JOURNAL OF
EMERGING INVESTIGATORS

Article

Building an affordable model wave energy converter using a magnet and a coil

Landon Choy[1], Grant Yamashita[1], Lori Choy[1]
[1] Kamehameha Schools Kapālama, Honolulu, Hawaii

SUMMARY

Locally produced, renewable energy is of paramount importance for Hawai'i and other island communities to secure a sustainable future. Hawai'i, which has the highest electricity prices in the United States, is also the most petroleum-dependent state in the nation. Existing solutions like solar and wind power can only generate energy 20-30% of the time. In contrast, the ocean can generate power 90% of the time, making it a much more reliable source of clean energy. This project investigates an affordable, small-scale model wave energy converter (WEC) that can convert the potential energy in waves into electricity. Oscillating water levels from waves can be used to move a magnet through a coil using a float to produce electricity, employing Faraday's Law of Induction. We attached a fishing float to a neodymium magnet that moved through a coil to induce a voltage inside a fabricated wave tank. We tested coil diameter, wave amplitude, the number of coil turns, the number of magnets, and corrosion to observe their effects on the device's energy output. We found that increasing all variables aside from corrosion led to an increase in voltage and current production. We increased the coil diameter, the number of coil turns, and the number of magnets to produce 92.6 mV and 61.0 mA compared to the original 3.5 mV and 1.9 mA. This device demonstrates Faraday's Law of Induction in action while generating energy using waves. Wave energy is a promising and underexplored resource that can mitigate the reliance on fossil fuels in Hawai'i and other island communities.

INTRODUCTION

Hawai'i is the most isolated populated landmass in the world (1). All of its goods are imported across more than 2,500 miles from the continental United States. As a result, Hawai'i residents experience the highest cost of living in the nation (2). A large contributing factor to this cost is the price of electricity (3). In 2021, Hawai'i residents paid an average of 28.7 cents per kWh (kilowatt-hour), which is almost triple the U.S. average of 10.5 cents per kWh (4). As an isolated island community that heavily relies on energy imports, Hawai'i consumes over 12 times more energy than it produces, making it the highest petroleum-dependent state in the nation (4). In 2019, Hawai'i consumed 90 Tera-watt hours (TWh) while only producing 7 TWh (4).

Beyond Hawai'i, fossil fuels are a major contributor to carbon dioxide in the atmosphere and to climate change (5). In recent years, its effects have been felt across the world, including extreme weather conditions such as stronger hurricanes, more drought, and rising sea levels that directly impact Hawai'i and other island communities (5-7). Island communities are also subject to heavy flooding from storm surges and coastal erosion that take away their already limited land mass (7, 8). Experts also expect that 90% of coral reefs, home to many marine species, will suffer severe degradation due to ocean acidification and warmer temperatures (8).

Unlike fossil fuels, clean energy emits little to no carbon dioxide, making it a more environmentally friendly alternative. Much of this clean energy is generated through solar panels and wind turbines. However, there are times when the sun isn't out and the wind isn't blowing, rendering these energy sources less effective. On average, solar and wind power can generate electricity only 20-30% of the time (9). It can also be expensive to build the infrastructure to harness this natural energy (10). Investigation into more efficient, locally produced, clean energy sources is needed.

One potential answer to the problem of limited clean energy alternatives is ocean waves. Unlike wind and solar power, ocean waves can potentially generate electricity 90% of the time (9). In fact, it has the highest energy density among renewable energy sources of 50 J/m^3 compared to that of solar's 0.0000015 J/m^3 and wind's 7 J/m^3 (11). Hawai'i's unique geography presents an even bigger opportunity for this form of energy generation (12). A 2021 study conducted by the National Renewable Energy Laboratory evaluated the potential energy that could be generated along the outer shelf of U.S. territory through ocean waves (12). It was found that Hawai'i could potentially generate 390 TWh/yr (12). This is over four times the amount of energy currently needed to sustain the entire state of Hawai'i for one year. Even if only a fraction of this energy is produced, it will greatly accelerate Hawai'i's goal to be completely free from fossil fuel dependency by 2045 (13).

