in the range of 0.3 to 0.5 m/s during the eddy-generated flow events. Weaker semi-diurnal tidal flows of 0.1 to 0.2 m/s are superimposed on the mean eddy flow, and predominate during periods when eddies are not present. Although eddy events occur an average of nine times per year, exactly when they occur, how they will move, and how long they will last is not well understood and the impacts of the eddies on coastal currents is not predictable.

The evaluation of underwater turbine technology completed for this study had two objectives: first, to determine the present state of development of the technology; and second, to determine if any of the turbine technologies presently under development or in the conceptual stage could be applied to the ocean current resource in Hawaii.

Underwater turbines have three advantages over wind and wave energy systems. First, the energy source is predictable, as tides and tide-driven currents can be predicted decades in advance. Second, the turbines are located underwater and there is no visual evidence of the system unless the mounting components penetrate the water surface. Third, the energy density of flowing water is high relative to wind, so a much smaller turbine is required to generate the same amount of electricity.

Underwater turbine designs fall into several categories. The most common are horizontal and vertical axis turbines, and they can be ducted or un-ducted. Unducted turbines are similar to conventional windmills, and generally use technology and designs based upon wind generators. This has the advantage of utilizing existing, proven technology, but the mechanical systems involved (pitch control, gearboxes, generators) must be modified for use underwater. More moving parts and seals underwater usually lead to increased maintenance and more potential failure modes.

Ducted turbines increase the efficiency of fixed mount turbines by funneling water flow into the turbine from a range of directions. This can be an advantage in reversing tidal flows, because the flows do not usually reverse exactly 180 degrees, and the duct can eliminate the need for pitch and yaw controls on the turbine blades. The ducts can also be designed to increase current velocity, enabling more energy to be extracted from a given flow. Some ducted horizontal axis turbines utilize relatively new generator technology, with designs based on direct drive permanent magnet generators. These generators have only one moving part, the rotor assembly containing the blades. The elimination of drive shaft, gearbox, seals, and yaw and pitch control should increase reliability.

Thirty tidal turbine developers were identified and contacted during this study. The flow speeds required to generate electrical power vary from vendor to vendor. The speed at which most units start to generate power ranges from 0.5 to 1 m/s. However, the flow speed necessary for economic operation is considerably higher. For reversing tidal currents, an average current speed of 2 to 2.5 m/s is the lower threshold for economic power generation. Since the current speed varies over a tidal cycle, the average speed given above approximately corresponds to peak speeds of 3 to 4 m/s. Power increases with the cube of water velocity, so small increases in current speed have a large impact on the available power and the economics of an installation. Some developers are targeting uni-directional ocean currents such as the Gulf Stream, and average currents as low as 1.5 m/s may be economically feasible. Our research found no indication of any technology being developed that would lower the required flow speeds below these levels.

The maturity level of the existing marine turbine technology ranges from conceptual to pre-commercial. Although many companies are planning multi-megawatt installations in the next few years, the power being generated by turbines presently in the water is quite small, ranging from 25 kW to 300 kW. Most of the installations, even those connected to an electrical grid, are in the realm of demonstration or proof of concept and do not yet represent commercial applications. Europe is presently the leader in tidal current power, in particular Ireland, the United Kingdom, and Norway - all countries with extensive tidal current resources.

A comparison of the required speeds for efficient turbine operation with the available resource in Hawaii leads to the conclusion that, given the present technology, generation of electrical power with underwater turbines is not feasible at this time. The three locations with the strongest currents have mean flow speeds that just reach the cut in speeds required for most turbines, and are approximately one-third of that required for the threshold of economical operation. It will take a significant, and at this point unforeseen, technological advance to make the generation of electrical power by underwater turbines feasible in Hawaii.

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1
INTRODUCTION

1.1 Objective

There are five potential sources of renewable ocean energy: tidal, ocean current, wave, salinity gradient, and ocean thermal gradient. Interest in the conversion of the kinetic energy of flowing water due to ocean current and tidal flow into electrical power has greatly increased in recent years. Sea Engineering, Inc. (SEI) was contracted in July 2007 by Hawaiian Electric Company, Inc. (HECO) to assess the feasibility of utilizing the ocean currents around the Hawaiian Islands as a renewable energy resource. This assessment actually includes two of the five potential energy sources because in Hawaii the tides are one of the primary driving forces for ocean currents. Tidal flow implies reversing currents while ocean current flow can be either reversing (if driven primarily by the tides) or uni-directional. An example of a uni-directional ocean current would be the Gulf Stream current off the east coast of the United States.

Advances in the area of tidal or ocean current energy conversion have been well documented in a series of reports by the Electric Power Research Institute (EPRI), an independent, non profit energy research center. Many of their reports are referenced in this document. EPRI uses the term TISEC (Tidal In-Stream Energy Conversion) for the conversion of the kinetic energy of a tidal "stream" to a more useful form. TISEC, for purposes of this report, will be applied to all devices that convert kinetic energy into electrical power, whether from reversing or uni-directional flows since the technology applies to both. The focus of this report is on the ocean current resource in Hawaii, which includes tidal flows as well as uni-directional oceanic current flows. The terms tidal power and ocean current power will be used interchangeably in this report.

TISEC devices harness the kinetic energy of the moving water without the use of dams, tidal barrages, or other types of impoundments that extract energy based upon the differences in height (potential energy) across a barrier. This minimizes or completely avoids the significant environmental and visual impacts of dams and tidal barrages. Some TISEC devices are entirely subsurface and therefore eliminate any visual impact.

TISEC has three major advantages over wind and wave energy. First, the energy source is predictable, as tides (and the tide-driven currents) can be predicted decades in advance. Second, the turbines are located underwater and cannot be seen or heard. There is no visual evidence of the system unless the mounting components penetrate the water surface. The ongoing debates over offshore wind farms illustrate the controversies that can arise over actual or perceived visual impacts. Third, the energy density of flowing water is high relative to wind. Water is 830 times denser than air, so a much smaller turbine is required to generate the same amount of electricity.

For example, a tidal turbine 20 m in diameter in a current of 3 m/s can generate the same power as a 60 m diameter wind turbine in a wind of 15 m/s.

1.2 Scope of Work

The scope of work of this study was to evaluate the ocean current resources around the main Hawaiian Islands, assess the present state of underwater turbine development, and determine the potential applicability of that technology to the resource in Hawaii. The geographic area covered includes the waters around the main Hawaiian Islands (with the exception of Kauai) out to approximately the 2,000 m depth contour. This boundary includes the channels between the islands as well as offshore banks or ledges that might provide an energy resource.

The assessment of the ocean current resource includes a discussion of the driving forces for currents in the Hawaiian Islands, and the factors that result in localized variations in the currents. A state of the art circulation model developed by the University of Hawaii that simulates tide-driven currents around the Hawaiian Islands was used to develop contour plots of the ocean current resource. Available information from past current studies was then used to validate the model results.

The evaluation of the underwater turbine technology was based upon an extensive available information study that included both written reports and internet sources. The available information study was supplemented by follow-on contact with the technology developers that were identified.

Preliminary literature reviews completed early in this project indicated that the technology presently under development would probably not be applicable to Hawaii due to insufficient current flow speeds. Particular care was therefore taken to identify any technologies that might be applicable to relatively low current speeds.

2
OCEAN CURRENTS IN HAWAII

2.1 Existing Information

Currents around the Hawaiian Islands are complex, driven by varied forces such as large scale oceanic currents, tides, sporadic eddies and wind stress. The resultant current at a particular site is also influenced by the bathymetry of the site and the configuration of the adjacent coastline.

The ocean circulation and currents around the islands have been extensively investigated over the past 40 years. Laevastu, Avery and Cox (1964) summarized existing circulation data around the main Hawaiian Islands, and conducted the most extensive current measurements up to that time. Their discussion of the components of coastal currents included the underlying permanent flow, the diurnal and semi-diurnal tidal components, the convergence and divergence of tidal currents in Mamala Bay, and the downstream eddies in the lee of the prevailing westerly flow. Wyrtki, Graefe and Patzert (1969) installed a series of current meter moorings in the Hawaiian Islands from 1965 to 1969. The work included meter emplacements off Diamond Head and Barbers Point and the results confirmed the importance of the semi-diurnal tide component to the overall flow.

The Oahu Water Quality Program (Engineering-Science, Inc., et al, 1971) was an extensive oceanographic study conducted around the island to characterize water quality and to evaluate the suitability of potential outfall sites. The study resulted in detailed description of the circulation and water quality conditions around Oahu. Data collection period was from June 1970 to March 1971.

The oceanographic study for the Barbers Point Ocean Outfall System (R.M. Towill Corporation, 1976) was a one year study conducted from August 1972 to August 1973 to obtain data required for the design of the outfall and evaluation of the water quality impacts. The study covered the 16 km long coastal sector from Barbers Point to Pearl Harbor, from the shoreline to the 100 m depth.

The Mamala Bay Study, completed in 1995, was conducted under the terms of a consent decree between the City and County of Honolulu and the Sierra Club Legal Defense Fund (1996, The Mamala Bay Study). The agreement required a thorough investigation of the water quality conditions in Mamala Bay (Figure 2.1). An independent commission, the Mamala Bay Commission, was established and the City of Honolulu contributed nine million dollars to fund the commission's investigation. The resulting study was by far the most extensive ever conducted in Hawaii. The overall goal of the study was to develop a water quality management plan for Mamala Bay, extending from Diamond Head to Barbers Point. Included in the study was the most comprehensive measurement and analysis of regional circulation in Hawaii to-date

(Hamilton, Singer, Waddell - Project MB-6). This circulation study had eleven mooring arrays within Mamala Bay, at depths ranging from 6 to 500 m. Measurements were focused on four transects: one at each of the two outfall sites and one at each boundary of the study area, Barbers Point and Diamond Head.

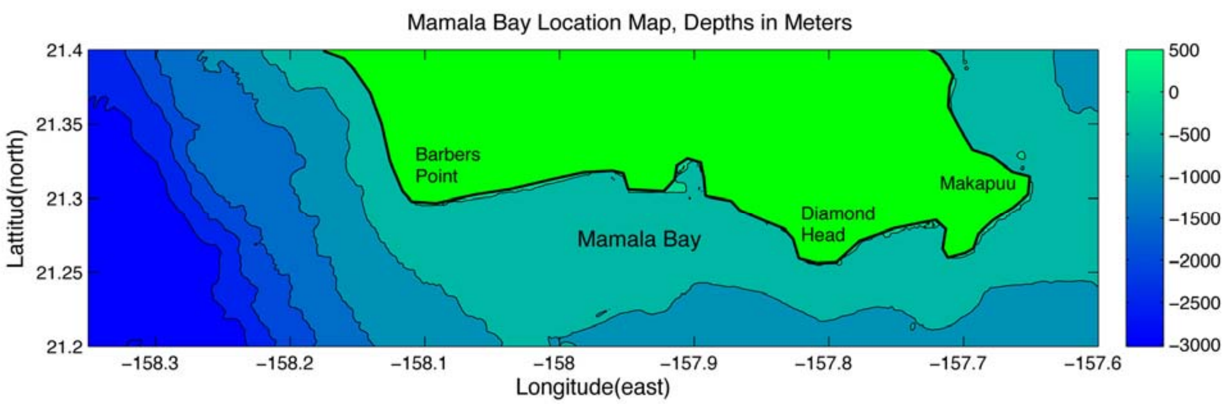


Figure 2-1
Mamala Bay, Oahu

More recently, the University of Hawaii (UH) has been funded by the National Science Foundation for a long-term research project titled the Hawaii Ocean Mixing Experiment (HOME). The objective of HOME is to further the understanding of turbulent mixing processes in the ocean. The project has included numerous data collection cruises, deployment of current meter, density measurements, and extensive modeling analysis. The UH Tidal Model being used in this HECO-funded tidal current evaluation has been developed and applied as part of the HOME project. This work has increased the understanding of tidal processes driving currents around the islands.

In addition to the major investigations described above, numerous other project specific studies have been undertaken that involved deployment of current meters and collection of water quality data. These have been conducted for outfall pipelines, offshore thermal energy conversion facilities, storm drain discharges, and on-land development projects with a potential impact on coastal waters. Most measurements have been relatively short term (two months or less). Longer-term studies tend to be clustered about either heavily developed or industrialized areas of the state. For example, on Oahu there are long-term measurements available off Kahe Point, Barbers Point, Ewa Beach, Pearl Harbor, Diamond Head, Sand Island and in Kailua Bay.

The findings of the above studies have been fairly consistent, with each one adding incrementally to the overall body of knowledge. The description of prevailing circulation in Laevastu's study is still valid, but much more is now known about the driving forces for the circulation. The primary driving forces for currents in the Hawaiian Islands are tidal currents which result from the passage of the semi-diurnal and diurnal tide waves, the North Pacific Equatorial Current which flows in a generally westerly direction through the islands, the sporadic influence of offshore eddy development on the leeward side of the islands, particularly the island of Hawaii, and wind stress on the surface water layers.

2.2 Tidal Currents

The term tide refers to the alternating rise and fall of sea level produced by the gravitational attraction of the moon and sun on the earth. *Tidal in stream energy* occurs due to the moving mass of water with speed and direction caused by the gravitational forces of the sun and moon, and centrifugal and inertial forces on the earth's waters. Due to its proximity to the earth, the moon exerts roughly twice the tide-raising force of the sun. The gravitational forces of the sun and moon, and the centrifugal/inertial forces caused by the rotation of the earth around the center of mass of the earth-moon system create two "bulges" in the earth's oceans: one closest to the moon, and the other on the opposite side of the globe. As the earth rotates, a point on the earth passes through these bulges twice, resulting in two high water levels and two low water levels per lunar day. This is called the semi-diurnal lunar tidal component (M_2), with a period of 12.42 hours. These two highs and lows are not equal because the axis of the earth's rotation is tilted such that the moon and sun are not directly above the equator. This creates a diurnal (daily) inequality to the tides. When the sun and moon are aligned (during the new and full moon), tidal ranges are larger, and are called spring tides. When the moon is in its first or last quarter, smaller neap tides result. This occurs on a cycle of about fourteen days. This is depicted in Figure 2.2, reproduced from Bedard (2005).

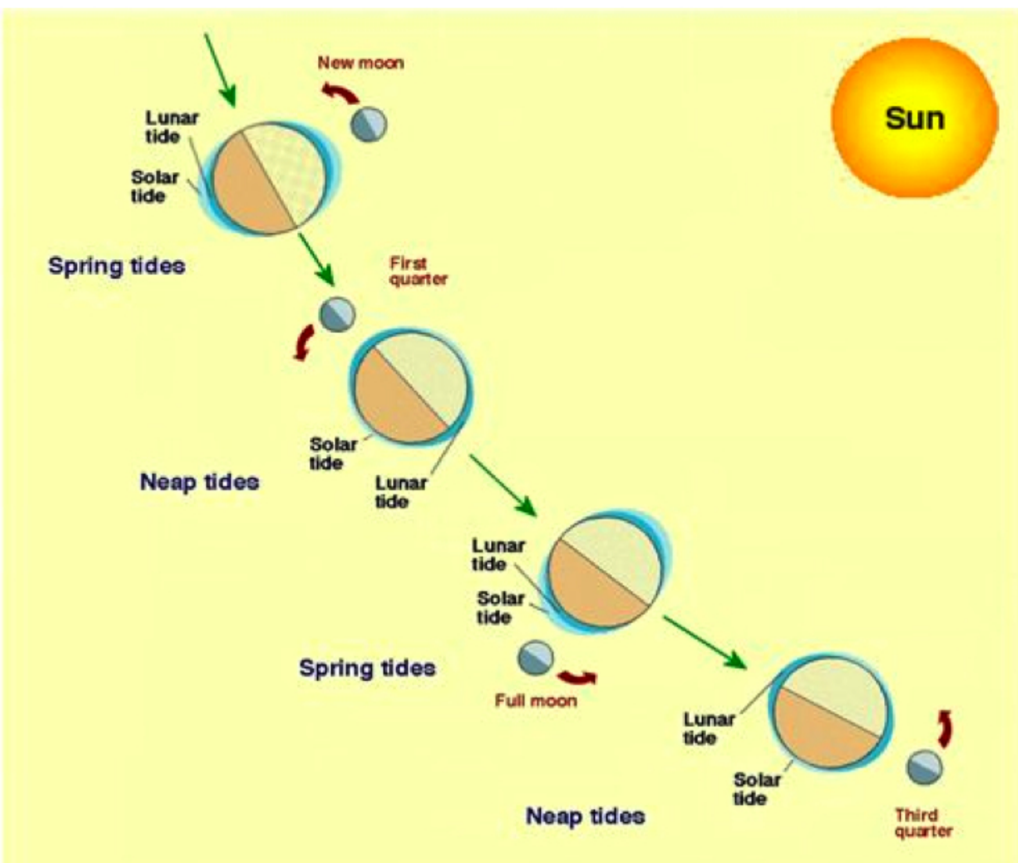


Figure 2-2
Spring, neap tidal cycle, from Bedard (2005)

Tides in Hawaii are semi-diurnal with pronounced diurnal inequalities. Figure 2.3 shows predicted tides for Honolulu Harbor during December, 2007, and illustrates the semi-diurnal component, the diurnal inequality and the spring-neap cycle. The typical range of tidal elevations is 2 to 3 feet.

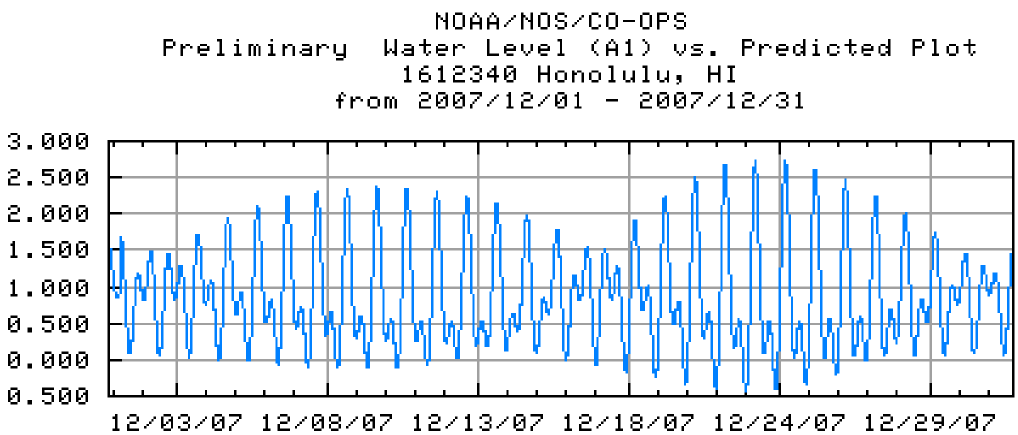


Figure 2-3
Predicted tides for Honolulu Harbor during December 2007

The rise and fall of sea level caused by the tides forces current flow, termed barotropic currents. As the tidal wave approaches the islands from the deep ocean basins, the resulting barotropic currents are compressed and forced to flow upward over the steep topography of the Hawaiian ridge. The barotropic currents accelerate and also often induce waves in the interfaces between layers of different density in the water. These internal waves, called baroclinic waves, also drive currents (baroclinic currents), that can vary or reverse at different depths in the water.

Near shore circulation in most areas of Hawaii is strongly driven by this combination of barotropic and baroclinic tides, with currents typically reversing with the semi-diurnal tide, and flowing parallel to the depth contours. Internal or baroclinic tides are an active area of research in Hawaii (Merrifield, 2001; Carter et al., 2007), and their generation and propagation are not yet well understood. The amplitude and speed of the internal wave, for example, is strongly dependent on local variations in ocean stratification, which are difficult to characterize. Thus, at any particular time or place around the islands, the baroclinic tide may not be in phase with the barotropic tide. So although coastal currents typically reverse with the semi-diurnal tide, the timing of the current reversals and the strength of the currents is variable and difficult to predict because of the variability of the baroclinic currents.

The semi-diurnal tide wave approaches the Hawaiian Islands from the northeast, and then splits and travels around the main islands, converging again on the opposite side. On Oahu, for example, the semi-diurnal tide splits off the windward coast, travels around both sides of the island, and then converges in west Mamala Bay. During ebb tide flow the opposite occurs; the tidal current diverges off Mamala Bay, moves in both directions around the island, and then converges on the north or northeast side of the island. As a result, the flood tide currents flow to the west at Diamond Head, and to the east at Barbers Point. Ebb tide currents flow to the east at Diamond Head and to the west at Barbers Point.

2.3 North Pacific Equatorial Current

The large-scale ocean current that influences the Hawaiian Islands is the North Pacific Equatorial Current (NEC). This current is generated by the prevailing trade winds, and flows from east to west. The speed averages 8 cm/s, with a strong seasonal variability ranging from 5 cm/s to 15 cm/s (Holland and Mitchum, 2001). As the NEC approaches Hawaii, it branches into a southern component of the NEC, and a northern component called the North Hawaiian Ridge Current (NHRC) which flows to the northwest along east side of the island chain. The companion current on the west side of the islands is sometimes called the Hawaiian Lee Current. The large wind wake formed by the islands also results in the formation of the Hawaiian Lee Counter Current, which flows from west to east toward the Big Island. A schematic of this large-scale current structure is presented in Figure 2.4 (Lumpkin, 1998).

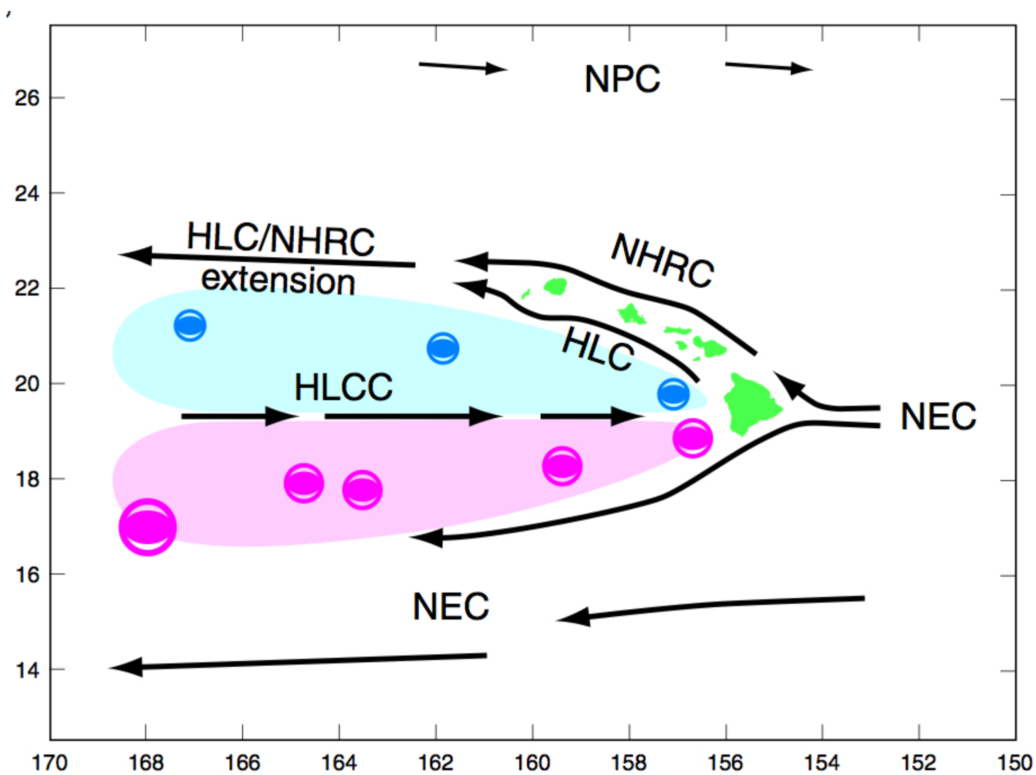


Figure 2-4
Schematic of the large-scale current structure around Hawaii. Blue and red circles indicate regional wind driven eddies. (From Lumpkin (1998)

In coastal areas of Hawaii, the influence of the NEC is relatively small, and its presence is often difficult to detect within the dominant tidal flows (Laevastu et al., 1964). After 18 months of detailed measurements, the Mamala Bay Study, for example, concluded that mean currents in the bay are complex and not adequately resolved by the measurement program they conducted. Sea

Engineering’s one-year deployment of a current meter offshore of Pearl Harbor revealed a net transport to the northwest of 1cm/s.

2.4 Eddies

The presence of regional scale oceanic eddies in the lee of the island of Hawai'i has been well documented (e.g. Wyrtki et al, 1967; Patzert, 1969; Lumpkin, 1998). These eddies have diameters of approximately 180 km. The eddies are relatively shallow in depth, typically penetrating to depths of 250 to 300 m. Eddy formation has also been observed in the lee of O'ahu and Kauai, but not with the same regularity as in the lee of Hawaii. These eddies are generated by strong trade wind flow funneling between the restricted passages between the islands, particularly between Maui and Hawai'i. They form over a five to twenty day period, and then slowly drift westward at average speeds of 6 cm/s. They have lifetimes of three to eight months or more in the lee of the islands before they disappear.

Eddies frequently dominate the circulation patterns on the west coast of Hawai'i, and their influence could be responsible for some of the unexplained complexities in nearshore circulation in other parts of the islands. They can result in extended periods of strong currents in one direction, superimposed on the tidal currents. In a 1985 current study along the Kona Coast, Sea Engineering found that strong flow in one direction occurred approximately 75% of the time. The duration of these uni-directional flow events ranged from three to thirty days, with net transport speeds as high as 46 cm/s. Less pronounced occurrences of uni-directional flow occur occasionally in other parts of the islands, and may be due to the passage of these regional wind driven eddies.

2.5 Wind-driven Surface Currents

The prevailing winds influence approximately the top 5 m of the water column. Data collected by Zapka and Krock (1983) indicate that wind effects do not penetrate to the 10 m depth. Surface currents can be expected to move consistently with the wind during the summer, when the northeast trade winds occur 80 to 90 percent of the time. During the winter, the trade wind frequency decreases to 60 percent. During light and variable wind conditions, underlying tidal flow will influence the surface layer, and reversing alongshore transport should predominate.

2.6 Summary

Coastal currents in Hawaii are complex, driven by a combination of tides, large-scale oceanic currents, regional eddies, wind and local topography. In most areas of Hawaii, currents are driven by a combination of barotropic and baroclinic tides, typically reversing with the semi-diurnal tide, and flowing parallel to the depth contours. The timing of the current reversals and the instantaneous strength of the currents are often variable and difficult to predict because of the variability of the baroclinic tides, and the sporadic influence of eddies and oceanic currents. The coastal current resource, however, can be reasonably quantified with a combination of measurements and numerical modeling. The Kona Coast of Hawaii requires special consideration, because regional wind driven eddies frequently occur, and drive uni-directional flow for extended periods of time.

3
NUMERICAL MODEL

As discussed in the previous section, there is an extensive amount of available information from past current studies in the Hawaiian Islands, but the study areas are widely spaced, and there are large sectors where no circulation information is available. Most measurements have been relatively short term (two months or less), and longer-term studies are restricted to only a few locations, typically where ocean outfalls are located. To provide a more comprehensive assessment of the tidal current resource available in Hawaii, a numerical model was applied to the Hawaiian Islands and validated using existing available current data.

3.1 Model Description

A state-of-the-art tidal circulation model developed by the University of Hawaii (UH) was selected for use in this project. The model is based on the Princeton Ocean Model, which is one of the most widely used and verified ocean circulation models. Researchers at the University of Hawaii have developed, improved and applied the model over the past several years to simulate tidal currents around the Hawaiian Islands as part of the ongoing National Science Foundation sponsored Hawaii Ocean Mixing Experiment (HOME) (Merrifield et al., 2001; Carter et al., 2007).

The UH Hawaii Tidal Model is three-dimensional, and based on the fundamental equations describing fluid motion. Bathymetry is represented in the model through the creation of a grid and the specification of a depth at each grid point. The bathymetry is derived from multibeam survey data. The horizontal grid spacing is one-hundredth of a degree, corresponding to 1111.9 m in latitude and 1023.5 to 1042.4 m in longitude. The water column is divided into sixty-one layers. Stratification in the water column is specified using time-averaged temperature and salinity profiles measured over ten years at Station Aloha, a UH Hawaii Ocean Time Series (HOT) measurement site located 100 km north of Oahu. This average stratification is applied to the entire computational grid (Carter et al., 2007).

The model is driven through the specification of tidal elevations and currents along all open boundaries. For the NSF HOME project, the model has primarily been applied to simulate and analyze the characteristics of the most energetic tidal component, the M_2 lunar semi-diurnal tide. The model domain was restricted to depths greater than 50 m, and did not include the Big Island. For this project, UH researchers led by Dr. Mark Merrifield have extended model capabilities to include the eight primary semi-diurnal and diurnal tidal components, added a domain for the island of Hawaii, and have extended the inshore water depth limit to 10 m. Figure 3.1 shows the primary domain boundaries used in this study. The model can also be applied to user specified sub-domains within the domains shown in Figure 3.1.

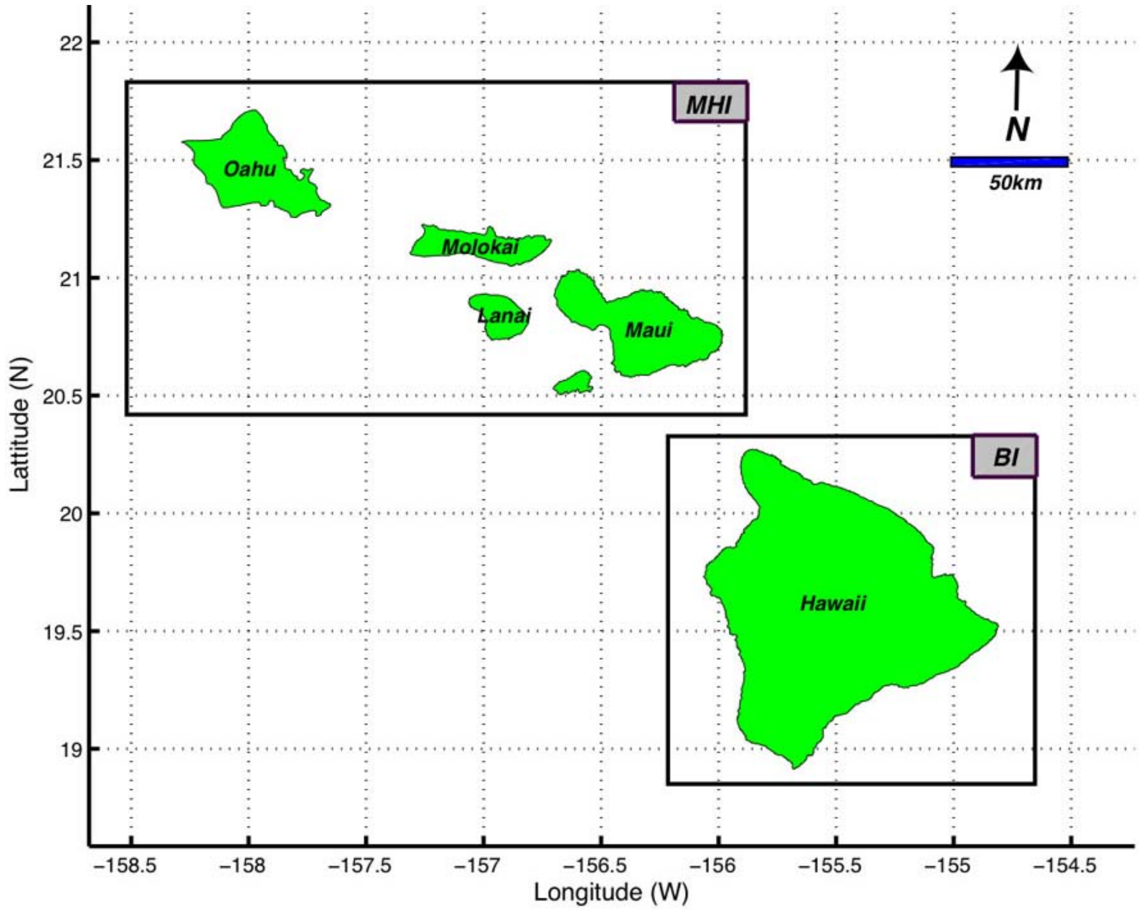


Figure 3-1
UH Tidal Model Domains

The UH tidal model can be run in two modes: barotropic and baroclinic. The barotropic mode computes depth-averaged velocities and water surface elevations resulting from the surface tidal waves. The baroclinic mode reproduces the currents generated by the propagation of internal tides. As discussed in Section 2, nearshore circulation in most areas of Hawaii is strongly driven by the combination of barotropic and baroclinic tides. Model results are therefore presented for the combined barotropic and baroclinic tidal flow. To minimize data output, baroclinic model results are output for near-bottom, middle and surface layers of the water column. These correspond to layers 57, 30 and 1 (surface), respectively, out of a total of 61.

3.2 Limitations

Although this model is the most advanced tool available to assess currents around the islands, it does have some limitations. It is based upon the tidal currents and therefore does not take into account large or small-scale eddy formation or the effect of the North Pacific Equatorial Current. However, in most areas around the island, tidally driven flow comprises most of the flow and this tidal component is more predictable over the long term. Predicted tidal flows therefore provide a logical basis for determining the location of turbine systems. The North Pacific Equatorial Current is typically a weak component of the overall flow, and variable in both direction and speed. The eddy driven currents along the Kona coast of Hawaii are discussed as a special case in Section 4 of this report.

The model also does not include wind as a forcing mechanism, and they are therefore not represented in the model results. Field measurements indicate that these currents are important only in the upper 5 m of water depth, which limits their utility for power generation.

In addition, the model grid spacing is approximately 1 km by 1 km. Fine scale features of bathymetry and topography, may therefore not be captured by the model.

3.3 Model Validation

3.3.1 University of Hawaii Investigations

Model results for the most energetic tidal component, the M_2 semi-diurnal tide, have recently been validated using satellite and in-situ sea level observations as well as current velocities from two moorings (Carter et al., 2007). Model calculated M_2 water surface elevations and phases were compared with NOAA sea level gauges at Port Allen, Nawiliwili, Honolulu, Mokuoloe and Kahului. With the exception of Honolulu and Kaneohe Bay, where the one-kilometer model grid does not adequately represent the harbor, model computed elevations were within 2 to 7 mm of the observed elevations. In Honolulu Harbor and Kaneohe Bay, the differences in observed and model elevations were 10 to 13 mm. In deeper water away from land, satellite altimetry data was compared with the model-simulated water surface elevations. Figure 3.2 shows this comparison. The difference between the model-computed and observed elevations and phases was 0.8 to 1.3 cm and 3.3 to 5.1 degrees, respectively.

The modeled current structure was validated by comparing the calculated M_2 current component with measurements from two ADCP current meter moorings between Oahu and Kauai. Mooring A2 was located on the southern edge of the Kaena Ridge, and a second mooring, C2, was located south of the ridge at a depth of 4000 m. Figure 3.3 shows the comparison of the computed current profiles with five months of ADCP data (Carter et al., 2007). The difference in current magnitudes ranges from 0.017 to 0.037 m/s.

This agreement between the UH Tidal Model computations and field observations indicates that the model accurately reproduces the dynamics of the major tidal forcing of currents in the Hawaiian Islands.

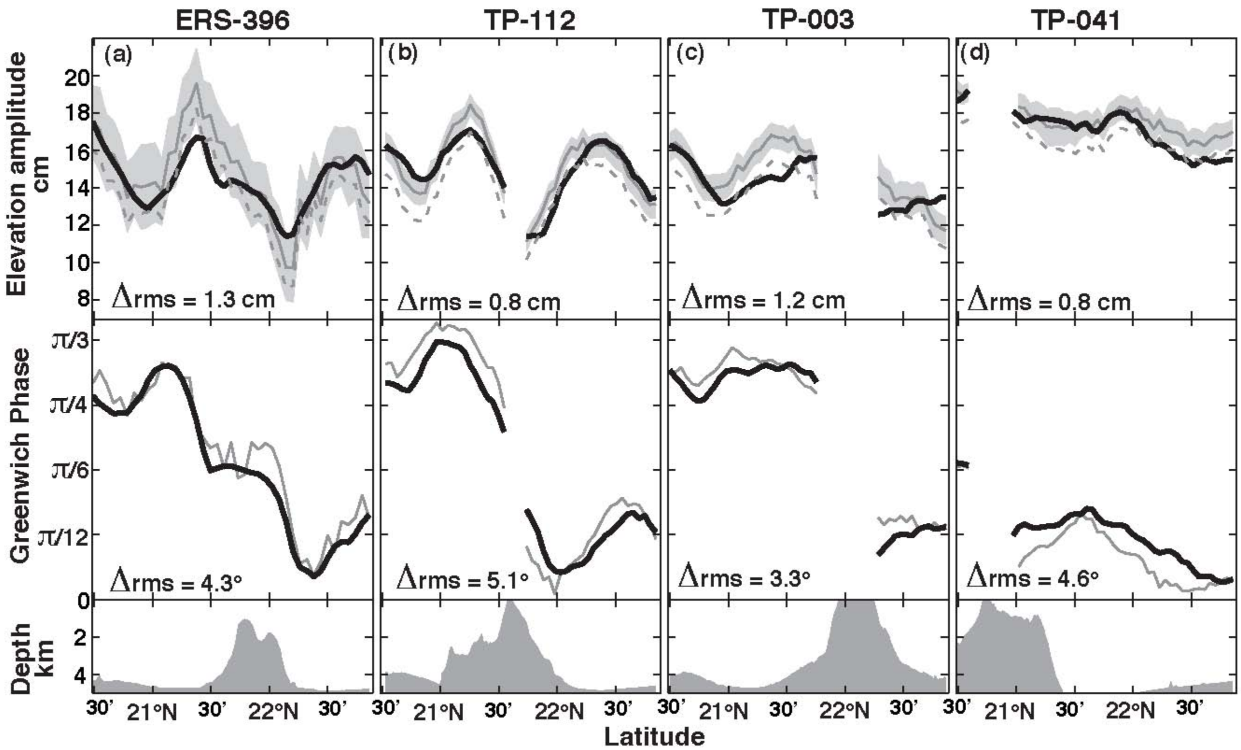


Figure 3-2
Comparison of total M_2 surface elevation (barotropic plus baroclinic) from the model and from satellite altimetry. The gray shading in the amplitude panels shows ±1 standard error for the satellite amplitude measurements (from Carter et al., 2007)

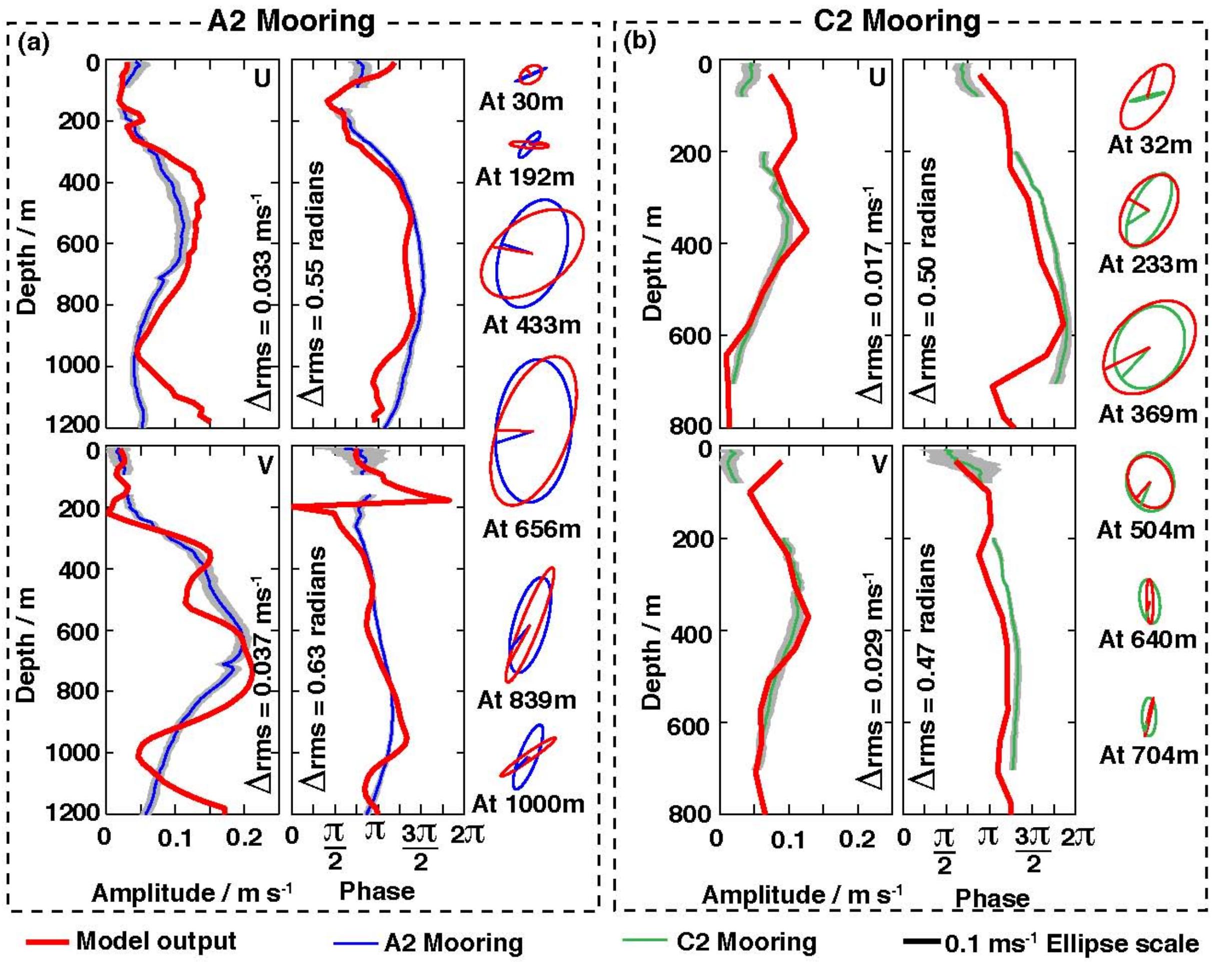


Figure 3-3
Comparison of the M_2 component of currents from the model and 5 months of moored ADCP data. (a) A2 mooring on the edge of the ridge crest; (b) C2 mooring south of the ridge. Ellipses are from depths where the model velocities were nearly co-located with ADCP observations (from Carter et al., 2007)

3.3.2 Validation with Available Current Meter Data

SEI further validated the model for this project by comparing model results with existing current meter records from various locations around Hawaii. Current meter data were obtained from University of Hawaii archives of various research projects around the state, and from previous Sea Engineering projects and records. Table 3-1 presents a list of the location, water depth, and deployment period of the current meter data used for this validation. Figures 3.4 and 3.5 show the locations of the current meters. The measurement locations are spread across Oahu, Maui, Molokai and the Big Island, and include most of the headlands and points known for strong currents. The current meter data were processed to determine mean current speed and maximum speed during the deployment period.

