WAVE ENERGY CONVERSION AND OCEAN THERMAL ENERGY CONVERSION POTENTIAL IN DEVELOPING MEMBER COUNTRIES

ASIAN DEVELOPMENT BANK

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CONTENTS

List of Tables and Figures iv
Abbreviations v
Weights and Measures v
Foreword vi
Preface vii
Executive Summary viii
1 Wave Energy Resources 1
  Introduction 1
  Technical Background 4
  Hawaii Offshore Theoretical Wave Resources 4
  Hawaii Shallow-Water Theoretical Wave Resources 6
  Wave Energy Conversion Device Performance Evaluation 8
  Siting and Ocean Area Requirements 10
  Licensing and Permitting 11
  Challenges and Barriers 11
  Conclusions and Recommendations 12

2 Ocean Thermal Resources 14
  Introduction 14
  Worldwide Market 15
  Technology 17
  History 17
  Site Selection 19
  Limitations and Challenges 23
  Economics 24
  Capital Costs 25
  Capital Cost: 50-Megawatt Ocean Thermal Energy Conversion Plantship 26
  Operational Costs and Cost of Production 27
  Economics of a 50-Megawatt Plant 27
  Environmental Impact 30
  Regulations 31
  Incentives 31
  Conclusions and Recommendations 31

Appendixes

1 State-of-the-Art Ocean Thermal Energy Conversion 33
2 Levelized Cost of Electricity 56
3 Wave Power Analysis for Representative Hawaiian Island Sites 58
4 Wave Energy Conversion Device Performance Evaluation 97
5 Survey of Ocean Thermal Energy Conversion Companies 105
6 Survey of Wave Energy Conversion Companies 113
7 Tidal Energy Conversion 120

Bibliography 124

TABLES AND FIGURES

Tables

1 Annual Averages of Offshore Wave Power Flux 2

2 Locations of Nearshore Hawaii Sites Selected for Simulating Waves Nearshore Model Analysis 6

3 Hawaii Monthly Average Wave Power Flux 7

4 Hawaii Annual Average Wave Power Flux 7

5 Site- and Device-Specific Electricity Generation with Wave Energy Conversion Devices under Development 8

6 Estimates of the Levelized Cost of Electricity with Wave Energy Conversion Devices and Arrays 10

7 Baseline Wave Energy Conversion Potential in Developing Member Countries: Conclusions and Recommendations 13

8 Areas with Appropriate Ocean Thermal Resources within Their 200-Nautical Mile Exclusive Economic Zones 15

9 Annual Electricity Generation with 100-Megawatt Ocean Thermal Energy Conversion Plant 21

10 Electricity and Desalinated Water Production Rates for Ocean Thermal Energy Conversion 27

11 Baseline 50-Megawatt Closed-Cycle Ocean Thermal Energy Conversion for Levelized Cost of Electricity under a Commercial Loan 28

12 Baseline 50-Megawatt Open-Cycle Ocean Thermal Energy Conversion, Break-Even Electricity, and Water Rates Required under a Commercial Loan 29

13 Baseline Ocean Thermal Energy Conversion Potential in Developing Member Countries: Conclusions and Recommendations 32

Figures

1 Global Distribution of Annual Wave Power Flux from Wave Watch III Wind-Wave Model 3

2 Global Distribution of Annual Wave Power Flux from Fugro OCEANOR WorldWaves Model 3

3 Wave Energy Conversion 4

4 Hawaii Wave Power Climate Patterns 5

5 Monthly Average of Wave Power Flux for Six Sites in Hawaii 7

6 Daily Wave Power Flux at the Kaneohe and Kilauea Sites, 2009 9

7 Ocean Thermal Energy Conversion Summary 14

8 210-Kilowatt Open-Cycle Ocean Thermal Energy Conversion Experimental Apparatus 18

9 Worldwide Average Ocean Temperature Differences between 20- and 1,000-Meter Depths 20

10 Vertical Temperature Profile from World Ocean Atlas Compared to Measurements by the Philippine Navy 20

11 100-Megawatt Ocean Thermal Energy Conversion Plant Annual Output 21

12 Capital Cost Estimated for First-Generation Closed-Cycle Ocean Thermal Energy Conversion Plants 25

13 Levelized Cost of Electricity Production for First-Generation Closed-Cycled Ocean Thermal Energy Conversion Plants as a Function of Plant Size with Loan Terms as Parameters 26

ABBREVIATIONS

ADB – Asian Development Bank
BOEM – Bureau of Ocean Energy Management
CC-OTEC – closed-cycle ocean thermal energy conversion
DMC – developing member country
EEZ – exclusive economic zone
FERC – Federal Energy Regulatory Commission
NOAA – National Oceanic and Atmospheric Administration
OC-OTEC – open-cycle ocean thermal energy conversion
OTEC – ocean thermal energy conversion
OWC – oscillating water column
TRL – technology readiness level
WEC – wave energy conversion

WEIGHTS AND MEASURES

GWh – gigawatt-hour
km – kilometer
km^2 – square kilometer
kW – kilowatt
kWh – kilowatt-hour
m – meter
MW – megawatt

FOREWORD

We must develop clean domestically sourced forms of energy if we are to ensure the energy security of developing countries in Asia and the Pacific and lower the region's greenhouse gas emissions.

Our region's oceans have great energy potential, but this has yet to be tapped. This can change through the development of technologies focusing on ocean waves, tidal movements, and heat differentials. Decades of inconsistent funding, regulatory and licensing barriers, and higher costs have prevented ocean power from matching the contribution of other renewable technologies. If marine-based power generation is to become a viable alternative energy source, it will take sustained research and investment to commercialize the technology. With Asia and the Pacific's energy demand set to reach new highs in the coming decades, we cannot ignore development of this low-carbon source of power.

Many of us working in the clean energy sector are well acquainted with challenges related to policy coverage and finance availability. This study aims to articulate these challenges and their potential solutions for the popular ocean power technologies of wave energy conversion and ocean thermal energy conversion. The study also looks at the application of these technologies in the developing countries of Asia, and recommends areas where near-term research and development could help bridge the knowledge gap.

The Asian Development Bank hopes that this report will highlight the potential for ocean power in developing Asia and the Pacific, and impress upon key stakeholders the possibility and benefits of deploying this technology in support of our region's low-carbon future.

Bindu Lohani
Vice-President, Knowledge Management and Sustainable Development
Asian Development Bank

PREFACE

This report was prepared by Luis A. Vega, Consultant to the Asian Development Bank (ADB) and Program Manager of the Hawai'i National Marine Renewable Energy Center (HINMREC), part of the Hawaii Natural Energy Institute at the University of Hawai'i. The study was designed and supervised by Pradeep Tharakan, Senior Climate Change Specialist, Energy Division, Southeast Asia Department, ADB. Coordination and editorial support was provided by Charity L. Torregosa (Senior Energy Officer, Regional and Sustainable Development Department, ADB) and Maura Lillis (Consultant, ADB). ADB's Energy Community of Practice offered valuable support and guidance throughout the writing of this study. This report is an outcome of the Energy Community of Practice's work program for 2013.

This report reviews the history and status of two emerging clean energy technologies—wave energy conversion and ocean thermal energy conversion—for providing ocean-generated power in developing member countries of ADB. The study builds on past research in the sector of marine-generated power to outline the major technological and economic challenges constraining the future development of these resources, and recommends near-term research and development needs.

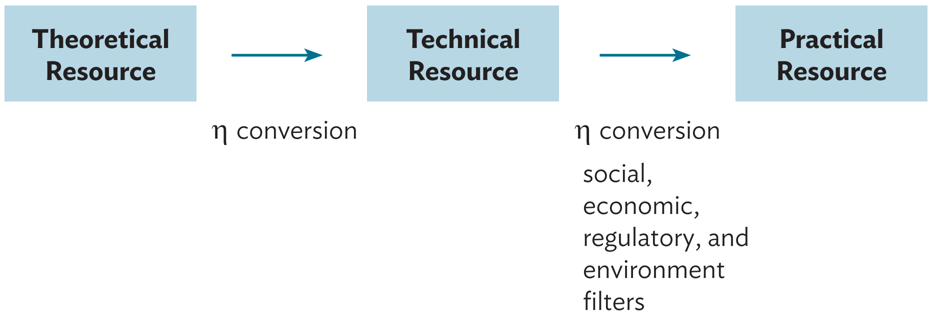
Realizing the benefits of these emerging technologies will require sustained research and investment over time, but could bring about radical changes in power generation among ADB's developing member countries that have long coastlines. We are therefore pleased to offer this report to facilitate the understanding and promotion of marine-based renewable energy technologies in Asia.

EXECUTIVE SUMMARY

This report summarizes the wave energy and ocean thermal resource information available in the public domain and assesses the viability of using these resources to produce electricity in developing member countries (DMCs) of the Asian Development Bank (ADB). In addition, the report identifies supplementary resource information that is required for system design and evaluates the development status of the equipment required. Ocean thermal resources can support the generation of base-load electricity, while wave energy resources are intermittent.

This report discusses the degrees of readiness and potential of marine-based renewable energy generation for use in DMCs: wave energy conversion (WEC) and ocean thermal energy conversion (OTEC). To understand the process used to assess these resources, three terms are used:[1] theoretical resource, technical resource, and practical resource. When discussing wave energy, the theoretical resource is usually represented by the power flux contained in waves. This is the power per length of wave crest, representing all of the hydrodynamic energy crossing a vertical plane of unit width per unit time. When discussing ocean thermal energy, the theoretical resource is the temperature difference between surface water and water from a depth of around 1,000 meters (m).

The technical resource is the portion of the theoretical resource that can be captured using a specific technology. The parameter η refers to the conversion efficiency. The practical resource is that portion of the technical resource that is available after considering all other constraints (e.g., social, economic, regulatory, and environmental).



For wave energy resources, this report presents the theoretical resource and discusses the technical resource by assessing the energy conversion potential of devices currently in their preliminary stages of development. For ocean thermal resources, this report presents the technical resource that can be captured with OTEC equipment. However, analyzing the practical resource is country- and site-specific, and is therefore beyond the scope of this report.

In general, when considering the development status of a particular technology, reference is made to technology readiness levels (TRLs), with a value of one (TRL-1) referring to technology at the conceptual stage based solely on desktop studies, with higher numbers indicating systems that are already commercially available from different suppliers. Technologies with documented records of field operations are considered to have reached TRL-9.

Evidence available in the public domain indicates that OTEC systems using ocean thermal resources have achieved the TRL-7 level, while WEC devices are in the early stages, i.e., TRL-3 to TRL-5. WEC devices are now at the level of wind turbine generators (WTGs) 30 years ago when numerous designs were still being evaluated. This eventually led to the current situation of WTGs wherein one design (e.g., vertical axis, three-bladed) comprises the majority of all WTG installations throughout the world. A developer of wind farms for sites with the required wind resource can now, for example, choose equipment from several vendors with documented operation and maintenance records, so the cost of electricity production can be estimated accurately.

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[1] US Department of Energy. http://energy.gov/eere/renewables/water.

Given the current stage of development of WEC devices, it is premature to discuss capital cost and cost of electricity estimates. Based on this report, however, it can be concluded that because their potential capacity factor falls in the range of photovoltaic and WTG installations, to achieve cost-competitiveness, the capital cost target of WEC devices must not exceed that of those installations. This should not be construed as a negative conclusion about their potential use. On the contrary, wave energy resources are ample in numerous locations throughout the world, but the equipment required to generate electricity still requires 1–2 decades of diligent development to achieve full commercialization.

For OTEC, the state of development is such that cost estimates can be provided, indicating that under certain scenarios, cost-competitive base-load electricity could be produced in DMCs.

To evaluate the potential for using WEC devices in DMCs, experience acquired measuring and evaluating the theoretical wave energy resources off Hawaii was used to identify DMCs that may merit further consideration. Deep-water offshore wave resource data were extracted from the two primary references available in the public domain. These provide theoretical annual averages of offshore wave power flux from numerical wind-wave models. This parameter represents the hydrodynamic (i.e., theoretical resource) power that must be converted into useful energy by one of the WEC devices currently under development.

Hawaii was included as a reference site because of the extensive work that has already been conducted there—modeling and correlating the offshore resource with the nearshore resource. The aim was to identify DMCs to be considered for future work that would encompass nearshore numerical modeling and subsequently in-situ wave measurements in water depths of about 50 m and no more than 1–3 kilometers from the shoreline and electricity distribution lines. At first, based on the Hawaii experience, DMCs with theoretical offshore resources of at least 20 kilowatts per meter (kW/m) were identified; however, only the Cook Islands and Indonesia qualified for evaluation. Given the relative coarseness (0.5° latitude and longitude grid) of the resource distribution available from the worldwide models, it was thus decided to include all DMCs with annual averages above 10 kW/m. That threshold extended the list to basically all Pacific island DMCs, India, Indonesia, the Maldives, the Philippines, and Sri Lanka.

For OTEC systems, the technology has been validated with experimental plants, so for a given theoretical thermal resource, as represented by the temperature difference between surface waters (i.e., warm resource) and water from a 1,000 m depth (i.e., cold resource), the technical resource can be expressed, with appropriate accuracy, as the electrical energy generated at the plant. For the purpose of identifying DMCs with an appropriate thermal resource, the annual electricity production with a 100-megawatt (MW) OTEC plant located within a 200-nautical-mile exclusive economic zone was estimated.

To illustrate the OTEC technology readiness level, the output from a 100 MW plant was considered. A plant of this size would not be appropriate for some of the smaller Pacific island DMCs; however, the output from a smaller plant would be proportional, so a 10 MW plant would generate 1/10 of the value. Therefore, it appears that OTEC technology is applicable for the majority of DMCs that are not landlocked.

The following table summarizes the major conclusions reached based on the work presented in this report as well as recommendations for work required beyond this report.

Summary Table: Wave Energy Conversion and Ocean Thermal Energy Conversion Potential in Developing Member Countries

	Theoretical Resource Availability	Equipment Siting Requirements	Additional Resource Information Needed	Equipment to Convert Resource into Electricity	Cradle-to-Grave Environmental Impact	Development Incentives	Overall Assessment	Overall Recommendation
WEC	Yes, in several DMCs but based on deep-water offshore data	Water depths less than 80 m Coastal area: About 0.7 km^2 for 10 MW array (comparable to offshore wind farm requirements)	Commission nearshore theoretical resource study using existing wind and wave numerical models. Requires bathymetry information. Identify any wave measurements available from DMCs to calibrate models.	Under early stages of development; not currently available	Not different from well-established technologies and ocean installations except for submarine power cables	Implement feed-in tariff for WEC installations. At current technology readiness level, it is premature to estimate cost of electricity, but target should be comparable to photovoltaic and offshore wind.	WEC devices will not be commercially available for installation at DMCs for 1–2 decades. Premature to estimate cost of electricity	Obtain nearshore wave resource model for DMCs identified. Monitor progress in the development of WEC devices.
OTEC	Yes, widely available	Water depths greater than 1,000 m 100 MW plant housed in moored ship-shaped vessel the size of a standard super-tanker Submarine power cable connected to land	Identify sites close to electricity distribution lines. Identify any ocean temperature data available from DMCs (vertical distribution to 1,000 m).	Available off-the-shelf but capital-intensive	Not different from well-established technologies and ocean installations except for submarine power cables and seawater return to ocean below the photic layer	Implement multiple-year feed-in tariff for OTEC installations (base-load resource). Loan guarantees Target tariff should be greater than \$0.25/kWh for a greater than 50 MW plant and \$0.50/kWh for a 10 MW plant	Need to implement pilot plant to obtain operational record required to secure financing. Appropriately sized OTEC plants could be available for DMCs in about 5–10 years.	Perform the tasks listed under “Additional Resource Information Needed.” Monitor progress of pilot projects and implementation of small plants on small islands.

DMC = developing member country, km = kilometer, kWh = kilowatt-hour, m = meter, MW = megawatt, OTEC = ocean thermal energy conversion, WEC = wave energy conversion.
Source: Author.

1 WAVE ENERGY RESOURCES

Introduction

Generating energy from the natural movement of ocean waves through wave energy conversion (WEC) devices is a promising technology in the early stages of development. Intended for energy planners and project developers, this chapter of the report focuses on the potential of using WEC devices in developing member countries (DMCs) of the Asian Development Bank (ADB).

Currently, only one WEC device in the world has been transmitting electricity to distribution lines for more than 1 year: a 500-kilowatt (kW), shore-based, oscillating water column (OWC), land-installed marine-powered energy transformer in Islay, Scotland, operational since 2000. In addition, some prototypes are being tested at the European Marine Energy Centre and in Australia. Other than these early trials, however, the technology remains largely experimental in nature.

Numerous WEC concepts are discussed in the literature, ranging from simple sketches to reports of at-sea tests. Some are shoreline-based, while others are seabed-mounted or moored in depths of less than 80 meters (m). According to their directional characteristics, they can be classified as point absorbers, terminators, and attenuators. Point absorbers have dimensions that are small relative to ocean wave lengths and are usually axis-symmetric.[1] The principal axis of terminators is aligned perpendicularly to the direction of wave propagation; for attenuators,[2] it is parallel to the direction of propagation. These have dimensions in the order of the wave lengths.

Given that the majority of DMCs that may have the appropriate resources for WEC are Pacific island DMCs, WEC devices currently being considered for Hawaii are assumed to be representative of future options for these DMCs. These can be categorized under two operating principles: wave-activated point absorbers and OWC. OWC devices use wave action to expand and compress air above a water column to rotate an air turbine generator (e.g., Oceanlinx). The wave-activated devices oscillate due to wave action relative to a fixed part of the device, and use one of three generation systems: (i) a hydraulic system to turn a motor generator; (ii) a linear generator, which generates electricity by moving a magnetic assembly within a coil; or (iii) direct rack and pinion mechanical coupling.

Table 1 lists the DMCs that are not land-locked, plus relevant offshore resource data extracted from the appropriate references. It must be noted that this table contains annual averages of offshore wave power flux based on 10-year wind data inputted into their respective numerical wave models. However, the levels will vary significantly over the year and will be different nearer to the coast. Hawaii is included as a reference site because of existing extensive work modeling and measuring the nearshore resource (Appendix 3).

First, based on the Hawaii experience, DMCs with theoretical, annual average offshore resources of more than 20 kW/m were identified for nearshore numerical modeling and in-situ wave measurements in water depths of 50–80 m, no more than 3 kilometers (km) from shorelines and electricity distribution lines. However, under these standards, only the Cook Islands and Indonesia qualified for further evaluation. Thus, given the relative coarseness of the resource distribution available from the worldwide models (Figures 1 and 2), all DMCs with averages above 10 kW/m were included. That threshold extended the list to all Pacific island DMCs, India, Indonesia, the Maldives, the Philippines, and Sri Lanka.

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[1] The 40 kW Ocean Power Technologies (OPT) heaving buoy was tested over 9 years in Kaneohe Bay, Oahu, Hawaii.

[2] The third-generation Pelamis (about 500 kW) is under testing at the European Marine Energy Centre.

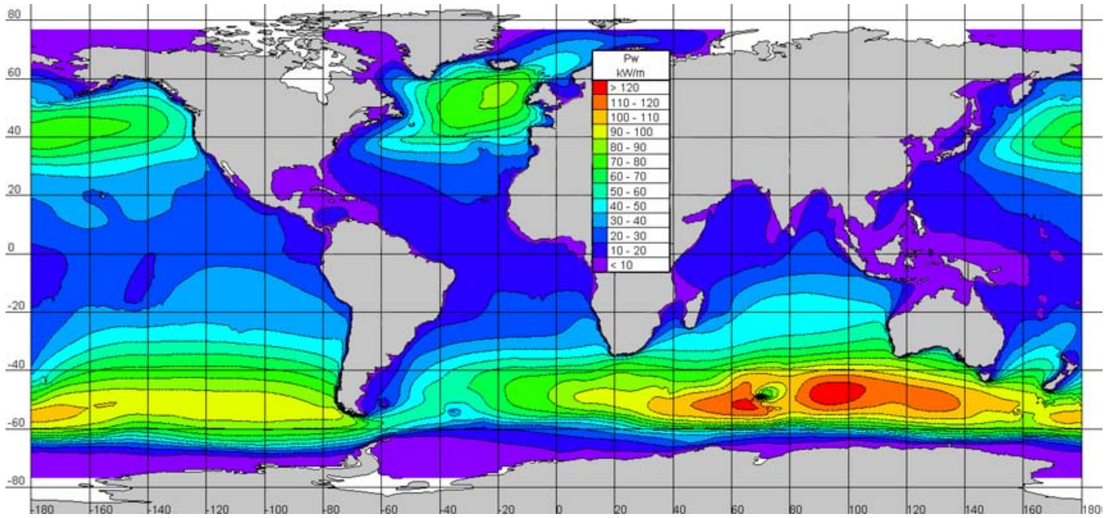
Table 1 Annual Averages of Offshore Wave Power Flux

(kilowatt per meter)

Region and Country	Cornett (2008)	Mork et al. (2010)	Wave Resource Greater than 10
Central and West Asia			
Pakistan	less than 10	5–10	No
East Asia			
People's Republic of China	less than 10	5–10	No
Pacific			
Reference Site (Hawaii Global)	North: 30–40 South: 20–30	North: 30–40 South: 20–30	Yes
Cook Islands, Rarotonga (~160°W, 22°S)	30–40	~20–30	Yes
Fiji (~178°E, 17°S)	10–20	less than 20	Yes
Kiribati, Tarawa (~175°E, 2°N)	less than 10	5–10	No
Marshall Islands, Majuro (~170°E, 5°N)	10–20	10–15	Yes
Federated States of Micronesia (Global)	10–20	10–15	Yes
Nauru (~165°E, 0°)	10–20	10–15	Yes
Palau (~135°E, 5°N)	less than 10	10–15	No
Papua New Guinea (Global)	less than 10	5–10	No
Samoa (~172°W, 12°S)	10–20	10–15	Yes
Solomon Islands (~160°E, 10°S)	less than 10	10–15	No
Timor-Leste (Global)	less than 10	5–10	No
Tonga (~175°W, 22°S)	10–20	15–20	Yes
Tuvalu (~180°, 5–10°S)	10–20	15–20	Yes
Vanuatu (~165°E, 15°S)	10–20	10–15	Yes
South Asia			
Bangladesh	less than 10	10–15	No
India	South coast off Nadu: 10–20 Elsewhere: less than 10	Arabian Sea: 15–20 West and south coasts: 10–15	Yes
Maldives	10–20	10–15	Yes
Sri Lanka	South coast off Matara: 10–20 Elsewhere: less than 10	15–20	Yes
Southeast Asia			
Brunei Darussalam	less than 10	less than 5	No
Cambodia	less than 10	5–10	No
Indonesia	South Java: 20–30 Elsewhere: less than 10	South Java: 20–30	Yes
Malaysia	less than 10	less than 5	No
Myanmar	less than 10	5–10	No
Philippines	North (Luzon and Babyan islands): 10–20 Elsewhere: less than 10	North: 15–20 Elsewhere: less than 5	Yes
Thailand	less than 10	less than 5	No
Viet Nam	less than 10	less than 5	No

Sources: A. M. Cornett. 2008. *A Global Wave Energy Resource Assessment.* Proceedings of the 18th International Offshore and Polar Engineering Conference. Vancouver. 6–11 July; and G. Mork, S. Barstow, A. Kabuth, and T. Pontes. 2010. Assessing the Global Wave Energy Potential. Paper presented at the 29th International Conference on Ocean, Offshore Mechanics and Arctic Engineering. Shanghai. 6–11 June.

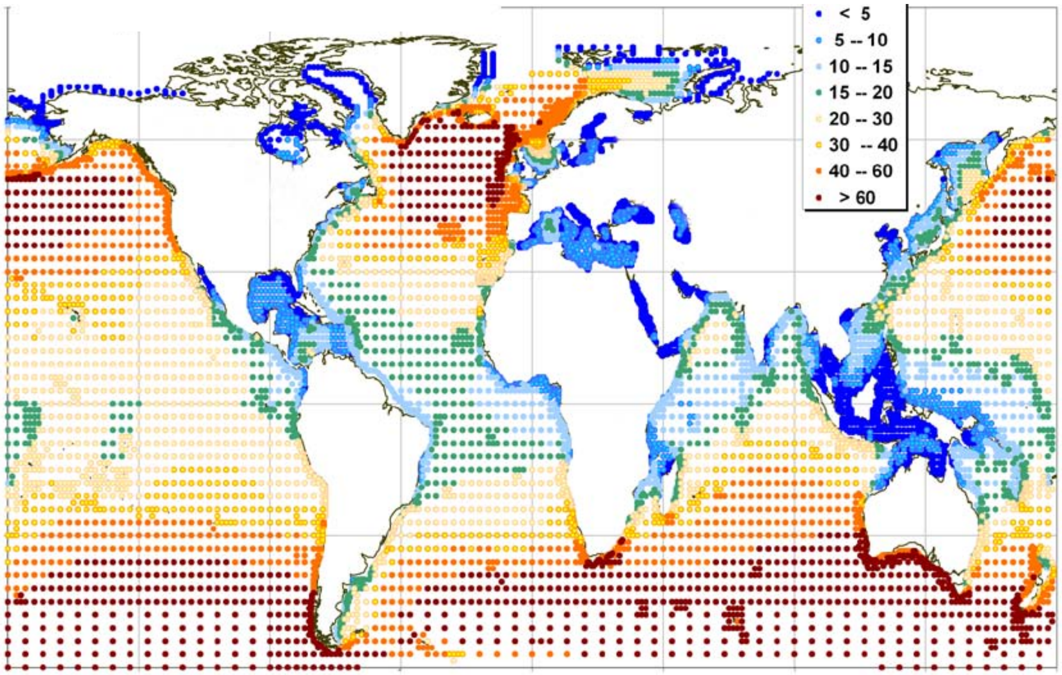
Figure 1 Global Distribution of Annual Wave Power Flux from Wave Watch III Wind-Wave Model (kilowatt per meter)



kW = kilowatt, m = meter, Pw = power flux.

Note: From 1997–2006 wind records, with a 0.5° latitude and longitude grid. Model calibrated with satellite altimeter data and buoy data from A. M. Cornett. 2008. A Global Wave Energy Resource Assessment. Proceedings of the 18th International Offshore and Polar Engineering Conference. Vancouver. 6–11 July.

Figure 2 Global Distribution of Annual Wave Power Flux from Fugro OCEANOR WorldWaves Model (kilowatt per meter)



Note: From 1997–2006 wind records, with a 0.5° latitude and longitude grid. Model calibrated with satellite altimeter data and buoy data from G. Mork, S. Barstow, A. Kabuth, and T. Pontes. 2010. Assessing the Global Wave Energy Potential. Paper presented at the 29th International Conference on Ocean, Offshore Mechanics and Arctic Engineering. Shanghai. 6–11 June.

Technical Background

Power in ocean waves originates as wind energy that is transferred to the sea surface when wind blows over large areas of the ocean. The resulting wave field consists of a collection of waves at different frequencies traveling in various directions, typically characterized by a directional wave spectrum. These waves can travel efficiently away from the area of generation across the ocean to deliver their power to nearshore areas.

The theoretical resource estimate is a measure of how much power flux is in the observed wave fields along coasts. To estimate the theoretical resource, wave power density is usually characterized as power per length of wave crest and expressed in units of kilowatt per meter; it represents all of the energy crossing a vertical plane of unit width per unit time. This vertical plane is oriented along the wave crest and extends from the sea surface down to the seafloor. Because wave energy travels in a particular direction, care must be taken when interpreting maps that show wave power flux as a function of location but do not indicate predominant wave directions.

It also must be recognized, as in the case of wind energy, that if a device removes energy from the wave field at one location, less energy will be available in the shadow of the extraction device. The planning of any large-scale deployment of wave energy devices (i.e., wave arrays or farms) require sophisticated, site-specific field and modeling analyses of the wave field and the devices' interactions with the wave field.

As illustrated in Figure 3, spectral parameters (i.e., significant wave height H_s, and energy period, T_e) are used to quantify estimates of the wave power flux P_o (Appendix 3). Designers use their proprietary transfer function[3] to estimate daily, monthly, and annual electricity production for specific sites. In addition, they incorporate the extreme events into their survivability design.

Figure 3 Wave Energy Conversion

Resource	Transfer Function	Product
P_o(kW/m) = f (H_s; T_e; θ)	Proprietary	kWh
Ocean Area	not 24/7	

H_s = significant wave height, kW = kilowatt, kWh = kilowatt-hour, m = meter, P_o = wave power flux, T_e = energy period.
Source: Author.

Hawaii Offshore Theoretical Wave Resources

To illustrate the type of additional information required for the DMCs identified in Table 1, the situation in Hawaii is summarized below and in Appendix 3.

The wave power resources off of Hawaii consist of three main climate patterns: swells from the North and South Pacific, and year-round wind waves from the northeast (Figure 4). The Hawaiian islands are exposed to swells from distant storms as well as seas generated by trade winds. The island chain creates a localized weather system

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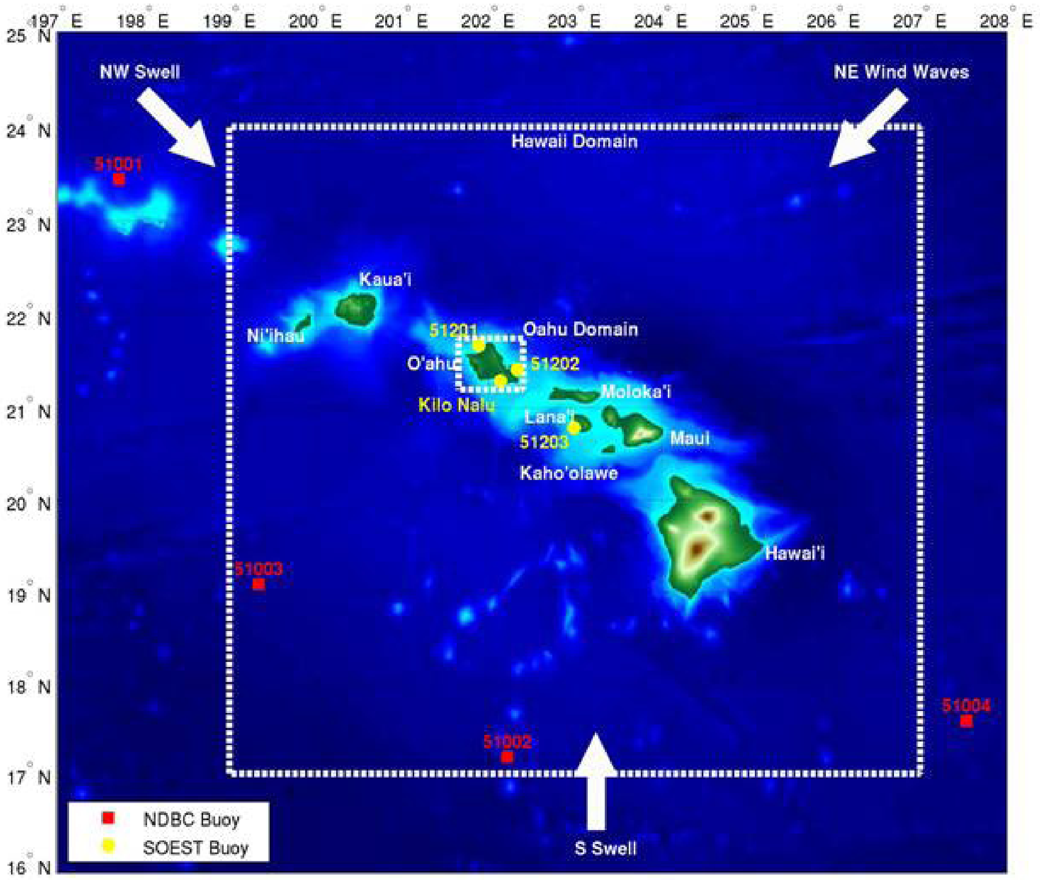
[3] Currently, these transfer functions are proprietary and under development by private companies. In general, details are not available in the public domain, so independent estimates of device performance are limited.

that modifies the wave energy resources from the far field. University of Hawaii researchers working for the Hawaii National Marine Renewable Energy Center implemented a nested computational grid across the major Hawaiian islands in the global WaveWatch3 Model and utilized the Weather Research Forecast Model to provide high-resolution mesoscale wind forcing (Stopa et al. 2013). The resulting winds and deep-water ocean waves estimated in this fashion compare favorably with satellite and buoy measurements.

Figure 4 Hawaii Wave Power Climate Patterns



NDBC = National Data Buoy Center , SOEST = School of Ocean and Earth Science and Technology.
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Modeling reveals that significant seasonal variations are presented at all island sites between the winter and summer months (noting that Hawaii is in the Northern Hemisphere). The validated model reveals that under deep-water conditions (i.e., greater than a 150 m depth)[4] and during the winter months, northwest swells have relatively large amounts of wave power flux (i.e., more than 60 kW/m of power per wave-crest unit length). However, in the summer months, the wave power flux, due to northwest swells, is less than 10% of the winter values. South swells, prevalent in the summer months, have lower power levels of less than 15 kW/m. The wind waves are the most consistent throughout the year and yield offshore power levels of 5–25 kW/m.

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[4] Note that these results are in agreement with Cornett (2008) and Mork et al. (2010). The intention is to illustrate how the offshore resource may vary at specific costal sites under shallow-water conditions.

The consistency of the wave climate and proximity to shore play an important role in selecting optimal locations for deploying WEC devices. While the north- and the south-facing shores would capture seasonal swell energy, the most favorable sites are, in general, areas exposed to the direction of the wind waves. This deep-water model, however, is not applicable to shallow-water conditions (e.g., water depths less than 100 m), and the WEC devices currently under development are intended for installation in water depths of at most 80 m, so the wave energy resources must be evaluated for shallow-water conditions.

Hawaii Shallow-Water Theoretical Wave Resources

To estimate the shallow-water resources at six sites in Hawaii (Table 2), the Simulating Waves Nearshore (SWAN) Model was used with spectral wave data hindcasted from the WaveWatch3 Model to obtain 20 years—from January 1990 to December 2009—of the parametric wave data required by designers of WEC devices.

Table 2 Locations of Nearshore Hawaii Sites Selected for Simulating Waves Nearshore Model Analysis

Site	Location	Latitude (°N)	Longitude (°W)	Depth (meter)
Kaneohe	Kaneohe, Oahu	21.465	157.752	27
Kaneohe Rov7	Kaneohe, Oahu	21.477	157.750	86
Pauwela	Pauwela, Maui	20.958	156.322	73
Upolu	Upolu, Hawaii	20.275	155.863	47
South Point	South Point, Hawaii	18.910	155.681	40
Kilauea	Kilauea, Kauai	22.236	159.422	53

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table 3 and Figure 5 provide the average monthly wave power flux (i.e., the theoretical resource). Table 3 includes the maximum–minimum monthly average ratio for each site indicating the seasonal variation, which constitutes a major challenge to designers of WEC devices.

Table 4 presents the annual average for each site, as well as an estimate of extreme wave heights and periods over a long return time frame. These parameters are particularly important, considering the survival conditions during the design process. In Hawaii, the locations exposed to the North Pacific swells (e.g., Kilauea and Pauwela) yield the largest estimates, with significant wave height at 8.2 m and peak period at 16.3 seconds.

As stated above, the wave climate in Hawaii is composed of north and south swells, plus year-round wind waves from the northeast. Therefore, the majority of the sites are characterized by higher power flux in winter and lower values in summer (Figure 5).

Table 3 Hawaii Monthly Average Wave Power Flux
(kilowatt per meter)

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Maximum/ Minimum
Kaneohe	16.1	16.0	14.1	11.4	6.5	5.0	5.2	5.4	6.1	9.8	17.2	17.1	3.4
Kaneohe Rov7	17.8	17.6	15.5	12.9	7.4	5.9	6.1	6.3	6.9	10.9	18.9	19.3	3.3
Pauwela	48.7	42.4	31.5	20.8	10.4	7.2	7.0	7.5	9.7	16.3	31.3	44.8	7.0
Upolu	15.1	15.6	14.4	12.0	7.2	6.7	7.0	7.6	7.1	9.4	15.9	17.1	2.6
South Point	17.6	16.3	13.6	11.7	9.1	9.5	9.8	10.3	9.7	8.8	10.6	15.5	2.0
Kilauea	49.2	40.8	28.8	16.5	8.1	4.5	4.4	4.2	7.2	13.7	27.6	39.7	11.7

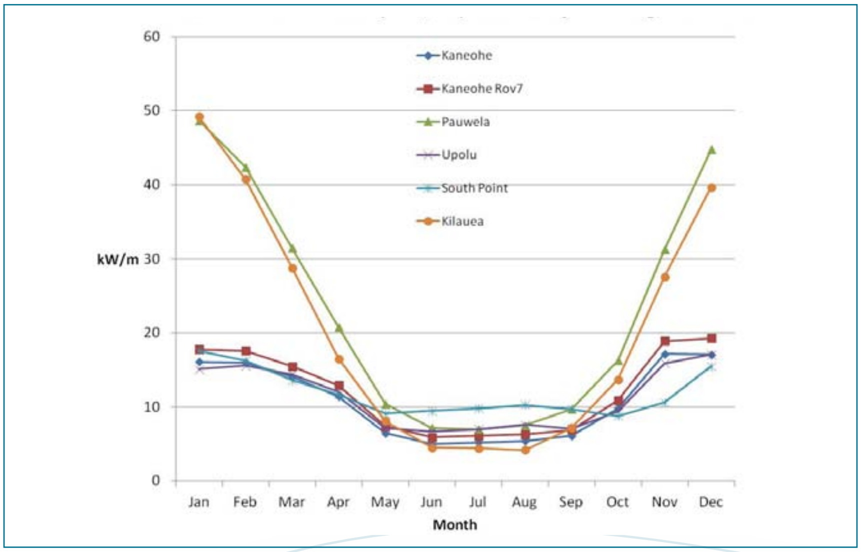
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table 4 Hawaii Annual Average Wave Power Flux

Site	Power Flux (kilowatt per meter)	H_s, 100 Years (meter)	T_p, 100 Years (second)
Kaneohe	10.8	6.2	14.4
Kaneohe Rov7	12.1	6.5	14.4
Pauwela	23.1	8.2	16.3
Upolu	11.3	6.3	13.0
South Point	11.9	4.1	16.3
Kilauea	20.4	8.2	16.3

H_s = significant wave height, T_p = peak period.
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure 5 Monthly Average of Wave Power Flux for Six Sites in Hawaii
(kilowatt per meter)



kw = kilowatt, m = meter.
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Wave Energy Conversion Device Performance Evaluation

To illustrate the challenges faced by this nascent industry and for the purpose of this report, the performance of electricity-producing WEC devices was assessed using the power matrix[5] concept (Appendix 4). This should be done using field data obtained for each WEC device to tabulate the relationship between its power output (kW) and appropriate wave parameters like significant wave height (H_s, m) and energy period (T_e, s). Although a third party should conduct field tests to obtain the required information, at the current stage of WEC technology, this type of data is not available. Therefore, electricity generation estimates are given in this report using power matrixes published by developers in the process of testing their equipment. These unconfirmed power matrixes are used in conjunction with wave scatter information available for Hawaii (Appendix 3) to estimate the energy output of the device over the specified period (Table 5).