Harnessing wave energy has generally proven to be a challenge due to the ocean's hostile environment (9). Many devices fail ocean testing due to reliability (9). However, those that succeed in becoming commercially viable supply large quantities of power to the grids in which they are implemented. For example, Pelamis, the world's first commercial wave energy converter project, has been supplying 2.25 MW to Portugal since 2006 (14).

There are also few environmental impacts of wave energy converters (WECs) according to existing research. A State of the Science report produced by Ocean Energy Systems that was supported by the International Energy Agency found that the potential impact of WECs on marine life is small (15). There have been no significant reported changes to marine animal habitats or collisions with these animals by any wave energy systems undergoing field testing (15). However, the report identified potential environmental stressors such as underwater noise, electromagnetic fields, encounters with mooring cables, and oceanographic changes (15). This is still a very new technology, and a lot of work and research is being done to identify its faults.

The main objective of this study was to build an affordable, small-scale model WEC capable of harnessing energy in a wave tank. We did not include any mechanical parts in the design to increase reliability. The secondary objectives were to optimize its energy production by evaluating the effects when changing different device variables, and evaluate the prototype's scalability, taking into consideration environmental issues and cost. We also tested for corrosion among the device's metal parts and its effect on the energy output. The concept of the WEC employs Faraday's Law of Induction to generate electricity: if a magnet is moved in and out of a metal coil, a voltage will be induced in the coil. We hypothesized that a floating buoy can be attached to a magnet that remains inside a coil to generate voltage and current from the oscillating motions of the waves.

To increase the energy production of the device, the mathematical equations for Faraday's Law of Induction and magnetic flux were analyzed and the variables that affected the voltage output and current output of the WEC were identified. Faraday's Law of Induction states:

$$EMF = -N\left(\frac{\Delta\Phi}{\Delta t}\right) \quad \textbf{(Eqn 1)}$$

In this case, EMF (Electromotive force) is the voltage induced. N is the number of coil turns, Φ is the magnetic flux, and t is time. Magnetic flux has its own equation that can also explain the collected data. Current is also directly proportional to voltage so an increase in voltage leads to an increase in current. Applying **Equation 1** to the investigation, the relationship between EMF and its variables can be determined. The mathematical equation for magnetic flux is:

$$\Phi = BAcos\theta \quad \textbf{(Eqn 2)}$$

Like **Equation 1**, Φ is magnetic flux. *B* is the magnetic field and A is the area of the coil. *θ* is the angle between the magnetic field and the normal line, which is perpendicular to the coil face. The relationship between magnetic flux and its variables can be determined by applying **Equation 2** to the investigation.

The variables tested were coil diameter, wave amplitude, the number of coil turns, the number of magnets, and corrosion that were identified from **Equation 1** and **Equation 2**. We hypothesized that increasing all of these variables, aside from corrosion, would increase the voltage and current output of WEC. A larger coil diameter would increase A in **Equation 2**, a larger wave amplitude would decrease *Δt* in **Equation 1**, a larger number of coil turns would increase *N* in **Equation 1**, and a larger number of magnets would increase B in **Equation 2**, thus all increasing Electromotive Force (*EMF*) in **Equation 1**. On the other hand, corrosion was hypothesized to decrease the voltage and current output because it would decrease *B* in **Equation 2** and cause a decrease in *EMF* in **Equation 1**.

From the experiments, we found the WEC could successfully and optimally produce energy from the variables identified in **Equation 1** and **Equation 2**. Before any variables were changed, the design could produce 3.6 mV and 1.9 mA. After optimization, the WEC could produce 92.6 mV and 61.0 mA. All hypotheses were supported in the experiments. These results demonstrate that harnessing wave energy is feasible using a simple design and household materials. We also evaluated the WEC prototype for scalability and found potential for the device to be scaled-up for ocean deployment but requires significantly more research to do so. We are still determining cost-efficiency, but the prototype itself was built with $25 in household materials, demonstrating its replicability and simplicity.