Table 3-1
Model Validation Locations

ID	Location	Date Range		Depth (m)		Location	
		From	To	Bottom	Meter	Latitude (N)	Longitude (W)
MA3	North Beach	11/10/92	02/18/93	32	18	20.9402	156.6973
MA3	North Beach	05/20/93	09/30/93	32	18	20.9402	156.6973
O2	Kaena Point	04/26/66	05/17/66	70	35	21.6150	158.3017
O3	Kahuku Point	04/26/66	05/17/66	80	10	21.7300	157.9900
O4	Kaena Point	09/20/66	10/07/66	80	10	21.6050	158.2950
O1	Makapuu	02/11/65	03/07/65	110	20	21.2650	157.6050
O1	Makapuu	03/16/65	04/08/65	110	20	21.2650	157.6050
O8	Barbers Point	07/29/88	10/03/88	120	30	21.3140	158.1313
MO2	Laau	03/12/68	03/28/68	60	20	21.1083	157.3567
MO1	Ilio Point	07/26/66	08/12/66	80	10	21.2267	157.2767
MO3	Kamalo Point	09/27/94	04/07/96	75	25	20.9833	156.9333
MA1	Hawea	10/24/64	11/14/64	80	10	21.0000	156.6917
MA2	Hana	08/03/68	09/08/68	60	18	20.7183	155.9700
H3	Upolu Point	07/22/67	08/12/67	60	10	20.2633	155.9067
H8	Upolu Point	11/25/84	03/31/85	169	20	20.2833	155.9000
H1	Mano Point	09/23/80	12/20/80	1345	15	19.9147	156.1488
H6	Mano Point	12/26/80	04/14/81	1346	101	19.9083	156.2055
H2	Keahole Point	04/30/67	05/21/67	80	10	19.8100	156.0583

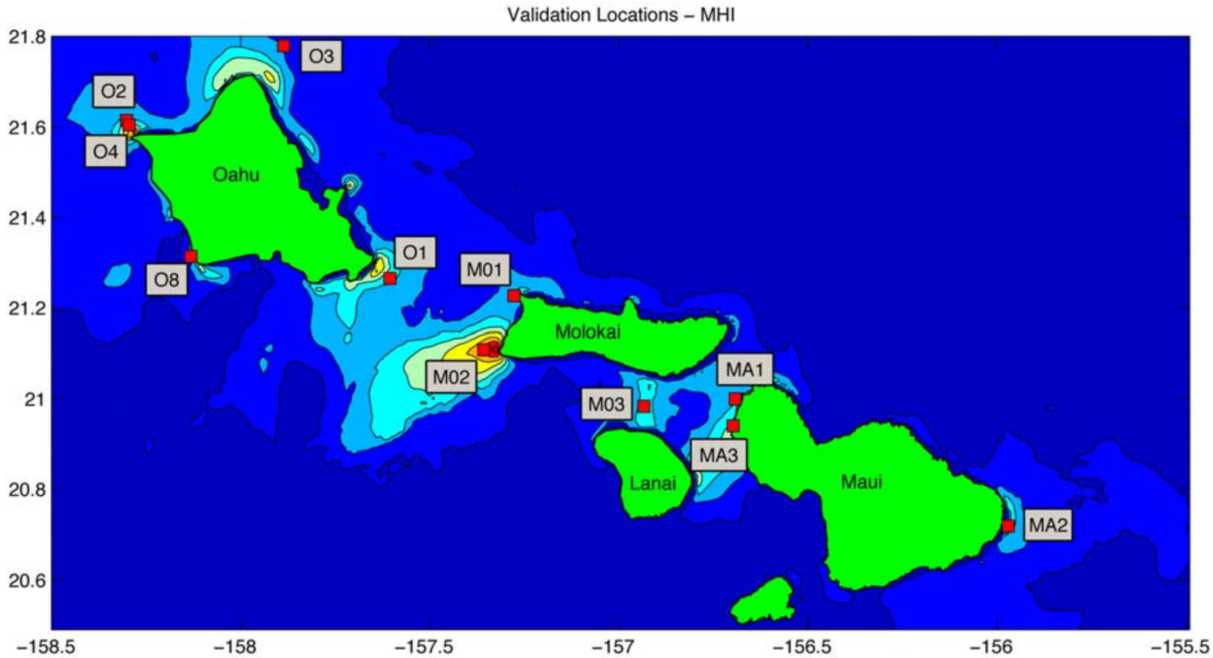


Figure 3-4
Locations of current meter data used for validation

The UH Hawaii Tidal Model was run for the same time periods as each current meter deployment, using a grid focused on the current meter location. The model computed mean and maximum current speeds were then compared to the current meter mean and maximum speeds. Table 3-2 presents results of the comparison.

Measured mean current speeds ranged from 0.12 to 0.57 m/s, while the model computed mean speeds ranged from 0.22 to 0.70 m/s. Both the model and the observed measurements indicated that the strongest mean and maximum currents occurred offshore of Laau Point, Molokai, and Upolu Point on the Big Island. Analysis of the difference between the observed and modeled mean speeds indicated that the model generally over-predicted mean speeds by 0.08 m/s. Similar analysis of the maximum speeds indicated no clear bias of the model to either over or under predict the maximums. The UH Tidal Model shows reasonable agreement with current meter data and captures the major features of coastal currents in Hawaii that are important for energy resource assessment, including the location of maximum currents and the general magnitudes of the mean and maximum current speeds.

Results from three locations along the Kona Coast of the Big Island are evaluated separately and shown in Table 3-3. The model computes currents in this area with mean speeds of 0.04 to 0.08 m/s, and maximum speeds of 0.13 to 0.20 m/s for the observation period of approximately seven months. By contrast, the measurements show mean and maximum speeds as high as 0.29 and 0.95 m/s, respectively. Thus the model shows poor agreement with field observations for this area. This is consistent with the numerous observations and studies that have shown the prevalence of large scale eddies that drive currents along these coasts, and the fact that the UH Tidal Model does not include eddies as a forcing mechanism.

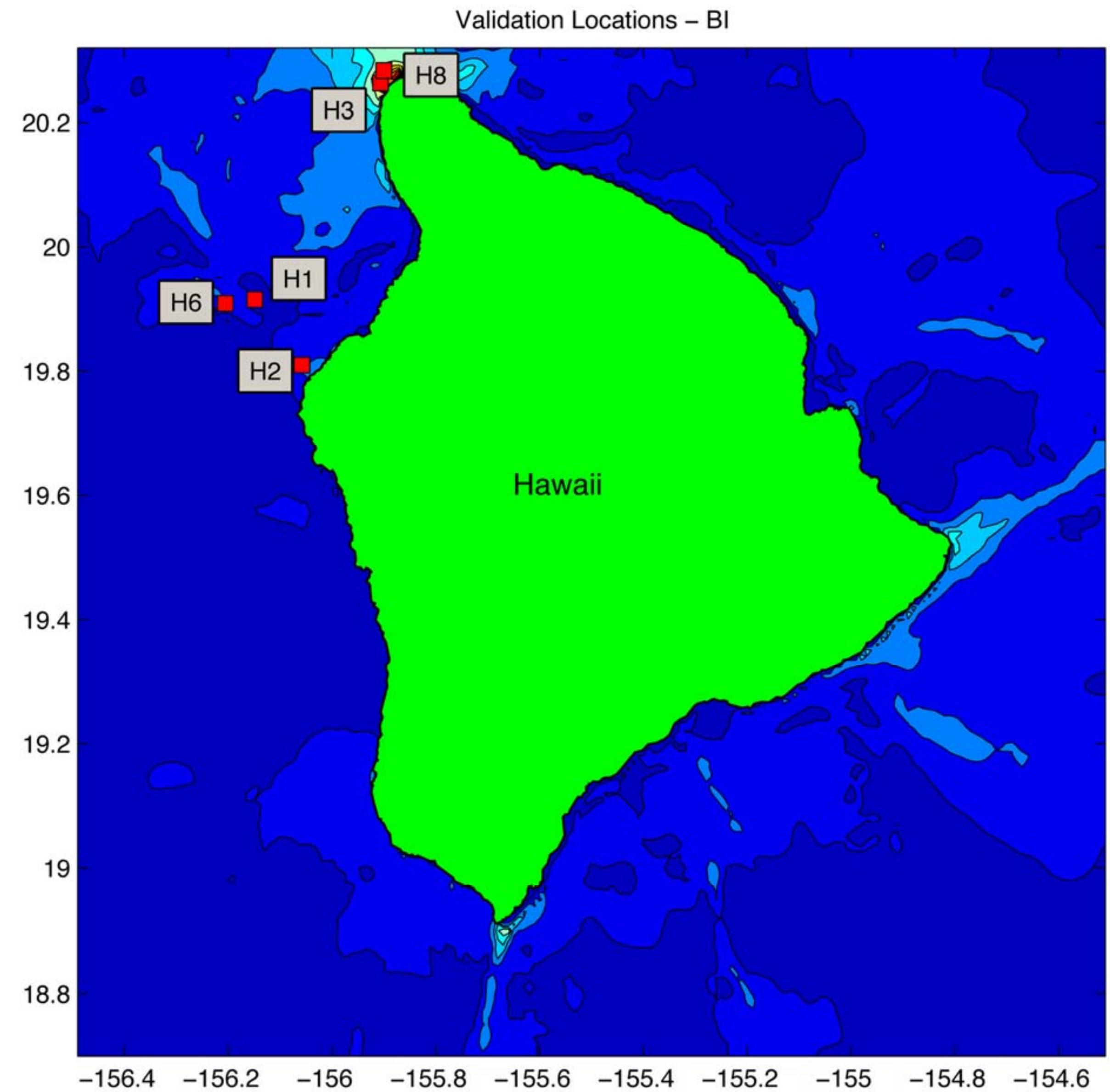


Figure 3-5
Locations of current meter data used for validation

Table 3-2
Comparison of current meter data with model results

Model Validation Summary											
ID	Location	Date Range		Depth (m)		Mean Speed (m/s)		Max Speed (m/s)		Obss-Mod Δ (m/s)	
		From	To	Bottom	Meter	Obs.	Model	Obs.	Model	Mean	Max
MA3	North Beach	11/10/92	02/18/93	32	18	0.23	0.37	1.00	1.15	-0.15	-0.15
MA3	North Beach	05/20/93	09/30/93	32	18	0.20	0.36	0.98	1.10	-0.16	-0.12
O2	Kaena Point	04/26/66	05/17/66	70	35	0.33	0.35	1.31	1.00	-0.02	0.31
O3	Kahuku Point	04/26/66	05/17/66	80	10	0.25	0.44	1.10	1.15	-0.19	-0.05
O4	Kaena Point	09/20/66	10/07/66	80	10	0.26	0.30	1.09	0.65	-0.04	0.44
O1	Makapuu	02/11/65	03/07/65	110	20	0.26	0.35	1.02	1.00	-0.09	0.02
O1	Makapuu	03/16/65	04/08/65	110	20	0.20	0.30	0.61	0.80	-0.10	-0.19
O8	Barbers Point	07/29/88	10/03/88	120	30	0.24	0.22	0.75	0.65	0.02	0.10
MO2	Laau	03/12/68	03/28/68	60	20	0.57	0.70	1.41	1.70	-0.13	-0.29
MO1	Ilio Point	07/26/66	08/12/66	80	10	0.19	0.25	0.55	0.70	-0.06	-0.15
MO3	Kamalo Point	09/27/94	04/07/96	75	25	0.23	0.32	1.10	0.95	-0.09	0.15
MA1	Hawea	10/24/64	11/14/64	80	10	0.12	0.27	0.29	0.75	-0.15	-0.46
MA2	Hana	08/03/68	09/08/68	60	18	0.26	0.35	0.78	1.00	-0.09	-0.22
H3	Upolu Point	07/22/67	08/12/67	60	10	0.55	0.45	1.62	1.00	0.10	0.62
H8	Upolu Point	11/25/84	03/31/85	169	20	0.36	0.40	1.35	1.20	-0.04	0.15
									bias	-0.08	0.01
									rmse	0.11	0.28
									SI	0.38	0.28

RMSE = root mean square error
SI = scatter index

Table 3-3
Comparison of current meter data with model results along the Kona Coast of the Big Island

Model Validation Summary - Keahole, Hawaii											
ID	**Location**	**Date Range**		**Depth (m)**		**Mean Speed (m/s)**		**Max Speed (m/s)**		**Obss-Mod**	
		From	**To**	**Bottom**	**Meter**	**Obs.**	**Model**	**Obs.**	**Model**	**Mean**	**Max**
H1	Mano Point	9/23/1980	12/20/80	1345	15	0.14	0.05	0.51	0.13	0.09	0.38
H6	Mano Point	12/26/80	04/14/81	1346	101	0.29	0.04	0.95	0.13	0.25	0.82
H2	Keahole Point	04/30/67	05/21/67	80	10	0.22	0.08	0.87	0.20	0.14	0.67
									bias	0.16	0.62
									rmse	0.17	0.65
									SI	0.80	0.84

RMSE = root mean square error
SI = scatter index

4

UH TIDAL MODEL RESULTS

The objective of this study was to evaluate the potential for ocean current power generation in the Hawaiian Islands (except for Kauai). The UH Tidal Model was applied to characterize currents around the islands and identify possible resource sites. Several run and output options are available with the model including period and duration of model run; barotropic or baroclinic run modes; the model domain; data output for surface, middle and bottom water layers; and output units. The options selected for our analysis are outlined below:

- Run period and duration – An objective of the study is to determine mean annual speeds and power density for tidal currents in Hawaii. Model runs for a full year period would require a prohibitive amount of computation time and memory. Fortunately, the tidal characteristics of a site can be almost entirely captured within a monthly tidal cycle. For this project, therefore, model runs were limited to a period of one month - July 2007. A comparative analysis was completed for a small area offshore of Kaena Point to confirm that the monthly run is representative of annual conditions. Figures 4.1 to 4.3 illustrate the results. Figures 4.1 and 4.2 show mean near-bottom current speeds calculated by the model offshore of Kaena Point for the entire year of 2007 and for only the month of July. The mean current characteristics are nearly identical. This is confirmed in Figure 4.3, which plots the differences between the annual and monthly results. The maximum difference in the calculated mean current speeds is 2.5 cm/s. These results confirm that monthly model runs for July 2007 can be considered representative of annual conditions.
- Barotropic and baroclinic run modes – The UH Tidal Model is capable of simulating the free surface, depth-averaged tidal currents (barotropic), or depth varying currents caused by internal waves in density interfaces in the water column (baroclinic). Coastal currents in most areas of Hawaii are strongly driven by a combination of the two. For this analysis, model runs were completed to simulate combined barotropic and baroclinic currents.
- Model domain – The model domain refers to the geographic area encompassed by the model. The UH Tidal Model consists of two separate domains – one encompassing the middle Hawaiian Islands (MHI) of Oahu, Molokai and Maui; and a separate domain for the Big Island (BI)(see Figure 3.1). Model runs were completed for the entirety of each of these domains. Model runs were also completed for more focused, zoomed-in domains including Oahu, Maui-Molokai, and selected headlands and points around the islands.
- Surface, mid-depth and bottom output – The numerical model is 3-dimensional, and computed velocities are output for surface, middle and near-bottom layers in the water column. Figures 4.4 to 4.6 show results for each layer. The figures show that the differences are not significant. Because of severe design waves, tidal current generation systems applicable to Hawaii will likely be installed on the seafloor or in the lower water column. For this project, therefore, model results are presented primarily for near-bottom currents.

- Velocity and power density units – The numerical model computes current velocities in units of meters per second. Energy conversion systems are often evaluated in terms of mean power density, with units of watts per square meter. Power density is defined as $\frac{1}{2} \rho U^3$ (where ρ = seawater density and U = current speed). The model computed velocity time series can be converted to units of power density, and mean power density can readily be obtained as the time-average of power density.

Since the velocity magnitude and resultant power density exhibit considerable spatial variation, the term "peak" will refer to the spatial maximum of a value. The terms "mean" and "maximum" should be interpreted in the temporal sense. For example "peak mean velocity magnitude" refers to the spatial maximum of the time-averaged magnitude of velocity. Similarly, "peak maximum power density" should be interpreted as the spatial maximum of the highest instantaneous power density value, or more simply, the highest single value for a given area.

Because currents are generally weak in Hawaii and power density is proportional to the cube of velocity, the computed ranges of power density are small and display poorly in the large domain model runs. Tidal turbine technology capabilities are also always referenced to current speeds. Thus, in this report, model results are displayed as mean and maximum current speeds. Equivalent plots of power density are included in Appendix A.

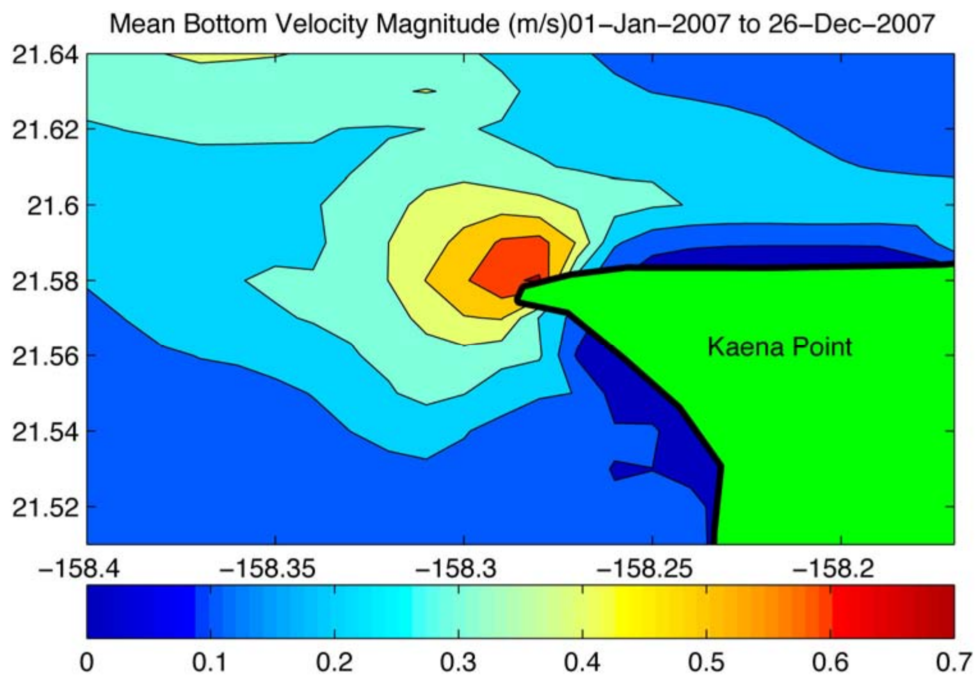


Figure 4-1
Mean near-bottom currents off Kaena Point for 2007

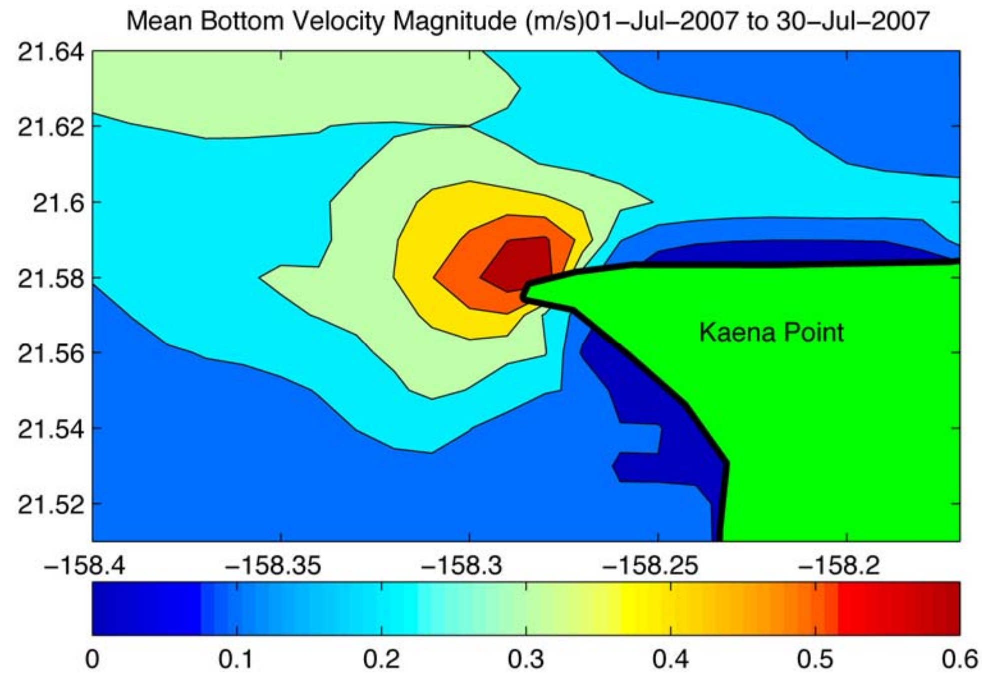


Figure 4-2
Mean near-bottom currents off Kaena Point for July 2007

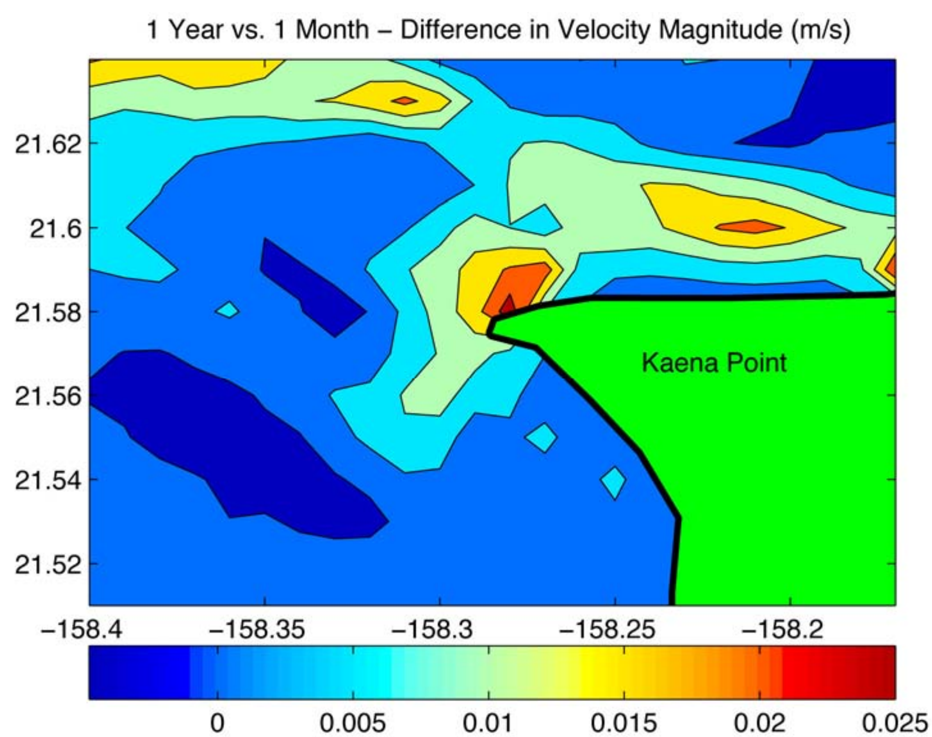
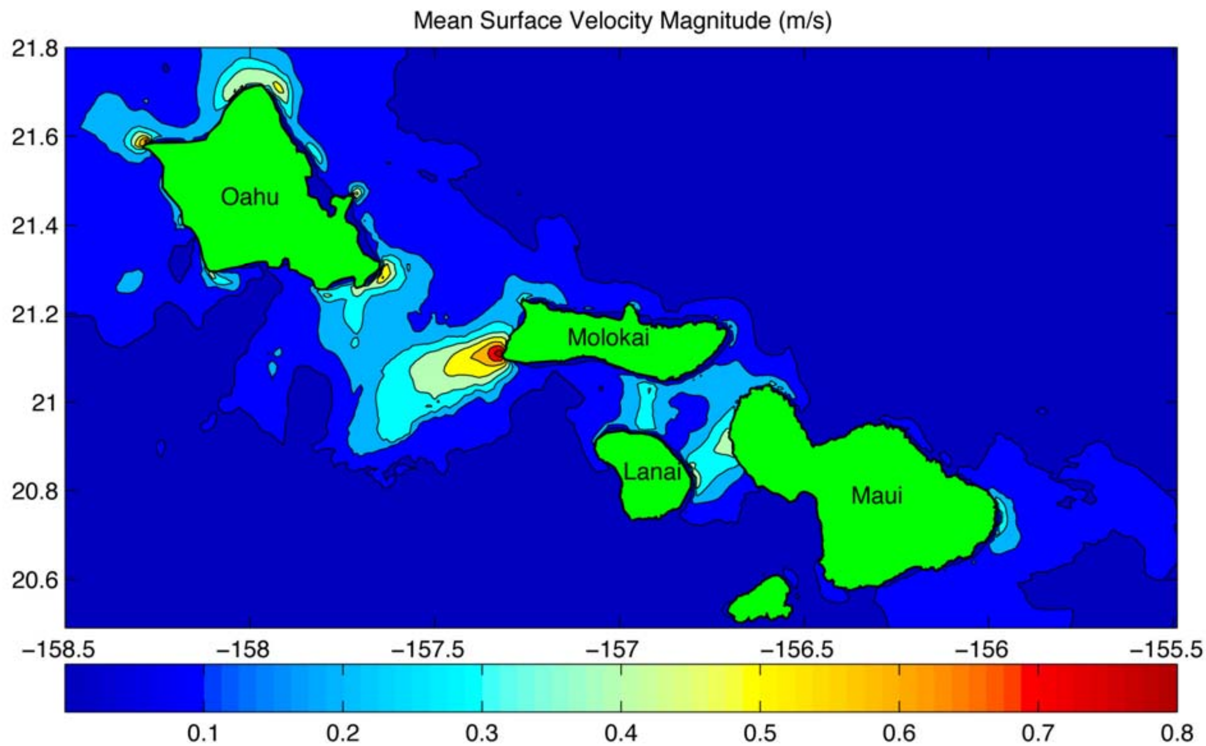


Figure 4-3
The difference in model computed annual and July near-bottom currents off Kaena Point

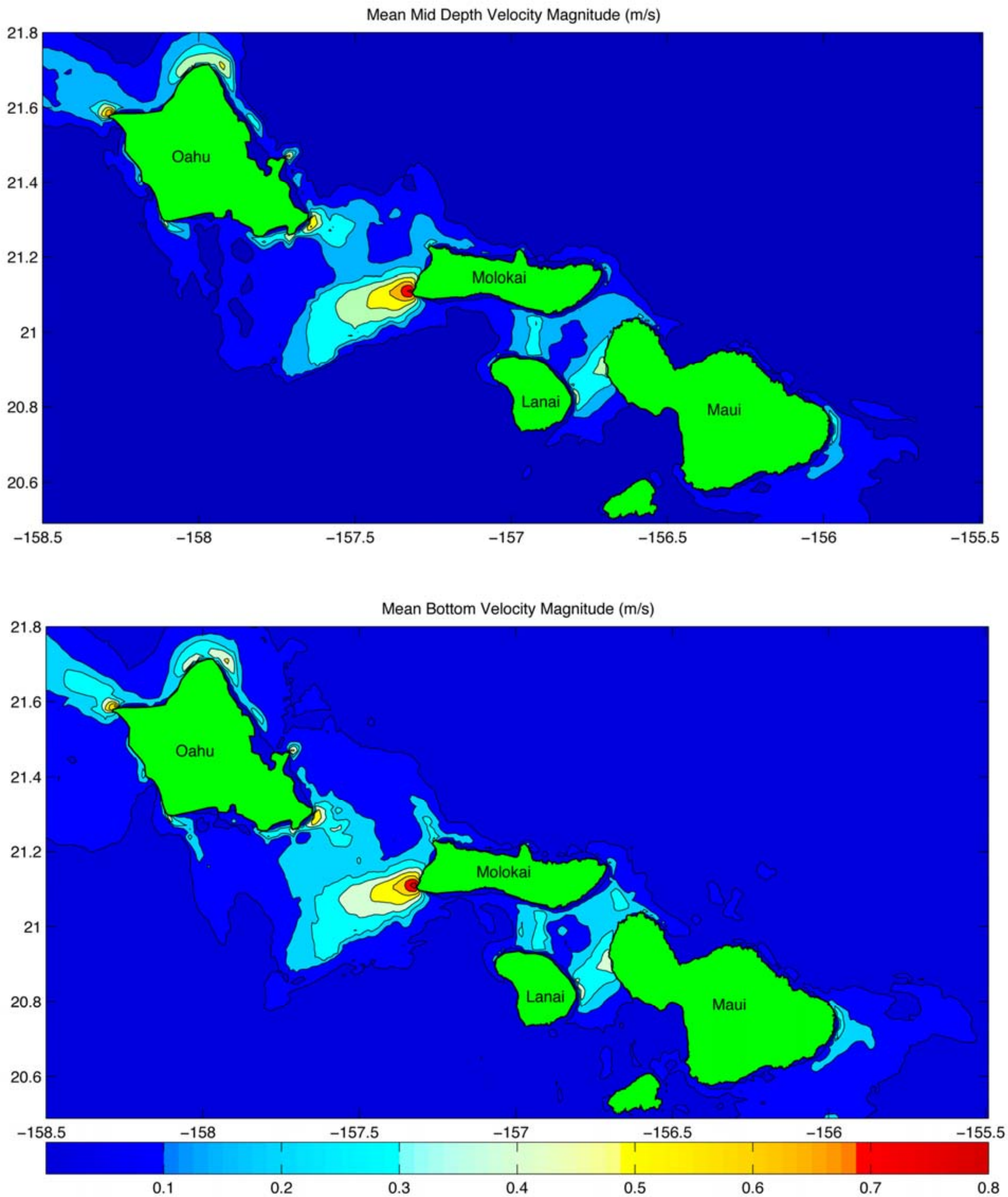
4.1 Middle Hawaiian Islands – Oahu, Maui, Molokai

The model-calculated mean surface, mid-depth and near-bottom currents speeds around Oahu, Molokai and Maui are presented in Figure 4.4. The figures indicate that in general, mean current speeds around the islands are typically less than 0.3 m/s. Stronger currents tend to occur offshore of headlands and points. The strongest computed mean currents in the middle Hawaiian Islands group are approximately 0.8 m/s and occur along Penguin Bank, off the southwest tip of Molokai. Figure 4.4 presents the mean currents for the surface, mid-depth and near bottom layers. The figures show that in the areas of strong currents there is little difference in model computed current magnitudes and patterns of occurrence between the surface, mid-depth and near-bottom water layers.

Figure 4.5 presents the maximum computed current speeds. The patterns are similar to the mean currents with stronger currents off headlands and points. Maximum currents of 2.2 m/s are predicted off the southwest tip of Molokai. Maximum currents of approximately 1.2 to 2.1 m/s are calculated off the major points of Oahu.



(a) Surface and mid-depth mean current speeds around Oahu, Molokai and Maui



(b) Mean mid-depth and near-bottom current speeds around Oahu, Molokai and Maui

Figure 4-4
(a) Surface and mid-depth mean current speeds around Oahu, Molokai and Maui;
(b) Mean mid-depth and near-bottom current speeds around Oahu, Molokai and Maui

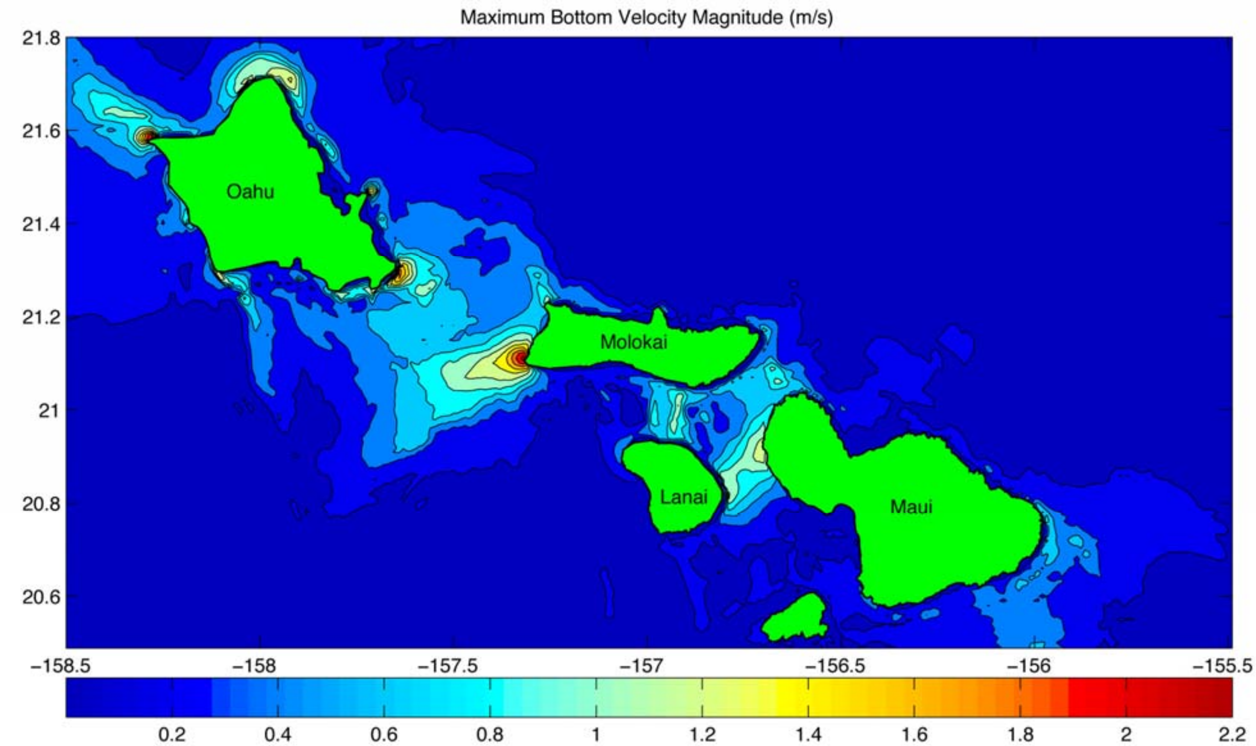


Figure 4-5
Maximum near-bottom current speeds around Oahu, Molokai and Maui

4.1.1 Oahu

Detailed model results for Oahu are presented in Figures 4.6 and 4.7. Expanded views of the areas with the strongest currents are shown in Figures 4.8 to 4.12. Figures 4.6 and 4.7 indicate that the strongest currents occur directly off the major points and headlands around the island. In other locations, currents are weak, typically averaging less than 0.2 m/s, with maximum currents of less than 0.6 m/s. The strongest currents around Oahu are at Kaena Point and Makapuu Point. Mean current speeds at Kaena Point are calculated to be up to 0.7 m/s, while maximum current speeds are 2.1 m/s. This corresponds to a mean power density of 438 watts/m^2, and a maximum power density of 4746 watts/ m^2 (Appendix A). A current meter deployed in 70m of water off Kaena Point for three weeks in May 1966 measured maximum currents of 1.3 m/s and mean speeds of 0.33 m/s (Table 3-2). Offshore of Makapuu, mean and maximum calculated current speeds were 0.6 m/s and 1.9 m/s, corresponding to mean and maximum power densities of 293 and 3515 watts/ m^2 (Appendix A). A current meter deployed in 110 m of water off Makapuu for 1.5 months in 1965 measured maximum currents of 1.02 m/s and mean speeds of 0.26 m/s (Table 3-2). Both the Kaena Point and Makapuu current meters were deployed slightly outside the peak current locations indicated by the model, and thus recorded currents speeds that were less than the peak model results (Figure 3.4).

Other areas around Oahu with relatively strong currents include Kahuku Point, Diamond Head/Portlock, and Barbers Point. Kahuku is predicted to have mean current speeds as great as 0.5 m/s, and maximum currents of 1.4 m/s. Corresponding mean and maximum power densities are 150 watts/m^2 and 1406 watts/m^2 (Figure 4.10). A three-week current meter deployment in 1966 recorded mean currents of 0.25 m/s and maximum speeds of 1.1 m/s, slightly less than model results because the current meter location was outside the peak current locations indicated by the model. Current speeds at Diamond Head/Portlock and Barbers Point are calculated to be weaker, with mean speeds of approximately 0.4 m/s and maximum speeds of 1.2m/s. Mean power densities are only 102 and 104 watts/m^2 offshore of Portlock and Barbers Point, respectively, and maximum power densities are 991 to 11144 watts/ m^2 (Appendix A). A summary of notable locations around Oahu is presented below in Table 4-1.