It appears that the Wave-Star WEC device is best suited for the locations considered herein. However, it must be noted that the Wave-Star, at a location with a much higher wave power flux (e.g., Kilauea versus Kaneohe), produces essentially the same output. This device stops production for a significant wave height greater than 3 m, so, as indicated in the table, there would have been 22 days in Kilauea when generation would have been curtailed to avoid equipment damage.

Table 5 Site- and Device-Specific Electricity Generation with Wave Energy Conversion Devices under Development

	Name Plate (kW)	**Kaneohe, Oahu**	**Kilauea, Kauai**	**Pauwela, Maui**	**Kaneohe, Oahu**
Wave Scatter Data (Year)		2009	2009	1990–2009	1990–2009
Site Depth		58 m	53 m	73 m	86 m
Site Wave Power Flux: P_o		13.8 kW/m	21.6 kW/m	23.1 kW/m	12.1 kW/m
WEC Device		Annual MWh:	Annual MWh:	Annual MWh:	Annual MWh:
Point Absorber IEC/TS 62600-100 www.iec.ch	1,000	1,048 MWh CF: 0.12	1,343 MWh CF: 0.15	1,951 MWh CF: 0.22	1,105 MWh CF: 0.13
Pelamis www.pelamiswave.com	750	826 MWh CF: 0.13	743 MWh CF: 0.11		
Wave-Star C5 http://wavestarenergy.com	600	2,494 MWh CF: 0.47 Curtail 4 days	2,331 MWh CF: 0.44 Curtail 22 days		

CF = capacity factor, kW = kilowatt, m = meter, MWh = megawatt-hour.
Source: Generated by author.

The concept of capacity factor (CF) can be used to estimate the fraction of time that a WEC device would have produced at its name plate, that is: annual production (kWh) divided by the product of 8,760 hours x name plate (kW). Estimates of capacity factor are included in Table 5.

It must be emphasized that the values given in Table 5 represent the total annual energy output and that, due to the seasonal dependence of ocean wave generation, the output will vary throughout the year. One way to illustrate this is to consider the daily wave power flux estimated in 2009 at the Kaneohe 58-m and Kilauea 53-m sites (Figure 6). Clearly, the relationship between wave power flux and electricity production with the three devices considered in Table 5 is not linear.

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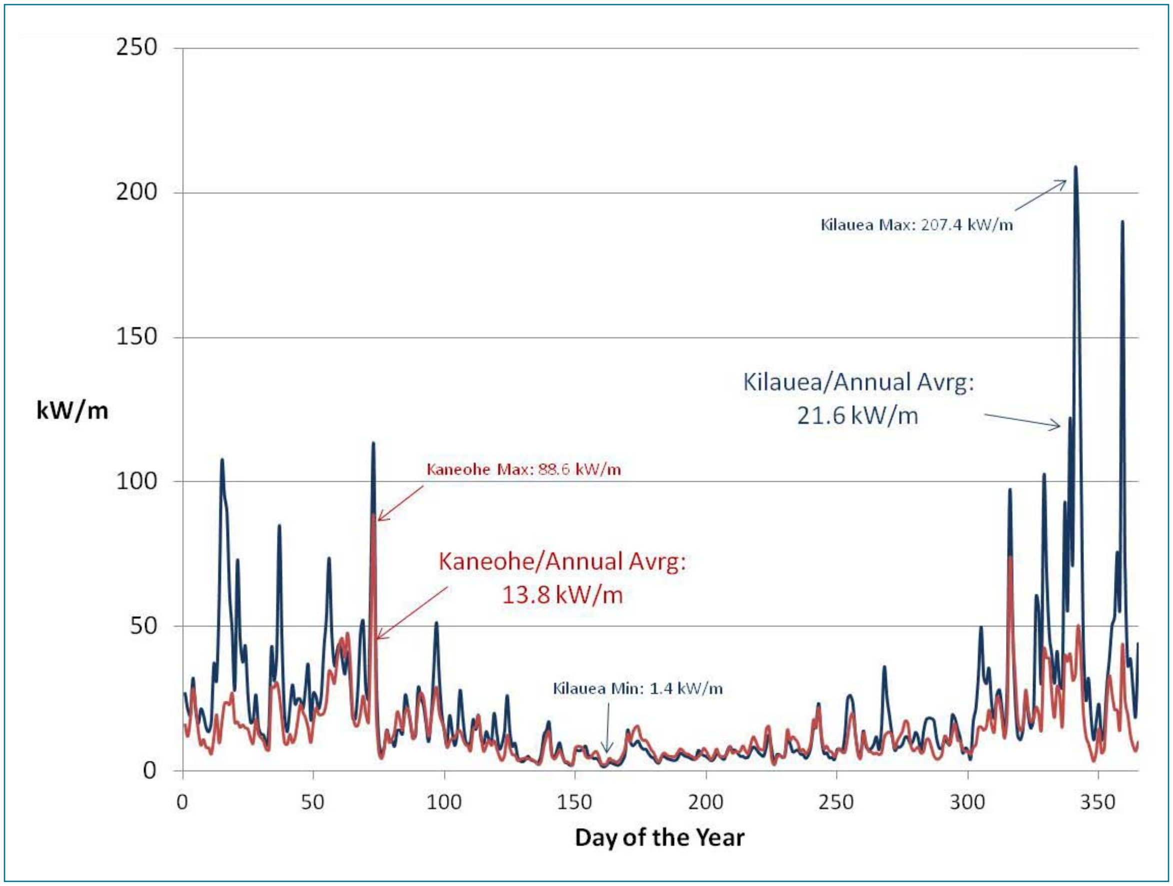
[5] Analogous to the method of bins utilized to obtain the power curve (i.e., power output versus wind speed) of wind turbine generators.

WEC devices may yield capacity factors similar to those obtained with well-established photovoltaic arrays (i.e., 0.16–0.20) and wind farms (i.e., 0.20–0.45). Considering the concept of levelized cost of electricity (Appendix 2), the capital cost target for WEC devices is within the range corresponding to photovoltaic arrays (i.e., less than $6,000/kW) and wind arrays (i.e., less than $2,000/kW). At this stage of development, it is premature to discuss cost estimates available. These, however, range from $3,000/kW once commercialization is achieved at least 10 years from now to as much as $30,000/kW for the all-inclusive costs associated with the prototypes under development.

Figure 6 Daily Wave Power Flux at the Kaneohe and Kilauea Sites, 2009



kW = kilowatt, m = meter.

Notes:

Daily wave power flux at the Kaneohe site ranges from 2.2 kW/m in early June to 88.6 kW/m (factor of about 40) in mid-March, with an annual average of 13.8 kW/m.

At the Kilauea site, the values range from 1.4 kW/m in mid-June to 207.4 kW/m in early December (factor of about 146), with an annual average of 21.6 kW/m.

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table 6 is presented to illustrate the challenges faced by developers of WEC devices. Sites wherein devices under development can achieve capacity factors of more than 0.3 and with installed costs of about $3,000/kW are required to achieve cost-competiveness.

Table 6 Estimates of the Levelized Cost of Electricity with Wave Energy Conversion Devices and Arrays

Case	**Size**	**Capacity Factor**	**CC** ($/kW)	**Loan (I/N)** (%/years)	**COE** $_{cc}$ ($/kWh)	**COE** $_{omr\&r}$ ($/kWh)	**COE** ($/kWh)
Future	90 MW	0.40	3,000	8/15	0.1	0.070	0.17
"		"	"	2.5/20	0.055	0.077	0.13
Future	90 MW	0.25	3,000	8/15	0.16	0.112	0.27
"		"	"	2.5/20	0.088	0.123	0.21
Future	90 MW	0.15	3,000	8/15	0.267	0.187	0.45
"		"	"	2.5/20	0.147	0.206	0.35
First Generation	750 kW	0.40	10,000	8/15	0.333	0.233	0.57
		"	"	2.5/20	0.183	0.257	0.44
First Generation	750 kW	0.25	10,000	8/15	0.534	0.372	0.91
		"	"	2.5/20	0.293	0.411	0.70
First Generation	750 kW	0.15	10,000	8/15	0.891	0.623	1.51
		"	"	2.5/20	0.489	0.687	1.18

CC = capital cost, COE = cost of electricity, I/N = interest/number of years, kW = kilowatt, kWh = kilowatt-hour, MW = megawatt.

Notes:
The case labeled “future” refers to projections for wave farms consisting of numerous devices, and “first-generation” refers to single devices currently under development assuming often-quoted capital cost estimates from press releases.
Two types of loans are assumed: a commercial loan with a rate of 8% over 15 years, and a concessionary loan from a multilateral development bank with rate of 2.5% over 20 years.

An average annual inflation rate of 3% is assumed for all cases.

The COE$_{cc}$ parameter provides the amount required to cover loan amortization, and the COE$_{omr\&r}$ refers to the levelized amount that must be recovered to cover operation, maintenance, repairs, and replacement over the life of the loan.

The COE provides the estimate of the amount that must be recovered to break even. This excludes profits or any environmental tax credits that might be available.

Source: Author

Siting and Ocean Area Requirements

A wave farm consists of arrays of WEC devices spaced so interactions between components are minimized. For example, as much as 7 square kilometers (km^2) of ocean area are required for 100 x 1 MW or 200 x 0.5 MW WEC devices arranged into a 100 MW wave farm.[6] For comparison, consider that a 100 MW offshore wind farm requires about 12 km^2.

Given the limited availability of unpopulated coastlines in Pacific island DMCs, the siting of WEC devices would be challenging. In addition, WECs are currently designed to operate in waters shallower than about 80 m, and, because of the relatively narrow insular shelves surrounding the islands, wave farms would have to be deployed

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[6] For example, 11 km along the coastline x 0.6 km away from coastline or other equivalent rectangular area.

within 1–3 km from the shoreline in full public view. Siting considerations and the corresponding nearshore area requirements, in addition to the issues of resource variability discussed earlier pose daunting challenges to the implementation of wave farms (as well as for offshore wind farms) in such DMCs.

Licensing and Permitting

The situation in Hawaii is summarized here to illustrate the cumbersome permitting process that may be applicable in DMCs.

In the United States, the proposed location determines the various relevant agencies and regulations. In general, one must consider the Federal Energy Regulatory Commission (FERC); Bureau of Ocean Energy Management, Regulation and Enforcement (BOEM), Department of the Interior; Army Corps of Engineers; Environmental Protection Agency; National Oceanic and Atmospheric Administration, Department of Commerce; United States Coast Guard; and various state, county, and city agencies. In addition to the licenses and permits that must be secured from different agencies, the project must comply with several other applicable laws.

Independent of location, licensing WEC devices is the responsibility of FERC. In Hawaii, the state government has jurisdiction up to 3 nautical miles offshore. The federal government has jurisdiction in the outer continental shelf, extending between the outer limits of state waters and the inner boundary of international waters, which begins about 200 nautical miles offshore. BOEM defines the outer continental shelf as including submerged lands, subsoil, and the seabed.

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

For wave energy projects located in state waters, BOEM has no jurisdiction, but licenses still need to be issued by FERC and all other requirements are under state, county, and city rules.

Challenges and Barriers

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

Major challenges can be summarized as follows:

- There are no first-generation WEC systems that are cost-competitive with other technologies that also use intermittent resources (e.g., photovoltaic and wind).
- Consistent funding is lacking, which is required for the industry to proceed from concept design to the pilot phase.

- In addition, considering DMCs that might have permitting processes similar to those encountered in the United States:
  - The burdensome, although necessary, process of obtaining licenses and permits must be streamlined, including environmental impact statements. The process is project-specific, expensive, and requires about 3 years for commercial projects.
  - A situation represented by a "one stop shop" must evolve where industry can process all documentation stipulated for licensing and permitting avoiding duplicity, contradictory requirements, and interdepartmental jurisdictional disputes.

In Denmark, Germany, and Spain, a lesson can be learned from the successful commercialization of wind energy that was due to consistent government funding and support of pilot projects, thus leading to appropriate and realistic determination of technical requirements and operational costs. In this context, "commercialization" means that equipment can be financed under terms that yield cost-competitive electricity. This depends on site-specific conditions.

Conclusions and Recommendations

Table 7 summarizes the major conclusions reached based on this report as well as recommendations for work required beyond this report.

Table 7 Baseline Wave Energy Conversion Potential in Developing Member Countries: Conclusions and Recommendations

	Theoretical Resource Availability	Equipment Siting Requirements	Additional Resource Information Needed	Equipment to Convert Resource into Electricity	Cradle-to-Grave Environmental Impact	Development Incentives	Overall Assessment	Overall Recommendation
WEC	Yes, in several DMCs but based on deepwater offshore data	Water depths greater than 80 meters Coastal area: about 0.7 square kilometers for 10-megawatt array (comparable to offshore wind farm requirements)	Commission near-shore theoretical resource study using existing wind and wave numerical models, which requires bathymetry information. Identify any wave measurements available from DMCs to calibrate models.	Under early stages of development not currently available	Not different from well-established technologies and ocean installations except for submarine power cable	Implement feed-in tariff for WEC installations (intermittent resource). At current technology readiness level, it is premature to estimate cost of electricity, but target should be comparable to photovoltaic and offshore wind.	WEC devices will not be commercially available for installation at DMCs for 1–2 decades. Premature to estimate cost of electricity	Obtain nearshore wave resource model for DMCs identified herein. Monitor progress in the development of WEC devices.

DMC = developing member country, WEC = wave energy conversion.

Source: Author.

2 OCEAN THERMAL RESOURCES

Introduction

Ocean thermal energy conversion (OTEC) technology uses the temperature difference between surface warmer water and deeper colder water encountered in tropical oceans as the source of thermal energy. At this time, OTEC systems are in the pilot phase. Several experimental projects have already demonstrated that the base-load technology works 24/7, although operational records required to proceed into commercialization are lacking (Vega 2012; NOAA 2009). In this context, commercialization means that a project can be financed under terms that yield cost-competitive electricity and desalinated water, which depends on site-specific conditions (Vega 2010).

The major analytical conclusion continues to be that there is a potential market of more than 7 terawatts for OTEC plants that produce electricity and desalinated water. However, operational records must be obtained by building and operating floating pilot plants that are scaled down from sizes identified as potentially cost-effective. The pilot projects must be operated in situ and for at least 1 continuous year to obtain these records. A floating 5 MW pilot plant (Vega and Nihous 1994) should be operated prior to implementing the 50–100 MW plants that would be cost-competitive throughout the world. There is also a market for smaller, land-based plants operating in Pacific island DMCs with the appropriate resources (Nihous, Syed, and Vega 1989).

As illustrated below, the OTEC process is well understood, and the technical resource can be readily estimated based on the theoretical resource. Designers can use the widely available transfer function to estimate daily, monthly, and annual electricity production for specific sites as defined by the thermal resource.[7]

Figure 7 Ocean Thermal Energy Conversion Summary

Resource	Transfer Function	Product
ΔT (ºC) = $T_{20m} - T_{1,000m}$	Public Domain	kWh; H_2O, AC
Ocean Volume	24/7	

AC= air conditioning, H_2O = water, kWh = kilowatt-hour, m = meter, T = temperature.

Source: Author.

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[7] For OTEC systems, the information required to estimate electricity generation, for a given thermal resource, is in the public domain and readily available to qualified engineers.

Worldwide Market

Ninety-eight economies with access to the required ocean thermal resources within their 200-nautical mile exclusive economic zone (EEZ) have been identified (Table 8). There is also a market for industrialized economies that could manufacture and supply the equipment required for OTEC plants, even if they do not have the required ocean thermal resources within their EEZs. The worldwide resource is equivalent to more than 7 terawatts (i.e., equivalent to 70,000 plants with 100 MW capacity). Each 100 MW plant requires a capital investment of about $750 million, so the ultimate market, in a few decades, would be valued in the trillions of dollars.

In discussing OTEC's potential, it is important to remember that implementing a floating pilot plant would take about 5 years after the order is placed. A survey of factories that could supply the required equipment indicates that no technical breakthroughs are required but that some components would require as long as 3 years to be delivered (Appendix 1). Based on experience with offshore projects of similar size, it is expected that 1 year would be required to mobilize and complete the deployment, with a second year set aside for commissioning. The floating pilot plant would be operational (i.e., supplying electricity to the distribution grid) within 5 years, and would then need to be operated for a few years to gather technical as well as environmental impact information. Some of the valid questions regarding potential environmental impacts to the marine environment can only be answered by operating pilot plants that are large enough to represent the commercial-sized plants of the future.

The design of the first commercial plant, sized at 50–100 MW, would be completed and optimized after the pilot plant's first year of operations. This would be followed by installing several plants connected to shore via submarine power cables. The design of the grazing factory plantships that would produce the fuels of the future, such as hydrogen and ammonia (Nihous and Vega 1993), could be initiated as early as 15 years after OTEC is commercialized.

Table 8 Areas with Appropriate Ocean Thermal Resources within Their 200-Nautical Mile Exclusive Economic Zones

GEOGRAPHICAL AREA				
	MAINLAND		ISLAND	
AMERICAS				
	Belize	Honduras	Antigua	Haiti
	Brazil	Mexico	Aruba	Jamaica
	Colombia	Nicaragua	Bahamas	Martinique
	Costa Rica	Panama	Barbados	Montserrat
	El Salvador	Suriname	Barbuda	Puerto Rico
	French Guiana	United States	Cuba	St. Kitts
	Guatemala	Venezuela	Curacao	St. Lucia
	Guyana		Dominica	St. Vincent
			Dominican Republic	The Grenadines
			Grand Cayman	Trinidad & Tobago
			Grenada	Virgin Islands
			Guadeloupe	

continued on next page

GEOGRAPHICAL AREA				
	MAINLAND		**ISLAND**	
AFRICA				
	Angola	Kenya	Aldabra	Gabon
	Benin	Liberia	Ascension	Madagascar
	Cameroon	Mozambique	Comoros	Sao Tome & Principe
	Congo	Nigeria		
	DR Congo	Sierra Leone		
	Eq. Guinea	Somalia		
	Ghana	Tanzania		
	Guinea	Togo		
	Ivory Coast			
INDIAN/PACIFIC OCEAN				
	Australia	Malaysia	Cook Islands	Philippines
	Bangladesh	Myanmar	Diego Garcia	PNG
	Brunei Darussalam	PRC	Fiji	Samoa
	Hong Kong, China	Thailand	French Polynesia	Samoa
	India	Viet Nam	Guam	Seychelles
	Japan		Hawaii	Solomon Islands
			Indonesia	Sri Lanka
			Kiribati	Taipei,China
			Maldives	Tonga
			Mauritius	Tuvalu
			Nauru	Vanuatu
			New Caledonia	Wake Island
			Northern Marianas	Wallis & Futuna Is.
			Okinawa	

PNG = Papua New Guinea, PRC= People's Republic of China.

Source: L. Vega. 2010. Economics of Ocean Thermal Energy Conversion (OTEC): An Update. Paper presented at the Offshore Technology Conference. Houston. 3–6 May.

Technology

There are two OTEC cycles, closed and open, whose technology has been proven and for which all required equipment is available.

The first concept uses the relatively warm (24°C–30°C) surface water of tropical oceans to vaporize pressurized ammonia through a heat exchanger (i.e., evaporator). The resulting vapor is then employed to drive a turbine generator. The cold ocean water transported to the surface from 800–1,000 m depths, with temperatures ranging from 8°C–4°C, condenses the ammonia vapor through another heat exchanger. Because the ammonia circulates in a closed loop, this concept has been named closed-cycle OTEC (CC-OTEC).

The CC-OTEC concept was demonstrated in 1979, when Hawaii and a consortium of United States companies produced more than 50 kW of gross power, with a net output of up to 18 kW, from a small plant mounted on a barge off of Hawaii. Subsequently, a 100 kW gross power, land-based plant was operated in Nauru by a consortium of Japanese companies. These plants were operated for a few months to demonstrate the concept, and they were too small to be scaled to commercial-sized systems (Vega 2012).

Alternatively, the second cycle uses ocean water as the working fluid. The surface water is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine generator, and the relatively colder deep seawater is used to condense the steam after it has passed through the turbine. This cycle can, therefore, be configured to produce desalinated water as well as electricity. This cycle is referred to as open-cycle OTEC (OC-OTEC), because the working fluid flows once through the system.

History

OC-OTEC was first demonstrated in Cuba by its inventor, Georges Claude, in 1930 with a small land-based plant using a direct contact condenser. Therefore, desalinated water was not a by-product. The plant failed to achieve net power production because of poor site selection (i.e., thermal resource) and a mismatch of the power and seawater systems. However, the plant did operate for several weeks.

Claude, subsequently, designed a 2.2 MW floating plant for the production of up to 2,000 tons of ice for Rio de Janeiro.[8] Claude housed his power plant in a ship (i.e., plantship), about 100 km offshore. Unfortunately, he failed in his numerous attempts to install the vertical long pipe (i.e., the cold-water pipe) required to transport the deep ocean water to the ship and had to abandon his enterprise in 1935. His failure can be attributed to the absence of the offshore industry and ocean engineering expertise presently available.

Recently, a team installed a small OC-OTEC land-based experimental facility in Hawaii (Figure 8, Vega and Evans 1994). The turbine generator was designed for an output of 210 kW for 26°C surface water and 6°C deep water. A small fraction (10%) of the steam produced was diverted to a surface condenser for the production of desalinated water. The experimental plant was successfully operated from 1993 to 1998. The highest production rates achieved were 255 kW with a corresponding net power of 103 kW and 0.4 liters per second of desalinated water. These are world records for OTEC.

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[8] This was prior to the wide availability of household refrigerators.

Figure 8 210-Kilowatt Open-Cycle Ocean Thermal Energy Conversion Experimental Apparatus

Source: L. Vega and D. Evans. 1994. Operation of a Small Open-Cycle OTEC Experimental Facility. *Proceedings of Oceanology International*. 94 (5). March.

The use of the cold deep water as the chiller fluid in air-conditioning systems has been proposed and implemented (Syed, Nihous, and Vega 1991). It has been demonstrated that these systems, referred to as seawater air-conditioning, provide significant energy conservation and have been installed independently of OTEC.

OTEC energy could be transported via chemical, thermal, and electrochemical carriers. The technical evaluation of nonelectrical carriers led, for example, to the consideration of hydrogen produced using electricity and desalinated water generated with OTEC technology. The product would be transported from the OTEC plantship located at distances of about 1,500 km[9] to a port facility in liquid form to be primarily used as a transport fuel. A 100 MW-net plantship can be configured to yield, by electrolysis, 1,300 kilograms per hour of liquid hydrogen. Unfortunately, the production cost of liquid hydrogen delivered to the harbor would be equivalent to about $400 barrel of crude oil (i.e., approximately four times the present cost). The situation is similar for the other energy carriers considered (e.g., anhydrous ammonia). Presently, the only energy carrier that is cost-effective for OTEC energy is submarine power cables. This situation may be different in future decades in the post-fossil fuels era.

Many possible configurations for OTEC plants have been proposed, ranging from floating plants to land-based plants, including shelf-mounted towers and other offshore structures. The primary candidate for commercial-sized plants appears to be the floating plant, positioned close to land, transmitting power to shore via a submarine power cable (NOAA 2009).

Two decades ago, the detailed evaluation of the economic feasibility and financial viability of OTEC revealed that, in general, plants must be sized at about 50–100 MW to produce cost-competitive base-load electricity (Vega 2010). Smaller plants could be cost-effective in some niche markets (Nihous, Syed, and Vega 1989). It was also concluded

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[9] Selected to represent the nominal distance from the tropical oceans to major industrialized centers throughout the world.

that, although experimental work with relatively small plants had demonstrated continuous production of electricity and desalinated water, it would be necessary to build a pilot plant sized around 5–10 MW to establish the operational record required to secure financing for the commercial-sized plants. The pilot plant would produce relatively high-cost electricity and desalinated water, so support funding was required from the national and local governments. Unfortunately, development did not proceed beyond experimental plants sized at less than 0.25 MW.

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

Site Selection

As previously stated, the OTEC concept utilizes the differences in temperature, ΔT, between the warm (T_w of about 22°C–29°C) tropical surface waters and the cold (T_c of about 4°C–5°C) deep (i.e., 1,000 m) ocean waters, as the source of the thermal energy required.

Deep seawater flows from the polar regions. This polar water, which represents up to 60% of all seawater, originates mainly from the Arctic for the Atlantic and North Pacific oceans, and from the Antarctic (Weddell Sea) for all other major oceans. Therefore, T_c at a given depth, below 500 m, does not vary much throughout all regions of interest for OTEC. It is also a weak function of depth, with a typical gradient of 1°C per 150 m between 500 m and 1,000 m. These considerations may lead one to regard T_c as nearly constant, with a value of 4°C–5°C at 1,000 m (Vega 2012; Rajagopalan and Nihous 2013).

A desirable OTEC thermal resource of at least 20°C requires typical values of T_w of 25°C. Generally, regions between latitudes 20°N and 20°S are adequate. Some definite exceptions exist due to strong cold currents: (i) along the west coast of South America, tropical coastal water temperatures remain below 20°C, and are often 15°C; and (ii) a similar situation prevails to a lesser extent for the west coast of Southern Africa. Moreover, T_w varies throughout the year, and sometimes exhibits a significant seasonal drop due to the upwelling of deeper water induced by the action of the wind. A careful OTEC site selection requires comprehensive knowledge of local climate features as they may affect T_w seasonally.

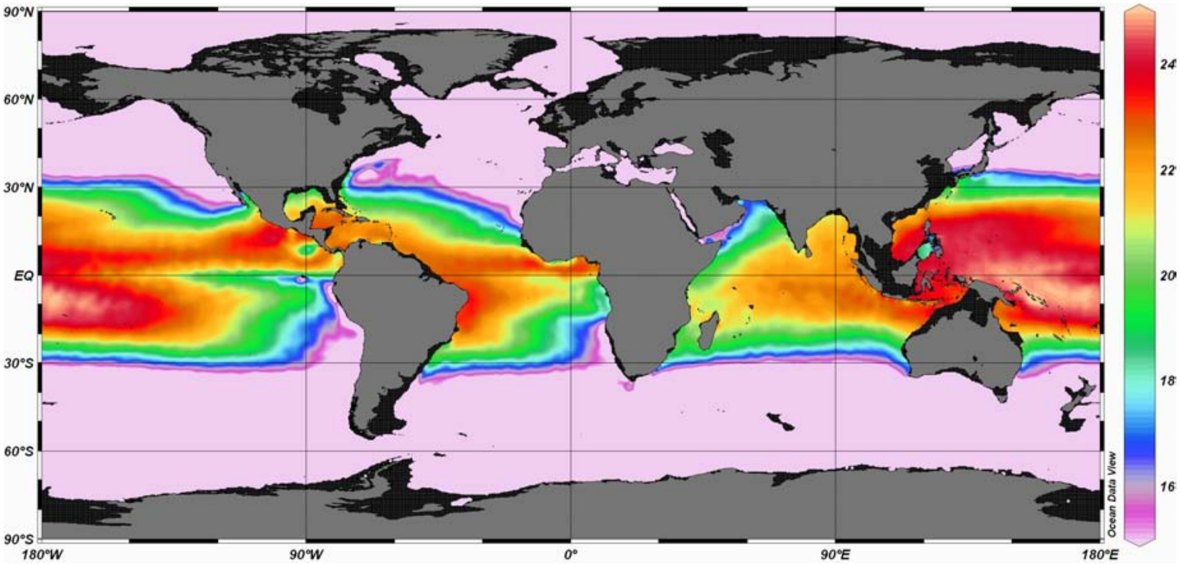
The following summarizes the availability of the OTEC thermal resource throughout the world:

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

The most recent (2005) version of the World Ocean Atlas compiled by the United States National Ocean Data Center is a valuable source of objectively analyzed statistical fields, including ocean temperature. The data include long-term historical averages of variables that have been determined from all available oceanographic measurements. Monthly averages also are available. The data are provided with a resolution of 0.25° latitude by 0.25° longitude. The historical (2005) annual average of ΔT are given in Figure 9.

For this report, site-specific field measurements performed by the Philippine Navy near Cabangan were made available by Energy Island and found to validate the vertical temperature distribution extracted from the World Ocean Atlas (Figure 10). This is an important finding given that the ocean thermal resource potential evaluated for DMCs uses the World Ocean Atlas as the primary reference.

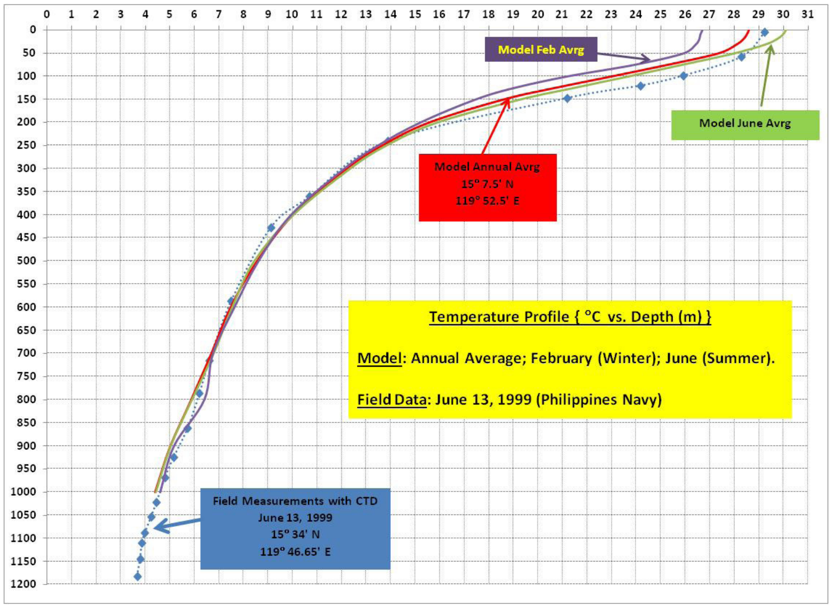
Figure 9 Worldwide Average Ocean Temperature Differences between 20- and 1,000-Meter Depths



Note: The color palette is from 15°C to 25°C.

Sources: United States National Ocean Data Center. 2005. World Ocean Atlas. http://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html; and G. Nihous. Mapping Available Ocean Thermal Energy Conversion Resources around the Main Hawaiian Islands with State-of-the-Art Tools. *Journal of Renewable and Sustainable Energy*. 2 (043104).

Figure 10 Vertical Temperature Profile from World Ocean Atlas Compared to Measurements by the Philippine Navy

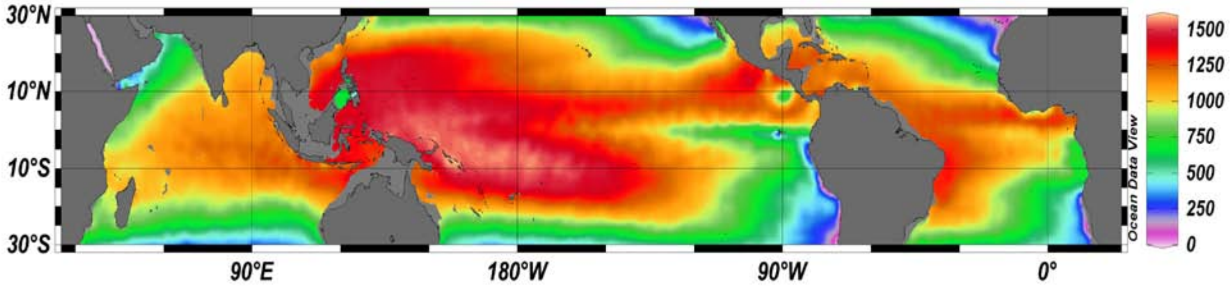


CTD = Conductivity, Temperature and Depth.

Source: Energy Island, and United States National Ocean Data Center. 2005. World Ocean Atlas. http://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html

As stated, OTEC technology has been validated with pilot plants; therefore, for a given theoretical thermal resource, the technical resource can be expressed, with appropriate accuracy, as the electrical energy generated at the plant. For the purpose of identifying DMCs with a thermal resource comparable to Hawaii, the annual electricity production with a 100 MW OTEC plant located within the 200-nautical mile EEZ was estimated from the database used to generate Figure 11 with results summarized in Table 9.

Figure 11 100-Megawatt Ocean Thermal Energy Conversion Plant Annual Output
(gigawatt-hour)



Note: The reference electricity generation is 877 gigawatt-hours per year at ΔT = 20°C (T_{ww} = 26.9°C; T_{cw} = 6.9°C).

Source: Provided by G. C. Nihous using tools described in G. Nihous. 2010. Mapping Available Ocean Thermal Energy Conversion Resources around the Main Hawaiian Islands with State-of-the-Art Tools. *Journal of Renewable and Sustainable Energy*. 2 (043104).

Table 9 Annual Electricity Generation with 100-Megawatt Ocean Thermal Energy Conversion Plant

Region and Country	Appropriate Ocean Thermal Resource within Exclusive Economic Zone	Annual Production (gigawatt-hour)	Reference Longitude	Reference Latitude
Central and West Asia				
Pakistan	Too low	580	66	24°N
East Asia				
People’s Republic of China	Yes	1,100	115°E	20°N
Pacific				
Reference Site (Hawaii)	Yes	1,040	158°W	21°N
Cook Islands, Rarotonga	Yes	1,040	160°W	22°S
Fiji	Yes	1,320	178°E	17°S
Kiribati, Tarawa	Yes	1,450	175°E	2°N
Marshall Islands, Majuro	Yes	1,430	170°E	7°N
Federated States of Micronesia	Yes	1,430–1,500	140°E–165°E	0°–10°N
Nauru	Yes	1,490	167°E	0.5°S
Palau	Yes	1,460	135°E	7°N
Papua New Guinea	Yes	1,230	145°E	10°S
Samoa	Yes	1,500	172°W	12°S
Solomon Islands	Yes	1,520	160°E	10°S
Timor-Leste	Yes	1,320	125.5°E	8.5°S

continued on next page

Region and Country	Appropriate Ocean Thermal Resource within Exclusive Economic Zone	Annual Production (gigawatt-hour)	Reference Longitude	Reference Latitude
Tonga	Yes	980	175°W	22°S
Tuvalu	Yes	1,520	180°	5°–10°S
Vanuatu	Yes	1,370	165°E	15°S
South Asia				
Bangladesh	No	Not applicable	91°E	22°N
India	Yes	1,070	90°E	16°N
Maldives	Yes	1,130	72.6°E	3.1°N
Sri Lanka	Yes	1,090	82°E	8°N
Southeast Asia				
Brunei Darussalam	Yes	1,400	113.5°E	5.1°N
Cambodia	No	Not Applicable	103°E	11°N
Indonesia	Yes	1,200	100°E	5.1°S
Malaysia	Yes	1,410	114°E	6.1°N
Myanmar	Yes	1,080	93°E	18°N
Philippines	Yes	1,410	119°E	14°N
Thailand	Yes	1,150	97°E	7°N
Viet Nam	Yes	1,160	110°E	14°N

Note: Excludes land-locked developing member countries.
Source: Provided by G. C. Nihous using tools described in G. Nihous. 2010. Mapping Available Ocean Thermal Energy Conversion Resources around the Main Hawaiian Islands with State-of-the-Art Tools. *Journal of Renewable and Sustainable Energy*. 2 (043104).

As stated above, to illustrate the OTEC technology readiness level, the output from a 100 MW plant was considered. A plant of this size would not be appropriate for some of the smaller Pacific island DMCs; however, the output from a smaller plant would be proportional so that a 10 MW plant would generate 1/10 of the value given in Table 9. It appears, therefore, that OTEC technology is applicable for the majority of DMCs that are not landlocked.

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

This presents an interesting question about the size of the OTEC resource: Could a massive deployment of this technology affect ocean temperatures on which the process itself depends? In other words, could OTEC be self-limiting?

Gerard Nihous at the University of Hawaii utilized a 3-D oceanic general circulation model to account for the complex interplay between planetary heat fluxes and potentially large OTEC intakes and discharges spread over more than 100 million km^2 to estimate a 30-terawatt[10] maximum for global OTEC power production (Rajagopalan

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[10] This amount is more than current worldwide energy consumption by all sectors.

and Nihous 2013). As OTEC flow rates increase, the erosion of vertical seawater temperature gradients is much slower in 3-D ocean models, because any heat locally added to the system can be horizontally transported and redistributed at a relatively fast rate. Another distinctive feature of the model is the persistence of slightly cooler surface waters in the OTEC region. This is compensated, however, by a warming trend at higher latitudes. A boost of the planetary circulation responsible for the overall supply of deep cold seawater is also shown. A more modest OTEC scenario with a global potential of the order of 7 terawatts shows little impact (Rajagopalan and Nihous 2013). It must be noted that the baseline commercial OTEC plant is sized at 100 MW, so 70,000 plants would correspond to 7 terawatts.

Limitations and Challenges

The performance of OTEC cycles is assessed with the same thermodynamic concepts used for conventional steam power plants. The major difference arises from the relatively large quantities of warm and cold seawater required for heat transfer processes, resulting in the consumption of a portion of the power generated by the turbine generator in the operation of pumps. The power required to pump seawater is determined by accounting for the pipe-fluid frictional losses and, in the case of the cold seawater, for the density head (i.e., gravitational energy due to the differences in density between the heavier, colder water inside of the pipe and the surrounding water column). The seawater temperature rise, due to frictional losses, is negligible for practical designs.

The thermal performance of CC-OTEC and OC-OTEC is comparable. OTEC design parameters are, therefore, generalized as follows:

- In-house or parasitic electrical loads P_{loss} represent about 30% of P_{gross}, such that the exportable power (P_{net}) is about 70% of P_{gross};
- A cold-water flow rate (Q_{cw}) of 2.7 cubic meters per second is required per MW_{net}; and
- The optimal warm water flow rate (Q_{ww}) is about 1.9 x Q_{cw}.

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

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

where, β and P_{loss} are system-specific. Considering nominal values, it can be shown that a 1°C change in ΔT leads to a change of about 15% in P_{net}. In summary, in the absence of seawater flow rate constraints, extractable power can be characterized by providing ΔT estimates.

For example, a 100 MW CC-OTEC plantship moored within 20 km of the shoreline under a baseline average ΔT of 20°C would generate 877 gigawatt-hours (GWh) per year. The site-specific electricity generation for the DMCs (Table 9) indicates that, for example, in Southeast Asia, the production would be 27% higher (1,100 GWh) such that the levelized cost of electricity would be 20% lower. For Fiji, production would be 53% higher (1,320 GWh), resulting in a levelized cost of electricity reduction of 35%; and in the Philippines, production would be 63% higher (1,410 GWh) with a levelized cost of electricity 38% lower.

The design and installation of a cost-effective pipe to transport large quantities of cold-water to the surface (i.e., a cold-water pipe) presented an engineering challenge of significant magnitude, complicated by a lack of evolutionary experience. This challenge was met in the United States with a program relying on computer-aided analytical studies integrated with laboratory and at-sea tests. The outcome achieved has been the design, fabrication, transport, deployment, and at-sea test of an instrumented 2.4 m diameter, 120 m long, fiberglass-reinforced plastic sandwich construction pipe attached to a barge (Vega 2012). The data obtained were used to validate the design technology developed for pipes suspended from floating OTEC plants. This type of pipe is recommended for floating OTEC plants (Appendix 1).