RESULTS

To construct the WEC, a magnet and float were connected. We placed the magnet inside a test tube that was wrapped in copper wire and held down with a weight **(Figure 1)**. We tested this model prototype inside a fabricated manual wave tank **(Figure 2)**. Voltage and current outputs were graphed and averaged.

The WEC was successful in producing energy, generating an average of 3.5 mV and 1.9 mA (Figure 3). The largest coil diameter of 25 mm generated the highest voltage and current output **(Figure 3)**. The largest wave also produced the most voltage and current **(Figure 4)**. As the wave amplitude doubled, the voltage increased by 177% while the current increased by 351%. The coil with the largest number of coil turns generated the most voltage and current In the experiments, the voltage output increased by 220% and the current output increased by

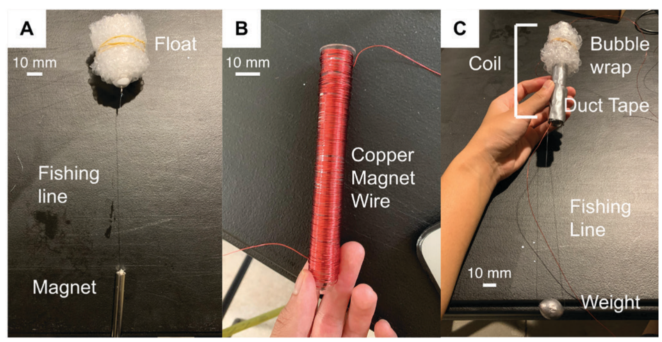

Figure 1: WEC construction. A) Magnet and float contraption, B) bare coil, and **C)** final coil contraption. The float was attached to a neodymium magnet. Copper magnet wire was wrapped around a test tube and secured with duct tape. The coil was held down with a fishing weight and stood vertical in the water with the bubble wrap.

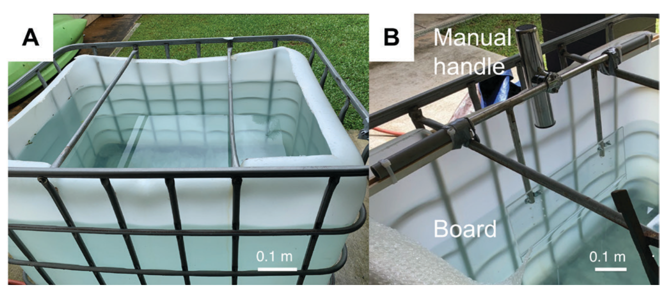

Figure 2: Fabricated wave tank. A) Tank and **B)** wave generator system. The crystalline board was connected to a manual handle that was laid across the top metal bars of the 275-gallon chemical tote tank.

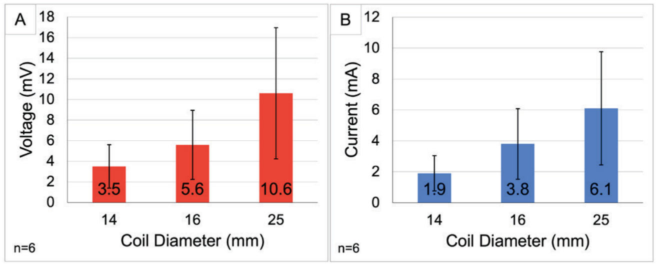

Figure 3: The largest coil diameter generated the most voltage and current. A) Average voltage and **B)** average current with respect to coil diameter. Coil diameters of 14, 16, and 25 mm were tested individually inside the wave tank. Error bars represent standard deviation.

