



OPEN Development and operation of a 100 W wave energy converter for persistent ocean observation

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Much of the existing literature for wave energy converters focuses on devices tailored to grid-scale performance. In this paper, we present the development of TigerRAY, a small, blue-economy scale wave energy converter, designed to generate 100 W in fetch limited waves. This development process involved in-lab dynamometer testing, two years of drifting field tests, and a two month moored deployment on Lake Washington. Through this process, we show the impact of proper ballasting to TigerRAY's performance, and highlight the importance of dynamometer testing to PTO development and characterization. We also show that power electronics are critical not only to the power output of the device, but to the device dynamics as well. We demonstrate the feasibility of a wave energy converter hosting a dock for an uncrewed underwater vehicle in the field, successfully docking the vehicle with the wave energy converter in all six demonstration attempts. Finally, we provide analysis of data from field testing. TigerRAY's relationship between power output and significant wave height remains relatively constant through changing wave directions, float locations, and power electronics functionality.

Wave energy converters (WECs) are devices that convert the power of ocean waves into usable power. While much of the research and development to date has focused on future grid-scale devices, there is an emerging emphasis on blue economy markets. These are applications where small amounts of power (10's to 100's of Watts) are valuable enough to make wave energy a feasible power solution. The U.S. Department of Energy's *Powering the Blue Economy Report*¹ specifically identifies applications in thematic areas of power at sea and resilient coastal communities. These applications include power for ocean observation and navigation, underwater vehicle recharging, marine aquaculture, desalination, and community-scale isolated power systems. Additional power-at-sea applications identified in a separate report include weather coastal buoys, high frequency radar, tsunami detection, and drifting profilers².

Although many prototype WECs have undergone field testing, few have been designed specifically for blue economy applications. McLeod and Ringwood³ published a comprehensive review article identifying 22 devices operating between the mW and kW scales. Of these, only 5 were deployed at sea, and 3 operated in the 10's to 100's of W range. The U.S. Department of Energy's (DOE) Marine and Hydrokinetic Data Repository (MHKDR) contains data from field tests of a few WECs^{4–7}, but most of these tests are prototype systems designed to eventually operate at grid scale. An example of a successful blue economy scale WEC is the MBARI power buoy. This is a point absorber WEC that has been deployed in Monterey Bay each year for more than ten years^{8–10}. It generates 100–300 W in the most common wave states⁹, and is designed to support the payloads of oceanographic sensors and an AUV¹⁰. The University of Hawaii at Manoa tested a WEC both moored and drifting with a drogue anchor, and found that the moored system generated an average of 10 W with a resistive load¹¹. MiniWEC is a small-scale point absorber WEC that was deployed in the field in hours-long drifting tests¹². It burned its power in resistors and therefore did not generate usable electricity, but was used to test the impact of heave plate geometry on WEC dynamics. Another example, the Pioneer WEC, is being integrated into a buoy at sea, and expected to generate 10–100 W¹³.

Power electronics are critical to the conversion of ocean wave energy to electricity, and off-the-shelf units are rarely suitable for wave energy applications. CPower discusses the hardware used in their larger, SeaRAY device, in their final report¹⁴. The power electronics topology for the WEC presented in this paper is similar, with a power rectifier and a DC-DC converter required between the generator and power storage system. This DC-DC converter is the unit that we will refer to as our power electronics, but we note that some systems can integrate the rectifier and DC-DC converter into one single unit. The DC-DC converter is also responsible for control, and can provide a variable load to the generator. Additional work by Darwish and Aggidis¹⁵ reviews a broader range

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of power electronics topologies that may be employed for marine energy converters, highlighting the wide range of directions that future research could take.

For the WEC presented in this paper, TigerRAY, a two body point absorber, is investigated for blue economy applications. Prior work on heave plate hydrodynamics was critical to the WEC's design. Previous work identified that asymmetry in heave plate geometry does not yield significant hydrodynamic asymmetry due to the outsized role of added mass in the overall hydrodynamic force¹⁶. Other work identifies the method in which heave plate hydrodynamics scale with the Keulegan-Carpenter number¹⁷. These results were critical in selecting the size and shape of heave plate for the prototype WEC discussed in this paper.

The blue economy application targeted for demonstration with our WEC is underwater vehicle docking and charging¹⁸. Autonomous Underwater Vehicles (AUVs) are inherently power limited, and operation in the open ocean often requires recovery via research vessel to recharge batteries and offload data¹⁹. Prior work to understand the power requirements for such a system identified multiple wave climates and WECs capable of supporting existing AUVs^{19,20}. Availability of a wave energy-powered recharge station for AUVs could serve to greatly increase vehicle up time and reduce vessel costs.

This paper highlights the development process for TigerRAY. This WEC is designed to generate about 100 W of power in fetch limited waves, and demonstrate the potential for a WEC to act as a docking and charging station for underwater vehicles. This paper also aims to contribute to the need for more documentation of this development process for blue economy scale WECs. The remainder of the paper will go into detail about the system components, provide a summary of the development and commissioning process, and then provide detailed analysis of results from moored testing.