Table 4-1
Peak and Mean Current Speeds and Power Density, Island of Oahu

Location	Velocity Magnitude (m/s)		Power Density (W/ m^2)	
	Peak Max	Peak Mean	Peak Max	Peak Mean
Kaena Point, Oahu	2.1	0.7	4746	438
Makapuu Point, Oahu	1.9	0.6	3515	293
Kahuku Point, Oahu	1.4	0.5	1406	150
Barbers Point, Oahu	1.3	0.4	1144	104
Diamond Head, Oahu	1.2	0.4	991	102

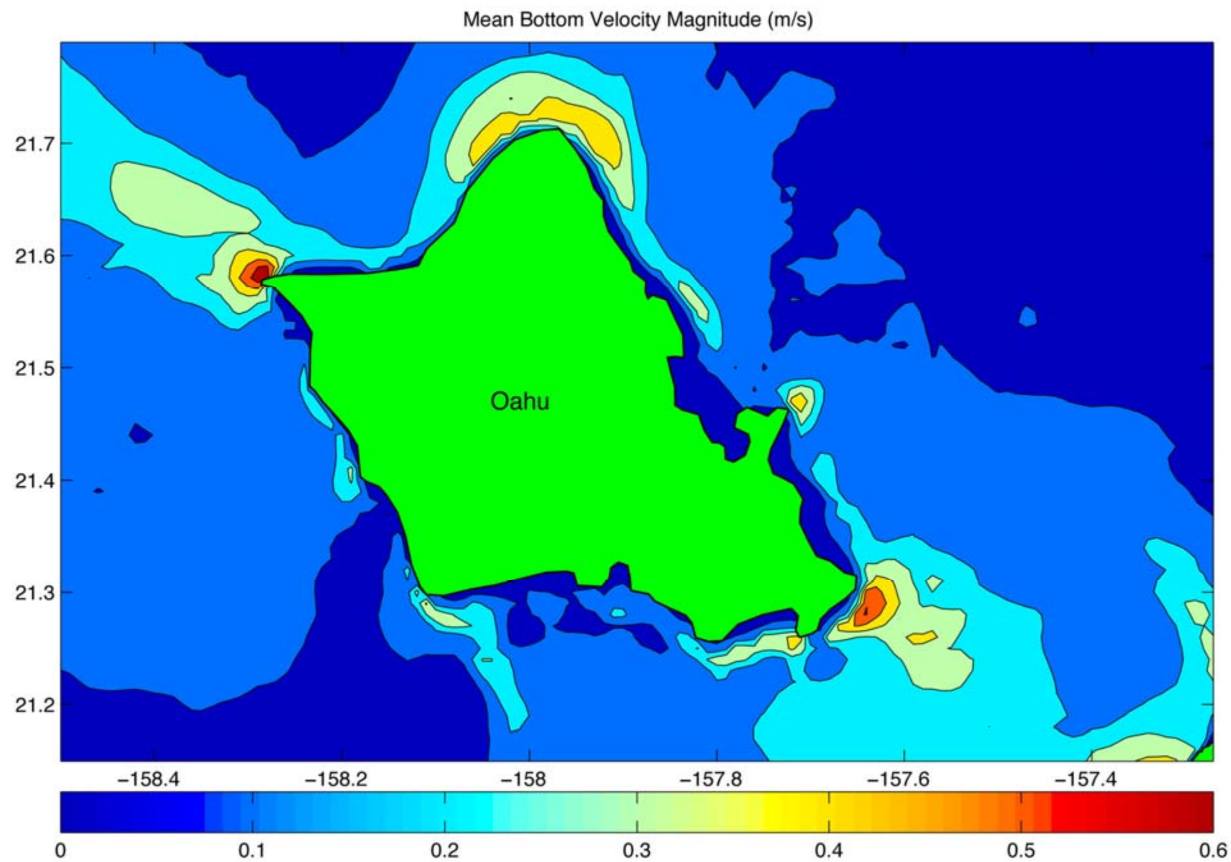


Figure 4-6
Mean near-bottom current speeds around Oahu

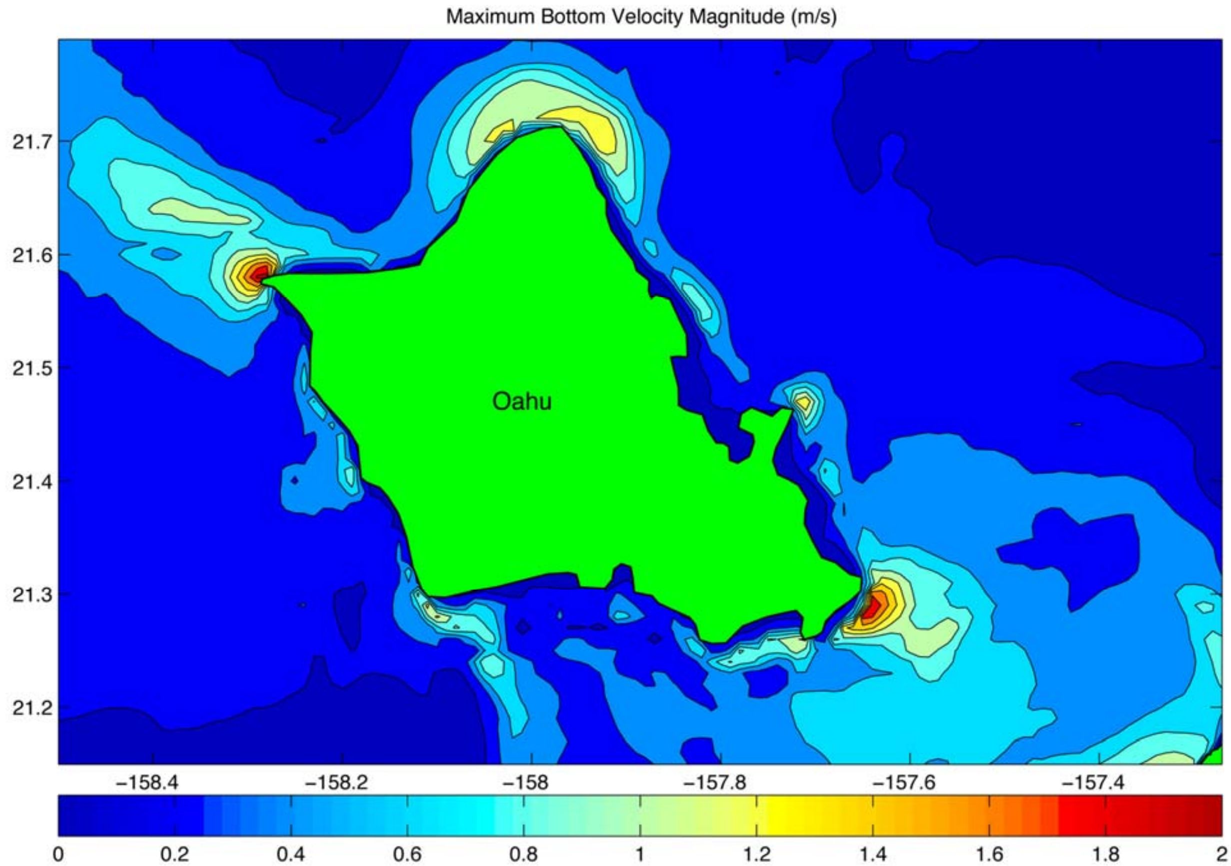


Figure 4-7
Maximum near-bottom current speeds around Oahu

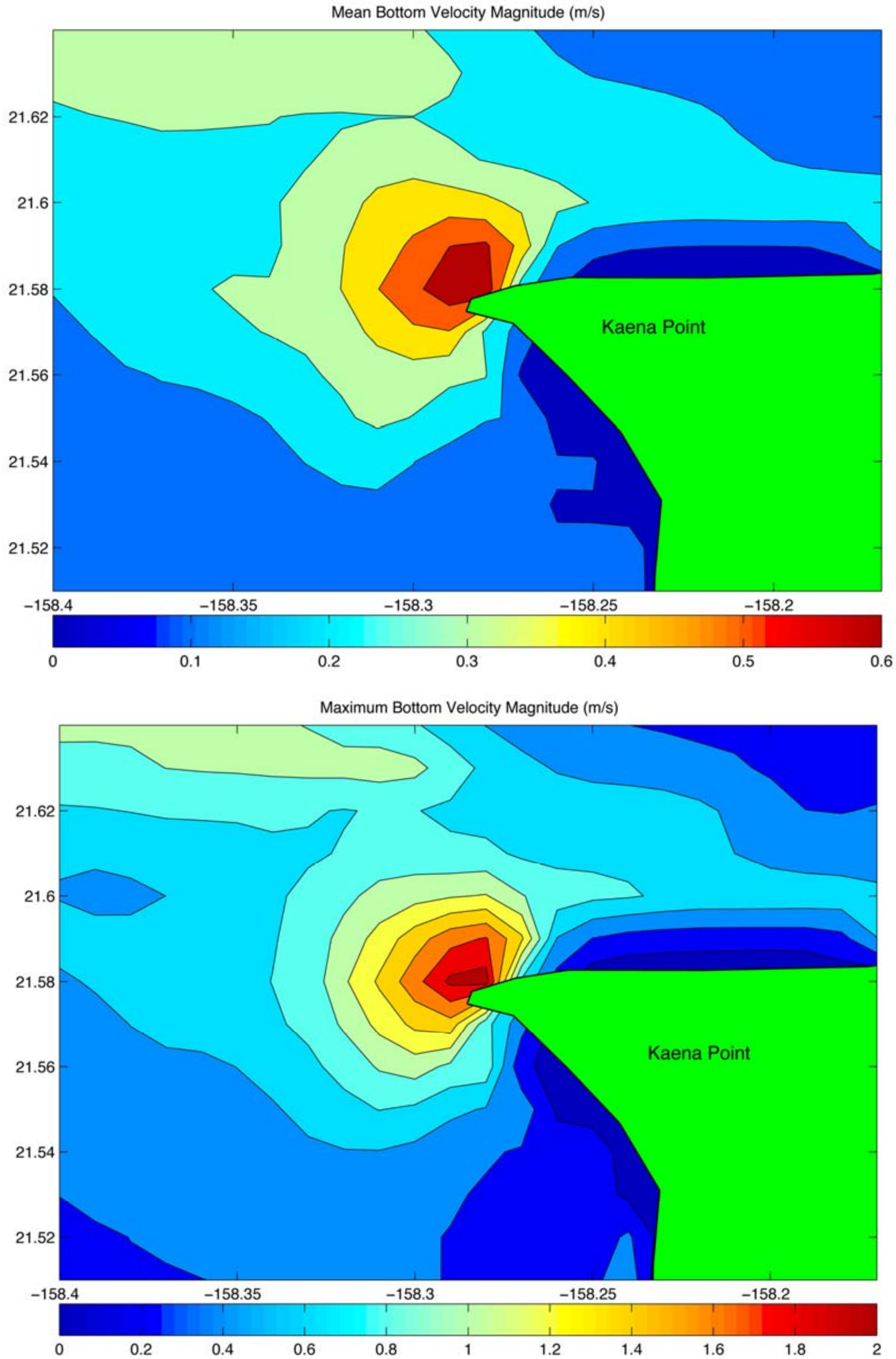


Figure 4-8
Mean and maximum near-bottom current speeds off Kaena Point, Oahu

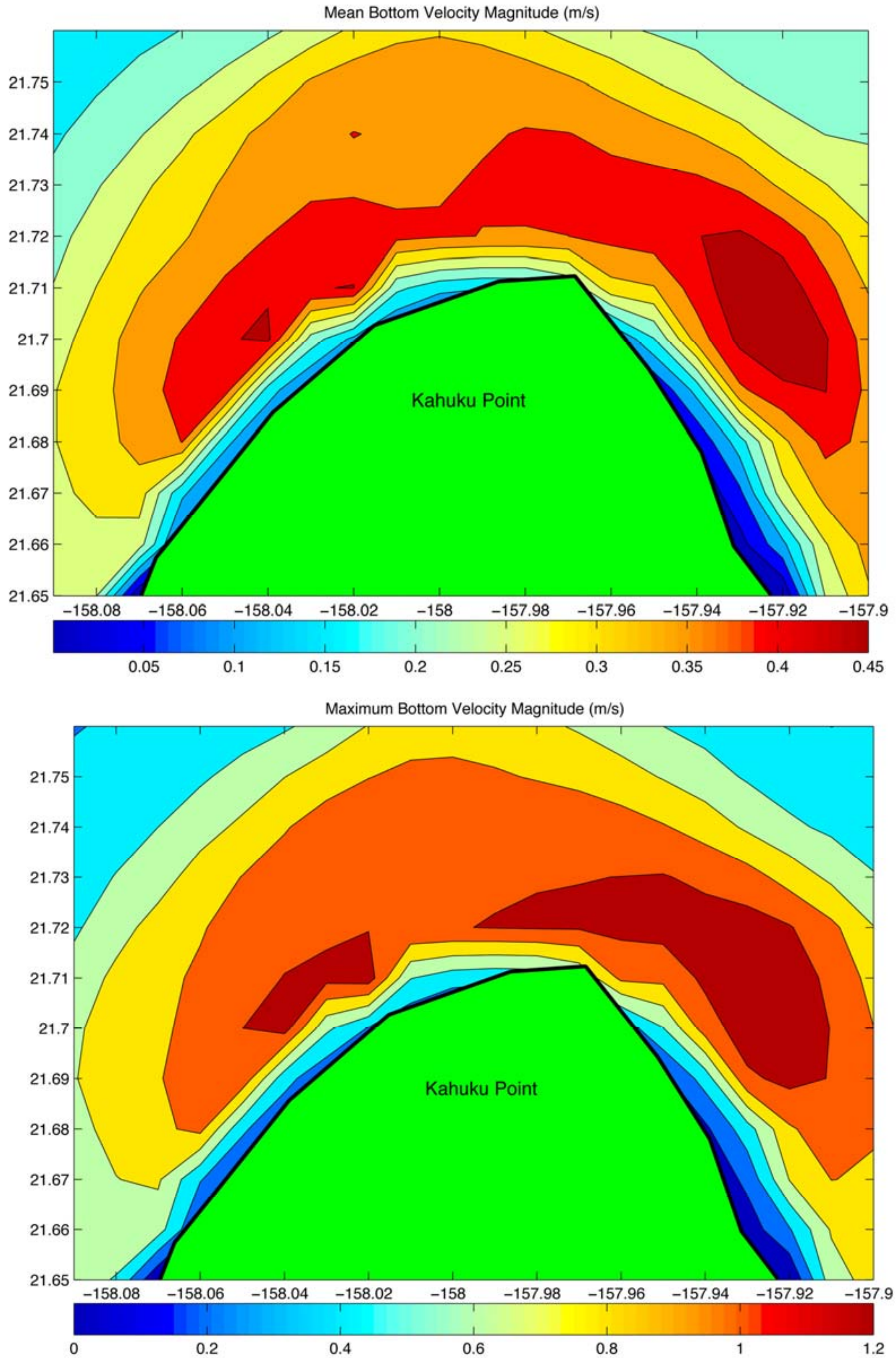


Figure 4-9
Mean and maximum near-bottom current speeds off Kahuku Point, Oahu

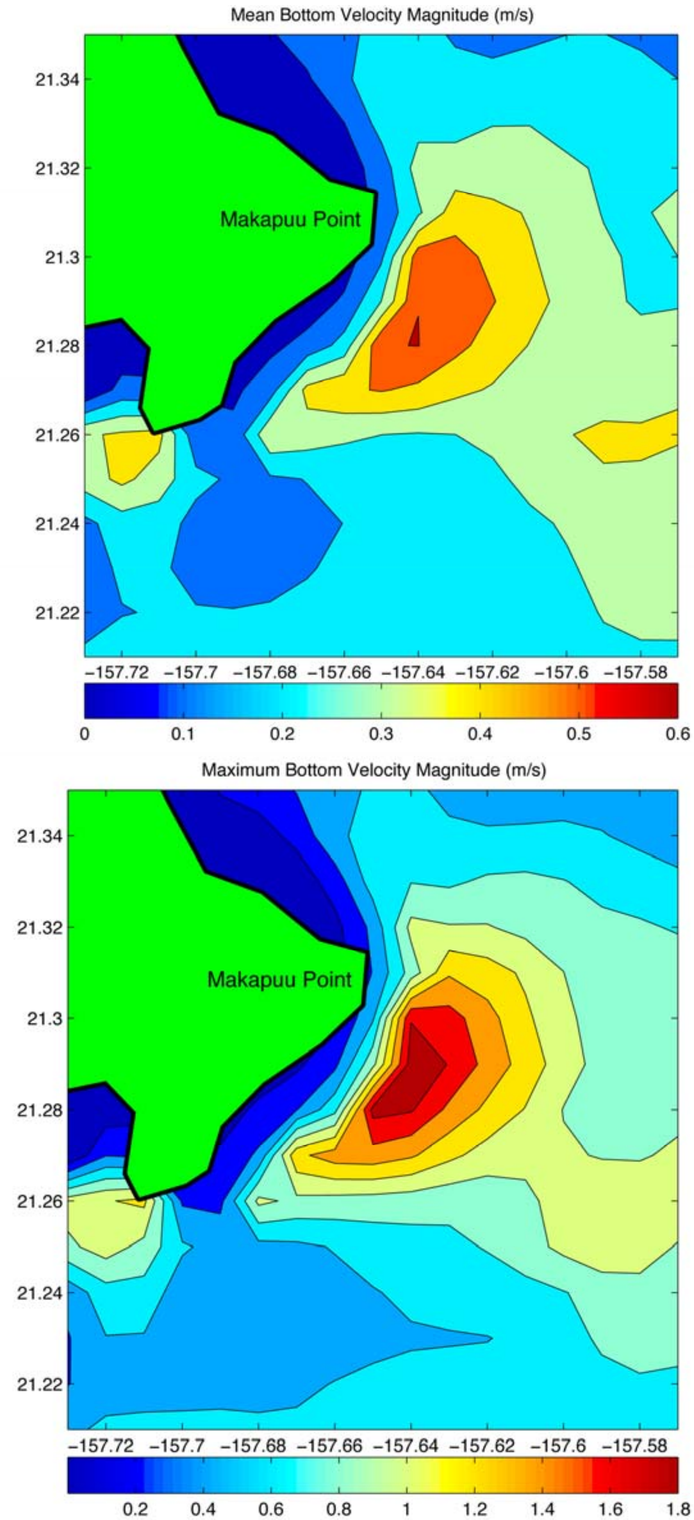


Figure 4-10
Mean and maximum near-bottom current speeds off Makapuu Point, Oahu

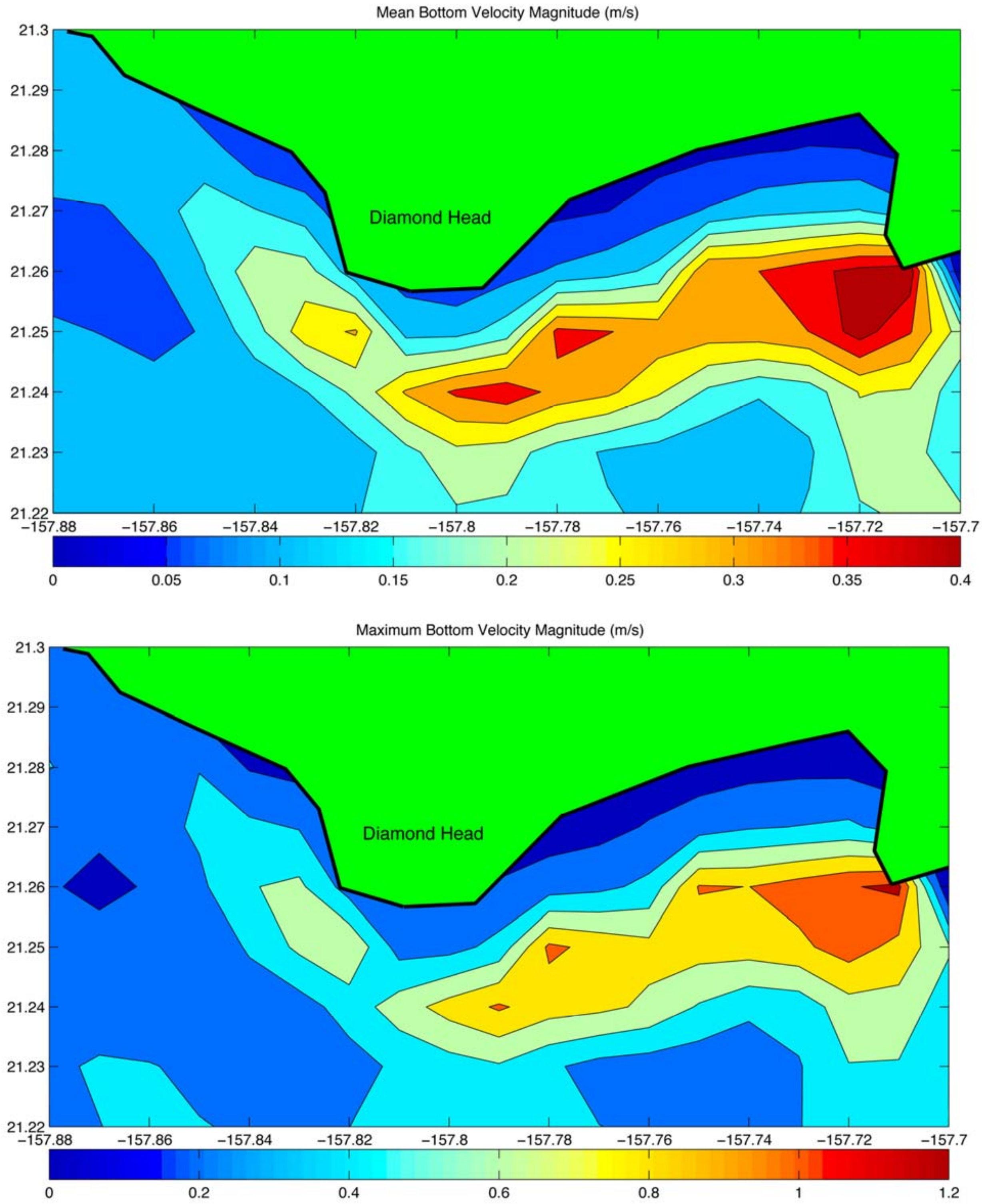


Figure 4-11
Mean and maximum near-bottom current speeds off Diamond Head/Portlock, Oahu

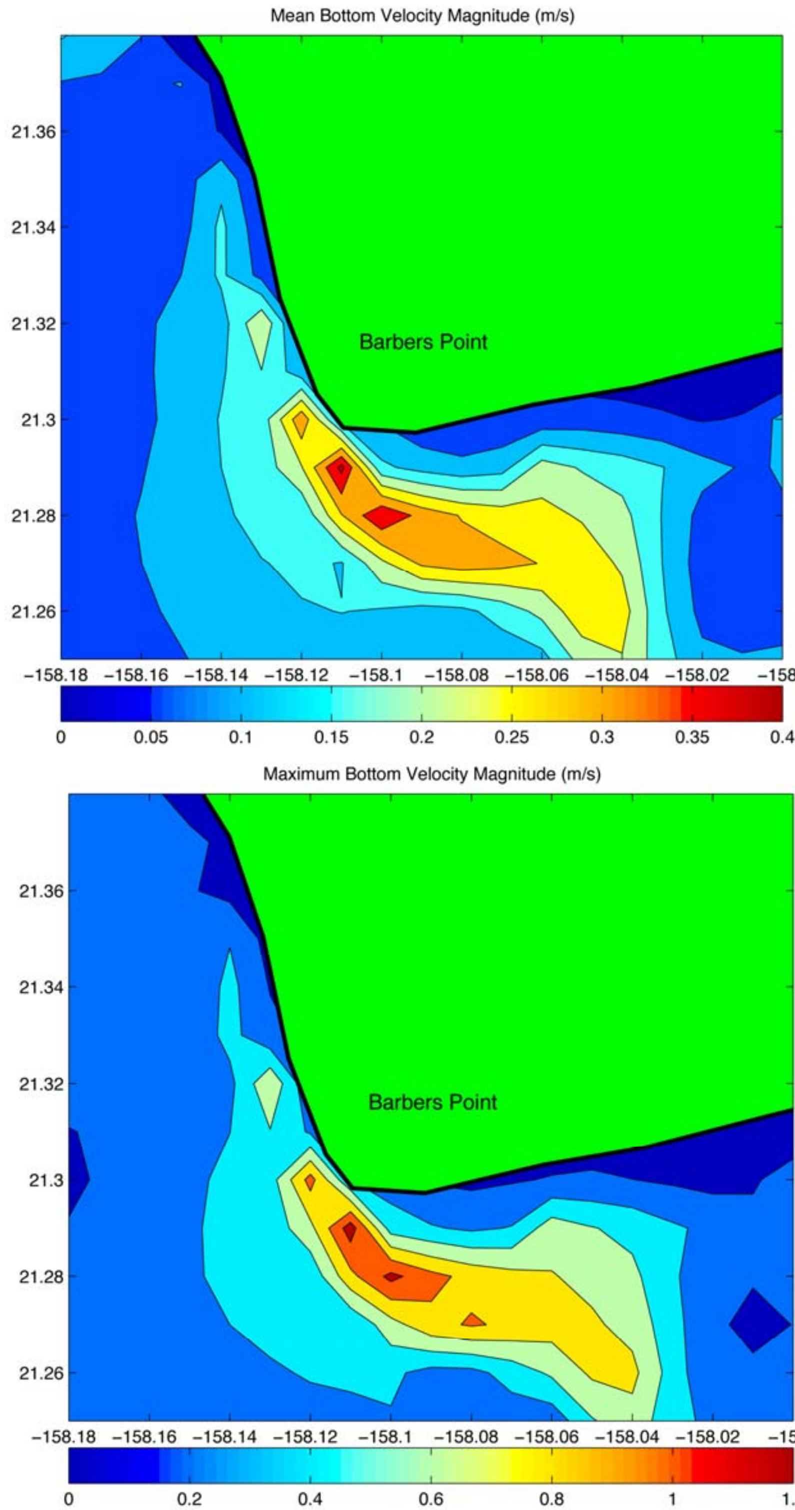


Figure 4-12
Mean and maximum near-bottom current speeds off Barbers Point, Oahu

4.1.2 Molokai, Lanai and Maui

Model results for the islands of Molokai, Maui and Lanai are presented in Figures 4.13 and 4.14, and expanded views of the areas with the strongest currents are shown in Figures 4.15 and 4.16. Figures 4.13 and 4.14 indicate that the strongest currents in this island group occur at Laau Point at the southwest corner of the Molokai, and in the vicinity of Lahaina, Maui. The strongest currents are located off Laau Point, Molokai on the Penguin Bank. This is a broad shoal area extending to the southwest from Laau Point, with water depths typically less than 50 m. Mean current speeds at Laau Point are calculated to be up to 0.8 m/s, while maximum current speeds are 2.2 m/s (Figure 4.15). This corresponds to a mean power density of 653 watts/m^2, and a maximum power density of 5487 watts/ m^2 (Appendix A). A current meter deployed in 60 m of water for 2 weeks in March 1968 measured maximum currents of 1.4 m/s and mean speeds of 0.57 m/s (Table 3-2). The current meter was located southwest of the modeled peak current speed location (see Figure 3.4).

Mean and maximum calculated current speeds off Lahaina were 0.5 m/s and 1.4 m/s, corresponding to mean and maximum power densities of 162 and 1496 watts/ m^2 (Figure 4.16). Relatively strong currents were confirmed in this area during a Sea Engineering study off north Kaanapali. A current meter deployed for eight months in 1992-1993 at a water depth of 32 m measured maximum currents of 1.0 m/s and mean speeds of 0.23 m/s (Table 3-2). This current meter was located north of the model predicted peak current site. The other notable site around Maui is off Hana, along the southeast coast. Mean and maximum currents were 0.4 m/s and 0.9 m/s, respectively (Figure 4.17). Mean and maximum estimated current speeds near Kikoa Point, Lanai were found to be 0.4 m/s and 1.2 m/s respectively. A summary of the notable locations near Maui, Molokai, and Lanai is presented below in Table 4-2.

Table 4-2
Peak and Mean Current Speeds and Power Density, Maui, Molokai and Lanai

Location	Velocity Magnitude (m/s)		Power Density (W/ m^2)	
	Peak Max	Peak Mean	Peak Max	Peak Mean
Lahaina, Maui	1.4	0.5	1496	162
Hana, Maui	0.9	0.4	339	53
Penguin Banks, Molokai	2.2	0.8	5487	653
Kikoa Point, Lanai	1.2	0.4	933	120

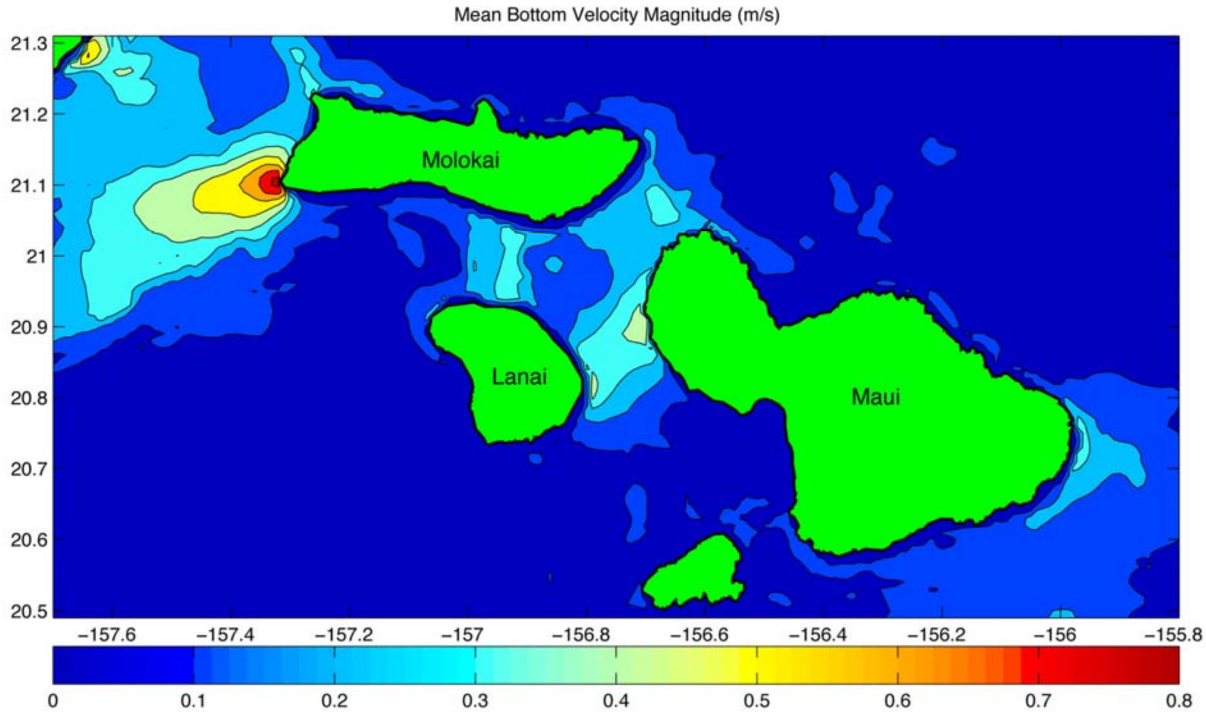


Figure 4-13
Mean near-bottom current speeds around Molokai, Maui and Lanai

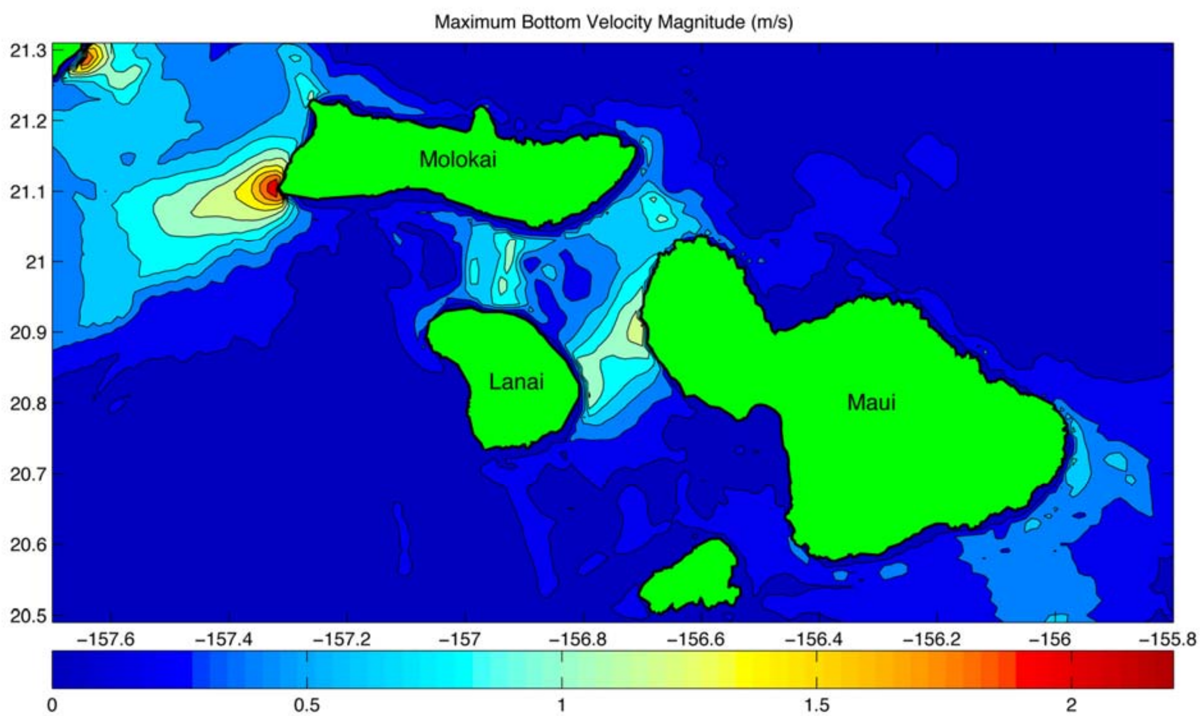


Figure 4-14
Maximum near-bottom current speeds around Molokai, Maui and Lanai

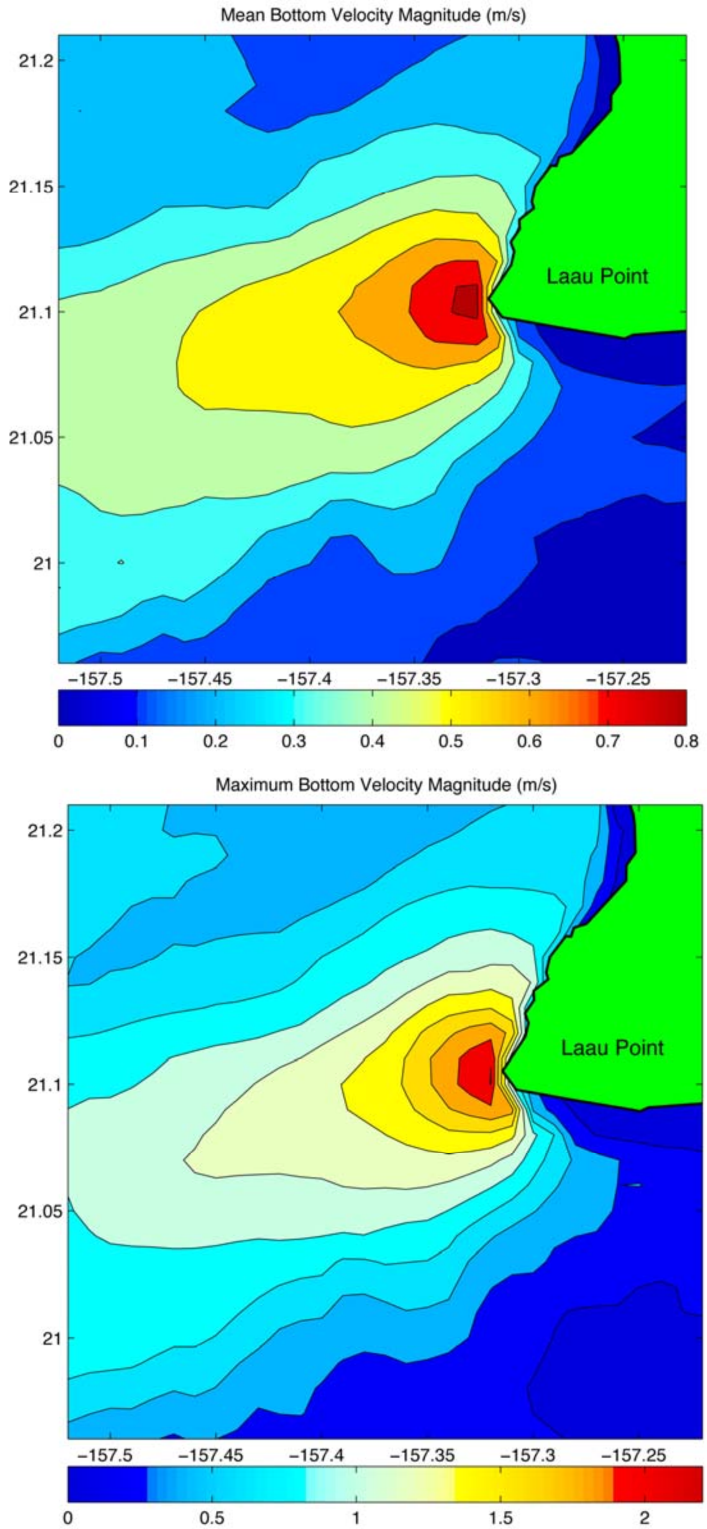


Figure 4-15
Mean and maximum current speeds off Laau Point, Molokai

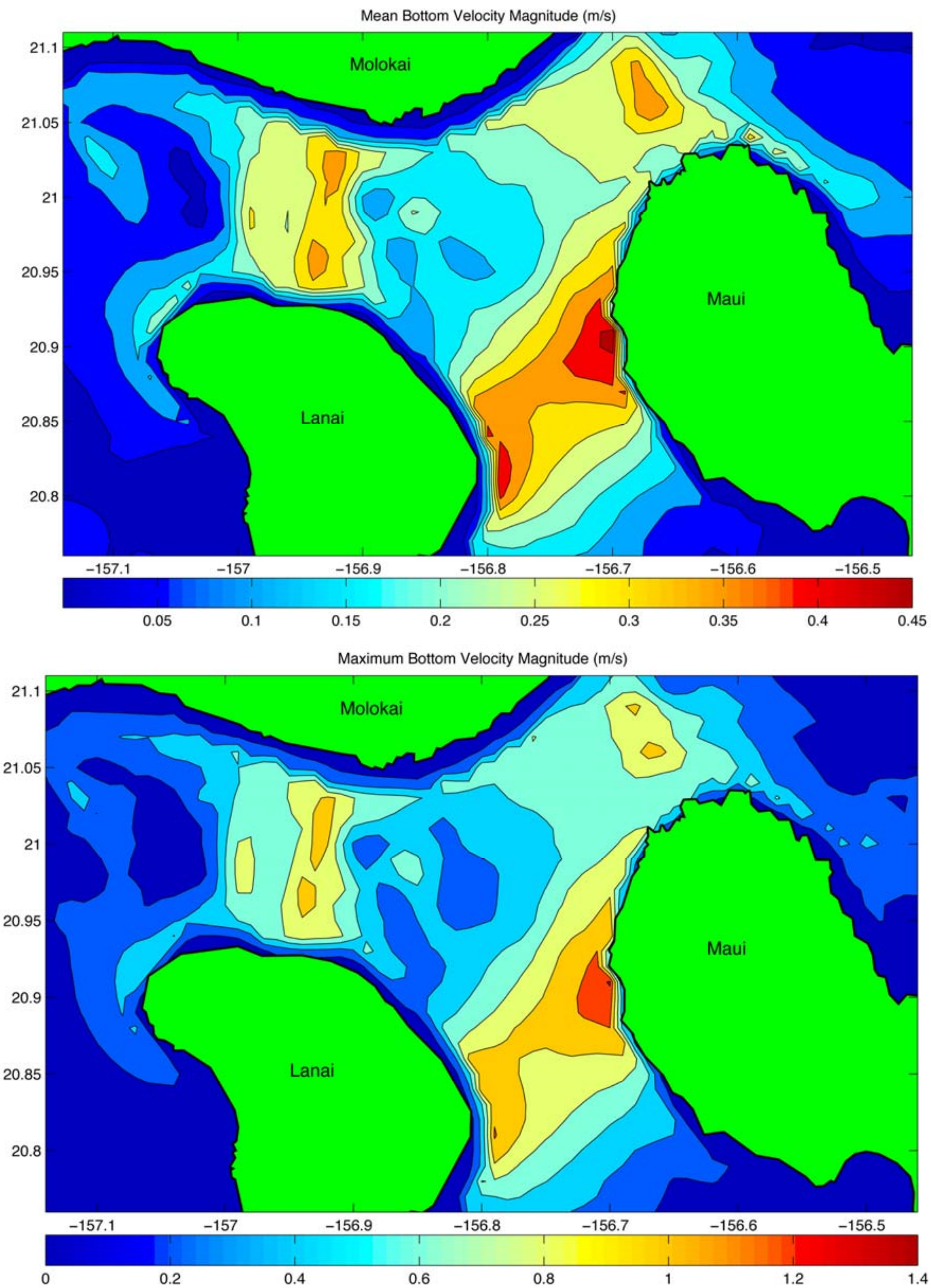


Figure 4-16
Mean and maximum current speeds off Lahaina, Maui

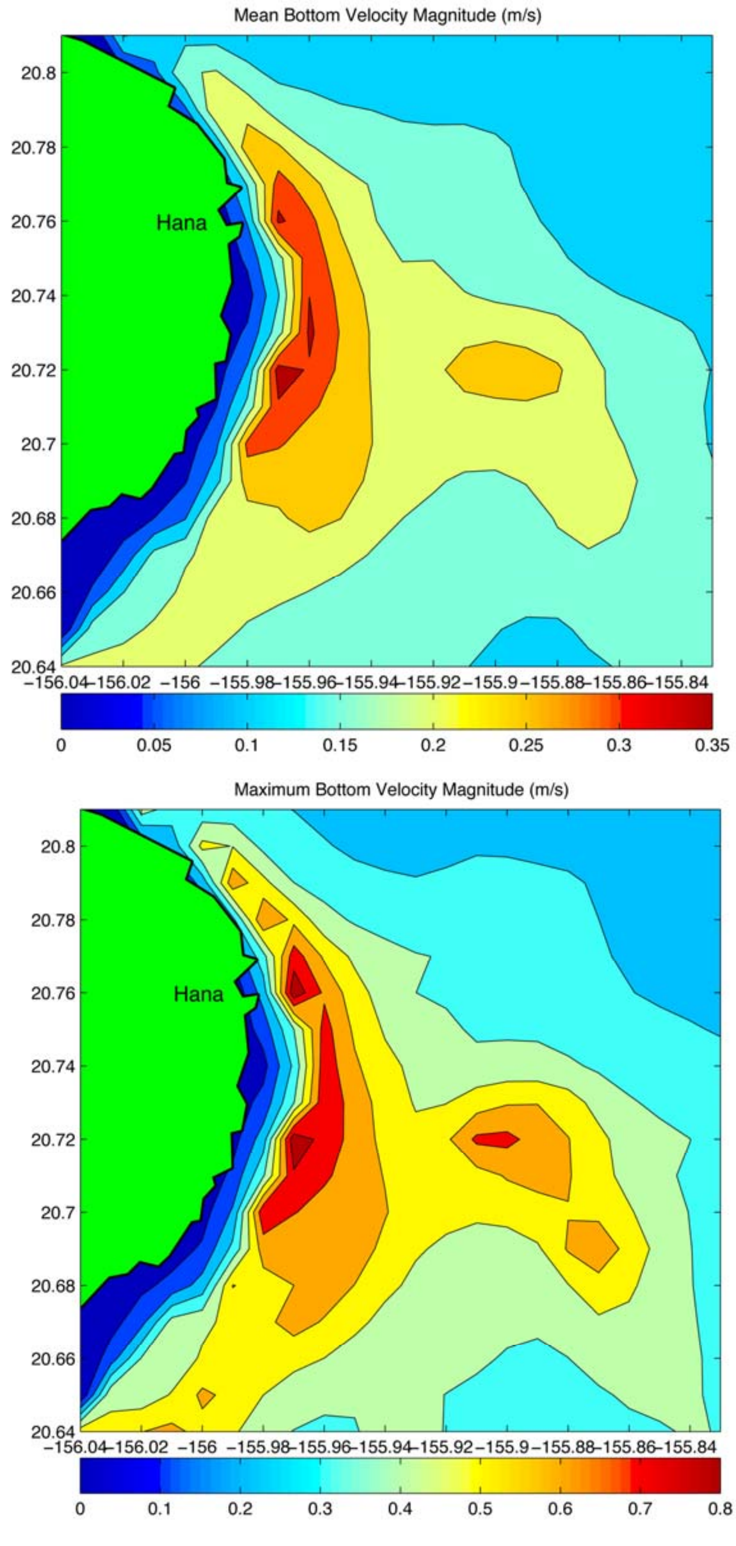


Figure 4-17
Mean and maximum near-bottom current speeds off Hana, Maui

4.2 The Big Island

4.2.1 Big Island Model Results

Model results for the Big Island are presented in Figures 4.18 and 4.19, and expanded views of the areas with the strongest currents are shown in Figures 4.20, 4.21 and 4.22. Figures 4.18 and 4.19 indicate that the model calculates strong currents at Upolu Point at the north tip of the island, and to a lesser degree at Cape Kumukahi at the eastern tip and South Point at the southern tip. Upulo Point is predicted to have mean currents of 0.6 m/s and maximum current speeds of 1.4 m/s (Figure 4.20). This corresponds to a mean power density of 205 watts/m^2, and a maximum power density of 1431 watts/m^2 (Appendix A). Current meters deployed offshore of Upolu Point for 3 weeks in 1967 and 4 months in 1985 measured maximum currents of 1.62 and 1.35 m/s, respectively, and mean currents of 0.55 and 0.36 m/s, respectively (Table 3-2).

