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# LOW-COST UTILITY-SCALE WAVE ENERGY ENABLED BY MAGNETOSTRICTION

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## ABSTRACT

Oscilla Power, Inc. (OPI) is developing a patented magnetostrictive wave energy harvester (MWEH) that could enable the disruptively low-cost production of grid-scale electricity from ocean waves, a large-scale resource that is more predictable and more proximal to demand growth than solar or wind. Designed to operate cost-effectively across a wide range of wave conditions, the MWEH will be the first use of reverse magnetostriction for large-scale energy production.

## INTRODUCTION

Wave energy has been estimated to have the potential to supply approximately 2,000 TWh/year of electricity [1], or nearly 10% [2] of global electricity consumption. Unlike wind or solar energy, wave energy is forecastable several days in advance, leading to lower costs for grid integration. Additionally, wave energy is located close to coastal areas with growing demand whereas solar and wind energy must increasingly be located in remote areas.

Inventors around the world have tried to turn this low frequency, low-amplitude resource into large-scale quantities of usable electricity for decades. Unfortunately these attempts have been universally characterized by the use of power generation technologies with moving parts, resulting in high operating and maintenance costs and the need for large amounts of structural mass, which in turn drives up capital costs.

Furthermore, systems that rely on wave motion to move a floating body are intrinsically "narrow-band" technologies designed to operate at resonance with a specific wave period. As wave conditions change, these systems must be "tuned" in real-time to respond to changing conditions. Even with such tuning, these systems are inefficient at extracting power from the full range of frequencies present in any given wave condition. Different technologies have different approaches to tuning, but no combination has sufficiently increased efficiency to compensate for the high capital and operating costs.

The levelized cost of electricity (LCOE) for wave energy has been estimated to be between 25-60 cents/kWh [3,4]. While reductions over time due to learning curves are anticipated, such reductions will require massive subsidy regimes to enable private investors to support a build-out that can drive such learning. Such a large-scale build out is unlikely in the foreseeable future given the global financial situation and alternative opportunities open to project finance investors focused on the renewable energy. This situation could, however, be resolved though new technological developments.

In their recent report [3] for the U.S. Department of Energy, RE Vision Consulting concluded that the required reductions in the cost of electricity from wave energy technologies are more likely to come from "radically different" approaches rather than established technologies.

### The Ideal Wave Energy Harvester

In order to achieve the cost structure required to compete with electricity from coal or natural gas, without subsidies, new wave energy technologies should aim to achieve the following criteria:

1. **Converts wave energy into electricity at high efficiency across a wide range of conditions.** *In practice, this can be achieved through an extremely efficient and cost-effective tuning methodology or by technologies that do not rely on narrow-band resonant operation.*
2. **Can tap energy from the full spectrum of frequencies for a given wave state.**
3. **Can survive extreme events.**
4. **Has high reliability and low operating and maintenance costs.** *In practice, this likely requires minimizing or eliminating moving parts.*
5. **Has low capital costs.** *In practice, this means reducing the ratio of structural mass to active mass, not using any expensive materials, and being easy to manufacture and install.*

### What Is Magnetostriction?

Magnetostriction is a well understood electromagnetic phenomena in which changes in the magnetic field experienced by specific metal alloys result in strain (i.e., shape) changes within those alloys. The phenomenon is reversible and can be used to generate flux changes in alloy rods, which in combination with electromagnetic induction can be used to convert high-magnitude, but low-displacement, mechanical load changes into electricity.

Over the past few decades, advancements in the field have focused on higher performing alloys [5,6] for very small-scale actuator, sensor and transducer applications. These rare-earth alloys (e.g., Terfenol-D and iron-gallium alloys) are prohibitively expensive for power production at the utility scale. Iron-aluminum (Fe-Al) alloys were amongst the earliest magnetostrictive alloys identified and studied [7], but have not attracted much attention recently in the field as they have been superseded by the rare-earth alloys for conventional applications.

### The iMEC™ Technology Platform

OPI's patented iMEC technology platform, which includes critical features such as alloy pre-compression and closed loop flux paths, enable low-cost Fe-Al alloys, which can be manufactured by conventional metal casting techniques, to provide the required performance for power production applications. The driving magnetomotive force is provided by small permanent magnets which make up a very small fraction (i.e., typically under 1%) of the generator mass. A conceptual illustration of the magnetic circuit used in the MWEH's power generators is shown in Figure 2 .