System overview

The WEC is a two-body, point absorber device. As shown in Figure 1a, it consists of a 'TigerRAY' floating surface body and a submerged heave plate, which also acts as a docking station for an ROV. There are two connections between TigerRAY and the heave plate: 1) A tether that supports the load of the heave plate, and 2) a cable that carries power and communication signals. This demonstration device was designed for drifting operations

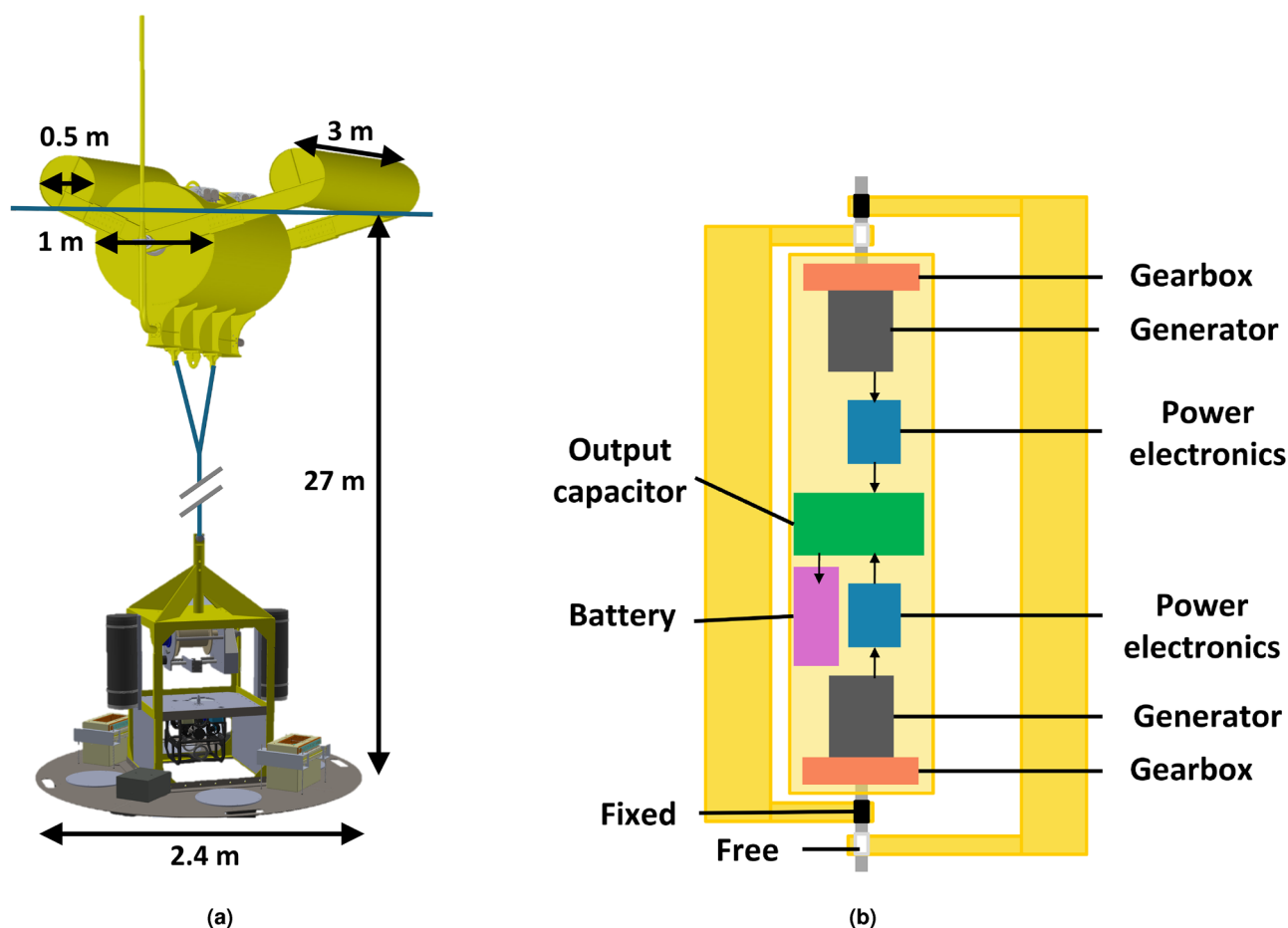


Fig. 1. (a) Schematic of TigerRAY wave energy converter (WEC) and heave plate and (b) overview of TigerRAY nacelle main internal components. The arrows denote the direction of power flow in the system. The battery powers onboard sensing and communication hardware.

in Puget Sound and Lake Washington (WA, USA). From prior site characterization²¹, we anticipated target operating conditions with a significant wave height $H_s \sim 0.5$ m and peak wave period $T_p \sim 3.2$ s.