Currents in other parts of the island are predicted to be weaker. East of Cape Kumukahi, mean and maximum calculated current speeds were only 0.2 m/s and 0.6 m/s (Figure 4.21), corresponding to mean and maximum power densities of only 16 and 134 watts/m^2 (Appendix A). Currents speeds off South Point were marginally stronger; mean and maximum calculated current speeds were 0.3 m/s and 0.9 m/s (Figure 4.22), with corresponding mean and maximum power densities of 33 and 341 watts/m^2 (Appendix A). A summary of the notable locations near the Big Island is presented below in Table 4-3.

Table 4-3
Peak and Mean Current Speeds and Power Density, Island of Hawaii

Location	Velocity Magnitude (m/s)		Power Density (W/ m^2)	
	Peak Max	Peak Mean	Peak Max	Peak Mean
Upolu Point, Hawaii	1.4	0.6	1431	205
South Point, Hawaii	0.9	0.3	341	33
Cape Kumukahi, Hawaii	0.6	0.2	134	16

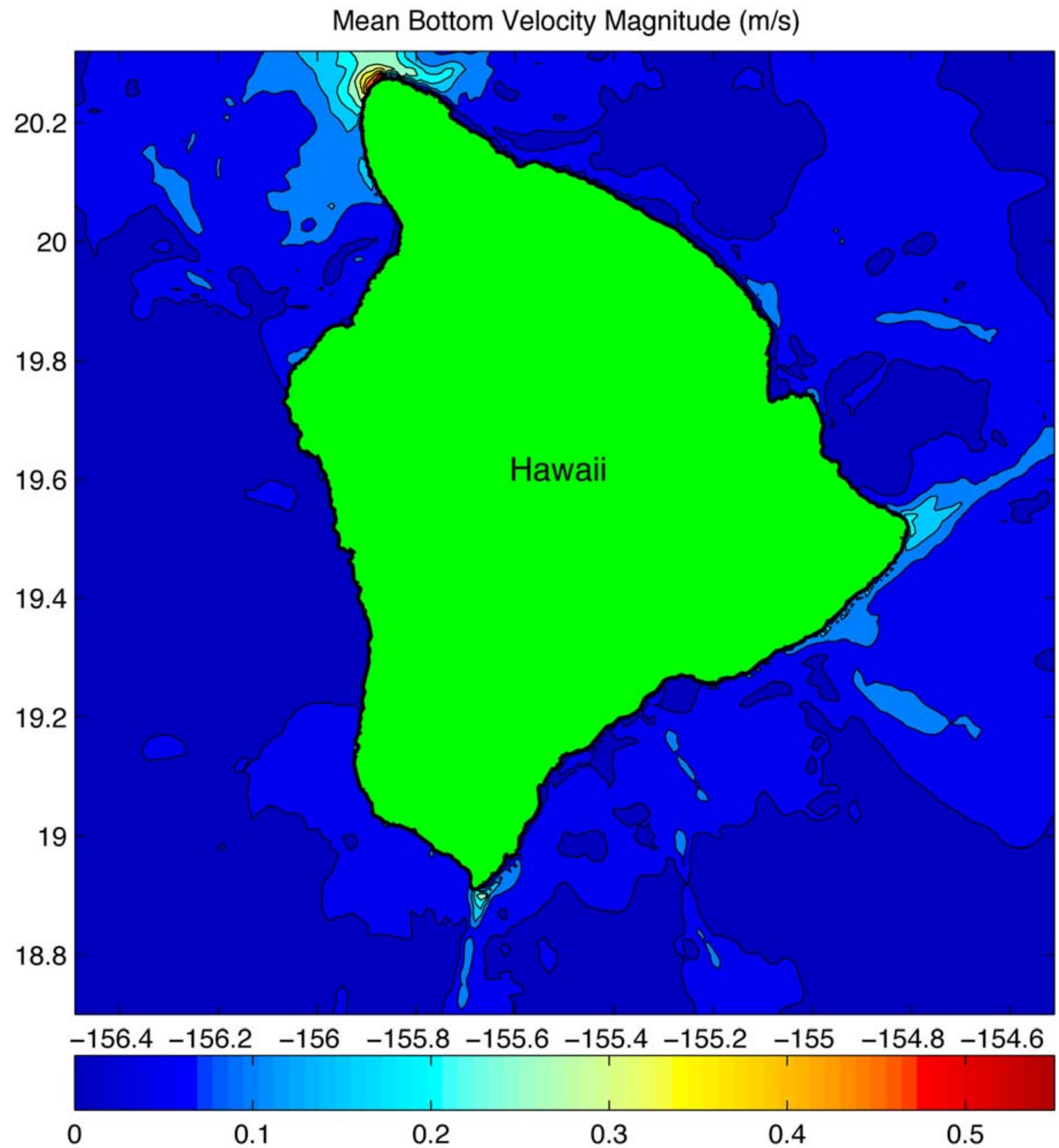


Figure 4-18
Mean near-bottom current speeds around the Big Island

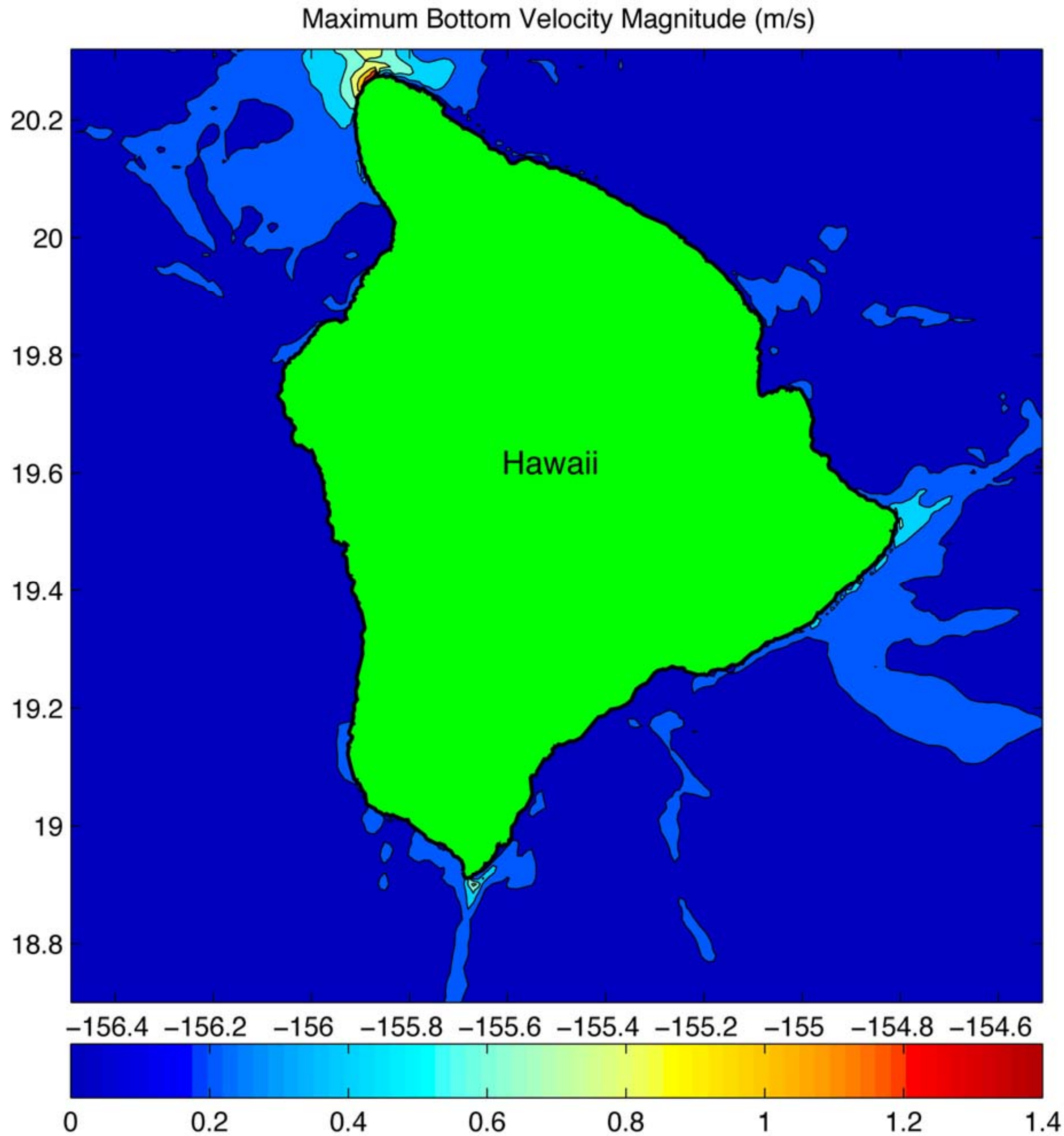


Figure 4-19
Maximum near-bottom current speeds around the Big Island

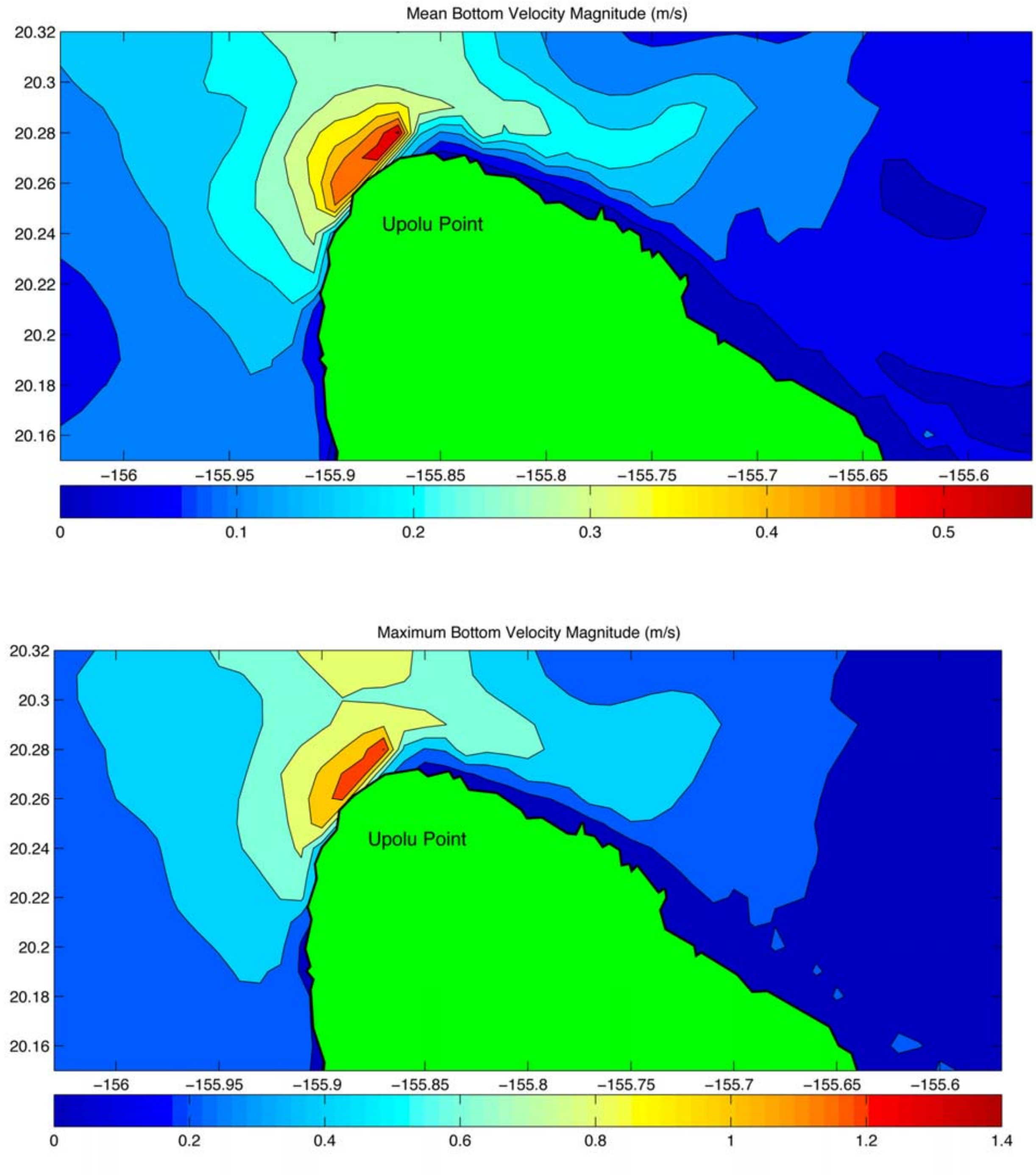


Figure 4-20
Mean and maximum near-bottom current speeds off Upolu Point, Hawaii

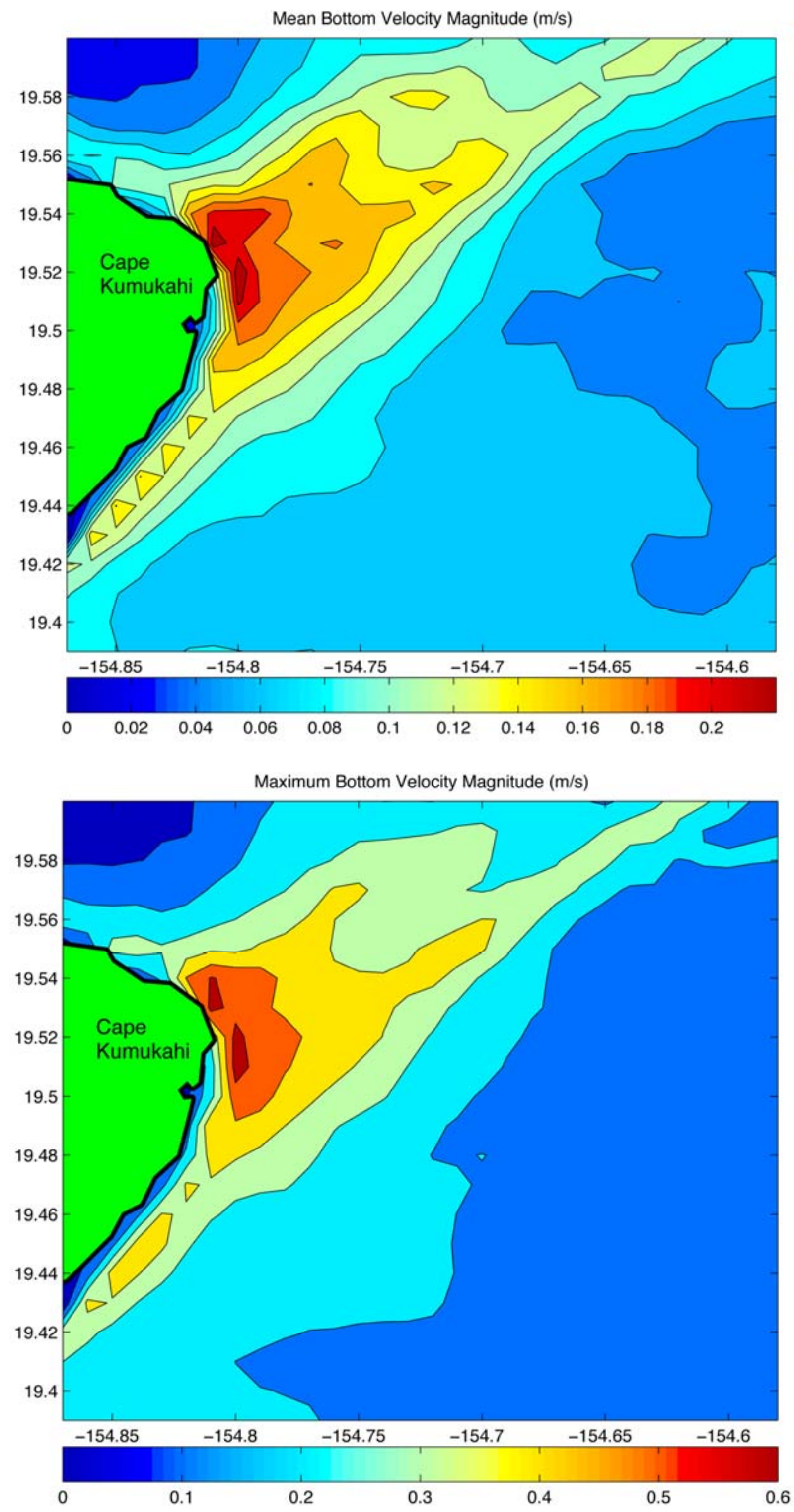


Figure 4-21
Mean and maximum near-bottom current speeds off Cape Kumukahi, Hawaii

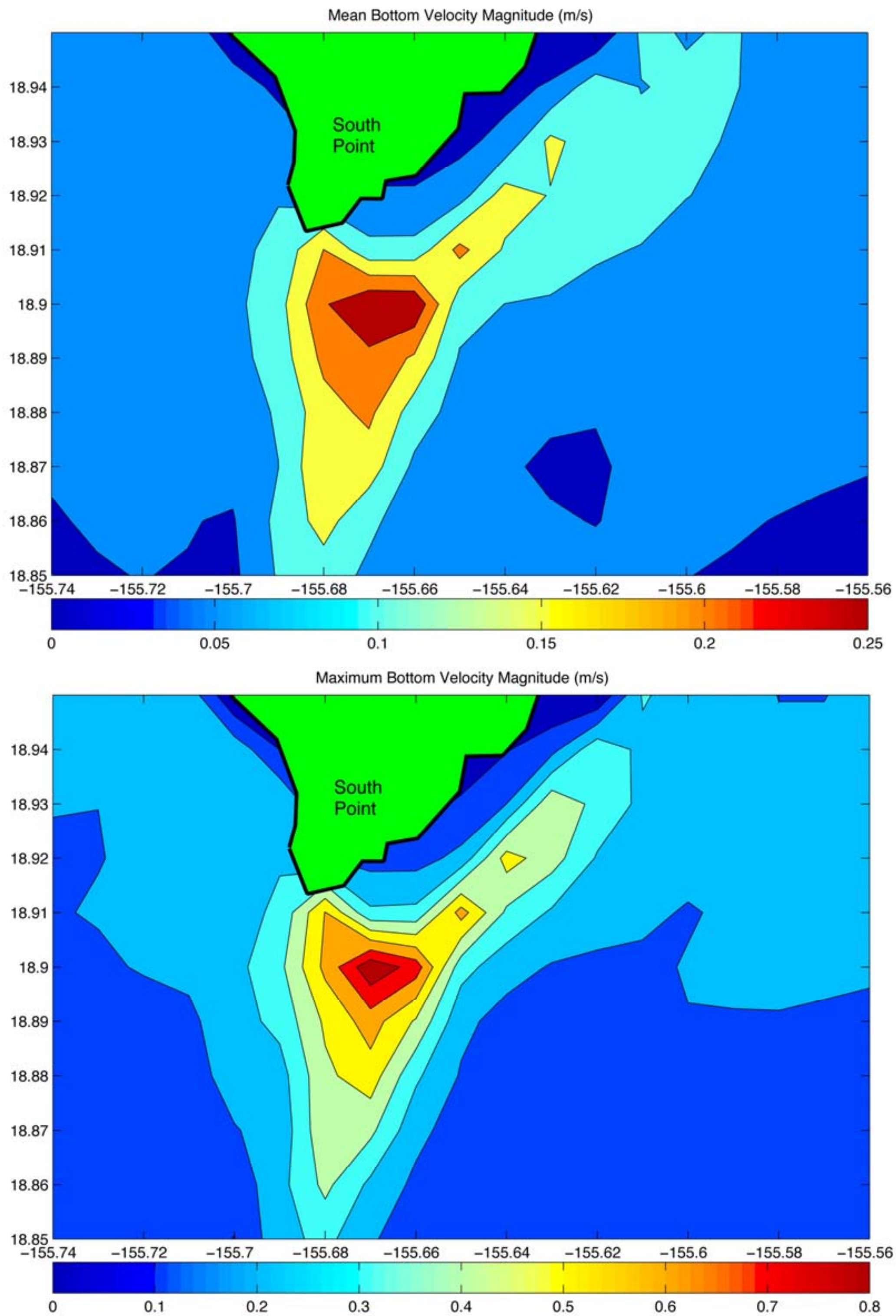


Figure 4-22
Mean and maximum near-bottom current speeds off South Point, Hawaii

4.2.2 Eddy Generated Currents along the Kona Coast

As Figures 4.18 and 4.19 indicate, the UH Tidal Model calculates weak currents along the Kona Coast of the Big Island. The model validation comparison with current meter recordings showed that model results were not consistent with field observations, significantly under predicting current speeds. This is consistent with the numerous observations and studies that have shown that this coastal region is unique in the islands due to the prevalence of regional eddies that drive the currents. The UH Tidal Model does not include eddies as a forcing mechanism, and thus does not completely represent the currents along this coast.

The presence of regional scale eddies in the lee of the island of Hawai'i has been well documented (e.g. Wyrtki et al, 1967; Patzert, 1969, Lumpkin ,1998). Patzert (1969) utilized data from 20 research cruises, while Lumpkin (1998) used a combination of satellite-tracked drifters, twenty-two cruises with ADCP measurements, and satellite remote sensing measurements. Their results are consistent and indicate that cyclonic (counter-clockwise) eddies are generated by strong tradewinds funneling through the restricted Alenuihaha Channel between Maui and Hawaii. These eddies have typical diameters of 180 km. The eddies are relatively shallow in depth, typically penetrating no deeper than 250 to 300m. Lumpkin (1998) observed an average of nine eddies forming per year. Patzert found that the eddies slowly drift to the west-northwest at average speeds of 6 cm/s. The cyclonic eddies result in flow divergence, and upwelling of nutrient rich, colder water. They are therefore readily identified by sea surface temperature, and satellite altimetry. Figure 4.23 shows a typical eddy, as indicated by satellite sea surface temperature measurements. Sea surface temperatures are about 3 degrees cooler in the core of the eddy than surrounding waters.

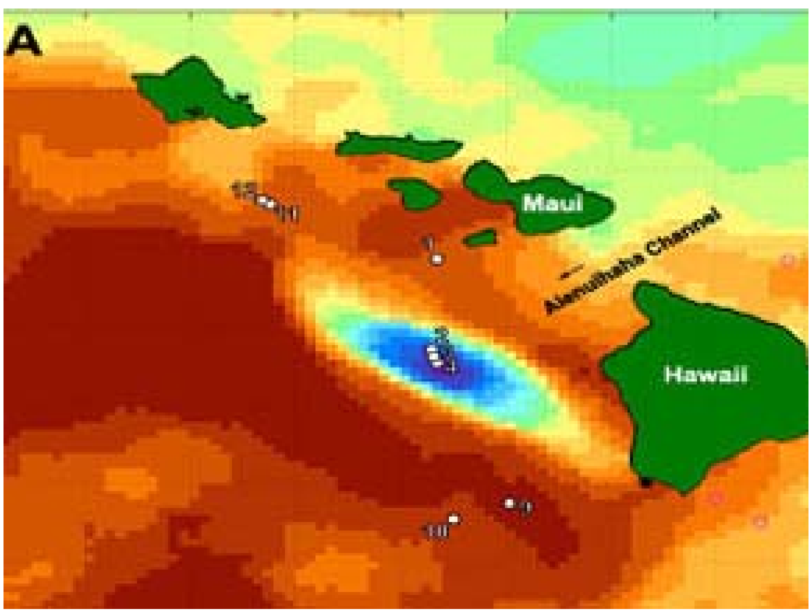


Figure 4-23
Eddy off the Kona Coast, measured by GOES-10 satellite system (Bidigare et al., 2003)

Eddies frequently dominate the circulation patterns on the west coast of Hawaii, and their influence could be responsible for some of the unexplained complexities in nearshore circulation in other parts of the islands. They can cause extended periods of strong currents in one direction, superimposed on the tidal currents. In a 1985 current study along the Kona Coast, Sea Engineering found that during the year-long measurement program, strong flow in one direction occurred approximately 75% of the time. These uni-directional flows had durations of 3 to 37 days, and were characterized by net transports of up to 46 cm/s. Table 4-4 summarizes some of these observations from Station 3, a current meter deployed at a water depth of 400 feet, offshore of Kaiwi Point, approximately 10 km south of Keahole Point. Current measurements were recorded at a depth of 120 feet between April 5, 1984 and January 7, 1985. In spite of these periods of strong uni-directional currents, the overall mean current speed for the measurement period was 27 cm/s; the maximum recorded speed was 123 cm/s.

Table 4-4
Periods of uni-directional flow recorded by a Sea Engineering current meter at Kaiwi Point between April 5, 1984 to January 7, 1985

Dates	Flow Conditions	Net transport (cm/s)	Direction (degrees)
4/14/84 – 5/21/84	North	22	302
7/29/84- 8/28/84	South	46	142
9/13/84 – 9/23/84	South	46	141
10/31/84 – 11/25/84	North	43	304
12/9/84 – 12/16/84	South	40	133
12/24/84 – 1/6/85	North	26	302

Other significant current meter studies in this area include Wyrtki et al. (1969) – 2 months of data in 1967 and 1968; RM Towill Corporation (1973) – 5 weeks of data in February and March of 1973; Noda (1979) – 4 months of data between September 1978 and January 1979. These studies are consistent with the findings described above.

In summary, numerous site specific current meter deployments, as well as in-depth research investigations at the University of Hawaii indicate that the regional scale eddies generated by trade winds funneling through the channels between the islands often dominate coastal currents along the Kona Coast of Hawaii. As described above, the resultant flow can be to the north or to the south for extended periods of time depending on the location of the offshore eddy. Mean current velocities are in the range of 30 to 50 cm/s during the eddy generated flow events.

Semi-diurnal tidal flow is superimposed on the mean eddy flow, and predominates during periods when eddies are not present. The tidal flows are much weaker, typically 10 to 20 cm/s.

Although eddies are known to occur frequently, averaging nine per year, exactly when they occur, how they will move, and how long they will last is not well understood. Thus, the impacts of eddies on coastal currents is not predictable. Currents along the Kona Coast should therefore be characterized as highly variable, with intermixed periods of relatively strong uni-directional flow, and weak semi-diurnal tidal flow.

5
UNDERWATER TURBINE TECHNOLOGY ASSESSMENT

5.1 Objectives of the Assessment

This chapter describes the present state of underwater turbine technology. The assessment is intended to complement the previous resource evaluation and has two objectives: first, to determine the current speeds at which electrical power generation is presently feasible; and second, to determine if any of the turbine technologies presently under development or in the conceptual stage could be applied to the ocean current resource in Hawaii.

The Electric Power Research Institute (EPRI) completed a thorough survey of Tidal In-Stream Energy Conversion (TISEC) Devices in 2005 (Bedard, 2005). A review of this report was the starting point for this technology assessment. The 2005 report provided a base of information for a number of manufacturers. A detailed literature search was then completed to locate additional turbine manufacturers and to determine what advances, if any, had been made in turbine technology since the 2005 EPRI report. Information sources included websites, conference proceedings, reports, and other energy assessments. Attempts were made to contact all of the companies located, either verbally or via email, to obtain up to date information on the present research and development status of their technology.

5.2 Technology Developers

Table 5-1 below lists thirty tidal turbine developers that were identified and contacted or for whom contact was attempted during this study. Additional details on each company and their technology are presented in Appendix B. The table is separated into three subheadings based upon approximate maturity levels of the technologies. These are: companies with ocean installations connected to an on-land electrical grid, companies that have tested unconnected prototypes in the ocean, and companies with technologies that have not yet been installed in field conditions.

If a company could not be reached or did not reply to repeated requests for information, the information provided in this report is based solely on available literature or website information. No information is provided on Gulfstream Technologies or Oceana.

Table 5-1
List of Manufacturers

Company		Contact Method	Field Installations/Tests	Future Plans
Turbines Installed, Connected to Shore Grid				
1	Hammerfest Strom	Email	300 kW installed in Norway in 2003 - still operating	2009 - 1 MW demonstration unit 2010 - 5 to 10 MW pre-commercial park
2	Verdant Power	Email, Verbal	175 kW installed in East River, NY in 2007	Objective is to increase generating capacity to 10 MW
3	Clean Current Power Systems	Email	65 kW installed in British Columbia in 2006, now out of water for overhaul	2008 - re-install 65 kW unit
4	Ponte di Archimedia International	Email	25 kW installed in Italy in 2001	2008 - installation of three more prototypes
In-Water Test of Prototype or Demonstration Unit				
5	Lucid Energy	Verbal	2002- test of 10 kW turbine in Korea 2004 - testing in Massachusetts	1 MW tidal plant under construction in Korea
6	Marine Current Turbines	Email	300 kW installed off UK in 2003, now decommissioned.	2007 - 1.2 MW commercial prototype installation pending availability of barge
7	Seapower	No Contact	2003 - turbines tested from anchored ship	2005 - plans in place for pilot plant installation - no additional information available
8	Open Hydro	Verbal	2007 - 250 kW pilot installed at EMEC*, turbine has been removed	New turbine unit presently being installed at EMEC* 2007 - selected by Nova Scotia Power for Bay of Fundy demonstration project

Table 5-1 (continued)
List of Manufacturers

Company		Contact Method	Field Installations/Tests	Future Plans
9	UEK Corporation	Email, Verbal	1986 to present - various tests in Chesapeake Bay, Ontario River	2007 - Demonstration installation in Delaware, followed by 10 MW, 25 unit project. On hold due to concerns about impacts on recreational fishing. 2007 - 60 kW project beginning in Manitoba River 2007 - 100 kW pilot project in Eagle River Alaska for Alaska Power
10	Sea Snail	Email	2005 - 150 kW unit installed in Orkney , UK - now removed for modifications	2008 - planned redeployment of unit
11	Tidal Sails	Email, Verbal	2007 - 6 month prototype installation	2009 - full scale grid connected prototype 2010 - full scale commercial installation
12	Tidal Hydraulic Generators	No Contact	2001 - river tests of turbine in UK	3.5 MW system being designed for Ramsey Sound, Wales
13	Blue Energy	Verbal	1983 - 20 kW unit in Nova Scotia 1984 - 100 kW unit in Nova Scotia Numerous tow tank trials	250 kW off grid unit under development
Small Scale Tests or Design Work Only				
14	Lunar Energy	Email, Verbal		2008 - 1 MW installation at EMEC* 2010 - 8 MW project in UK
15	SMD Hydrovision	Email	2006 - tow tank testing of 1/10 scale model	2009 - 1 MW installation at EMEC*

Table 5-1 (continued)
List of Manufacturers

Company		Contact Method	Field Installations/Tests	Future Plans
16	Swan Turbines	Email, Verbal	2001 - 1.5 kW prototype tested	2008 - installation of 350 kW system
17	Tidal Stream	Email	2001 - 1.5 m turbine tested in Thames River	2009 - 2 MW installation off Scotland
18	Scotrenewables	Verbal	2005 - small scale sea trials and tow tank testing 2007 - Ocean testing at 1/40 scale	2009 - 1.2 MW installation at EMEC*
19	Ocean Flow Energy	Verbal	2007 - flume testing of 1/10 scale model	2009 - installation of 500 kW prototype
20	Neptune Renewables	Email	2005 - 1/100 scale model tests	2008 - 500 kW full scale demonstration in Humber River, UK
21	Pulse Generation	Email	2006 - scale model tank tests	2008 - 100 kW prototype installation in Humber River, UK
22	Statkraft	Email	2004 - initial plans for 1 MW demonstration plant off Norway	2008 - planned 1 MW installation
23	Current to Current	Verbal		2008 - testing off Guatemala 2009 - testing off US East Coast
24	Ocean Renewable Power Company	Verbal		2007 - 32 kW proof of concept testing off Maine 2008 - 250 kW commercial scale demonstration project in Alaska
25	Tidal Generation	Email		2008 - 500 kW prototype to be installed at EMEC*
26	Bourne Energy	Email		2008 - planned installations

Table 5-1 (continued)
List of Manufacturers

Company		Contact Method	Field Installations/Tests	Future Plans
27	E3 Inc, Natural Currents LLC	Verbal		2008 - barge mounted testing of 20 kW system
28	Hydro Green Energy	No Contact	Prototype turbines tested	
29	Oceana	Email, did not want to be included		2007 - A subsidiary, Golden Gate Energy, teamed with Pacific Gas and Electric to evaluate an installation beneath the Golden Gate Bridge
30	Gulfstream Technologies	Email, not included		
	* European Marine Energy Center, Orkney Islands, UK			

5.3 Turbine Types

Underwater turbine designs fall into several categories. The most common are horizontal and vertical axis turbines. Both types can be either ducted or un-ducted. Un-ducted turbines appear similar to conventional windmills while ducted turbines are enclosed around their periphery. Most manufacturers of un-ducted horizontal axis turbines use technology and designs based upon wind generators. Examples of companies using this technology are Hammerfest Strom, Verdant Power, and Marine Current Turbines, Ltd. Utilizing wind energy technology can be both an advantage and a disadvantage. On the positive side, the approach is based upon existing, proven technology, which theoretically reduces and simplifies the development process. On the negative side, tidal turbines based upon wind energy technology require pitch control, gearboxes, and standard generators. These must be modified for use either on or under the water. Typically, for underwater installations, more moving parts and/or seals lead to more maintenance and more potential failure modes. Maintenance on equipment under water can be difficult and expensive, and the service and repair requirements can easily be underestimated. Work on the water is weather dependent, and accessing a site may consume a significant part of a working day. Diving, if required, is expensive.

Ducted turbines increase the efficiency of fixed mount turbines by funneling water flow into the turbine from a range of directions. This can be an advantage in reversing tidal flows, because the flows do not usually reverse exactly 180 degrees, and the duct can eliminate the need for pitch and yaw controls on the turbine blades. The ducts may also be designed to increase current velocity, enabling more energy to be extracted from a given flow. Lunar Energy has designed a ducted turbine, the Rotech Tidal Turbine that eliminates the need for yaw control and variable pitch blades.

Some of the ducted horizontal axis turbines utilize relatively new generator technology. Open Hydro, Underwater Electric Kite (UEK), and Clean Current have designs based on direct drive permanent magnet generators. These generators have only one moving part, the rotor assembly containing the blades. The variable speed magnet generators are embedded in the duct. The elimination of drive shaft, gearbox, seals, and yaw and pitch control should decrease maintenance and increase reliability. The trade-off is that the low speed of direct drive rotors means that a larger number of poles are required in the stator to maintain frequency and this leads to larger rotor diameter.