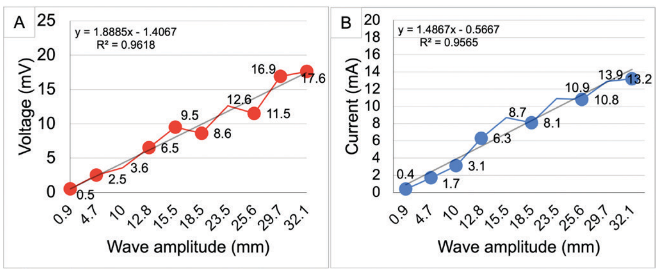

Figure 4: The largest wave produced the most voltage and current. A) Voltage and **B)** current with respect to wave amplitude. The 25 mm coil was tested across varying wave amplitudes generated by the wave tank. A linear trendline was observed in Excel.

205% when the number of coil turns was doubled **(Figure 5)**. Similarly, the WEC iteration with the largest number of magnets produced the most voltage and current **(Figure 6)**. Doubling the number of magnets increased the voltage output by 156% and the current output by 154%.

The corrosion tests run on the device's metal components showed that the unprotected magnet generated less voltage and current than the protected magnet **(Figure 7)**. Using the corroded magnet led to 11% less voltage and 15% decrease in current.

DISCUSSION

The results of all the tests suggest that this WEC can indeed generate energy from the oscillating water level in the tank, thus supporting the original hypothesis. We observed that a larger coil diameter, wave amplitude, number of coil turns, and number of magnets increased the voltage and current output of the device while corrosion decreased the output. These findings were consistent with **Equation 1** and **Equation 2**.

The larger coil diameter increased coil area, *A*, which led to larger voltage and current because of the increased magnetic flux, Φ (**Equation 2**). This led to a higher voltage output, EMF, in the largest coil diameter of 25 mm **(Figure 3)**. The higher amplitude wave produced more energy because the magnet moved faster through the coil during that instant, thus decreasing time in the denominator, Δt **(Figure 4, Equation 1)**. The wave amplitude measurements were taken to emphasize the varying efficiency of the device according to its environment. Inconsistencies in the trend were due to water that got on the plastic sheeting beneath the motion sensor. This caused an irregular motion of the sheet giving

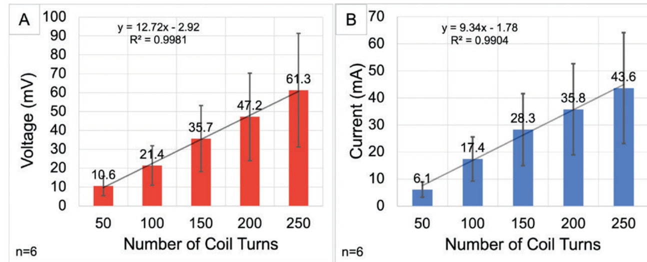

Figure 5: The largest number of coil turns generated the most voltage and current. A) Average voltage and **B)** average current with respect to number of coil turns. The 25 mm coil diameter was used in the experiments. The number of coil turns was tested individually in increments of 50. Error bars represent standard deviation. The linear trendline was observed in Excel.

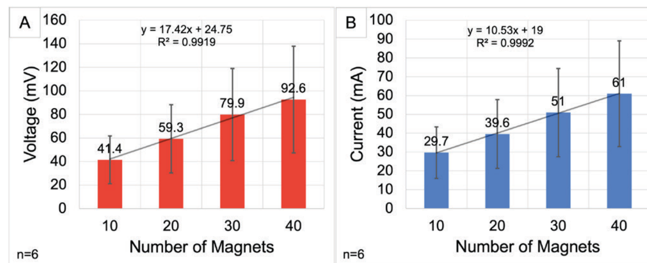

Figure 6: The largest number of magnets produced the most voltage and current. A) Average voltage and **B)** average current with respect to number of magnets. The 25 mm coil diameter with 250 coil turns was used in the experiments. The number of magnets was tested individually in increments of 10. Error bars represent standard deviation. The linear trendline was observed in Excel.

