Renewable and Sustainable Energy Reviews 74 (2017) 1300–1313

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Ocean wave energy in the United States: Current status and future perspectives

Marcus Lehmann[a], Farid Karimpour[a], Clifford A. Goudey[b], Paul T. Jacobson[c], Mohammad-Reza Alam[a,*]

[a] University of California, Berkeley, CA 94720, USA
[b] C.A. Goudey & Associates, Newburyport, MA 01950, USA
[c] Electric Power Research Institute, Glenelg, MD 21737, USA

ARTICLE INFO

Keywords:
Marine and hydrokinetic energy (MHK)
Marine renewable energy
Ocean energy
Wave energy converter (WEC)
Research and development in the United States
Wave Energy

ABSTRACT

Ocean waves are a more predictable resource with a higher energy density compared to solar and wind. In addition, and specifically for the United States, resource locations with high wave power are close to major load centers being located along coastlines. These features have sparked a surge of attention in the United States on trying to economically harness ocean wave power. The aim of this article is to provide a concise review of the current state of ocean wave energy conversion technologies and industry status in the United States including research and development as well as commercial activities and governmental support, concluding with a discussion of future industry perspectives. Existing facilities, softwares as well as laboratory and open-water test facilities and resources, active research groups and commercial activities have been identified. Over one third of commercially active wave energy developers worldwide are located within the United States, but only a few have reached a high Technology Readiness Level. These findings, together with a relevant practical resource located within the U.S. and the advantageous nature of the resource compared to other renewable resources, indicate that the United States is well positioned to advance the wave energy industry in the near future.

1. Introduction

Ocean wave energy offers a renewable resource with the advantage of being predictable several days in advance, consistent throughout the day and night, and significantly higher in its energy density compared to wind and solar energies. Moreover, ocean wave power is available in close proximity to the coastal load centers of the United States. In fact, in the United States, half of the population lives within 50 miles of coastlines [1]. The adjacent oceans provide a total technically recoverable wave power resource of 1170 TWh/yr over the U.S. outer continental shelf to the notional 200 m depth contour [2]. This is equal to 30% of the annual electricity consumption of the United States, which is about 4000 TWh/yr [3].

However, currently there is no commercially grid-connected Wave Energy Converter (WEC) capacity installed in the U.S., and only a few megawatts are installed worldwide [4] (Table 1 provides an overview of global installed capacity of wave and tidal energy technologies as of 2014, see also [5]). According to the World Energy Council, state-of-the-art wave energy technologies operate at a LCOE (Levelized Cost of Energy, defined as the energy price at which the produced electricity needs to be sold for the project investment to be profitable) of 49.6 cents/kWh [6–9] (with an upward trend). This is significantly above the Department of Energy's (DOE's) 2030 goal for WECs to operate at 12 to 14 cents/kWh. According to PG&E, which cancelled its WaveConnect™ project in 2010, utility-scale wave farm projects in California were abandoned primarily due to the complexity and higher-than-expected permitting and installation cost, and a lack of cost-competitive WEC technologies [10,11]. Today's state-of-the-art WEC designs face operational and engineering limitations [12], but are also fundamentally restricted by hydrodynamic and design constraints that require trade-offs between Capital Expenditures and Operating Expenditures (CAPEX/OPEX) [108,109].

Although investment and research have been accelerating the Marine Hydrokinetic (MHK) industry worldwide, the industry still finds itself in its early stages of technological development. For example, in contrast to the wind industry in which horizontal-axis wind turbines (HAWT) are being widely used, the wave industry has not converged to a dominant design.

Compared to the U.S., Europe has historically supported the renewable energy industry with much more funding and supportive policies such as feed-in-tariffs. Moreover, most of the driving force within the industry since the 1970s, with investments and R&D in

* Corresponding author.

http://dx.doi.org/10.1016/j.rser.2016.11.101
Received 23 February 2016; Received in revised form 26 July 2016; Accepted 3 November 2016
Available online 27 March 2017
1364-0321/

Table 1
Global installed capacity of wave and tidal energy technologies as of 2014 (Based on IEA Ocean Energy Systems).

Country	Tidal Installed Capacity [kW]	Wave Installed Capacity [kW]	Tidal Consented Projects [kW]	Wave Consented Projects [kW]
USA	–	–	1350	1365
Canada	20,000	–	20,450	–
UK	5600	3730	96,000	40,000
Sweden	7.5	180	–	10,500
Norway	–	200	–	–
Denmark	–	–	–	115
Netherlands	130	–	3000	–
Spain	–	296	–	300
Portugal	–	700	–	
Belgium	–	–	–	20,000
Singapore	–	16	2.5	
Republic of Korea	1000	500	1300	300
China	4070	350	4700	2860

both academia and industry, were located in Europe. The European Commission report [4] in 2015 highlights a short list of 45 WEC developers that have reached open-sea deployment; 7 are U.S. based, 26 are EU based, 6 are Australian, and the rest are from other international developers. The report also projects an increase in the deployment rate by 2025 and an expected global installed wave energy capacity of 25.9 MW by the end of the decade and consented projects of 1365 kW within the United States, despite a recent report from Bloomberg New Energy Finance indicating a reduction in its projection of global installed capacity for 2014 [6].

Furthermore, the report of the EU Commission predicts that around 14% of this capacity will be installed in Australia and 76% in Europe using various existing wave energy infrastructures ranging from 0–100 m water depth and 0–16 km distance from shore. The report concludes that the main roadblock to the industry is the lack of reliable and operable devices for open waters. But the report also highlights the lack of convergence on a dominant design that would allow a higher rate of knowledge exchange and supply chain engagement. Furthermore, no clear industry trend towards shallow-water or deep-water WEC designs can be predicted, which has significant implications on the supply chain and other elements of the entire value chain of the industry, thus imposing a risk factor in evaluating the economic viability of the WECs.

In this paper, we provide a review of the current status of wave energy research and development (R & D) in the United States. Section 2 outlines the wave energy resources available in the United States. In Section 3, an overview of the U.S. government activities in the field of wave energy conversion is provided. Section 4 highlights the academic research centers and universities with facilities suitable for research on wave energy conversion. Section 5 reviews publically available resources developed in the United States that are supporting investigations of ocean waves and WECs. In Section 6, the nonprofit and commercial activities needed to commercialize wave power in the United States are reviewed. Finally, Section 7 provides conclusions and future perspectives. While the information provided is a snapshot of the present state of wave power in the U.S., our intention is that this review will establish a foundation for further advancements of the wave energy industry through collaborations and economical utilization of existing expertise and resources.

The goal of this paper is to review the status of the research and the industry of wave energy in the United States, and to identify existing domestic facilities, softwares, closed and open-water test facilities, and resources, as well as active research groups and commercial activities. Over one third of commercially active wave energy developers are located within the United States, but only a few have reached a high Technology Readiness Level. These findings together with a relevant practical resource and its advantages indicate that the United States is well positioned to advance the wave energy industry in the near future.

2. Ocean wave energy resource in the United States

For all renewable energy resources, especially ocean renewable energy, it is required to assess and differentiate between the *theoretical resource,* the *technical resource,* and the *practical energy potential* [13]. In the assessment process, the theoretical resource is based on model and input data and can also be defined as the power density of waves approaching the shore [14]. This input power is reduced by extraction filters such as wave converter device specific parameters, cut-in/out constraints, and survival constraints, which results in the technical resource. The technical resource is further reduced by social, economic, and environmental filters that eventually lead to the practical resource [13,14].

For comparison, the theoretical global wave energy potential is about 32,000 TWh/yr [15] (Fig. 1). Excluding areas where the theore-

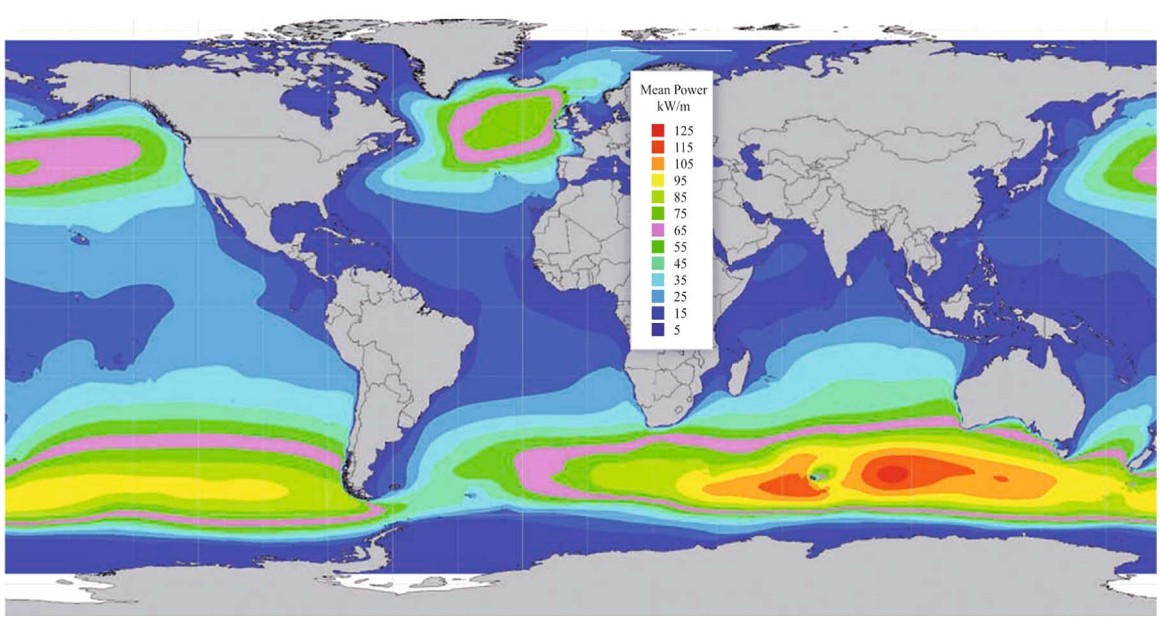


Fig. 1. Global distribution of mean wave power density in kW/m [4].