On vertical axis turbines the shaft is usually vertical, though it can be any orientation perpendicular to the current flow. Vertical axis turbines sometimes appear similar to an eggbeater, and are also referred to as Darrieus turbines. The designs of Blue Energy Canada and Ponte de Archimedia International are based upon variations of vertical axis turbines. Vertical axis turbines can also be ducted or un-ducted.

Helical turbines have airfoil shaped blades that are twisted into helixes. An advantage of this design is that the blades turn faster than the flowing water, and efficiency of power generation is greater than for some other turbine types. Lucid Energy Technologies, LLC and Ocean Renewable Power Company, LLC have designs based upon helical turbines.

Other companies, such as Sea Snail, SMD Hydrovision and Tidal Stream have designs based upon standard turbine technology, but have innovative approaches to the mooring of the systems.

5.4 Required Flow Speeds

The flow speeds required to generate electrical power vary from vendor to vendor. Cut in speeds, the speeds at which the units start to generate power, generally range from 0.5 to 1 m/s. However, the current speed necessary for economic operation is considerably higher. As shown in Figure 5.1, power increases with the cube of water velocity, so small changes in current speed have a large impact on the available power. At a current speed of 1 m/s five hundred watts of fluid power is available over a one meter square area. At 2 m/s four kilowatts is available.

Average current speeds of 2 to 2.5 m/s or more, are generally considered necessary for economic power production. These average speeds approximately correspond to 3 to 4 m/s peak current velocities for reversing tidal currents. The Phase II UK Tidal Stream Energy Resource Assessment (Black and Veatch, 2005) stated that sites with mean spring peak tides of 2.5 to 4.5 m/s are the most suited to near term development.

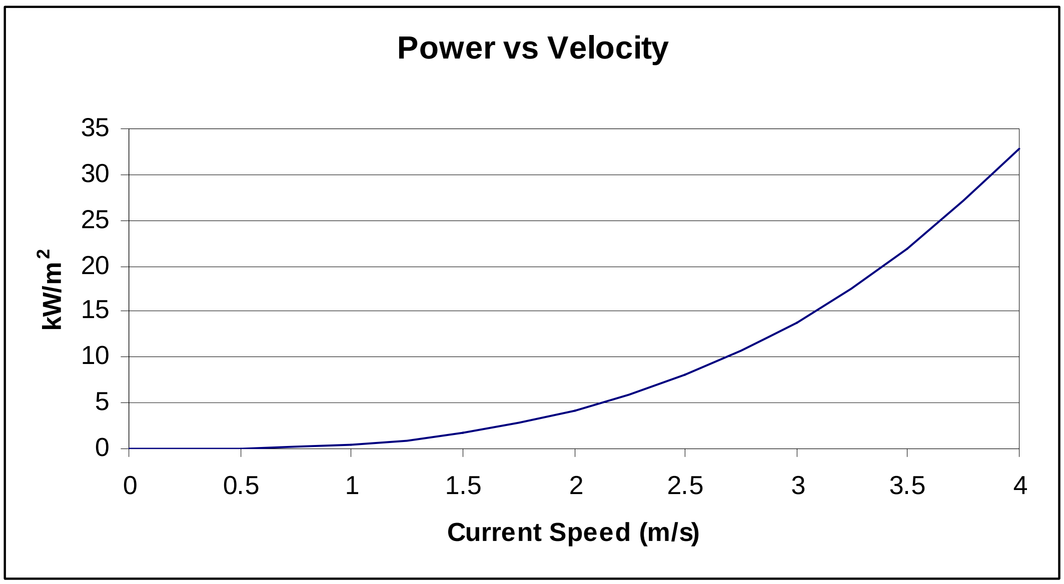


Figure 5-1
Power versus Current Velocity

The exact current speeds required for economic operation are site and vendor specific. Most of the technology is being developed for application to reversing tidal flows, where the peak speed is significantly higher than the average speed. Some developers are targeting uni-directional ocean currents such as the Gulf Stream, and average currents as low as 1.5 m/s may be economically feasible. Underwater Electric Kite (UEK), Current to Current and Ocean Renewable Power Company (ORPC) are evaluating installations in the Gulf Stream off Florida. The Federal Energy Regulatory Commission has granted six preliminary permits to ORPC to evaluate and file construction and operation licenses for ocean power plants in the Gulf Stream.

5.5 Development Status

Table 5-1 illustrates the wide range of maturity levels of the existing marine turbine technology – from conceptual to pre-commercial. The listing of technologies in this report by maturity level should not be construed as being an endorsement of any one technology or any class of technologies. There are several technologies in the initial testing or conceptual stages that have unique and well thought out approaches that may ultimately have distinct advantages over some of the more mature technologies. As Table 5-1 indicates, the power being generated by actual in-water projects is quite small, ranging from 25 kW to 300 kW. Most of these projects, even those connected to an electrical grid, are in the realm of demonstration or proof of concept and do not yet represent commercial applications.

Notable advances have been made in Europe by Open Hydro (Ireland) and Marine Current Turbines (MCT) (United Kingdom). Both companies have installed tidal current turbines that are generating more than 100 kW and have other installations pending. Open Hydro is installing a new turbine at the European Marine Energy Center (EMEC) in Scotland and MCT has a 1.2 MW system ready to go in the water. The installation has been delayed due to schedule constraints of the installation barge. Hammerfest Strom and the Sea Snail have both generated more than 100 kW, but are not at the state of development of MCT and Open Hydro. In North America, Verdant Power and Clean Current Power Systems, Inc. have installed turbines that are connected to on-shore facilities. Verdant Power has deployed six grid-connected turbines that have a combined capacity of 175 kW in the East River, New York. Clean Current has deployed a single 65 kW turbine in British Columbia that is connected to battery storage and displaces diesel fuel in a remote off-grid application.

Europe is presently the leader in tidal current power, in particular Ireland, the United Kingdom, and Norway, all countries with extensive tidal current resources. The Scottish government released more than £13 million to promote wave and tidal energy in 2007. Of the companies detailed in this report, ScotRenewables received £1.796 million, Open Hydro £1.214 million, and Tidal Generation £0.077 million (as of December 2007, one British pound was worth $1.98 U.S. dollars). These European countries are followed by Canada and then the United States in terms of tidal energy development. Korea has tested turbines made by Lucid Energy (formerly GCK) and is attempting to install a 1 MW total power system consisting of many smaller Lucid turbines.

6
CONCLUSIONS

6.1 Applicability of TISEC Technology to Hawaii

The assessment of the existing underwater turbine technology in Section 5 of this report indicated that required average speeds for the threshold of economical power generation ranged from 2 m/s to 2.5 m/s. For reversing tidal currents, this corresponds to peak speeds of 3 to 4 m/s. We found no evidence of any technology presently being developed that would lower these required flow speeds. Turbine cut in speeds for the technologies described in Appendix A typically range from 0.7 to 1.0 m/s. The lowest cut in speed was 0.5 m/s and the highest listed was 1.5 m/s. This is the speed at which the turbines start to generate power, but considerably higher speeds are required for efficient power generation (see Figure 5.1). The low end 0.5 m/s cut in speed was listed by three turbine developers, but even those firms offer no promise of feasible turbine operation at lower speeds. Lucid Energy Technologies listed a cut in speed of 0.5 m/s but recommended average water velocities of at least 1.5 m/s. Rated power is achieved at 4.5 m/s. Swan Turbines, Ltd. also lists a cut in speed of 0.5 m/s. At present, they have tested only a 1.5 kW prototype and a 350 kW system is being designed. Statkraft, with a cut in speed of 0.5 m/s, has been planning a 1 MW demonstration power plant since 2004 to determine actual turbine efficiencies and economics but the present status of the project is unknown.

The evaluation of the ocean current resource described earlier in this report identified twelve areas in the project area with relatively high peak and mean current speeds. They are summarized in Table 6-1, which shows power density as well as velocity magnitudes.

A comparison of the required speeds for efficient turbine operation with the available resource in Hawaii leads to the conclusion that, given the present technology, generation of electrical power with underwater turbines is not feasible at the present time. The three locations with the strongest mean currents barely equal the cut in speeds required for most turbines, and the mean speeds at those areas are only about one-third of that required for efficient operation. It will take a significant, and at this point unforeseen, technological advance to make the generation of electrical power by underwater turbines feasible in Hawaii. Even the Kona Coast, with its sporadic occurrence of relatively high uni-directional flow speeds does not have a sufficient current resource. The upper limit of the average flow during these events just approaches 0.5 m/s, and the occurrence of such flow is not steady or predictable.

Table 6-1
Peak and Mean Current Speeds and Power Density

Location	Velocity Magnitude (m/s)		Power Density (W/ m^2)	
	Peak Max	Peak Mean	Peak Max	Peak Mean
Penguin Bank	2.2	0.8	5487	653
Kaena Point, Oahu	2.1	0.7	4746	438
Makapuu Point, Oahu	1.9	0.6	3515	293
Lahaina, Maui	1.4	0.5	1496	162
Upolu Point, Hawaii	1.4	0.6	1431	205
Kahuku Point, Oahu	1.4	0.5	1406	150
Barbers Point, Oahu	1.3	0.4	1144	104
Diamond Head, Oahu	1.2	0.4	991	102
Kikoa Point, Lanai	1.2	0.4	933	120
South Point, Hawaii	0.9	0.3	341	33
Hana, Maui	0.9	0.4	339	53
Cape Kumukahi, Hawaii	0.6	0.2	134	16

6.2 Siting Considerations for Hawaii

If underwater turbine technology does eventually advance to the point that application in Hawaii appears feasible, many physical and environmental factors will have to be considered when evaluating potential sites. Some of the physical factors include: current flow characteristics, forces on the structure and its moorings due to hurricane forces and north swell events, depth of operation, water depth, proximity to an onshore grid connection point, and seabed configuration and composition. Some of the environmental factors include: visual and other aesthetic impacts, user conflicts, and impacts to benthic communities and marine mammals.

The most important factor is the nature of the current flow. Without sufficient mean speed, power cannot be economically generated, and any site without that mean speed will not be feasible no matter how favorable the other factors may be. Detailed current measurements will almost certainly be required at potentially feasible sites to further define the nature and extent of the current resource.

Wave forces will also be a major factor in site selection and the design of turbine anchoring or mooring systems. Unlike many of the units installed to date, any underwater turbine system in Hawaii will have to be installed in the open ocean and will therefore be exposed to large design waves. The eleven sites identified in Table 6-1 are exposed to either long period North Pacific swell or hurricane waves. The most protected of all the areas is Lahaina, and even it is potentially exposed to hurricane waves. Most of the turbines installed to date have been in protected waters of fjords or estuaries that have relatively strong tidal flows but little severe wave exposure. The wave forces acting on an underwater turbine could be reduced for some of the devices by installing them in deeper water where the wave forces will be smaller. For example the Current to Current turbine can be installed in a range of depths although the design is still unproven.

There are potential problems specific to some of the systems described in Appendix B. The mechanically simple units, in particular the ones utilizing the variable speed magnet generators, are quite large and therefore will be subject to larger forces than competing technologies. Selection of installation depth for these types of units will be a trade-off between wave forces and the increase in maintenance and installation costs as the depth increases. All bottom mounted units can be stabilized, but at a cost.

The systems that are moored in the water column such as Underwater Electric Kite, SMD Hydrovision and Scotrenewables and Ocean Renewable Power Company will also be subject to wave forces, but the compliant moorings may help mitigate that factor. By the time the technology has advanced sufficiently for installation in Hawaii some of these mid-water column systems should have an installation track record. Installing these systems in reversing flow situations will present design and maintenance issues related to the routing of the electrical cable from the turbines to the ocean bottom.

An environmental advantage of ocean current power is its “invisibility” if the system is entirely underwater. Approximately one-half of the systems described in Appendix B utilize floating components or components that pierce the surface. Installation of significant numbers of units with surface signatures will increase permitting difficulties in Hawaii, and the surface components will have to be designed to survive severe wave events.

6.3 Future Outlook

As Table 5-1 illustrates, many firms have plans for relatively ambitious future projects. These proposed installations will be a significant advance over the small in-water projects presently underway. Although the number of these larger projects is indicative of a high degree of interest in tidal power, commercial application of underwater turbine technology is still in the development stage. There are no full scale systems presently connected to an electrical grid, but there are several planned full scale grid-connected systems scheduled to be in place by 2010.

The development history to date, however, has indicated that delays have been common. There seems to be two development stages where delays are most likely to occur. The first is the initial deployment of large scale prototypes into the actual marine environment. Design and maintenance flaws, if present, will come to the forefront when the units are impacted by the harsh marine environment. The second stage is during installation of full scale grid-connected systems. Many issues not directly related to the basic innovative technology will have to be addressed at that point. As examples, sub sea installation of electrical cabling and recovery of components for scheduled maintenance will both require significant planning and design work, and there will be a learning curve associated with the initial full scale installations. These problems are common to the development of any new marine technology. The ocean wave energy industry is presently going through the same painful development stages.

Another cause of delay in the development process has been the need for the smaller companies to obtain funding. Many of the technology companies were formed specifically to develop their particular innovation. Such companies are often small and under funded, and the task of obtaining necessary funds through grants or investors tends to delay progress. Some of the small companies are now starting to move toward project development and new companies are forming with the objective of commercializing TISEC technology developed by others. Some of these development companies have financial backing from investors or venture capitalists, so the pace of development may begin to quicken in the future.

Numerous preliminary permit applications have recently been filed with the Federal Energy Regulatory Commission (FERC) by these and other companies, another indication of growing interest in the field. FERC is the federal agency tasked with permitting hydropower projects. The preliminary permits are valid for a three year period and allow companies to conduct studies at potential installation sites. This permit does not authorize construction, but it does give the permit holder priority for the subsequent application for a license while a site is being evaluated. In February 2007, as a result of an increasing pace of permit applications, FERC began the process of revising their processing of preliminary permits. They intend to more closely scrutinize proposed projects to prevent “land banking” by unqualified companies or by companies formed just to gain access to potential sites.

At the moment it is not clear which technologies will dominate this new industry. In any case, it appears unlikely that any device will be developed in the near future that will substantially lower the necessary current speed for economical power generation. The cubic relation between power and velocity (Figure 5.1) makes this unlikely. The power is just not available at low flow speeds without a marked advance in technology. One of the primary objectives of our literature search was to find evidence of promising technologies that might indicate the possibility of such an advance. We were unable to find any evidence of such an advance at even the earliest developmental level.

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A

APPENDIX A: TIDAL CURRENT POWER DENSITY

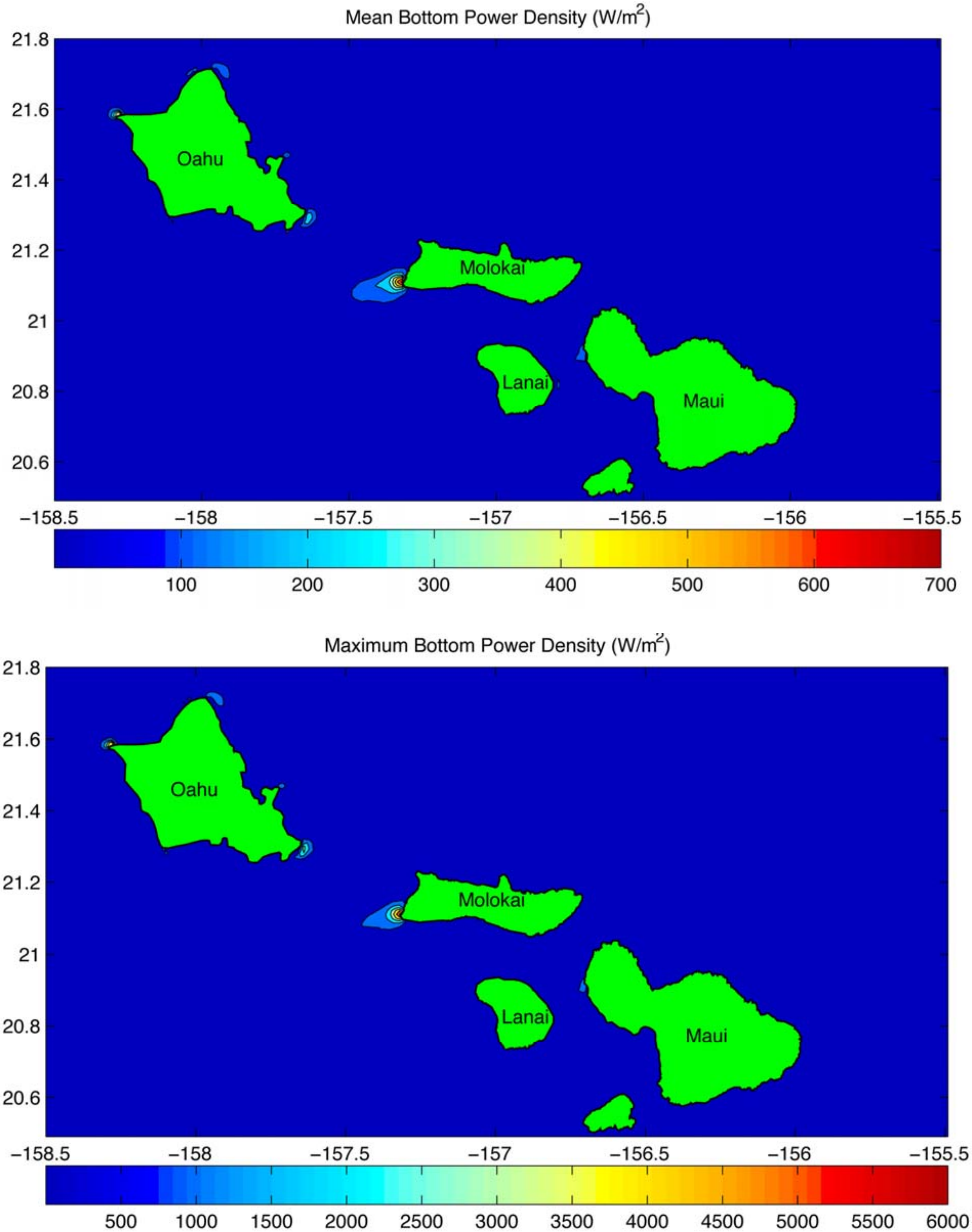


Figure A-1
Mean and maximum near-bottom current power density around the middle Hawaiian Islands

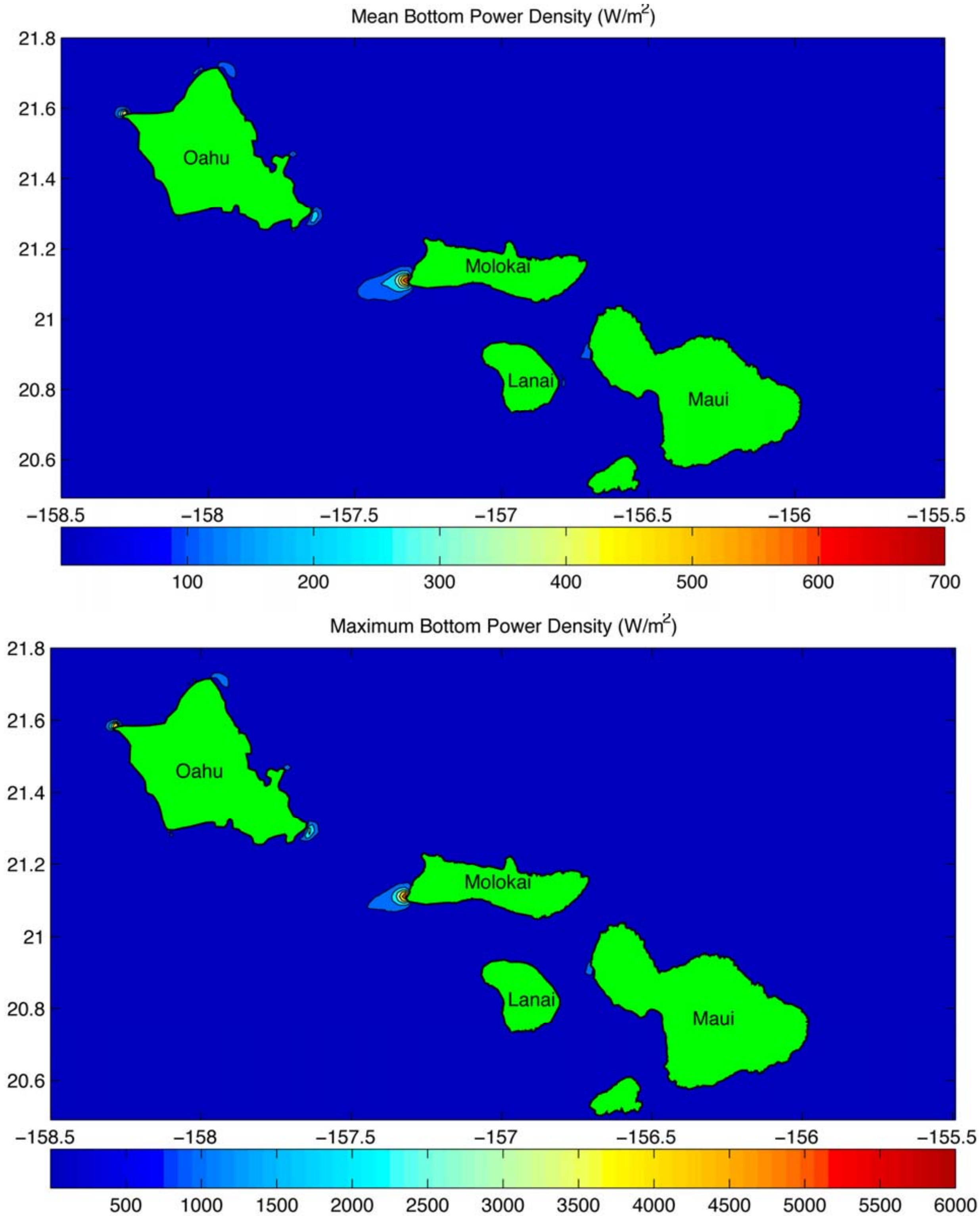


Figure A-2
Mean and maximum near-bottom current power density around Oahu

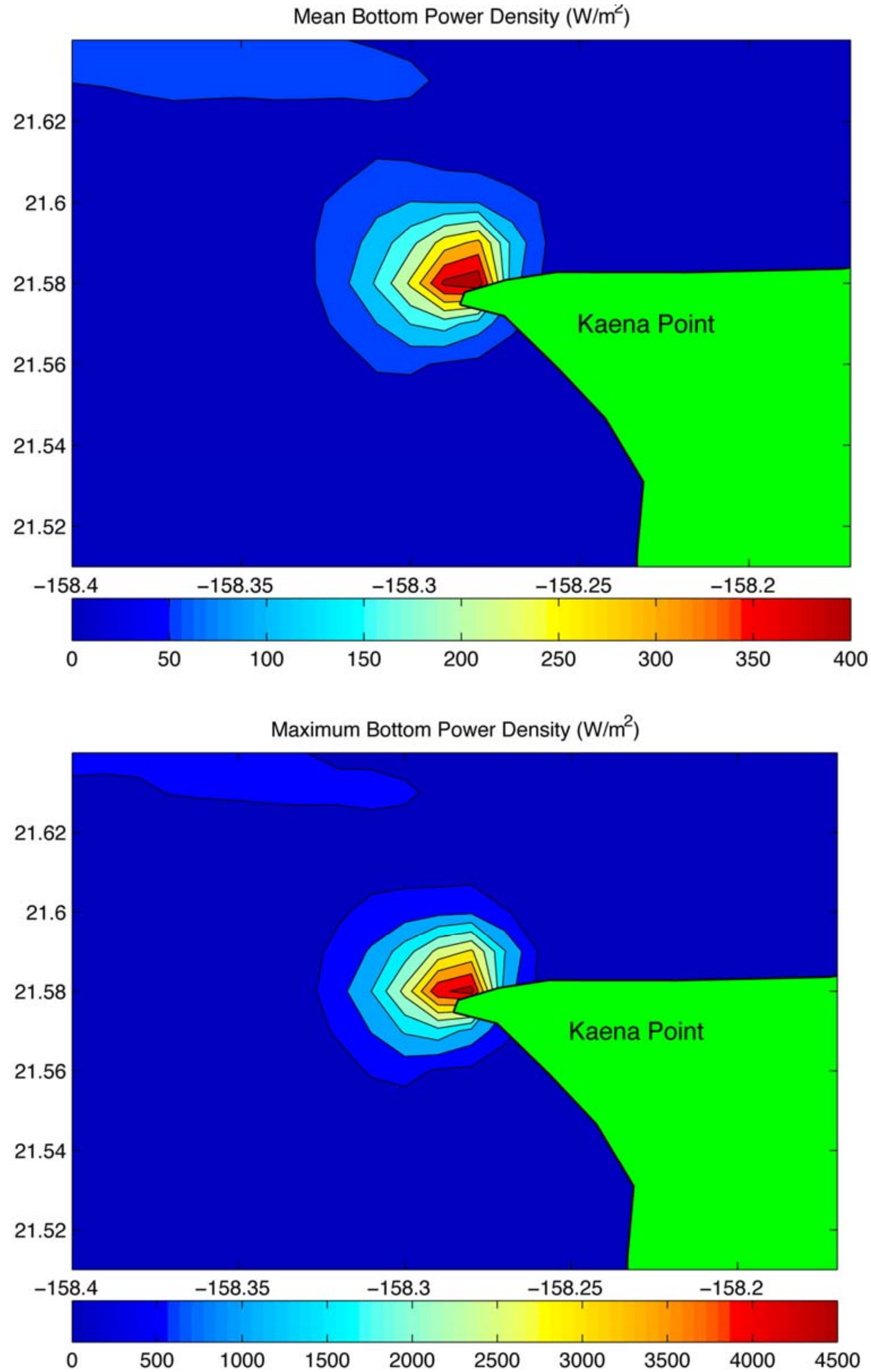


Figure A-3
Mean and maximum current power density off Kaena Point

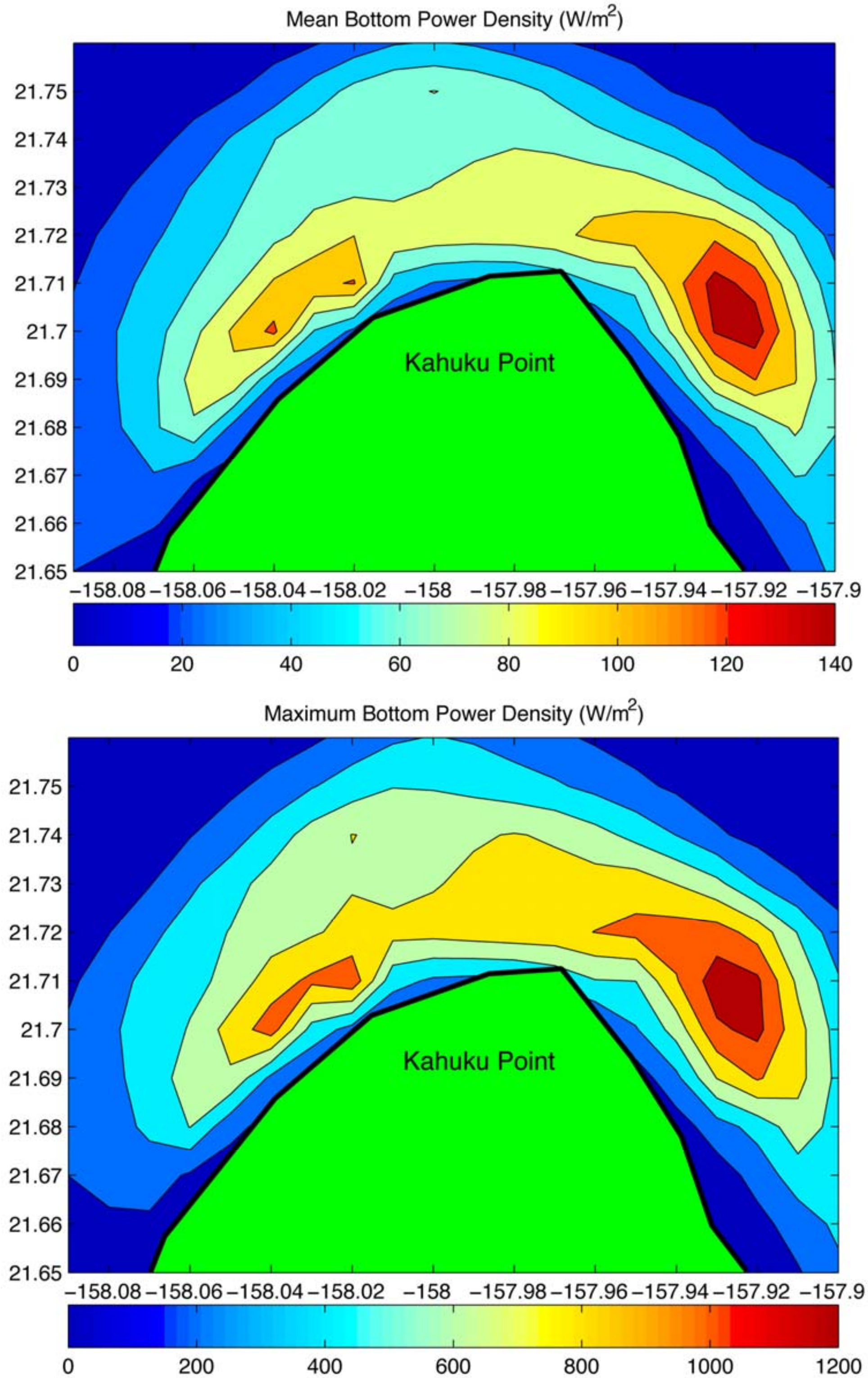


Figure A-4
Mean and maximum current power density off Kahuku Point

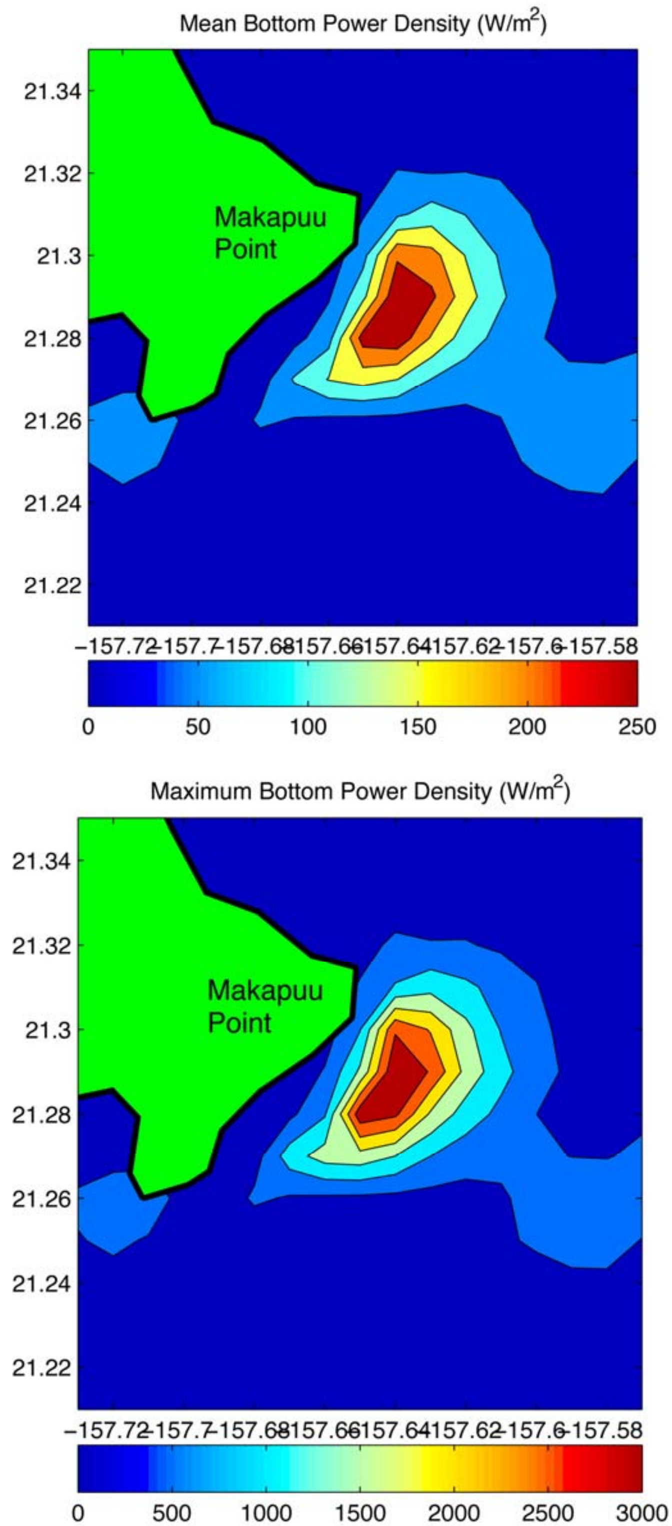


Figure A-5
Mean and maximum current power density off Makapuu Point

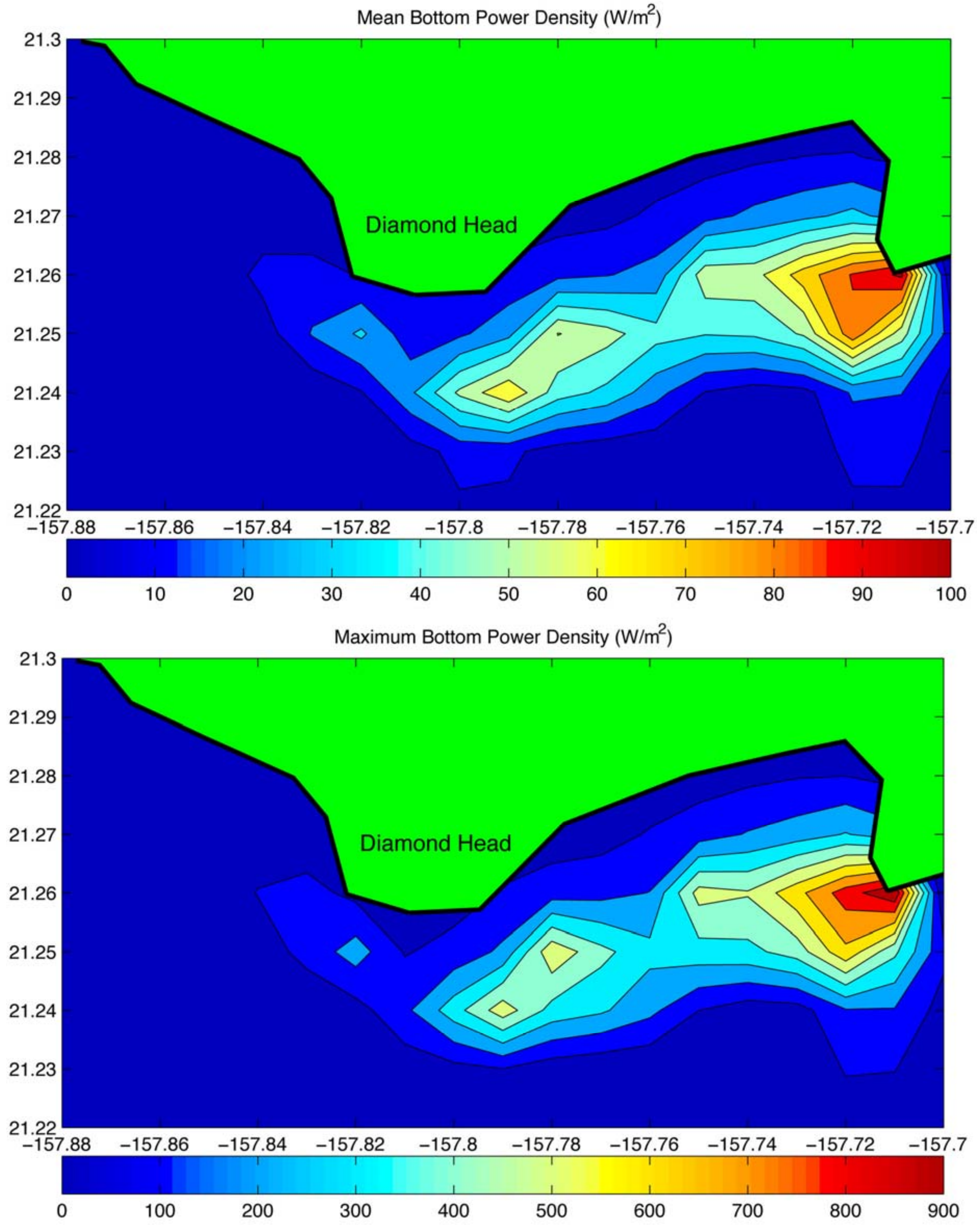


Figure A-6
Mean and maximum current power density between Diamond Head and Portlock