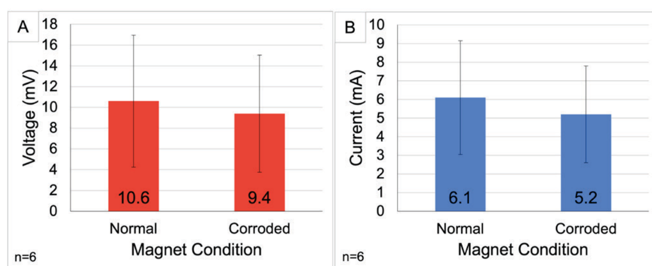

Figure 7: The corroded magnet produced less voltage and current than the normal magnet. A) Average voltage and **B)** Average current with respect to magnet condition. A neodymium magnet was dipped in ocean water for 18 days and tested against a brand-new neodymium magnet. Error bars represent standard deviation.

slightly skewed measurements. A higher number of coil turns, *N*, increased the energy output because *EMF* is directly proportional to *N* **(Figure 5, Equation 1)**. Similarly, increasing the number of magnets *B* increased magnetic flux, Φ, which led to an increase in the overall voltage and current output **(Equation 2, Figure 6)**. Changes to variables were consistent with expectations of Faraday's Law of Induction and Magnetic Flux. The angle between the magnetic field and the normal line, θ, was not altered as it was approximately 90 degrees in the system. Thus, the variable was already optimized as the maximum value for the cosine function is 1 **(Equation 2)**.

It's important to note that there was no conversion from alternating current to direct current, so each value was ±

because the energy was alternating current. The voltage and current were subject to negative values, causing a large standard deviation in the coil diameter, number of coil turns, number of magnets, and corrosion graphs.

The corrosion tests run on the device's metal components demonstrated the importance of a protective coating **(Figure 7)**. The corroded magnet led to a decrease in voltage and current because of the lower magnetic field produced and thus, a decrease in magnetic flux **(Equation 2)**. These tests were done to observe how the device would fare in a marine environment with an unprotected magnet. To prevent corrosion, we applied marine paint to the magnet. Future research will investigate its effect on the energy output of the WEC.

In terms of energy optimization of this model WEC, it is essential to further adjust the variables we tested (aside from corrosion) within a reasonable design. With the ocean's larger waves comes an increase in energy output. Comparatively, one of the highest wave amplitudes measured by the motion sensor in this experiment was 32.1 mm. In Hawai'I the average wave height ranges from one to four meters, making it up to one thousand times larger than what was produced in the wave tank (16). The current WEC design is not suitable for ocean deployment and would break due to the strength of the materials and small scale. To withstand ocean waves, the device would need to be significantly scaled up. Changes would need to be made to the design such as a strong mooring system that can restrict the float's horizontal movement, and the implementation of stronger materials such as steel to create the coil. A buoy could also be used as the float with metal rods to connect it to the magnet. The positive linear slope that was observed is expected to remain the same on a larger-scale WEC as both designs still abide by Faraday's Law of Induction **(Figure 2)**. Saturation effects are expected with limitations in coil length as the magnet moves beyond the coil with an exceptionally large wave.

The main components that need to be addressed for ocean deployment are corrosion, strong waves, animal inhabitants, and maintenance. Corrosion and biofouling can be addressed through the application of marine paint as seen in the tests. However, after being in the ocean for long periods of time, it is inevitable for the metal parts in the ocean to sustain organism growth and biofouling, which would require the occasional replacement of parts and temporary service on the device. This is why cost-efficiency is a crucial factor when building a WEC, which is something that can be explored in experiments on the small-scale model. The energy output would need to be maximized before efforts are made to scale up the device. This can be done in various ways including increasing the tested variables and hooking multiple devices up in series.