Fig. 2. U.S. Wave Energy Prize and Navy's test facility in Carderock [18].

tical wave power averaged over the year is less than 5 kW/m, the theoretical wave energy potential of the world reduces to 29,500 TWh/yr (i.e. ~8% lower) [15]. However, as is shown in the global distribution map, much of this energy is in the southern ocean and arguably unavaiable for direct energy production purposes. The theoretical wave energy potential of the United States is 1594-2640 TWh/yr along the outer continental shelf. The theoretical resource is estimated to be 898-1229 TWh/yr and the technical resource is 378–472 TWh/year [1,2,13]. The technical resource with at least 8 kW/m power density is 899 TWh/yr, which represents 22.2% of the U.S. Annual Energy Production (AEP) and the maximum practical resource is 522 TWh/yr representing 12.9% of the U.S. AEP along the 100-m-depth contour as assessed by the U.S. DOE [1]. Extracting 5% of the resource could power up to 6-8 million (5%-7%) U.S. homes.

More specifically, the Electric Power Research Institute (EPRI) has examined regional details of the theoretical wave-energy potential distribution along the outer continental shelf of the United States: the theoretical wave energy is 590 TWh/yr on the West Coast, 240 TWh/yr on the East Coast, 80 TWh/yr in the Gulf of Mexico, 1570 TWh/yr in Alaska, 130 TWh/yr in Hawaii and 30 TWh/yr for Puerto Rico [2]. Regionally, this represents 60% of the West Coasts' AEP (CA, OR, WA) and over 100% of Alaska's and Hawaii's AEP based on these states' electrical profiles for 2012 [1].

Clearly, the theoretical wave energy potential on the West Coast is more than twice the wave energy potential of the East Coast. EPRI reports the total available wave energy along the inner shelf of California is 205 TWh/yr and according to the Pacific Gas and Electric Company PG & E, the total energy consumption of California in 2005 was 272 TWh [2,10].

3. United States government and ocean wave energy

The United States government promotes research and development in the field of ocean wave energy through several agencies, programs, and supportive policies. It also regulates the activities in wave industry through various mandatory regulatory permits and processes.

3.1. Government agencies

There are a number of entities within the U.S. government that financially and/or technically support research and development in wave energy. They include the Department of Energy's The wind and water activities have been split into separate offices. Water Power Technologies Office (WPTO), the Department of Defense, National Science Foundation (NSF), and the DOE-supported National Laboratories. In the following, we briefly discuss these entities, their facilities, and their activities in the development of ocean wave energy.

3.1.1. The Wind and Water Power Technologies Office

The Water Power Technologies Office (WPTO) is part of the U.S. DOE's Office of Energy Efficiency and Renewable Energy (EERE), which supports and promotes the development, deployment and commercialization of water energy technologies [3]. The WPTO works with stakeholders with the aim to increase installed capacity of renewable energy technologies through promoting R & D for improvement of technology and decreasing its costs.

The WPTO provides wave energy R & D funding in two major areas: "Hydropower" and "MHK" projects. While conventional hydropower is a mature industry, the MHK industry is nascent, requiring research, development and technology demonstrations to achieve commercial viability. The program's current goal is to reduce the LCOE for wave power by 80% compared to the 2015 baseline targeting LCOE values of 0.84 $/kWh for wave power technologies by 2030. To support this process, DOE invested $116 million in 95 MHK projects from FY 2008 to FY 2014, and nearly 90% of the funding was directed toward technology development [3]. The two sources of funding for these MHK projects came from Congressional Appropriations and Congressionally Directed Projects. Thirteen MHK projects were awarded $13 million through Congressionally Directed funds [16].

In addition to the WPTO, DOE's Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs also support research and development for improving energy efficiency and enhancing renewable energies. In recent years, DOE's SBIR and STTR Programs have funded several projects related to wave energy [17].

In March 2015, DOE's Water Power Program announced the U.S. Wave Energy Prize with the goal to reduce the cost of wave energy in order to achieve competitiveness with other energy solutions through game-changing enhancements in technical and economic performance of WEC devices. In order to decrease the cost of energy production by WEC devices and improve their performance, $6.5 million was provided for a new competition to foster innovation among individuals, existing and emerging companies and universities [18]. Ninety-two eligible teams registered to compete to become one of ten finalists to test their WEC devices at the U.S. Navy's Maneuvering and Seakeeping Basin in Carderock, Maryland in 2016 (Fig. 2). In November 2016, the DOE announced that four teams have exceeded the prize metrics minimum threshold value to capture 3 meters of coastline per million dollars of structural cost. The so called ACE metrics were used as a simplified LCOE assessment of WEC technologies at a prototype development stage. ACE is calculated as the ratio between Average Climate Capture Width (ACCW) and Characteristic Capital Expenditure (CCE). ACCW is a measure of the effectiveness of a WEC at absorbing power from the incident wave energy field assessed for wave climates relevant for the U.S. CCE is a measure of the capital expenditure in commercial production of the load bearing device structure.

The prize administration concluded that the current state of the art of existing WEC concepts achieve an ACE value of 1.5 m/$M. The teams AquaHarmonics, CalWave Power Technologies and Waveswing America were awarded first, second and third place, respectively. The effectiveness of this mechanism in spurring innovation and technical progress remains to be determined; however, it should be noted that the competition aims at early stage technologies that could benefit from the provided test program.

3.1.2. National Laboratories

Several national laboratories have initiated research and development of wave energy technology through funding supplied by WPTO. These include the National Renewable Energy Laboratory, the Sandia National Laboratory, and the Pacific Northwest National Laboratory.

3.1.2.1. National Renewable Energy Laboratory (NREL). The National Renewable Energy Laboratory has conducted research in water power for about 35 years with the aim of helping the DOE's WPTO to reach its goal to improve wave energy and hydropower generation, including the recent MHK-specific report that reviewed the status and outlook of the U.S. MHK industry [2].

One tool designed by NREL is the Regional Energy Deployment System (ReEDS), which is a deterministic model designed to analyze the issues and potentials of the electricity industry of the United States [19]. This model considers almost all renewable resources, including wave energy, in its analysis. NREL also provides material and component testing facilities and expertise, high fidelity numerical simulation capabilities, and was the lead in collaboration on the open source Wave Energy Converter Simulation tool, WECSim (see Section 5.1 for more details).

3.1.2.2. Sandia National Laboratory (SNL). Sandia National Laboratories, in support of the Department of Energy's WPTO, conduct research focused on bringing water-power technologies to market, improving the performance of existing hydropower facilities, and leading the development of DOE Reference Model Project in collaboration with other national laboratories and institutions see Fig. 3, [20]. The DOE Reference Models are developed for wave, tidal, and river in-stream devices for full systems and at the component and resource levels. These reference models could serve as benchmarks for users in laboratories, industry, and universities to validate their computational models [20]. Table 2 provides a summary of the economic assessment and results of the DOE Wave Energy Converter Reference Models.

The SNL also focuses on the environmental impact of MHK on marine mammals and ecosystems, control optimization of wave energy Power Take Offs (PTOs), and survivability of wave energy conversion technologies [21].

3.1.2.3. Pacific Northwest National Laboratory (PNNL). In order to address the issues associated with the environmental aspects of MHK, PNNL is developing a program of research and development to address the following areas: 1) Categorizing and evaluating effects of stressors by compiling data from *in-situ* testing and experiments in a knowledge management system called Tethys [22]; 2) Investigating the physical systems by computational modeling of the effect of the wave energy extraction by employing short-term and long-term operation of MHK; 3) Testing experiments to evaluate the adverse effect of MHK devices on aquatic organisms.

Inputs from MHK technology and project developers, regulators, and natural resources management agencies will be used for developing a user interface for Tethys and also for validating the numerical modeling results with experiments for the exposure of test animals to MHK stressors [23].

3.1.3. The United States Department of the Navy

The United States Department of the Navy plans to supply half of its energy requirement from renewable resources by 2020 and currently considers wave energy as one potential technology to reach this goal [24]. Therefore, the Navy actively supports research and development on marine renewable energy. For example, in 2014 the U.S. Navy allocated $8 million to the Applied Physics Laboratory at the University of Washington through a four-year contract from the Naval Facilities Engineering Command (NAVFAC) in order to perform research on MHK [25]. The Navy also collaborates with the University of Hawaii, Manoa, to develop the Wave Energy Test Site (WETS) located in Kaneohe Bay near Marine Corps Base, Hawaii. WETS supports wave energy harvesting by providing a suitable location to test wave energy conversion devices offering gird-connected test berths in a partially sheltered open-water location for devices of TRL 5–7. It is currently configured for testing point absorbers and oscillating water column devices [26].

3.1.4. National Science Foundation

The National Science Foundation (NSF) is one of the major U.S. government agencies that supports basic research in science and engineering. The NSF provides funding for research across broad range of topics, including wave energy, through different funding programs such as the Faculty Early Career Development Program (CAREER) or the Cyber-Innovation for Sustainability Science and Engineering (CyberSEES) Program. For example, in 2014, the NSF funded $12.5 million to 26 projects in 15 states to advance sustainability by developing new models. In this award, CyberSEES considered wave energy harvesting as one of the untapped resources for supplying the United States' electricity needs [27].