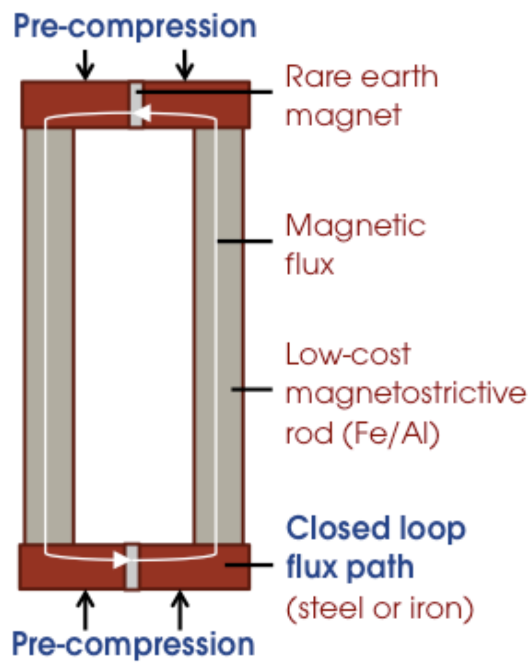


**FIGURE 2. iMEC™ MAGNETIC CIRCUIT**

The generators convert tension changes into changes in the magnetic permeability of the Fe-Al alloy rods, resulting in changes in flux density within the magnetic circuit. This is accomplished with no perceptible relative motion (i.e., <200 ppm of deformation) between the generator components. Electricity is generated by conventional electromagnetic induction, using copper coils wound around the alloy rods. A photograph of a "Gen 0" generator, which uses 2.86 cm diameter Fe-Al rods, without its compression hardware, is shown in Figure 3.

**FIGURE 3. GEN 0 MAGNETOSTICTIVE GENERATORS WITHOUT COMPRESSION HARDWARE (13.3 cm W x 5.7 cm D x 37.5 cm L)**

Fatigue-related failures might be a concern if the rods operated in tension. The pre-compression levels, however, are set such that the rods never go out of compression during normal operation. During abnormal conditions that would otherwise cause the rods to go into tension, safety bolts are engaged that pick up the excess mechanical loading. These design features should eliminate fatigue-related failures.

Small-scale magnetostrictive harvesters have been shown to operate with >80% mechanical to electrical efficiency [8]. Through our ongoing development efforts, we aim to demonstrate that similar efficiency levels are possible with generators at the scale that we are developing.

**Oscilla Power's Magnetostrictive Wave Energy Harvester**

Illustrated in Figure 4 below, the MWEH's architecture is similar to that of tension leg platforms used in the oil & gas industry; it consists of a partially submerged buoy, anchored to a catenary-moored heave plate by taut tethers. These tethers are largely made up of, or are connected to, discrete, robust power takeoff modules (PTOs) that contain power generators such as that described above. Hydrodynamic forces on the buoy cause the line tension of each tether to continuously change, resulting in a high-force, but low-displacement mechanical energy input which is converted to electrical energy in the PTOs.

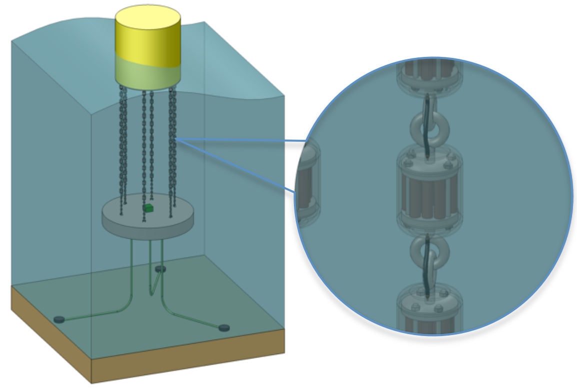

**FIGURE 4. MAGNETOSTRICTIVE WAVE ENERGY HARVESTER**

The Oscilla Power MWEH has numerous advantages over other approaches to wave energy generation, giving it the strong potential to achieve the criteria specified above:

- **No moving parts:** To our knowledge, the MWEH is unique among wave energy technologies being developed for utility-scale power production because it can produce energy from waves with no significant relative motion between or significant dimensional change of its components. This eliminates sub-system (e.g. lubrication, bearings, seals for moving components) costs and will significantly reduce O&M costs due to the elimination of the need to periodically service joints, bearings, and other such components.
- **Low cost materials:** The MWEH's materials set does not include significant quantities of any supply limited or expensive materials. Key materials include aluminum, iron, copper, and steel. Concrete and glass-reinforced plastic may also be used. While small quantities of commercially available rare earth magnets are used to create a driving magnetomotive force, these could be replaced by ferrite magnets if their cost or availability become an issue.
- **Low cost manufacturing:** All components used in the MWEH's PTO are amenable to low-cost, high-volume, automotive-scale manufacturing. In addition, the buoys and anchors have no

complex parts, which facilitates their low-cost manufacture.