The ocean contains the highest energy density among renewable sources and the method explored was one of many ways to go about harnessing this energy. Fossil fuels continue to be the main energy source today, but that is changing. This topic still demands considerable research to fully incorporate waves into the world's energy production. Places like Hawai'i have an abundance of still-untapped renewable energy sources like waves. By taking advantage of them, its heavy reliance on fossil fuels will decrease. The energy from this clean source will also decrease the number of oil tankers arriving in Hawai'i, and thus lower the devastating effects of ships on marine life. These include chronic underwater noise, oil and chemical spills, garbage releases, ship strikes, and the introduction of invasive species (17). Wave energy will also help Hawai'i fulfill its 100% renewable energy goal by 2045 and move it one step closer to a sustainable future. The device we built shows that this source of energy can be harnessed without the use of professional equipment. The small-scale WEC has a large potential for improvement that can translate to ocean deployment. There is much more energy in ocean waves than those of the wave tank in which the WEC was tested. Nevertheless, this research demonstrates the potential of wave energy and its feasibility for a more sustainable Hawai'i.

MATERIALS AND METHODS

WEC Fabrication

A small-scale WEC prototype and wave tank were constructed **(Figure 1, 2)**. All materials for the WEC were purchased from Amazon. One end of a monofilament fishing line was tied to a magnetic clasp attached to the top of a cylindrical neodymium magnet. The other end was attached to a float wrapped in bubble wrap. A copper magnet wire (24 AWG, 0.051 mm) was wrapped around a 14 mm diameter test tube to construct the coil. Duct tape secured the coil to the test tube. The bubble wrap kept it upright in the water while being anchored down by the lead weight. Two more coil diameters were built with 16 mm and 25 mm diameters. Wave amplitude was observed across 10 observations with a plastic sheet laid on the surface of the water a Vernier motion sensor placed above to measure its displacement that mimicked the wave motion. Each observation was made at a different wave amplitude and plotted with voltage output and current output. The number of coil turns was increased in increments of 50, up to 250. The number of magnets was changed in increments of 10, up to 40 magnets. These magnets were 15 mm wide and 2 mm tall discs that were different from the initial 10 mm wide and 76 mm tall cylindrical magnet to observe the effect of a varying magnetic field on the system. The cost of the 25 mm diameter coil with 250 turns and 40 magnets was roughly $25 to fabricate.

Wave Tank Fabrication

The wave tank where the device was deployed was a leftover 275-gallon chemical tote tank with the top section removed. All other materials were purchased from Amazon. The wave generator in the tank was a push-and-pull system using a manual handle to create an oscillating water level. With the forward and backward movement of the handle, a board moved through the water to create the wave action. The system was laid across the top metal bars with welded rods used to extend the crystalline board into the water. Wave amplitude was measured using a Vernier motion sensor that interfaced with the LoggerPro software. Since the system was manual, the oscillating water level and wave amplitude was not constant. An estimated equal manual force was applied into the generator to produce each wave. A maximum wave amplitude was observed consistently at approximately 35 mm with a ±3 mm error. A wave was generated approximately every 2 seconds.

Experimental Assay or Experimental Outline

A voltmeter and current probe were attached to the ends of the coil to measure the voltage and amperage output.

These and the motion sensor were plugged into a Vernier interface connected to a laptop for data readings in real-time using the Vernier LoggerPro 3.16 software. Six tests were performed for each variable of the WEC that was changed (except wave amplitude). Each test was done over a period of 18 seconds with a reading every 0.1 seconds. Voltage and current outputs were collected with the LoggerPro software and analyzed. Corrosion tests were also conducted on the metal components of the WEC over the course of 18 days. The effect of corrosion on the energy output was observed. No methods were used to analyze the different parameters since both positive and negative values were observed and the standard deviation was so large.

ACKNOWLEDGMENTS

Thank you to physics mentor, Peter Grach, for helping us understand the physics concepts. Thank you to research mentor, Gail Ishimoto, who helped us refine our paper and hone the direction of our research. Kamehameha Schools Kapālama provided materials to conduct the investigation at home. Thank you to Michael Choy for his constant support throughout the process.