3.1.5. Bureau of Ocean Energy Management (BOEM)

The Bureau of Ocean Energy Management operates within the U.S. Department of Interior, and monitors the energy exploration and exploitation activities in U.S. waters. BOEM seeks to enhance economic development by meeting energy needs while protecting the environment. Besides activities related to oil and gas production, BOEM's Renewable Energy Program facilitates activities in renewable energy by granting leases and easements to qualified projects [28], as well as by funding a variety of environmental and ocean use analyses [29]. BOEM

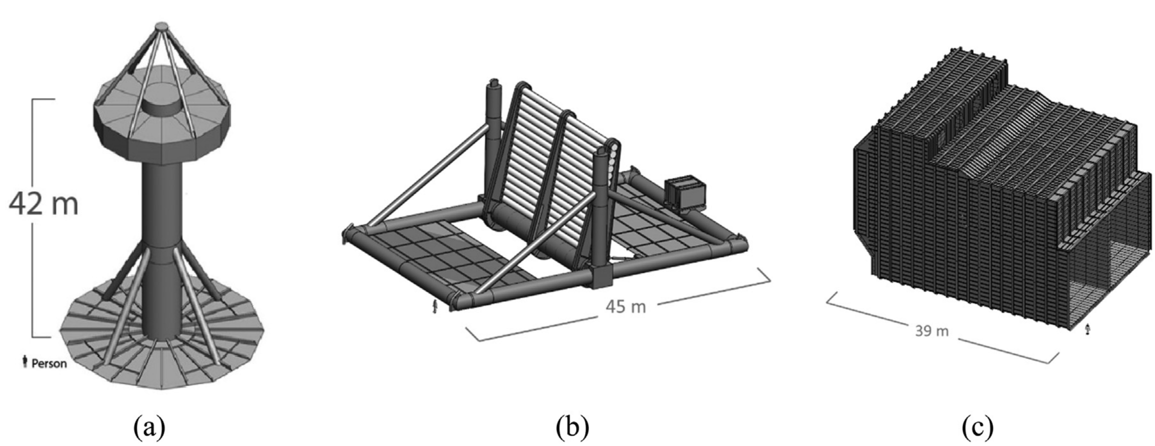


Fig. 3. DOE Reference Models, (a) RM 3 Point Absorber, (b) RM 5 Oscillating Surge and (c) RM 6 Oscillating Water Column [Sandia National Laboratory].

Table 2
Summary of economic assessment of the SNL Reference Models.

RM # -	Type -	AEP MWh/year	Rated Power kW	Mass Tons	LCOE for 1 Unit $/kWh	LCOE for 10 Units $/kWh	LCOE for 50 Units $/kWh	LCOE for 100 Units $/kWh
3	Point absorber	701	286	674	4.36	1.41	0.83	0.73
5	Surge	881	373	820	3.59	1.44	0.77	0.69
6	OWC	904	373	100	4.79	1.98	1.20	1.06

also operates a saltwater wave basin in Leonardo, NJ that has been used for numerous WEC evaluations [30].

3.2. U.S. permitting process for wave energy projects

The federal permitting system for wave energy projects on the Outer Continental Shelf requires two major federal actions. First, a grid connected wave project must receive a Federal Hydroelectric License from the Federal Energy Regulatory Commission (FERC). Second, a wave project must also receive a site use lease from the Bureau of Ocean Energy Management. These two federal agencies share jurisdiction over wave energy pursuant to a 2009 Memorandum of Understanding [31]. Projects that are located in state waters only need to be permitted by FERC, and the site lease will be provided by a state agency. FERC regularly updates a list of preliminary and pending preliminary permits issued for hydrokinetic projects including tidal, wave, and riverine projects. This list and some other useful information can be found at the FERC website [32]. In addition to the two major federal actions from FERC and BOEM, developers must also seek a variety of supplemental permits and consultations with federal agencies, including those listed in the following table.

Even for wave energy projects that exist solely in federal waters, a variety of state-based permits and consultations would be required due to cables crossing state waters and littoral zone impacts. The states have the authority, conferred by the Coastal Zone Management Act (CZMA), to ask any project that receives a federal permit or funding and has reasonably predictable effects on the water or land of the state to be consistent with the federally approved Coastal Zone Management Plan [31]. (Table 3).

4. Academic research and development

With the rise in importance of renewable energies, more funding for research has been allocated to universities by funding agencies, such as the NSF and DOE. Academic research on wave energy in the United States addresses all aspects of research and development including: 1) new wave energy device ideas apparent from the increasingly higher number of patents filed in this category (only in the first 6 month of 2016, more than 25 patents have been issued on “Ocean Wave Energy” in the United States), 2) theoretical analysis of a. wave energy device response and dynamics under various wave conditions, b. wave resource estimation and predictions, c. extreme wave conditions, and d. active and passive control of wave energy devices, 3) developing computational tools exclusively designed for wave energy research (see Section 5), 4) different scale laboratory tests (see Table 4) and 5) open ocean tests. It is to be noted that while theoretical analysis research (item 2) and direct simulations (item 3) have some synergies with other traditional ocean engineering applications, there are specifics that are exclusive to wave energy devices and are not of typical interest to those traditional applications. For instance, wave energy devices are designed to be at resonance with the ocean waves whereas in most other applications this resonance is avoided.

In the past few years, wave energy has attracted interest of researchers in the U.S. and we briefly introduce some of them here. Due to the importance of the wave energy converters, reliability for harvesting the energy and surviving risks, Lenee-Bluhm et al. [33] assessed six different quantities for hourly sea-states at the U.S. Pacific Northwest coast and observed seasonal variability of wave mean energy and energy flux, where the energy in winter was much greater compared to summer and energy flux has longer periods than the summer ocean. Considering the abundance of wave energy at the Pacific Northwest coast of U.S., Parkinson et al. [34] investigated the operational impact of large-scale development in the Pacific Northwest and found reduced production variability due to geographic diversification. Reikard et al. [35] ran models to forecast all three renewable energies of wind, solar and wave in the U.S. Pacific Northwest and observed that the forecast of wind had the highest error while wave was the most accurately predicted energy resource. Another example for works of U.S. researchers is the study of Yeung et al. [36] who developed and tested a wave energy converter at UC Berkeley with a linear generator. Oskamp and Özkan-Haller [37] studied the efficiency of point absorbers on the Oregon coast using the boundary element method for a potential flow. They also observed that the passive tuning in timescales of hours negligibly improved power takeoff. Due to the importance of the location on total production energy from a wave farm, Moarefdoost et al. [38] at Lehigh University proposed models and heuristic algorithms for optimal selection of the WEC locations in a farm. As point absorbers are considered as one of the most efficient converters, in 2011 Li and Yu [39] from NREL in Colorado extensively studied different methods for modeling point absorbers. Arinaga and Cheung [40] at the University of Hawaii focused on the wave climate and available power of the wave. They used surface wind data from

Table 3
Overview of permit related stakeholders and agencies arranged by federal and state authorizations.

Permits	*Compliance*	*State*	*Local*
Research Lease or Site Lease (BOEM)	*NEPA*	*Site Lease (DSL)*	*Local Land Use Compatibility Statement*
Hydroelectric License (FERC)	*Endangered Species Act*	*Coastal Zone Management Act Consistency (DLCD)*	*Conditional Use Permit*
Nationwide Permit # 52 (USACE)	*Marine Mammal Protection Act*	*Water Quality Certification (DEQ)*	
Private Aids to Navigation Permit (USCG)	*Essential Fish Habitat*	*Removal-Fill Permit (DSL)*	
	Migratory Bird Treaty Act	*Easements for Cables in Territorial Sea (DSL/ DLCD)*	
	National Historic Preservation Act	*Ocean Shore Alteration Permit (OPRD)*	
		Water Right (WRD)	
(a) FEDERAL AUTHORIZATIONS		(b) STATE & LOCAL AUTHORIZATIONS	

Table 4
List of closed water test facilities in the United States.

Name of the Facility	Affiliation	Tank Size in meters (Length x Width x Depth)
Adv. Structures & Composites Cent. at Univ. Maine [43]	Academic	30.5 × 9 × 4.5
Alden Research Laboratory [44]	Independent	30.5 × 21.3 × 1.22
David Taylor Model Basin - Shallow Basin [45]	Navy	92.35 × 15.54 × 3.05
David Taylor Model Basin - Deep Basin [45]	Navy	568.76 × 15.54 × 6.70
David Taylor Model Basin - MASK Basin [45]	Navy	109.8 × 73.2 × 6.70
Davidson Lab at Stevens Ins. Tech. [46]	Academic	95.4 × 4.9 × 2.0
DeFrees Hydraulics Lab, Cornell University [47]	Academic	32 × 0.6 × 1
Fluid Mech. Lab. Clemson University [48]	Academic	9.14 × 0.61 × 0.61
Haynes Coastal Eng. at Texas A&M Univ. [49]	Academic	36.6 × 22.9 × 1.5
Hydr. Lab. Scripps Inst. Oceanography [50]	Academic	44.5 × 2.39 × 2.44
Iowa Ins. Hyd. Res. at Univ. Iowa [51]	Academic	40 × 20 × 3
Jere A. Chase Ocean Eng. Lab. Univ. New Hampshire [52]	Academic	30.5 × 3.65 × 2.4
Marine Hydrodynamics Lab. (MHL) Uni. Michigan [53]	Academic	109.7 × 6.7 × 3.05
Massachusetts Institute of Technology [54]	Academic	30.5 × 2.4 × 1.2
Offshore Res. Tech. at Texas A&M Univ. [55]	Academic	45.7 × 30.5 × 5.8
Ohmsett [30]	U.S. Department of the Interior	203 × 20 × 3.4
Oregon State University [56]	Academic	104 × 3.7 × 4.6
School Nav. Arch. Mar. Eng. Univ. New Orleans [57]	Academic	39 × 4.6 × 2.1
St. Anthony Falls Lab. (SAFL) Univ. Minnesota [58]	Academic	84 × 2.75 × 1.8
University of California, Berkeley [59]	Academic	68 × 2.6 × 2.0
University Houston Hyd. Lab. [60]	Academic	36.57 × 1.22 × 1.22
University of Rhode Island [61]	Academic	30 × 3.6 × 1.8
U.S. Naval Academy Towing Tank [62]	Navy	115.8 × 10.4 × 4.88

Final Global Tropospheric Analysis (FNL) and computed wave parameters, which showed good comparison with buoy and altimetry measurements. Stopa et al. [41] used SWAN to study the locations, which are considered for deployment of WECs near Hawaii. The computed wave heights compared well with measurements from buoys.

Several universities have initiated research programs with a focus on wave energy and other forms of ocean energy, especially universities with existing and active ocean engineering groups (see e.g. NREL Hydrodynamic Testing Facilities Database [42]). The following are among the U.S. universities conducting research related to wave power: Oregon State University, The University of Washington, University of Alaska Fairbanks, Humboldt State University, The University of California, Berkeley, University of Hawaii at Manoa, University of Florida, Texas A&M University, The University of Iowa, the Massachusetts Institute of Technology, Clemson University, Virginia Tech, and the University of Houston. The remainder of this section discusses some of these universities' wave energy research initiatives. There are also a few research centers that are actively involved in wave research, and provide services to universities including: David Taylor Model Basin in Carderock, Maryland; Ohmsett located in Leonardo, New Jersey; and Alden Research Laboratory located in Holden, Massachusetts. Table 4 contains a listing of the facilities used by academic institutions, along with their dimensions.