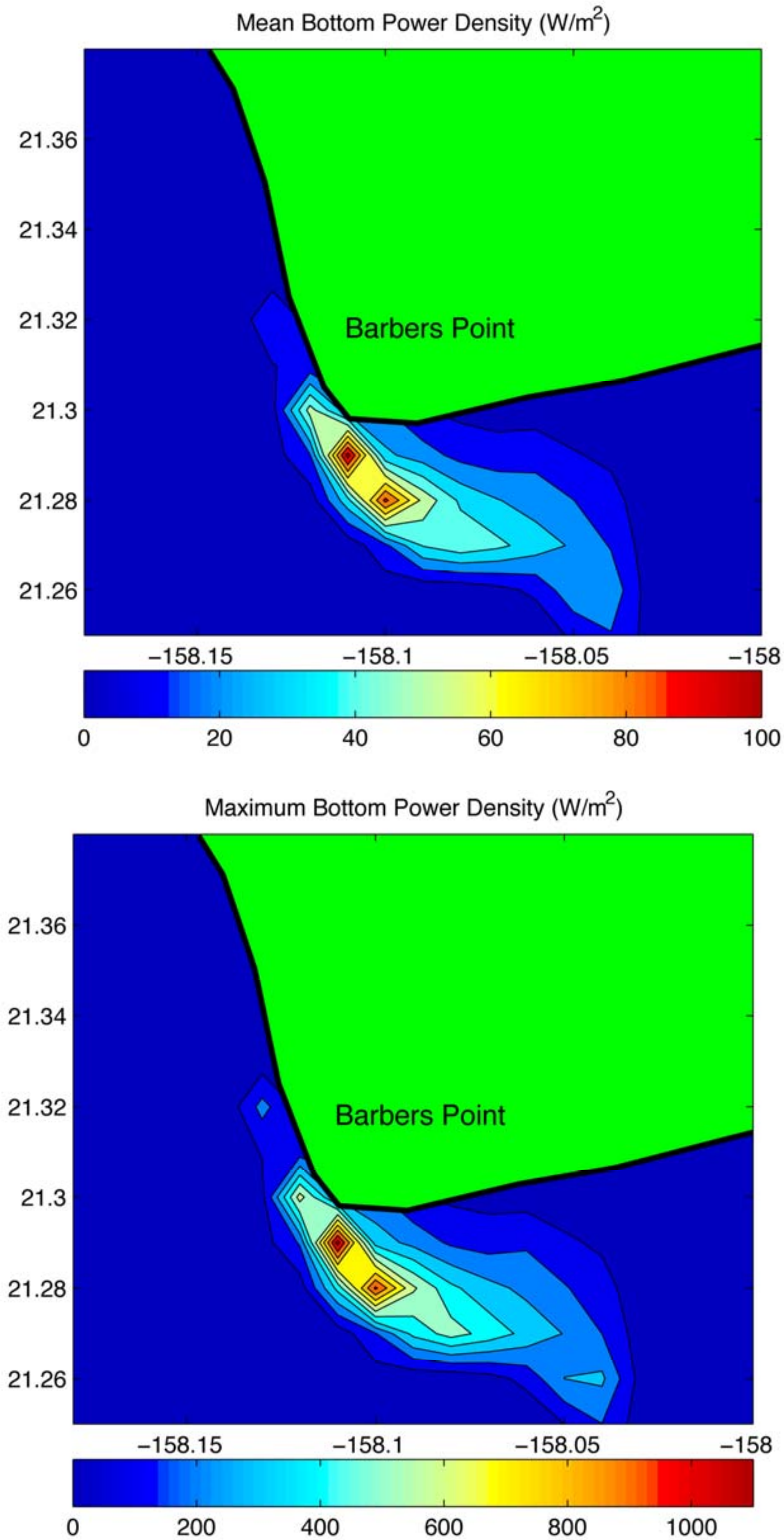


Figure A-7
Mean and maximum current power density off Barbers Point

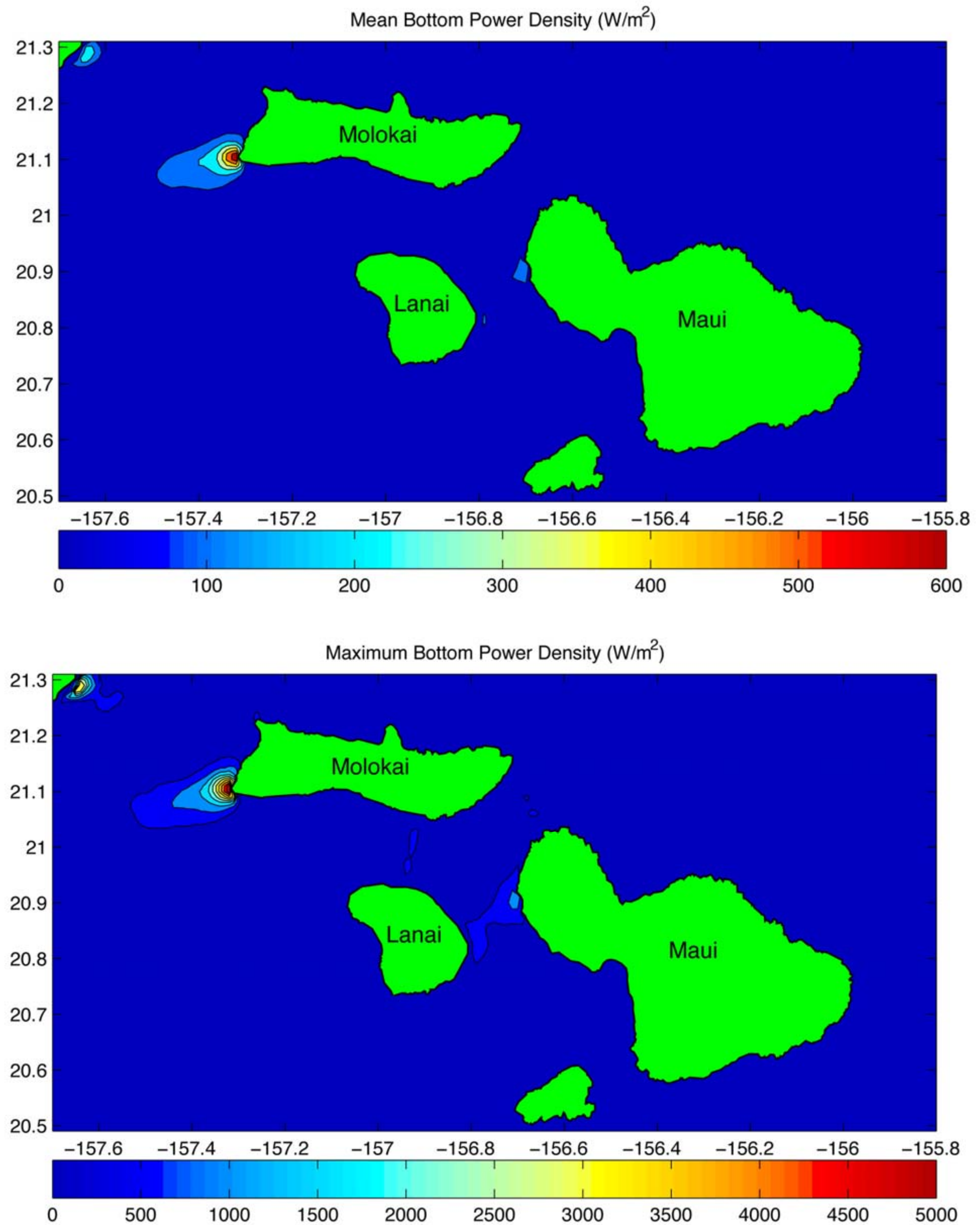


Figure A-8
Mean and maximum near-bottom current power density around Molokai, Maui and Lanai

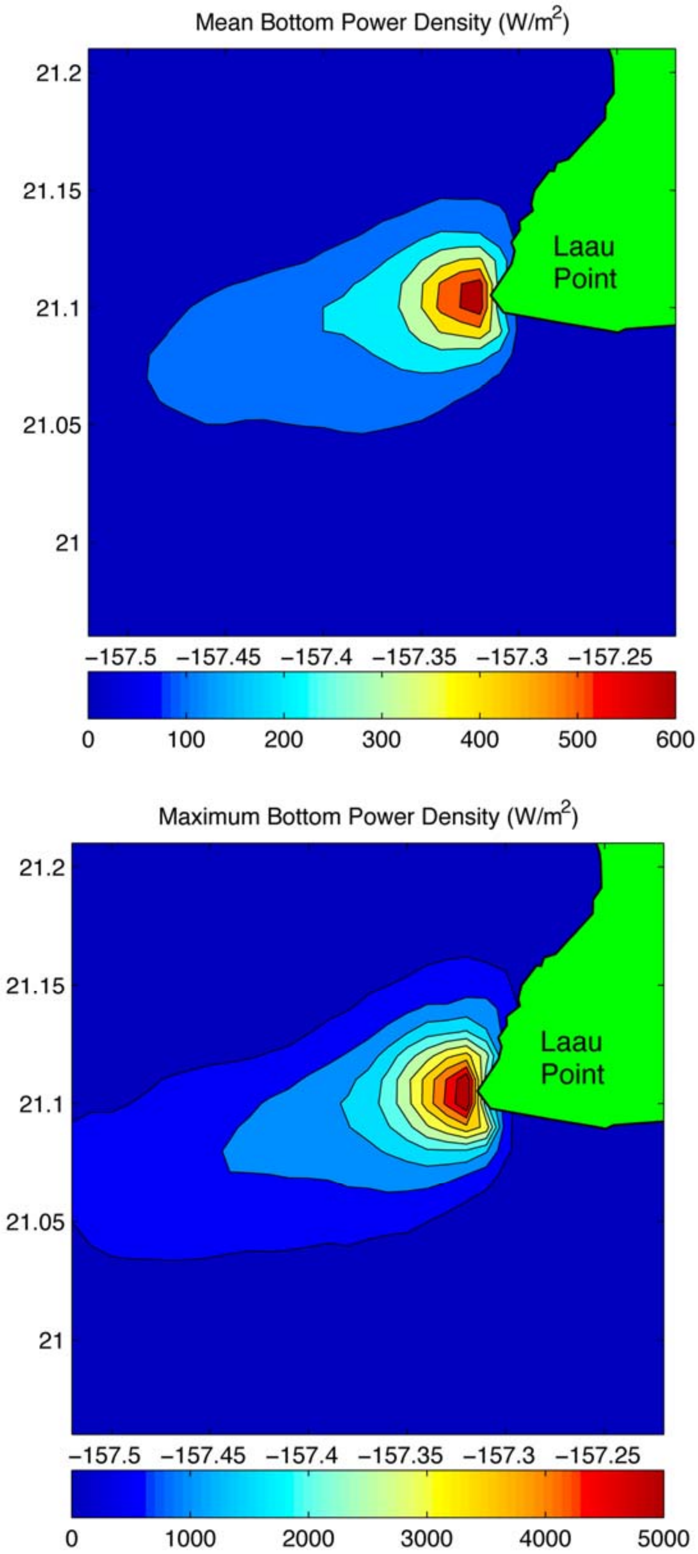


Figure A-9
Mean and maximum current power density off Laau Point, Molokai

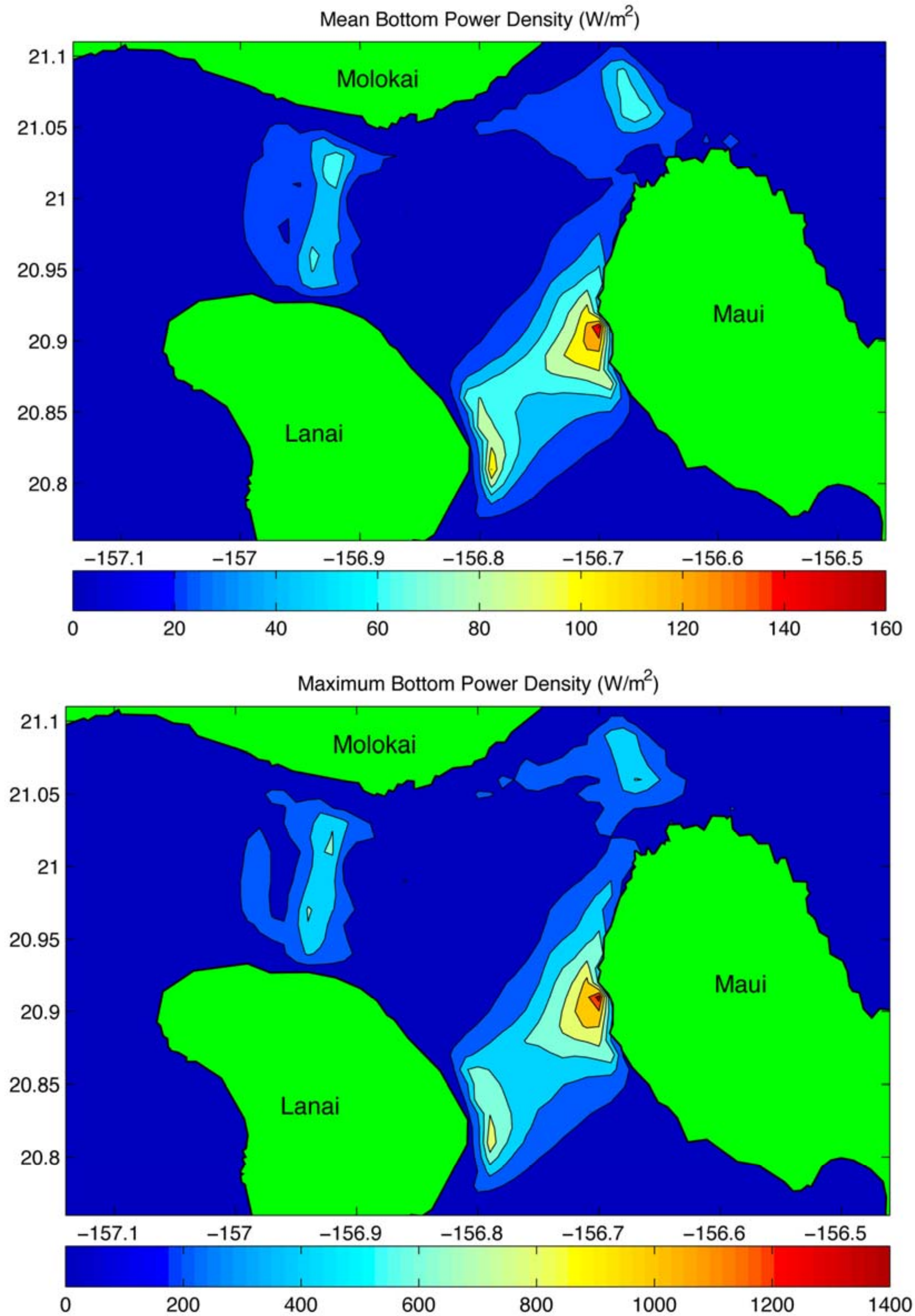


Figure A-10
Mean and maximum current power density off Lahaina, Maui

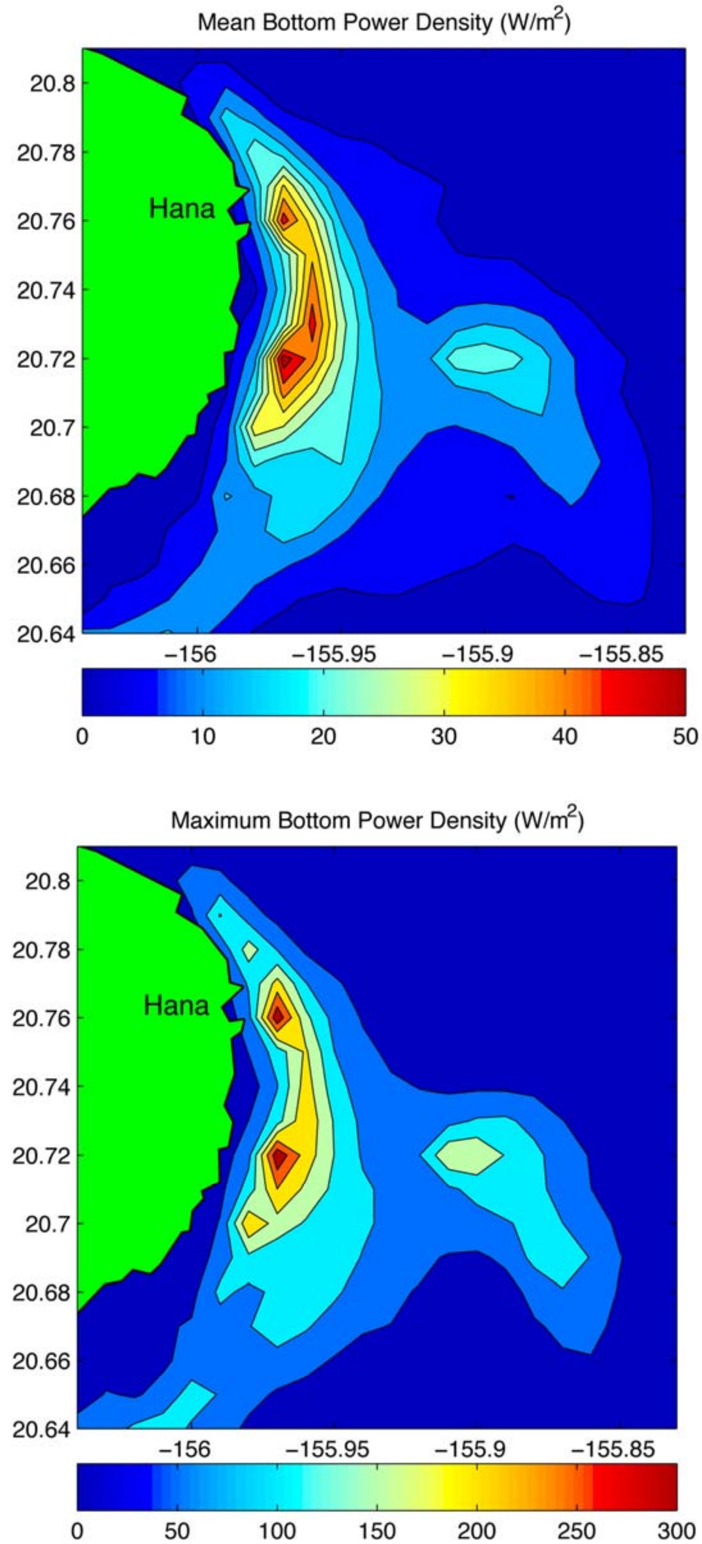
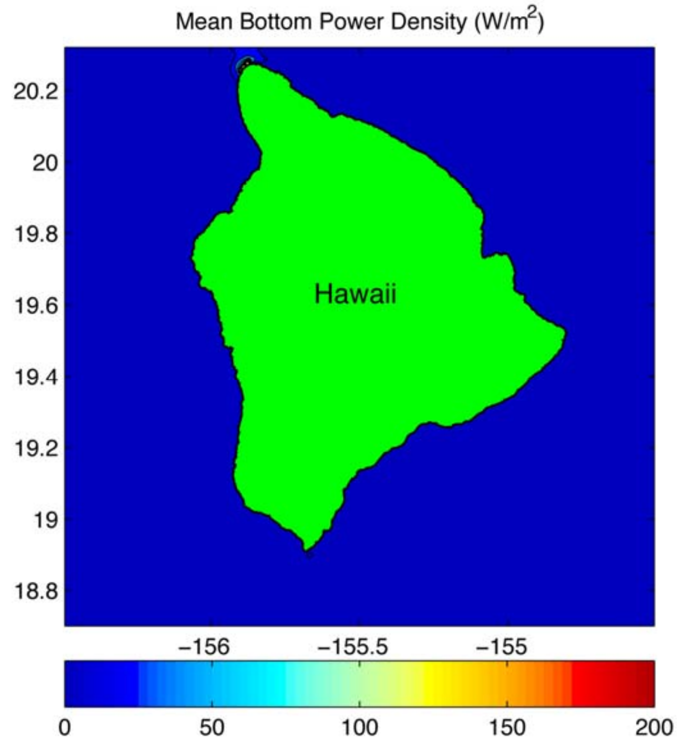


Figure A-11
Mean and maximum near-bottom current power density off Hana, Maui



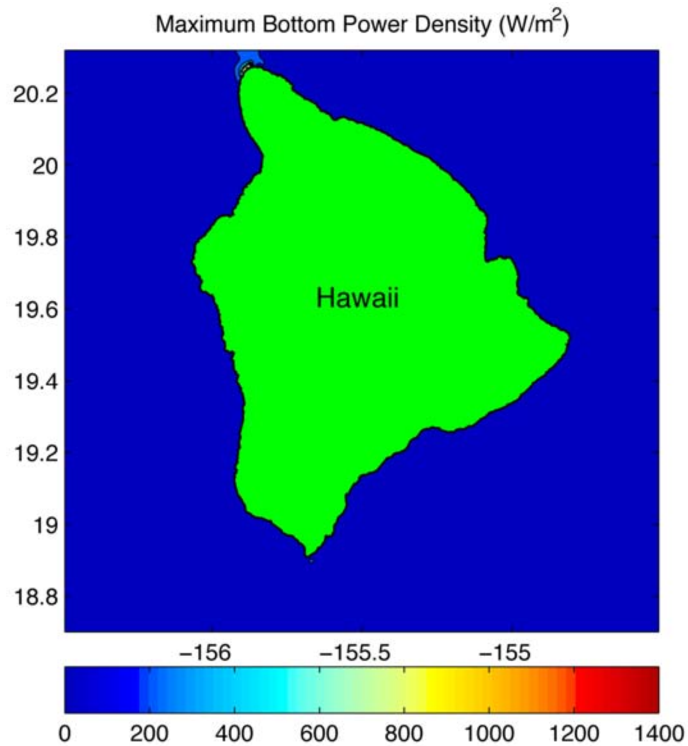


Figure A-12
Mean and maximum near-bottom current power density around the Big Island

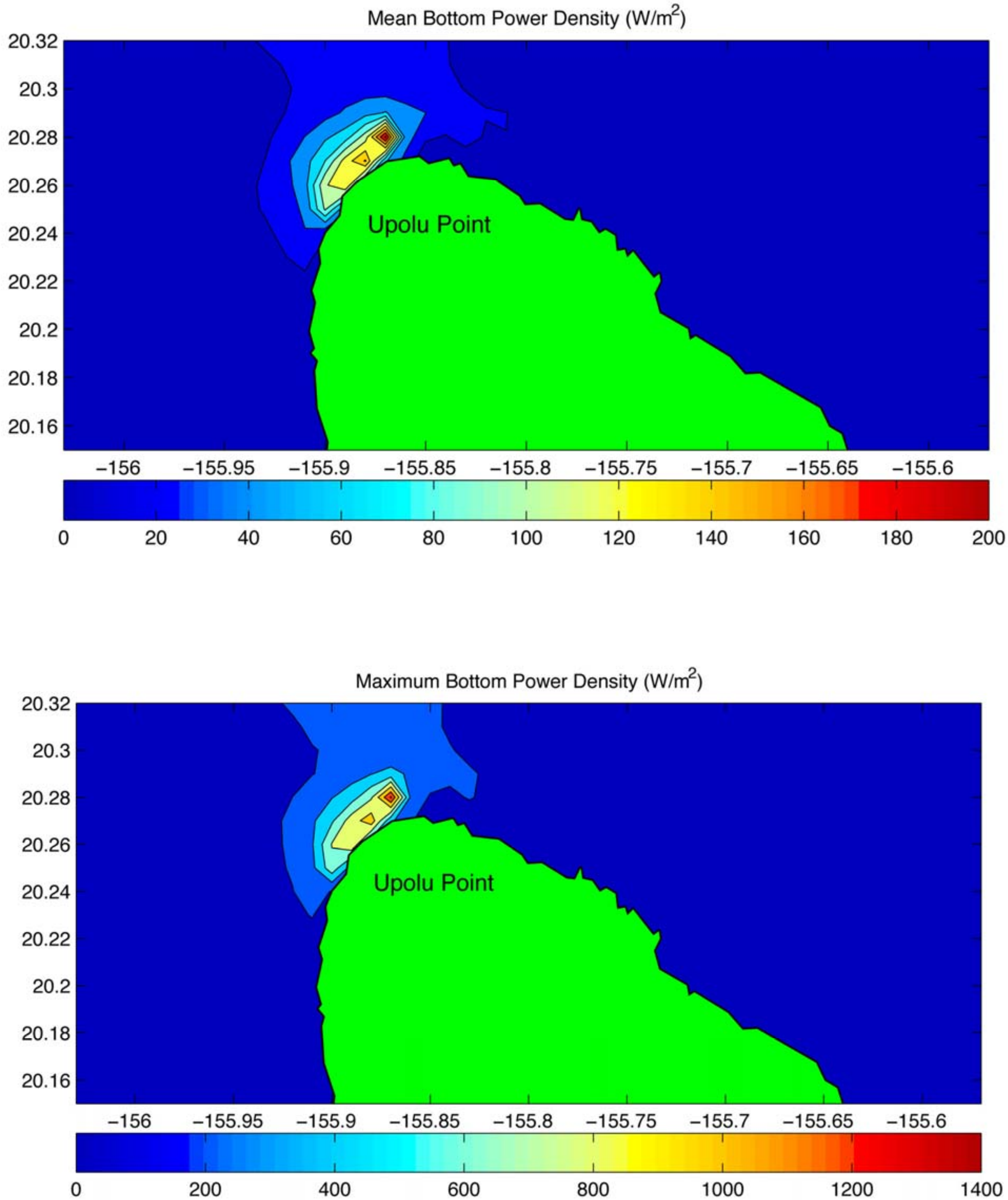


Figure A-13
Mean and maximum near-bottom current power density off Upolu Point, Hawaii

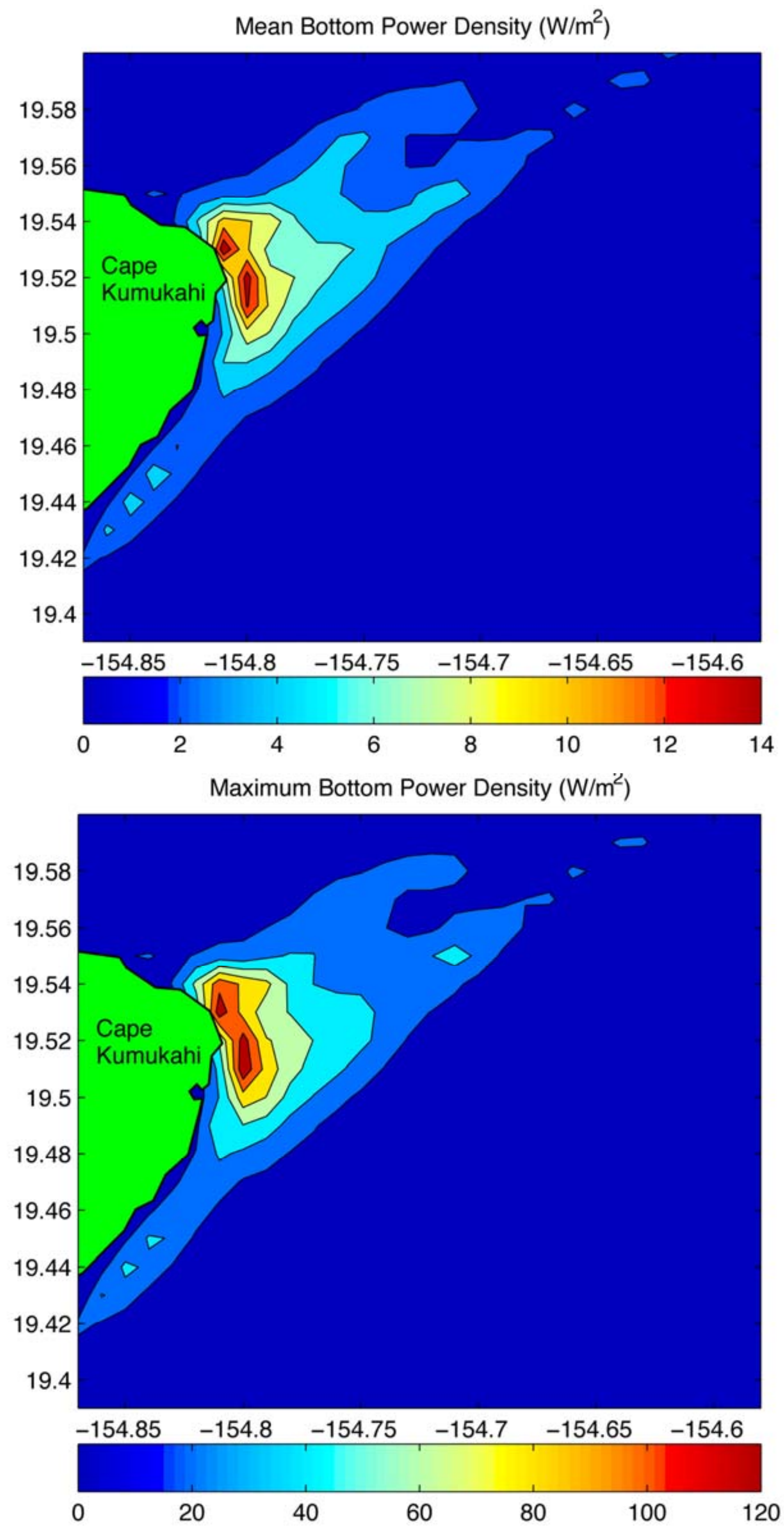


Figure A-14
Mean and maximum near-bottom current power density off Cape Kumukahi, Hawaii

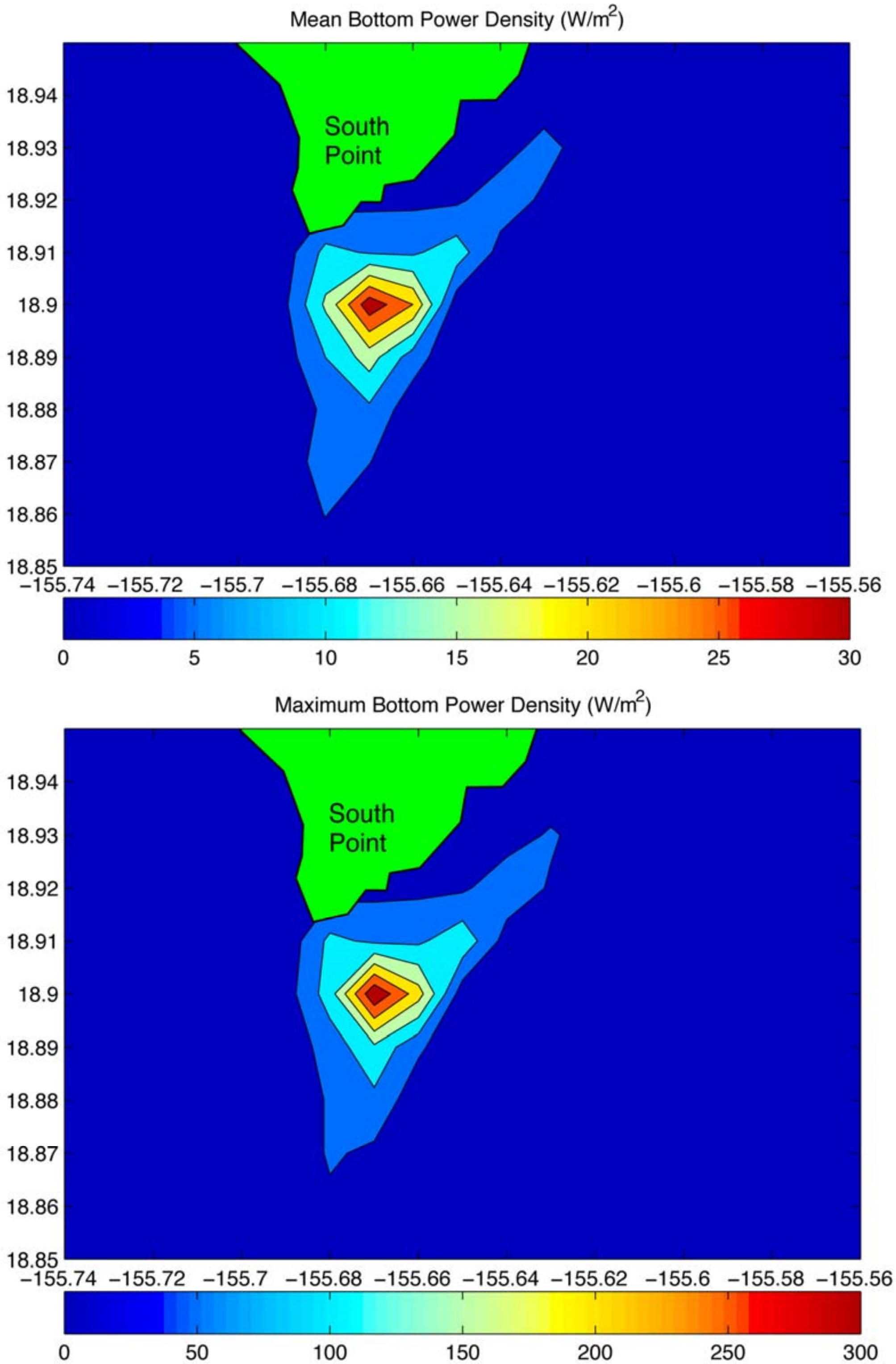


Figure A-15
Mean and maximum near-bottom current power density off South Point, Hawaii

B
APPENDIX B: UNDERWATER TURBINE DEVELOPERS

B-1 Hammerfest Strom/ Hammerfest UK

Contact Information

Hammerfest Strom
Strandgt. 1
9613 Hammerfest
Norway

47 97 96 79 48

www.tidevannsenergi.com

Harald Johansen

System Description

Hammerfest Strom has designed a 300 kW horizontal axis 3 bladed turbine 20 m in diameter. The turbine is mounted on a weighted tripod base. Their technology is based upon standard wind power components, including blades driving a horizontal shaft, which is connected by gearbox to a generator.

Figure B-1
300 kW Hammerfest Turbine (Source: Hammerfest Strom©)

Performance

The average flow velocity at the installation site is 1.8 m/s, with a maximum flow velocity is 2.5 m/s.

Development Status

Hammerfest Strom was established in 1997. In 2003 a 300 kW turbine was deployed at Kvalsundet Fjord and is still in operation. It is connected to electrical grid of the town of Hammerfest. In 2007 an agreement was signed between Hammerfest and Scottish Power to develop Scottish tidal energy. A 1 MW unit is planned for installation in 2009 and a 5 to 10 MW pre-commercial park is planned for 2010.

B-2 Verdant Power

Contact Information

Verdant Power
The Octagon
888 Main Street
New York, NY 10044
USA

212-688-3383

www.verdantpower.com

Hannah Abend

System Description

The Free Flow™ is a three bladed propeller connected to a streamlined fuselage and piling, similar in appearance to a standard windmill. The blade design is patented and efficient over a wide range of speeds. Six turbines with 5 m diameter blades were installed as part of the Roosevelt Island Tidal Energy (RITE) project and are rated at 35 kW. The turbines are scalable depending on specific site requirements and designed to be mounted on monopile foundations.

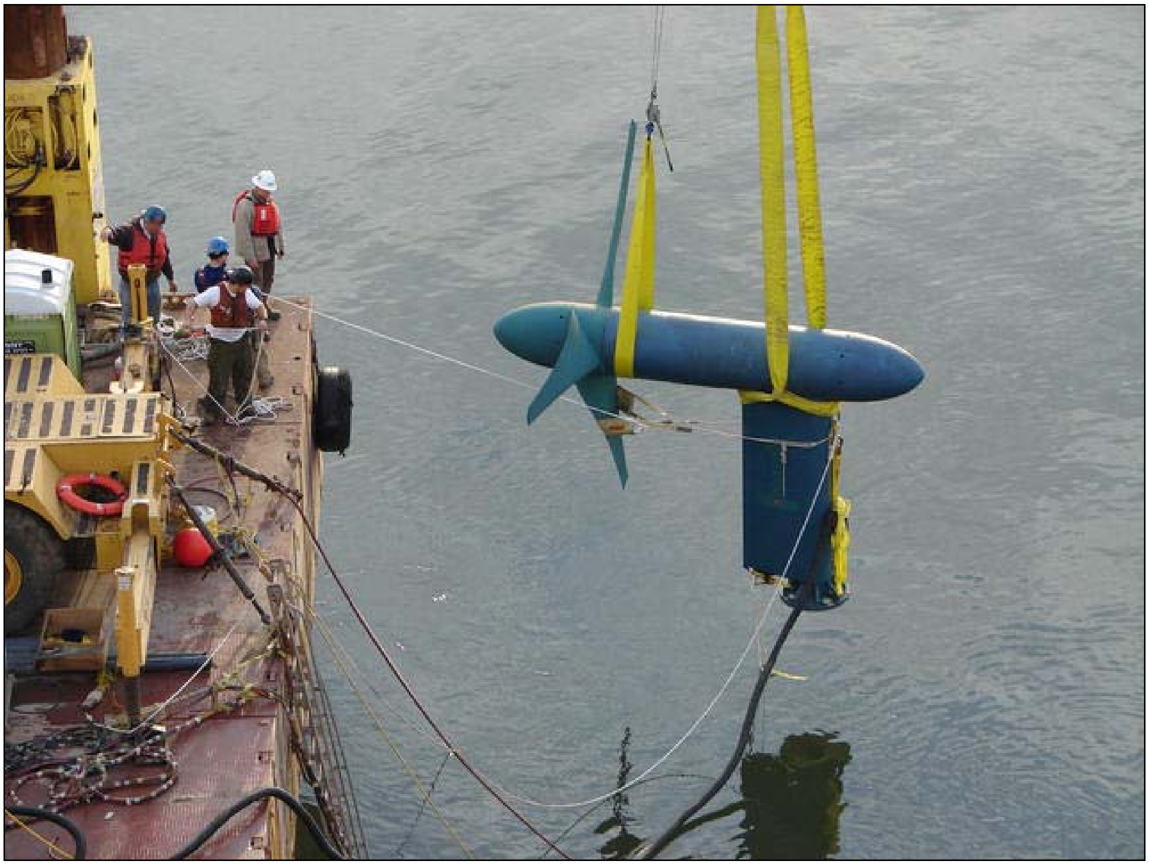


Figure B-2
Turbine being installed for RITE project. (Source: Verdant Power)

Performance

The cut in speed is 0.7 m/s. Rated power of 35 kW is generated at 2.2 m/s.

Development Status

Verdant PPower was established in 2000 to advance and commercialize blade development work conducted at New York University from 1983 to 1986, and testing completed in Pakistan in 1989. A third generation model was tested in 2002 in Maryland and the East River. In 2007 six turbines were deployed in 10 m of water in the East River in New York. Five are rated at 35 kW apiece and the sixth is for testing. The turbines produced over 7000 hours of power in April and May and began supplying the electrical grid in June. Cost of the project was eight million dollars.

This project is noteworthy because it involves the first installation of an array of turbines. The ultimate objective is to install up to 10 MW of generating capacity at an installed cost of $2,500 to $3,000 per kW.

B-3 Clean Current Power Systems Inc.

Contact Information

Clean Current Power Systems Incorporated
405-750 West Pender Street
Vancouver, British Columbia
V6C 2T7
Canada

(604) 602-1222

Cleancurrent.com

Glen Darou

System Description

Clean Current was formed in 2001 to commercialize tidal generator concepts. They have designed a bi-directional ducted horizontal axis direct drive generator. The direct drive variable speed permanent magnet generator is a proprietary design which improves efficiency. The design is simple with only one moving part – the motor assembly that contains the blades. There is no drive shaft and no gearbox. These are replaced by a variable speed magnet generator. The device requires no underwater controls.

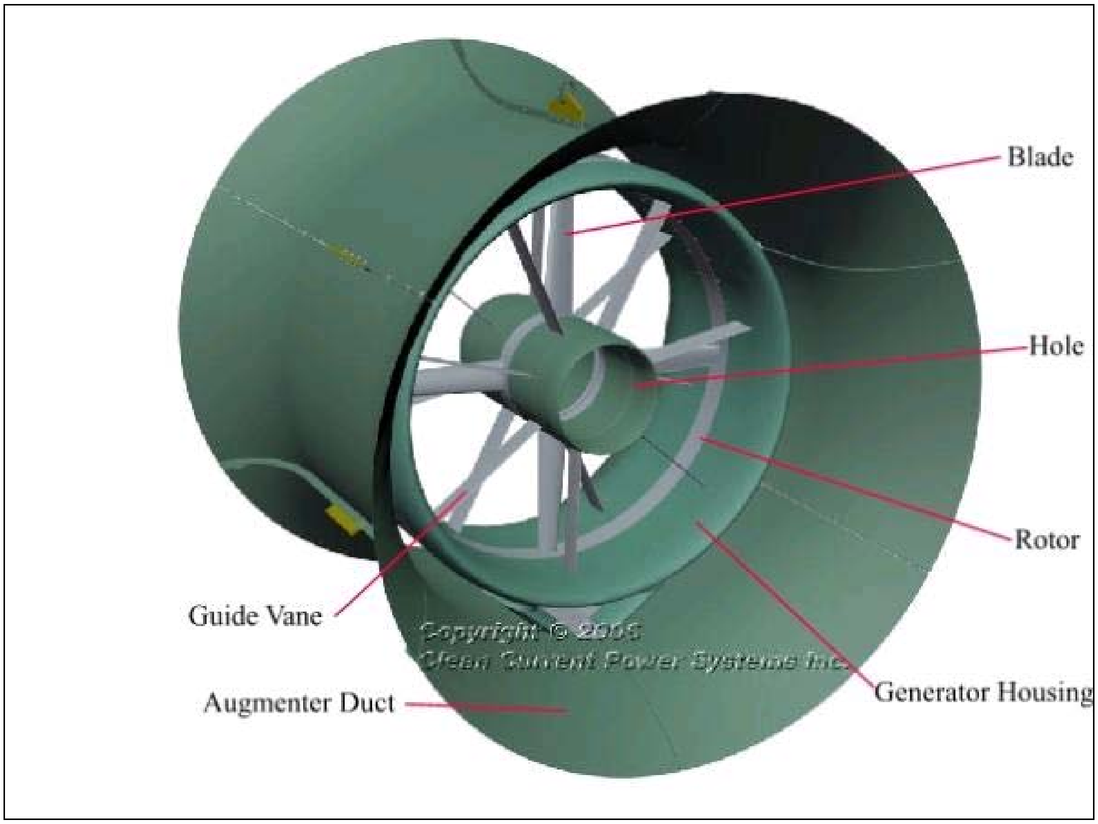


Figure B-3
Clean Current Turbine (Source: Clean Current©)

The generator can possibly be scaled up and sizes can potentially range up to 14 to 24 meters in diameter with generated power ranging up to 1.7 to 5 MW at 3.5 mps current speed. A test unit was installed at Race Rocks Ecological Reserve in British Columbia on a 0.9 m diameter monopile, but the turbines can also be mounted on gravity bases.

Performance

The design has a cut in speed of approximately 1 m/s with rated power at 3.5 m/s.

Development Status

Proof of concept testing was completed in 2004 and the company installed a 3.5 m diameter 65 kW (in a 3 m/s current) test generator at Race Rocks Ecological Reserve, a remote reserve south of Vancouver Island, in 2006. The unit was tested for two months after which it was placed on the grid supporting the reserve. In June 2007 the test unit was removed due to problems with the water lubricated bearings. It is currently being overhauled, including the installation of new bearings and blades, and will be reinstalled in the spring of 2008.