TigerRAY surface float

The surface float was designed and constructed by C-Power, and integrated with the rest of the system by the University of Washington Applied Physics Lab (UW APL) (Figure 1a). TigerRAY consists of three interconnected bodies: the nacelle, a forward float, and an aft float. The nacelle, which is the central cylinder shown in Figure 1b, contains all of the electronics and equipment for power generation. Through each end of the nacelle, a drive shaft penetrates a shaft seal, and is rigidly connected to one of the floats. The other float is free to rotate about the drive shaft (on the respective non-drive end). Each float drives a separate Power Take-Off (PTO), and the motion of one float is not coupled to the motion of the other. Inside the nacelle, each drive shaft is connected to its own gearbox, which increases the shaft speed by 100x. Each gearbox is then coupled to a generator, which is connected to its own power electronics unit (Figure 1b). This controls the current (and therefore damping) in the generator windings. Power output from both PTOs is stored in one central supercapacitor, which is used to recharge onboard batteries through a power supply. In the event of prolonged periods with small waves, a plug on the mast can be connected to a support vessel to recharge the internal batteries.

TigerRAY is equipped with many sensors to allow data collection throughout deployment. Internally, the nacelle houses a battery bank and a processor to save and transmit collected data, and a cellular modem for data transmission. There are also leak sensors and a camera inside the nacelle that can be accessed remotely to verify that there are no leaks. For the electronics, there are sensors recording current and voltage exiting the generator and exiting the power electronics units. The system also records the voltage for the control signal and the current that the controller is targeting. There are also encoders mounted between each generator and its drive shaft, and an IMU mounted in the nacelle. The nacelle contains two watertight hatches for access to internal components. One hatch is outfitted with ten bulkhead connectors, to allow connection from internal communications and electronics to external sensors and antennae. A mast is connected to the lower nacelle yoke (see Figure 1a), and is 2.8 m tall. Cabling running from the bulkhead connectors to the mast must pass down the flat end of the nacelle to the bottom of the mast to avoid potential damage from float arm rotation. Two submersible pressure sensors are mounted to the nacelle yoke, one on each end, and one is mounted to the mast to measure ambient pressure. Also mounted on the mast are antennae (wifi antenna, 5G cellular antenna), a GPS puck connected to the IMU, a satellite compass, and a flashing light for visibility at night. A power and communications cable also runs from the nacelle hatch bulkheads to the heave plate.

Umbilical

The umbilical, which connects the surface body to the heave plate in Figure 1a, consists of two parts. 1) A nylon tether, acting as the strength umbilical, and 2) a SubConn cable, acting as a power and communication connection. The power and communications cable was strain-relieved along the strength umbilical, with small amounts of slack every 1 m between cable wrapping. The total length of strength umbilical was different for drifting and moored deployments. For drifting deployments, heave plate depth is approximately 30 m, and for the moored deployment, heave plate depth is approximately 20 m. Either depth is below the level of no motion for the 3 s period waves specified in the design process. The strength umbilical is a 1" Cortland Nylon 12 Plait, chosen for its high stretch and shock absorption. The longer tether (30 m) used in the original drifting tests providing additional stretch to avoid shock loads during the initial sea trials.

Heave plate and docking station

The heave plate, shown at the bottom of Figure 1a serves as both a reaction body for the wave energy converter and an ROV docking station. The bottom plate is circular with a 2.4 m diameter, and supports two batteries for power storage. A frame 1.7 m in height is mounted to the circular plate, and hosts a docking area for the ROV, a submersible winch for the ROV tether, and housings for electronics and power distribution equipment. The heave plate includes two pressure sensors, an IMU, and a load cell at the tether connection to the frame. For the moored deployment, the heave plate is ballasted to a dry weight of 945 kg (730 kg wet weight in freshwater).

BlueROV2

The ROV used for docking tests is a BlueROV2, made by BlueRobotics. The only modifications made to the ROV for this deployment are: 1) replacement of the main tether penetrator with a bulkhead connector, and 2) attachment of a custom panel atop the ROV with magnetic pins for alignment in the dock, and a sheath to protect the tether as it passes through the ceiling of the ROV garage. A custom, submersible winch was built by Okeanus to manage the ROV tether, and mounted above the docking area of the heave plate. The ROV enters and exits the dock through the bottom of the heave plate.

Operating principles

This WEC operates through a differential in hydrodynamic excitation. The nacelle is designed with low reserve buoyancy, and faces additional hydrodynamic resistance through its connection to the heave plate. As a result, the nacelle is relatively unreactive to wave disturbance. In contrast, the two floats have high reserve buoyancy, and tend to follow the motion of incoming waves. This difference in motion between the nacelle and floats leads to rotation of the floats relative to the nacelle, which leads to rotation of shafts (and thus power production via gearbox and generator). The forward and aft floats have different arm lengths, and different damping values as a result. The difference in arm length allows the forward float to rotate up and over the nacelle during extreme waves, landing in the water on the aft side without colliding with the aft float. This asymmetry also causes the device to tend to maintain orientation of the forward float facing the direction from which waves are arriving.