4.1. Oregon State University and the Northwest National Marine Renewable Energy Center

The Northwest National Marine Renewable Energy Center (NNMREC) is located at Oregon State University as a partnership with the University of Washington and the University of Alaska Fairbanks. It was established in 2008 with funds from the DOE to study and develop technologies for harnessing marine energies, such as wave energy. The University of Washington focuses primarily on tidal energy research, Oregon State University focuses primarily on wave energy research, and the University of Alaska Fairbanks primarily researches riverine hydrokinetics [63].

NNMREC's testing facilities, including both open water and laboratory facilities, operate under the moniker of the Pacific Marine Energy Center (PMEC) [63]. For laboratory-scale testing, researchers make use of instruments available at the Wallace Energy Systems and Renewables Facility, as well as the wave tanks at the O.H. Hinsdale Wave Research Laboratory at Oregon State University.

NNMREC's North Energy Test Site is suitable for full scale wave energy devices up to 100 kW power rating by connecting to the Ocean Sentinel, their mobile ocean test buoy, as an alternative to grid connection. The Ocean Sentinel consumes and measures the power generated from the wave energy converter to which it is connected. The South Energy Test Site (SETS) is in the permitting phase, and is planned to be operational in 2018. SETS will provide testing and demonstration capabilities for deep water wave energy technologies. The site will be grid connected and will provide up to four testing berths that can accommodate arrays of devices. Four independent power cables will accommodate a total of 20 MW of installed capacity [63].

4.2. The University of Washington

The University of Washington's Harris Hydraulics Laboratory operates and maintains a current flume and small-scale wave flume. Wave energy devices of an intermediate scale can be tested in open-water conditions with the support of UW at Puget Sound and Lake Washington [63]. Also, the wind/wave test flume at the Harris Hydraulics Laboratory is being upgraded to be suitable for scale testing of wave energy devices [63].

4.3. The University of Alaska Fairbanks

The Alaska Center for Energy and Power at the University of Alaska Fairbanks is focused on developing clean energy alternatives to diesel-based energy systems unconnected to the grid [64]. The Alaska Hydrokinetic Research Center (AHERC) conducts applied research to determine whether emerging marine hydrokinetic technologies are economically and environmentally sustainable in meeting Alaska's energy needs [64]. Their research areas include determining key characteristics that might impact the installation of current, tidal, or wave hydrokinetic technologies, wildlife interactions with turbines, and the identification of optimal sites for the implementation of hydrokinetic technologies [64,65].

4.4. David Taylor Model Basin

The David Taylor Model Basin is at the Carderock Division of the Naval Surface Warfare Center located in West Bethesda, Maryland. It was founded in 1939, with the purpose of accurate investigation of ship model performance and is one of the largest basins in the world. It consists of a shallow water, deep water and a high-speed basin, and the Maneuvering and Seakeeping Basin (MASK), and is equipped with wave makers, towing carriages, and measuring instruments [45]. The size of its shallow water, deep water, and MASK basins are given in Table 4.

4.5. University of Hawaii at Manoa and the Hawaii National Marine Renewable Energy Center

The Hawaii National Marine Renewable Energy Center (HINMREC) is part of the Hawaii Natural Energy Institute at the University of Hawaii at Manoa. It is funded by the DOE and works in close conjunction with Marine Corps Base Hawaii (MCBH), Kaneohe Bay. HINMREC is supervising the Wave Energy Test Site (WETS) in collaboration with the Navy, which supports research and development of renewable energies by testing deep-water WECs at MCBH (see Fig. 4). In addition to device testing, HINMREC is conducting research on bio-fouling, corrosion of materials in the marine environment, and the environmental impacts of wave energy conversion [66]. Another major focus of HINMREC research is advancing wave-forecasting capabilities. A wave atlas of the Hawaiian Islands is being developed and the center is working to improve high-resolution wind simulations, which will further increase the accuracy of wave climate modeling [66].

In October 2014 [67], the DOE, in coordination with the Navy, announced grants totaling $10 M to Ocean Energy USA and Northwest Energy Innovations for one year of full-scale testing in the new deep water test berths at the WETS facility. In July 2015, the scaled device named Azura by Northwest Energy Innovations was deployed at the 30-meter berth at WETS and is currently delivering electricity to the grid [68].

4.6. The University of North Carolina Coastal Studies Institute

The University of North Carolina Coastal Studies Institute (UNC-CSI) is a research institute formed in 2003 with the goal of facilitating research, providing education and outreach, and communicating to the people and institutes related to North Carolina maritime sectors [69]. One of the main objectives of UNC-CSI is to focus on coastal engineering and ocean energy to investigate the potential of waves and tides for energy generation. The programs are in collaboration with the Colleges of Engineering at North Carolina State, UNC Charlotte, and North Carolina A & T Universities [69].

4.7. Institute for Advanced Technology and Public Policy at Cal Poly San Luis Obispo

The Institute for Advanced Technology and Public Policy (IATPP) was created in 2012 at Cal Poly and has started a project named "CalWave" in order to assess the feasibility of siting a national test facility for wave energy at the place with the best characteristics along the coast of California. For this aim, DOE has granted $750,000 to the CalWave project at Cal Poly [70].

5. Open source databases, simulation and reference models

In order to facilitate the development of wave energy, several publically available tools have been developed that are intended to reduce the time and cost of research and development. This section presents several of the open source databases, simulation, and reference models related to wave energy converter technologies.

5.1. WEC-Sim and OpenWARP

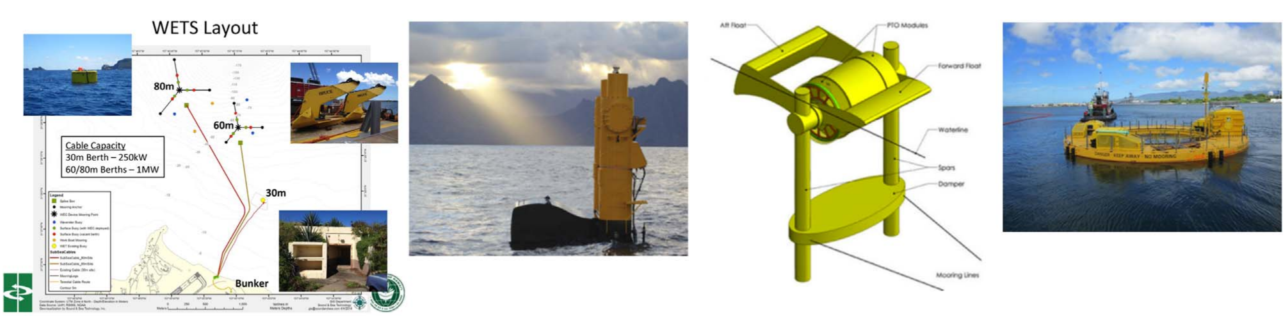
The NREL, with the support of a global community of developers through funding by the WPTO, offers a range of open-source software tools supporting the development of water-power technologies. These software tools cover engineering solutions for computer-aided engineering, design, sizing, and costing as well as the development of integrated systems. Relevant tools include OpenWARP-Nemoh (hydrodynamic coefficients using Boundary Element Method [71]), WEC-Sim (Wave Energy Converter SIMulator), WEC Extreme Conditions Modeling, MAP++(Mooring Analysis Program), and MoorDyn (lumped-mass mooring dynamics) [72]. WEC-Sim is a MATLAB-based multi-body dynamics solver and can model rigid bodies, power-take-off systems, and mooring systems [73]. During the International Conference on Ocean, Offshore and Arctic Engineering (OMAE2015), the WEC-Sim team won the Hydrodynamic Modeling Competition, which was hosted by the Center for Ocean Energy Research [74].

5.2. Tethys

In order to meet the needs of the DOE's WPTO and improve information and data exchange about the effects of MHK and offshore wind technology on the environment, the Pacific Northwest National Laboratory (PNNL) has developed Tethys. Groups such as the National Ocean Council, regional planning bodies, the U.S. Bureau of Ocean Energy Management are involved in facilitating the exchange of relevant information and data [1]. Tethys' data compilation is obtained from *in-situ* tests and experiments, which facilitates the creation and exchange of information regarding the environmental risks arising from the effects of MHK [23]. Tethys supports the Environmental Risk Evaluation System (ERES) developed by PNNL to address the key fundamental concerns from offshore renewable energy devices, and is publicly accessible [75].

5.3. OpenEI

OpenEI is an open platform collecting energy information from



(a) (b) (c) (d)

Fig. 4. Wave Energy Test Site (WETS) in collaboration with Navy Marine Corps Base Hawaii (MCBH), Kaneohe Bay (a) Layout, and current WECs funded to test are (b) Azura, (c) Sting Ray, (d) Lifesaver.