- **Relative ease of deployment:** While deployment will involve ships to haul and tow MWEH components off shore, standard vessels that do not have to be customized to hold equipment in a specific direction or to deploy devices onto the ocean floor can be used.
- **High efficiency across the wave spectrum:** Operating substantially below the resonant frequency, the MWEH does not experience steep reductions in efficiency on either side of a nominal/rated condition, as is the case with many other WEC technologies. This means that it operates as a wide-band device and for the same rated generator capacity can produce a much greater average power than any wave energy harvester that requires the buoy to move at amplitudes comparable to those of the waves to drive the energy conversion.

### Technology Development

Development of our technology has proceeded along three general thrusts: (1) generator design and optimization, including validation and improvement of our performance model; (2) design and optimization of the power take off module and overall system, including the buoy and anchor; (3) deployment of sub-scale systems in wave tanks and open water environments.

#### *Generator Design & Model Validation*

In 2010, we demonstrated the production of more than 1 tesla of magnetic flux change from a pre-Gen 0 generator using a 2.5 cm diameter Fe-Al rod using load changes that such rods would experience in a utility-scale MWEH. This level of performance was both sufficient to achieve the power density and energy generation assumed in our cost model and was consistent with the "first-principles" finite-element model that we developed to predict the performance of the generators. Since then, we have designed, constructed and tested "Gen 1" generators that use two 5.1 cm diameter x 47 cm long rods, shown in Figure 5 below, and "Gen 2" generators that use a two 10.2 sq. cm x 45.7 cm long Fe-Al cores, as shown in Figure 6 below. To date, all of our generator testing has validated the accuracy of our predictive models.

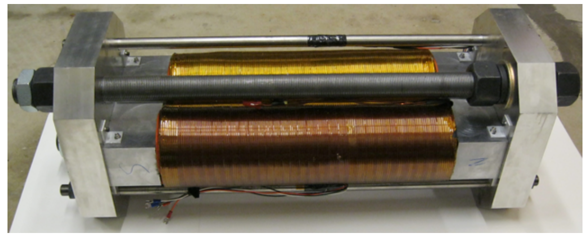

**FIGURE 5. "GEN 1" MAGNETOSTRICTIVE GENERATOR (25.4 cm W x 29.8 cm D x 83.8 cm L)**

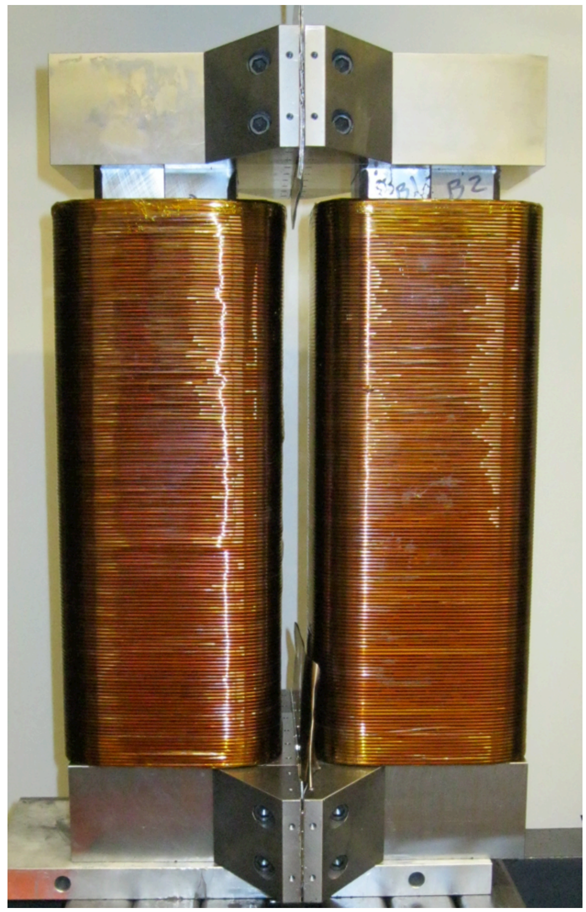

**FIGURE 6. "GEN 2" MAGNETOSTRICTIVE GENERATOR (34.6 cm W x 31.8 cm D x 58.42 cm L)**

We have tested a Gen 1 generator to 1.5 million loading cycles using an accelerated frequency of 40 Hz. This is approximately 2.4% of the number of cycles that a system would expect to see over a 20-year operating lifetime. Following an initial decrease of approximately 2.5%, which can be attributed to core and coil heating, the power production levels out and remains constant.