This tendency is limited during the moored deployment by the three point mooring. In later sections, we show that device performance shows limited impact from changing wave directions, even while moored.

Summary of development and commissioning

Dynamometer testing

Dynamometer testing was a critical component of TigerRAY's development process²². For this testing, we couple a rotary motor to a nacelle drive shaft via a gearbox. We specify the motor speed, and the dynamometer includes a torque cell to measure torque on the drive shaft. Prior to each round of field testing, changes to the PTO were tested on the dynamometer to characterize system performance. We were also able to tune PTO control and develop a relationship between shaft speed and system torque through these tests.

Typical testing involves three stages: 1) constant velocity, 2) sinusoidal oscillation, and 3) irregular oscillation. First, we step through the full range of expected operating velocities, holding constant at each velocity step for approximately 5 seconds. We are able to characterize the friction in the system by running a constant velocity test with the generator in freewheel. With the generator active, we record torques to understand the additional force from the generator across the operating region. After this characterization, we drive the system using sinusoidal oscillations of velocity. Through this testing, we are able to determine the rotational inertia in the PTO, and test the functionality of the power electronics units through zero crossings. Finally, we drive the system using modeled drive shaft velocities for the system operating in expected sea states. This testing comes as close to open water behavior as we can get in the lab. Performance in these tests helps us characterize how well the system handles intermittent periods with inputs below cut-in speed, and is used to validate representations of friction and inertia from earlier tests.

Figure 2 highlights the results from this testing. Shown in the black points are the individual constant speed steps and the resulting torques measured at those steps. We see a discontinuity from low to high speed. Shown in blue are results when driving the dynamometer using the system's modeled response to irregular waves. We see that the torque-speed relationship for this irregular motion closely follows the low-speed linear region of the constant speed tests (black circles). When deployed, TigerRAY does not contain a torque cell, so we use this data to estimate the torque experienced by the drive shafts in the field. We calculate estimated torque as $\tau_{fit} = c\omega + I\dot{\omega}$, where c is the slope of the low-speed linear region in Figure 2, ω is the angular velocity of the drive shaft, I is the rotational inertia of the driveshaft-gearbox-generator assembly (calculated during dynamometer testing), and $\dot{\omega}$ is the rotational acceleration of the drive shaft. Shown in pink in Figure 2 is this estimate of torque using shaft speed data from the 2024 moored TigerRAY field testing data. We see the approximate spread of this data matches closely with the measured data from dynamometer testing, lending confidence to our approximation of the torque-speed relationship. Additional analysis revealed that this fit over-predicted peak torques by about 10%, but generally agreed with measured data closely for more commonly measured torque values. We use this approximation in the Results section to calculate the capture width of the device. Additional work by Okushemiya et al. uses this relationship to represent the PTO in a hydrodynamic model of TigerRAY^{23,24}

Deployment and recovery procedures

Deployment and recovery of TigerRAY occurred from R/V Jack Robertson, a 56' long research vessel owned and operated by UW APL. This vessel is equipped with a 12' wide, 12' tall A-frame on the back deck, and a crane with a 30,000 ftlb capacity and 23' reach. Figure 3 shows the layout on the back deck during transit for the drifting deployments. TigerRAY was secured to the A-frame using two straps connected to its pick point. The mast-side of TigerRAY is suspended off the aft of ship's deck, since the mast height is greater than the A-frame clearance.

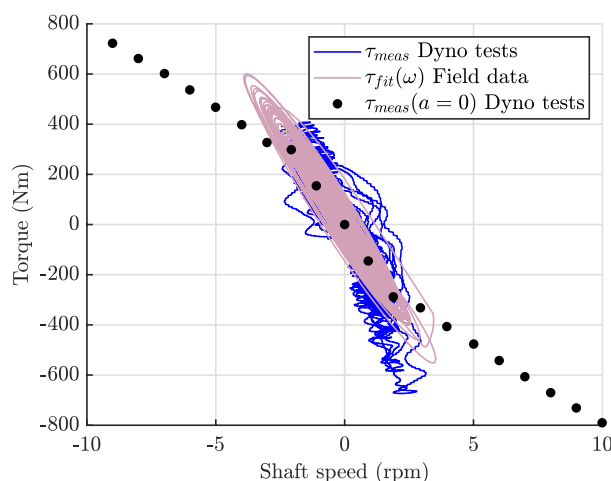


Fig. 2. Torque speed relationship for TigerRAY PTO, highlighting results from multiple stages of testing. The scatter points are derived from constant speed tests, and the increased scatter shown in the blue lines results from system inertia. When accounting for system inertia, the pink line highlights the close agreement between estimated torque in the field and dynamometer tests.