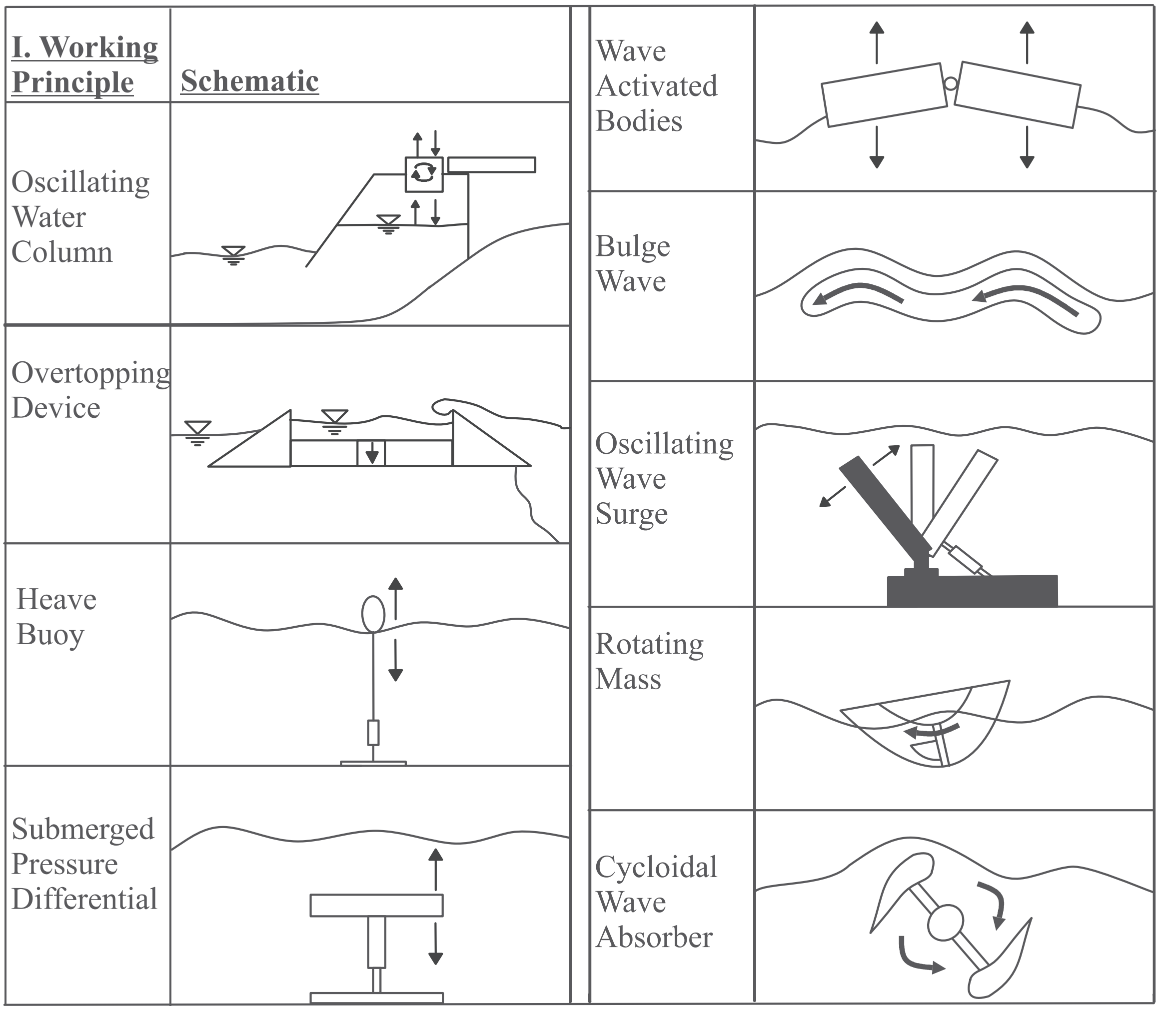


Fig. 5. Wave Energy Converter classification – working principles (based on OSU).

industry and government agencies. This database is part of the DOE's effort to provide publicly accessible data and is developed and maintained by several MHK-active national laboratories. It includes a comprehensive section on renewable energy, including MHK R & D, as well as project reports executed within the U.S. and other parts of the world. OpenEI also includes information collected on energy conversion technologies, projects, and companies that are active in the MHK arena [76].

5.4. NREL MHK Resource Atlas

The MHK Resource Atlas is a mapping tool used for exploration of marine and hydrokinetic resources such as ocean wave and current power, tidal stream power, and riverine hydrokinetic resources. The interactive Resource Atlas, developed by NREL, is capable of assessing various aspects of wave resources, such as wave height, density, and wave energy period [42].

6. Nonprofit and commercial activities in wave power

This section focuses on the current status of commercial activities, with a special emphasis on currently active renewable wave energy technology developments in the United States. After the 2014 shutdown of the Ocean Renewable Energy Council (OREC), which was established in 2005, the Marine Energy Council became part of the National Hydro power Association which along with the Oregon Wave Energy Trust, and the Maine Wind and Ocean Energy Initiative are active associations exclusively focusing on promotion of MHK within the United States [77].

6.1. Oregon Wave Energy Trust (OWET) and the Pacific Ocean Energy Trust (POET)

The Oregon Wave Energy Trust (OWET), located in Portland, Oregon, is a nonprofit partnership, which works on the development of ocean energy and cooperates with different stakeholders in industry and government. OWET hosts an annual conference called the Ocean Renewable Energy Conference, providing a comprehensive overview of the current wave energy industry status in the U.S. [78]. Pacific Ocean Energy Trust (POET) is a new nonprofit organization that is building on the foundation laid down by OWET. POET will expand its focus to the entire U.S. and Canadian Pacific region, and will include all forms of offshore renewable energy, as well as non-conventional riverine hydrokinetics.

6.2. Currently active developers of Wave Energy Converters in the U.S.

In the following section we provide an overview of currently active WEC developers located within the United States. For a global comparison, the European Marine Energy Centre lists 256 wave energy developers worldwide where 97 (38%) are located in the United States. Although the U.S. Wave Energy Prize has attracted over 90 applicants and developers, this review focuses on active U.S. WEC technology

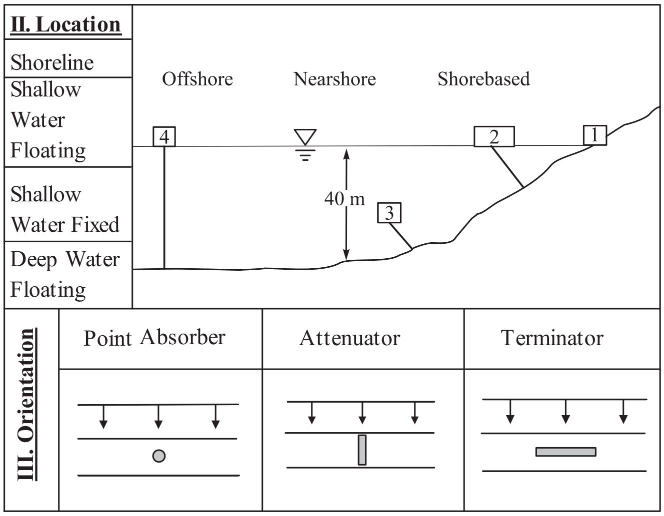


Fig. 6. Wave Energy Converter classification – Location and orientation.

developers having received public or private funding or that have advanced to a TRL of 3 or higher [79]. A TRL level of 3 includes conceptual validation, active research and development by analytical and experimental studies, and also a demonstration of technical feasibility [80]. The players and projects are described, as well as their date and location of establishment, device name and classification, funding amounts, dates and sources, past achievements, deployments, partners and other news and updates. In order to classify the wide range of technical solutions, we are using the five categories based on previous classification efforts by Falnes [81], Falcao [82], Drew [83] and Cruz [84]: 1) Working Principle, 2) Location, 3) Orientation, 4) Power Take Off System and 5) Technology Readiness Level (Figs. 6 and 7). We have identified nine different working principles (not all of which are currently being developed in the U.S.): 1) Oscillating Water Column, 2) Overtopping Device, 3) Heaving Buoy, 4) Submerged Pressure Differential, 5) Wave Activated Bodies, 6) Bulge Wave, 7) Oscillating Wave Surge, 8) Rotating Mass, and 9) Cycloidal Wave Absorber.

Table 5
List of United States' based Ocean Wave Energy companies and their device type.

	Name	Classification and PTO Type
1	Atargis Energy Corporation	Cycloidal Propeller
2	Atmocean, Inc.	Point Absorbers with hydraulic PTO
3	Columbia Power Technologies	Wave Activated Body with rotary generator
4	California Wave Power Technologies, LLC	Submerged Pressure Differential with hydraulic PTO
5	Ecomerit Technologies (Centipod)	Point Absorber
6	M3 Wave	Submerged Pressure Differential with pneumatic PTO
7	Northwest Energy Innovations	Wave Activated Body with rotary generator
8	Ocean Energy Industries	Point Absorber with hydraulic or mechanical PTO
9	Ocean Energy USA LLC	Oscillating Water Column
10	Ocean Power Technologies	Point Absorber with hydraulic PTO
11	Ocean Motion International	Point Absorber with hydraulic PTO
12	Oscilla Power	Point Absorber with magnetostrictive alloy PTO
13	Resen Waves	Point Absorber with mechanical PTO
14	Resolute Marine Energy	Oscillating Surge Converter with a hydraulic PTO
15	Spindrift Energy	Floating Tube-Like Body with a wave-driven Venturi tube
16	Waveberg Development Limited	Wave Activated Body with a hydraulic PTO

Fig. 5 lists the distribution of the first four classification categories among wave energy projects worldwide as reported by Magagna and Andreas [4] in 2014 and Table 5 provides a summary of the companies' devices classification and type of PTOs.

6.2.1. *Atargis Energy Corporation*

The Atargis Energy Corporation, founded in 2010 and located in Pueblo, Colorado, is developing a patented Cycloidal Wave Energy

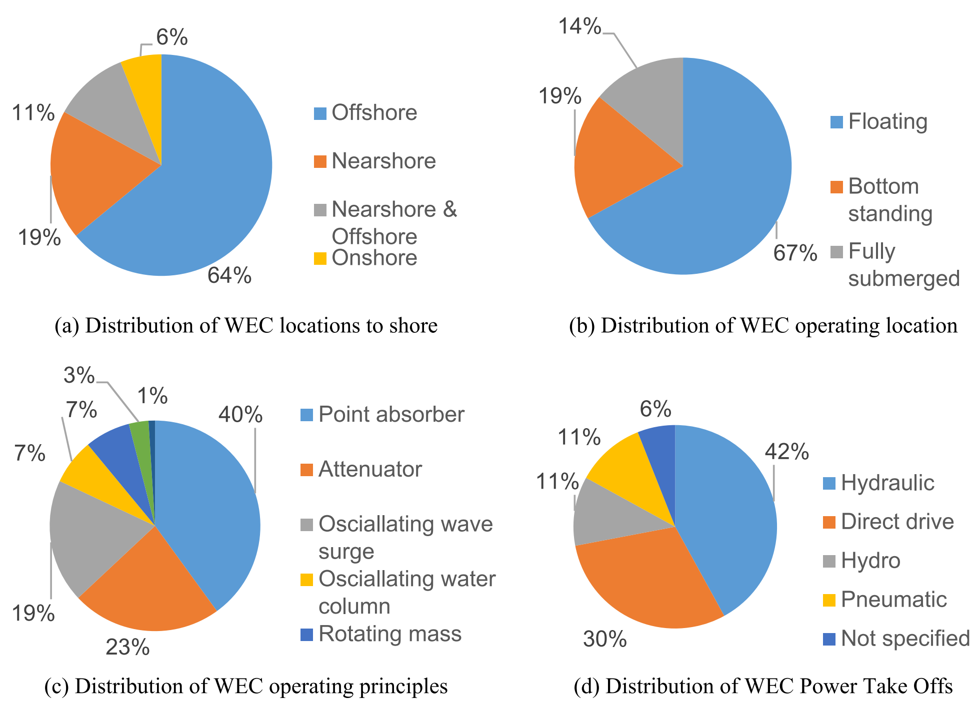


Fig. 7. Distribution of the first four classification categories among wave energy projects worldwide based on [4]. (a) Distribution of WEC locations to shore (b) Distribution of WEC operating location (c) Distribution of WEC operating principles (d) Distribution of WEC Power Take Offs.