***PTO & System Design***

In parallel, we have executed design, prototype testing and modeling activities to optimize the PTO and overall system design to best achieve the five criteria noted above. With regards to the PTO, this work has focused on finite element design engineering to maximize load transfer from the tethers to the magnetostrictive generator as well as the evaluation, through design and prototype testing, of a variety of proven sealing methodologies.

At the system level, our work has focused on the modeling and simulation of a utility-scale system in Central Oregon coast wave conditions. Executed in Orcaflex by marine engineering consultancy Marine Innovation and Technology (MI&T), these simulations have as their primary output a time series of tether tensions; the results from one such simulation is shown in Figure 7 below. When combined with the experimentally validated generator performance model described above, we are able to predict power generation as a function of the wave conditions and the system design. Beyond performance predictions, a key focus of these simulations was to enable us to design a system that is capable of surviving extreme events (i.e., a 100-year wave).

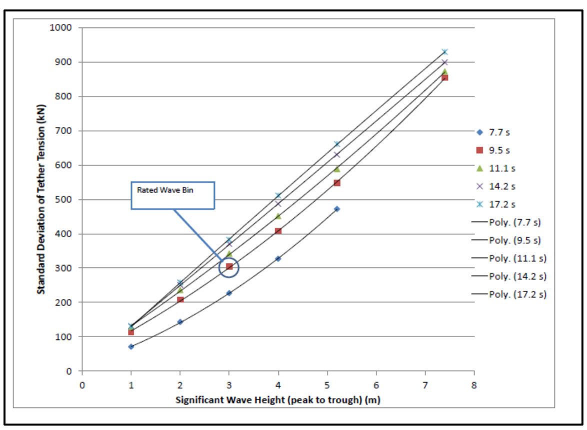


**FIGURE 7. RESULTS FOR RESULTANT TETHER TENSION CHANGES FOR DIFFERENT WAVE HEIGHTS AND PERIODS OBTAINED THROUGH HYDRODYNAMIC SIMULATION**

We worked with Powertech Labs, a subsidiary of Canadian utility BC Hydro and a leading expert on power electronics for ocean energy devices, to develop conceptual designs for the power electronics and transmission components of the MWEH system, both of which can use off-the-shelf hardware.

Together with a team of external experts, including naval engineering consultancies MI&T, Garrad Hassan and Cardinal Engineering as well as University of Maryland Professor Alison Flatau, an expert in magnetostrictive alloys who sits on OPI's Technical Advisory Board, we have prepared an exhaustive Design Failure Modes & Effects Analysis to prioritize technical risks associated with the MWEH.

***Wave Tank and Open Water Deployments***

In 2010, we conducted two rounds of wave tank testing at the University of California at Berkeley's tow tank using Gen 1 generators housed in prototype PTOs. One of these systems is shown in the tank in Figure 8. In addition to accomplishing preliminary reduction to practice, we were able to demonstrate high correlation ($R^2$ = 93%) between the predicted and actual output of the generator.

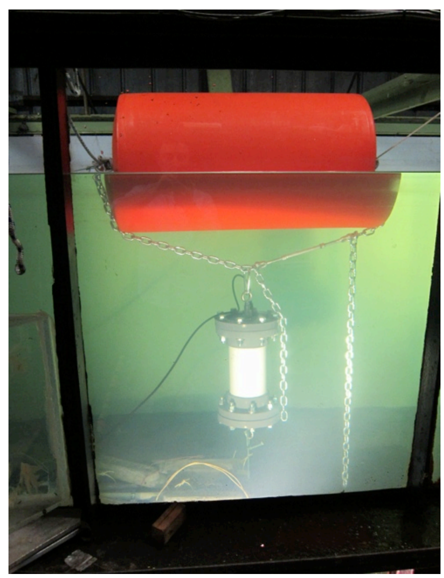

**FIGURE 8. WAVE TANK TESTING**

In the fall of 2012, APL-UW designed a mooring system that enabled us to conduct the first testing of iMEC-enabled hardware in uncontrolled conditions. Lake Washington was chosen as a deployment location due to the high frequency of winter storms, each of which would give us sufficient wave activity to test the functionality and performance of the generator, and the relatively calm baseline conditions, which would make it easy to conduct deployment, recovery and, if necessary, maintenance operations. A schematic of the mooring system is shown in Figure 9 below.