Fig. 3. Layout of TigerRAY components during transit on the back deck of R/V Jack Robertson. Picture taken by Curtis Rusch from February 2023 drifting tests.

TigerRAY's aft float is resting on and strapped to the deck in transit. The heave plate is located forward on the starboard side of the deck, with the blue communications umbilical flaked onto the deck between TigerRAY and the heave plate.

TigerRAY is deployed first from the A-frame, with the upper portion of the strength umbilical already connected to the 'yoke' frame beneath the nacelle. TigerRAY is then held off to the side of the vessel (at the water surface) with tag lines, and the rest of the umbilical is flaked on deck. The heave plate is shifted to the aft portion of the deck and deployed from the A-frame and lowered to depth with the lower section of the strength umbilical. When the umbilical junction is at deck height, the load of the heave plate is transferred to a second 'recovery' line and the umbilical sections are connected. The recovery line is used to lower the heave plate the final few meters, until the completed umbilical takes the load and the heave plate is suspended at depth below TigerRAY at the surface. At this point, the recovery line is slack, and the upper end is tied to a float for easy access to initiate recovery. For drifting deployments, a string of four SWIFTs²⁵ are connected to the upper end of the recovery line, and stretch out down-wind of TigerRAY. For the moored deployment, the upper end of the recovery line is secured to the mast to reduce the potential for tangled lines.

For the moored deployment, the final step is deployment of the three anchors. For each anchor, a small support vessel is used to attach the anchor line (156 m of 5/8" yale lugger line) to TigerRAY. The R/V Robertson then pays out anchor line while maneuvering the target anchor location and lowers the anchor by a crown line. A SWIFT buoy is attached to the crown line after the anchor is fully resting on the seabed. This process is repeated for the remaining anchors.

Recovery generally follows the same procedure in reverse order. R/V Jack Robertson approaches the SWIFTs first for both configurations. Once the SWIFTs and the anchors are recovered, the recovery line is used to partially raise the heave plate and again access to the umbilical junction. Then the heave plate is recovered using the lower umbilical section, and finally TigerRAY is recovered using a pick-point on the top of the nacelle.

Drifting deployments

Drifting deployments with TigerRAY were another critical component of the development process. Because TigerRAY's PTO acts on the reaction force of the heave plate, it can be tested without anchoring the device. Advantages of testing in a drifting configuration include 1) ease of rapid iteration on the device's physical parameters, 2) control over deployment conditions, 3) flexible test location, and 4) reduced permitting requirements.

We tested TigerRAY in a drifting configuration seven times over a two-year period. Data from 2023 drifting tests can be found on DOE's MHKDR²⁶. Drifting tests were conducted mostly on Lake Washington. These tests target weather systems producing wind out of the south, and as such, drifting deployments begin near the southern end of the portion of Lake Washington closest to the University of Washington campus (near the 520 floating bridge, highlighted in pink in Figure 7). After deployment, TigerRAY drifts to the north-northeast, with wave heights tending to increase as it moves into water with larger fetch lengths. Recovery occurs before TigerRAY reaches the northern shoreline. These tests provided valuable data and insight into the factors that impact device performance. Drifting tests in the first year exposed issues with power electronics performance and ballasting, which were key parameters addressed prior to moored deployment. The power electronics issues, and improvements, and highlighted in the PTO improvements section below.

System ballasting was not part of formal test procedures in the first year, but was identified as a critical step for subsequent tests. TigerRAY is specifically sensitive to the nacelle's level of submergence, and during the first year, it was determined that differences between design buoyancy and the actual buoyancy of the float caused the device to sit at an improper waterline when ballasted to its design weight. The original ballast left the nacelle sitting too high, leading to a stiff device with low PTO activation. Figure 4 shows the impact of heave plate weight