Converter (CycWEC). The WEC's working principle is similar to a cycloidal propeller in which the blades are attached to a rotating radius, which is linked to a main shaft [85].

6.2.2. Atmocean, Inc.

Atmocean uses its arrays of point absorbers to drive seawater pumps, sending the output to shore for desalination and drip irrigation of coastal deserts. Atmocean has received grants from Sandia and Los Alamos National Laboratories, Oregon Wave Energy Trust, Oregon State University, and the UK's Technology Strategy Board and Plymouth University COAST (wave tank). With over 100 days of sea trials, Atmocean is anticipating its first commercial deployment in Peru by end of year 2016. It has several U.S. and international patents pending [86].

6.2.3. Columbia Power Technologies

Columbia Power Technologies, established in 2005, has offices in Corvallis, Oregon and Charlottesville, Virginia. Columbia Power is in final validation stages of a WEC called “StingRAY”, targeting a deep water operating location [87]. The StingRAY is classified as a Wave Activated Body, capturing heave and surge forces. It uses a composite hull and a direct-drive rotary generator [88]. The initial linear design was developed at Oregon State University. The current 3rd-generation rotary system is proprietary and will achieve TRL6 in 2016. Funding has been received from private investors, Oregon Angel Fund, Oregon Wave Energy Trust, U.S. Navy, DARPA and DOE.

6.2.4. California Wave Power Technologies (CalWave)

California Wave Power Technologies, established in 2014 in Berkeley, California, [87] is developing a WEC inspired by the natural phenomenon of strong wave damping by bottom mud in certain shallow water surf zones. The approach is based on an idea developed at the University of California, Berkeley in 2012 [89,90]. CalWave is developing a device called WaveCarpet that is classified as a submerged pressure differential WEC. CalWave has received funding from the Lawrence Berkeley National Laboratory, and has reached the Technology Gate 2 of the U.S. Wave Energy Prize.

6.2.5. Ecomerit Technologies (Centipod)

Ecomerit Technologies, formed in 2009 and located in Santa Barbara, California, is investigating a WEC called Centipod that is classified as a point absorber array [91]. Centipod is comprised of five point-absorber bodies, which use a common, stable, floating reference structure to extract power primarily from wave heave. Recently, Ecomerit Technologies has received DOE support for the development of advanced control algorithms and an associated power takeoff system to optimize power capture.

6.2.6. M3 Wave

M3 Wave LLC is located in Oregon, with testing facilities in Salem and a mobile office in Corvallis. M3 Wave LLC is developing several devices based on their “DMP” technology that is classified as a submerged pressure differential device using a pneumatic PTO [92]. The team has received funding from the DOE, OWET, and OregonBEST, and completed an open ocean deployment at Camp Rilea in Northern Oregon in 2014 and has reached Gate 2 of the U.S. Wave Energy Prize.

6.2.7. Northwest Energy Innovations

Northwest Energy Innovations (NWEI) is based in Portland, Oregon and is developing a WEC called Azura, which was formerly known as WEC-NZ. Azura is classified as a Wave Activated device operating in heave and pitch. The company has successfully deployed in New Zealand and Oregon. With the support of a DOE grant, the team is currently has its Azura device in the water and connected to the grid at the Hawaiian WETS [93].

6.2.8. Ocean Energy Industries

Ocean Energy Industries is a corporation registered initially in Florida 2009, while the office is located in Oakhurst, New Jersey. Their WEC is called WaveSurfer, and is classified as a point absorber [94].

6.2.9. Ocean Energy USA LLC

Initially founded in Ireland [95], the U.S. subsidiary Ocean Energy USA LLC was founded in 2014 in Sacramento, California, and is developing a system called OceanEnergy buoy, which is classified as an Oscillating Water Column. The device has been tested for survivability in the Atlantic Ocean, and has received a DOE grant to test at the WETS test site in 2016 [67] and has reached Gate 2 of the U.S. Wave Energy Prize [18].

6.2.10. Ocean Power Technologies

Ocean Power Technologies (OPT), with its primary headquarters in Pennington, New Jersey, also operates in Warwick, United Kingdom and Melbourne, Australia, and is developing a WEC called PowerBuoy that is classified as a point absorber [96]. OPT has deployed various iterations of its PowerBuoy, and is currently focused on a 350 W device designed to operate autonomously [96].

6.2.11. Ocean Motion International

Located in Arvada, Colorado, Ocean Motion International seeks to produce electricity, drinking water, and hydrogen by using wave energy [97]. They have developed a system called WavePump, which was tested in Scripps Institution of Oceanography in September 2014. This system creates pressurized water that can be used for running turbines to generate electricity, as well as for reverse-osmosis desalination [98].

6.2.12. Oscilla Power

Oscilla Power was founded in 2009 in Seattle, Washington, and their WEC is called the Triton Wave Energy Harvester, which has a large buoy connected by a tether to a plate under the sea. The change of the tension in the tether caused by the motion of the floating buoy relative to the heave plate induces current in the tether, which is constructed of magnetostrictive alloys. The first generation of this system was tested in 2013 in Isle of Shoals, New Hampshire for nine weeks. The company is working on the design and development of the next two generations of the device called “Gen 2″ and “Gen 3″ [99]. The team has reached Gate 2 of the U.S. Wave Energy Prize in 2015 [18].

6.2.13. Resen Waves

Resen Waves has patented a WEC called “Lever Operated Pivoting Float system (LOPF)” designed to allow even small buoys to survive in large 11 m waves. It consists of a low weight buoy and a lever arm that connects the buoy to the seabed, with a tensioned line. As the wave travels, the buoy absorbs energy in the vertical as well as in the horizontal movements, by turning the lever. A gearbox and a generator integrated in the waterproof lever, generates direct electric energy, which is sent to the seabed through a cable in the mooring line. Automatic tensioning of the line compensates for tidal variation [100].

6.2.14. Resolute Marine Energy

Resolute Marine Energy, Inc. was founded in 2007, and has offices in Boston, Massachusetts, Ireland and South Africa. The company has attracted funding from DOE to support the development of its SurgeWEC technology, an oscillating wave surge converter (OWSC) device that is bottom mounted and completely submerged. OWSC extracts wave energy in the near-shore regions dominantly by horizontal oscillation in surges. Tank and wave basin tests led to two prototype tests off the Outer Banks in N.C. SurgeWEC is designed to generate electrical power or to provide pressurized seawater for desalination [101]. Resolute has already received funding from the

Oregon Wave Energy Trust to assist with its planned deployment at Camp Rilea, Oregon in 2017 [101].

6.2.15. Spindrift Energy

Spindrift Energy was founded in 2009 in California, and is developing a patented WEC comprising a wave-driven, deeply submerged Venturi tube (U.S. Patent 8,925,313). The inertia of water inside the tube causes it to resist the up-and-down accelerations of the wave-driven tube. The Venturi tube converts pressure into additional speed, and an accelerated flow drives a turbine located in the center of the tube. The team has received funding through an Energy Innovation Small Grant awarded by the California Energy Commission. Following an initial failed deployment in 2014 [102], the EISG-funded prototype was planned to be tested again in first quarter of 2016.

6.2.16. Waveberg Development Limited

Waveberg Development Limited is located in San Diego, California. Its technology, called the Waveberg, which is classified as a Wave Activated Body device using a hydraulic PTO [103].

6.3. Macro Assessment of the U.S. Wave Energy Industry

Similar to the rapidly growing wind industry in the U.S. today, the wave energy sector has the potential to become a job driver in coastal regions of the U.S. Yet, as described in Section 1, the U.S. wave energy sector in installed capacity of demonstration projects falls behind in global comparison. In order to comprehensively assess the status of the wave energy industry within the United States based on the existing industry reports [1–3,5,9–11,13,26,76–78,104] including all active and passive stakeholders, the PESTEL framework was selected, assessing the five areas of Political, Economic, Social, Technological, Legal and Environmental factors driving the industry. As these areas are driven by external and internal drivers, which can be interrelated, the strength, weaknesses, opportunities and threats for the five areas of the industry are highlighted and summarized in Table 6. Due to the maturity stage of the industry, specific categories of the PESTEL framework have a higher impact on the industry's development path. It has been found that there are over 90 wave energy technology developers within the U.S. but no clear path towards one dominant design, not even classification category such as point absorbers can be identified. Thus, the political, social and legal stakeholders' involvement in the industry is lower (when compared with technical advancements) and rather focus on industries such as offshore wind and tidal energy as other forms of marine renewable energy. Ideally, the wave energy industry can follow the pathways of these more mature industries, once higher TRL and cost competitiveness of commercial activities have been reached. This would shorten the development time frame and cost for non-technical challenges of the industry such as [...].