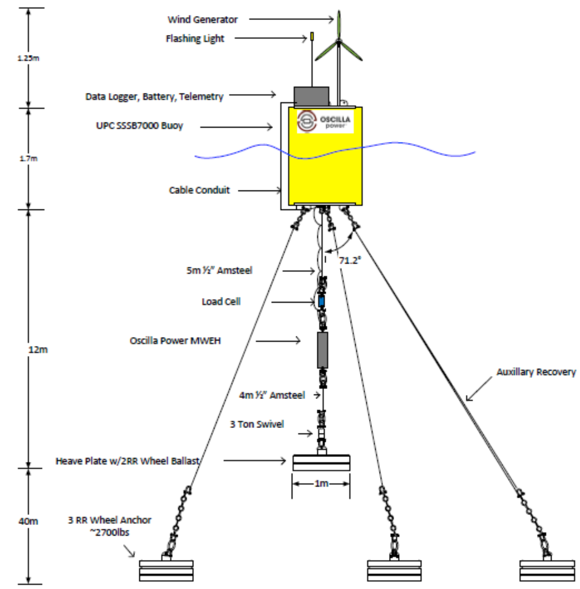


**FIGURE 9. LAKE WASHINGTON MOORING**

The mooring system, without the two PTOs, was deployed in Lake Washington in December 20th, 2012. This allowed us to confirm the stability of the mooring prior to deployment of the PTOs. A Datawell Waverider MK III buoy was deployed nearby on the same date to monitor wave height, period, direction and spectra every 30 minutes. Following intensive testing of the PTOs on a hydraulic test stand, the PTOs were installed on January 10th, 2013. A surface photograph of the deployed system is shown in Figure 9 below. Figure 10 is shows the two PTOs on the deck of the deployment vessel.


**FIGURE 9. LAKE WASHINGTON BUOY**

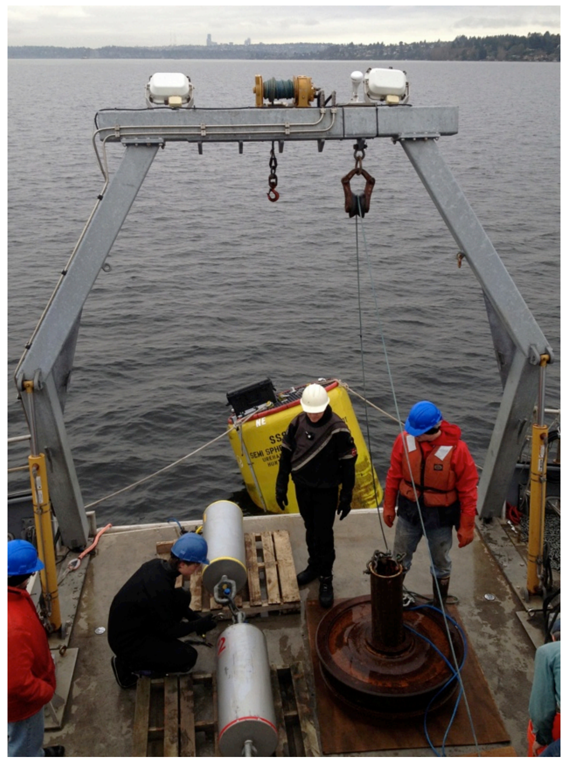

**FIGURE 10. TWO GEN 1 POWER TAKEOFF MODULES**

During the three-month long deployment, approximately 20 wave events were recorded. Figure 11 shows the full time series of wave heights, along with the range of tether loads and the vertical accelerations of the surface buoy. Tether load changes are consistent with predictions and meet the desired specification of approximately 1000 lb load variations.