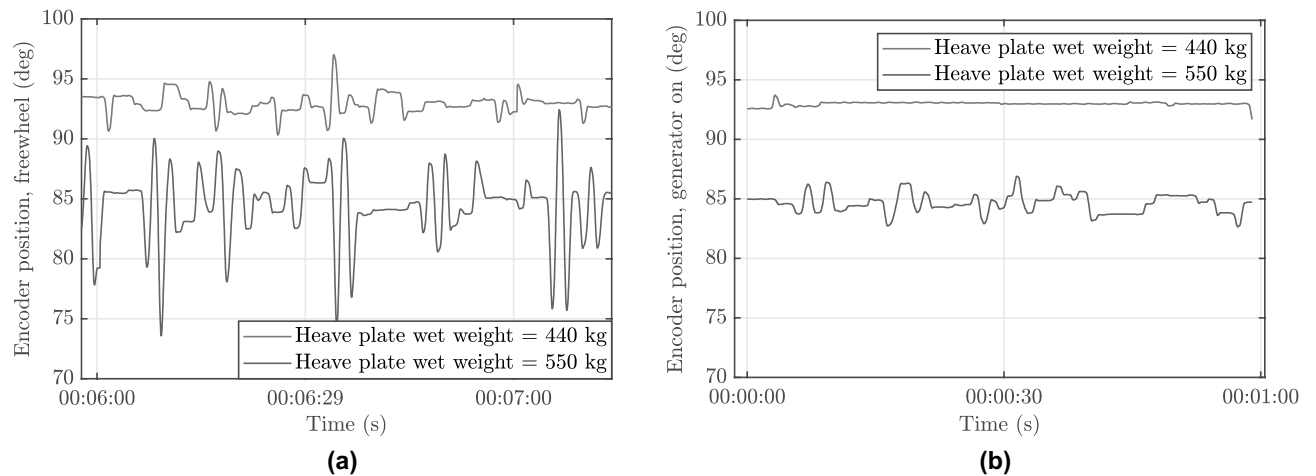


Fig. 4. (a) Comparison of forward float arm angle with the generator in freewheel with two different heave plate weights and (b) comparison of the impact of heave plate weight on arm angle with the generator on.

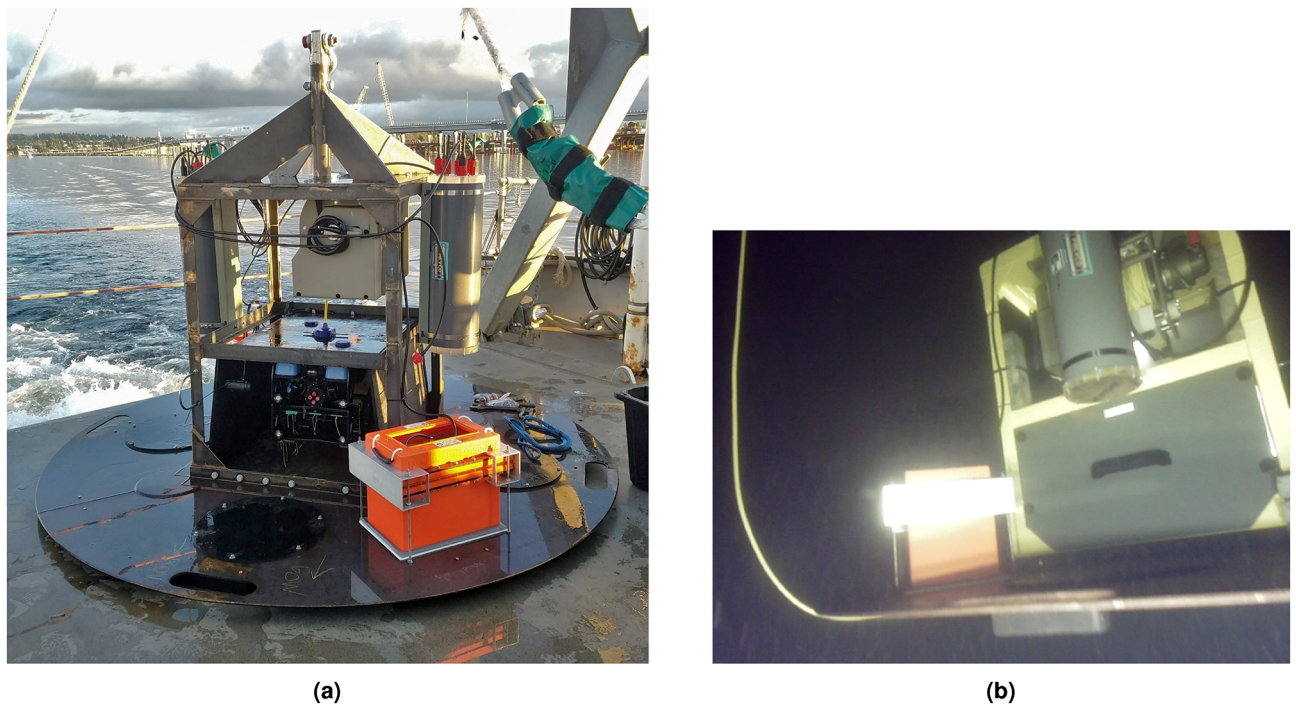


Fig. 5. (a) TigerRAY's heave plate, with a side panel removed to show the ROV parked in the docking area. During operation, the dock is enclosed on all sides, with an opening in the bottom of the heave plate for entry and exit from the dock. Picture taken by Curtis Rusch. (b) An image taken from the BlueROV2 while being remotely piloted around the heave plate during deployment in Lake Washington.

on the performance during drifting tests in 2022. Figure 4a shows testing with the generator in freewheel. With a wet weight of 550 kg, we see a decrease in the average arm angle (a result of the nacelle sitting lower in the water), and an increase in the range of motion of the arm. Figure 4b shows that, for the 440 kg heave plate wet weight, the arm experiences virtually no motion with the generators on. However, with a wet weight of 550 kg, the PTO is actuated with the device in waves. In follow-on tests, a heave plate wet weight of 730 kg is used. This value yields the design waterline. A sticker was added to each end of the nacelle with lines to indicate the desired waterline, and measurements above and below that waterline.