For land-based plants, there is a validated design for high-density polyethylene pipes of a diameter of less than about 2 m (Nihous, Syed, and Vega 1989). In the case of larger diameter pipes, offshore techniques used to deploy large segmented pipes made of steel, concrete, or fiberglass-reinforced plastic are applicable. Pressurized pipes made of reinforced elastomeric fabrics (e.g., soft pipes), with pumps located at the cold-water intake, seem to offer the most innovative alternative to conventional concepts. However, the operability of pumps in 800–1,000 m water depths over extended periods must be verified, and the inspection, maintenance, and repair constraints established before soft pipes can be used in practical designs.

Other components for OTEC floating plants that present engineering challenges are the position-keeping system and the attachment of the submarine power cable to the floating plant. Deep ocean-mooring systems, designed for water depths of more than 1,000 m, or dynamic positioning thrusters developed by the offshore industry can be used for position keeping. The warm-water intake and the mixed return water also provide the momentum necessary to position the surface vessel (Nihous and Vega 1993). The offshore industry also provides the engineering and technological backgrounds required to design and install the riser for the submarine power cable.

The design of OTEC cold-water pipes, mooring systems, and submarine power cables must consider survivability loads as well as fatigue-induced loads. Survivability loads are based on extreme environmental phenomena, with a relatively long return period, that may result in ultimate strength failure. Fatigue-induced loads may result in fatigue-induced failure through normal operations.

Economics

The analytical model available to estimate the levelized cost of electricity production can be used to assess scenarios under which OTEC might be competitive with conventional technologies (Appendix 1). First, the OTEC capital cost is estimated. Subsequently, the relative cost of producing electricity, offset by the desalinated water production revenue, is equated to the fuel cost of electricity produced with conventional techniques to determine the scenarios (i.e., fuel cost and cost of freshwater production) under which OTEC could be competitive. For each scenario, the cost of desalinated water produced from seawater via reverse osmosis is estimated to set the upper limit of the OTEC water production credit. No attempt was made to speculate the future cost of fossil fuels. It is simply stated that if a location is represented by one of the scenarios, OTEC would be cost-competitive.

In this fashion, two distinct markets were previously identified: (i) industrialized countries, and (ii) small island developing states with modest needs for power and freshwater. OC-OTEC plants could be sized at 1–10 MW, with 450,000–9.2 million gallons of freshwater per day (1,700–35,000 cubic meters per day) to meet the needs of developing communities with populations ranging from 4,500 to 100,000 residents. This range encompasses the majority of small island developing states throughout the world and specifically DMCs.

Floating plants of at least a 50 MW capacity are required for the larger DMCs like the Philippines. These would be moored or dynamically positioned a few kilometers from land, transmitting the electricity to shore via submarine power cables. The moored vessel could also house an OC-OTEC plant and transport the desalinated water produced via flexible pipes (Vega 2012).

OTEC-based, mariculture operations and air-conditioning systems could only make use of a small amount of the seawater available, and therefore could only impact small plants. The use of energy carriers (e.g., hydrogen and ammonia) to transport OTEC energy generated in floating plants, drifting in tropical waters, was determined to be technically feasible but requires increases in the cost of fossil fuels equivalent to $400 per barrel to be cost-competitive.

Presently, the external costs of energy production and consumption are not included in the charges to the consumer. Considering all stages of generation, from initial fuel extraction to plant decommissioning, no energy technology is completely environmentally benign. The net social costs of the different methods of energy production continue to be studied. Estimates of costs due to corrosion, health impacts, crop losses, radioactive waste, military expenditures, employment loss, and subsidies (e.g., tax credits and research funding for present technologies) can be found. In the United States, for example, the range of all estimates is equivalent to adding from \$80–\$400 per barrel. Accounting for these externalities might eventually help the development and expand the applicability of OTEC, but in the interim, the scenarios summarized earlier should be considered as the market entry point.

Conventional power plants pollute the environment more than an OTEC plant would, and the fuel for OTEC is vast and free, as long as the sun heats the oceans. However, it is futile to use these arguments to convince the financial community to invest in an OTEC plant without operational records.

Capital Costs

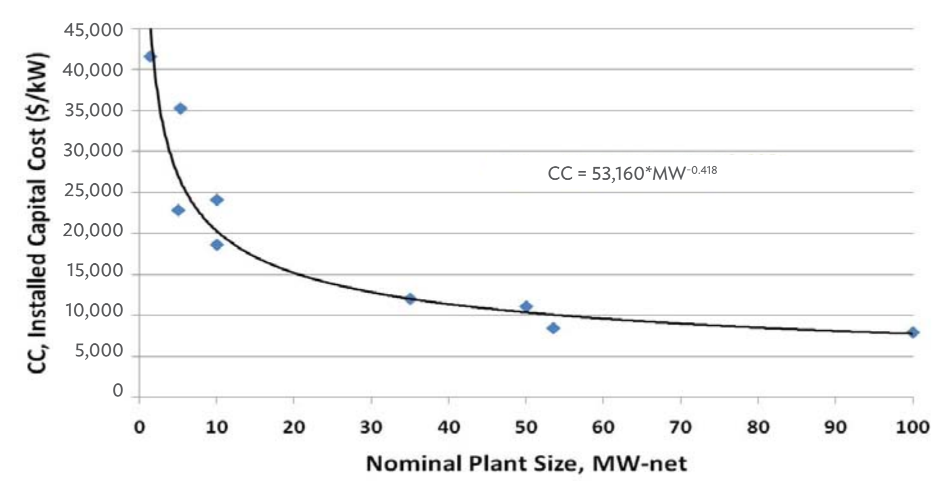
OTEC archival information can be converted to present-day costs using the United States 20-year average for equipment price index inflation. Current technical specifications for 10, 50, and 100 MW OTEC plants were used to solicit budgetary quotes. All estimates are summarized in Figure 12.

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

Figure 12 also illustrates that the OTEC capital cost is a strong function of plant size. For convenience and future reference, a least-squares curve fit is provided:

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

Figure 12 Capital Cost Estimated for First-Generation Closed-Cycle Ocean Thermal Energy Conversion Plants



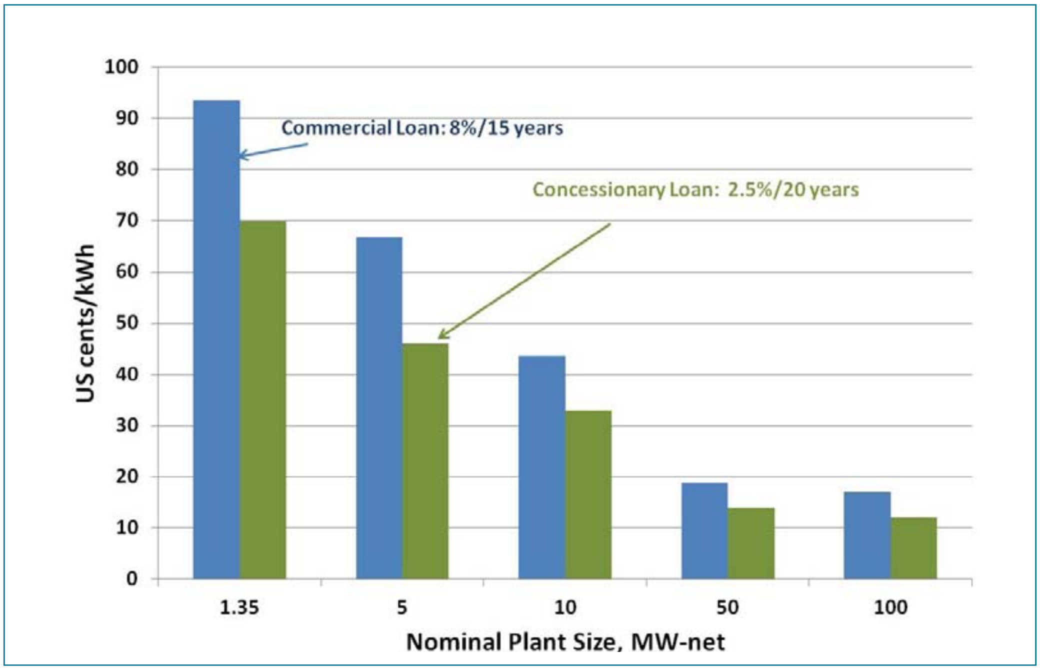
CC= capital cost, kW = kilowatt, MW = megawatt.

Source: L. Vega. 2010. Economics of Ocean Thermal Energy Conversion (OTEC): An Update. Paper presented at the Offshore Technology Conference. Houston. 3–6 May.

A 100 MW OTEC plant, for example, could be housed in a floating platform stationed less than 10 km offshore, and would have the capability of delivering more than 877 GWh to the electrical grid every year. Budgetary quotes from potential equipment suppliers indicate that the installed cost would be $790 million using state-of-the-art components (Appendix 1).

The annual costs for operation and maintenance, including repairs and equipment replacement, are estimated at $40 million. Under realistic financing terms (i.e., a 15-year loan at 8% annual interest and 3% average annual inflation), electricity could be produced at a levelized cost of less than $0.17/kWh under the baseline thermal resource of ΔT = 20°C generating 877 GWh every year. If the plant could be funded via a concessionary loan with a rate of 2.5% over 20 years, the levelized cost of electricity would be $0.12/kWh (Figure 11). Thus, a power purchase agreement from the national utility at around $0.20/kWh would provide an ample return on investment.

Figure 13 Levelized Cost of Electricity Production for First-Generation Closed-Cycle Ocean Thermal Energy Conversion Plants as a Function of Plant Size with Loan Terms as Parameters



kWh = kilowatt-hour, MW = megawatt.

Note: Annual inflation assumed constant at 3%.

Source: Author.

Capital Cost: 50-Megawatt Ocean Thermal Energy Conversion Plantship

The capital costs estimated for 50 MW OTEC first-generation plants utilizing either closed-cycle or open-cycle technology are summarized in Appendix 1. The estimate for the CC-OTEC plant is $451 million and for the OC-OTEC plant is $551 million. The plantship required for the CC-OTEC system is comparable to typical double-hulled vessels and could be constructed in numerous shipyards throughout the world. The OC-OTEC system, incorporating desalinated water production, requires a vessel that is about three times wider than the standard tanker and container ships and may limit the number of shipyards with appropriate fabrication capabilities.

The combined needs for relatively large amounts of cold seawater and minimal pumping power losses result in a relatively large-diameter cold-water pipe. A 1,000-meter-long, 8.7-meter fiberglass-reinforced plastic sandwich construction pipe was selected. The electricity would be transmitted to shore via a submarine power cable and the desalinated water via a flexible pipe (e.g., hose).

The CC-OTEC plant could support a population of 500,000 with a per capita daily consumption of 2.3 kWh. This value is representative of the all-encompassing per capita consumption in some DMCs. In addition, the OC-OTEC system could also supply 240 liters per day per capita. The per capita water consumption in some DMCs, for example, is estimated at 160 liters per day in the domestic sector and 940 liters per day for all sectors (i.e., domestic, industrial, and agricultural).

Table 10 Electricity and Desalinated Water Production Rates for Ocean Thermal Energy Conversion

System	Electricity (MWh/year)	Water (m^3/day)	Capital Cost (\$/kW_{net})
Closed Cycle	**432,609**	**0**	**8,430**
(53.5 MW)			
Open Cycle	**414,415**	**118,434**	**10,751**
(51.25 MW)			
(1,485 kg/s)			

kg = kilogram, kW = kilowatt, m^3 = cubic meters, MW = megawatt, MWh = megawatt-hour, s = second.
Data generated by author.

Operational Costs and Cost of Production

The methodology used to estimate the levelized cost of electricity production is documented in Appendix 2. This is defined by adding the amortized annual capital loan repayment divided by the annual production to the annual levelized cost incurred due to operation, maintenance, repair, and equipment replacement divided by the annual electricity production.

Economics of a 50-Megawatt Plant

The levelized costs of production with a baseline CC-OTEC plant is given in Table 11, and for a baseline OC-OTEC in Table 12.

An 8% loan over 15 years was considered for the capital investment and for the operation, maintenance, repair, and replacement costs. Current-dollar levelization was evaluated at a fixed annual inflation rate of 3%. For the continuous operation of OTEC plantships, a crew of 17 full-time employees is required, comprising 1 administrator and 16 operators for the power plant and the ship systems. Eight operators would be on duty at one time while the other eight rest. The administrator would work a regular schedule. Using United States labor rates, the fully loaded annual salary costs would be about $3.4 million. This figure is taken as the first-year operation and maintenance portion of recurring costs; and, based on replacement costs, the first year annual costs associated with repair and replacement are $20.1 million for the CC-OTEC plant and $23.4 million for the OC-OTEC plant.

Excluding profits and credits, the break-even point for the baseline 50 MW CC-OTEC plant is given by a 15-year power purchase agreement for at least $0.19/kWh. Under a concessionary loan (2.5% over 20 years), the required amount would be $0.14/kWh.

In the case of the baseline OC-OTEC plant, there are two scenarios that illustrate the break-even point: (i) sell electricity for at least $0.15/kWh and water for $0.80 per cubic meter, or (ii) sell electricity for at least $0.07/kWh and water for $1.60 per cubic meter.

Table 11 Baseline 50-Megawatt Closed-Cycle Ocean Thermal Energy Conversion for Levelized Cost of Electricity under a Commercial Loan

Current-Dollar Levelization (constant annual cost)		
Inputs in Blue	**Output in Red**	
System Net Name Plate	53.5 MW	SOA Components
System Availability	92.3%	4 weeks downtime/ module
Site Annual Average Capacity Factor	100.0%	Design Selection
Annual Electricity Production	432,609 MWh	
Daily Desalinated Water Production	0.00 MGD	
	0 m^3/day	
Installed Cost (CC)	$451.00 million	8,430 $/kW
1st Year OMR&R	$23.50 million	
I, interest (current-dollar discount rate)	8.00%	
ER, annual escalation (inflation) rate for entire period	3.00%	All elements
N, system Life	15 years	
Capital Payment		
Investment Levelizing Factor for I and N (Capital Recovery Factor)	11.68%	
Levelized Investment Cost (CC x CRF)	$52.690 million	“Annual Amortization”
COE_{cc} : Fixed CC Component of COE	0.122 $/kWh	
OMR&R Costs		
Expenses Levelizing Factor for I, N, and Escalation (ELF)	1.22	
Capital Recovery Factory, f (I,N)	11.68%	
Present Worth Factor accounting for Inflation, f (I,ER,N)	10.5	
Levelized Expenses Cost (OMR&R x ELF)	$28.780 million	“Annual Levelized OMR&R”
$COE_{omr\&r}$: Levelized OMR&R Component of COE	0.067 $/kWh	
Total (CC + OMR&R) Levelized Annual Cost of Electricity Production	$81.470 million	

Total Levelized Cost of Electricity (no profit; no environmental or tax credits)
$COE = COE_{cc} + COE_{omr\&r} = 0.188$ $/kWh

CC = capital cost, COE = cost of electricity, CRF = capital recovery factor, kW= kilowatt, kWh = kilowatt-hour, m^3 = cubic meter, MGD = million gallons per day, MW =megawatt, MWh = megawatt-hour, OMR&R = operation and maintenance repair and replacement costs.

Source: Author.

Table 12 Baseline 50-Megawatt Open-Cycle Ocean Thermal Energy Conversion, Break-Even Electricity, and Water Rates Required under a Commercial Loan

Current-Dollar Levelization (constant annual cost)		
Inputs in Blue	**Output in Red**	
System Net Name Plate	51.25 MW	SOA Components
System Availability	92.3%	Experimental Plant
Site Annual Average Capacity Factor	100.0%	Design Selection
Annual Electricity Production	414,415 MWh	
Daily Desalinated Water Production	31.29 MGD	
	118,434 m^3/day	
Installed Cost (CC)	$551.00 million	10,751 $/kW
Yearly OMR&R	$26.80 million	
I, interest (current-dollar discount rate)	8.00%	
ER, annual escalation (inflation) rate for entire period	3.00%	All elements
N, system Life	15 years	
Capital Payment		
Investment Levelizing Factor for I and N (Capital Recovery Factor)	11.68%	
Levelized Investment Cost (CC x CRF)	$64.373 million	“Annual Loan Amortization”
OMR&R Costs		
Expenses Levelizing Factor for I, N and Escalation (ELF)	1.22	
Capital Recovery Factor, f (I,N)	11.68%	
Present Worth Factor accounting for Inflation, f (I,ER,N)	10.5	
Levelized Expenses Cost (OMR&R x ELF)	$32.821 million	“Annual Levelized OMR&R”
Total (CC + OMR&R) Annual Cost of Electricity and Water Production	**$97.194 million**	
		Rates
Breakeven Annual Sales (no profit, no credits)		
Electricity	$62.991 million	0.152 $/kWh
Water	$34.263 million	3.0 $/kilogallon
Total Annual Sales	**$97.254 million**	

CC = capital cost, COE = cost of electricity, CRF = capital recovery factor, kW= kilowatt, kWh = kilowatt-hour, m^3 = cubic meter, MGD = million gallons per day, MW =megawatt, MWh = megawatt-hour, OMR&R = operation and maintenance repair and replacement costs.

Source: Author.

Environmental Impact

OTEC may offer a benign power production technology, since the handling of hazardous substances is limited to the working fluid (e.g., ammonia for CC-OTEC), and no noxious by-products are generated. For example, the amount of carbon dioxide released from electricity-producing plants (expressed in grams of carbon dioxide per kilowatt-hour) ranges from 1,000 for coal-fired plants to 700 for fuel-oil plants, and 500 for natural gas plants. For OC-OTEC plants, it is at most about 1% of the amount released by fuel-oil plants. The value is even lower in the case of a CC-OTEC plant (Vega 2012; NOAA 2010).

To have effective heat transfer, it is necessary to protect the heat exchangers from biofouling. It has been determined that, with proper design, biofouling only occurs in CC-OTEC heat exchangers exposed to surface seawater. Therefore, it is only necessary to protect the CC-OTEC evaporators by, for example, intermittent chlorination (50–100 parts per billion chlorine for 1 hour per day). This amount is well below what is allowed under current United States regulations. The use of biocides and ammonia are similar to other human activities. If occupational health and safety regulations like those in effect in the United States are followed, working fluid and biocide emissions from a plant should be too low to detect outside of the plant sites. Ammonia is used as a fertilizer and in ice-skating rink refrigeration systems. Chlorine is used in municipal water treatment plants and in steam power plants. No chlorination is required in the OC-OTEC process (Vega 2012).

A sustained flow of cold, nutrient-rich, bacteria-free deep ocean water could cause sea surface temperature anomalies and biostimulation if resident times in the mixed layer and the euphotic zone, respectively, are long enough (i.e., upwelling). The euphotic zone is the upper layer of the ocean in which there is sufficient light for photosynthesis. This has been taken to mean the 1% light penetration depth (e.g., 120 m in Hawaiian waters). This is conservative, because most biological activity requires radiation levels of at least 10% of the sea surface value. Since light intensity decreases exponentially with depth, the critical 10% light penetration depth corresponds to, for example, 60 m in Hawaiian waters.

The analyses of specific OTEC designs indicate that mixed seawater returned at depths of 60 m results in a dilution coefficient of 4 (i.e., one part OTEC effluent is mixed with three parts of the ambient seawater) and equilibrium depths below the mixed layer throughout the year. This water return depth also provides the vertical separation, from the warm water intake at about 20 m, required to avoid reingestion into the plant. This value will vary as a function of ocean current conditions. It follows that the marine food web should be minimally affected and that persistent sea surface temperature anomalies should not be induced. These conclusions need to be confirmed with actual field measurements that could be performed with pilot plants.

Other potentially significant concerns are related to the construction phase. These are similar to those associated with the construction of any power plant, shipbuilding, and the construction of offshore platforms. OTEC operations may affect commercial and recreational fishing. Fish will be attracted to the plant, potentially increasing fishing in the area. However, the losses of inshore fish eggs and larvae, as well as juvenile fish, due to impingement, entrainment, and the discharge of biocides may reduce fish populations. The net effect of OTEC operation on aquatic life would depend on the balance achieved between these two effects. Through adequate planning and coordination with the local community, recreational assets near an OTEC site may be enhanced.

Potential environmental impacts must be evaluated, and all licensing and permitting requirements must be fulfilled. However, the only process that differentiates OTEC from other well-established human activities and industries is the use of ocean water drawn from 1,000 m depths and its return to the ocean below the photic zone. Given the intricate and dynamic nature of the ocean, it is nearly impossible to determine what would be the effect of such process through basic research or the development of ecological theory. The only way to evaluate the OTEC environmental differentiator is to obtain field data with a pilot plant operating with flow rates corresponding to at least a 5 MW plant. Such a plant must be operated and monitored through ongoing and adaptive experience for 1–2 continuous years.

Regulations

Currently, the only OTEC-specific regulations are found the United States. The 1980 OTEC Act gives the National Oceanic and Atmospheric Administration (NOAA) the authority to license the construction and operation of commercial OTEC plants. After the promulgation of the OTEC Act in 1981, licensing regulations were developed by NOAA, but NOAA rescinded these regulations in 1996 and eliminated its OTEC office, because no applications had been received. NOAA is currently in the process of developing new licensing regulations. Under the OTEC Act, NOAA is required to coordinate with coastal states and the United States Coast Guard as well as other federal agencies. An environmental impact statement is required for each license. It is expected that the majority of federal, state, and local requirements would be handled through the NOAA licensing process.

The original act gave the Secretary of Energy the authority to exempt test plants from NOAA's licensing requirements. A test plant was defined as "a test platform which will not operate as an OTEC facility or plantship after conclusion of the testing period." An environmental impact statement could be required if "there are other permits to be obtained that are considered a major federal action."

Incentives

There are no OTEC-specific incentives. However, some countries have energy production tax credits and feed-in tariffs for other renewable energy technologies such as wind, photovoltaic, waves, and small hydro. These could be extended to OTEC. In this context, it must be noted that OTEC is a base-load technology available every day of the year.

Conclusions and Recommendations

There are sufficient petroleum resources (about 1,400 billion barrels) to meet worldwide current demand for almost 50 years. Production, however, is peaking, and humanity will face a steadily diminishing petroleum supply and higher demand due to emerging economies like Brazil, the People's Republic of China, India, and the Russian Federation. Coal and natural gas resources can only meet current worldwide demand for 100 years and 120 years, respectively.

In theory, ocean thermal resources could be used to generate most of the energy required. The major challenge to OTEC implementation is posed by the need to secure financing for a capital-intensive technology without an operational record. How can a developer secure, for example, the more than $750 million for a 100 MW plant without a track record and without invoking national security, global warming, or environmental credits?

The next step requires the realistic determination of the costs and the potential global environmental impact of OTEC plants, and this can only be accomplished by deploying and subsequently monitoring operations with first-generation plants.

Ninety-eight nations and territories with access to the OTEC thermal resource within their 200-nautical mile EEZ have been identified. There is also a market for countries that could manufacture and supply the equipment required for OTEC plants. As outlined in this report, the worldwide resource, for example, is equivalent to plants of at least 7 terawatts or 70,000 plants of 100 MW capacity. Each 100 MW plant will require a capital investment of about $750 million, so the ultimate market, in a few decades, would be valued in the trillions of dollars.

Recommendations for future work regarding ocean thermal resources beyond this report are given in Table 13.

Table 13 Baseline Ocean Thermal Energy Conversion Potential in Developing Member Countries: Conclusions and Recommendations

	Theoretical Resource Availability	Equipment Siting Requirements	Additional Resource Information Needed	Equipment to Convert Resource into Electricity	Cradle-to-Grave Environmental Impact	Development Incentives	Overall Assessment	Overall Recommendation
OTEC	Yes, widely available	Water depths greater than 1,000 meters 100 MW plant housed in moored ship-shaped vessel the size of a standard super tanker Submarine power cable connected to land	Identify sites close to electricity distribution lines. Identify any ocean temperature data available from DMCs (vertical distribution to 1,000 meters).	Available off the-shelf but capital-intensive system	Not different from well-established technologies and ocean installations with the exception of submarine power cables, and seawater return to ocean below photic layer	Implement multiyear feed-in tariff for OTEC installations (base-load resource) Loan guarantees Target tariff of more than $0.25/kWh (for a greater than 50 MW plant) and $0.50/kWh (for a 10 MW plant)	Need to implement pilot plant to obtain operational record required to secure financing Appropriately sized OTEC plants could be available for DMCs in 5–10 years	Perform the tasks listed under Additional Resource Information Needed. Monitor progress of pilot projects and implementation of small plants on small islands.

DMC = developing member country, kWh = kilowatt-hour, MW = megawatt, OTEC = ocean thermal energy conversion.

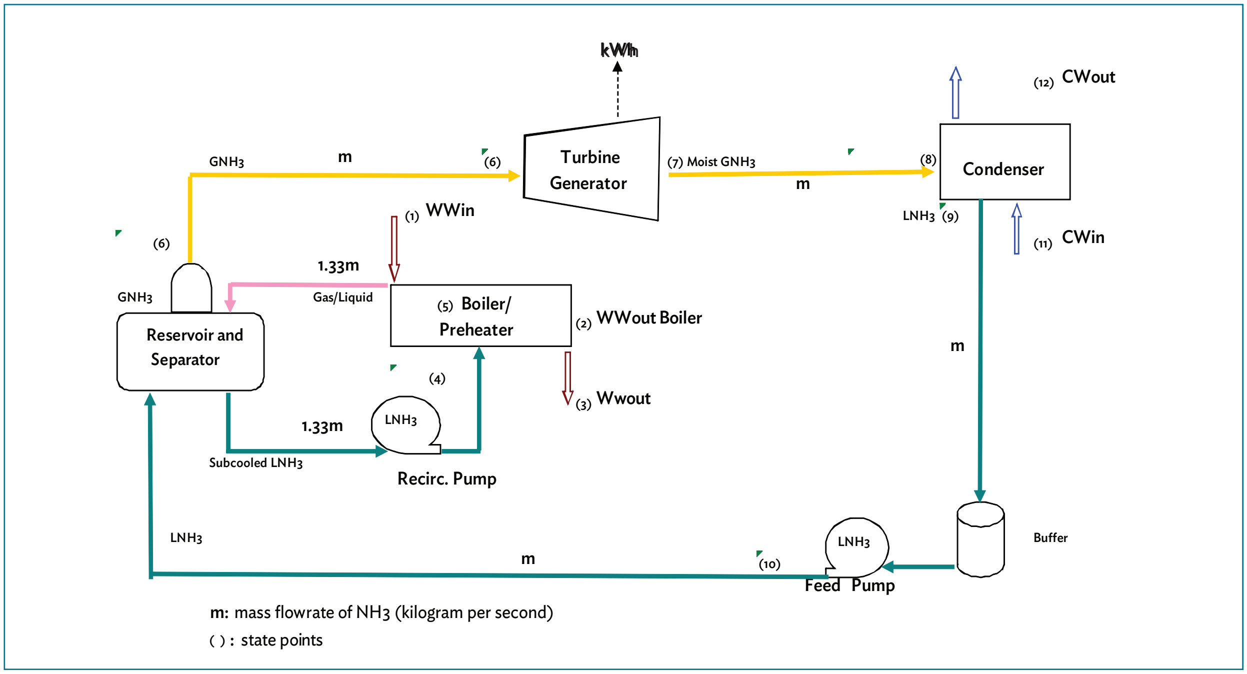
Source: Author

APPENDIX 1: STATE-OF-THE-ART OCEAN THERMAL ENERGY CONVERSION

Technology

In 1881, Arsene D'Arsonval documented a concept to use the relatively warm (i.e., 24°C–30°C) surface water of tropical oceans to vaporize pressurized ammonia through a heat exchanger and use the resulting vapor to drive a turbine generator. The cold ocean water transported to the surface from 800–1,000 meter (m) depths, with temperatures ranging from 8°C–4°C, would condense the ammonia vapor through another heat exchanger. D'Arsonval's concept is grounded in the thermodynamic Rankine cycle used to study steam power plants. Because the ammonia circulates in a closed loop, this concept was named closed-cycle ocean thermal energy conversion (CC-OTEC). The basic process diagram for CC-OTEC is depicted in Figure A1.1.

Figure A1.1 Closed-Cycle Ocean Thermal Energy Conversion Process Flow Diagram

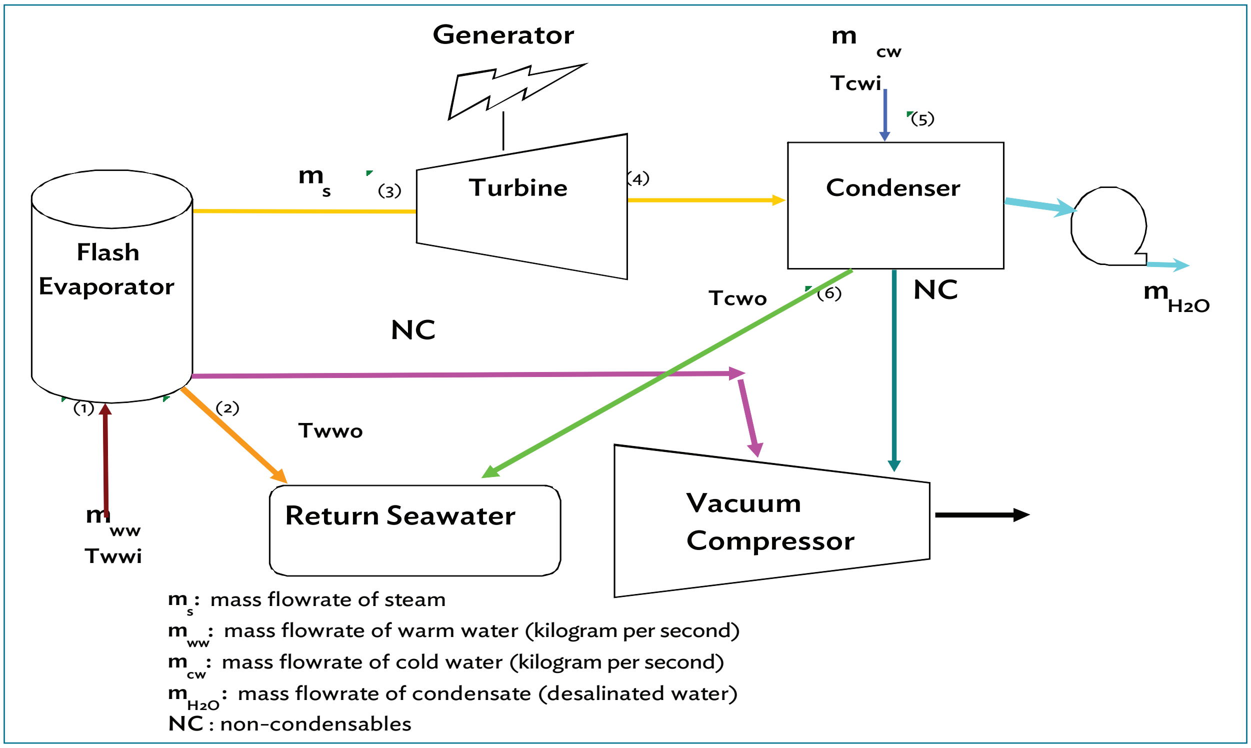


Source: Author.

D'Arsonval's concept was demonstrated in 1979, when Hawaii and a consortium of companies in the United States produced more than 50 kilowatts (kW) of gross power, with a net output of up to 18 kW from a small plant mounted on a barge off of Hawaii. Subsequently, a 100 kW gross power, land-based plant was operated in Nauru by a consortium of Japanese companies. These plants were operated for a few months to demonstrate the concept but were too small to be scaled to commercial systems (Vega 2012).

Forty years after D'Arsonval, Georges Claude, another French inventor, proposed to use ocean water as the working fluid. In Claude's cycle, the surface water is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine generator, and the relatively colder deep seawater is used to condense the steam after it has passed through the turbine. This cycle can, therefore, be configured to produce desalinated water as well as electricity. Claude's cycle is referred to as open-cycle ocean thermal energy conversion (OC-OTEC) because the working fluid flows once through the system.

Figure A1.2 Open-Cycle Ocean Thermal Energy Conversion Process Flow Diagram



Source: Author.

Claude demonstrated this cycle in Cuba in 1930 with a small land-based plant, making use of a direct-contact condenser. Therefore, desalinated water was not a by-product. However, although the plant operated for several weeks, it failed to achieve net power production due to poor site selection and a mismatch of the power and seawater systems.

Claude then designed a 2.2-megawatt (MW) floating plant for the production of up to 2,000 tons of ice (as this was prior to the wide availability of household refrigerators) for Rio de Janeiro. Claude housed his power plant in a ship about 100 kilometers offshore. Unfortunately, he failed in his numerous attempts to install the vertical long pipe required to transport the deep ocean water to the ship and had to abandon his enterprise in 1935. His failure can be attributed to the absence of the offshore industry and ocean engineering expertise presently available.

A small OC-OTEC land-based experimental facility in Hawaii has since been created (Vega and Evans 1994). The turbine generator was designed for an output of 210 kW for 26°C surface water and 6°C deep water. Ten percent of the steam produced was diverted to a surface condenser for the production of desalinated water. The experimental plant was successfully operated from 1993 to 1998. The highest production rates achieved were 255 kW with a corresponding net power of 103 kW and 0.4 liters per second of desalinated water. These are world records for ocean thermal energy conversion (OTEC).

A two-stage OTEC hybrid cycle, wherein electricity is produced in a first stage (i.e., closed cycle) followed by water production in a second stage, has been proposed to maximize the use of the thermal resource available to produce water and electricity (Vega 2012). In the second stage, the temperature difference available in the seawater effluents from an OTEC plant (e.g., 12°C) is used to produce desalinated water through a system consisting of a flash evaporator and a surface condenser (basically, an open cycle without a turbine generator). In the case of an open-cycle plant, the addition of a second stage results in doubling water production.

The use of the cold deep water as the chiller fluid in air-conditioning systems has also been proposed and implemented (Syed, Nihous, and Vega 1991). It has been demonstrated that these systems, referred to as seawater air-conditioning, provide significant energy conservation and have been installed independently of OTEC.

OTEC energy can be transported via chemical, thermal, and electrochemical carriers. The technical evaluation of nonelectrical carriers led, for example, to the consideration of hydrogen produced using electricity and desalinated water generated with OTEC technology. The product would be transported from the OTEC plantship, located at distances of about 1,500 kilometers to the port facility, in liquid form to be primarily used as transport fuel. A 100 MW-net plantship can be configured to yield by electrolysis 1,300 kilograms per hour of liquid hydrogen. The production cost of liquid hydrogen delivered to the harbor would be equivalent to about $400 barrel of crude oil (i.e., about four times present cost). The situation is similar for the other energy carriers considered (e.g., anhydrous ammonia). Presently, the only energy carrier that is cost-effective for OTEC energy is a submarine power cable. This situation would be different in future decades in the post-fossil fuels era.

A number of possible configurations for OTEC plants have been proposed. These range from floating plants to land-based plants, including shelf-mounted towers and other offshore structures. The primary candidate for commercial plants appears to be the floating plant, positioned close to land, transmitting power to shore via a submarine power cable (NOAA 2009).

Two decades ago, the detailed evaluation of economic feasibility and financial viability of OTEC revealed that, in general, plants would have to be sized at about 50–100 MW to produce cost-competitive base-load electricity (Vega 2010), although smaller plants could be cost-effective in some niche markets (Nihous, Syed, and Vega 1989). It was also concluded that, although experimental work with relatively small plants had demonstrated continuous production of electricity and desalinated water, it would be necessary to build a pilot plant sized around 5–10 MW to establish the operational record required to secure financing for commercial plants. The plant would produce relatively high-cost electricity and desalinated water so that support funding was required from governments. Unfortunately, development did not proceed beyond experimental plants sized at less than 0.25 MW.

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

Limitations and Challenges

The performance of OTEC cycles is assessed with the same thermodynamic concepts used for conventional steam power plants. The major difference arises from the large quantities of warm and cold seawater required for heat transfer processes, resulting in the consumption of a portion of the power generated by the turbine generator in the operation of pumps. The power required to pump seawater is determined accounting for the pipe fluid frictional losses and, in the case of the cold seawater, for the density head (i.e., gravitational energy due to the differences in density between the heavier, colder water inside the pipe and the surrounding water column). The seawater temperature rise, due to frictional losses, is negligible for practical designs.

The ideal energy conversion for 26°C and 4°C warm and cold seawaters is 8%. An actual OTEC plant will transfer heat irreversibly at various points in the cycle, yielding an energy conversion of 3%–4%. These values are small compared to efficiencies obtained for conventional power plants; however, OTEC uses a resource that is constantly renewed by the sun.

The thermal performance of CC-OTEC and OC-OTEC is comparable. As a reference, consider a 10 MW CC-OTEC plant. The seawater flow rates are 27.7 cubic meters per second (m^3/s) (28,450 kilograms/second [kg/s]), of 4.5°C cold water drawn from a depth of 1,000 m; and, 52.8 m^3/s (54,000 kg/s) 26°C warm water drawn from a depth of about 20 m, with an output of 16 MW at the generator terminals (P_{gross}) with 5.3 MW (P_{loss}) required to pump seawater and the working fluid (e.g., anhydrous ammonia) through the plant. The net output (P_{net}) would, therefore, be 10.7 MW. To keep pumping losses at about 30% of P_{gross}, an average speed of less than 2 m per second is considered for the seawater flowing through the pipes transporting the seawater resource to the OTEC power block. OTEC design parameters are, therefore, generalized as follows:

- In-house or parasitic electrical loads P_{loss} represent about 30% of P_{gross}, such that the exportable power (P_{net}) is about 70% of P_{gross};.
- A cold-water flow rate (Q_{cw}) of 2.7 m^3/s is required per MW_{net};.
- The optimal warm water flow rate (Q_{ww}) is about 1.9 x Q_{cw}.

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

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

where β and P_{loss} are system-specific. Considering nominal values, it can be shown that a 1°C change in ΔT leads to a change of about 15% in P_{net}.

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

The design and installation of a cost-effective pipe to transport large quantities of cold water to the surface (i.e., a cold-water pipe) presented an engineering challenge of significant magnitude complicated by a lack of experience. This challenge was met in the United States with a program relying on computer-aided analytical studies integrated with laboratory and at-sea tests. The greatest outcome achieved has been the design, fabrication, transport, deployment, and at-sea test of an instrumented 2.4 m diameter, 120 m long, fiberglass-reinforced plastic sandwich construction pipe attached to a barge (Vega 2012). The data obtained were used to validate the design technology developed for pipes suspended from floating OTEC plants. This type of pipe is recommended for floating OTEC plants.

For land-based plants, there is a validated design for high-density polyethylene pipes of a diameter of less than about 2 m (Nihous, Syed, and Vega 1989). In the case of larger-diameter pipes, offshore techniques used to deploy large segmented pipes made of steel, concrete, or fiberglass-reinforced plastic are applicable. Pressurized pipes made of reinforced elastomeric fabrics (i.e., soft pipes), with pumps located at the cold-water intake, seem to offer an innovative alternative to conventional concepts. However, the operability of pumps in 800–1,000 m water depths over extended periods must be verified and the inspection, maintenance, and repair constraints established before soft pipes can be used in practical designs.