Received: October 31, 2022
Accepted: March 14, 2023
Published: July 5, 2023

REFERENCES

1. Hawaii–WSRGN." *WSRGN,* www.westernstatesgenetics.org/states/hawaii. Accessed 15 May 2023.
2. "Cost of Living Data Series." *Missouri Economic Research and Information Center,* meric.mo.gov/data/cost-living-data-series. Accessed 15 May 2023.
3. "Consumer Price Index, Honolulu Area – March 2023." *U.S. Bureau of Labor Statistics,* www.bls.gov/regions/west/newrelease/consumerpriceindex_honolulu.htm. Accessed 15 May 2023.
4. *State Electricity Profiles – Energy Information Administration.* www.eia.gov/electricity/state. Accessed 18 Jan. 2022.
5. Jackson, Randal. "The Effects of Climate Change." *Climate Change: Vital Signs of the Planet,* climate.nasa.gov/effects. Accessed 24 Oct. 2022.
6. "Climate Change Impacts." *National Oceanic and Atmospheric Administration,* www.noaa.gov/education/resource-collections/climate/climate-change-impacts. Accessed 24 Oct. 2022.
7. "Impacts of Climate Change." *US EPA,* www.epa.gov/climatechange-science/impacts- climate-change. Accessed 15 March 2023.
8. Parsons, Chris. "The Pacific Islands: The Front Line in the Battle against Climate Change." NSF, *new.nsf.gov/science-matters/pacific-islands-front-line-battle-against-climate.* Accessed 15 Oct. 2022. beta.nsf.gov/sciencematters/pacific-islands-front-line-battle-against-climate.
9. Drew, B., *et al.* "A Review of Wave Energy Converter Technology." *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy,* vol. 223, no. 8, SAGE Publications, Dec. 2009, pp. 887–902. doi.org/10.1243/09576509jpe782.
10. "Weaning U.S. Power Sector off Fossil Fuels Would Cost $4.7 Trillion: Study." *Reuters.* www.reuters.com/article/us-usa-carbon-report/weaning-u-s-power-sector-off-fossil-fuels-would-cost-4-7-trillion-study-idUSKCN1TS0GX. Accessed 15 May 2023.
11. Layton, Bradley E. "A Comparison of Energy Densities of Prevalent Energy Sources in Units of Joules per Cubic Meter." *International Journal of Green Energy,* vol. 5, no. 6, Informa UK Limited, Dec. 2008, pp. 438–55. doi.org/10.1080/15435070802498036.
12. Levi Kilcher, *et al. Marine Energy in the United States: An Overview of Opportunities.* NREL/TP-5700-78773, National Renewable Energy Laboratory, 2021, www.nrel.gov/docs/fy21osti/78773.pdf.
13. Kun, Joseph. "Hawai'I Clean Energy Initiative." *Hawai'I State Energy Office,* energy.hawaii.gov/Hawaii-clean-energy-initiative. Accessed 22 June 2022.
14. "Pelamis, World's First Commercial Wave Energy Project, Agucadoura." *Power Technology,* www.power-technology.com/projects/pelamis. Accessed 21 Jan. 2022.
15. Hemery, Lenaig. "OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES)." *U.S. Department of Energy Office of Scientific And Technical Information,* Sept. 2020, doi.org/10.2172/1632878.
16. "Wave Observations: Kāne'ohe Bay, O'ahu, Hawai'i | PacIOOS." *Pacific Islands Ocean Observing System (PacIOOS)*, www.pacioos.hawaii.edu/waves/buoy-kaneohe. Accessed 18 Oct. 2022.
17. Sheppard, Charles. *World Seas: An Environmental Evaluation: Volume III: Ecological Issues and Environmental Impacts.* 2nd ed., Academic Press, 2018.