During drifting deployments, we also demonstrated the WEC's ability to act as a host for a remotely operated vehicle (ROV). Shown in Figure 5, the components for docking were housed on the WEC's heave plate. Figure 5a shows the heave plate after a drifting test, with a side panel of the lower docking station removed to show the ROV in the dock. The dock is open to the bottom of the heave plate during deployment. The ROV, a BlueROV2,

is outfitted this a custom 'roof rack' that hosts alignment pins, which contain magnets that help hold the ROV in place when it enters the dock. The submersible winch can also be seen above the ROV docking area in Figure 5a. During deployment, operators can connect to the system via wifi. Through this interface, one operator is able to drive the ROV using a video game controller through its standard piloting software, and a second operator manages the tether by spooling in and out on the winch. Video cameras on the dock and ROV allowed operators to monitor the test. Over the course of the project, we piloted the ROV out of the dock six times, with successful docking after each demonstration. Figure 5b shows an image taken by the ROV of the heave plate during a deployment in Lake Washington.

Moored deployment

The final phase of the project was a moored deployment for 2 months in Lake Washington. The goals were to test the endurance, as well as to enable testing in more energetic waves (which would be dangerous to deploy and recover for drifting tests). Overall, this test was successful, as TigerRAY was operational through every storm that produced waves on the lake during the two month deployment.

Lake Washington wave data

TigerRAY was designed to operate in small, fetch-limited waves on Lake Washington or in Puget Sound. The target conditions are $H_s = 0.5$ m and $T_p = 3.2$ s, chosen based on conditions experienced during testing of an Oscilla Power WEC in 2013²⁷. Lake Washington typically experiences calm conditions throughout the summer, and periods of more energetic conditions in the winter months. Winter months still contain numerous periods of calm conditions. Winds out of the south are associated with the most energetic conditions in this test location. Figure 6 shows the distribution of sea states on Lake Washington. The vast majority of the time, the conditions are calm, but when active, wave heights below 0.5 m, with periods below 3.2 seconds, are common. The majority of the energy occurs for waves with a height between 0.3 and 0.5 m, and periods between 2 and 2.4 seconds.

Moored configuration

The mooring location and orientation are shown in Figure 7. This was designed to maximize the wave height during storms with wind out of the S-SW, which is the predominant wind direction for winter storms in the Seattle area. The portion of Lake Washington shown in the figure below has the longest continuous fetch for SSW winds, which begin to build north of the floating 520 bridge. TigerRAY was oriented with the forward float is perpendicular to the incoming wave direction, and the WEC hangs evenly off of two anchors for wind out of this direction. Each anchor consists of two train wheels stacked on a custom-built wheel stack frame (approximately 800 kg total). The specific locations for the anchors, and TigerRAY, during the moored deployment, can be found in Table 1.

A diagram showing a side view of the moored configuration is shown in Figure 8. The deployment depth is 52 m, and each anchor is connected to TigerRAY and a SWIFT. A more detailed drawing can be seen in Figure 16, in the Appendix.

SWIFTs (Surface Wave Instrument Floats, with Tracking), are buoys developed at UW APL that measure wave heights and report them back to a public server. This allows the team to monitor wave conditions in real-time and access the data for use in post-processing. The crown lines are 44 m of 3/8" amsteel, connected to a 30 kg float, with 21 m of 3/8" amsteel line and 0.25 m 9 mm chain connected to the SWIFT. This yields an approximate watch circle radius of 15 m for the SWIFTs.

Summary of conditions

Deployment of TigerRAY occurred on January 10th, 2024, and recovery occurred on March 5th, 2024. Figure 9 shows the significant wave height measured throughout this deployment window. TigerRAY can generally

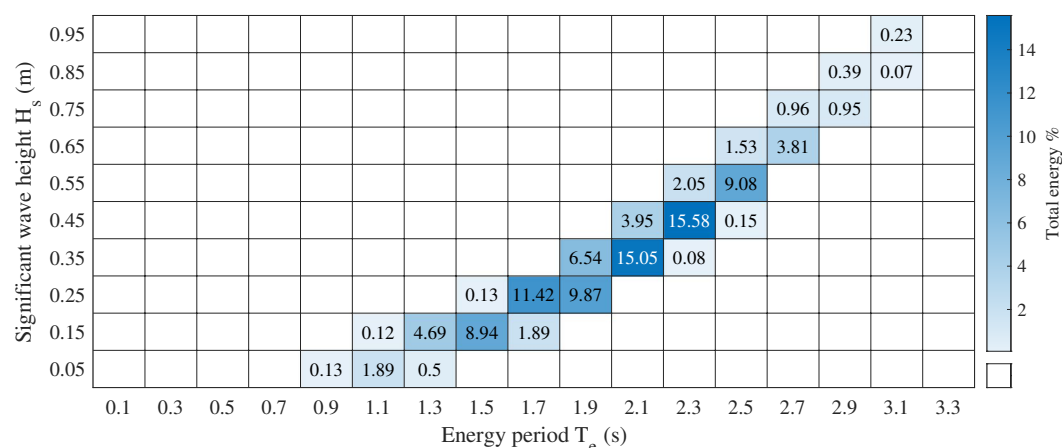


Fig. 6. Lake Washington wave states colored by the percentage of total energy. Figure reproduced from Dallman and Neary, 2014²¹.