Other components for OTEC floating plants that present engineering challenges are the position-keeping system and the attachment of the submarine power cable to the floating plant. Deep ocean-mooring systems, designed for water depths of more than 1,000 m, or dynamic-positioning thrusters developed by the offshore industry can be used for position keeping. The warm water intake and the mixed return water also provide the momentum necessary to position the surface vessel (Nihous and Vega 1993). The offshore industry also provides the engineering and technological backgrounds required to design and install the riser for submarine power cables.

The design of OTEC cold-water pipes, mooring systems, and submarine power cables must consider survivability loads as well as fatigue-induced loads. The first kind is based on extreme environmental phenomena, with a relatively long return period, that may result in ultimate strength failure. The second may result in fatigue-induced failure through normal operations.

Important lessons learned from these experiences can be summarized as follows:[1]

- All components must be considered in technical and economic assessments, as OTEC plants consist of several components or subsystems that must be integrated into a system.

- The entire lifecycle must be incorporated into the design process.

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[1] Note that these lessons are also applicable to the development of wave energy conversion devices.

- Equipment must be manufactured using commercially available practices in existing factories.
- Embellishment leads to negative consequences, creating credibility barriers for others and unrealistic expectations from the public.

Other significant lessons learned (or relearned) and observations from the perspective of an operator of the OTEC experimental plant facility were the following:

- make the plant user-friendly from the standpoint of troubleshooting, maintenance, repair, and modification;
- include technical field support from suppliers of major equipment, but be prepared to solve most problems on your own;
- select equipment with excess capacity, as it is appropriate to optimize design point performance but there will always be off-design operations requiring additional capacity;
- if equipment has moving parts, evaluate the bearing system and ask the potential supplier to provide references of successful application of its design before purchase;
- consider the corrosive saltwater, condensate, and typically harsh environment of OTEC sites when making design decisions, especially regarding material selection and placement of mechanical and electrical equipment; and
- avoid metal components, but, if unavoidable, use the hot dip-galvanized process from a factory with proven quality-control procedures.

Economics

The analytical model available to estimate the levelized cost of electricity production can be used to assess scenarios under which OTEC might be competitive with conventional technologies (Vega 2010). First, the OTEC capital cost is estimated. Subsequently, the relative cost of producing electricity, offset by the desalinated water production revenue, is equated to the fuel cost of electricity produced with conventional techniques to determine the scenarios (i.e., fuel cost and cost of freshwater production) under which OTEC could be competitive. For each scenario, the cost of desalinated water produced from seawater via reverse osmosis is estimated to set the upper limit of the OTEC water production credit. No attempt is made at speculating about the future cost of fossil fuels. It is simply stated that if a location is represented by one of the scenarios, OTEC could be competitive.

In this fashion, two distinct markets are identified: (i) industrialized nations, and (ii) small island developing states with modest needs for power and freshwater. OC-OTEC plants could be sized at 1–10 MW, with 450,000–9.2 million gallons of freshwater per day (1,700–35,000 cubic meters per day) to meet the needs of developing communities with populations ranging from 4,500 to 100,000. This range encompasses the majority of small island developing states throughout the world, and specifically Pacific island developing member countries.

Floating plants of at least 50 MW capacity would be required for larger developing member countries such as the Philippines. These would be moored or dynamically positioned a few kilometers from land, transmitting the electricity to shore via submarine power cables. The moored vessel could also house an OC-OTEC plant and transport the desalinated water produced via flexible pipes (Vega 2012).

It was also established that OTEC-based, mariculture operations and air-conditioning systems could only make use of a small amount of the seawater available and therefore, could only impact small plants. The use of energy carriers (e.g., hydrogen or ammonia) to transport OTEC energy generated in floating plants, drifting in tropical waters, was determined to be technically feasible but requiring increases in the cost of fossil fuels equivalent to $400 per barrel to be cost-competitive.

Presently, the external costs of energy production and consumption are not included in the determination of the charges to the consumer. Considering all stages of generation, from initial fuel extraction to plant decommissioning, no energy technology is completely environmentally benign. The net social costs of the different methods of energy production continue to be a topic under study. Estimates of costs due to corrosion, health impacts, crop losses, radioactive waste, military expenditures, employment loss, and subsidies (e.g., tax credits and research funding for present technologies) are found in the literature. In the United States, for example, the range of all estimates is equivalent to adding $80–$400 per barrel. Accounting for these externalities might eventually help the development and expand the applicability of OTEC, but in the interim the scenarios summarized earlier should be considered as the market entry point.

The industry did not take advantage of the information, because in the 1990s, the prices of oil fuels and coal were such that conventional power plants produced cost-effective electricity (excluding externalities). Moreover, the power industry would only invest in plants whose designs were based on similar plants with an operational record. It was concluded that before OTEC could be commercialized, a prototypical plant must be built and operated to obtain the information required to design commercial systems and to gain the confidence of the financial community.

Conventional power plants pollute the environment more than an OTEC plant would, and the fuel for OTEC is vast and free, as long as the sun heats the oceans. However, it is futile to use these arguments to convince the financial community to invest in an OTEC plant without operational records.

Capital Costs

OTEC archival information can be converted to present-day costs using the United States 20-year average for equipment price index inflation. Current technical specifications for 10, 50, and 100 MW OTEC plants were used to solicit budgetary quotes. All estimates are summarized in Table A1.1 and in Figure A1.3.

Table A1.1 First-Generation Ocean Thermal Energy Conversion Plant Capital Cost Estimates

Nominal Plant Size (MW-net)	Installed Capital Cost ($/kW)	Land/Floater	Source (Extrapolated)
1.4	41,562	L	Vega (1992)
5	22,812	L	Wenzel (1995)
5.3	35,237	F	Vega et al. (1994)
10	24,071	L	Vega (1992)
10	18,600	F	Vega (2010)
35	12,000	F	"
50	11,072	F	Vega (1992)
53.5	8,430	F	Vega (2010)
100	7,900	F	"

kW = kilowatt, MW = megawatt.

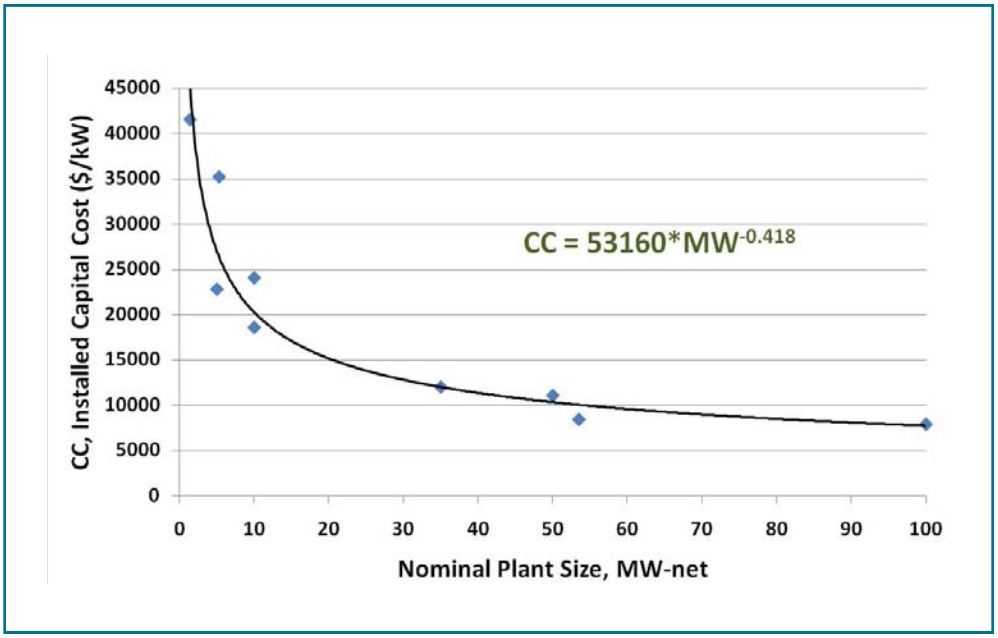
Note: Extrapolated archival estimates (1 –50 MW) and current estimates (10–100 MW) in $/kW-net.

These estimates are applicable for equipment purchased in the Europe, Japan, and the United States and with installation by firms from the United States. Deployment and installation costs are included. Based on the implementation of similar technologies, later-generation designs may reach cost reductions of as much as 30%. However, the premise herein is to indicate that first-generation plants can be cost-effective under certain scenarios, if the cost estimates presented are met.

Figure A1.3 illustrates that OTEC capital cost is a strong function of plant size. For convenience and future reference, a least-squares curve fit is provided:

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

Figure A1.3 Capital Cost Estimated for First-Generation Closed-Cycle Ocean Thermal Energy Conversion Plants



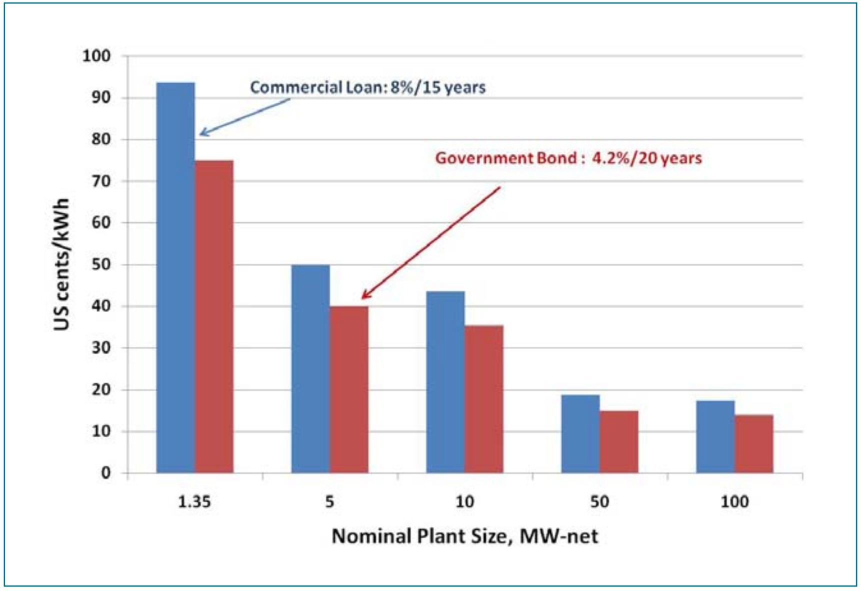
CC = capital cost, kW = kilowatt, MW = megawatt.

Source: L. Vega. 2010. Economics of Ocean Thermal Energy Conversion (OTEC): An Update. Paper presented at the Offshore Technology Conference. Houston. 3–6 May.

A 100 MW OTEC plant, for example, could be housed in a floating platform stationed less than 10 kilometers offshore, and would have the capability of delivering 800 million kilowatt-hours (kWh) to the electrical grid every year. Budgetary quotes from potential equipment suppliers indicate that the installed cost would be $790 million using state-of-the-art components.

The annual costs for operation and maintenance, including repairs and equipment replacement, are estimated at $40 million (Table A1.2), such that under realistic financing terms (e.g., a 15-year loan at 8% annual interest and 3% average annual inflation), electricity could be produced at a levelized cost of less than $0.18/kWh. Therefore, a power purchase agreement from the utility at around $0.20/kWh would include an ample return on investment. If the plant could be funded via government bonds at a realistic rate of 4.2% over 20 years, the cost of electricity would be $0.14/kWh.

Figure A1.4 Levelized Cost of Electricity Production for First-Generation Closed-Cycle Ocean Thermal Energy Conversion Plants



kWh = kilowatt-hour, MW = megawatt.
Note: Annual inflation assumed constant at 3%.

Table A1.2 Levelized Cost of Electricity for Closed-Cycle Ocean Thermal Energy Conversion Plants

Identifier Nominal Size (MW)	Capital Cost ($/kW)	O&M ($ million/ year)	R&R ($ million/ year)	COE_{cc} (¢/kWh)	$COE_{omr\&r}$ (4/kWh)	COE (¢/kWh)
1.35	41,562	2.0	1.0	60	38.7	94.0
5	22,812	2.0	3.5	33	17	50.0
10	18,600	3.4	7.7	26.9	16.8	44.0
53.5	8,430	3.4	20.1	12.2	6.7	19.0
100	7,900	3.4	36.5	11.4	6	18.0

8%/15 years

COE = cost of electricity, kW = kilowatt, kWh = kilowatt-hour, MW = megawatt, O&M = operation and maintenance
OMR&R = operation maintenance repair and replacement, R&R = repair and replacement.

Notes: With capital costs amortized through an 8%, 15-year loan and annual inflation at 3%, considering United States labor rates for operation and maintenance and first-year repair and replacement cost as indicated. The first two entries are land-based with lower operation and maintenance.

Source: L. Vega. 2010. Economics of Ocean Thermal Energy Conversion (OTEC): An Update. Paper presented at the Offshore Technology Conference. Houston. 3–6 May.

A 50-megawatt ocean thermal energy conversion plantship. The capital costs estimated for 50 MW OTEC first-generation plants utilizing either closed-cycle or open-cycle technology are summarized in Table A1.3. The estimate is $451 million for the CC-OTEC plant and $551 million for the OC-OTEC plant. The CC-OTEC plant would require a 198 m ship-shaped platform with a 39 m beam and an operating draft of 16 m, resulting in a 120,600-ton displacement. The OC-OTEC plant would be shorter at 176 m but the beamer would be at 90 m resulting in a displacement of 247,400 tons.

The plantship required for the CC-OTEC system is comparable to typical double-hulled vessels and could be constructed in numerous shipyards throughout the world. The OC-OTEC system, incorporating desalinated water production, requires a vessel that is about three times wider (beam direction) than the standard tanker and container ships and may limit the number of shipyards with appropriate fabrication capabilities.

The combined needs for large amounts of cold seawater (138.6 m^3/s), and minimal pumping power losses result in a relatively large-diameter cold-water pipe. A 1,000 m long, 8.7 m inside diameter fiberglass-reinforced plastic sandwich construction cold-water pipe was selected. This will be attached to a gimbal at midship. Applicable single-point mooring systems, including electrical and fluid swivels, are available from the offshore industry. The aluminum plate-fin heat exchangers, considered for the ammonia cycle, can be manufactured in the United States. The electricity is transmitted to shore via a submarine power cable and the desalinated water via a flexible pipe (e.g., hose). Several firms manufacture the submarine power cable required for the OTEC plant.

Given that the cost of a ship-shaped vessel is proportional to displacement, the OC-OTEC platform subsystem (excluding other subsystems) would cost twice as much as the CC-OTEC platform. Costs associated with all other subsystems (e.g., power block, seawater pipes, pumps, submarine power cable, mooring, and positioning) are approximately the same for the CC-OTEC and the OC-OTEC designs. Therefore, the capital cost estimate of the OC-OTEC design is higher by an amount given by the platform cost differential. It follows that concept selection is site-specific depending on the value of the desalinated water product.

The CC-OTEC plant can support a population of 500,000 with a per capita daily consumption of 2.3 kWh. This value is representative of the all-encompassing per capita consumption in some developing countries. In addition, the OC-OTEC system could also supply 240 liters per day per capita. The per capita water consumption in some developing countries, for example, is estimated at 160 liters day in the domestic sector and 940 liters day for all sectors (i.e., domestic, industrial, and agricultural).

Table A1.3 50-Megawatt Closed-Cycle and Open-Cycle Ocean Thermal Energy Conversion Capital Cost Estimates

	Closed Cycle				
Size	53.5 MW-net				
Date	Feb 2009				
Component	$ million	$/kW	Percentage	Ops 1st Year ($ million)	Replacement 1st Year ($ million)
Floating Vessel	100	1,869	22%		3.3
Mooring	24	449	5%		0.8
Submarine Power Cable (10 km)	41	766	9%		1.4
Seawater Pipes Installed	60	1,121	13%		2.0
Seawater Pumps Installed	24	449	5%		1.6
Power Block (15 MW-gross modules)					
Heat Exchangers	95	1,776	21%		6.3
Turbine-Generator	33	617	7%		2.2
Electrical/NH3/Cl2/Controls	31	579	7%		1.0
Installation Mechanical and Electrical	43	804	10%		1.4
All Components Total	**451**	**8,430**	**100%**	**3.4**	**20.1**
					15-year 30-year

Cl2 = chlorine, km = kilometer, kW = kilowatt, MW = megawatt, NH3 = ammonia.

Notes:

Capital Cost

* Vega's archival information for manufacturers from the European Union, Japan, and the United States.
* At the conceptual level, the capital cost for the open cycle plant will double the cost of a floating vessel.
* Assume the sum of all other cost are equivalent to closed cycle. Therefore, the capital cost for the open cycle plant is $551 million.

Operations, Maintenance, Repair, and Replacement (OMR&R)

* A total staff of 17 is required to manage and operate the floating plant in shifts 24/7.
Using United States labor rates, the operations and maintenance portion for the first year is $3.4 million (for both open cycle ocean thermal energy conversion and closed cycle ocean thermal energy conversion).
* To estimate the repair and replacement (R&R) portion for the first year: pumps, heat exchangers, and turbine generators replaced in 15-years; all other components in 30 years.
First-year estimate for R&R portion is (as given in table) $20.1 million for CC-OTEC and $23.4 million for OC-OTEC.
If vessel and heat exchangers are manufactured in the People's Republic of China, the R&R portion would be $17.7 million instead of $20.1 million.

Source: Author.

Electricity and desalinated water production rates are given in Table A1.4. The products are 432,609 megawatt-hours per year for the CC-OTEC, and 414,415 megawatt-hours per year and 118,434 cubic meters per day for the OC-OTEC.

Table A1.4 Electricity and Desalinated Water Production Rates for Open-Cycle and Closed-Cycle Ocean Thermal Energy Conversion

System	Electricity (MWh/year)	Water (m³/day)	Capital Cost ($/kWnet)
Closed Cycle	**432,609**	**0**	**8,430**
(53.5 MW)			
Open Cycle	**414,415**	**118,434**	**10,751**
(51.25 MW)			
(1,485 kg/s)			

kg = kilogram, kW = kilowatt, MW = megawatt, MWh = megawatt-hour, s = second.

Source: Author.

Operational Costs and Cost of Production

The methodology used to estimate the cost of electricity production is documented in Appendix 2. The cost of electricity is defined by adding the amortized annual capital loan repayment divided by the annual production to the annual levelized cost incurred due to operation, maintenance, repair, and equipment replacement divided by the annual electricity production.

These levelized costs were estimated for an 8%, 15-year commercial loan. Figure A1.5 includes the cost of electricity for a capital improvement loan based on government bonds (e.g., in Hawaii a 4.2%, 20-year rate is realistic). All cases consider a fixed inflation rate of 3%.[2] Figure A1.5, for example, can be used to determine the CC-OTEC plant size that would be cost-competitive in a specific location. Presently, in Hawaii, for example, costs less than about $0.20/kWh must be achieved and, therefore, plants larger than about 50 MW are required. In the case of American Samoa, a 35 MW plant (not included in Figure A1.5) would be cost-competitive, producing about 282,000 MWh to meet current and forecast demand under a power purchase agreement at $0.25/kWh for 15 years.

50-megawatt ocean thermal energy conversion plants. Using as input the capital costs given in Table A1.3 for 50 MW plants, the levelized costs of production can be determined for the CC-OTEC plant (Table A1.5). In the case of the OC-OTEC plant, the combination of electricity rate and desalinated water rate required to break even can be estimated (Table A1.6).

An 8% loan over 15 years was considered for the capital investment, and, for the operation, maintenance, repair, and equipment replacement costs, current-dollar levelization was evaluated at a fixed annual inflation rate of 3%. For continuous operation of OTEC plantships, a crew of 17 full-time employees is required. This includes 1 administrator and 16 operators for the power plant and the ship systems. Eight operators would be on duty at one time while the other eight rest. The administrator works a regular schedule. Using United States labor rates, annual salary costs would be about $3.4 million. This figure is taken as the first-year operation and maintenance portion of recurring costs. Based on replacement costs for the capital investment, the first year annual costs associated with repair and replacement are $20.1 million for the CC-OTEC plant (Table A1.5) and $23.4 million for the OC-OTEC plant (Table A1.6).

As shown in Table A1.4, excluding profits and credits, the break-even point (i.e., levelized annual costs = annual revenue) for the 50 MW CC-OTEC plant is given by a 15-year power purchase agreement for at least $0.19/kWh.

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[2] This corresponds to the 20-year US average, 1988–2007.

In the case of the OC-OTEC plant, there are two (of many) scenarios that illustrate the break-even point: (i) sell electricity for at least $0.15/kWh and water for $0.80 per cubic meter, or (ii) sell electricity for at least $0.07/kWh and water for $1.60 per cubic meter.

It must be emphasized that the economic analysis summarized here is based in capital and operational cost applicable in the United States.

Table A1.5 50-Megawatt Closed-Cycle Ocean Thermal Energy Conversion, Levelized Cost of Electricity Production

Current-Dollar Levelization (constant annual cost)		
Inputs in Blue	**Output in Red**	
System Net Name Plate	53.5 MW	SOA Components
System Availability	92.3%	4 weeks downtime/ module
Site Annual Average Capacity Factor	100.0%	Design Selection
Annual Electricity Production	432,609 MWh	
Daily Desalinated Water Production	0.00 MGD	
	0 m^3/day	
Installed Cost (CC)	$451.00 million	8,430 $/kW
1st Year OMR&R	$23.50 million	Table 3
I, interest (current-dollar discount rate)	8.00%	
ER, annual escalation (inflation) rate for entire period	3.00%	All elements
N, system life	15 years	
Capital Payment		
Investment Levelizing Factor for I and N (Capital Recovery Factor)	11.68%	
Levelized Investment Cost (CC x CRF)	$52.690 million	"Annual Amortization"
COE_{cc} : Fixed CC Component of COE	0.122 $/kWh	
OMR&R Costs		
Expenses Levelizing Factor for I, N and Escalation (ELF)	1.22	
Capital Recovery Factory, f (I,N)	11.68%	
Present Worth Factor accounting for Inflation, f (I,ER,N)	10.5	
Levelized Expenses Cost (OMR&R x ELF)	$28.780 million	"Annual Levelized OMR&R"
$COE_{omr\&r}$: Levelized OMR&R Component of COE	0.067 $/kWh	
Total (CC + OMR&R) Levelized Annual Cost of Electricity Production	$81.470 million	

Total Levelized Cost of Electricity (no profit; no environmental or tax credits)
$COE = COE_{cc} + COE_{omr\&r} = 0.188$ $/kWh

CC= capital cost, COE= cost of electricity, CRF= capital recovery factor, kW= kilowatt, kWh= kilowatt-hour, m^3 = cubic meter, MGD= million gallons per day, MW=megawatt, MWh=megawatt-hour, OMR&R= operation and maintenance repair and replacement costs.

Source: Author.

Table A1.6 50-Megawatt Open-Cycle Ocean Thermal Energy Conversion, Breakeven Electricity, and Water Rates Required

Current-Dollar Levelization (constant annual cost)		
Inputs in Blue	**Output in Red**	
System Net Name Plate	51.25 MW	SOA Components
System Availability	92.3%	Experimental Plant
Site Annual Average Capacity Factor	100.0%	Design Selection
Annual Electricity Production	414,415 MWh	
Daily Desalinated Water Production	31.29 MGD	
	118,434 m^3/day	
Installed Cost (CC)	$551.00 million	10,751 $/kW
Yearly OMR&R	$26.80 million	Table 3
I, interest (current-dollar discount rate)	8.00%	
ER, annual escalation (inflation) rate for entire period	3.00%	All elements
N, system life	15 years	
Capital Payment		
Investment Levelizing Factor for I and N (Capital Recovery Factor):	11.68%	
Levelized Investment Cost (CC x CRF):	$64.373 million	"Annual Loan Amortization"
OMR&R Costs		
Expenses Levelizing Factor for I, N and Escalation (ELF)	1.22	
Capital Recovery Factor, f (I,N)	11.68%	
Present Worth Factor accounting for Inflation, f (I,ER,N)	10.5	
Levelized Expenses Cost (OMR&R x ELF)	$32.821 million	"Annual Levelized OMR&R"
Total (CC + OMR&R) Annual Cost of Electricity and Water Production	$97.194 million	
		Rates
Breakeven Annual Sales (no profit, no credits)		
Electricity	$62.991 million	0.152 $/kWh
Water	$34.263 million	3.0 $/kilogallon
Total Annual Sales	$97.254 million	

CC = capital cost, COE = cost of electricity, CRF = capital recovery factor, kW = kilowatt, kWh = kilowatt-hour, m3 = cubic meter, MGD = million gallons per day, MW = megawatt, MWh = megawatt-hour, OMR&R = operation and maintenance repair and replacement costs.

Note: One of many scenarios given here with $0.152/kWh and $0.80/$m^3$ ($3/kilogallon).

Source: Author.

Site Selection

The OTEC concept utilizes the differences in temperature, ΔT, between the warm (T_w ~ 22°C–29°C) tropical surface waters and the cold (T_c ~ 4°C–5°C) deep ocean waters available at depths of about 1,000 m, as the source of the thermal energy required.

Deep seawater flows from the polar regions. These polar waters, which represent up to 60% of all seawater, originate mainly from the Arctic for the Atlantic and North Pacific oceans, and from the Antarctic (Weddell Sea) for all other major oceans. Therefore, T_c at a given depth, approximately below 500 m, does not vary much throughout all regions of interest for OTEC. It is also a weak function of depth, with a typical gradient of 1°C per 150 m between 500 m and 1,000 m. These considerations may lead to regard T_c as nearly constant, with a value of 4°C–5°C at 1,000 m (Vega 2012; Rajagopalan and Nihous 2013).

A desirable OTEC thermal resource of at least 20°C requires typical values of T_w of the order of 25°C. Globally speaking, regions between latitudes 20°N and 20°S are adequate. Some definite exceptions exist due to strong cold currents: along the west coast of South America, tropical coastal water temperatures remain below 20°C, and are often of the order of 15°C; a similar situation prevails to a lesser extent for the west coast of Southern Africa. Moreover, T_w varies throughout the year, and sometimes exhibits a significant seasonal drop due to the upwelling of deeper water induced by the action of the wind. A careful OTEC site selection requires a comprehensive knowledge of local climate features inasmuch as they may affect T_w seasonally.

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

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

The most recent, 2005 version of the World Ocean Atlas compiled by the United States National Ocean Data Center represents a valuable source of objectively analyzed statistical fields, including ocean temperature. The data include long-term historical averages of variables that have been determined from all available oceanographic measurements. Monthly averages also are available. The data are provided with a resolution of 0.25° latitude by 0.25° longitude. The historical monthly averages of ΔT for February 2005 are depicted in Figure A1.5 and for August 2005 in Figure A1.6. The annual average values are given in Figure A1.7.

For this report, site-specific field measurements performed by the Philippines Navy near Cabangan were made available by Energy Island and found to validate the vertical temperature distribution extracted from the World Ocean Atlas (Figure A1.8). This is an important finding given that the ocean thermal resource potential evaluated herein for developing member countries using the World Ocean Atlas as the primary reference.

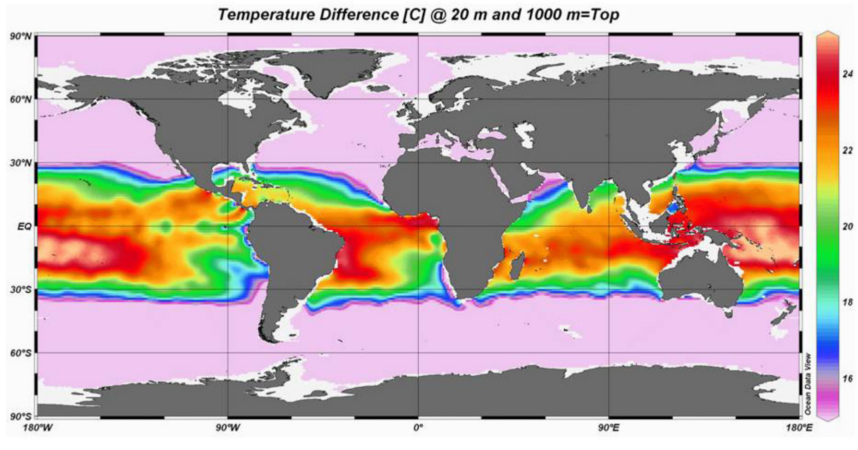
The accessibility of deep cold seawater represents the most important physical criterion for OTEC site selection, once the existence of an adequate thermal resource has been established. In the case of a floating plant, the issue of cold seawater accessibility is only relevant inasmuch as submarine power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

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

This brings out an interesting question about the size of the OTEC resource: Could a massive deployment of this technology affect ocean temperatures on which the process itself depends? In other words, could OTEC be self-limiting?

Recent analysis using a 3-D oceanic general circulation model to account for the complex interplay between planetary heat fluxes and potentially large OTEC intakes and discharges spread over more than 100 million square kilometers confirmed a 30-terawatt maximum for global OTEC power production (Rajagopalan and Nihous 2013). As OTEC flow rates increase, the erosion of vertical seawater temperature gradients is much slower in 3-D ocean models, because any heat locally added to the system can be horizontally transported and redistributed at a relatively fast rate. Another distinctive feature of the model results is the persistence of slightly cooler surface waters in the OTEC region. This is compensated, however, by a warming trend at higher latitudes. A boost of the planetary circulation responsible for the overall supply of deep cold seawater is also shown. A more modest OTEC scenario with a global potential of the order of 7 terawatts shows little impact (Rajagopalan and Nihous 2013). It must be noted that the baseline commercial size OTEC plant is sized at 100 MW, so 70,000 plants corresponds to 7 terawatts.

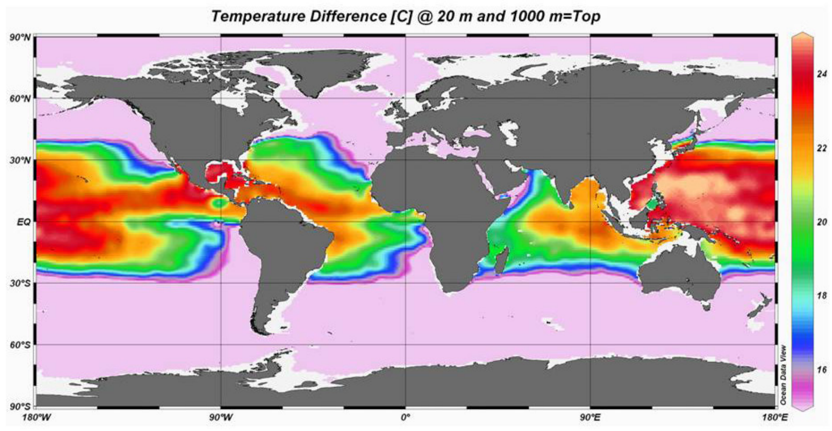
Figure A1.5: Historical Monthly Average of ΔT, February 2005



m = meter.

Source: G. Nihous. 2010. Mapping Available Ocean Thermal Energy Conversion Resources around the Main Hawaiian Islands with State-of-the-Art Tools. *Journal of Renewable and Sustainable Energy*. 2 (043104).

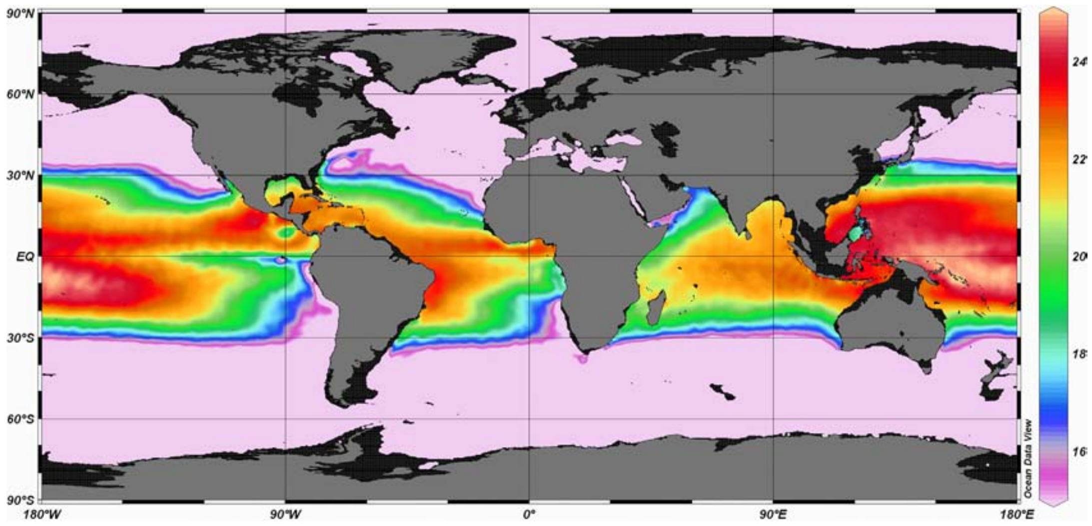
Figure A1.6 Historical Monthly Average of ∆T, August 2005



m = meter.

Source: G. Nihous. 2010. Mapping Available Ocean Thermal Energy Conversion Resources around the Main Hawaiian Islands with State-of-the-Art Tools. *Journal of Renewable and Sustainable Energy*. 2 (043104).

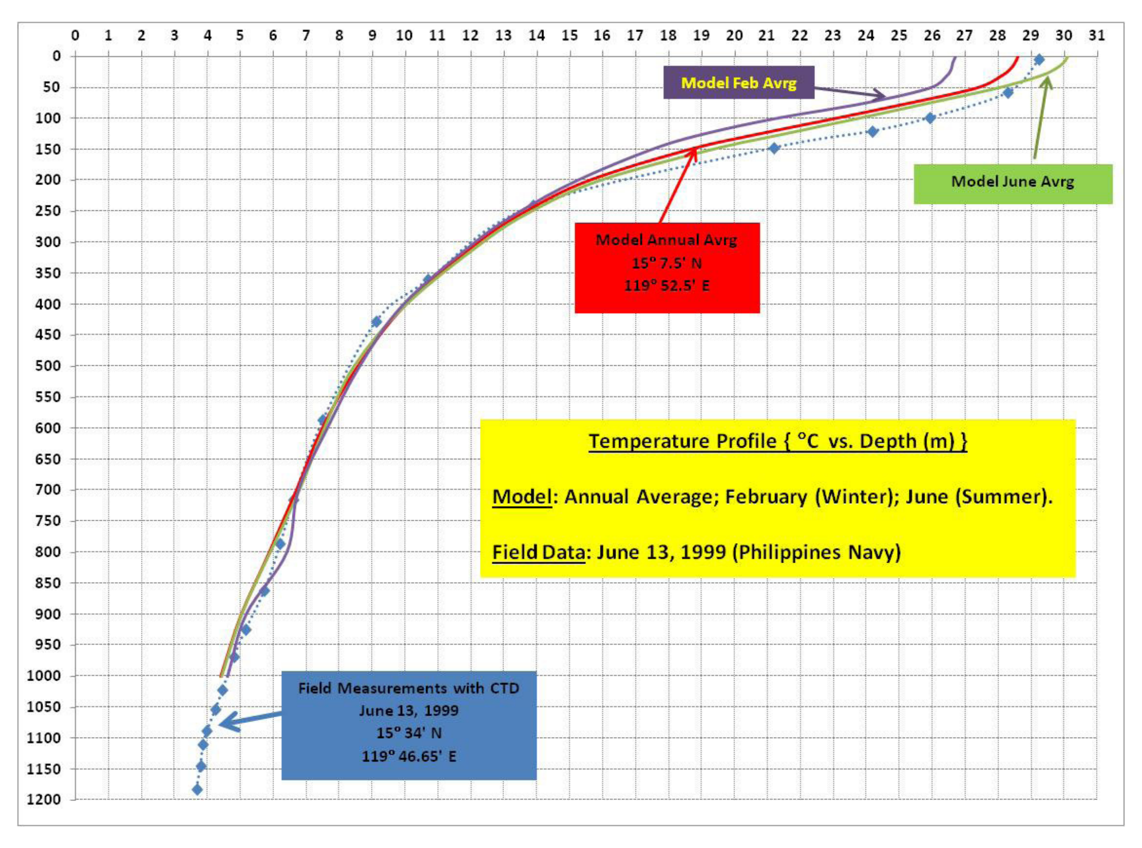
Figure A1.7 Worldwide Average Ocean Temperature Differences



Note: Between 20-meter and 1,000-meter water depths. The color palette is from 15°C to 25°C.

Sources: From World Ocean Atlas 2005 data.

Figure A1.8 Vertical Temperature Profile from the World Ocean Atlas Compared to Measurements by the Philippine Navy



m = meter.

Source: Provided by Energy Island.

Environmental Impact

OTEC may offer a relatively benign power production technology, since the handling of hazardous substances is limited to the working fluid (e.g., ammonia for CC-OTEC) and no noxious by-products are generated. For example, the amount of carbon dioxide released from electricity-producing plants (expressed in grams of carbon dioxide per kWh) ranges from 1,000 for coal-fired plants, to 700 for fuel-oil plants, and 500 for natural gas plants, while for OC-OTEC plants, it is at most about 1% of the amount released by fuel oil plants. The value is even lower in the case of a CC-OTEC plant (Vega 2012; NOAA 2010).

To have effective heat transfer, it is necessary to protect the heat exchangers from biofouling. It has been determined that, with proper design, biofouling only occurs in CC-OTEC heat exchangers exposed to surface seawater. Therefore, it is only necessary to protect the CC-OTEC evaporators by, for example, intermittent chlorination (50–100 parts per billion chlorine for 1 hour per day). This amount, for example, is well below what is allowed under current United States regulations. The use of biocides and ammonia are similar to other human activities. If occupational health and safety regulations like those in effect in the United States are followed, working fluid and biocide emissions from a plant should be too low to detect outside the plant sites. Ammonia is used as a fertilizer and in ice-skating rink refrigeration systems. Chlorine is used in municipal water treatment plants and in steam power plants. It must be emphasized that no chlorination is required in the OC-OTEC process (Vega 2012).

A sustained flow of cold, nutrient-rich, bacteria-free deep ocean water could cause sea surface temperature anomalies and biostimulation if resident times in the mixed layer and the euphotic zone, respectively, are long enough (i.e., upwelling). The euphotic zone is the upper layer of the ocean in which there is sufficient light for photosynthesis. This has been taken to mean the 1% light-penetration depth (e.g., 120 m in Hawaiian waters). This is conservative, because most biological activity requires radiation levels of at least 10% of the sea surface value. Since light intensity decreases exponentially with depth, the critical 10% light-penetration depth corresponds to, for example, 60 m in Hawaiian waters.

The analyses of specific OTEC designs indicate that mixed seawater returned at depths of 60 m results in a dilution coefficient of 4 (i.e., one part OTEC effluent is mixed with three parts of the ambient seawater) and equilibrium (neutral buoyancy) depths below the mixed layer throughout the year. This water return depth also provides the vertical separation, from the warm water intake at about 20 m, required to avoid reingestion into the plant. This value will vary as a function of ocean current conditions. It follows that the marine food web should be minimally affected and that persistent sea surface temperature anomalies should not be induced. These conclusions need to be confirmed with actual field measurements that could be performed with pilot plants.