B-4 Ponte de Archimedia International S.P.A.

Contact Information

Ponte di Archimede International S.p.A
Viale Libertà IS.515
98121 – Messina
Italy

39 090 44973

http://www.pontediarchimede.it/language_us/

Elio Matacena

System Description

Ponte di Archmede is an international company, established in 1983, that specializes in the research and development of alternative and renewable energy sources. It has deployed a system named Enermar in the Strait of Messina in Italy. The unit sits in 20 m of water and is 150 m offshore, held in place by a 4-point mooring. The device is a 6 m diameter vertical axis Kobold turbine suspended below a 10 m diameter support structure. The blade span is 5 m. Power generation is 25 kW. The Kobold turbine is a patented variation of a vertical axis turbine in which the wings are allowed to pivot slightly to optimize power generation. The turbine rotates independently of the current direction.

Figure B-4
Ponte de Archimedia Enermar System and Kobold Turbine (Source: Ponte de Archimedia©)

Performance

This turbine requires an average 1.5 m/s current, generating 25 kW at this speed. The average current speed in the strait is 2 m/s.

Development Status

The Enermar 25 kW system was deployed in the Strait of Messina in 2001. Its turbine design is based on research done at the University of Naples. In 2006 it was connected to the local power grid for the city of Messina. Tests are presently underway to improve the components for mechanical transmission and connection to the generator. Ponte di Archmede is planning on installing three prototypes within the next year in the Peoples Republic of China, the Philippines, and Indonesia. The generator is on the surface platform and the systems will have to be designed to resist typhoon conditions in these areas.

B-5 Lucid Energy Technologies

Contact

Lucid Energy Technologies, LLC (formerly GCK Technology, Inc.)
3535 Corrie Drive
Goshen, IN 46550
USA

www.lucidenergy.com

Ed Kurth

System Description

The Lucid Energy Technologies approach is based upon the Gorlov Helical Turbine (GHT). This turbine has airfoil shaped blades that are twisted into helixes. Water flow onto the blades creates a thrust force and the wing generates lift. As a result of this force, the blades can rotate at twice the speed of the flowing water. Due to its axial symmetry, the GHT rotates in the same direction even when the current direction reverses. The turbines are constructed from marine grade aluminum alloys. GHTs are reportedly more efficient as compared to other turbine types, capturing 35% of the flow energy as compared to 16 to 23% for other turbine types. Lucid Technology has started commercial production of a 40 kW model, 1 m in diameter and 2.5 m long. A commercial model 2 m in diameter and 5 m long will go into production soon and a 3 m diameter model is under design. Several chord lengths will be available for the 2 m model.

The GHT can be installed in a variety of configurations and depths, making it potentially applicable to many different areas. The turbine can be installed either vertically or horizontally, and in water as shallow as four feet, as long as the shaft is perpendicular to the current flow. The turbines can be installed in modular arrays, either side by side or with multiple turbines on the same shaft. The modules can be suspended in the water column, attached to the ocean bottom or attached to the shoreline.

Figure B-5
Gorlov Helical Turbine (Source: Lucid Energy Technologies, LLC©)

Performance

The cut in speed is 0.5 m/s but due to concerns about the efficiency of energy conversion, currently recommended (2007) water velocities are 1.5 m/s or greater. At a 4.5 m/s current speed the rated power is 40 kW for the 1 m diameter model, 150 kW for the 2 m diameter model, and 360 kW for the 3 m diameter model.

Development Status

A GHT has been installed in the Amazon River in Brazil since 2001. It has been used to recharge vehicle batteries and power electrical devices. The Korea Ocean Research and Development Institute (KORDI) tested a 1 m diameter turbine in the Udolmok Strait in Korea in 2002. The turbine generated 10 kW in a 2 m/s current. In 2004 two months of testing were completed in the Merrimack River in Amesbury, MA. Tidal current speeds during the test reached a maximum of only 1.5 m/s. The turbine efficiency at this speed was only about 50% of that reported by earlier tests at the University of Michigan. Subsequent testing at Woods Hole indicated that turbine installation too close to the water surface was responsible for the degraded performance. Lucid Energy is presently working on several projects in British Columbia, one example being a tidal plant in Owens Bay on Sonora Island. A 1 MW tidal plant utilizing GHTs is presently under construction by KORDI to be installed in the Udolmok Strait.

B-6 Marine Current Turbines, Ltd

Contact Information

Marine Current Turbines Ltd
The Court, The Green
Stoke Gifford, Bristol
BS34 8PD
United Kingdom

44 117 979 1888

www.marineturbines.com

Peter Fraenkel

System Description

Marine Current Turbines Ltd (MCT) is developing the SeaGen. The MCT approach is based upon wind turbine technology. MCT believes that this is the most economical and efficient approach to solving the problem of bi-directional flow. Their prototype system has twin axial flow rotors of 16 m diameter mounted on wing like extensions on either side of a tubular steel monopile set into a socket drilled into the seabed. Each rotor drives a generator via a gearbox.

Rated power is 1.2 MW. Larger diameter rotors may eventually become more cost effective. A unique patented feature of this system is that both rotor structures can be raised on the monopile above the water surface for maintenance.

The monopile component limits this system to water depths less than 30 m. The SeaGen has been designed for installation with no underwater operations conducted by either divers or ROVs. This is based upon the assumption that divers or ROVs would have only short periods of efficient working time during slack flow in reversing tidal streams. The concept of mounting the turbines on the on the monopile and lowering them into the water was therefore developed and patented.

There are disadvantages to the monopile installation. Multiple monopole installations will be visually intrusive and may make permitting more difficult. It might also limit the areas of potential application since open ocean installations would have to be designed to withstand severe design wave conditions. These disadvantages could be overcome for full commercial applications by designing a system with a different anchoring scheme.

Performance

The cut in speed is 0.7 m/s. The effective current range is up to 3.5 m/s.

Development Status

Marine Current Turbines deployed the Seaflow, a 300 kW single rotor test turbine with 11 m blades off Lynmouth, Devon, UK in 2003. The turbine is presently in a state of preservation

prior to being decommissioned following successful operation. Installation of a twin rotor SeaGen 1.2 MW commercial prototype was planned for August 2007 off Northern Ireland. The deployment was delayed due to temporary non-availability of the installation jack-up barge. The system will be installed by Sea Generation Ltd, a wholly- owned subsidiary of MCT. SeaGen has secured funding of £7.5 million for this project.

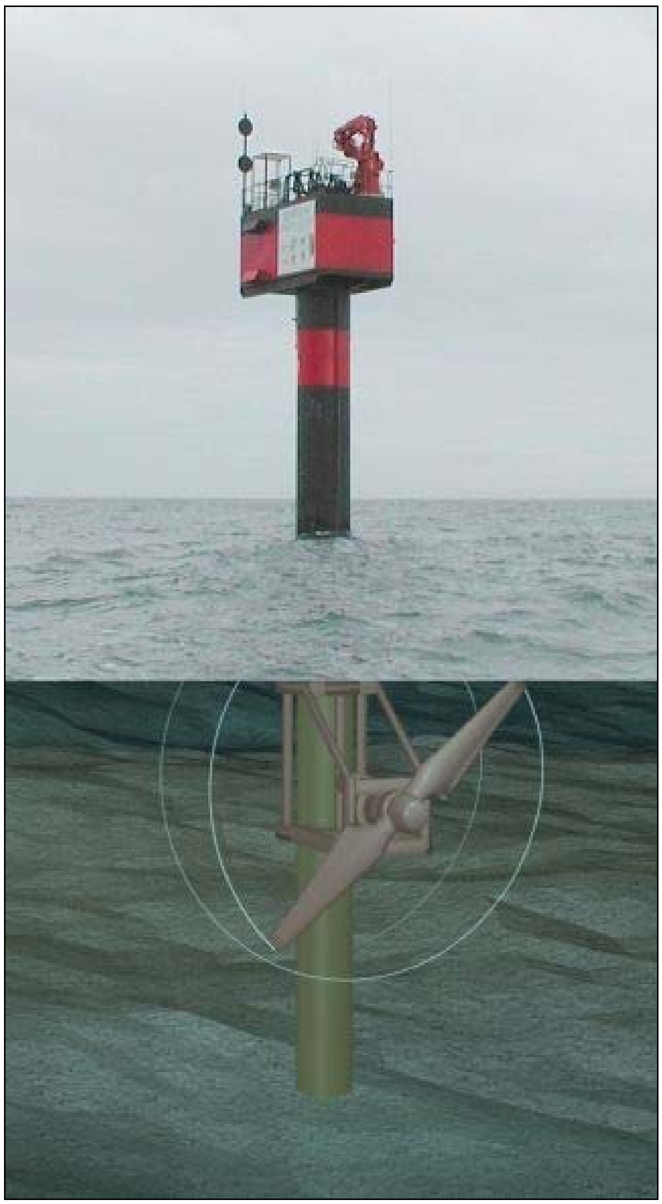


Figure B-6
Seaflow 300 kW Test Turbine. (Source: Marine Current Turbines Ltd.©)

B-7 Open Hydro

Contact Information

Open Hydro
66 Fitzwilliam Square
Dublin 2
Ireland

353 (0) 1 703 7300

www.openhydro.com

Nick Wells

System Description

The Open Hydro turbine has an outer fixed rim and an inner single-piece rotating disc. It is mechanically very simple with only one moving part, the turbine itself. No gearbox is required since the magnetic generator is encapsulated in the outer rim and there are no seals. The fixed symmetrical blades allow operation for bi-directional flow conditions. The design assembly consists of twin 15 m outer diameter turbines. Rated power is 1.5 MW.

Figure B-7
Open Hydro 6 m Turbine Installed at EMEC (Source: Open Hydro©)

This turbine represents an approach based upon relatively new technology. The US Navy designed the permanent magnet rim generator utilized in the 3 m generator. Magnetic rim generators are becoming more common with applications in wind power and rim driven thrusters for marine propulsion. Enercon, a wind turbine manufacturer has constructed wind turbines rated to 4.5 MW using this technology. A possible major advantage of this system is it simplicity and robust design for application to harsh marine environments.

Planned installations have included gravity bases and piles. In is anticipated that commercial installations will be twin counter-rotating twin turbines to offset torque. Since there are no seals, there are no theoretical limits on installation depths. The 250 kW 6 m diameter unit installed at EMEC is on twin monopiles. This was done to ease installation and maintenance. Future installations can be entirely subsurface. The turbines are very large and therefore will be subject to large wave induced forces if installed in the open ocean. However, there is no stated depth limit and the units can possibly be installed in deep enough water so that the forces are reduced.

<u>Performance</u>

Power results from 3m turbine tests correlate with a theoretical model using Blade Momentum Theory. The cut in speed is 0.7 m/s. The design twin turbine unit is rated at 1.5 MW in 2.5 m/s currents

<u>Development Status</u>

Open Hydro was formed in 2005, in part through the purchase of open center technology developer Florida Hydro. In 2005 a 3m diameter open center turbine was sea tested in bi-directional flows by the US Navy under a Cooperative Research and Development Agreement (CRADA). In 2006 Open Hydro installed their 6 m single turbine at EMEC. Installation was completed in early 2007 and in February 2007 funding was granted to install a second turbine at EMEC. The turbine installed in 2007 has been removed and a new unit is being installed on the same base.

In 2007 Open Hydro was selected to provide Nova Scotia Power with turbine technology for a Bay of Fundy project demonstration project. One reason given for their selection was that Open Hydro had been successful in demonstrating their ability to design increasing sizes of turbines. When completed, the demonstration project will be the largest in-stream tidal generating unit integrated into an electrical grid in the world. If successful, it may lead to large scale tidal utility farms in the Bay of Fundy. In March 2007, Open Hydro signed an agreement with Alderney Renewable Energy, Ltd. to supply turbines for the Channel Islands between England and France. Open Hydro has raised over 40 million in a recent round of equity funding.

B-8 Blue Energy Canada Inc.

Contact Information

Blue Energy
Box 29068
1950 W. Broadway
Vancouver, BC V6J 1Z0
Canada

(604)682-2583

Bluenergy.com

Martin Burger

System Description

The Blue Energy design utilizes the four bladed vertical axis Davis turbine, an outgrowth of the Darrieus turbine, and is the culmination of twenty years of research and development. Their design places the turbine in a duct, which has been shown to improve performance.

The generator and gearbox is placed on the surface above the turbine shaft for easy access and maintenance. The duct and generator support structure is a concrete caisson anchored to the seafloor. Various power systems are proposed ranging from 5 to 500 kW, and larger ones are a possibility. All utilize the ducted vertical axis turbine. Blue Energy is presently concentrating on a 250 kW unit intended for off grid applications in the 1.5 to 3 m/s current range. Blue Energy feels the technology is mature, and applications are dependent on market forces to make them economically viable.

Development Status

Flume tests, begun in 1981, found that ducting markedly increased the performance of the turbine. In 1983 a 20 kW unit was installed in Ontario and connected to Niagra power. In 1984 a 100 kW unit in Nova Scotia produced only 70 kW of power due to duct restrictions. A 1.2 m diameter, 1.2 m long unit moored in 1985 at a depth of 200 ft in the Gulf Stream produced 4 kW of power. Further work in the Gulf Stream was not conducted since no cost advantage could be shown over conventional generation. A river test was conducted in 1987 with a 5 kW unit in Nova Scotia. Power was produced but the site proved too shallow for proper operation. Since then, Blue Energy has focused on tow tank trials, completing over 1500 tests at the University of British Columbia. They recently received a new round of financing and are developing a 250 kW off grid unit for 1.5 to 3 m/s currents.

The proposed designs all extend from the ocean bottom to above the water surface. This design limits potential applications and will make permitting more difficult for many areas.

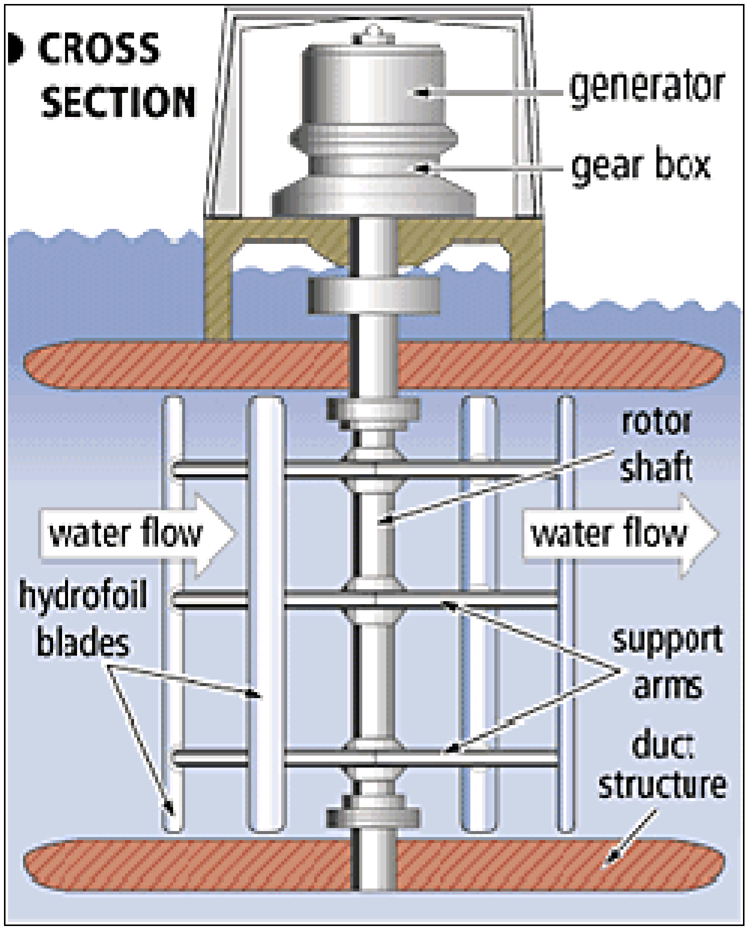


Figure B-8
Blue Energy Turbine (Source: Blue Energy©)

B-9 SeaPower, Inc.

Contact Information

Seapower International AB
Essingeringen 72C
S-11264 Stockholm
Sweden

www.seapower.se

System Description

The EXIM Tidal Turbine Power Plant (TTPP) by Seapower is based on the Savonius Turbine. This turbine turns relatively slowly but generates high torque. The rotor is connected to a generator via a standard gearbox. The prototype unit consists of dual vertical axis rotors, 1 m diameter by 3 m high. The EXIM is moored by four anchors and chains or by piles and chains. This is a surface mounted system which would expose it to large wave forces, if installed in open ocean areas.

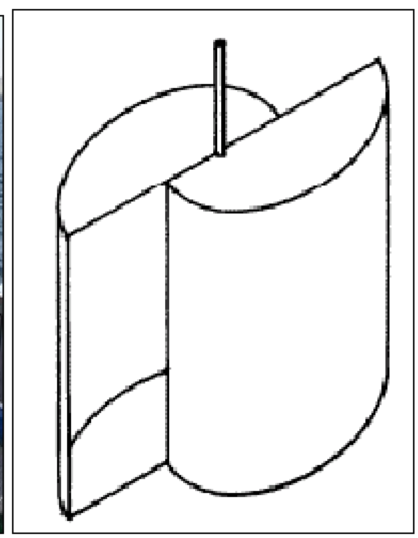


Figure B-9
Seapower EXIM Turbine and Savonius Turbine blades (Source: Seapower©)

Performance

The cut in speed is 0.7 m/s. The rated power is 44 kW at a peak flow speed of 3 m/s.

Development Status

In 2003 Seapower conducted installation studies for the Shetland Islands and tested their EXIM turbines attached to an anchored ship. In 2004, two sites were identified for further testing and permits were obtained. Plans were in place for a pilot plant installation in 2005, but Seapower has been unavailable for comment regarding these and future plans.

B-10 Tidal Hydraulic

Contact Information

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Mumbles
Swansea
SA3 4HY
United Kingdom

44 (0)1792 360400

http://www.dev.onlinemarketinguk.net/THG/index.html

System Description

Tidal Hydraulic has designed a four bladed horizontal axis turbine. The generator is a hydraulic accumulator system and the turbine blades are relatively small.

Figure B-10
Tidal Hydraulic Turbine (Source: Tidal Hydraulic©)

Development Status

Tidal Hydraulic tested their turbine in the Cleddau River in 2001. They are designing a 3.5 MW turbine system for the Ramsey Sound in Wales. The sound is 50 to 65 m deep and has a maximum current flow of 3 m/s. The generating unit will be 80 m square and 15 m high. It will be installed in deep water below the zone of significant wave forces.

B-11 Underwater Electric Kite

Contact Information

UEK Corporation
P.O. Box 3124
Annapolis, MD 21403
USA

410-267-6507

Uekus.com

Peter Virden

System Description

The Underwater Electric Kite (UEK) is a twin horizontal axis turbine which has a high solidity (the frontal area of the turbine blades is high relative to the swept area) turbine design and an augmentor ring to increase the internal velocity of the water flow. Their approach is based upon existing hydropower turbine technology. The system has a permanent magnet, variable speed generator.

Figure B-11
UEK Twin Axis Turbine (Source: UEK Corporation©)

Blade design can be optimized for flow conditions. The size of a single prototype 400 kW system with a 4 m diameter rotor was 5.2 m by 9.5 m by 7 m. Weight was 3.5 tons.

The UEK has a conventional fixed pitch blade axial propeller and achieves its efficiency by the Augmentor Ring. This flared ring creates a zone of low pressure behind the turbine, thus accelerating the water passing through the turbine.

The mooring design is proprietary and consists of two anchors and two cables. They are rigged so that the device can orient itself toward either the upstream or downstream anchor, making it suitable for bi-directional flow. The turbine is buoyant on the mooring.

Performance

The cut in speed is 1.5 m/s. The 4 m diameter single axis turbine is rated at 400 kW at 3 m/s flow speed.

Development Status

In 1985 UEK tested a 1.2 m diameter single turbine with an Augmentor ring. Testing of a 1 m diameter single unit continued intermittently from 1986 through 1988. In 1995 a single stage 2.4 m turbine was tested. This was the first fully successful test. Flume tests were conducted in 2000 in the DeQew Hydroelectric Power Plant.

Work is presently ongoing with the state of Delaware for a 10 MW, 25 unit project in the Indian River Inlet in southern Delaware for the Old Dominion Electric Company. The first step will be the installation of a demonstration unit, with subsequent installation of the 25 turbines. The environmental permitting for this project is currently on hold, pending resolution of concerns pertaining to recreational fishing in the inlet.

Permits have been obtained for a New Hampshire tidal project, and a 60 kW project is beginning in the Manitoba River in conjunction with the University of Manitoba and Manitoba Hydro. In 2008 work is scheduled to begin on a 100 kW river project for Alaska Power in Eagle, Alaska.

The UEK is also applicable to lower speed uni-directional ocean currents such as the Gulf Stream. Depth of the UEK system is limited only by the economics of the installation and power cable routing.

B-12 Tidal Sails

Contact Information

Kunnskapsparken, Karmsundsgaten 51
N-5531 Haugesund
Norway

47 90 16 86 86

www.tidalsails.com

Are Børgesen

System Description

Tidal Sails has designed a patented system where ocean currents push "sails" underwater along guide wires. The sails are attached to cables which drive generators. The entire installation is intended to be fully submerged.

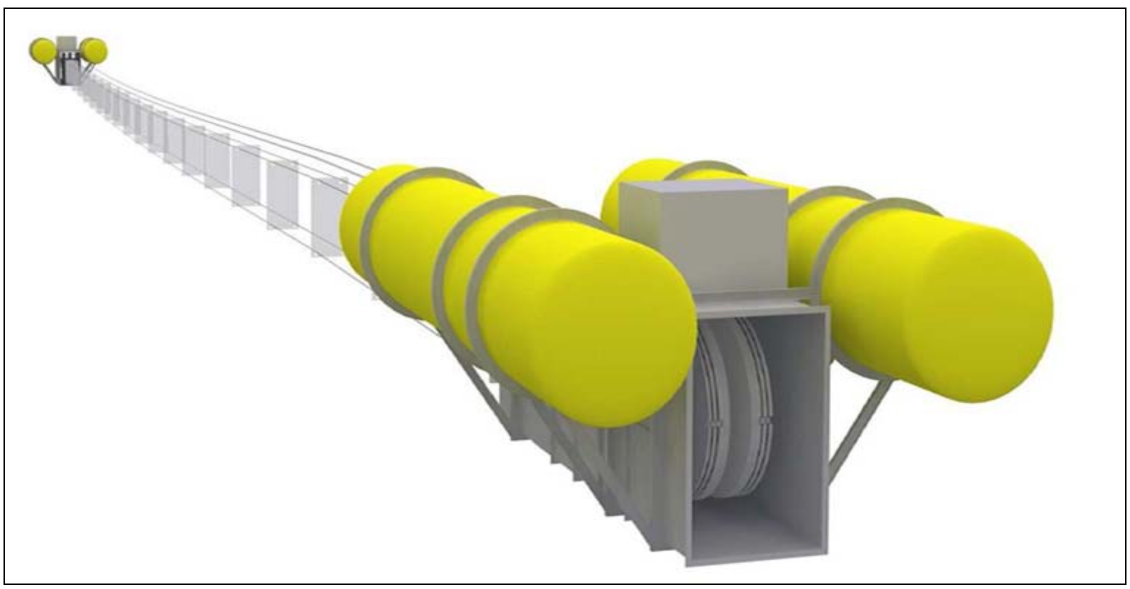
Tidal Sails believes their design has several advantages over conventional turbines. The sails expose a larger area to the current than turbine blades, and this may lead to higher power output than conventional turbines at a lower cost. The system also has the ability to span deep water channels.

Performance

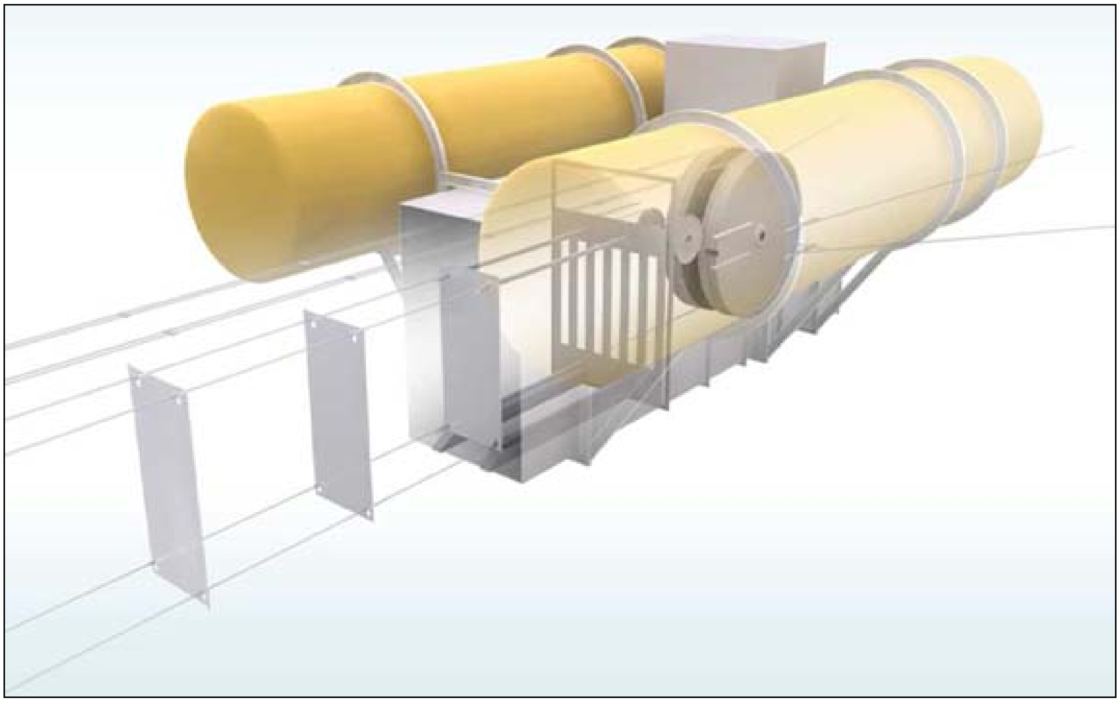
A 2 m/s current is necessary for economic operation.

Development Status

Tidal Sails was established in 2004 to commercialize this sail technology. Computational fluid dynamic analysis was conducted in 2005. The concept was patented and tank testing was conducted in 2006 and a 25 m prototype has been deployed for 6 months in 2007. Plans are to deploy a grid connected full scale prototype in 2009 with the first full scale commercial installation in 2010.



(a) Tidal Sails (Source: Tidal Sails©)



(b) Cutaway of Tidal Sails Generator (Source: Tidal Sales©)

Figure B-12
(a) Tidal Sails; (b) Cutaway of Tidal Sails Generator

B-13 Sea Snail

Contact Information

Robert Gordon University
Schoolhill
Aberdeen, AB10 1FR Scotland
United Kingdom

www.rgu.ac.uk

System Description

The Sea Snail, developed at Robert Gordon University, is a large tubular frame, 15 m x 12 m, upon which sits a 150 kW turbine and generator. Total weight of the device is 30 tons. This design provides a novel way of securing the system to the seafloor. Upturned hydrofoils are attached to the frame to provide the necessary downward force to keep the Snail in place, eliminating the need for any additional anchoring devices. The downward force increases as the flow speed increases. The hydrofoils theoretically simplify and anchoring and placement of the device, eliminating the need for multi-point moorings or drilled bases.

Figure B-13
Sea Snail (Source: Robert Gordon University©)

Development Status

The Sea Snail was installed in Burra Sound in Orkney in 2005. It is presently undergoing modifications to improve its ability to accommodate flows from any direction and will be redeployed in 2008.

B-14 Lunar Energy (Rotech Tidal Turbine)

Contact Information

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Parkgate House Office
Park, Ferriby Road
Hessle, East Yorkshire
United Kingdom

44 (0)1482 648964

www.lunarenergy.co.uk

Donald Stewart

System Description

The Rotech Tidal Turbine (RTT), designed by Lunar Energy, is a horizontal axis turbine located within a symmetrical duct. The fixed duct is a unique design feature (patent pending) that eliminates the need to turn the unit to take full advantage of the oncoming flow. This eliminates the need for several mechanical components, including yaw control and variable pitch blades. Tidal currents do not always reverse by exactly 180 degrees and the bi-directional duct guides the flow into the turbine from a wide range of directions. The duct ensures that, at angles of up to 45 degrees to the flow, as much power is generated as when the flow is directly in line with the RTT turbine axis. The turbine drives a commercially available hydraulic pump. This sacrifices some efficiency as compared to direct drive but increases reliability.

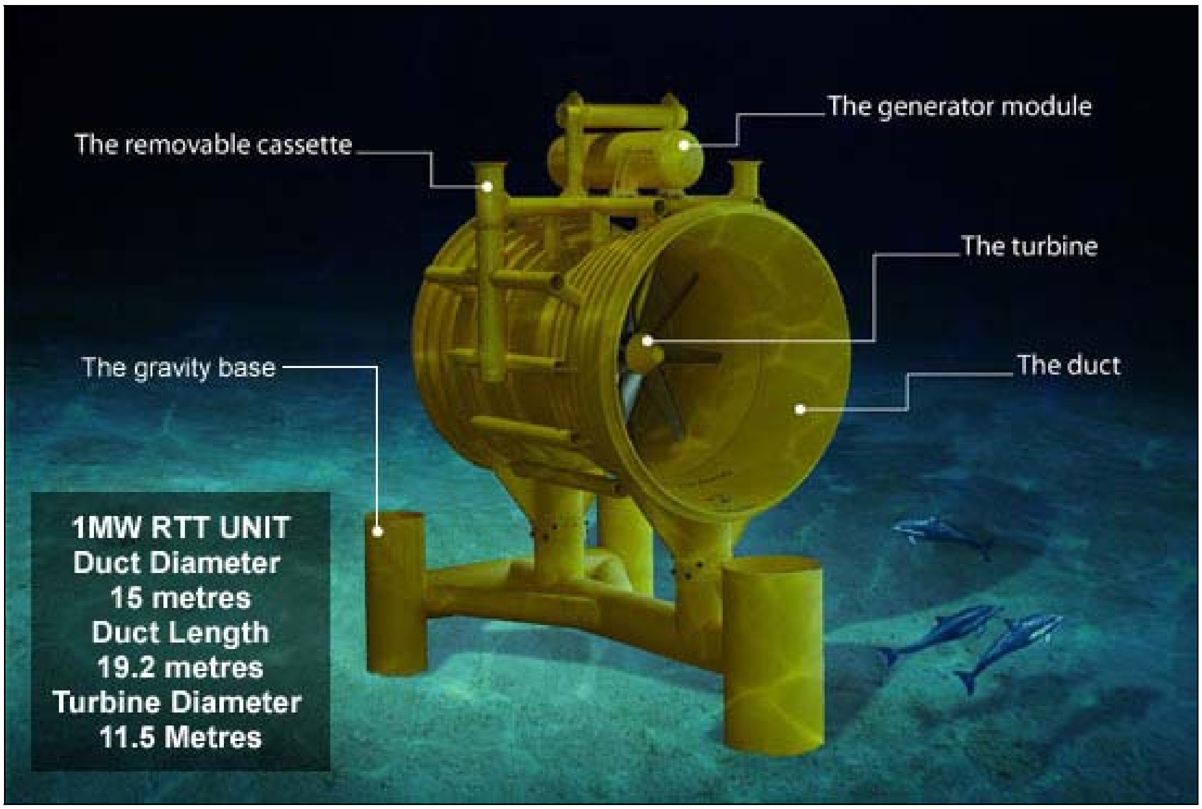

Figure B-14
Rotech Tidal Turbine. (Source: Lunar Energy Ltd. ©)

The RTT is bottom mounted on a gravity base. The estimated size of the RTT 2000 is 105 feet high by 100 feet long, with a weight of 2,500 tons. The water depth must be deep enough to allow clearance for ship passage over the 105 ft high unit. There is no upper limit on working depth, but the economic constraints of working in deep water will limit depths.

<u>Performance</u>

The cut in speed is 1 m/s. The full scale prototype is designed to produce 1MW of electricity and the initial commercial unit, the RTT 2000 is designed to produce 2 MW from a 3 m/s tidal flow.

Development Status

Lunar Energy was founded in 2001 to commercially develop the RTT. In 2007 Lunar Energy partnered with Eon UK, a large energy generation and distribution company, to develop commercial tidal power. Lunar Energy has plans to deploy a 1 MW turbine at the European Marine Energy Center in Orkney in 2008 and has plans for an 8 MW project located in the UK in 2010.

B-15 SMD Hydrovision

Contact Information

Soil Machine Dynamics Ltd,
Wincomblee Road
Newcastle upon Tyne NE6 3QS
United Kingdom

44 191 234 2222

Smdhydrovision.com

Michael Jones

System Description

SMD Hydrovision's (SMDH) TidEl system consists of two horizontal axis counter rotating 500 kW turbines linked by a crossbeam. The mooring chains allow the crossbeam to orient the rotors downstream of the prevailing current. The assembly is buoyant. The rotors are 18.5 m diameter and are separated by the 22 m long crossbeam. Each rotor is connected to a pod 8 m long containing a planetary gearbox and electrical generator. The turbines counter rotate, balancing the torque. The power train is similar to that for a wind turbine except that no yaw or pitch controls are required. System weight is 70 tons.

The TidEl system is installed at mid-depth to minimize weather and boundary layer effects. No support structure other than the anchors and chains are required. The mooring system is similar to that for a submerged taut line buoy in that increasing current flow will cause the system to increase its angle to the vertical. In exposed coastal waters, this system will be subject to wave induced forces and the mooring would be designed accordingly. The reversing orientation of the system may make the routing of the electrical cable from the generator pod to the bottom difficult.

Performance

The cut in speed is 0.7 m/s. At the peak speed of 2.3 m/s almost 1 MW of power is generated.

Development Status

SMD conceived their tidal energy concept in 2001. In 2004 they received a grant to analyze the economics of a 1000 MW tidal energy plant. Tow tank testing of a 1/10 scale model was completed in 2006. An installation of a 1 MW turbine is planned at the European Marine Energy Center in 2009.

Figure B-15
TidEL Turbine (Source: SMD Hydrovision©)

B-16 Swan Turbines Ltd.

Contact Information

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Talbot Building
Singleton Park
Oystermouth Road
Swansea
SA2 8PP
United Kingdom

44 1792 295217

www.swanturbines.co.uk

James Orme

System Description

Swan Turbines has designed a 3 bladed telescoping monopile turbine, similar in appearance to a conventional windmill. The turbines utilize a gearless low speed generator which is claimed to be efficient over a wide range of speeds and require minimal maintenance.

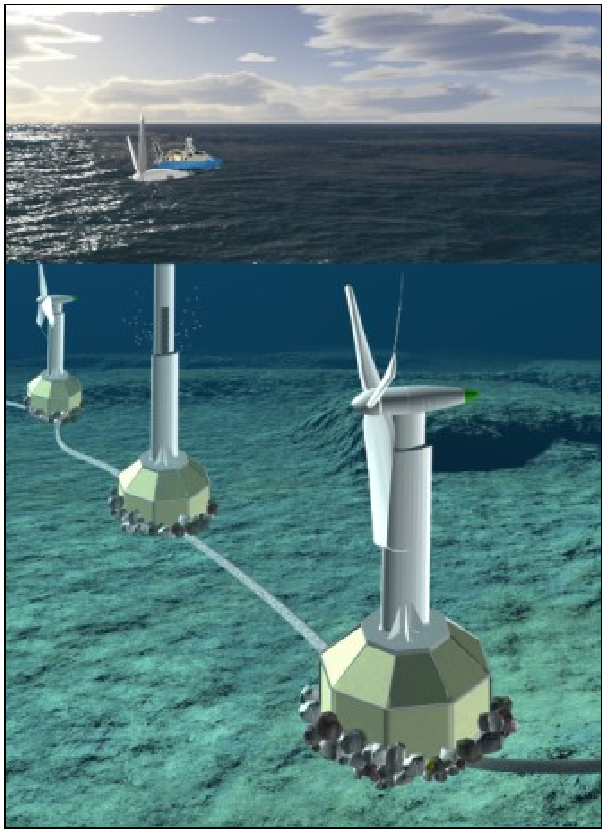


Figure B-16
Swan Turbines (Source: www.swantidal.co.uk©)

The telescoping option allows the unit to be raised to the water surface for maintenance. Installation of these systems in exposed coastal areas would probably limit the surface maintenance to very calm conditions.

Performance

The cut in speed is estimated at 0.5 m/s and the cut out speed at 8 m/s.

Development Status

Swan turbines began investigation into rotor efficiency and biofouling in 2000, and the company has established a research affiliation with the University of Swansea. In 2001 a 1.5 kW prototype was tested. Design of a 350 kW system is underway, and this is intended to demonstrate the technology at a medium scale. Installation of the 350 kW unit is planned for the summer of 2008.

B-17 Tidal Stream

Contact Information

Tidal Stream
76 Dukes Avenue
London W4 2AF
United Kingdom

01926 811292

www.tidalstream.co.uk

Michael Todman

System Description

This design presently consists of either twin or quad 20 m diameter rotors supported on arms off either side of a floating spar attached via swivel to a gravity base. The technology and components utilized were developed and proven in the wind industry. The twin turbine is rated at 1 to 2 MW, depending on current speed. The innovative spar and rotor assembly is designed to be floated into place, where it would then be sunk and attached to the base. The floating feature has led to a UK patent and is termed the Semi Submersible Turbine (SST). The floating spar and rotor assembly is designed to ease maintenance, installation, and removal.

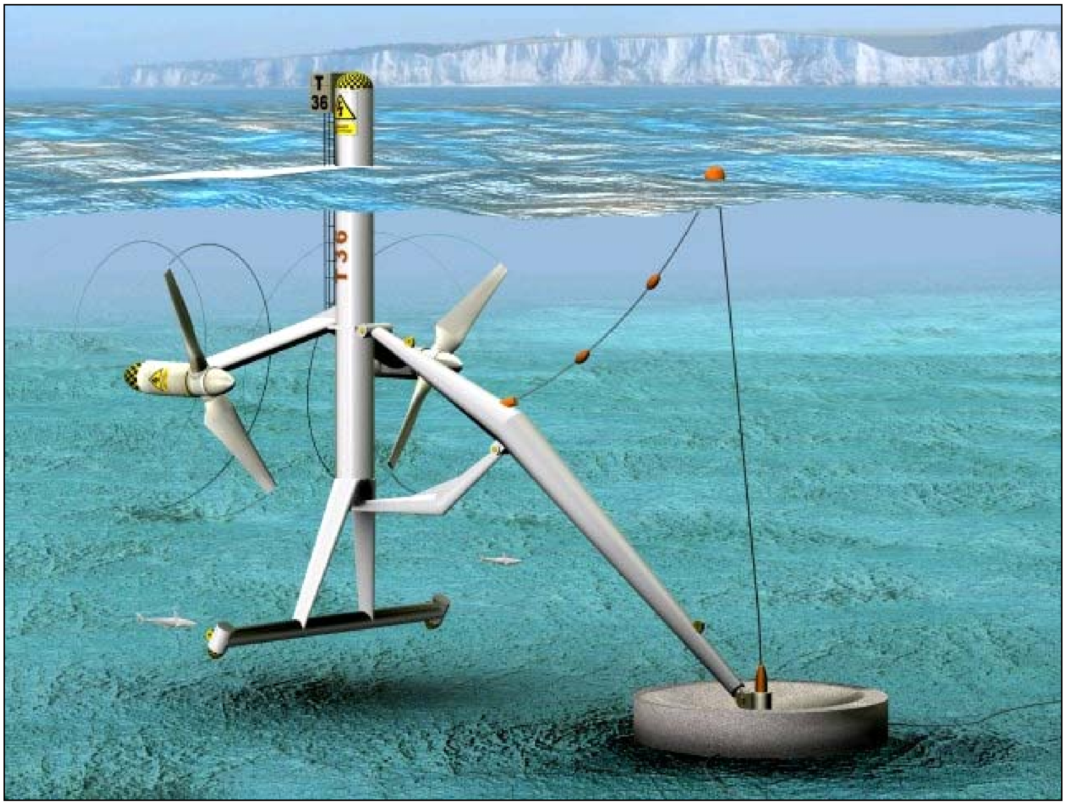


Figure B-17
Tidal Stream Twin Rotor Device (Source: Tidal Stream©)

The two rotor device is designed for depths of 35-60 m and the four rotor system for depths of 55-100 m. This system is designed for deep water applications commonly found in the Northern United Kingdom. It is applicable to locations where rigidly mounting a turbine to the seafloor is impractical due to water depth and where the water surface is too rough for devices that float.