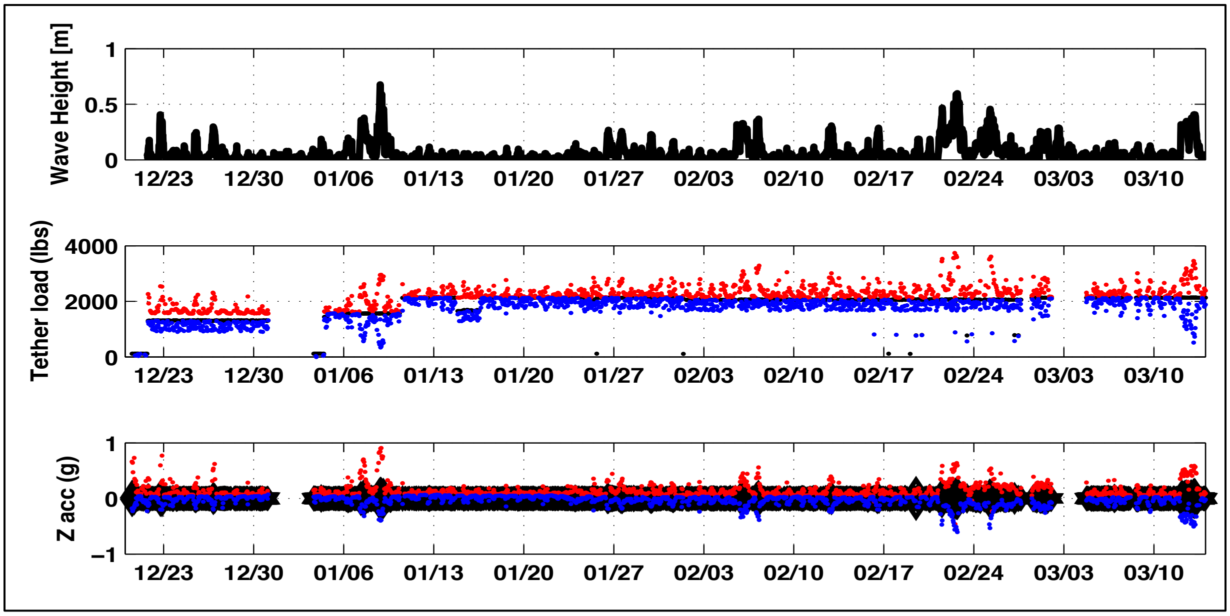


FIGURE 11. LAKE WASHINGTON MOORING

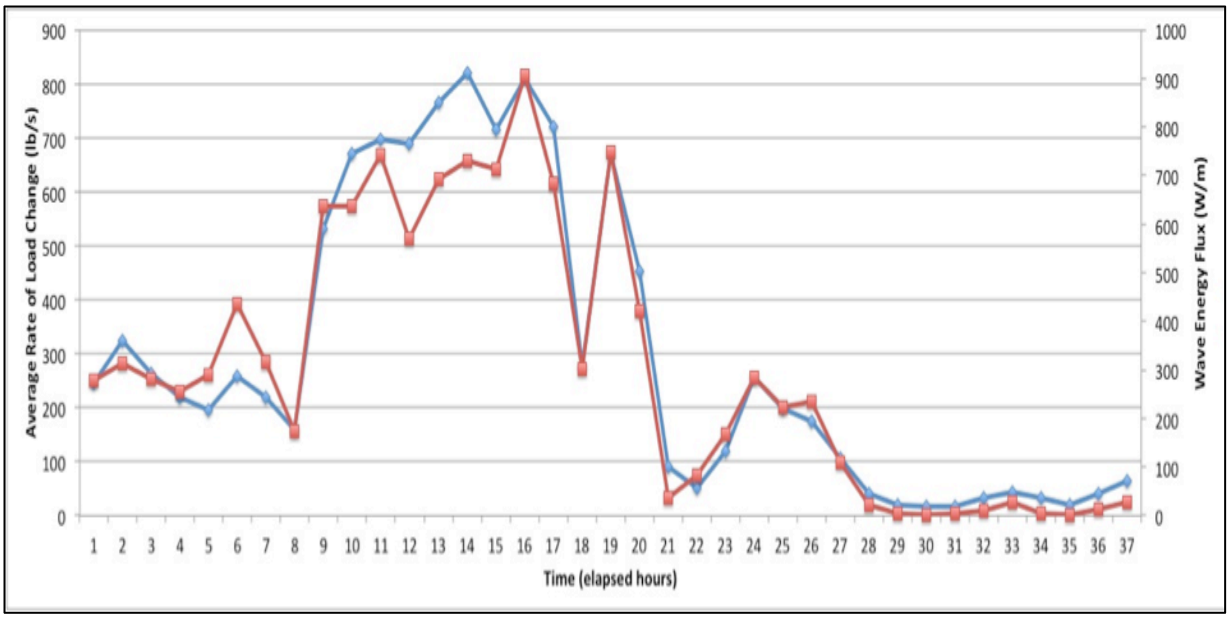


FIGURE 12. AVERAGE LOAD CHANGE RATE AND WAVE POWER DENSITY DURING A STORM EVENT

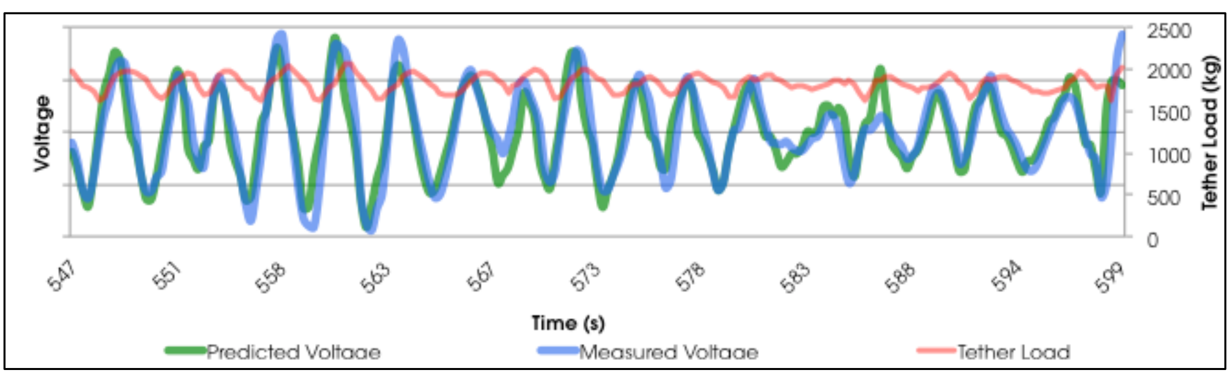


FIGURE 13. TETHER LOAD, PREDICTED VOLTAGE AND MEASURED VOLTAGE DURING A STORM EVENT

A more detailed analysis of the hourly average tether load rate of change was conducted for the storm on February 22-23, 2013, to validate the dependence on wave height. As shown in Figure 12, the average load changes are a strong function of wave height on an hourly basis.

We were also able to validate a strong correlation ($R^2$=86%) between predicted output of the PTOs, calculated using the tether loading, and their actual output, as illustrated in Figure 13.

Finally, testing on the Lake allowed us to validate the broad frequency response of the PTOs. Figure 14 shows example frequency spectra of mooring loads and motions, incident waves, and PTO voltages. The response is strong across all of the wave frequencies present (i.e., power is successfully harnessed at the dominant frequency and the across the full range of the wave energy spectrum).