Other potentially significant concerns are related to the construction phase. These are similar to those associated with the construction of any power plant, shipbuilding, and the construction of offshore platforms. OTEC operations might affect commercial and recreational fishing. Fish will be attracted to the plant, potentially increasing fishing in the area. However, the losses of inshore fish eggs and larvae, as well as juvenile fish, due to impingement and entrainment and to the discharge of biocides may reduce fish populations. The net effect of OTEC operation on aquatic life would depend on the balance achieved between these two effects. Through adequate planning and coordination with the local community, recreational assets near an OTEC site may be enhanced.

To better understand the risks that these impacts pose, a site-specific environmental baseline is required prior to installation. This baseline should include monitoring for presence and abundance of large and small biota, as well as the physical and chemical seawater characteristics. For certain impacts, a longer baseline may be desired to capture multiyear variability. Monitoring for changes to the baseline should occur during the operation phase, and would provide information on how the facility is impacting the local environment. Physical, chemical, and biological criteria should be monitored, including temperature; salinity; dissolved oxygen; pH; trace metals; and abundance, diversity, mortality, and behavioral changes in plankton, fish, marine mammals, turtles, and other biota (NOAA 2010).

Potential environmental impacts must be evaluated, and all licensing and permitting requirements must be fulfilled. However, the only process that differentiates OTEC from other well-established human activities and industries is the use of ocean water drawn from about 1,000 m depths and its return to the ocean below the photic zone. Given the intricate and dynamic nature of the ocean, it is nearly impossible to determine what would be the effect of such process through basic research or the development of ecological theory. The only way to evaluate the OTEC environmental differentiator is to obtain field data with a pilot plant operating with flow rates corresponding to at least a 5 MW plant. Such plant must be operated and monitored through ongoing and adaptive experience for 1–2 years (i.e., an adaptive management process).

Environmental impact monitoring. The only aspect of OTEC operations that is unique and not found in other marine industries can be addressed by asking about the environmental impact of the redistribution of relatively large deep ocean seawater masses. Another aspect that must be considered, although it is not unique to OTEC, is the entrainment of organisms through the seawater-intake pipes and their impingement as they travel through the plant into the seawater discharge-piping system.

To answer these questions, monitoring sampling during actual operations of OTEC plants is necessary to track primary productivity, organisms' abundance and density, and entrainment and impingement. The most important directive is to establish a protocol for monitoring the environmental effect of plant operations. Numerical models provide a first step, but only through field observations can the impact be quantified.

Monitoring the following parameters, during the actual operation of OTEC plants in relation to baseline conditions, will reveal the impact of the effluent plume on the environment.

Nutrients and Biological	Conductivity, Temperature, and Depth Casts	Carbonate Cycle
Nitrate	Temperature	Dissolved Inorganic Carbon
Phosphate	Salinity	pH
Silicate	Dissolved Oxygen	Alkalinity
Chlorophyll a		

Furthermore, the following can be considered a minimum effective list of parameters to monitor at the depth where the discharge effluent has reached neutral buoyancy away from the plant:

- chlorophyll a, nitrate and nitrite;
- temperature, salinity, and dissolved oxygen; and
- dissolved inorganic carbon and pH.

In addition, it has been proposed to determine the genome displacement due to the deepwater displacement.

Marine life entrainment and impingement effects can be monitored by, for example, adapting the United States. Environmental Protection Agency-approved protocols for the operations of conventional power plants utilizing seawater for cooling processes (Table A1.7).

Table A1.7 Frequently Asked Questions about the Ocean Thermal Energy Conversion Environmental and Social Impact

Environmental		
Land requirements for ocean thermal energy conversion plantships	What is the land requirement?	Land is only required for electrical substations with transformers and submarine power cable landing. Less than 0.1 hectare is required per plantship.
Ecological sensitivity	Is the land ecologically sensitive?	No, because the plantship is deployed at least 10 kilometers offshore.
Pollution effects	How will operations affect local air, water, and coastal or riparian quality?	Negligible
Local air emissions	What are the annual air emissions?	Not applicable
Greenhouse gas emissions	What are the greenhouse gas emissions?	Less than 1 gram per kilowatt-hour for closed-cycle ocean thermal energy conversion is emitted, compared to 1,000 grams per kilowatt-hour for coal-fired plants.
Noise and light pollution	Will there be a signification source of noise or light pollution during operation?	It will be comparable to regular ship operations.
Accidents and risks	What are the probabilities of accidents and the consequences?	The probabilities are low to negligible if industrial safety practices are followed.
Other	Possible enhancement of marine food web	The web will be enhanced only if effluent is somehow kept in the photic zone (i.e., depths of no more than about 100 meters)

continued on next page

Table A1.7 *continued*

Social		
Employment opportunities	What employment opportunities will be generated by construction or operation? What are the opportunities for local people to become part of the skilled labor force?	A crew of at least 20 per plantship will be needed.
Social infrastructure	Can the facility add to the existing social infrastructure?	Not applicable
Research and development opportunities	Is there opportunity for technological innovation or research and development?	Ongoing
Public acceptance	What actions could be taken to educate the public about the facility, technology, and/or green energy?	Public announcements and webpages
Aesthetics	What steps will be taken to increase the aesthetics of the built environment?	Not applicable
Future growth	What is the potential for growth?	Thousands of ocean thermal energy conversion plants could be grown throughout the world.
International collaboration	Is there an opportunity for international collaboration and/or foreign investment?	Yes

Tables A1.8–A1.13 provide information about major OTEC components.

Table A1.8 Cold-Water Pipe Information

FIRST-GENERATION BASELINE: Fiberglass-reinforced plastic sandwich per National Oceanic and Atmospheric Administration 1980s design and at-sea testing, with horizontal towing and upending in-situ; gimbal connected.

TOPIC	STATE-OF-THE-ART	ENGINEERING CHALLENGE
Processes		
Fabrication	Standard fiberglass-reinforced plastic	Syntactic foam spraying
Deployment	Tow tank tests led to model	Weather window
Construction	See fabrication	None
Installation	See deployment model	Weather window
Operation, maintenance, repair, and replacement	From marine risers	None
Environmental monitoring	From marine risers	None
Safe operating procedures	From marine risers	None
Decommissioning	Adapt from marine risers	Must incorporate into final design
Risks associated with process failure	NOT an option. This is a single component.	Must design for 30-year usable life
Component viability	Proven	Need fiberglass-reinforced plastic fatigue data beyond 15 years
Hurdles or limiting factors	None	Need fiberglass-reinforced plastic fatigue data beyond 15 years
Development time frame	Technology ready, but final design process of entire plant takes at least 1 year	Need fiberglass-reinforced plastic fatigue data beyond 15 years

Table A1.9 Heat Exchangers Information

BASELINE: Aluminum plate-fin evaporator and condenser manufactured by, for example, CHART

TOPIC	STATE-OF-THE-ART	ENGINEERING CHALLENGE
Processes		
Fabrication	Standard	Must get manufacturer involved in design
Deployment	Installed on shipyard	None
Construction	See fabrication	None
Installation	See deployment	None
Operation, maintenance, repair, and replacement		None
Environmental monitoring	Standard ammonia industry	None
Safe operating procedures	Standard ammonia industry	None
Decommissioning	Replace every 15 years and recycle aluminum	None
Risks associated with process failure	Minimal because modular design of heat exchanger and turbine generator combination	None
Component viability	Proven	Replace every 15 years
Hurdles or limiting factors	None	None
Development time frame	Long-lead item (at least 24 months); technology ready, but final design process of entire plant takes at least 1 year	Must get manufacturer involved in design

Table A1.10 Mooring Information

BASELINE: Single point mooring with power swivel (e.g., SBM) and dynamic thrusters

TOPIC	STATE-OF-THE-ART	ENGINEERING CHALLENGE
Processes		
Fabrication	Standard for existing offshore platforms	None
Deployment	Standard for existing offshore platforms	None
Construction	Standard for existing offshore platforms	None
Installation	Standard for existing offshore platforms	None
Operation, maintenance, repair, and replacement		None
Environmental monitoring	Standard for existing offshore platforms	None
Safe operating procedures	Standard for existing offshore platforms	None
Decommissioning	Reversible process and standard	None
Risks associated with process failure	None (other than power swivel, see Table A1.13)	None
Component viability	Proven	None
Hurdles or limiting factors	None	None
Development time frame	Long-lead item; technology ready, but final design process of entire plant takes at least 1 year	None

Table A1.11 Pumps and Turbines Information

BASELINE: Ammonia Turbine from GE (ROTOFLOW) or Mitsubishi, and submersible pumps from several manufacturers

TOPIC	STATE-OF-THE-ART	ENGINEERING CHALLENGE
Processes		
Fabrication	Turbine generator standard to about 16 megawatts Need multiple units to use state of the art submersible pumps (low head-high flow)	None
Deployment	Installed in shipyard	None
Construction	Installed in shipyard	None
Installation	Installed in shipyard	None
Operation, maintenance, repair, and replacement		None
Environmental monitoring	Standard from ammonia industry	None
Safe operating procedures	Standard from ammonia industry	None
Decommissioning	Standard	None
Risks associated with process failure	None, modular design of heat exchanger and turbine generator combination	None
Component viability	Proven	None
Hurdles or limiting factors	None	None
Development time frame	Long-lead items, at least 18–24 months; technology ready, but final design process takes at least 1 year	None

Table A1.12 Platform Information

BASELINE: Ship-shaped tanker or container ship

TOPIC	STATE-OF-THE-ART	ENGINEERING CHALLENGE
Processes		
Fabrication	Standard tanker or container ship construction	Is lower capital cost of single hull construction allowed?
Deployment	Shipyard	None
Construction	Shipyard	None
Installation	Shipyard	None
Operation, maintenance, repair, and replacement		None
Environmental monitoring	Standard	None
Safe operating procedures	Standard	None
Decommissioning	Standard	None
Risks associated with process failure	None, not applicable	None
Component viability	Proven	None
Hurdles or limiting factors	None	None
Development time frame	Technology ready, but final design process takes at least 1 year	None

Table A1.13 Submarine Power Cable

BASELINE: Several manufacturers

TOPIC	STATE-OF-THE-ART	ENGINEERING CHALLENGE
Processes		
Fabrication	Standard submarine power cables: (1) alternating current (AC) only with ethylene-propylene-rubber insulation $V \leq 35$ kilovolts (kV); $P \leq 25$ megawatts (MW) and $L \leq 100$ kilometers (km) (2) AC or discrete current (DC) with self-contained-fluid-filled insulation, $V \geq 138$ kV, $P \geq 100$ MW and $L < 50$ km (3) DC only with paper-impregnated-lead-covered insulation, $V < 450$ kV; $P < 500$ MW and $L < 200$ km	Not scalable from pre-commercial to commercial
Deployment	Standard and with mooring system	None
Construction	Standard	None
Installation	See deployment	None
Operation, maintenance, repair, and replacement		
Environmental monitoring	Standard	None
Safe operating procedures	Standard	None
Decommissioning	Standard	None
Risks associated with process failure	Major risk because baseline includes only one cable	Redundancy, conservative design
Component viability	Proven	None
Hurdles or limiting factors	None	None

P = power in MW, V = voltage in kV.

APPENDIX 2: LEVELIZED COST OF ELECTRICITY

Conventional Production of Electricity

The thermal efficiency (h) of well-maintained conventional steam power plants, fired with oil or coal, can be as high as 36%. This implies that 36% of the heat added is converted to net work. Net work is defined as the difference between the output from the turbine generator and the work required to run the plant.

The convention followed in power plant technology to express plant performance is to consider the heat added to produce a unit amount of net work. This parameter is called the heat rate of the plant and is usually given in British thermal unit (Btu) per kilowatt-hour (kWh). Therefore, the heat rate is inversely proportional to the thermal efficiency, h = 3,413/heat rate (i.e., 1 kWh = 3,413 Btu at 60°F), such that a thermal efficiency of 36% corresponds to a heat rate of 9,500 Btu/kWh.

The heating value of standard coal is 12,000 x (1 ± 0.17) Btu/British thermal units per pound mass (lbm), while with fuel oil, it is 144,000 x (1 ± 0.04) Btu/gallon. Therefore, within 6%, the fuel cost incurred in producing electricity with an oil-fired plant is

Cost of electricity $(COE)_{fuel} = 1.6 \times 10^{-3} \times CB$,
where CB is the cost of a (42 gallons) barrel of fuel.

Therefore, for example, at $62.50 per barrel, COE_{fuel} is $0.10/kWh.

The same expression can be used for diesel generators.

In the case of coal, the standard heating value is 12,500 Btu/lbm, so, for example, with a price of $62 per ton, the fuel cost incurred in producing electricity with a thermal efficiency of 36% would be $0.021/kWh. This is equivalent to oil fuel cost of $13 per barrel.

To estimate the total COE production, COE_{fuel} must be added to the capital cost as well as costs associated with operation, maintenance, repair, and replacement.

Conventional Production of Desalinated Water

For convenience, and because the first-generation OTEC plants are expected to be deployed around islands, it is assumed that the cost of seawater desalination with OTEC must be compared with that of reverse osmosis desalination of seawater.

Reverse osmosis plants require energy solely as shaft power from, for example, an electric motor. It can be shown that freshwater production by reverse osmosis costs 0.049 x CB.

Levelized Cost of Electricity: Methodology

The levelized COE expressed in constant annual cost is given by the sum of the levelized investment cost (i.e., the loan amortization payment) and the levelized operation, maintenance, repair, and replacement expense cost.

Referring to Table A1.5, the following terms are defined.

System net name plate. Ocean thermal energy conversion (OTEC) system net power is input based on design-specific conditions.

System (equipment) availability. Percentage of time that the system is available. Based on experimental data, it is assumed that this system consists of five modules with an annual maintenance downtime of 4 weeks per module, so that annual availability is 92.3%.

Site annual (resource) capacity factor. To account for resource variability, in this case, 100% because the design already accounted for resource variability (by the selection of a name plate for a site, with constant T_c and T_w ranging from 24°C to 28°C throughout the year). This parameter is used for evaluation of intermittent resources like wind and waves.

Annual electricity production. Name plate x availability x capacity factor x 8,760.

Daily desalinated water production. Used for open-cycle OTEC systems.

Installed cost. This is the amount of the loan: input cost estimate x name plate.

First-year operation, maintenance, repair, and replacement. Estimated to account for the funds that must be collected to cover all operational costs.

Interest. From the loan terms.

Escalation (inflation) rate. Taken at a constant 3%.

System life. As a conservative assumption, this is defined as the loan term (15 years for the commercial loan and 20 years for the bonds or concessionary loans), although the OTEC system is designed for a 30-year useful life. As illustrated in Appendix 1, for example, some components are replaced in 15-year intervals, while others require 30-year intervals.

Capital recovery factor. $[I\ x(1 + I)^N]/[(1+I)^N - 1]$ such that for parameters in Table A1.5, the capital recovery factor is 0.1168.

Levelized investment cost. Amount required yearly to pay capital loan: capital cost x capital recovery factor.

Fixed capital cost component of cost of electricity. Levelized investment cost/annual electricity production. This is the amount that must be collected per kilowatt-hour produced to pay the loan.

Present worth factor. $[(1 + ER)/(I - ER)]/[1 - \{(1 + ER)/(1 + I)\}^N]$, so for parameters given in Table A1.5, the present worth factor is 10.48 years.

Expenses levelizing factor. Present worth factor x capital recovery factor, so that for the parameters given in Table A1.5, the levelizing factor is 1.22.

Levelized expenses cost. The fixed amount that must be collected yearly to cover all operation, maintenance, repair, and replacement costs accounting for inflation. This is equal to the amount estimated for the first year (as given above) x expenses leveling factor. For the parameters and estimates given in Table A1.5, the value is 22% higher of what would be required the first year.

Levelized operation, maintenance, repair, and replacement component of cost of electricity. The levelized expenses cost/annual production of electricity.

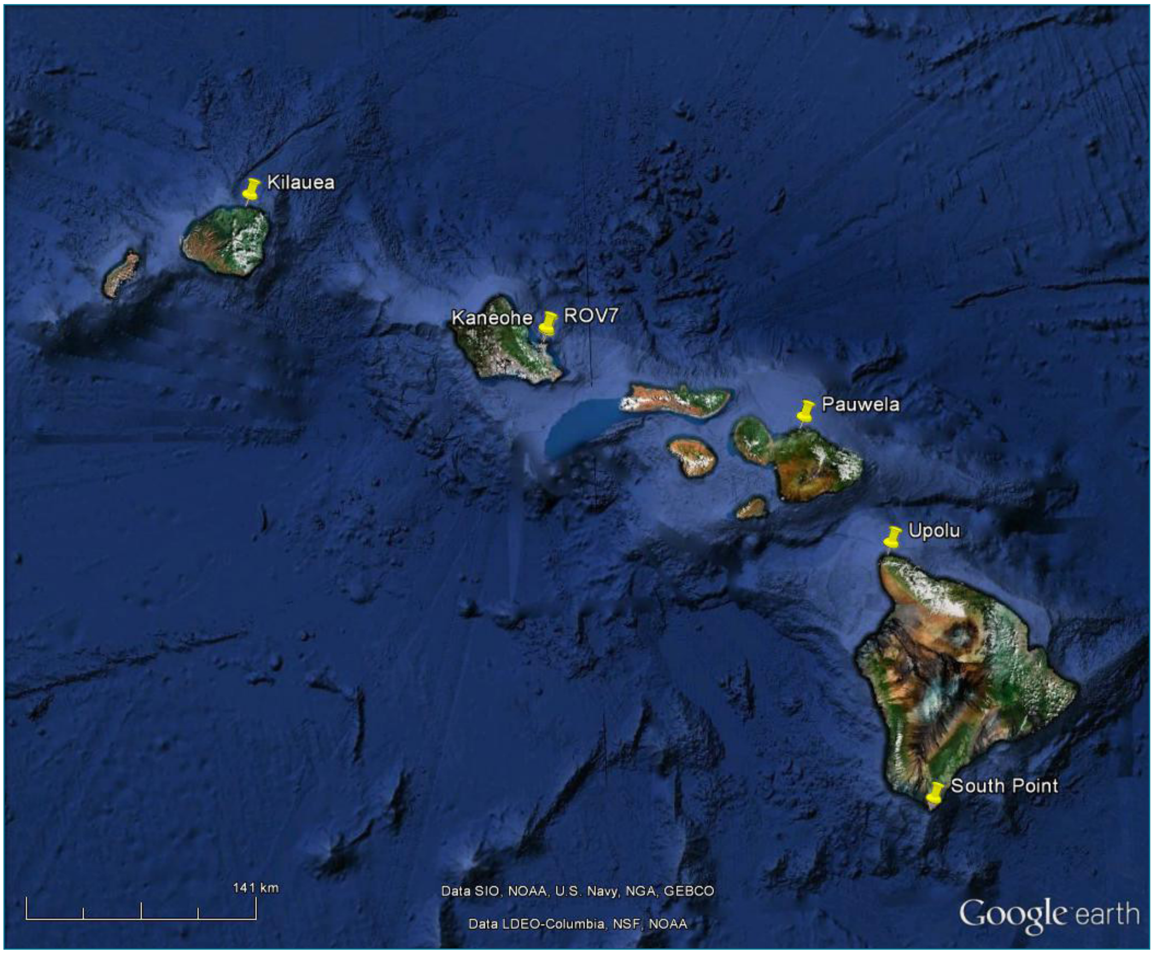
Total levelized cost of electricity. This is the sum of COE_{CC} and $COE_{omr\&r}$. The value given here excludes environmental credits, tax credits, and profit.

APPENDIX 3: WAVE POWER ANALYSIS FOR REPRESENTATIVE HAWAIIAN ISLAND SITES

Introduction[1]

Simulating Waves Nearshore (SWAN) version 40.85 was forced with spectral wave parameters hindcasted from WAVEWATCH III (WW3) version 3.14 to produce 20 years (i.e., January 1990–December 2009) spectral wave estimates for six sites around the Hawaiian islands (Figures A3.1 and A3.2). The boundary conditions provided by WW3 were obtained by using high-resolution winds from the University of Hawaii Meteorology's mesoscale model, weather, and forecasting. The water depth, latitude, and longitude of each site are presented in Table A3.1. The annual and monthly average wave power fluxes estimated for each of the six sites are presented in the next section.

Figure A3.1 Locations of Sites Selected by the Hawaii National Marine Renewable Energy Center



Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

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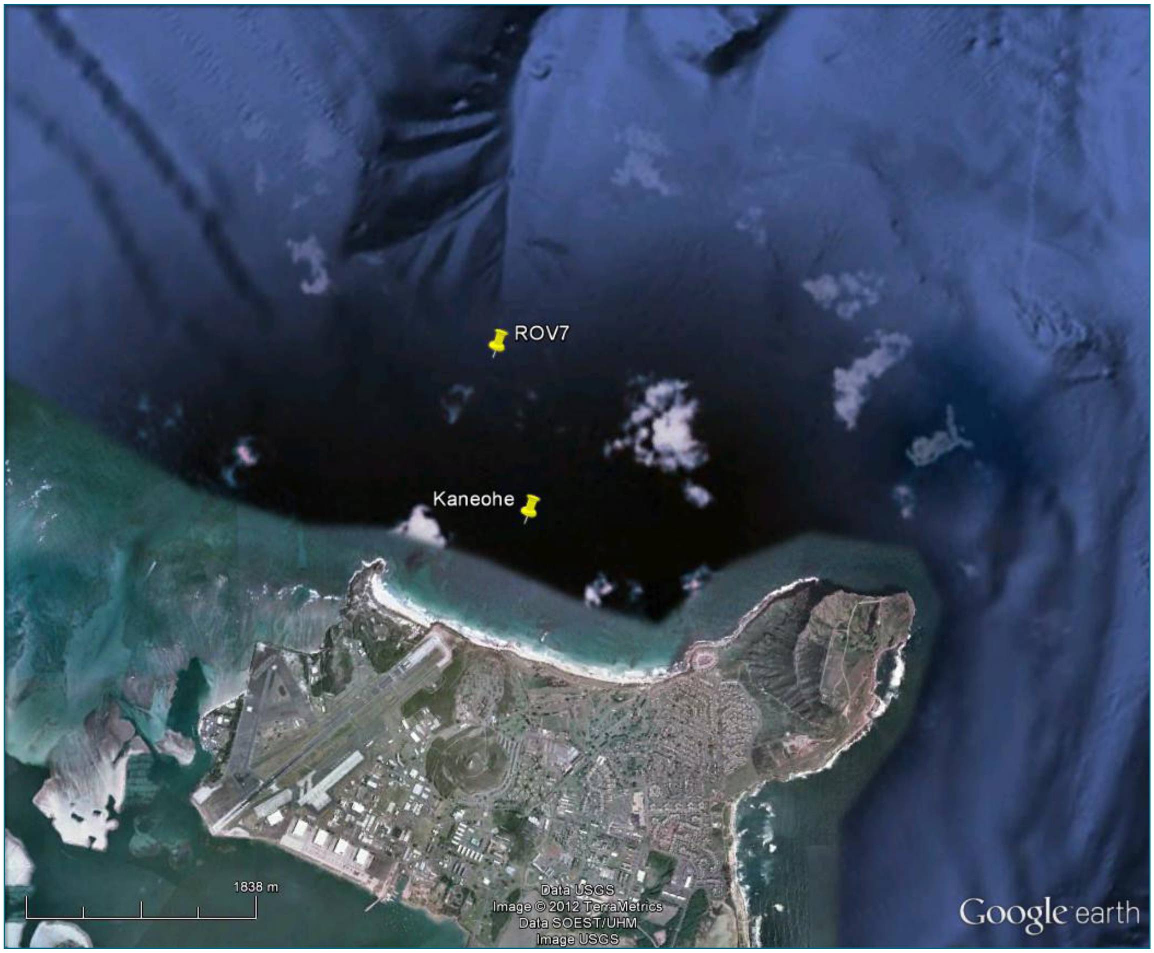
[1] N. Li and J. Stopa. 2012. *Wave Power Analysis for Representative Hawaiian Island Sites*. Report prepared for the Hawaii National Marine Renewable Energy Center. Honolulu: University of Hawaii.

Figure A3.2 Locations of Sites Selected by the Hawaii National Marine Renewable Energy Center at the Wave Energy Test Site



Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.1 Locations of Sites Selected by the Hawaii National Marine Renewable Energy Center for SWAN Analysis

Site	Location	Latitude (°N)	Longitude (°W)	Water Depth (m)
Kaneohe	Kaneohe, Oahu (WETS)	21.465	157.752	27
Kaneohe Rov7	Kaneohe, Oahu (WETS)	21.477	157.750	86
Pauwela	Pauwela, Maui	20.958	156.322	73
Upolu	Upolu, Hawaii	20.275	155.863	47
South Point	South Point, Hawaii	18.910	155.681	40
Kilauea	Kilauea, Kauai	22.236	159.422	53

m = meter, SWAN = Simulating Waves Nearshore, WETS = Wave Energy Test Site.

Source: N. Li, J. Stopa, and K.F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Results

The wave power flux was estimated using Equation 1 below. Table A3.2 summarizes the average monthly wave power flux for each site, indicating the seasonal variation. Table A3.3 presents the annual average wave flux for each site, indicating the highest annual average at the Pauwela site.

The peaks-over-threshold method was used for estimating the extreme wave heights and periods over a long return period at the sites of interest. These parameters are of particular importance in considering the survival conditions in the design process. The outcomes of the analysis are the 100-year significant wave heights (H_s) and peak periods (T_p) as given in Table A3.3. It should be noted that the statistics for each variable have been treated independently; therefore, the extreme values of H_s and T_p are very likely not related to the same event. The locations exposed to the North Pacific swells (e.g., Kilauea and Pauwela) yield the largest estimates, with H_s at 8.2 meters (m) and T_p at 16.3 seconds (s).

The daily and monthly average, median, and 5th and 95th percentile of the wave power is calculated and shown in Figures A3.3–A3.14. The power flux is defined by

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

where

$S(\omega,\theta,h)$ = local wave spectrum

θ = wave direction

ω = wave frequency

h = local water depth

Cg = local group speed

g = gravitational acceleration, 9.81 m/square meter

ρ = density of seawater, 1,025 kilogram/cubic meter.

The wave climate in Hawaii is composed of swells from the North and South Pacific and year-round wind waves from the northeast. Therefore, the majority of the sites are characterized by higher power flux in winter and lower wave power flux in summer. Between May and September, the average monthly wave power flux shows slightly higher valued (9.1–10.3 kilowatts per meter [kW/m]) at the South Point site, which is mainly driven by the wind seas associated with the trade winds and swells from the south. Between October and April, significantly higher values were observed at the Pauwela site (16.3–48.7 kW/m) and Kilauea site (13.7–49.2 kW/m) due to their exposure to the swells from the North Pacific. The power probability density function in Figure A3.15 shows a similar feature where the distributions are skewed toward the high values based on their exposure to the largest swells from the North Pacific. This explains why Pauwela and Kilauea have higher occurrences of events with wave power flux above 40 kW/m.

A convenient way to present the occurrence, magnitude, and direction of the wave climate at each site are wave rose plots presented in Figures A3.16–A3.21. The majority of the sites (i.e., Kaneohe, Pauwela, and Upolu) show waves from the east-northeast are most common with typical wave heights in the 1.0–2.5 m range. The exceptions are the Kilauea site, which is dominated by swells from the North Pacific, and the South Point site, which is dominated by wind waves from the east-southeast. Kilauea has a bimodal sea state with many occurrences of wind waves from the east-northeast and swells from the north-northwest. In addition, less pronounced bimodal sea states are seen at Kaneohe and Pauwela due to their more sheltered positions from the North Pacific swells.

Figure A3.22 shows the occurrence of events with wave power over the 15 kW/m threshold. The white areas are within the 50-m contour, where wave energy converters are typically deployed. The shores with open exposure to the swells from the northwest are the most energetic. The northern shores of Kauai, Maui, and Oahu have the highest occurrence of events over 15 kW/m for 50%–60% of the time. On the other hand, Hawaii Island has the most consistent wave power near Cape Kumukahi on the eastern point due to its exposure to the swells from the north, swells from the south, and east-northeast wind waves.

Lastly, the occurrence of events corresponding to binned significant wave height (H_s) and wave periods (T_e or T_{02}) are presented in Tables A3.4–A3.15 utilizing all 20-year estimates. These are useful for the estimation of possible power generated for a particular wave energy converter as represented by their power matrix.

Significant wave height, H_s, is defined by

$$Hs = 4\sqrt{\iint S(\omega,\theta)d\omega d\theta} \qquad (2)$$

T_e and T_{02} are defined by

$$T_e = \frac{m_{-1}}{m_0} \qquad (3)$$

$$T_{02} = \sqrt{\frac{m_0}{m_2}} \qquad (4)$$

where,

m_0 , m_1 , m_2 are the spectral moments. The nth spectral moment is defined as

$$m_n = \int_0^\infty f^n S(f)df \qquad (5)$$

It must be noted that these definitions do not account for shallow water conditions.

Table A3.2 Monthly Average Wave Power Flux
(kilowatt/meter)

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Maximum–Minimum
Kaneohe	16.1	16.0	14.1	11.4	6.5	5.0	5.2	5.4	6.1	9.8	17.2	17.1	3.4
Kaneohe Rov7	17.8	17.6	15.5	12.9	7.4	5.9	6.1	6.3	6.9	10.9	18.9	19.3	3.3
Pauwela	48.7	42.4	31.5	20.8	10.4	7.2	7.0	7.5	9.7	16.3	31.3	44.8	7.0
Upolu	15.1	15.6	14.4	12.0	7.2	6.7	7.0	7.6	7.1	9.4	15.9	17.1	2.6
South Point	17.6	16.3	13.6	11.7	9.1	9.5	9.8	10.3	9.7	8.8	10.6	15.5	2.0
Kilauea	49.2	40.8	28.8	16.5	8.1	4.5	4.4	4.2	7.2	13.7	27.6	39.7	11.7

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

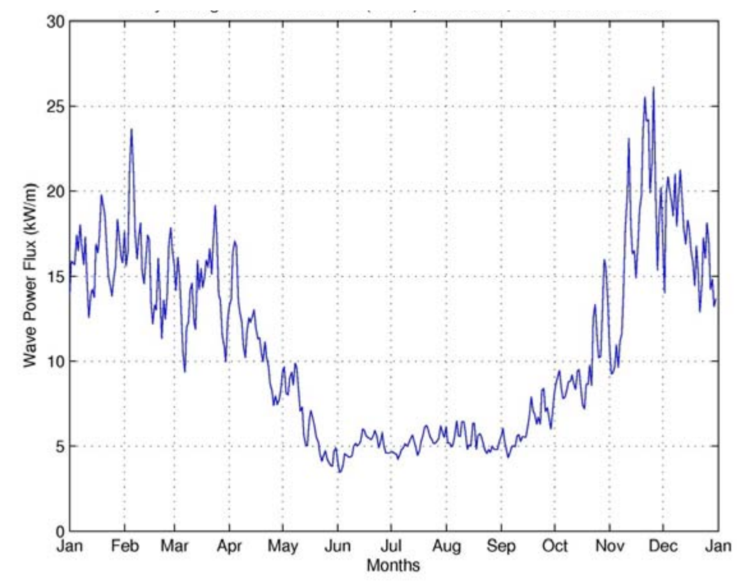
Table A3.3 Annual Average Wave Power Flux

Site	Power Flux (kilowatt /meter)	H_s, 100 Years (meter)	T_p, 100 Years (second)
Kaneohe	10.8	6.2	14.4
Kaneohe Rov7	12.1	6.5	14.4
Pauwela	23.1	8.2	16.3
Upolu	11.3	6.3	13.0
South Point	11.9	4.1	16.3
Kilauea	20.4	8.2	16.3

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

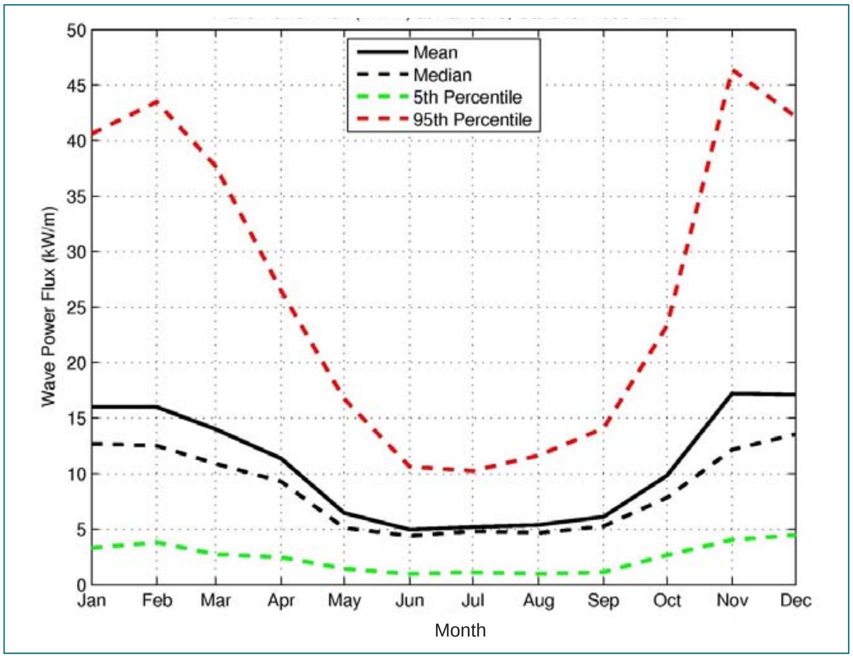
Figure A3.3 Daily Average Wave Power Flux for Kaneohe Site, 1990–2009

(kilowatt/meter)



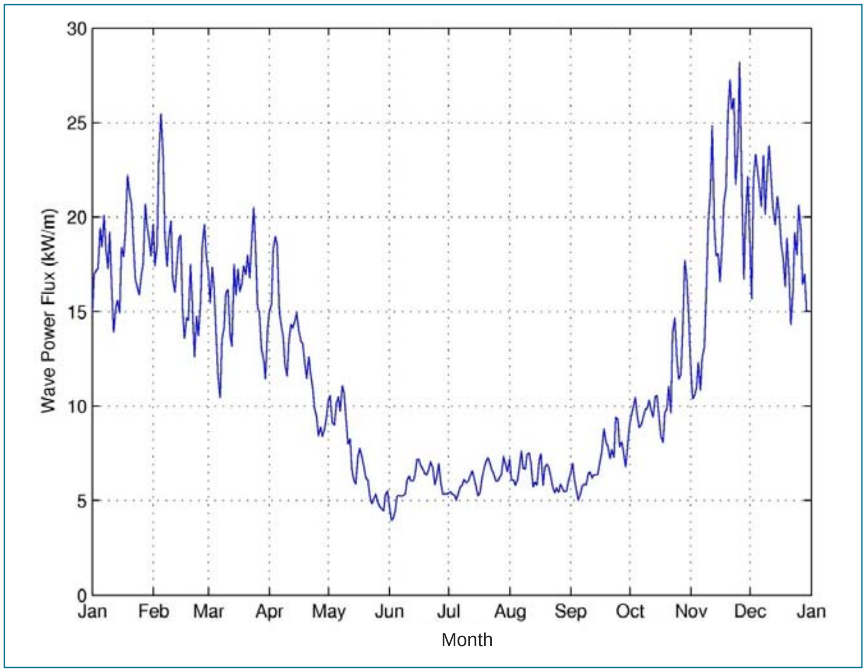
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.4 Monthly Average Wave Power Flux for Kaneohe Site, 1990–2009
(kilowatt/meter)



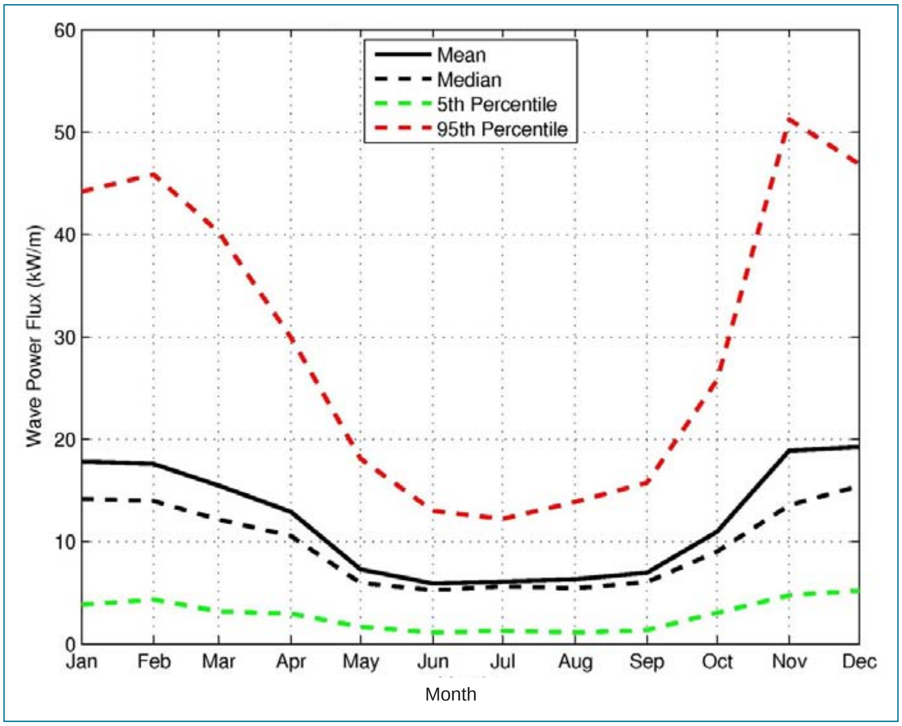
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.5 Daily Average Wave Power Flux for Kaneohe Rov7 Site, 1990–2009
(kilowatt/meter)



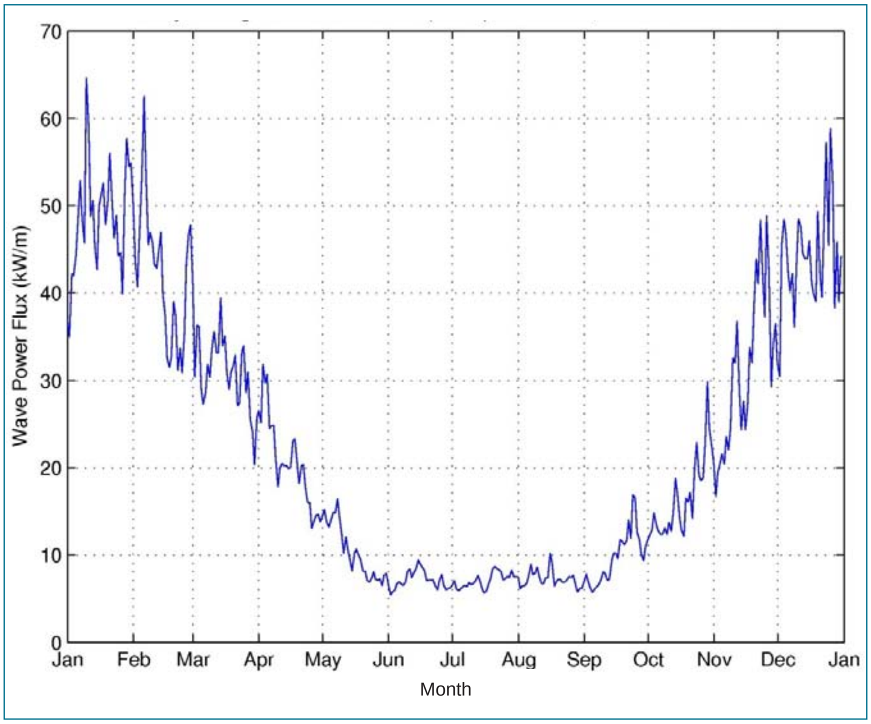
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.6 Monthly Average Wave Power Flux for Kaneohe Rov7 Site, 1990–2009
(kilowatt/meter)