Performance

The cut in speed is 1 m/s while the desired average current speed is 2 m/s

Development Status

Testing commenced on a 1.5 m diameter turbine in the Thames River in 2001. In 2003 a patent was received for the SST concept. Installation of a 2 MW dual rotor device off the coast of Scotland is planned for 2009.

B-18 Scotrenewables

Contact Information

Scotrenewables Ltd
Hillside Office
Stromness
Orkney
KW16 3HS
United Kingdom

44 01856 851641

http://www.scotrenewables.com

Mark Hamilton

System Description

This 1.2 MW design consists of two counter rotating horizontal axis turbines suspended by two streamlined struts hanging below a cylindrical buoyancy module. The turbine and strut are hinged to allow rotation upward for a shallower draft when towing. A four point bottom mooring converges to a single mooring line that connects to the buoyancy module and holds the unit on station. The design of this turbine system placed an emphasis on survivability, the use of off the shelf parts to minimize cost, adaptability, and the ability to deploy and retrieve the unit with moderately sized vessels. This last feature allows the unit to be towed to shore for maintenance.

Figure B-18
Scotrenewables SRTT in transport and operation mode (Source: Scotrenewables©)

Performance

The cut in speed is 1 m/s with rated power at 3 m/s.

Development Status

Scotrenewables, based in the Orkney Islands in Scotland, was formed in 2002 and specializes in renewable energy research and development. System stability analysis was completed in 2003 followed by scale sea trials and tow tank testing in 2005 and 2006. Ocean basin testing at 1/40th scale was performed in 2007. A 1.2 MW full scale prototype is being designed and will be installed and tested at the European Marine energy Centre (EMEC) in 2009.

B-19 Ocean Flow Energy

Contact Information

Ocean Flow Energy
12 Yeoman Street
North Shields
Tyne & Wear
NE29 6NL
United Kingdom

44 0191 296 6339

http://oceanflowenergy.com

System Description

The Ocean Flow Energy design, named Evopod™, incorporates a horizontal axis turbine suspended below two streamlined struts. It operates semi submerged. The support assembly design is similar to a small water plane area twin hull (SWATH) ship hull. The SWATH hull has been designed to minimize the pitch and roll of ocean going vessels. The Evopod utilizes off the shelf components where possible and a proprietary mooring system where the mooring lines run to a single point underwater. This point is then connected to the Evopod. The system is free to swing to maintain an optimum heading into the current flow. This mooring system has been designed to be easier and more economical to install than fixed mooring methods such as pilings. The mooring and device have been designed to operate in exposed deepwater sites exposed to severe winds and waves. A design goal is the ability to install thirty-nine 1.5 MW units in a 1 km^2 area. This design is scalable, and a 500 kW test unit will be followed by a 1.5 MW unit.

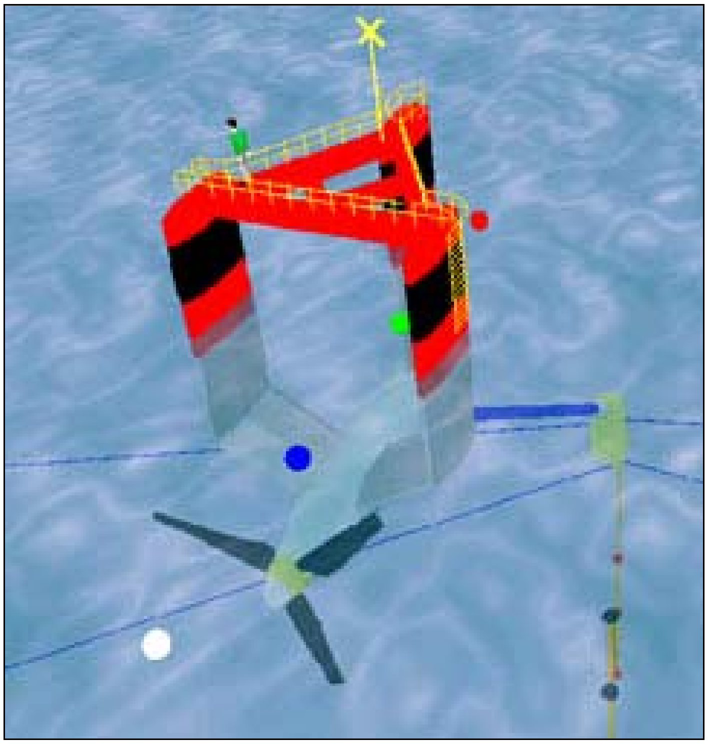
Performance

A 1.5 to 2 m/s current is required for feasible operation.

Development Status

Ocean Flow Energy was founded in 2007 to commercialize the Evopod system. Tests to validate stability and turbine efficiency have been carried out at the University of Newcastle on a 1/40th scale model. Flume testing was conducted in 2007 on a 1/10th scale model at the New and Renewable Energy Center (NaREC) in Northumberland England. A test in a bi-directional current is planned. A 500 kW prototype is under design and installation is planned for 2009.

(a)



(b)

Figure B-19
(a) 1/10th scale Evopod in Tees Barrage (Source: Ocean Flow Energy©); (b) Anchored Evopod (Source: Ocean Flow Energy©)

B-20 Neptune Renewables

Contact Information

Neptune Renewable Energy Ltd
Salisbury House,
29, The Weir,
Hessle, East Yorkshire
HU13 0SB
United Kingdom

44 (0) 1482 640224

www.neptunerenewableenergy.com

System Description

Neptune's Tidal 500 kW Power Pontoon is a vertical axis turbine in a patent pending accelerator duct suspended below an 8 m x 13 m barge. Power is generated by computer controlled shutters which direct currents onto the turbine blades. This design will theoretically produce thirty percent more power than a standard turbine and is intended primarily for shallow estuarine sites with no or minimal wave action. All vital components sit above water on the top of the barge and can be serviced on site. Standard shallow water barge moorings are used.

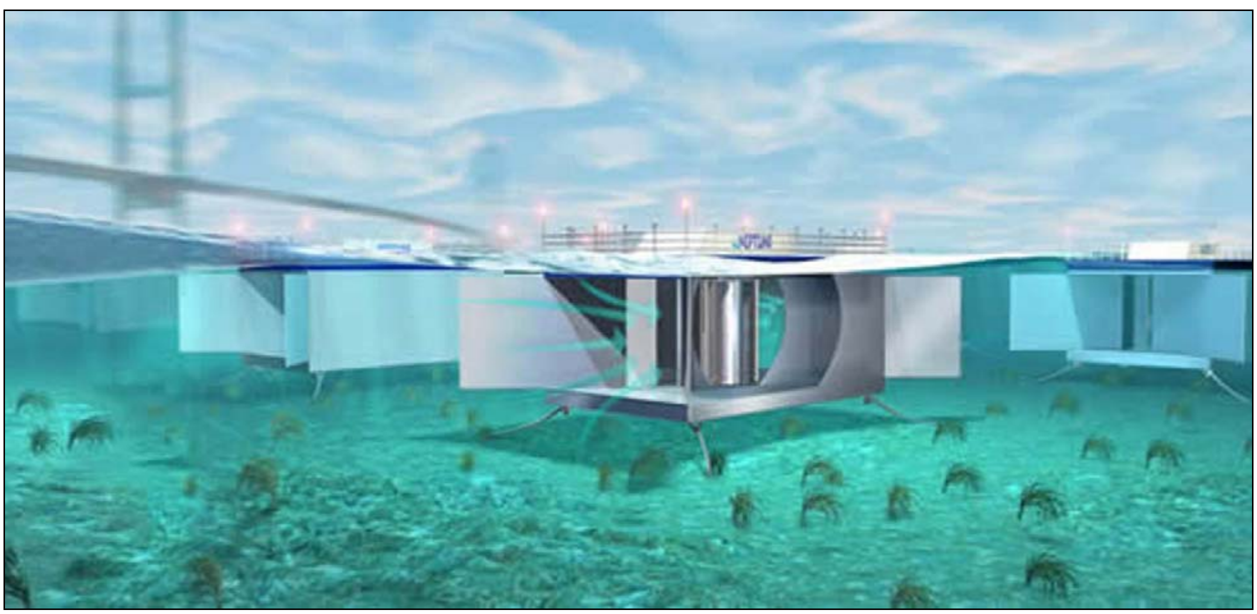


Figure B-20
Tidal Power Pontoon (Source: Neptune Renewable Energy©)

Performance

Current speeds of 2.5 m/s are required for economical operation.

Development Status

Neptune Renewable Energy was formed in 2005 to bring previously developed wave and tidal concepts to market. The company works with the University of Hull's Marine Renewable Research Group. The company conducted scale model test on a 1/100th scale device in 2005. Plans are underway to test a full scale demonstration unit in the Humber River in 2008.

B-21 Pulse Generation

Contact Information

Pulse Generation
Innovation Technology Centre
Advanced Manufacturing Park
Sheffield City Region
S60 5WG
United Kingdom

01142541232

http://www.pulsegeneration.co.uk/index.asp

Marc Paish

System Description

Pulse Power is designing a generator in which the angle of hydrofoils is adjusted to cause them to oscillate vertically. This oscillation drives connecting rods that rotate the generator unit. This system is intended for shallow water protected tidal areas. The hydrofoils can be raised above the water surface for maintenance or lowered for storms. A low maintenance permanent magnet alternator is utilized. A 1 MW commercial model is planned after the completion of tests of a 100 kW unit.

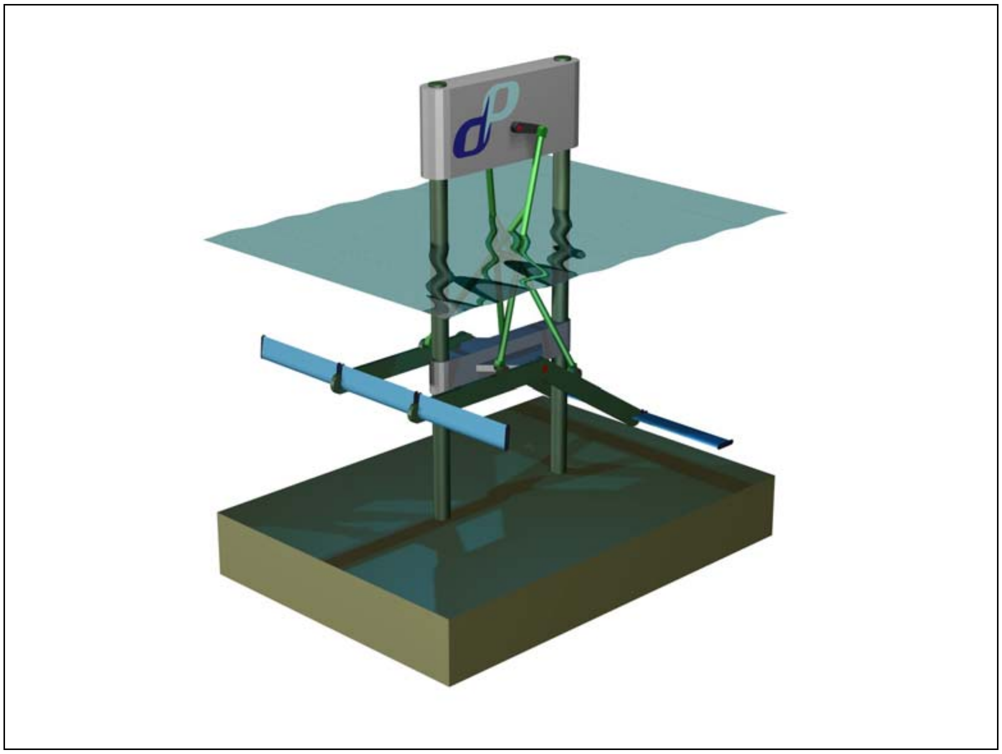


Figure B-21
Pulse Generation Design (Source: Pulse Generation©)

Performance

The cut in speed of this unit is 1 m/s. Rated power is generated at 2.4 m/s.

Development Status

Pulse Generation was formed in 2004. Scale model tank tests were conducted in 2006. Installation of a 100 kW prototype is planned for 2008 in the Humber River in Northern England.

B-22 Statkraft

Contact Information

Statkraft
Postboks 200
Lilleaker, 0216 Oslo
Norway

47 24 06 71 38

www.statkraft.com

Petter Hersleth

System Description

Statkraft is an established company in Norway and operates over 150 hydropower plants in Norway, Finland and Sweden. Figure B.22 is a conceptual drawing of a 1 MW plant. The system is composed of four axial flow turbines 22 m in diameter. Two turbines are connected to either end of a common generator. The entire array is suspended below a 38 m long by 15 m wide floating steel structure. The position of the structure is maintained by a standard deep sea mooring. The only footprint on the bottom is from the anchors and the plant can be easily moved from site to site. The surface unit will subject the unit to the effects of wave action, and this demonstration plant was designed for the 100-year wave event. The floating support structure allows the turbines to be brought to the surface for maintenance.

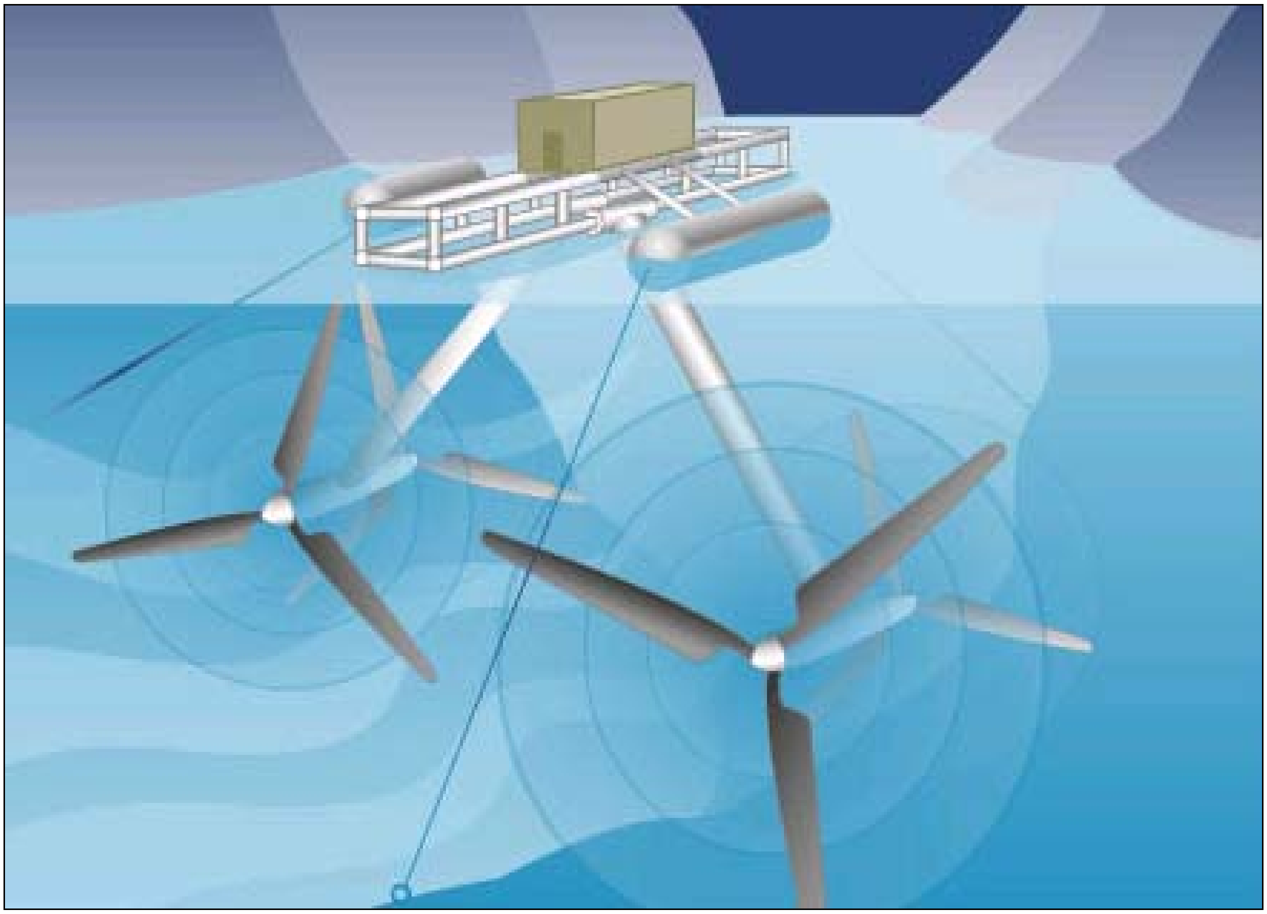


Figure B-22
Conceptual Drawing of Statkraft 1 MW Plant (Source: Statkraft©)

Performance

The cut in speed is estimated at 0.5 m/s. Rated power is 1 MW.

Development Status

In 2004, Statkraft teamed with Hydra Tidal Energy Technology, a branch of Polarkonsult, a Norwegian naval architect and marine engineering firm, to develop a full scale demonstration tidal power plant off Tromso, Norway. This is known as the MORILD project. The project is still underway, but a system has not been deployed and no updated timelines have been released. The stated objectives of the project are to determine the actual efficiency of the turbines, see if the structure could withstand the severe offshore environment, and to optimize the economics for future installations.

B-23 Current to Current

Contact Information

Current to Current
35 Corporate Drive
Burlington, MA 01803
USA

(781) 685-4992

Currenttocurrent.com

Dr. Manfred Kuehnle

System Description

Current to Current is a technology company focused on the generation of electricity from renewable sources. They have designed a Submersible Power Generator (SPG) that will generate electricity from the flow of water. The SPG is a catamaran style unit approximately 150 ft long and 250 ft wide. It contains two counter rotating 5 MW power turbines rotating at 12-15 rpm. The design is modular and final assembly can be accomplished on site or near the site. The unit can be remotely controlled, brought to the surface for maintenance or lowered to avoid storm or hurricane waves. Station keeping will be provided by a proprietary mooring design. It is designed for ocean currents.

Performance

The unit is designed for 2 m/s current velocity.

Development Status

The first unit is scheduled to be installed off the coast of Guatemala for testing in 2008. It will be relocated to a location between Bermuda and the US East Coast in either 2008 or 2009. In 2006, Current to Current signed a twenty year agreement with Bermuda Power and Light, with BPL agreeing to buy up to 20 MW of power.

B-24 Ocean Renewable Power Company, LLC.

Contact Information

Ocean Renewable Power Company, LLC
151 Martine Street, Suite 102-5C
Fall River, MA 02723
USA

(508)672-4970

Oceanrenewablepower.com

Christopher R. Sauer

System Description

Ocean Renewable Power Company (ORPC) has developed a proprietary Turbine Generator Unit (TGU) that is modular and can be stacked horizontally or vertically. Vertical axis turbines, which rotate in one direction regardless of the direction of water flow, sit on either side of the TGU. The turbines are directly coupled to the TGU, eliminating the need for a gearbox and increasing efficiency of the system. The overall system is known as OCGen technology, and was developed with assistance from the U.S. Navy. Design objectives were to keep the system mechanically simple with minimal moving parts. Figure 9 shows a two turbine module rated at 250 kW in a 3 m/s current. Each module is 2 m wide, 3 m high, and 18 m long. The proprietary permanent magnet turbine generator unit (TGU) is located in the center of the module.

Installations can be at any depth in the water column with conventional moorings holding the device on station. The modules can be theoretically be controlled and directed to surface or submerge for maintenance, deployment, or storms.

The initial focus of ORPC is on extracting tidal energy in the 3 m/s range. Longer range planning is focusing on ocean current power extraction in the lower velocity (1.5 m/s) but continuous Gulfstream Current off Florida.

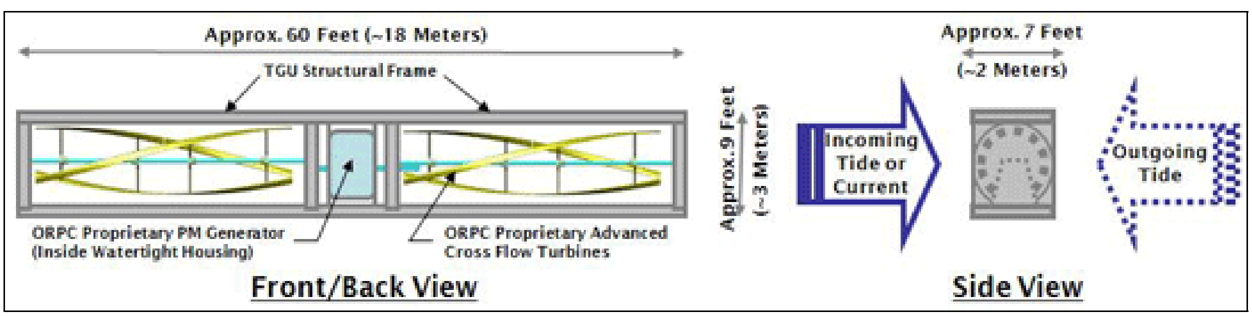


Figure B-23
ORPC Turbine Module. (Source: Ocean Renewable Power Company©)

For commercial applications, four 250 kW modules will be combined either vertically or horizontally to form 1 MW units. Each 1 MW unit will house buoyancy, ballast, and other support equipment. The exact support equipment will be tailored to each site.

Performance

Each module is rated at 250 kW in a 3.1 m/s current.

Development Status

The Ocean Renewable Power Company was founded in 2004. In 2005 they entered into a Cooperative Research and Development Agreement (CRADA) with the Naval Surface Warfare Center – Carderock. Installation of a 32 kW proof of concept test unit is scheduled for late 2007 in Eastport Maine. This system will be suspended 10 m below a 6 m by 5 m barge.

A commercial scale demonstration projects is planned for 2008 in Knik Arm, near Anchorage, Alaska. There are planned demonstration projects in Maine and in the Gulf Stream off Florida in 2009. If successful, full scale prototypes would be deployed approximately two years later.

B-25 Tidal Generation Limited

Contact Information

Tidal Generation Limited
University Gate East
Park Row
Bristol BS1 5UB
United Kingdom

44 (0) 117 915 1275

http://www.tidalgeneration.co.uk/contact.html

Tania Lake

System Description

Tidal Generation Ltd. is developing a 1 MW turbine designed for installation in water depths greater that 30 m. The turbine is a three bladed 18 m diameter horizontal axis turbine with a pivot which allows it to rotate 180 degrees to compensate for varying current directions. The generators are located in the nacelles. The propeller and nacelle can be raised off of the tripod and brought to the surface where it can easily be removed for maintenance or replaced. The tripod support structure was designed to be inexpensive and relatively lightweight to ease installation.

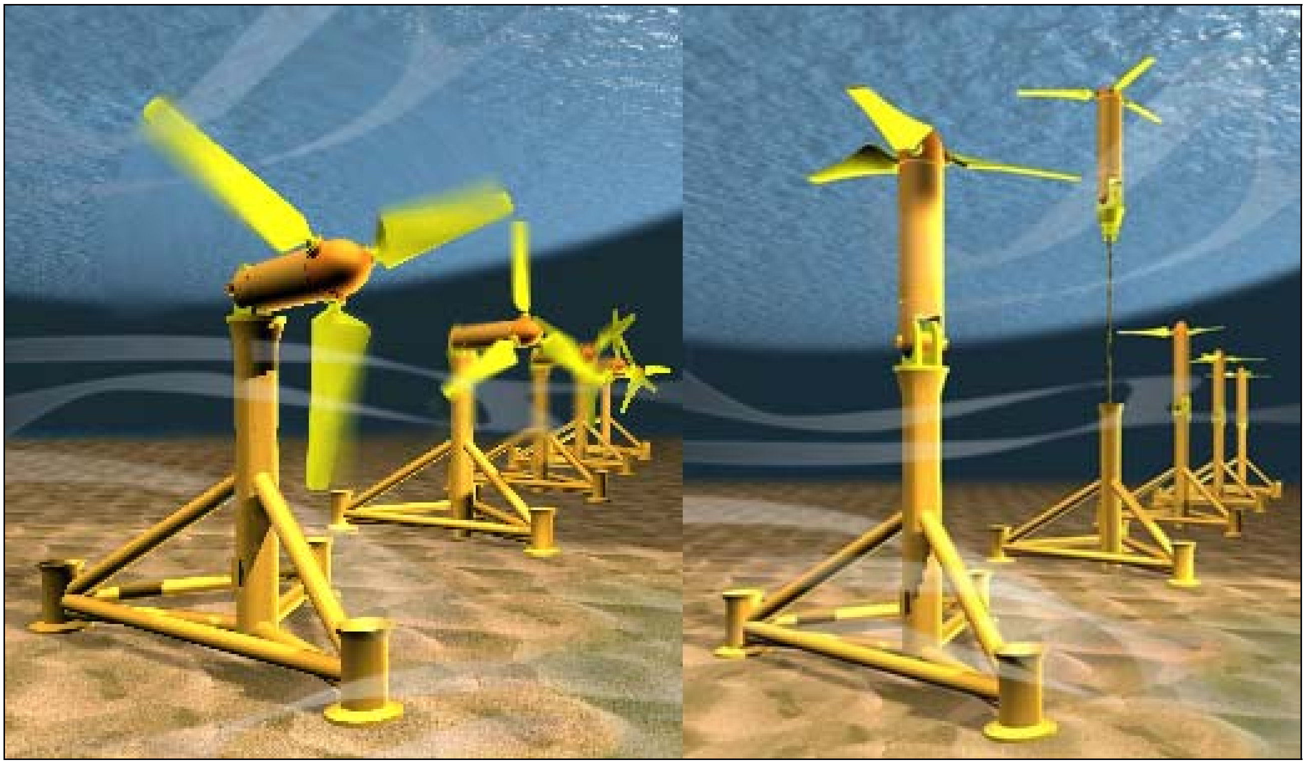


Figure B-24
Tidal Generation Turbine generating power and raised for maintenance (Source: Tidal Generation Ltd©)

Performance

For reversing tidal currents, peak flow speeds of at least 2.5 m/s are required; 3.5 m/s peak speeds are preferred.

Development Status

Concept design of this system is underway. Upon completion of the design, a 500 kW prototype will be built for installation at EMEC in 2008.

B-26 Bourne Energy

Contact Information

Bourne Energy
Box 2761
Malibu, CA 90256

(310) 456-8112

Bourneenergy.com

Chris Catlin

System Description

Bourne Energy is developing two designs intended to harness current energy, the Riverstar and the Tidalstar. The 50 kW Riverstar design is a proprietary horizontal axis turbine on a streamlined nacelle. Each unit is 6 m long. The nacelle is supported by a faired strut hanging from a buoyant surface module. The modules are interconnected and placed across rivers.

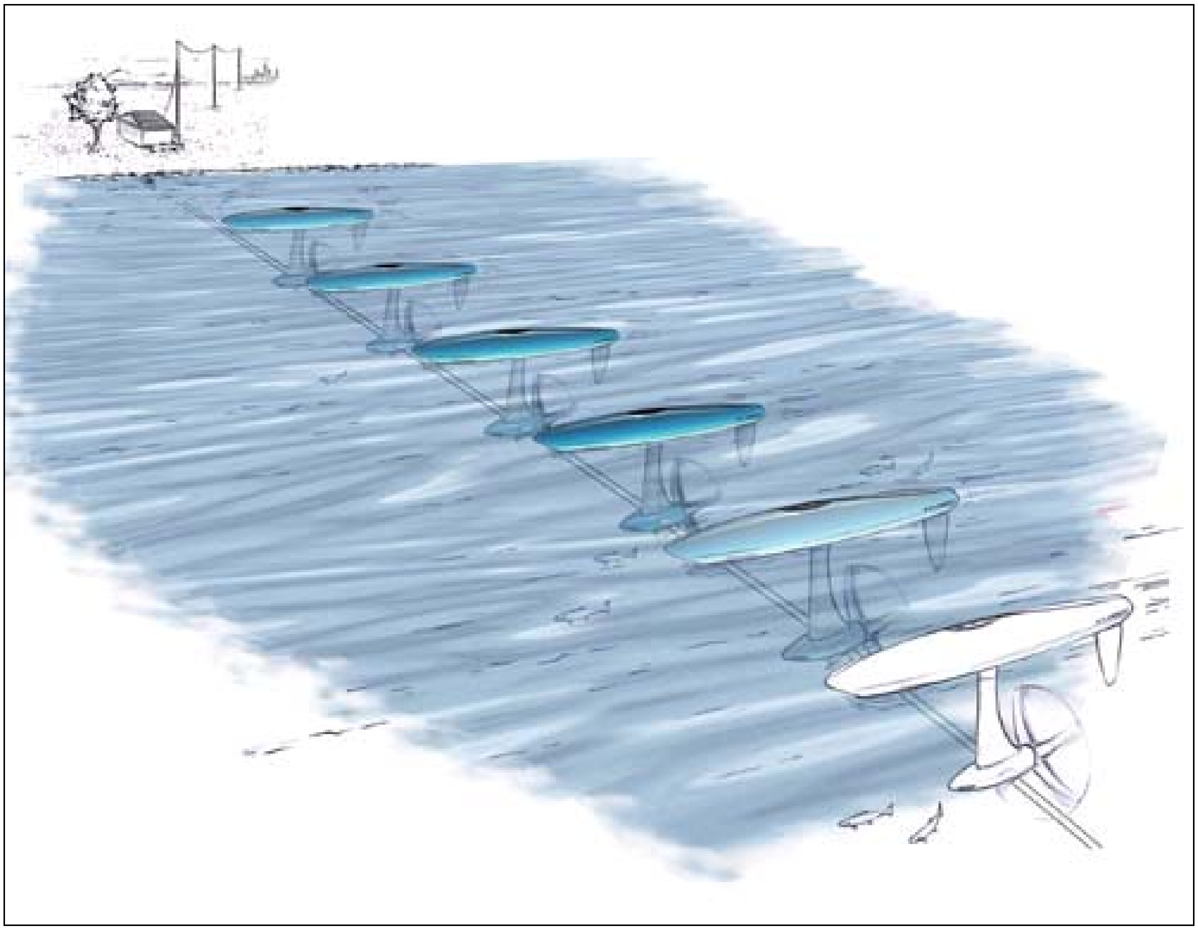


Figure B-25
Riverstar (Source: Bourne Energy©)

The bi-directional Tidalstar, also 50 kW, is similar except that it has propellers at either end of the nacelle. All designs have patents pending. Both designs are modular, designed to be as customizable as possible to a particular tidal site.

Various versions of the Riverstar have been developed to generate electrical power, fresh water, or compressed air for industrial or oxygenation purposes. The buoyant surface module can be modified for dual uses such as a dock or other floating structure. The system can also be tuned to best suit the conditions at a particular location.

Performance

The Tidalstar generates its rated power at 2 m/s. The company is presently working on lower RPM turbine designs.

Development Status

No working prototypes are in place. Bourne Energy hopes to have a number of Riverstar and Tidalstars in place by the end of 2008.

B-27 Natural Currents

Contact Information

E3, Inc. / Natural Currents Energy Services, LLC
24 Roxanne Boulevard
Highland, NY 12528
(845)691-4008

www.e3-inc.com

Roger Bason

System Description

Natural Currents has designed a vertical axis helical turbine. The 3.2m version is designed to generate 20 kW in a 3 m/s current. This design is scalable up to 1.5 MW and a 5 MW unit is being designed.

The 3.2 m version can be barge mounted, tethered to a pylon, or bottom mounted.

Performance

The cut is speed is 1.5 m/s. Rated power is at 3 m/s.

Development Status

Testing is planned for the first 3.2 m version suspended below a barge in 2008. Commercial units will be available in 2008. Natural Currents has permits for site study at seven sites in North America.

B-28 Hydro Green Energy

Contact Information

Hydro Green Energy
5090 Richmond Avenue, #390
Houston, TX 77056

(877)556-6566

www.hgenergy.com

System Description

Hydro Green Energy proposes a system of 250 kW modular, ducted, horizontal axis, low solidity ratio turbines. The modules are suspended below a barge and power is transmitted from the turbines to generators on the barge via hydraulics or mechanical linkage. The barge is moored with conventional moorings. The individual modules may be raised above the water surface for maintenance, avoiding underwater operations. Hydro Green claims this is the only modular, zero head current based system in the industry, and it is patented. These systems are promoted as low impact alternatives to dams for hydropower, for power generation downstream of existing dams, and for tidal applications. Barge mounting the systems decreases the Army Corps of Engineers permitting requirements for dredging and filling.

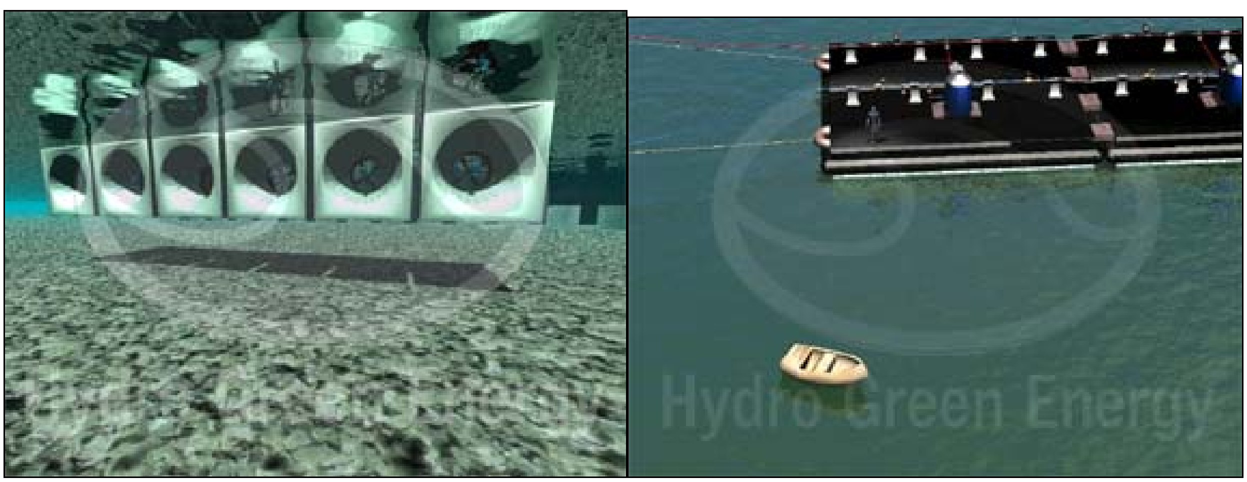


Figure B-26
Hydro Green subsurface modules and support barge (Source: Hydro Green Energy©)

Development Status

Prototypes of the turbines have been constructed and tested. Assistance in the modeling and optimization of the turbines has been received from the Space Alliance Technology Outreach Program (SATOP) in Computational Fluid Dynamics (CFD). Hydro Green has received preliminary permits for a number of sites in Alaska, Louisiana, Mississippi, Minnesota, and Maine.

B-29 BioPower Systems Pty Ltd.

Contact Information

BioPower Systems Pty. Ltd.
Suite 145 National Innovation Centre
Australian Technology Park
Eveleigh NSW 1430
Australia

61 2 9209 4237
61 2 9319 3874

http://www.biopowersystems.com/index.html

Dr. Tim Finnigan

System Description

BioPower Systems is developing a current energy device named the bioSTREAM. The device appears similar to a fish tail and oscillates in a current stream. The oscillation is converted into hydraulic energy which is utilized to power a electric generator. One-sixteenth scale models have been tested in laboratory conditions. The 250 kW unit mentioned below is 20 meters long and 17 meters tall. The units are intended for installation in water depths of 22 meters or more.

Advantages of this design include no above surface visual impact, a simple two part installation, continuous orientation to any flow direction, a large swept area, and the streamlined design, which will aid survivability in storm and hurricane conditions.

The bioBASE is another key feature of the bioSTREAM. It utilizes numerous small rockbolts holding a large socket base which is the mount for the bioSTREAM. The small rockbolts are more easily drilled than one large hole for the socket.

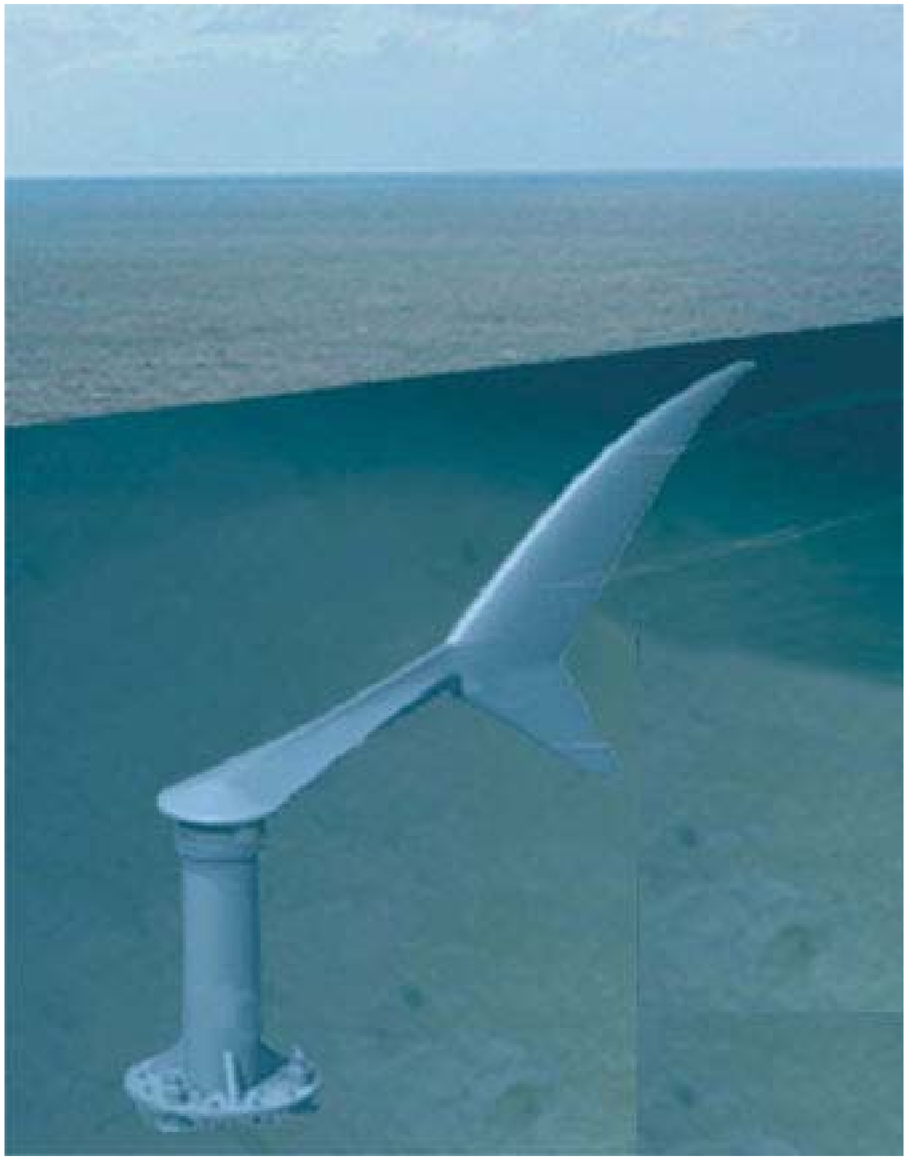


Figure B-27
The bioSTREAM device (Source: BioPower Systems Ltd©)

Performance

The cut in speed is estimated at 0.5 m/s. Design flow speed has not yet been determined

Development Status

A 250 kW unit is scheduled to be installed in mid 2009.

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