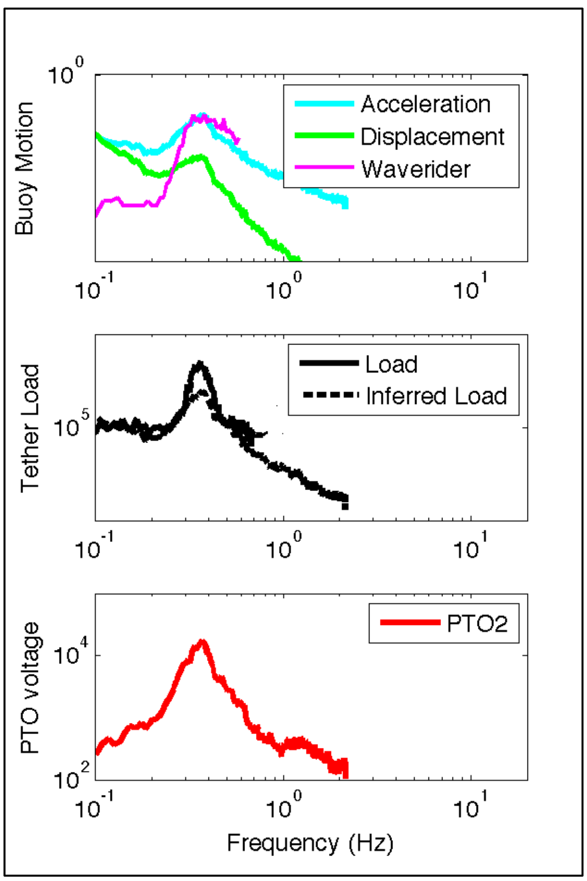


**FIGURE 14. EXAMPLE FREQUENCY SPECTRA DURING A STORM.**

### *Future Plans*

Over the next eighteen months, our technology development activities will include generator scale-up, additional prototype deployments, and the integration of component technologies to drive additional cost reduction. A prototype system that includes the buoy and Gen 1 PTOs used in the Lake Washington deployment will be tested at Isle of Shoals, NH together with the University of New Hampshire's Center for Ocean Renewable Energy later this year. We anticipate testing a sub-scale system with Gen 2 PTOs at the same site in the spring of 2014. Our target is to demonstrate such a system with "Gen 3" PTOs, which will have a substantially larger magnetostrictive core area than the Gen 2 PTOs, later in 2014. Testing of larger systems utilizing generators that have already been proven in sub-scale systems will follow.

### Levelized Cost of Electricity

Development of a detailed cost model to initially guide our opportunity and technology evaluation and then guide our technology development commenced prior to OPI's founding. The cost model is dynamically linked to both the Orcaflex simulations as well as the performance model that has been validated by three years of laboratory, tank and field testing, all of which are described above.

Costs for power electronics, conversion and transmission hardware as well as those for transportation, installation and permitting, were estimated based on formulas provided by or discussions with electric power or naval engineering consultancies with deep expertise on these aspects of ocean energy systems. In addition to the cost of hardware, the model incorporates our margins, project costs (e.g., infrastructure, site engineering, installation) and a 10% contingency factor. Annual operating and maintenance costs are, we believe, conservatively projected to be 12% of the annual capital charge, which was estimated using a 12.4% fixed charge rate.

Our cost modeling suggests that a utility-scale MWEH array using Gen 3 generators located off the central Oregon coast could produce electricity at less than 10 cents/kWh without incentives and without requiring significant learning curves.

### Environmental Impact

Broadly speaking, we believe that the MWEH's impacts will be more manageable than that of other approaches for five specific reasons:

1. **No narrow spaces**: Individual tethers are expected to be 8 or more meters apart from one another.
2. **Minimal electromagnetic field (EMF) leakage**: A core aspect of the enabling technology, the use of closed loop flux paths, ensures that minimal EMF leakage will occur beyond the PTO walls. Furthermore, absolute levels of EMF leakage can be managed in a cost-effective manner through the use of coatings.
3. **Anchor flexibility**: Despite our use of taut tethers, the MWEH will be capable of using a variety of anchor methods. As with most offshore installations, the specific method used for a given deployment will be determined on the basis of cost and environmental impact.
4. **Buoy surface profile flexibility**: The above water profile of the buoy can be designed to minimize its attraction to sea life.
5. **Minimal noise production:** Lack of moving parts, especially the lack of gearboxes, removes the potential for underwater noise pollution that might adversely affect marine mammals.

### Intellectual Property Portfolio

The work described herein has resulted in five granted patents. US Patents 7,816,797 (Oct 2010), 7,964,977 (Jun 2011) and 8,378,513 (Feb 2013) broadly cover the use of magnetostriction to generate electricity from waves, while US Patents 8,212,436 (Jul 2012) and 8,378,512 (Feb 2013) cover two specific innovations that enable high performance from low cost magnetostrictive alloys. OPI has over twenty patents pending in the US and globally.

## CONCLUSIONS

Wave energy has the potential to predictably and sustainably supply nearly 10% of the world's electricity. To date, wave energy harvesting technologies have been expensive, inefficient and prone to breakdown. We have developed a wave energy harvester enabled by magnetostriction and utilizing our patented iMEC technology platform that can convert wave energy into electricity at high efficiency across a wide range of conditions. With no moving parts, the Oscilla Power magnetostrictive wave energy harvester promises to be highly reliable, while demonstrating low capital, operating and maintenance.

As the MWEH has moved from the lab, to tank, to open water, the technology has performed successfully, with a strong correlation between predicted and actual output. Next steps include scaling up the generator, integration of component technologies for further cost reductions, and open ocean testing at Isle of Shoals, NH.

## ACKNOWLEDGEMENTS

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