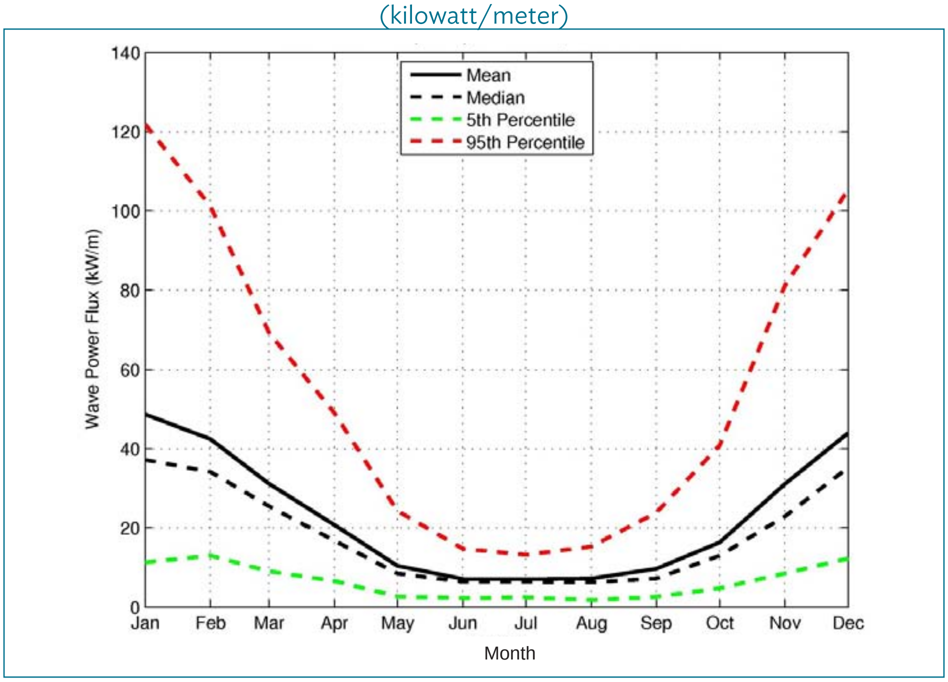
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.7 Daily Average Wave Power Flux for Pauwela Site, 1990–2009
(kilowatt/meter)



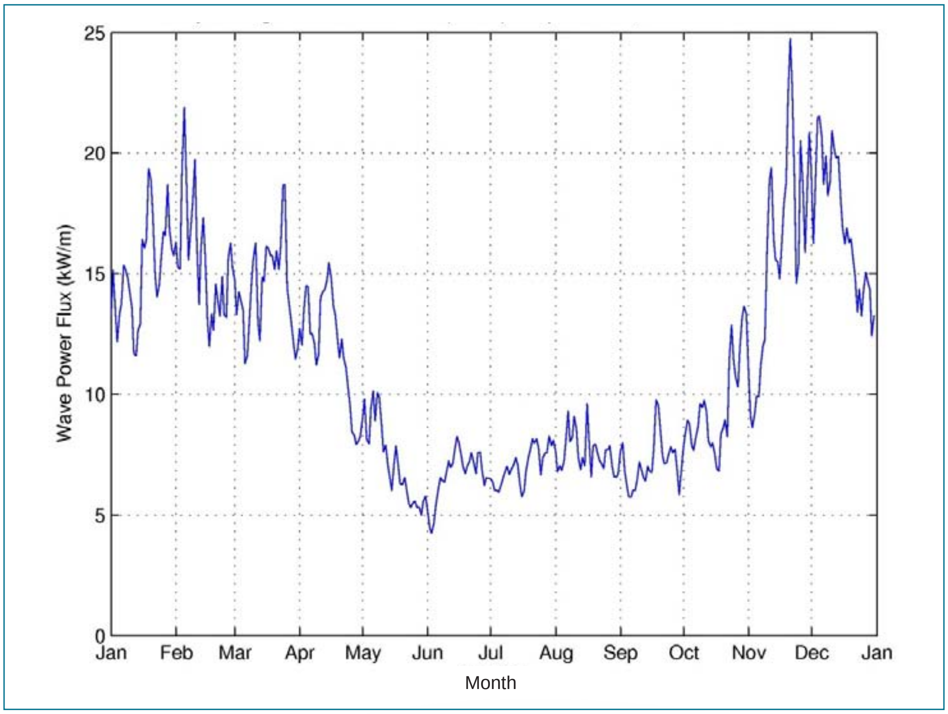
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.8 Monthly Average Wave Power Flux for Pauwela Site, 1999–2009
(kilowatt/meter)



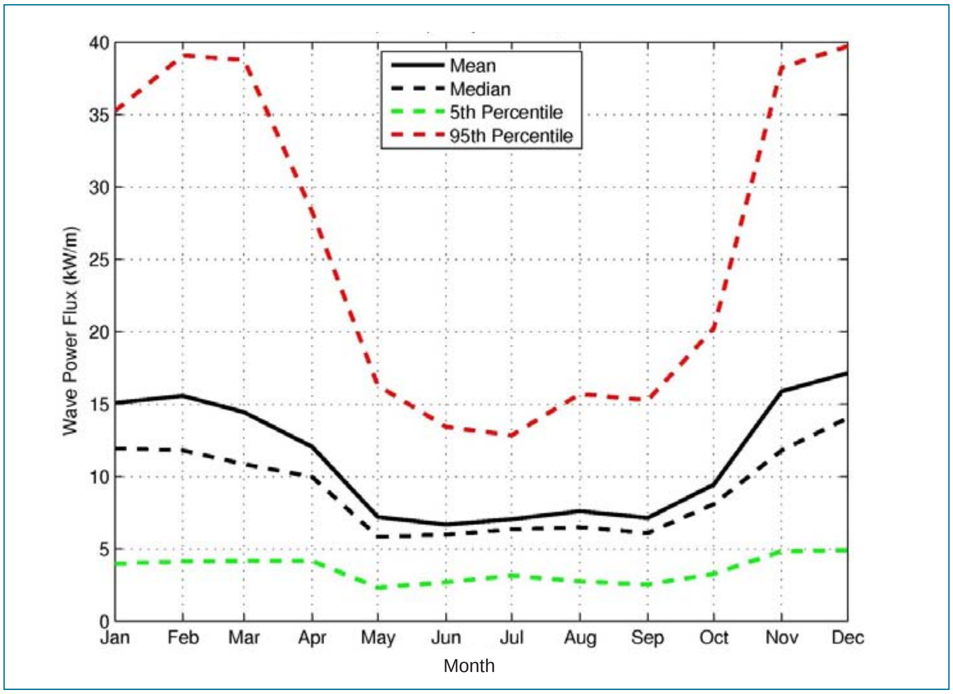
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.9 Daily Average Wave Power Flux for Upolu Site, 1990–2009
(kilowatt/meter)



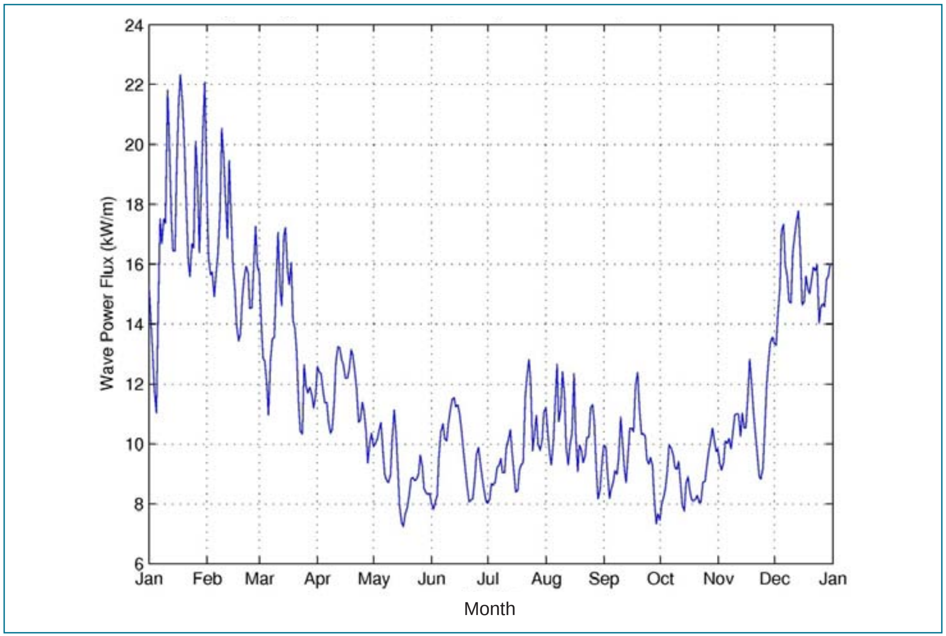
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.10 Monthly Average Wave Power Flux for Upolu Site, 1990–2009
(kilowatt/meter)



Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

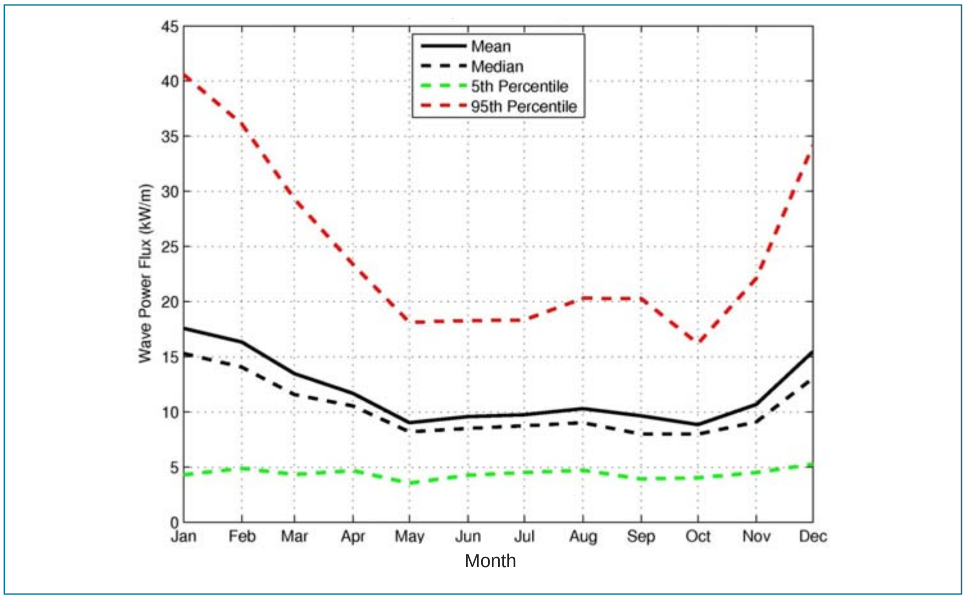
Figure A3.11 Daily Average Wave Power Flux for South Point Site, 1990–2009
(kilowatt/meter)



Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.12 Monthly Average Wave Power Flux for South Point Site, 1999–2009

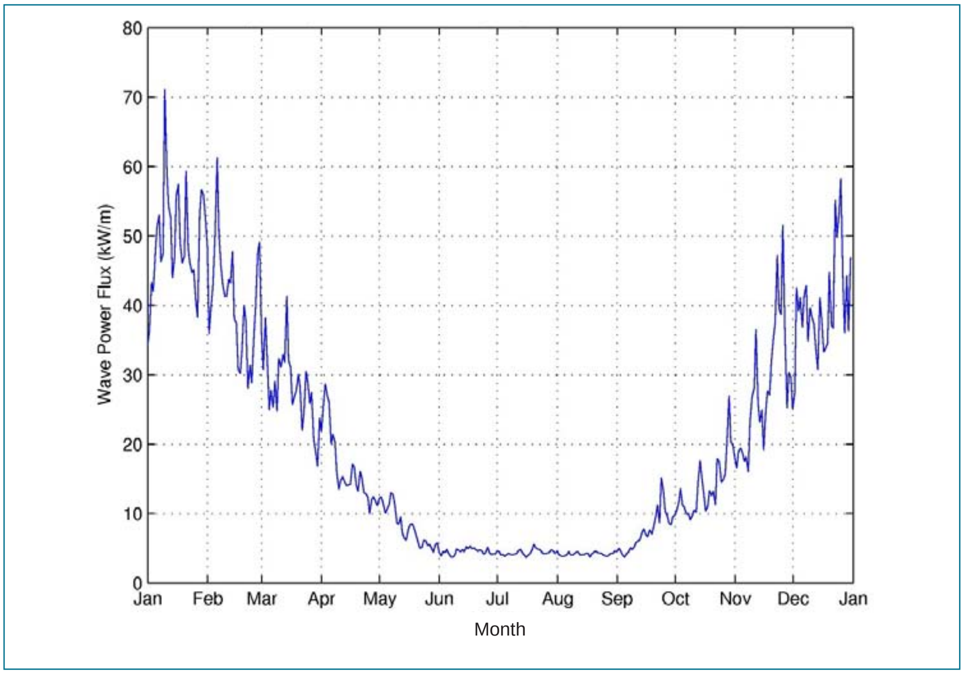
(kilowatt/meter)



Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.13 Daily Average Wave Power Flux for Kilauea Site, 1999–2009

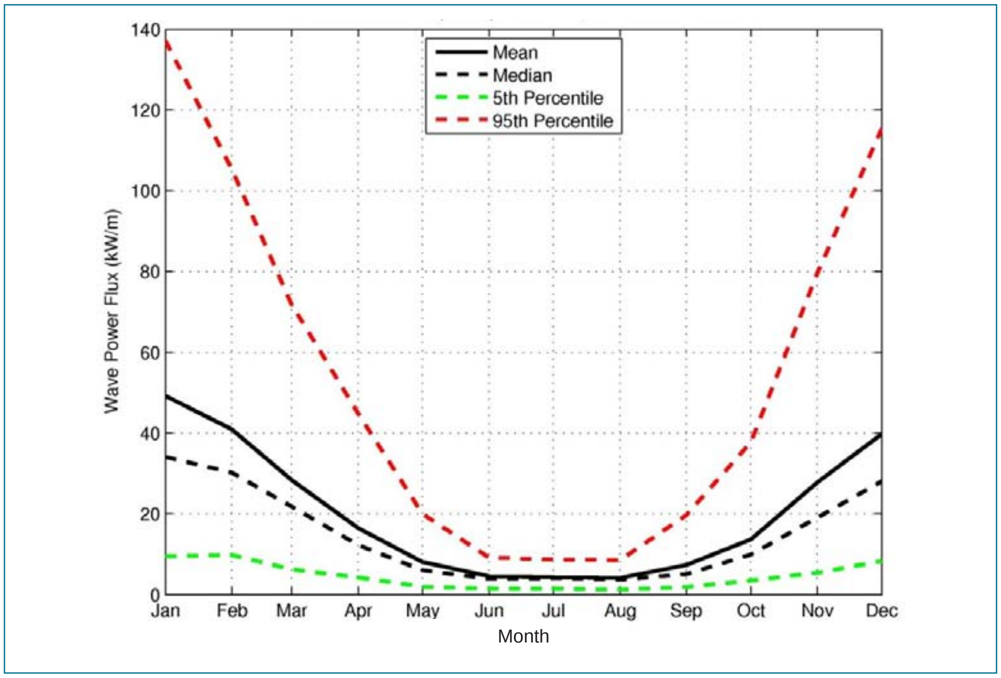
(kilowatt/meter)



Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.14 Monthly Average Wave Power Flux for Kilauea Site, 1999–2009

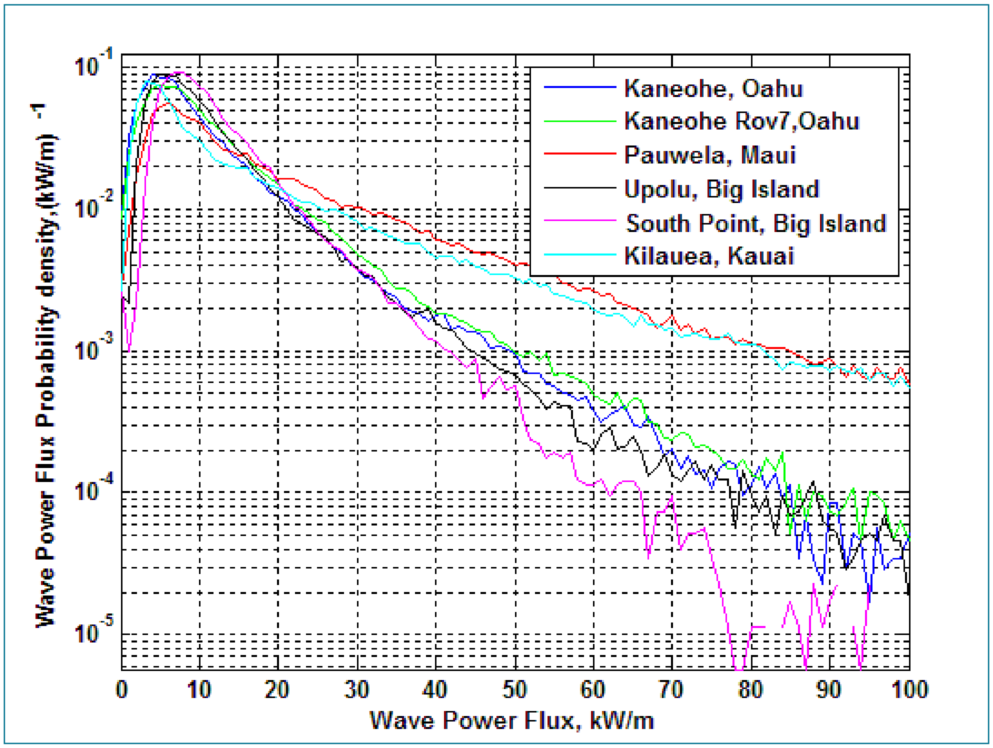
(kilowatt/meter)



Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

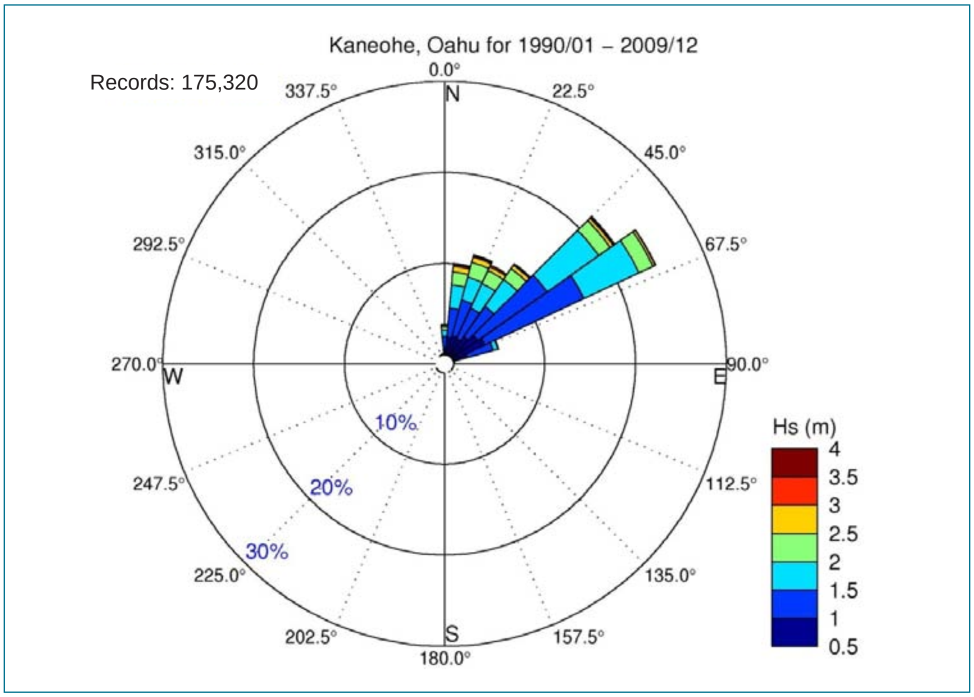
Figure A3.15 Wave Power Flux Probability Density Function, 1999–2009

(kilowatt/meter)



Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

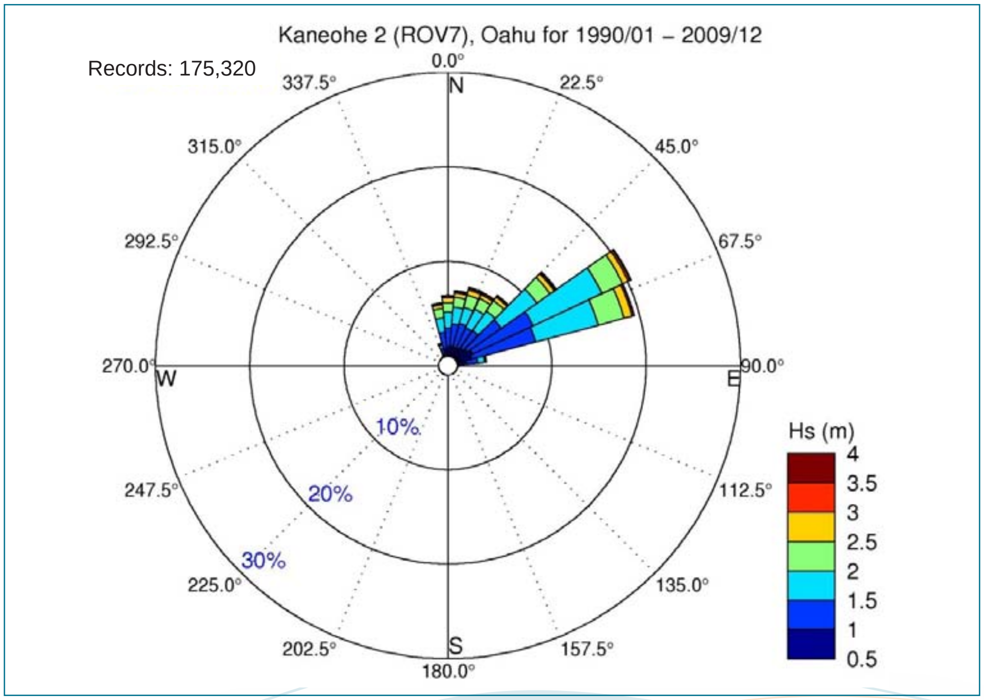
Figure A3.16 Rose Map of Significant Wave Height for Kaneohe Site, 1990/2001–2009/2012



m = meter.

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

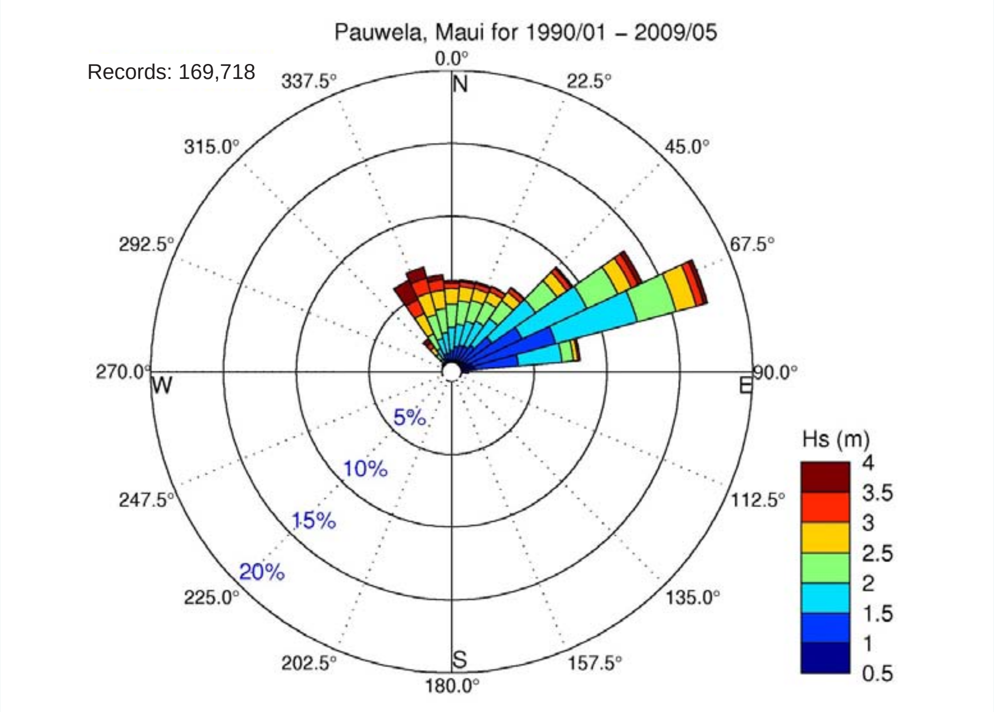
Figure A3.17 Rose Map of Significant Wave Height for Kaneohe Rov7 Site, 1990/2001–2009/2012



m = meter.

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

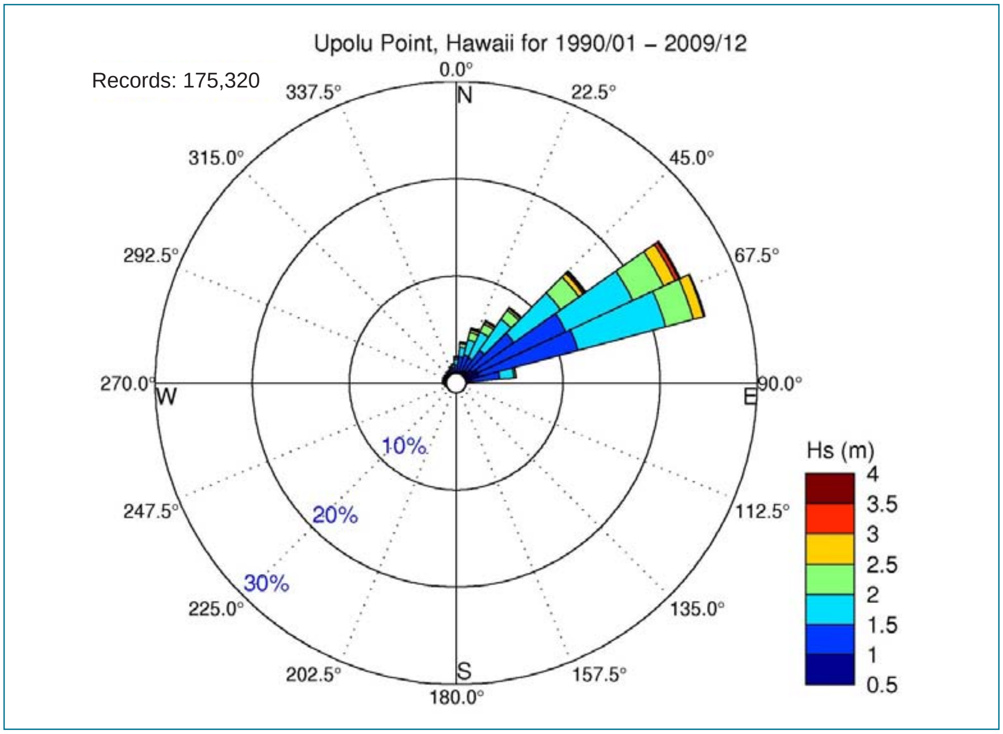
Figure A3.18 Rose Map of Significant Wave Height for Pauwela Site, 1990/2001–2009/2012



m = meter.

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

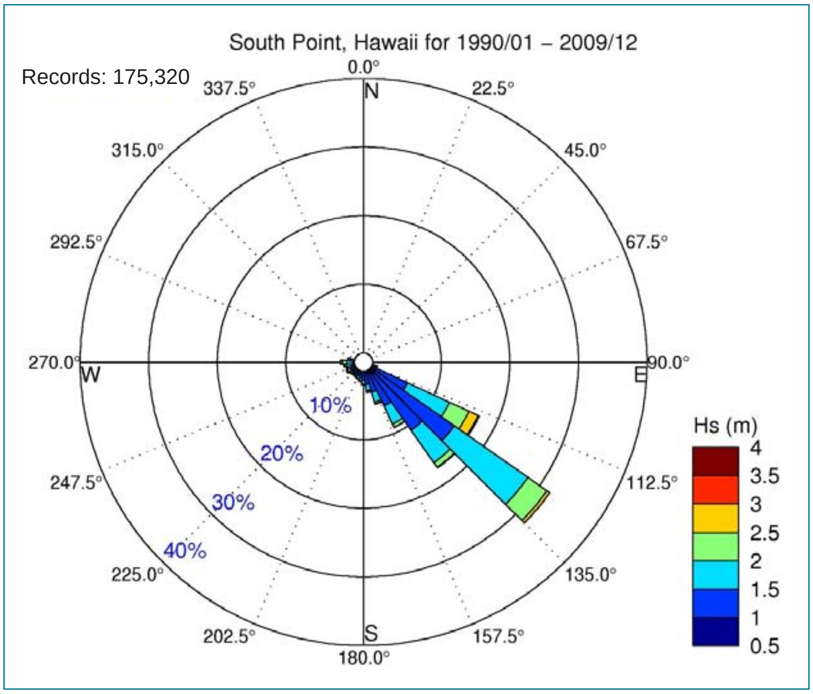
Figure A3.19 Rose Map of Significant Wave Height for Upolu Site, 1990/2001–2009/2012



m = meter.

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

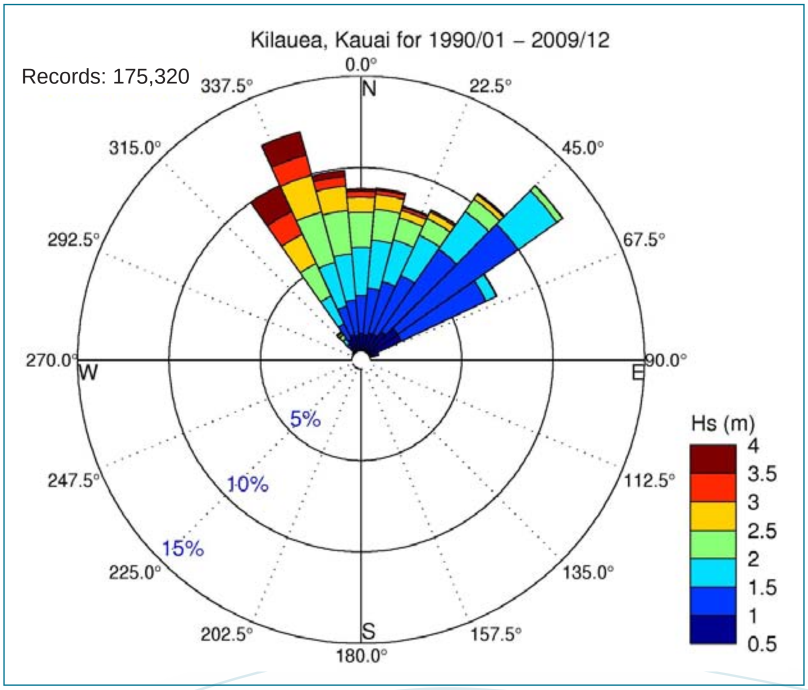
Figure A3.20 Rose Map of Significant Wave Height for South Point Site, 1990/2001–2009/2012



m = meter.

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

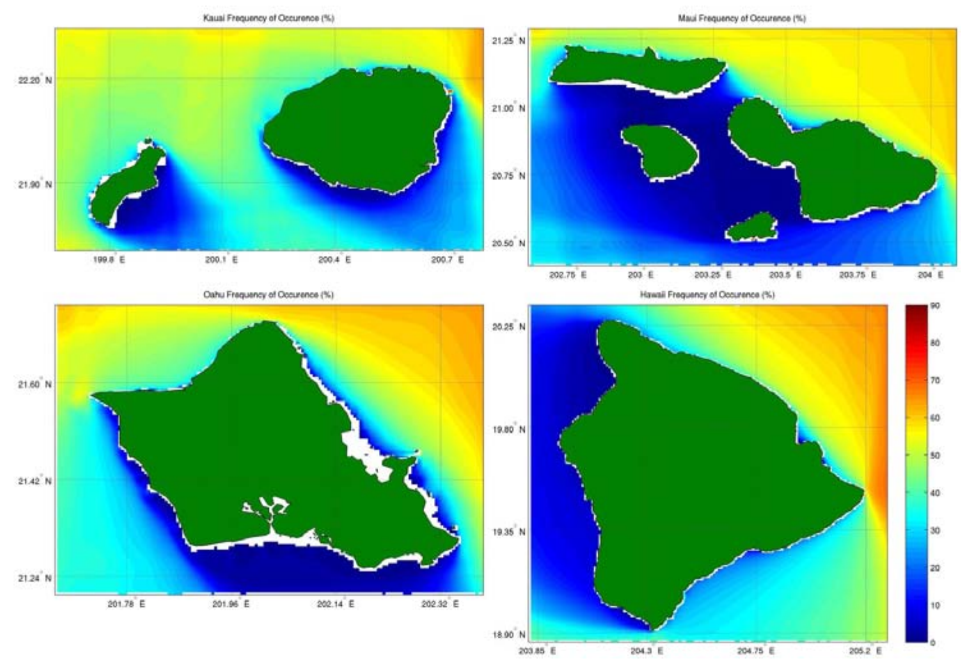
Figure A3.21 Rose Map of Significant Wave Height for Kilauea Site, 1990/2001–2009/2012



m = meter.

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Figure A3.22 Wave Power Occurrence of Events Larger Than 15 Kilowatts/Hour



m = meter.