Currently, in order to accelerate technical development of the industry growth, NREL and SNL are investigating WECs as an abstract system in a so called “Structured Innovation project” sponsored by the U.S. Department of Energy with the goal to derive comprehensive and design-agnostic system requirements using a systems engineering framework. This approach takes all stakeholders' interests into account to ensure sufficiency of the not-purely performance and technically driven system requirements, such as insurability, acceptability, regulatory and certification acceptability, lifecycle environmental and market acceptability, as well as others. These requirements are targeted to fulfill the following statement: The wave energy plant will convert ocean wave energy to electricity and deliver it to the continental grid market in a competitive and acceptable manner across the lifecycle [105].

As a conclusion of the analysis, we can see a strong correlation and interdependency among the different categories and stakeholder interests within the U.S. and internationally, which are all impacting the current and future progress of the wave energy industry. Specifically, technical progress is driven by the amount of R & D funding that the industry receives. This amount is dependent on governmental and industry support and interest, which are dependent on general macroeconomic drivers and public interest as well as regulatory and political progress and advocacy. This strong interdependency emphasizes the importance of collaborations and interactions that encompass the various stakeholder groups and categories.

7. Concluding remarks and future perspectives

Recent advancements and initiatives in the wave energy field by the government and private sector, from the increasing pressure for seeking novel sources of energy, and from society's attention to the environmental benefits of renewable resources have spawned increaseed activity and attention to this sector. Several universities and affiliated test sites, as well as numerous commercial activities, are actively working to help the industry increase the installed capacity of MHK generation technologies. Initiatives like the U.S. Wave Energy Prize also have the potential to facilitate development of the wave energy industry. The DOE has defined three focus areas in order to address the critical market acceleration and deployment opportunities: 1) data collection and experimentation, 2) development of monitoring and mitigation technologies and techniques and 3) information sharing and international collaboration [1].

The first commercial projects are expected to be implemented in niche markets in the U.S. and abroad. Recent regional–and industry–relevant and potentially complementary activities such as a 10 MW WaveRoller® wave farm in Mexico and grants for U.S. offshore wind farms by the Department of the Interior, as well as project-announced financing by the private sector, can be synergetic for the progress of the U.S. wave energy industry [106,107].

Similar to the global industry status, the United States wave energy industry is in a pre-commercial Technology Readiness Level (TRL) stage, and cannot yet contribute to the energy supply of the nation. However, the investment and research in this field by the government, universities, and the private sector will potentially lead to advancements that could introduce wave power as a cost competitive and sustainable energy resource for the United States. As highlighted in Section 2, wave power has the potential to significantly contribute to an increase of carbon-neutral installed electricity generating capacity using a considerable renewable energy resource with the advantages of higher power density, predictability, and consistency that is available close to the load centers of the U.S. population.

New mechanisms implemented by federal and state governments to support demand and supply of wave power could potentially facilitate the industry's development. Such mechanisms could include extending and expanding production and investment tax credits, a federal renewable portfolio standard, an increase of federal support from the DOE, and low-interest loans for research firms and manufacturers embedded in the supply chain for WECs [90]. Adoption of wave energy and renewable energy in general would benefit from a carbon tax that could begin to internalize the emission cost of fossil energy use. Similar mechanisms have supported the progress of solar and wind power to economic viability and adoption of utility-scale generators and installation of farms in the MW scale.

The industry's ultimate success and advancement to utility-scale power production depends on several factors, including the future technological improvements that cut down capital and operational cost, national policies that drive or hinder new energy technologies, and the extent to which large industry players become active in the industry, helping large scale wave energy technologies become cost competitive in power generation markets [89].

Table 6
Summary of U.S. wave energy industry using the PESTEL framework.

	Strength	Weakness	Opportunity	Threat
Political	● National & international emissionand renewable targets ● Paris Agreement COP21 ● Climate Action Plan (CAP) ● Renewable commitments of CA & Hawaii ● Clean Power Plan (2016)	● High initial investment requirements ● Uncertainty of economic feasibility and market competitiveness	● Regional leadership ● Potential for new job creation ● Extending and expanding the production and investment tax credits ● Federal renewable portfolio standard ● Low-interest loans for research firms and manufacturers	● Dependency on federal support
Economical	● Large underutilized renewable resource (~50 million U.S. homes) ● Lower real estate requirements and costs ● Proximity to load centers ● Predictable resource up to one week in advance ● No daily variability of resource	● Uncertain maintenance cost ● Higher dependency on economies of scale ● Higher initial R & D investment ● Lack of large industrial partners to invest in the industry	● New industry sector and markets in manufacturing and infrastructure ● New regional market opportunities ● Lower requirements of utility scale storage	● Declining LCOE for solar and wind ● Declining cost for utility scale storage
Social	● Potential for new job creation ● Less additional distance and cost for transmission lines ● Distributed nature of wave power generation	● Area of shared interest with the fishing and freighting industry as well as recreational usage especially for shallow water operating sites	● Clean, decentral and affordable power for island nations and remote communities	● Adoption by local or state population ● Rejection by local land owner or interest group
Technical	● Shared installation and maintenance infrastructure	● Lower Technology Readiness Level compared to tidal energy ● More difficult to test in fast iteration cycles	● New technical innovations	● Uncertainty of maintenance requirements over a power plant's lifecycle ● Higher capital and time requirements for full scale open ocean testing due to annual nature of the resource
Envirnomental	● Carbon negative	● Impact in complex and active environment	● Closer to baseload renewable energy allows to reach higher percentage of renewables	● Unknown environmental impact
Legal	● Facilitating existing frameworks from offshore wind and tidal energy sector	● Higher complexity and uncertainty of the permitting process compared to other renewable sources	● Establishing legal framework for other MHK technologies	● Uncertainty about an increasing in complexity of permitting process

Acknowledgements

The authors would like to thank Jason Busch from the Oregon Wave Energy Trust for his review and comments, and Thomas Boerner, Kabir Abiose, Ashank Sinha, Michael Kelly, Henry Pham, Mostafa Shakeri, Joyce Huan, and Nicholas Tom from U.C. Berkeley for their help during the preparation of this paper. We also would like to thank listed ocean wave energy developers for providing us with the description of their technology. We want to thank the contributors for the release of figures and graphs.

Furthermore, the authors want to thank the Lawrence Berkeley National Laboratory and the Cyclotron Road entrepreneurial program for their financial support.