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.4 T_e-H_s Occurrence in the Kaneohe Site, 1990–2009

(hours)

		T_e (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	0	30	3	3	11	118	123	155	154	154	229	301	224	271	311	234	170
	1.0	0	0	0	0	0	16	30	125	108	326	1,512	3,122	3,907	4,394	3,712	3,485	2,744	1,980	1,347
	1.5	0	0	0	0	0	0	0	8	9	178	1,907	10,427	15,621	10,169	7,496	6,378	4,482	3,771	2,912
	2.0	0	0	0	0	0	0	0	0	0	0	135	1,279	5,238	7,801	8,228	6,108	4,767	3,584	2,528
	2.5	0	0	0	0	0	0	0	0	0	0	10	24	322	1,013	2,060	3,040	2,389	2,180	1,550
	3.0	0	0	0	0	0	0	0	0	0	0	0	0	4	165	425	643	581	581	622
	3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	71	94	196	222	202
	4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	8	17	36	84
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	24
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

continued on next page

Table A3.4 *continued*

		T_e (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
Hs (meter)	0.5	127	113	91	31	17	4	3	3	0	0	0	0	0	0	0	0	2,880
	1.0	920	619	551	362	232	124	92	58	45	16	5	1	0	0	0	0	29,833
	1.5	2,241	1,729	1,330	844	609	465	218	202	140	68	15	4	3	1	0	1	71,228
	2.0	1,999	1,638	1,167	761	526	322	204	110	71	43	25	20	4	1	0	2	46,561
	2.5	1,205	1,020	784	510	326	189	177	138	93	69	17	3	2	5	0	4	17,130
	3.0	500	385	364	337	280	173	132	73	48	21	12	3	2	1	2	0	5,354
	3.5	213	156	97	96	101	67	49	33	37	32	19	3	5	0	0	0	1,693
	4.0	44	49	41	49	33	17	7	14	17	4	10	0	0	0	0	0	434
	4.5	0	2	8	27	22	29	3	3	41	4	0	0	0	0	0	0	165
	5.0	0	0	0	0	18	5	0	0	0	0	0	0	0	0	0	0	23
	5.5	0	0	0	0	0	5	7	0	0	0	0	0	0	0	0	0	12
	6.0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	7
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

H_s = significant wave height, T_e = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.5 Te-Hs Occurrence in the Kaneohe Rov7 Site, 1990–2009

(hours)

		T_e (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	0	27	6	3	16	103	108	154	134	169	201	204	180	218	215	136	113
	1.0	0	0	0	0	0	16	35	129	121	229	902	1,674	2,591	3,136	2,804	2,453	1,902	1,169	775
	1.5	0	0	0	0	0	0	0	8	11	166	1,823	8,677	10,918	8,510	6,587	5,680	4,326	3,759	2,645
	2.0	0	0	0	0	0	0	0	0	0	0	156	1,861	10,005	10,798	9,051	6,680	4,916	3,378	2,678
	2.5	0	0	0	0	0	0	0	0	0	0	1	71	547	2,166	4,559	4,300	3,756	2,913	1,918
	3.0	0	0	0	0	0	0	0	0	0	0	0	0	12	184	820	1,839	1,461	952	749
	3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	91	309	385	395	435
	4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	141	135	164
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	7	12	40
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	26
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.5 *continued*

		T_e (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	90	52	8	7	3	0	0	0	0	0	0	0	0	0	0	0	2,147
	1.0	565	442	339	205	107	77	37	28	21	1	0	0	0	0	0	0	19,758
	1.5	1,839	1,345	1,052	714	501	315	185	123	95	33	10	3	2	1	0	0	59,328
	2.0	2,105	1,733	1,124	767	474	230	169	75	56	18	29	7	2	0	0	3	56,315
	2.5	1,319	1,066	757	582	315	177	151	116	77	25	9	4	2	0	0	3	24,834
	3.0	681	560	414	384	279	171	126	64	54	11	3	2	2	2	1	0	8,771
	3.5	338	190	161	154	122	102	45	48	35	33	6	0	0	0	0	0	2,850
	4.0	128	95	55	47	59	18	20	24	24	10	3	0	0	0	0	0	950
	4.5	47	15	25	37	29	11	2	11	29	0	0	0	0	0	0	0	271
	5.0	6	0	0	4	29	8	0	0	0	0	0	0	0	0	0	0	74
	5.5	0	0	0	0	1	11	1	0	0	0	0	0	0	0	0	0	13
	6.0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	9
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_e = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.6 T_e-H_s Occurrence in the Pauwela Site, 1990–2009
(hours)

		T_e (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	0	14	21	7	6	25	31	11	0	1	0	0	1	0	5	23	15
	1.0	0	0	0	0	0	7	10	167	401	762	917	854	770	765	510	367	272	227	167
	1.5	0	0	0	0	0	0	0	0	195	1,033	4,480	9,339	7,796	5,164	3,612	2,607	1,791	1,199	758
	2.0	0	0	0	0	0	0	0	0	0	0	494	4,693	9,686	8,955	6,933	5,597	4,675	3,546	2,741
	2.5	0	0	0	0	0	0	0	0	0	0	0	13	761	2,922	4,122	4,171	4,069	4,445	3,925
	3.0	0	0	0	0	0	0	0	0	0	0	0	0	1	178	950	1,896	2,191	2,140	2,335
	3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	4	80	479	855	855	911
	4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	43	130	281	264
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	29	138
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.6 *continued*

		T_e (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	165
	1.0	188	84	47	15	7	5	3	1	1	0	0	0	0	0	0	0	6,547
	1.5	510	367	214	111	59	22	29	7	5	4	0	1	0	0	0	0	39,303
	2.0	1,951	1,337	888	560	331	150	107	82	59	12	7	1	0	0	1	1	52,807
	2.5	3,326	2,765	1,914	1,457	876	480	238	112	82	40	40	9	6	1	0	2	35,776
	3.0	2,162	2,240	2,420	1,990	1,487	950	652	374	154	89	62	26	15	11	1	1	22,325
	3.5	900	972	1,152	1,162	1,082	848	620	441	269	165	104	39	18	13	6	4	10,979
	4.0	241	233	276	365	498	485	601	449	299	192	124	73	22	12	11	7	4,607
	4.5	88	34	43	107	151	218	195	223	214	127	90	72	17	13	3	3	1,789
	5.0	76	3	0	4	31	53	56	63	96	113	110	42	21	4	1	2	711
	5.5	3	0	0	0	0	16	7	42	50	25	32	14	8	2	3	1	203
	6.0	0	0	0	0	0	0	6	8	10	8	8	9	10	0	0	1	60
	6.5	0	0	0	0	0	0	0	0	0	9	5	10	5	0	0	1	30
	7.0	0	0	0	0	0	0	0	0	0	0	0	2	3	3	0	2	10
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	4	8
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_e = wave period
Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.7 T_e-H_s Occurrence in the Upolu Site, 1990–2009

(hours)

		T_e (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	0	4	6	34	13	3	10	4	5	0	2	0	1	0	0	0	0
	1.0	0	0	0	0	0	3	20	16	16	120	900	1,865	2,039	2174	1,903	1,240	600	421	149
	1.5	0	0	0	0	0	0	0	0	0	217	3,201	13,273	15,797	12,284	8,431	6,228	4,270	2,630	1,702
	2.0	0	0	0	0	0	0	0	0	0	0	95	3637	14,433	14,490	10,668	6,743	4,249	2,707	1,611
	2.5	0	0	0	0	0	0	0	0	0	0	0	40	1,030	4,187	5,441	3,923	3,010	1,871	979
	3.0	0	0	0	0	0	0	0	0	0	0	0	0	7	134	1,195	2,000	1,455	636	563
	3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	103	276	619	361	273
	4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	87	115	181
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	14	83
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.7 *continued*

		T_e (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	82
	1.0	76	16	7	13	4	1	0	0	0	0	0	0	0	0	0	0	11,583
	1.5	851	499	259	143	101	50	25	13	7	0	0	0	0	0	0	0	69,981
	2.0	1,116	704	480	309	123	76	56	21	19	7	5	0	0	0	0	0	61,549
	2.5	583	368	294	233	172	50	36	44	24	15	6	0	0	0	0	0	22,306
	3.0	310	260	134	77	57	56	20	17	10	6	0	0	0	0	0	0	6,937
	3.5	148	117	30	20	52	16	10	5	8	3	0	0	0	0	0	0	2,042
	4.0	37	19	28	34	24	13	0	4	10	21	10	0	0	0	0	0	586
	4.5	28	17	7	4	9	10	0	0	2	18	0	0	0	0	0	0	194
	5.0	17	0	0	0	0	13	2	0	0	0	0	0	0	0	0	0	41
	5.5	0	0	0	0	0	0	9	4	0	0	0	0	0	0	0	0	13
	6.0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	6
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_e = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.8 T_e-H_s Occurrence in the South Point Site, 1990–2009

(hours)

		T_e (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	3	4	11	13	61	3	4	14	3	0	0	0	0	0	0	0	0
	1.0	0	0	0	0	0	7	14	45	23	26	66	98	364	644	1,122	1,143	949	795	363
	1.5	0	0	0	0	0	0	0	2	6	20	61	567	2,957	8,886	14,886	17,263	13,803	8,946	5,571
	2.0	0	0	0	0	0	0	0	0	0	0	0	122	1,129	4,390	9,519	13,790	12,053	7,994	5,638
	2.5	0	0	0	0	0	0	0	0	0	0	0	1	114	779	1,906	4,078	3,262	2,428	1,644
	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	189	709	1,388	737	452
	3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	76	115
	4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.8 *continued*

		T_e (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	116
	1.0	180	72	41	21	2	4	1	0	0	0	0	0	0	0	0	0	5,980
	1.5	3,542	2,116	1,138	579	356	181	58	13	12	4	1	0	0	0	0	0	80,968
	2.0	3,851	2,337	1,559	1,007	493	366	195	106	48	10	3	4	0	0	0	0	64,614
	2.5	1,074	1,005	684	410	330	172	130	44	25	16	8	1	2	0	0	0	18,113
	3.0	318	236	170	194	203	144	73	48	27	8	0	0	3	0	0	0	4,936
	3.5	70	57	55	12	53	44	24	24	17	4	4	4	4	0	0	0	582
	4.0	0	0	0	0	0	0	2	9	0	0	0	0	0	0	0	0	11
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_e = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.9 T_e-H_s Occurrence in the Kilauea Site, 1990–2009

(hours)

		T_e (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	0	5	11	5	2	17	27	44	54	22	12	6	0	0	0	0	0
	1.0	0	0	0	0	0	4	7	162	532	1,439	3,581	4,341	3,854	2,735	1,968	1,274	732	393	194
	1.5	0	0	0	0	0	0	0	1	13	408	4,678	11,971	11,544	8,175	6,404	5,028	3,874	3,096	2,359
	2.0	0	0	0	0	0	0	0	0	0	0	40	544	1,900	3,315	4,239	4,695	4,734	4,837	4,308
	2.5	0	0	0	0	0	0	0	0	0	0	3	1	71	274	935	1,265	1,957	2,714	2,962
	3.0	0	0	0	0	0	0	0	0	0	0	0	0	2	20	108	337	621	800	1,155
	3.5	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	53	97	250	355
	4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	36	86
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	8
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.9 *continued*

		T_e (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	205
	1.0	89	32	18	7	0	0	0	0	0	0	0	0	0	0	0	0	21,362
	1.5	1,542	885	441	190	119	50	25	6	1	0	1	0	1	0	0	0	60,812
	2.0	3,937	2,748	2,157	1,209	665	348	180	89	33	23	13	6	3	1	1	0	40,025
	2.5	3,074	3,131	2,685	2,240	1,638	1,007	620	389	176	123	46	30	21	10	7	1	25,380
	3.0	1,460	1,691	1,686	1,503	1,417	1,279	813	561	352	168	111	34	51	24	11	8	14,212
	3.5	479	595	769	686	825	764	666	430	336	296	171	85	59	34	16	13	6,983
	4.0	94	200	238	344	346	444	445	353	255	206	127	96	62	27	21	8	3,391
	4.5	5	18	94	175	187	192	246	215	160	147	155	68	37	23	15	13	1,763
	5.0	0	0	12	32	69	82	74	88	88	77	95	60	30	11	8	2	728
	5.5	0	0	0	4	4	35	34	66	64	43	41	31	20	0	2	2	346
	6.0	0	0	0	0	0	0	1	9	21	5	14	16	1	3	1	1	72
	6.5	0	0	0	0	0	0	0	0	2	2	5	7	2	0	0	1	19
	7.0	0	0	0	0	0	0	0	0	0	0	1	6	1	3	0	2	13
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	6	9
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_e = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.10 T_{02}-H_s Occurrence in the Kaneohe Site, 1990–2009

(hours)

		T_{02} (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	19	26	647	587	439	325	192	161	158	110	60	79	50	24	1	1	1
	1.0	0	0	0	0	88	569	1,593	3,509	5,989	6,042	4,127	2,696	1,971	1,356	961	451	212	130	81
	1.5	0	0	0	0	0	0	71	1,708	10,154	21,194	17,427	7,774	4,698	2,877	1,908	1,275	935	610	265
	2.0	0	0	0	0	0	0	0	26	1,717	7,319	13,454	11,103	5,752	2,837	1,607	1,158	737	392	243
	2.5	0	0	0	0	0	0	0	0	22	1101	3,184	3,932	3,481	2,275	1,372	753	382	257	150
	3.0	0	0	0	0	0	0	0	0	0	14	654	1,159	882	757	761	501	302	105	115
	3.5	0	0	0	0	0	0	0	0	0	0	3	257	354	330	196	163	147	90	42
	4.0	0	0	0	0	0	0	0	0	0	0	0	15	65	98	72	79	26	24	15
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	2	24	9	17	15	10	22
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	11	9
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.10 *continued*

		T_{02} (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2,880
	1.0	44	13	1	0	0	0	0	0	0	0	0	0	0	0	0	0	29,833
	1.5	159	106	38	18	7	4	0	0	0	0	0	0	0	0	0	0	71,228
	2.0	116	52	21	16	7	1	2	0	1	0	0	0	0	0	0	0	46,561
	2.5	76	52	51	22	9	1	2	5	1	2	0	0	0	0	0	0	17,130
	3.0	34	18	26	10	1	5	8	2	0	0	0	0	0	0	0	0	5,354
	3.5	38	37	27	8	1	0	0	0	0	0	0	0	0	0	0	0	1,693
	4.0	12	17	5	0	6	0	0	0	0	0	0	0	0	0	0	0	434
	4.5	27	22	10	2	5	0	0	0	0	0	0	0	0	0	0	0	165
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23
	5.5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
	6.0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_{02} = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.11 T_{02}-H_s Occurrence in the Kaneohe Rov7 Site, 1990–2009

(hours)

		T_{02} (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	3	35	465	556	371	222	153	104	89	61	53	33	2	0	0	0	0
	1.0	0	0	0	0	100	479	1,248	2,556	3,812	3,608	2,873	1,954	1,364	858	435	285	108	42	26
	1.5	0	0	0	0	0	0	61	1,384	8,325	17,936	13,311	6,632	4,031	2,853	1,896	1,138	776	450	254
	2.0	0	0	0	0	0	0	0	13	1,589	9,043	18,734	12,654	6,098	3,384	1,735	1,283	874	460	227
	2.5	0	0	0	0	0	0	0	0	24	1,104	4,817	6,969	5,403	2,892	1,566	863	471	297	220
	3.0	0	0	0	0	0	0	0	0	0	15	848	1,988	2,212	1,333	1,009	591	347	171	108
	3.5	0	0	0	0	0	0	0	0	0	0	15	367	670	607	382	347	176	112	57
	4.0	0	0	0	0	0	0	0	0	0	0	0	6	172	260	187	106	92	43	22
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	12	51	56	47	17	15	17
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	30	0	4	4	19
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.11 *continued*

		T_{02} (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2,147
	1.0	9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19,758
	1.5	147	71	40	12	11	0	0	0	0	0	0	0	0	0	0	0	59,328
	2.0	117	68	17	10	6	1	0	1	0	1	0	0	0	0	0	0	56,315
	2.5	82	44	43	21	8	7	0	1	1	1	0	0	0	0	0	0	24,834
	3.0	52	32	33	14	1	3	9	5	0	0	0	0	0	0	0	0	8,771
	3.5	52	33	21	8	3	0	0	0	0	0	0	0	0	0	0	0	2,850
	4.0	16	26	9	2	1	8	0	0	0	0	0	0	0	0	0	0	950
	4.5	28	14	9	3	2	0	0	0	0	0	0	0	0	0	0	0	271
	5.0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	74
	5.5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13
	6.0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_{02} = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.12 T_{02}-H_s Occurrence in the Pauwela Site, 1990–2009

(hours)

		T_{02} (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	2	25	47	26	16	4	4	10	8	11	5	7	0	0	0	0	0
	1.0	0	0	0	0	17	578	1,977	1,572	1,028	483	297	227	142	79	70	35	26	16	0
	1.5	0	0	0	0	0	0	717	6,980	16,155	7,874	3,119	1,743	1,045	751	401	200	116	70	66
	2.0	0	0	0	0	0	0	0	76	8,114	18,262	10,942	5,782	3,286	2,251	1,430	1,081	649	351	253
	2.5	0	0	0	0	0	0	0	0	6	2,751	9,571	7,267	5,045	3,680	2,600	1,608	1,145	867	596
	3.0	0	0	0	0	0	0	0	0	0	0	1,442	4,794	3,851	2,849	2,790	2,113	1,514	1,070	716
	3.5	0	0	0	0	0	0	0	0	0	0	12	1,115	1,900	1,375	1,254	1,249	1,325	939	618
	4.0	0	0	0	0	0	0	0	0	0	0	0	33	432	501	314	438	464	582	498
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	40	175	98	77	145	178	237
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	91	0	9	19	52
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	1
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.12 *continued*

		T_{02} (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	165
	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6,547
	1.5	56	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39,303
	2.0	140	104	58	18	8	2	0	0	0	0	0	0	0	0	0	0	52,807
	2.5	325	141	92	62	12	5	2	1	0	0	0	0	0	0	0	0	35,776
	3.0	461	276	262	86	58	23	10	8	2	0	0	0	0	0	0	0	22,325
	3.5	418	231	167	169	101	47	33	16	10	0	0	0	0	0	0	0	10,979
	4.0	496	333	161	108	91	75	40	27	14	0	0	0	0	0	0	0	4,607
	4.5	206	221	147	75	61	71	32	11	13	2	0	0	0	0	0	0	1,789
	5.0	77	85	117	109	31	42	36	15	2	2	0	0	0	0	0	0	711
	5.5	5	51	55	30	15	16	16	2	4	5	0	0	0	0	0	0	203
	6.0	0	17	9	9	6	6	7	6	0	0	0	0	0	0	0	0	60
	6.5	0	0	4	7	9	9	0	1	0	0	0	0	0	0	0	0	30
	7.0	0	0	0	0	0	4	4	0	2	0	0	0	0	0	0	0	10
	7.5	0	0	0	0	0	0	2	4	2	0	0	0	0	0	0	0	8
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_{02} = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.13 T_{02}-H_s Occurrence in the Upolu Site, 1990–2009

(hours)

		T_{02} (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	0	10	45	14	8	4	1	0	0	0	0	0	0	0	0	0	0
	1.0	0	0	0	0	2	41	472	3,531	3,012	1,716	1,094	830	516	270	64	32	1	1	1
	1.5	0	0	0	0	0	0	15	6,204	29,211	17,409	7,556	4,143	2,653	1,688	752	203	100	42	5
	2.0	0	0	0	0	0	0	0	24	5,784	27,284	16,481	6,093	2,644	1,534	979	406	205	80	21
	2.5	0	0	0	0	0	0	0	0	14	2,379	9,934	5,615	2,334	934	552	246	120	95	31
	3.0	0	0	0	0	0	0	0	0	0	7	915	3,546	1,219	634	305	180	77	27	15
	3.5	0	0	0	0	0	0	0	0	0	0	6	518	904	357	102	42	31	30	43
	4.0	0	0	0	0	0	0	0	0	0	0	0	0	171	224	62	42	29	10	8
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	2	94	48	7	0	9	11
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	24	0	0	0	6
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.13 *continued*

		T_{02} (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	82
	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11,583
	1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	69,981
	2.0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	61,549
	2.5	31	19	2	0	0	0	0	0	0	0	0	0	0	0	0	0	22,306
	3.0	5	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6,937
	3.5	6	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2,042
	4.0	6	7	12	2	4	6	3	0	0	0	0	0	0	0	0	0	586
	4.5	3	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	194
	5.0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41
	5.5	7	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13
	6.0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_{02} = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.14 T_{02}-H_s Occurrence in the South Point Site, 1990–2009

(hours)

		T_{02} (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	3	13	27	52	5	11	5	0	0	0	0	0	0	0	0	0	0
	1.0	0	0	0	0	7	53	93	478	1,290	1,648	1,197	603	346	130	107	26	2	0	0
	1.5	0	0	0	0	0	0	14	670	10,231	28,181	22,847	10,290	5,150	2,661	613	222	65	24	0
	2.0	0	0	0	0	0	0	0	8	837	11,398	25,167	15,461	6,693	3,170	1,174	408	224	67	7
	2.5	0	0	0	0	0	0	0	0	29	869	5,827	5,941	2,824	1,420	663	262	185	69	24
	3.0	0	0	0	0	0	0	0	0	0	8	432	2,227	996	446	360	298	122	31	14
	3.5	0	0	0	0	0	0	0	0	0	0	0	19	194	79	48	98	55	15	36
	4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.14 *continued*

		T_{02} (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	116
	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5,980
	1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80,968
	2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	64,614
	2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18,113
	3.0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4,936
	3.5	19	8	11	0	0	0	0	0	0	0	0	0	0	0	0	0	582
	4.0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_{02} = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

Table A3.15 T_{02}-H_s Occurrence in the Kilauea Site, 1990–2009

(hours)

		T_{02} (second)																		
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
H_s (meter)	0.5	0	0	2	8	15	67	56	35	21	1	0	0	0	0	0	0	0	0	0
	1.0	0	0	0	0	4	644	2,490	6,573	5,882	3,072	1,435	611	399	165	76	10	1	0	0
	1.5	0	0	0	0	0	0	48	4,105	18,987	18,163	8,830	4,684	2,658	1,601	928	499	230	61	15
	2.0	0	0	0	0	0	0	0	9	989	5,759	8,664	7,994	6,258	4,323	2,709	1,472	866	515	278
	2.5	0	0	0	0	0	0	0	0	5	358	2,049	3,482	4,077	4,420	3,712	2,747	1,828	1,195	769
	3.0	0	0	0	0	0	0	0	0	0	3	181	903	1,660	1,750	1,900	2,247	1,897	1,524	896
	3.5	0	0	0	0	0	0	0	0	0	1	3	72	421	659	663	761	908	1,040	792
	4.0	0	0	0	0	0	0	0	0	0	0	0	0	16	153	195	306	354	453	469
	4.5	0	0	0	0	0	0	0	0	0	0	0	0	5	4	13	133	185	187	211
	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	41	66	82
	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	42
	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table A3.15 *continued*

		T_{02} (second)																
		10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	>17.0	
H_s (meter)	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	205
	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21,362
	1.5	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60,812
	2.0	137	42	10	0	0	0	0	0	0	0	0	0	0	0	0	0	40,025
	2.5	399	245	72	17	4	1	0	0	0	0	0	0	0	0	0	0	25,380
	3.0	565	314	210	106	41	6	7	1	1	0	0	0	0	0	0	0	14,212
	3.5	531	372	318	253	89	55	27	15	0	3	0	0	0	0	0	0	6,983
	4.0	513	297	167	179	133	84	43	16	6	7	0	0	0	0	0	0	3,391
	4.5	238	256	166	94	113	91	46	15	4	2	0	0	0	0	0	0	1,763
	5.0	113	82	88	83	62	65	30	11	0	0	1	0	0	0	0	0	728
	5.5	48	62	60	42	29	25	17	6	1	0	3	0	0	0	0	0	346
	6.0	19	11	4	4	14	14	1	0	1	4	0	0	0	0	0	0	72
	6.5	0	2	1	6	6	3	0	1	0	0	0	0	0	0	0	0	19
	7.0	0	0	0	0	3	5	3	0	2	0	0	0	0	0	0	0	13
	7.5	0	0	0	0	0	0	0	4	5	0	0	0	0	0	0	0	9
	>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
																		175,320

H_s = significant wave height, T_{02} = wave period

Source: N. Li, J. Stopa, and K. F. Cheung, University of Hawaii. http://hinmrec.hnei.hawaii.edu/

APPENDIX 4: WAVE ENERGY CONVERSION DEVICE PERFORMANCE EVALUATION

The performance of electricity-producing wave energy conversion (WEC) devices can be assessed using the power matrix[1] concept. Ideally, this is done using field data for each device to obtain the relationship among power output, significant wave height (H_s), and energy period (T_e). The wave parameters are as defined in the spectral treatment of the sea surface elevation time series and are also referred to as time history records.

Wave data records are used to derive and present the following parameters: (i) significant wave height divided into bins centered between 1 and 7 meters (m) with spacing of 0.5 m (for example, the 1.5 m bin includes all data points between 1.25 m and 1.74 m); and (ii) the energy period divided into bins centered between 4 and 17 seconds with spacing of 1 second. The device electrical power output measured under all conditions corresponding to the bin pairs is tabulated in Table A4.1.

Field tests should be conducted by a third party to obtain the required time history records of WEC device power output as a function of environmental input, that is, the time series of sea surface elevation and power output at the device generator terminal, at a point where the output is in the form of alternating current at 60 (or 50) hertz (Hz) at a grid connection voltage. Unfortunately, at the nascent stage of WEC technology, this information is not available.

However, in this appendix, electricity generation estimates are provided, using power matrixes published by developers that are in the process of testing their equipment. These preliminary power matrixes are used in conjunction with wave scatter information available for Hawaii (Appendix 3). That is, a power matrix, in conjunction with the site-specific wave scatter matrix (percentage of occurrence of H_s/T_e bin pair), is used to estimate the energy output of the device over the specified period.

Table A4.2 and Figure A4.1, for example, provide the power matrix for a WEC device referred to as a point absorber with a nominal name plate of 1,000 kilowatts (kW). Table A4.3 provides the wave scatter matrix for a site at a 58 m depth off Kaneohe Bay in Hawaii with values corresponding to the year 2009. The data points are given as number of days estimated for that particular year. Note that the sum of all entries is equal to 365 days. Multiplying each bin in the power matrix times the number of hours (i.e., entries in Table A4.3 x 24 hours per day) yields the annual electricity generation for that bin, so the sum of all values shown in Table A4.3 yields the total estimate of 1,048,212 kilowatt-hours (kWh).

To illustrate, the wave scatter at a site near the 58 m depth is shown in Figure A4.2. Comparing Figures A4.1 and A4.2 (or Tables A4.2 and A4.3) shows that this WEC device is not tuned for the site shown in Figure A4.2. As depicted in Table A4.3, no days were recorded for the H_s/T_e bin that would generate at the device name plate (e.g., 1,000 kW in Table A4.2). In general, at this site, no days with H_s higher than 3.6 m were observed. Thus, this particular device should have a name plate of, at most, 700 kW at the specific site considered.

The concept of capacity factor can be used to estimate the fraction of time that the device deployed at the 58 m depth site would have produced at its name plate. Using annual production divided by the product of 8,760 hours x name plate, this device would have a capacity factor of 0.12 (i.e., a name plate of 1,000 kW) or 0.17 (a name plate of 700 kW).

Table A4.1 provides estimates of electricity generation for WEC devices represented by power matrixes provided by the different developers and not by independent parties. Specific sites for which wave scatter information was available were used. It appears as if the Wave-Star WEC device is better suited for the locations considered herein. However, it must be noted that the Wave-Star, at a location with a much higher wave power flux (e.g.,

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[1] Analogous to the method of bins utilized to obtain the power curve (i.e., power output versus wind speed) of wind turbine generators.

Kilauea versus Kaneohe), produces essentially the same output. This device curtails production for H_s higher than 3 m, and, as indicated in the table, there would have been 22 days in Kilauea when generation would have been curtailed to avoid equipment damage.

Table A4.1 Site- and Device-Specific Electricity Generation with Wave Energy Conversion Devices under Development

	Name Plate	Kaneohe, Oahu	Kilauea, Kauai	Pauwela, Maui	Kaneohe, Oahu
Wave Scatter Data (Year)		2009	2009	1990–2009	1990–2009
Site Depth		58 m	53 m	73 m	86 m
Site Wave Power Flux: P_o		13.8 kW/m	21.6 kW/m	23.1 kW/m	12.1 kW/m
WEC Device					
Point Absorber IEC/TS 62600-100 Annex A http://www.iec.ch	1,000 kW	1,048 MWh (annual) CF: 0.12	1,343 MWh (annual) CF: 0.15	1,951 MWh (annual) CF: 0.22	1,105 MWh (annual) CF: 0.13
Pelamis http://www.pelamiswave.com	750 kW	826 MWh (annual) CF: 0.13	743 MWh CF: 0.11		
Wave Star C5 http://wavestarenergy.com	600 kW	2,494 MWh CF: 0.47 Curtail 4 days	2,331 MWh CF: 0.44 Curtail 22 days		

CF = capacity factor, kW = kilowatt, MWh = megawatt-hour, m = meter, WEC = wave energy conversion.

Source: Author.

It must be emphasized that the values given above are the total annual energy output, but due to the seasonal dependence of ocean wave generation, the output will vary throughout the year. One way to illustrate this is to consider the daily wave power flux estimated during 2009 at the Kaneohe 58 m and Kilauea 53 m depth sites (Figure A4.4). Clearly, the relationship between wave power flux (annual averages of 21.6 kW/m versus 13.8 kW/m) and electricity production with the three WEC devices considered in the table above is not linear.

The information summarized in Table A4.1 indicates that WEC devices might yield capacity factors similar to those obtained with well-established photovoltaic arrays (0.16–0.20) and wind farms (0.20–0.45). Considering the concept of levelized cost of electricity, the capital cost target for WEC devices must be within the range corresponding to photovoltaic and wind arrays (i.e., less than \$6,000/kW to less than \$2,000/kW, respectively). At this stage of development, it is premature to discuss cost estimates, but these will range from \$3,000/kW once commercialization is achieved to \$30,000/kW for all costs associated with the prototypes under development.

Table A4.2 Point Absorber Power Matrix for Kaneohe Bay, Oahu
(kilowatt)

Bin H_s, m \ Bin T_e, s	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0
1.0	0	2	10	19	32	42	51	57	60	51		32	28	
1.5	1	5	16	46	71	94	114	128	134	111	92	81	68	64
2.0	1	8	35	86	130	166	200	228	237	201	167	139	118	110
2.5		17	51	122	193	258	317	356	376	314	255	231	184	167
3.0		10	81	171	291	365	454	513	526	448	360	321	0	242
3.5		36	96	235	396	512	618	696	726	622	520	435	358	
4.0			184	306	523	668	804	904	952	804	612	547	490	
4.5			159	366	655	827	1,027	1,131	1,140	1,001	836	729	549	529
5.0				573	769	1,032	1,261	1,316	1,323	1,251	1,090	876	775	606
5.5				546	1,000	1,292	1,345	1,290	1,277	1,342	1,206	1,090	851	796
6.0							1,289		1,280	1,312	1,395	1,175	1,005	
6.5								1,199		1,268	1,301		1,131	1,008

H_s = significant wave height, kW = kilowatt, m = meter, T_e = energy period.
Source: www.iec.ch

Table A4.3 Wave Scatter Matrix for Kaneohe Bay, Oahu
(number of days)

Bin H_s, m \ T_e, Energy Period (s)	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0
1.0			7	14	22	13	7	2	4					
1.5			19	34	31	31	24	3	4	4	1			
2.0				14	31	20	9	14	8	2	2	1		1
2.5					5	10	6	3		1	3	2	1	1
3.0						2	4	1	2					
3.5									1		1			
4.0														
4.5														
5.0														
5.5														
6.0														
6.5														
7.0														

H_s = significant wave height, kW = kilowatt, m = meter, s = second, T_e = energy period.
Note: At a 58-meter depth site, 1.5 kilometers offshore.
Source: Generated by author.

Table A4.4 Annual Electricity Generation for Kaneohe Bay, Oahu
(kilowatt-hour)

Bin T_e, s

Bin Hs, m

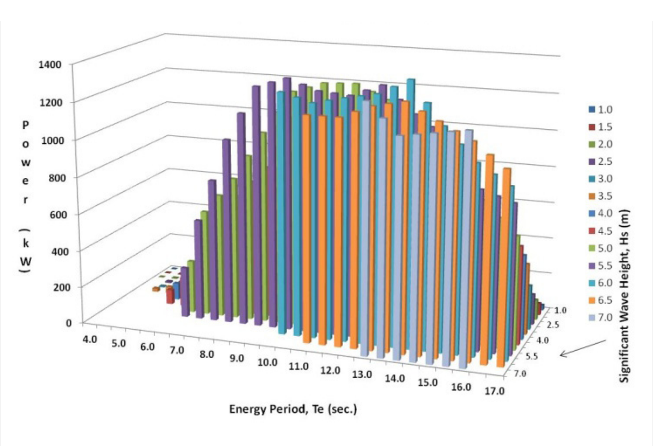
	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0
1.0	0	0	1,613	6,485	17,002	12,948	8,501	2,722	5,722	0	0	0	0	0
1.5	0	0	7,478	37,699	53,122	69,564	65,491	9,230	12,845	10,646	2,215	0	0	0
2.0	0	0	0	28,829	96,943	79,680	43,243	76,574	45,542	9,667	7,992	3,336	0	2,642
2.5	0	0	0	0	23,208	61,944	45,706	25,596	0	7,543	18,374	11,107	4,426	4,003
3.0	0	0	0	0	0	17,520	43,603	12,302	25,248	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	17,431	0	12,468	0	0	0
4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Hs = significant wave height, kW = kilowatt, m = meter, T_e = energy period.

Note: The point absorber device represented in Table A4.2 would have produced such yields operating at the specific site represented in Table A4.3. The sum of all entries yields 1,048,212 kilowatt-hours.

Source: Generated by author.

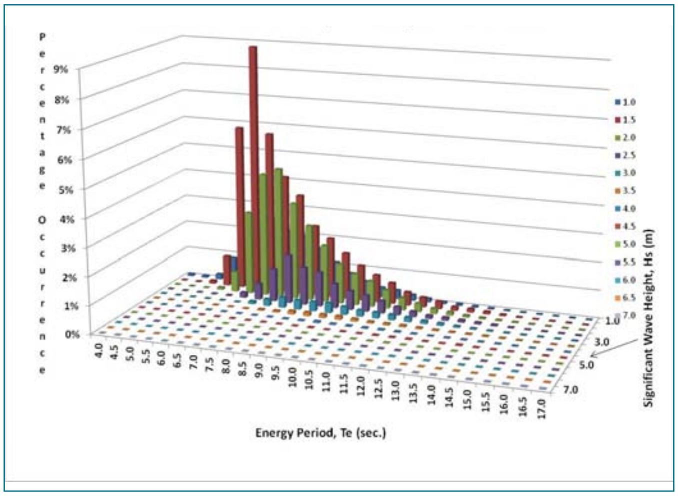
Figure A4.1 Point Absorber Power Matrix, Power Output for Each H_s/T_e Bin for Kaneohe Bay, Oahu



H_s = significant wave height, kW = kilowatt, m = meter, s = second, T_e = energy period.

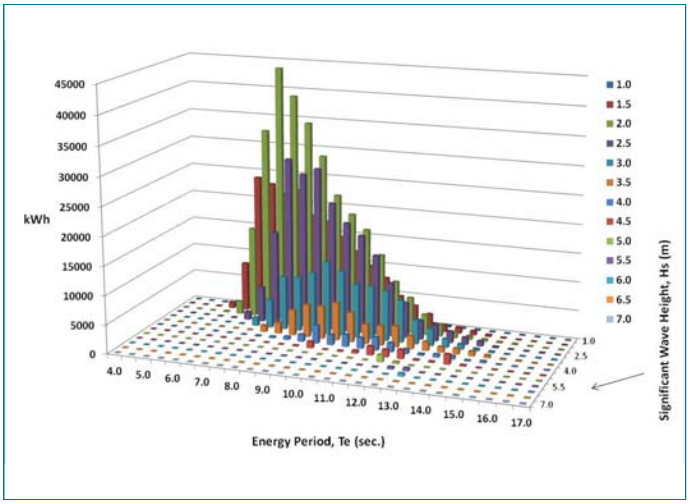
Source: Generated by author.

Figure A4.2 Annual Occurrence of Each H_s/T_e Bin at Kaneohe Bay, Oahu (%)



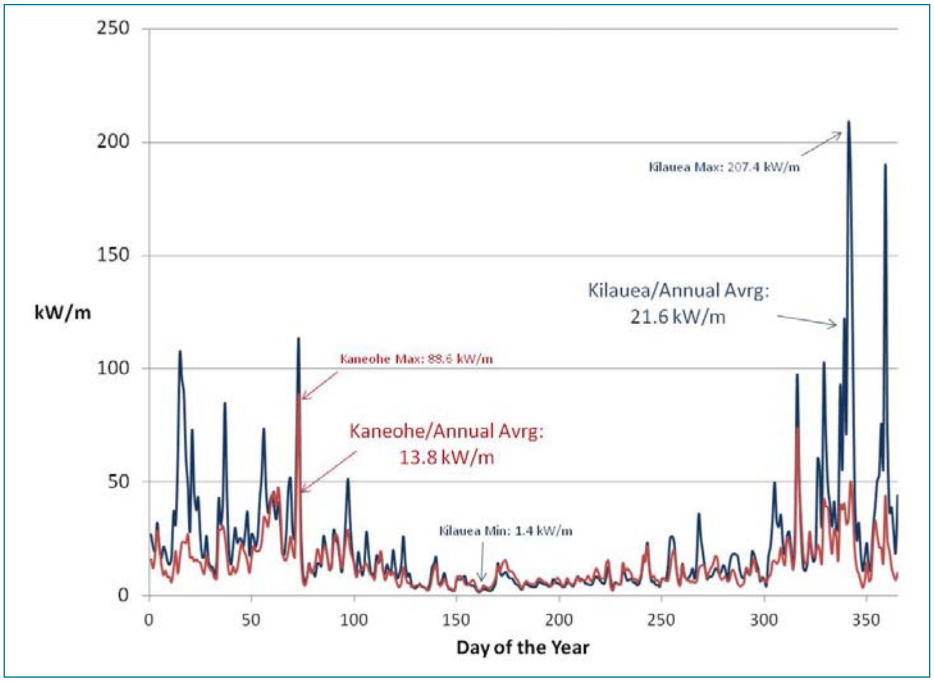
H_s = significant wave height, kW = kilowatt, m = meter, T_e = energy period.
Notes: At a 27 m depth. Percentage x 8,760 = number of hours per year.
Source: Generated by author.

Figure A4.3 Annual Electricity Generation for Each Hs/Te Bin at Kaneohe Bay, Oahu (kilowatt-hour)



H_s = significant wave height, kW = kilowatt, m = meter, T_e = energy period.
Notes: Power matrix (Figure A4.1) x number of hours per year = sum of all H_s/T_e estimates (Figure A4.2)
Source: Generated by author.

Figure A4.4 Daily Wave Power Flux at Kilauea, Kauai and Kaneohe, Oahu, 2009



kW = kilowatt, m = meter.

Notes: The daily wave power flux at the Kaneohe site ranges from 2.2 kW/m in early June to 88.6 kW/m (factor of about 40) in mid-March, with an annual average of 13.8 kW/m. At the Kilauea site, the values range from 1.4 kW/m in mid-June to 207.4 kW/m in early December (factor of about 146) with an annual average of 21.6 kW/m.

Figure A4.5 Wave-Star, Actual Test Installation

Figure A4.6 Wave-Star, Illustration

Source: http://wavestarenergy.com

Depicted above is the Wave-Star C5 with 20 floats (10 each side): 5-meter float diameter, 10-meter arm length. This device was developed in Denmark over the last 10 years beginning at Aalborg University. The floats are fixed by leaver arms to horizontal shafts connected through a gearbox to a generator. On the opposite side, there is a similar row of floats and an additional shaft, which is driven in the opposite direction.

Table A4.5 Wave-Star Power Matrix

Wave height H (m)	**Wave period T o,z** (s)										
	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13
0.0–0.5	0	0	0	0	0	0	0	0	0	0	0
0.5–1.0	0	49	73	85	86	83	78	72	67	63	59
1.0–1.5	54	136	193	205	195	182	167	153	142	132	123
1.5–2.0	106	265	347	347	322	294	267	244	224	207	193
2.0–2.5	175	429	522	499	457	412	372	337	312	288	267
2.5–3.0	262	600	600	600	600	540	484	442	399	367	340
3.0–	Storm protection										

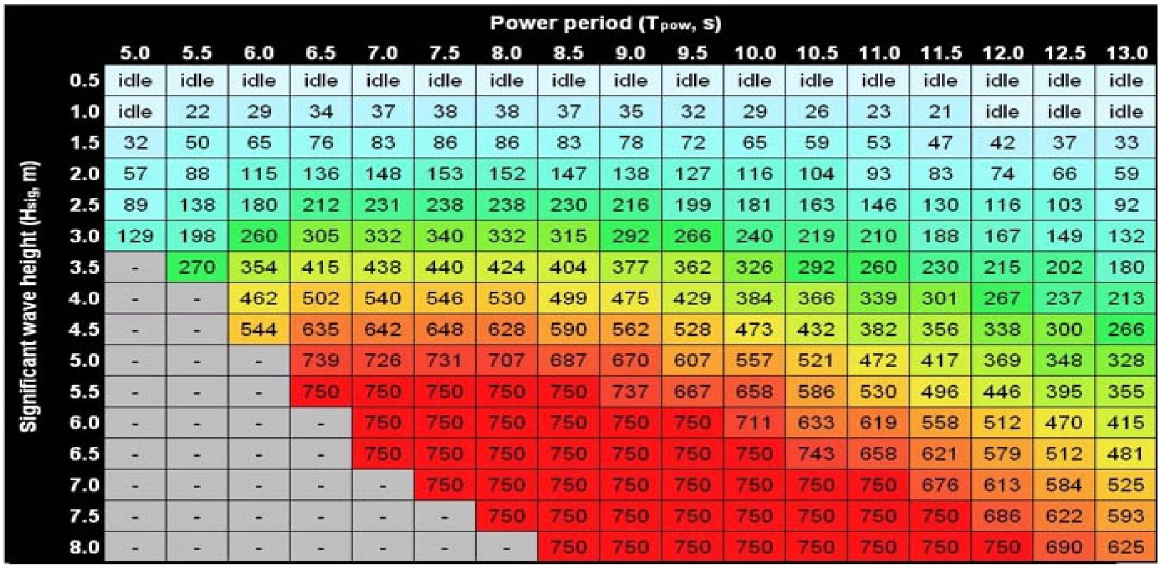
m = meter, s = second.
Source: http://wavestarenergy.com

Figure A4.7 Pelamis Sea Snake Wave Energy Converter

Source: www.pelamiswave.com

The Pelamis device is an offshore WEC device, operating in water depths greater than 50 meters (m). The machine consists of a series of semisubmerged cylindrical sections linked by hinged joints. As waves pass along the length of the machine, the sections move relative to one another. The wave-induced motion of the sections is resisted by hydraulic cylinders, which pump high-pressure oil through hydraulic motors via smoothing hydraulic accumulators. The hydraulic motors drive electric generators to produce electricity. The first-generation device for which the power curve has been made public was rated at 750 kilowatts. The device was 120 m long and 3.5 m in diameter. It consisted of four tube sections linked by three shorter power conversion modules. Currently, a second-generation device is under testing at the European Marine Energy Centre (EMEC), and the new power matrix has not been made public.

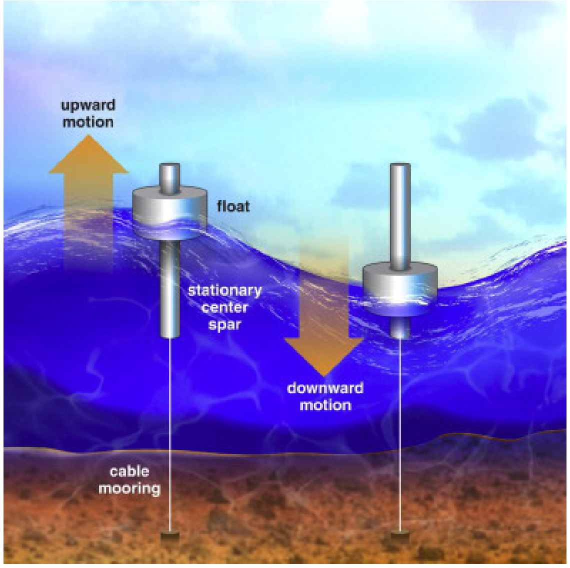
Table A4.6 Pelamis Power Matrix



	Power period (T_{pow}, s)																
Significant wave height (H_{sig}, m)	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**	**7.5**	**8.0**	**8.5**	**9.0**	**9.5**	**10.0**	**10.5**	**11.0**	**11.5**	**12.0**	**12.5**	**13.0**
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

H_{sig} = significant wave height, m = meter, s = second, T_{pow} = energy period.
Source: www.pelamiswave.com

Figure A4.8 Generic Point Absorber



Source: http://hinmrec.hnei.hawaii.edu

Generic point absorbers capture energy from the up-and-down (i.e., heaving) motion of the waves. They may be fully or partially submerged. The device is small compared to a typical wave length and can absorb energy in all directions. The power takeoff system (i.e., to convert wave energy to electrical energy) may take a number of forms, ranging from closed hydraulic system to rack and pinion.

APPENDIX 5: SURVEY OF OCEAN THERMAL ENERGY CONVERSION COMPANIES

January 11, 2013

Dear Colleague,

I have gathered the ocean thermal energy conversion (OTEC) resource information already available in the public domain to assess the viability of utilizing these resources for the production of electricity and desalinated water in developing member countries of the Asian Development Bank (ADB).

The table below lists the countries under consideration, and the thermal resource data are available from the work of Gerard Nihous at the University of Hawaii.

Please note that I included Hawaii as a reference site in the attached table, because we have done extensive work at the University of Hawaii modeling the resource throughout the state of Hawaii.

I would like to include information about your company in the following format:

Name and Location:
Point of Contact:
Ocean Thermal Energy Conversion Plants under Development:
Company Description: {no more than about 400 words}

Thank you,

Luis Vega

Information received from the following companies is provided in this appendix:

- Energy Island
- Lockheed Martin
- Ocean Thermal Energy Corporation
- OTEC International
- SBM Offshore

In addition, the following companies are known to be involved in the development of OTEC plants:

DCNS (http://www.dcnsgroup.com)

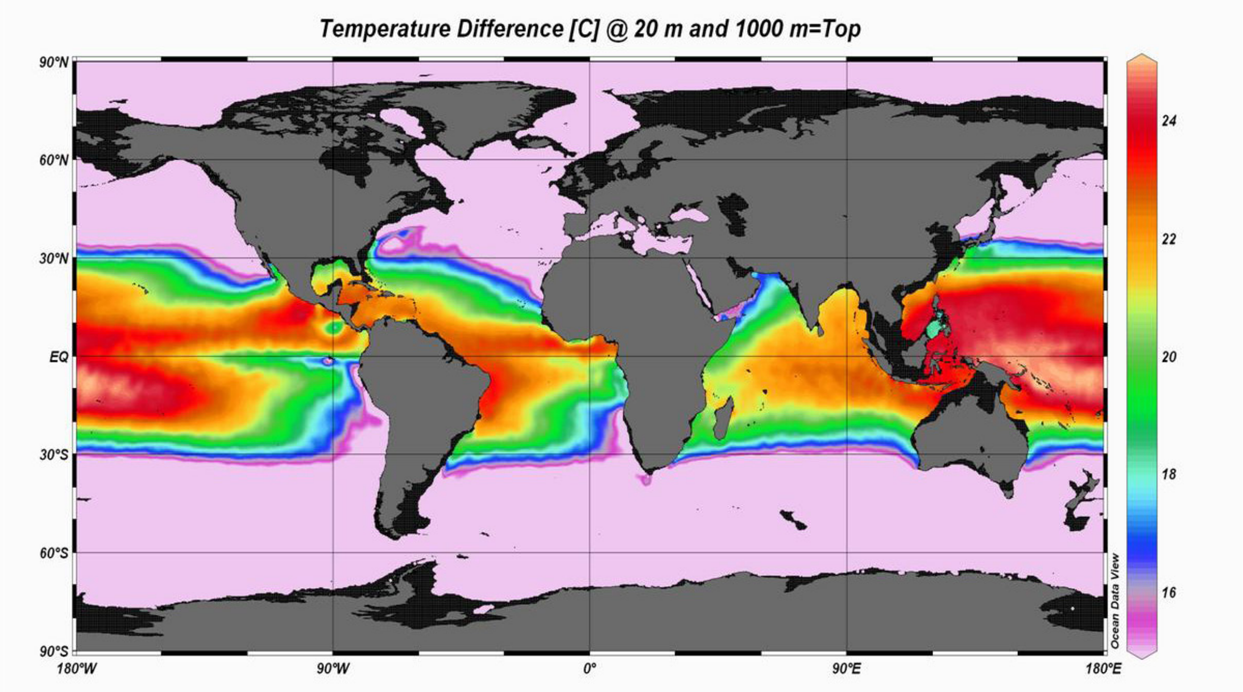
Xenesys (http://www.xenesys.com)

Table A5 Ocean Thermal Energy Conversion Resource Information

Region and Country	Reference Longitude	Reference Latitude
Central and West Asia		
Pakistan		
East Asia		
People's Republic of China		
Pacific		
Reference Site (Hawaii Global)		
Cook Islands/Rarotonga	160°W	22°S
Fiji	178°E	17°S
Kiribati/Tarawa	175°E	2°N
Marshall Islands/Majuro	170°E	5°N
Federated States of Micronesia (Global)	140°E–165°E	0°–10°N
Nauru	165°E	0°
Palau	135°E	5°N
Papua New Guinea (Global)		
Samoa	172°W	12°S
Solomon Islands	160°E	10°S
Timor-Leste (Global)		
Tonga	175°W	22°S
Tuvalu	180°	5°–10°S
Vanuatu	165°E	15°S
South Asia		
Bangladesh		
India		
Maldives		
Sri Lanka		
Southeast Asia		
Brunei Darussalam		
Cambodia		
Indonesia		
Malaysia		
Myanmar		
Philippines		
Thailand		
Viet Nam		

There are 98 countries with the ocean thermal resource required to operate ocean thermal energy conversion plants within their exclusive economic zone (200 nautical miles). The resource could be used in a sustainable way to generate over 50% of present worldwide consumption.

Figure A5.1 Worldwide Average Ocean Temperature Differences between 20- and 1,000-Meter Depths



Note: The color palette is from 15°C to 25°C.

Sources: United States National Ocean Data Center. 2005. World Ocean Atlas. http://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html; and G. Nihous. Mapping Available Ocean Thermal Energy Conversion Resources around the Main Hawaiian Islands with State-of-the-Art Tools. *Journal of Renewable and Sustainable Energy*. 2 (043104).

Name and Location:

SBM Offshore's corporate offices are in Monaco. Our execution centers are in Monaco; Houston, Texas; Kuala Lumpur, Malaysia; and Schiedam, Netherlands.

Point of Contact:

Stephen Kibbee
SBM Offshore
1255 Enclave Parkway
Houston, Texas 77077
USA
+1 (281) 848 6000
steve.kibbee@sbmoffshore.com

Ocean Thermal Energy Conversion Plants under Development:

SBM has no site-specific OTEC units under construction. However, SBM has continuously funded and conducted a significant research and development program on OTEC since 2010. This program is sponsored by SBM's chief technology officer.

SBM's core business is the design, construction, installation, and operation of floating production storage and offloading (FPSO) units. Our interest in OTEC stems from its similarity to our core technology and business models and the possibility of co-locating OTEC cogeneration modules in FPSOs for increased energy efficiency.

Company Description:

SBM Offshore is a leader in floating production and mooring systems, production operations, and terminals. With over 6,000 employees worldwide, we confidently supply floating production solutions through the entire product lifecycle including engineering, procurement, construction, installation, operation, and relocation.

SBM pioneered the development of the FPSO, starting with supply of the mooring system for the first FPSO in 1976 (for Shell's Castellon field in Spain) and providing the first leased FPSO in 1981 (the FPSO II, for Amoco's Cadlao field in the Philippines).

Since that time, we have been involved in over 40 FPSO projects worldwide. Our fleet of leased production vessels currently includes 11 FPSO vessels in operation, with a further 3 under construction and 1 on standby. To date, we have accumulated over 140 years of FPSO operating experience, more than any other FPSO operator worldwide.

Today, SBM Offshore focuses on projects where we can use our FPSO experience and expertise to meet the most difficult challenges in the industry. These include ultra deepwater (3,000-meter water depth), high pressure and/or high temperature fields, sour fields, and large complex topsides. Some of our current projects require a combination of all the above, with topsides exceeding 20,000 tons with total installed shaft power over 200 megawatts.

Moreover, we are designing, building, and operating increasingly complex process systems. Today, our development work includes enhanced FPSO products for liquefied natural gas production, compact gas-to-liquids processes, and ultra heavy oil production. In our laboratories, we have developed pioneering swivel technology for FPSOs.

SBM's core technology and business models are adjacent to the marine renewable energy systems of the future. The company has conducted significant research and development in OTEC and wave energy conversion.

Name and Location:

Energy Island Limited is a private company limited by shares registered in England and Wales with company number 05051123 and having its registered office at:

108 Palace Gardens Terrace
London W8 4RT
United Kingdom
+44 0 20 7221 1237
http://www.energyisland.com

Energy Island is committed to developing all forms of energy available at sea, including wave, wind, sea currents, all forms of solar energy conversion, and, particularly, OTEC.

Energy Island and its partners intend to commercialize OTEC, providing large-scale renewable power and desalinated water to states and utility companies worldwide. The team is ready to implement the design and construction of OTEC facilities on a commercial scale.

The team is made up of the following partners:

- Energy Island Ltd.
- Bell Pirie Power Corp.
- Vega Consulting
- Halcrow Group Ltd.
- Noble Denton Group Ltd.
- Parsons Brinckerhoff Inc.
- School of Engineering Sciences, Univ. of Southampton, UK.

Energy Island has partnered with Bell Pirie Power (Philippines) to form Energy Island Bell Pirie in order to develop and deliver multiple OTEC plants in the Philippines. The first project is based in the Zambales region and will be a 10-megawatt OTEC pilot plant located within 10 kilometers off the west coast of Luzon, around 120 kilometers north of Manila. The project will connect to the main transmission grid in Botolan and is not dependent on transmission upgrades. It is expected to offset approximately 84,121 metric tons of carbon dioxide a year and represents an investment of $180 million.

Bell Pirie Power has been awarded a service contract from the Government of the Philippines, and we are currently in negotiation for a renewable energy purchase agreement.

The experience gained from the pilot plant will play a vital role in our plans to expand to two further sites, each of which could potentially produce 600 megawatts.

In the Philippines also, we are working with the Philippines National Oil Company (PNOC), on a prototype 100-kilowatt wave energy converter suitable for small isolated islands.

Name and Location:

Ocean Thermal Energy Corporation

10432 Balls Ford Rd.
Manassas, VA 20109
USA
Also offices in Lancaster, PA; Hawaii; Bahamas; and London
+1 (540) 454 1484
http://www.OTEcorporation.com

Point of Contact:

Ted Johnson, Senior Vice President

Ocean Thermal Energy Conversion Plants under Development:

- Bahamas
- US Virgin Islands
- Cayman Islands
- Guam
- Philippines
- Hawaii
- India
- Various US bases
- Other countries that have signed MOUs for development

Company Description:

Ocean Thermal Energy Corporation (OTE) is a private US-based renewable power generation company and is a wholly owned subsidiary of JPF Venture Fund. It was incorporated in 1998. OTE is an internationally recognized leader in OTEC and Sea Water District Cooling (SDC) and as well as the by-products of OTEC, such as fresh water generation, aquaculture, farming, and fertilizer production. OTE is dedicated to sustainable, clean, secure energy and its by-products for all of the nations of the world.

OTE's business model is to design, build, own, and operate OTEC and SDC plants worldwide. OTE also provides all of the financing to build OTEC and SDC plants, so no capital cost is required from the host country. To date, the company has been funded by private investors. The OTE chairman and directors are invested in the company, which works with a number of financial firms, including Raymond James of Wall Street. OTE has also purchased the OCEES OTEC Company of Hawaii, which is now part of OTE and also added worldwide experts in OTEC technology.

OTE will have an initial public offering on the London Stock Exchange in the first half of 2013 and thereafter will be traded by the public worldwide. To date, OTE has over 50 private investors. OTE is presently in the process of expansion in personnel and facilities to meet the demand of a large number of customers who have signed memorandums of understanding to develop OTEC and SDC plants.

Name and Location:

OTEC International LLC

111 S. Calvert Street, Suite 2300
Baltimore, MD 21202
USA
http://www.oteci.com

Point of Contact:

Eileen O’Rourke

Ocean Thermal Energy Conversion Plants under Development:

- 1-megawatt demonstration at Host Park, NELHA, Hawaii
- 25-megawatt offshore facility (Grand Cayman)
- 100-megawatt offshore facility (Oahu, Hawaii)

Company Description:

OTEC International’s proprietary enabling technology comprises of 11 patent filings and a body of know-how culminating from over 5 decades of OTEC-specific research and development. OTEC International started with an exclusive license to the lifetime work of legendary inventor, James Hilbert Anderson (sea solar power), and built an accomplished team including experts in power plant engineering, offshore platforms, heat exchange performance, and composite materials.

Our company has been privately funded by a charitable foundation with the overriding goal to deliver the most OTEC power for the lowest capital cost without sacrificing reliability or environmental protection. We are able to provide clean, base-load renewable power at prices below avoided fuel costs in many tropical locations around the world.

The company’s technology has been validated by independent engineering firms, most recently on behalf of a major utility customer. Its 25-megawatt and 100-megawatt designs are the only OTEC facilities to receive “Approval In Principle” by ABS (formerly American Bureau of Shipping), validating the structural soundness, survivability, and safety features to protect both the crew and the ocean environment.

Under OTEC International’s leadership, OTEC is moving beyond research and development and into commercialization. Complementing our technical expertise, OTEC International is actively engaged in educational, political, and community outreach where our projects are currently under way. We are pursuing additional, attractive project opportunities in developed and developing regions of the world.

Name and Location:

Lockheed Martin, Mission Systems and Training

2323 Eastern Boulevard, Mail Drop E5
Baltimore, MD 21220
USA
http://www.lockheedmartin.com/us/products/otec.html

Point of Contact:

Emily Caruso
+1 (410) 682 0052, emily.caruso@lmco.com

Ocean Thermal Energy Conversion Plant Designs:

Lockheed Martin is engaged in the design of a 10-megawatt offshore OTEC plant, with the scale-up of that design leading to a 100-megawatt offshore OTEC plant.

Company Description:

Headquartered in Bethesda, Maryland, Lockheed Martin is a global security and aerospace company that employs about 120,000 people worldwide and is principally engaged in the research, design, development, manufacture, integration, and sustainment of advanced technology systems, products, and services.

Lockheed Martin's OTEC effort dates back to the 1970s when the company completed a study of the "practicality of generating electrical power at competitive busbar prices" using ocean thermal resources and by demonstrating a 50-kilowatt system known as Mini-OTEC. This early prototype remains the world's only floating OTEC system to generate power in excess of what is required for self-sustainment.

Over the past decade, Lockheed Martin has continued to mature and validate the critical technologies necessary for an OTEC system that can generate utility-scale power. We are maturing our composite cold-water pipe, developing low-cost, high reliability heat exchanger technologies, deploying heat exchangers for testing at the Natural Energy Laboratory Hawaii Authority (NELHA) Heat Exchanger Test Facility, and have developed our own OTEC heat exchanger test laboratory.

Some milestones achieved in the past 5 years include the following :

- In 2008, Lockheed Martin was awarded a United States (US) Department of Energy contract to demonstrate a modern fabrication approach for a cold-water pipe, a key component of the OTEC system.
- In 2009, the US Naval Facilities Engineering Command awarded Lockheed Martin a contract to further develop OTEC technology and develop pilot plant system designs.
- In 2009, Lockheed Martin partnered to conduct an OTEC feasibility study for Guam.
- In 2009, Lockheed Martin was awarded a contract to study OTEC feasibility for Taipei,China.
- In 2010, Lockheed Martin was awarded a US Department of Energy grant to model and graphically portray global ocean thermal energy resources.
- In 2010, Lockheed Martin was awarded a second US Department of Energy grant to assess OTEC life-cycle costs to estimate procurement, operations and maintenance, and overhaul costs for two types of OTEC plants.

Lockheed Martin envisions a future where OTEC plants provide safe, secure, reliable, environmentally friendly power around the globe; where local economies use their own energy resources rather than export their wealth; and where hundreds of thousands of new jobs in a new marine-industrial sector are created to design, build, install, operate, maintain, and improve these plants.

APPENDIX 6: SURVEY OF WAVE ENERGY CONVERSION COMPANIES

January 10, 2013

Dear Colleague,

I am gathering wave energy resource information already available in the public domain to assess the viability of utilizing these resources for the production of electricity and desalinated water in developing member countries of the Asian Development Bank (ADB).

The table on the next page lists the countries and areas under consideration and the offshore resource data as extracted from the following references:

(1) ***A Global Wave Energy Resource Assessment.*** A. M. Cornett (2008). Proceedings of the Eighteenth International Offshore and Polar Engineering Conference Vancouver, BC, Canada, July 6–11, 2008. Paper No. ISOPE-2008-579.

(2) ***Assessing the Global Wave Energy Potential*** G. Mork, S. Barstow, A. Kabuth, and T. Pontes (2010). 29th International Conference on Ocean, Offshore Mechanics, and Arctic Engineering, Shanghai, People's Republic of China, June 6–11, 2010. Paper No. OMAE2010-20473.

As you know, these are offshore wave power flux annual averages (kW/m) based on 10-year wind data inputted into their respective wave models. Furthermore, we all know that levels may vary significantly over the year and can be quite different nearer to the coast.

Please note that I included Hawaii as a reference site in the attached table because we have done extensive work at the University of Hawaii modeling the near-shore resource.

I would like to include information about your company in the following format:

Name and Location:
Point of Contact:
Wave Energy Conversion Device(s) under Development:
Company Description: no more than about 400 words

Thank you,

Luis Vega

Information received from the following companies is provided in this appendix:

- Atargis Energy Corporation
- Ocean Power Technologies
- Oscilla Power
- Resolute Marine Energy

In addition, the following companies are known to be involved in the development of wave energy conversion (WEC) devices:

Aquamarine Power (http://www.aquamarinepower.com)
Carnegie (http://www.carnegiewave.com)
Columbia Power Technologies (http://www.columbiapwr.com)
Oceanlinx (http://www.oceanlinx.com)
OceanEnergy (http://www.oceanenergy.ie)
Pelamis Wave Power (http://www.pelamiswave.com)
Wavenergy Technology New Zealand (http://www.wavenergy.co.nz)
Wave Star (http://wavestarenergy.com)
Wello Direct Conversion (http://www.wello.eu)

Table A6 Offshore Annual Average Wave Power Flux from Public Domain Information

Region and Country	Ref. 1 (Cornett)	Ref. 2 (Fugro OCEANOR)
Central and West Asia		
Pakistan	<10 kW/m	5–10 kW/m
East Asia		
People's Republic of China	<10 kW/m	5–10 kW/m
Pacific		
Reference Site (Hawaii Global)	North: 30–40 kW/m South: 20–30 kW/m	North: 30–40 kW/m South: 20–30 kW/m
Cook Islands/Rarotonga (~ 160°W, 22°S)	30–40 kW/m	~ 20–30 kW/m
Fiji (~ 178°E, 17°S)	10–20 kW/m	<20 kW/m
Kiribati/Tarawa (~ 175°E, 2°N)	<10 kW/m	5–10 kW/m
Marshall Islands/Majuro (~ 170°E, 5°N)	10–20 kW/m	10–15 kW/m
Federated States of Micronesia (Global)	10–20 kW/m	10–15 kW/m
Nauru (~ 165°E, 0°)	10–20 kW/m	10–15 kW/m
Palau (~ 135°E, 5°N)	<10 kW/m	10–15 kW/m
Papua New Guinea (Global)	<10 kW/m	5–10 kW/m
Samoa (~ 172°W, 12°S)	10–20 kW/m	10–15 kW/m
Solomon Islands (~ 160°E, 10°S)	<10 kW/m	10–15 kW/m
Timor-Leste (Global)	<10 kW/m	5–10 kW/m

continued on next page

Table A6 *continued*

Region and Country	**Ref. 1 (Cornett)**	**Ref. 2 (Fugro OCEANOR)**
Tonga (~ 175°W, 22°S)	10–20 kW/m	15–20 kW/m
Tuvalu (~ 180°, 5–10°S)	10–20 kW/m	15–20 kW/m
Vanuatu (~ 165°E, 15°S)	10–20 kW/m	10–15 kW/m
South Asia		
Bangladesh	<10 kW/m	10–15 kW/m
India	- South Coast off Nadu: 10 to 20 kW/m - Elsewhere < 10 kW/m	Arabian Sea: 15–20 kW/m West and South Coasts: 10–15 kW/m
Maldives	10–20 kW/m	10–15 kW/m
Sri Lanka	- South Coast off Matara: 10–20 kW/m - Elsewhere <10 kW/m	15 to 20 kW/m
Southeast Asia		
Brunei Darussalam	<10 kW/m	<5 kW/m
Cambodia	<10 kW/m	5–10 kW/m
Indonesia	- South Java: 20–30 kW/m - Elsewhere <10 kW/m	South Java: 20 to 30 kW/m
Malaysia	<10 kW/m	<5 kW/m
Myanmar	<10 kW/m	5–10 kW/m
Philippines	- North (Luzon and Babyan islands): 10–20 kW/m - Elsewhere <10 kW/m	- North (Luzon and Babyan islands): 15–20 kW/m - Elsewhere <5 kW/m
Thailand	<10 kW/m	<5 kW/m
Viet Nam	<10 kW/m	<5 kW/m

kW = kilowatt, m = meter.

Name and Location:

Ocean Power Technologies (OPT), Inc.

Pennington, New Jersey, USA
http://www.oceanpowertech.com

Point of Contact:

Greg Lennon
glennon@oceanpowertech.com

Wave Energy Converter Device(s) under Development:

Multiple sizes, in various stages

Company Description:

OPT's mission is to manufacture and sell globally PowerBuoy® systems to produce low-cost, clean, renewable electricity from ocean wave energy. Headquartered in Pennington, New Jersey, OPT is a public company listed on the US NASDAQ market as OPTT.

OPT is a leading renewable energy company specializing in cost-effective, advanced, and environmentally sound wave power technology. OPT's PowerBuoy® system integrates patented technologies in hydrodynamics, electronics, energy conversion, and computer control systems to extract the natural energy in ocean waves. The result is a leading edge, ocean-tested proprietary system that turns wave power into reliable, clean, and environmentally beneficial electricity.

Through its subsidiary, Reedsport OPT Wave Park, OPT is the sole owner of the 1.5-megawatt Reedsport project, located off the coast of Reedsport, Oregon.

- Certification by Lloyd's Register of PB150 structure and mooring system.
- Independent environmental assessments in Hawaii under the direction of the US Navy, and by US Department of Energy for the Reedsport, Oregon project; both resulted in "Finding Of No Significant Impact," the highest rating.
- Grid connection certified by Intertek (IEEE and UL standards)
- PowerBuoys insured by Lloyd's syndicates for property loss and third-party liability.
- US Department of Energy has assessed PowerBuoy PB150 as highest-rated wave energy system for commercial readiness (TRL 7-8).

Name and Location:

Oscilla Power, Inc.

Seattle, WA

Point of Contact:

Rahul Shendure

+1 (206) 999 5373

Wave Energy Converter Device(s) under Development:

Magnetostrictive Wave Energy Harvester

Company Description:

Founded in 2009 by successful energy and materials technology entrepreneurs, Oscilla Power, Inc. (OPI) is developing a platform of power generation devices using its iMEC™ technology platform. iMEC uses readily available and low-cost magnetostrictive alloys to convert mechanical to electrical energy without moving parts. Enabled by the iMEC platform, OPI's magnetostrictive wave energy harvester (MWEH) will deliver utility-scale power that is (i) cost competitive with coal or natural gas, (ii) robust to the ocean environment, (iii) close to demand growth, and (iv) predictable several days in advance.

The MWEH consists of a large buoy that is anchored with taut tethers that largely consist of sealed, iMEC-enabled power generators. The tether tension changes induced by hydrodynamic forces on the buoy are converted into magnetic field changes by magnetostrictive alloys in the generators. These magnetic field changes are converted into electricity via induction.

With support from the US Department of Energy, National Science Foundation, and National Oceanic and Atmospheric Administration, validation of OPI's modular and highly scalable wave energy technology has included lab and wave tank testing, extensive electromagnetic hydrodynamic modeling, and accelerated reliability testing on sub-scale component prototypes. OPI intellectual property portfolio includes 5 issued or allowed patents and more than 20 pending patents. Open-water testing of prototype hardware commenced in early 2013 in Washington state waters and will continue through 2014 at Isle of Shoals, New Hampshire. Initial commercial installations are expected to deliver electricity at a cost of 10¢–15¢ per kilowatt-hour (kWh), with costs of 5¢–10 ¢/kWh projected soon thereafter.

OPI's development partners include the University of New Hampshire Center for Ocean Renewable Energy, University of Washington Applied Physics Laboratory, and Florida State University Center for Advanced Power Systems as well as leading marine engineering consultancies such as BC Hydro's Powertech Labs, Cardinal Engineering, GL Garrad Hassan, and Marine Innovation & Technology. OPI operates out of offices in Seattle, Washington and Salt Lake City, Utah.

Name and Location:

Resolute Marine Energy, Inc.

3 Post Office Square – 3rd floor
Boston, MA 02109
http://www.resolutemarine.com

Point of Contact:

Bill Staby (CEO)
wstaby@resolutemarine.com
+1 (917) 626 6790

Wave Energy Converter Device(s) under Development:

Resolute Marine Energy (RME) is developing an oscillating wave surge converter (trade name: SurgeWECTM), which is a seabed-mounted hinged flap that oscillates in response to waves passing overhead and pressurizes a fluid that is piped ashore to generate electricity or directly drive a reverse-osmosis desalination system. RME chose to develop and commercialize SurgeWECTM because it is deployed near-shore in relatively shallow water (short energy transmission distances = lower costs) and, being bottom-mounted, it is relatively easy to protect from storm damage. A full-scale SurgeWECTM prototype is currently being tested in the ocean at the US Army Corps of Engineers field research facility in Duck, North Carolina.

Company Description:

Since its founding in 2007, RME's primary goal has been to commercialize the world's first WEC-driven seawater desalination system (Wave$_2$O™) that operates completely off-grid. RME's target customers for Wave$_2$O™ are coastal communities and resorts that have critical water shortages, limited or no grid connection, and a nearby energetic wave resource.

In developed countries, desalinating seawater using power from a central generating station is common practice. For developing countries, however, the capital investment requirements for new electrical transmission and base-load generating assets are prohibitive and, furthermore, they can take a decade or more to install. For this reason, RME is already seeing strong demand for Wave$_2$O™.

RME has two Wave$_2$O™ projects under development in Africa (first pilot plant installation expected in late 2013) and an electricity-generation project in development, i.e. Federal Energy Regulatory Commission preliminary permit application filed and resource assessment, site characterization, and environmental permitting under way for a remote community in Alaska that depends on diesel generators for its electricity supply.

To develop SurgeWEC™ and Wave$_2$O™, RME has received over $1.5 million in research and development grants from the US Department of Energy and the US Department of Interior, Bureau of Reclamation, and $1.5 million of matching private investment.

Name and Location:

Atargis Energy Corporation

3185 Janitell Rd. Ste. 101
Colorado Springs, CO 80906
USA

Point of Contact:

Stefan G. Siegel, President
http://www.atargis.com

Wave Energy Converter Device(s) under Development:

Cycloidal Wave Energy Converter

Company Description:

Atargis Energy Corporation was founded in 2010 to commercially develop the Cycloidal Wave Energy Convert (CycWEC). The CycWEC is a novel device that employs rotating hydrofoils to convert wave energy directly to rotating shaft energy, which can drive a low-speed generator directly. The device operates fully submerged and can thus survive storms that would destroy surface-based devices. It can be deployed on a monopile or jacket foundation, or a cluster of CycWEC converters can be operated free-floating attached to a platform.

Tank test results and simulations performed to date show the ability of the device to act as a wave terminator, extracting more than 95% of the incoming wave energy. Three-dimensional wave diffraction effects enable conversion rates beyond that, more than compensating frictional and harmonic wave generation losses. Thus, a relatively small device can achieve a name plate capacity of 1–5 megawatts or more depending on wave climate. All of these design and performance features combined enable a levelized cost of energy below that of other competing WEC technologies or even conventional non-renewable sources of electricity in many markets around the world.

The CycWEC has achieved Technology Readiness Level 4 in 2012 with financial support from the Department of Energy, and planning and design of an ocean-going prototype are under way.

APPENDIX 7: TIDAL ENERGY CONVERSION

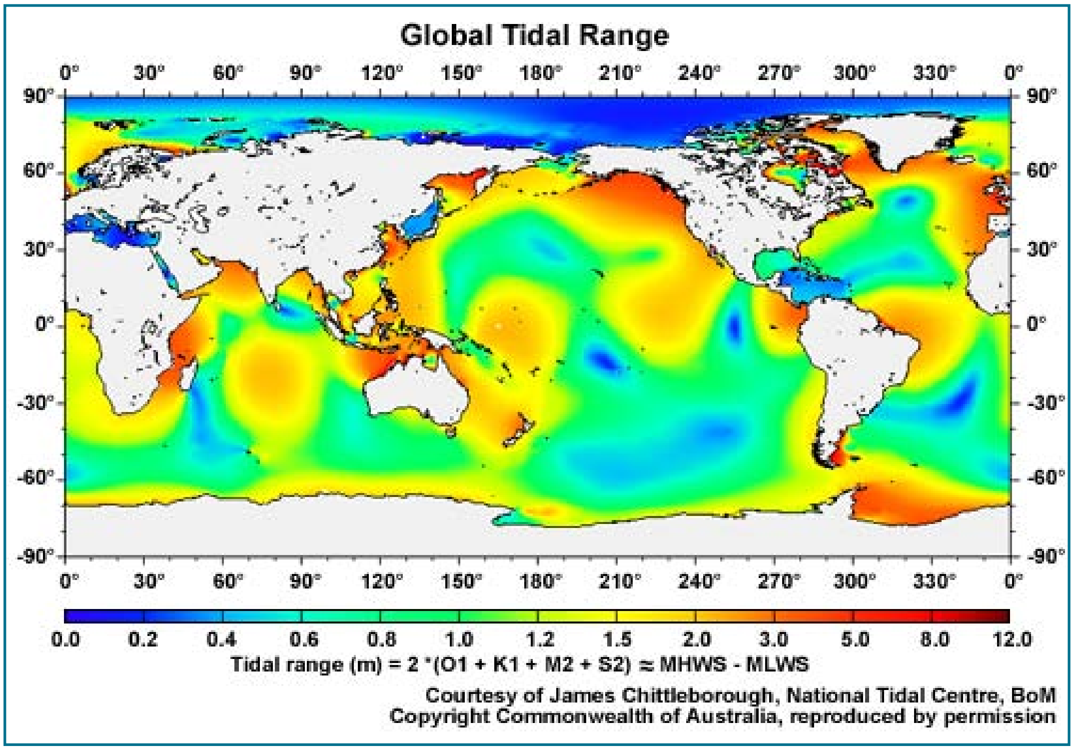
An additional method of marine-generated power exists in the form of tidal energy conversion. With appropriate equipment, global tidal energy resources can be converted into a useful form of electricity.

There are two concepts available to generate electricity using tidal energy: (i) using the potential energy in the water column, or (ii) using the kinetic energy available from the water currents induced by the tides. The first concept, which has already been implemented, uses the potential energy and is referred to as tidal barrages. The second concept, which is currently under development, is referred to as tidal in-stream plants or ocean current energy conversion.

Tidal Barrages

Existing barrage power plants use water-impounding dams to convert the potential energy (i.e., the head) of the elevated water into electricity using water turbines. Barrage power plant technology is commercialized and was established almost 5 decades ago using equipment based on designs that were available from conventional hydroelectric plants. In general, a tidal range of more than 5 meters is required. The required tidal range is found in the ocean areas shown by the color red in Figure A7.1. In general, the majority of developing member countries do not have the required tidal range. Although the resource is available in the People's Republic of China, India, and Pakistan, Pacific island developing member countries—which have a tidal range of less than 1 meter—are not viable areas for such power plants.

Figure A7.1 Global Tidal Range
(meters)



Courtesy of James Chittleborough, National Tidal Centre, BoM
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The tidal barrage power plant installed in the La Rance estuary in France has been operating since 1966. Information about this plant and others is summarized in Table A7.1. The table includes a pilot plant planned for the Gulf of Khambhat in India, the estimated total potential of which may reach as much as 7,000 megawatts (MW). Photographs of La Rance Estuary and the Sihwa Lake plants are provided in Figure A7.2.

Table A7.1 Tidal Barrage Power Plants around the Globe

Location	**Name Plate** (MW)	**Tidal Range** (m)	**Basin Area** (km^2)	**Generation** (GWh/year)	**CF**	**Cost** (year)
La Rance, France	240.0 (10 turbines)	8.5 (13.5 maximum)	22	500–600	0.25–0.30	$100 million (1966)
Sihwa Lake, Republic of Korea	254.0 (10 turbines)	5.6 (7.8 maximum)	30	..	..	$300 million (2011)
Jiangxia, Zhejiang Province, People's Republic of China	3.2 (5 turbines)	8.4	..	..	0.23	(1980)
Gulf of Khambhat (Cambay), India	50.0 (pilot plant)	6.8 (11.0 maximum)	..	..	..	..

.. = data not available, CF = capacity factor, GWh = gigawatt-hour, km^2 = square kilometers, m = meter, MW = megawatt.

Source: Author.

The tidal potential energy is given by $1/2 \rho g A H^2$ where, ρ is the density of water, g the acceleration of gravity, A the basin area, and H the water elevation (~ tidal range). It can be shown that the tidal potential power for a basin area and the water elevation is about 0.2 MW /(square kilometers [km$^{2]}$ – square meters [m^2]). For the tidal barrage plant in La Rance, for example, 240 MW divided by 22 km^2 and 8.5 m^2 yields 0.15.

Figure A7.2 Tidal Barrage Power Plants

La Rance

Sihwa Lake

In addition to the required tidal range in excess of 5 meters (m), tidal barrage power plants are therefore also limited to sites where a relatively large basin (of area A) can be formed. This typically requires substantial civil engineering work.

Tidal In-Stream Power Plants

Ocean water currents are generated by water density differences, wind stress, and tides. With the exception of major currents in the open ocean (e.g., the Gulf Stream off the coast of Florida in the United States, and the Kuroshio Current off the coast of Japan), the tides, acting in some natural coastal enhancements, induce currents of the magnitude required to produce electricity.

Tidal in-stream power plants are designed to harness the kinetic energy of the moving water. This technology is currently under development, with several pilot plants in operation though none yet fully commercialized. The in-stream plants are analogous to wind turbine generators operating underwater with a cut-in speed[1] of at least 1 m/second (i.e., about 2 knots) and rated speeds ranging from 2.5 to 3.5 m/second. Given that the water density is about 800 times the value of the air density, the tidal in-stream devices are smaller than wind-turbine generators.

Sites with the required current speeds are rare, however. For example, in Hawaii, tidal in-stream power plants are not feasible because the resource (i.e., a current speed of over 1 m/second) is not available due to the relatively low tidal range and the absence of coastal enhancements like narrow embayments connected to the open ocean.

There is no information available in the public domain about the ocean current resource in developing member countries. However, given the tidal range depicted in Figure A7.1, it is reasonable to expect that the required cut-in speed of at least 1 m/second may not be found in Pacific islands.

The available power available in a fluid current is given by $1/2\rho AU^3$ where, ρ is the density of the fluid, A is the capture area ($\pi D^2/4$ for a turbine of rotor diameter D), and U is the fluid speed. The wind power theoretical results and modeling are, therefore, applicable to the evaluation of tidal in-stream devices. The energy output assessment uses the concept of power curve,[2] using site-specific current data.

Table A7.2 Prototype Tidal In-Stream Power Generation Devices

Device	Name Plate	Water Depth (m)	Tidal Range (m)	Current Speed	Notes
SeaGen Twin Turbines, Ireland	1.2 MW, 16 m rotor diameter CF: 0.36 average	26	4.3	Rated: 2.4 m/second (Spring tide mean: 3.7 m/second)	£ 12M (2008)
Open Hydro Units	250 kW, 6 m diameter 1 MW, 15 m diameter 2 MW, 16 m diameter	.. .. 35 m	..	..	2008 Scotland 2009–2010 Canada Brittany Plans for 4 units (8 MW) at CC ~ $55 million
Verdant Power, East River, New York, United States	6 x 35 kW, 3-bladed and 5 m diameter CF: 0.23	..	..	..	Multiple-year testing underway. License for 30 x 35 kW awarded by Government of the United States

.. = data not available, CC=capital cost, CF=capacity factor, kW = kilowatt, m = meter, MW = megawatt.

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[1] Cut-in seed is the minimal current magnitude required for the device to generate electricity. The rated speed refers to the value required to produce at the name plate (i.e., power rating).

[2] This is the relationship between power output and current speed using bin methodology.

Figure A7.3 Prototype Ocean Current Energy Conversion Devices

SeaGen twin turbines with two 16-meter diameter rotors shown above water

Source: SeaGen.

Open Hydro Unit Shown above Water

Source: Verdant Power.

Figure A7.4 Verdant Power 35-Kilowatt Units

35 kW units shown before deployment in the East River, New York, United States.

Source: Verdant Power.

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Wave Energy Conversion and Ocean Thermal Energy Conversion Potential in Developing Member Countries

Wave energy conversion (WEC) and Ocean thermal energy conversion (OTEC) are two potentially significant sources of renewable energy that are available to help the Asian Development Bank's (ADB) developing member countries (DMCs) reduce their dependence on fossil-fuel based energy generation and bolster energy security.

This report summarizes WEC and OTEC information that is available in the public domain for the DMCs and assesses the viability of using these resources to produce electricity. In addition, the report identifies supplementary resource information that is required for system design and evaluates the development status of the required equipment.

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