References

[1] U.S. Department of Energy (DOE): Quadrennial Technology Review 2015, Chapter 4: Advancing Clean Electric Power Technologies, Technology Assessments.
[2] Jacobson PT, Hagerman G, Scott G. Mapping and assessment of the United States Ocean wave energy resource. Electric Power Research Institute; 2011.
[3] Marine and hydrokinetic projects, U.S. Department of Energy Wind and Water Power Technologies Office Funding in the United States.
[4] Magagna and Andreas: 2014 JRC Ocean Energy Status Report - Technology, market and economic aspects of ocean energy in Europe, Report EUR 26983 EN, European Commission, 2015.
[5] Ocean Energy Systems (OES): Annual Report 2014, ⟨http://www.ocean-energy-systems.org/library/oes-annual-reports/⟩.
[6] World energy perspective, cost of energy technologies World Energy Council, Bloomberg New Energy Finance 2013.
[7] Hayward J, Behrens S, Mcgarry S, Osman P. Economic modelling of the potential of wave energy. Renew Energy 2012;48:238–50.
[8] Short W, Packey DJ. A manual for the economic evaluation of energy efficiency and renewable energy technologies. University Press of the Pacific; 2005.
[9] Previsic M, Epler J, Hand M, Heimiller D, Short W, Eurek K, Power W, Program T. The Future Potential of Wave Power in the United States. RE Vision Consulting, LLC and National Renewable Energy Laboratory (NREL); 2012.
[10] Dooher, B.P., E.F. Cheslak, R. Booth, D. Davy, A. Faraglia, I. Caliendo, G. MOrimoto and D. Herman. 2011. PG&E WaveConnect Program: Final Report. Prepared by Pacific gas and Electric Company. Submitted to Department of Energy. DOE/GO/18170-1. December 2011.
[11] Wave Power Feasibility Study Report Prepared for City and County of San Francisco, URS (2009).
[12] MHK Technology Development Risk Management Framework, DOE NREL (2015).
[13] An evaluation of the U.S. Department of Energy's marine and hydrokinetic resource assessments, Marine and Hydrokinetic Energy Technology Assessment CommitteeNational Research Council. The National Academies Press; 2013.
[14] ⟨http://energy.gov/sites/prod/files/2015/10/f27/QTR2015-4N-Marine-and-Hydrokinetic-Power.pdf⟩.
[15] Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlomer S, von Stechow C, et al. Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change. Cambridge University Press; 2012.
[16] ⟨https://www.whitehouse.gov/share/climate-action-plan⟩.
[17] The SBIR & STTR Programs, ⟨http://science.energy.gov/sbir/⟩.
[18] U.S. Wave Energy Prize, ⟨http://waveenergyprize.org/⟩.
[19] Short W, Sullivan P, Mai T, Mowers M, Uriarte C, Blair N, Heimiller D, Martinez A. Regional Energy Deployment System (REEDS), Contract 303 (2011) 275–3000
[20] Northwest Sandia National Laboratories, SAND2014-9040, ⟨http://energy.sandia.gov/energy/renewable-energy/water-power/marine-hydrokinetic⟩.
[21] Sandia National Laboratories: Sandia Lake Facility, ⟨http://en.openei.org/wiki⟩
[22] ⟨http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22154.pdf⟩.
[23] PNNL support to marine and hydrokinetic ocean energy development, ⟨http://readthis.pnl.gov/marketsource/readthis/B3241_not_print_quality.pdf⟩.
[24] Strategy for Renewable Energy. Department of the Navy; 2012.
[25] ⟨http://www.washington.edu/news/2014/10/24/u-s-navy-awards-8-million-to-develop-wave-tidal-energy-technology/⟩.
[26] Water Power Technologies Peer Review Report. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy; 2011.
[27] ⟨http://www.nsf.gov/news/news_summ.jsp?Cntn_id=132978⟩.
[28] The Bureau of Ocean Energy Management, ⟨http://www.boem.gov/⟩.
[29] ⟨http://www.boem.gov/Environmental-Studies-Program-History/⟩.
[30] Ohmsett, ⟨http://www.ohmsett.com⟩.
[31] Campbell HV, Rising Tide A: Wave energy in the United States and Scotland, Sea Grant Law and Policy Journal 2 (2) (2009–2010) 29–48.
[32] Federal Energy Regulatory Commission Hydrokinetic Projects, ⟨http://www.ferc.gov/⟩.
[33] Lenee-Bluhm P, Paasch R, Özkan-Haller HT. Characterizing the wave energy resource of the U.S. Pacific Northwest. Renew Energy 2011;36(8):2106–19.
[34] Parkinson SC, Dragoon K, Reikard G, García-Medina G, Özkan-Haller HT, Brekken TKA. Integrating ocean wave energy at large-scales: a study of the U.S. Pacific Northwest. Renew Energy 2015;76:551–9.
[35] Reikard G, Robertson B, Bidlot J-R. Combining wave energy with wind and solar: short-term forecasting. Renew Energy 2015;81:442–56.
[36] Yeung RW, Peiffer A, Tom N, Matlak T. Design, analysis, and evaluation of the UC-Berkeley wave-energy extractor. J Offshore Mech Arct Eng 2012;134(2):021902.
[37] Oskamp JA, Tuba Özkan-Haller H. Power calculations for a passively tuned point absorber wave energy converter on the Oregon coast. Renew Energy 2012;45:72–7.
[38] Moarefdoost MM, Lawrence VS, Alnajjab B. Layouts for ocean wave energy farms: models, properties, and optimization. Omega 2017;66:185–94.
[39] Li Y, Yu Y-H. A synthesis of numerical methods for modeling wave energy converter-point absorbers. Renew Sustain Energy Rev 2012;16(6):4352–64.
[40] Arinaga RA, Cheung KF. Atlas of global wave energy from 10 years of reanalysis and hindcast data. Renew Energy 2012;39(1):49–64.
[41] Stopa Justin E, Filipot Jean-François, Li Ning, Kwok Fai Cheung , Chen Yi-Leng, Vega Luis. Wave energy resources along the Hawaiian Island chain. Renew Energy 2013;55:305–21.
[42] Hydrodynamic Testing Facilities Database, ⟨http://www.nrel.gov/gis/data_mhk.html⟩.
[43] Advanced Structures and Composite Center, ⟨http://composites.umaine.edu/w2⟩.
[44] Alden Research Laboratory, ⟨http://www.aldenlab.com⟩.
[45] Historic Mechanical Engineering Landmark, David Taylor model Basin, American Society of Mechanical Engineers, 1998.
[46] Davidson Laboratory of Stevens Institute of Technology, ⟨http://www.stevens.edu/ses/davidson/facilities/design-evaluation⟩.
[47] DeFrees Hydraulics Lab, ⟨http://www.cee.cornell.edu/about/facilities/defrees.cfm⟩.
[48] Fluid Mechanics Laboratory at Clemson University, ⟨http://www.clemson.edu/ces/coastal/facilities.html⟩.
[49] Haynes Coastal Engineering Laboratory, ⟨http://coastal.tamu.edu/forindustry.html⟩.
[50] The Hydraulics Laboratory of Scripps Institution of Oceanography, ⟨http://hydraulicslab.ucsd.edu/Facilities.html⟩.
[51] Richmond Field Station, ⟨http://www.iihr.uiowa.edu/facilities/shl⟩.
[52] Jere A Chase Ocean Engineering Laboratory, ⟨http://marine.unh.edu/facility/jere-chase-ocean-engineering-laboratory⟩.
[53] Marine Hydrodynamics Laboratory (MHL) of the University of Michigan, ⟨http://name.engin.umich.edu/facilities/mhl⟩.
[54] Massachusetts Institute of Technology, ⟨http://web.mit.edu/towtank/www/facilities.html⟩.
[55] Haynes Coastal Engineering Laboratory, ⟨http://coastal.tamu.edu/forindustry.html⟩.
[56] O.H. Hinsdale Wave Research Laboratory, ⟨http://wave.oregonstate.edu/facilities⟩.
[57] The School of Naval Architecture and Marine Engineering at the University of New Orleans, ⟨http://www.uno.edu/coe/naval-architecture-marine-engineering/facilities⟩.
[58] St. Anthony Falls Laboratory, ⟨http://www.safl.umn.edu/facilities/flumes-and-channels⟩.
[59] Richmond Field Station, ⟨http://rfs.berkeley.edu⟩.
[60] University of Houston Hydraulics Laboratory, ⟨http://www.cive.uh.edu/research/water-resources/hydraulics⟩.
[61] College of Engineering of the University of Rhode Island, ⟨http://egr.uri.edu/facilities⟩.
[62] United States Naval Academy, ⟨http://www.usna.edu/Hydromechanics/Facilities/⟩.
[63] Northwest National Marine Renewable Energy Center, ⟨http://nnmrec.oregonstate.edu⟩.
[64] The Alaska Center for Energy and Power, ⟨http://acep.uaf.edu/⟩.
[65] The Alaska Hydrokinetic Research Center, ⟨http://acep.uaf.edu/programs/alaska-hydrokinetic-energy-research-center⟩.
[66] Hawaii National Marine Renewable Energy Center, ⟨http://hinmrec.hnei.hawaii.edu⟩.
[67] ⟨http://energy.gov/eere/articles/energy-department-announces-10-million-full-scale-wave-energy-device-testing⟩.
[68] ⟨http://energy.gov/eere/success-stories/articles/catching-wave-innovative-wave-energy-device-surfs-power-hawaii⟩.
[69] SERC - Humboldt State University and Cal Poly San Luis Obispo, ⟨http://www.schatzlab.org⟩.
[70] ⟨http://www.iatpp.calpoly.edu/projects/energyinitiative.asp⟩.
[71] ⟨http://nrel.github.io/OpenWARP/⟩.
[72] ⟨https://nwtc.nrel.gov/Software⟩.
[73] The University of North Carolina Coastal Studies Institute, ⟨http://csi.northcarolina.edu/⟩.
[74] WEC-Sim (Wave Energy Converter SIMulator), ⟨http://energy.sandia.gov⟩.
[75] Tethys, ⟨http://tethys.pnnl.gov⟩.
[76] OpenEI, ⟨http://en.openei.org⟩.
[77] The Ocean Renewable Energy Coalition, ⟨http://www.oceanrenewable.com/about-orec/⟩.
[78] Oregon Wave Energy Trust, ⟨http://oregonwave.org/about/⟩.
[79] Technology Readiness Assessment (TRA) Guidance. Department Of Defense; 2011.
[80] ⟨http://esto.nasa.gov/files/trl_definitions.pdf⟩
[81] Falnes J. A review of wave-energy extraction. Mar Struct 2007;20(4):185–201. http://dx.doi.org/10.1016/j.marstruc.2007.09.001.
[82] Falcao AFDO. Wave energy utilization: a review of the technologies. Renew

Sustain Energy Rev 2010;14(3):899–918. http://dx.doi.org/10.1016/j.rser.2009.11.003.
[83] Drew, A review of wave energy converter technology. of Power and Energy 2009;223:887–902. http://dx.doi.org/10.1243/09576509JPE782.
[84] Cruz J. Ocean wave energy, current status and future perspectives. Springer; 2008.
[85] Artagis Energy Corporation, ⟨http://atargis.com⟩.
[86] Atmocean, Inc., ⟨http://atmocean.com⟩.
[87] CALWAVE, ⟨http://calwave.org⟩.
[88] Columbia Power Technologies, ⟨http://columbiapwr.com⟩.
[89] Alam M-RA. flexible Seafloor Carpet for High-Performance Wave Energy Extraction, ASME 2012 In: Proceedings of the 31st International Conference on Ocean, Offshore and Arctic Engineering OMAE2012 July 1-6, 2012, Rio de Janeiro, Brazil (OMAE2012-84034); 2012.
[90] Alam M-R. Nonlinear analysis of an actuated seafloor-mounted carpet for a high-performance wave energy extraction, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, doi http://dx.doi.org/10.1098/rspa.2012.0193; 2012.
[91] Ecomerit Technologies, ⟨http://www.ecomerittech.com⟩.
[92] M3 Wave LLC, ⟨www.m3wave.com⟩.
[93] Northwest Energy Innovations, ⟨http://azurawave.com⟩.
[94] Ocean Energy Industries, ⟨http://oceanenergyindustries.com⟩.
[95] Ocean Energy USA LLC, ⟨http://oceanenergy.ie⟩.
[96] Ocean Power Technologies, ⟨http://www.oceanpowertechnologies.com⟩.
[97] Wave Energy Prize, ⟨http://waveenergyprize.org/teams/ocean-motion-international⟩.
[98] Ocean Motion International, ⟨http://oceanmotionintl.com⟩.
[99] Oscilla Power, Inc., ⟨http://oscillapower.com⟩.
[100] Resen Waves, ⟨http://www.resenwaves.com⟩.
[101] Resolute Marine Energy, ⟨http://www.resolutemarine.com⟩.
[102] Spindrift Energy, ⟨http://www.spindriftenergy.com⟩.
[103] Waveberg Development Limited, ⟨http://www.waveberg.com⟩.
[104] Previsic M, Moreno A, Bedard R, Polagye B, Collar C, Lockard D, Toman W, Skemp S, Thornton S, Paasch R. et al., Hydrokinetic energy in the United States resources, challenges and opportunities. In: Proceedings of the 8th European Wave Tidal Energy Conference, pp. 76–84; 2009.
[105] ⟨http://energy.sandia.gov/industry-outreach-doe-and-wave-energy-scotland-co-sponsored-wec-technology-workshop/⟩.
[106] ⟨http://aw-energy.com/aw-energy-and-enal-signed-mou-for-10mw-waveroller-wavefarm-in-mexico⟩.
[107] ⟨http://www.mercurynews.com/science/ci_29086397/californias-first-ocean-wind-farm-works⟩.
[108] Bedard, R., P.T. Jacobson, M. Previsic, W. Musial, and R. Varley. 2010. An Overview of Ocean Renewable Energy Technologies. Oceanography 23(2):22-31.
[109] Jacobson, P.T. 2011. Challenges and Opportunities in Tidal and Wave Power. In: K.R. Rao (ed.). Energy and Power Generation Handbook. American Society of Mechanical Engineers, New York, NY.