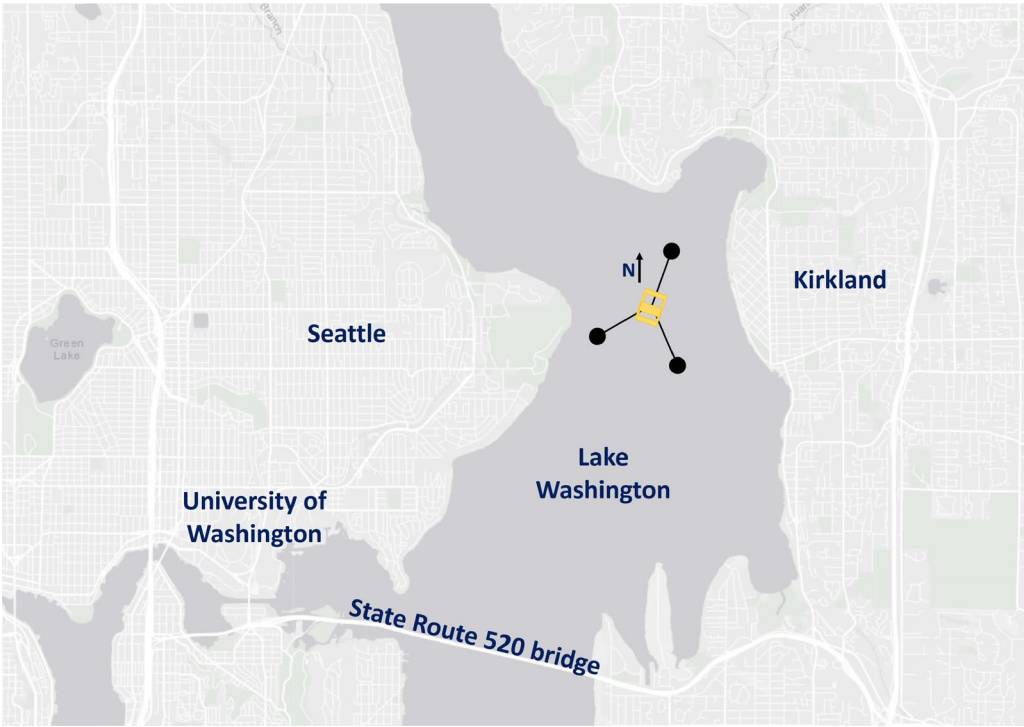


Fig. 7. Location and orientation of TigerRAY in Lake Washington during moored deployment (TigerRAY not to scale).

Object	Latitude	Longitude
TigerRAY	47.67952 N	122.23050 W
N anchor and SWIFT	47.68074 N	122.22990 W
SW anchor and SWIFT	47.67928 N	122.23242 W
SE anchor and SWIFT	47.67849 N	122.22922 W

Table 1. Target locations for moored deployment. Anchors were placed within 5 m of target locations.

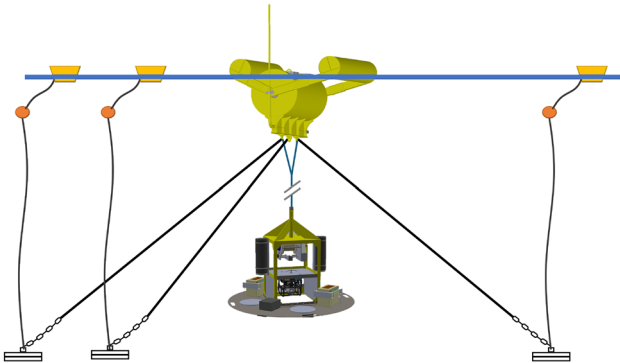


Fig. 8. Side view of TigerRAY moored deployment configuration (not to scale).

output power when significant wave heights exceed 0.3 m, which only occurred twice during the first month of deployment, due to calmer than usual winter weather in the Pacific Northwest. Fortunately, winds picked up during the second month. Table 2 highlights each day in which TigerRAY was turned on, as well as the duration of operation and the conditions on that day. This table includes the date of each data set, the amount of time the device operated for (hours:minutes), the maximum of the five minute average power during that period, maximum significant wave height, and the approximate wave direction. We note that the maximum wave height

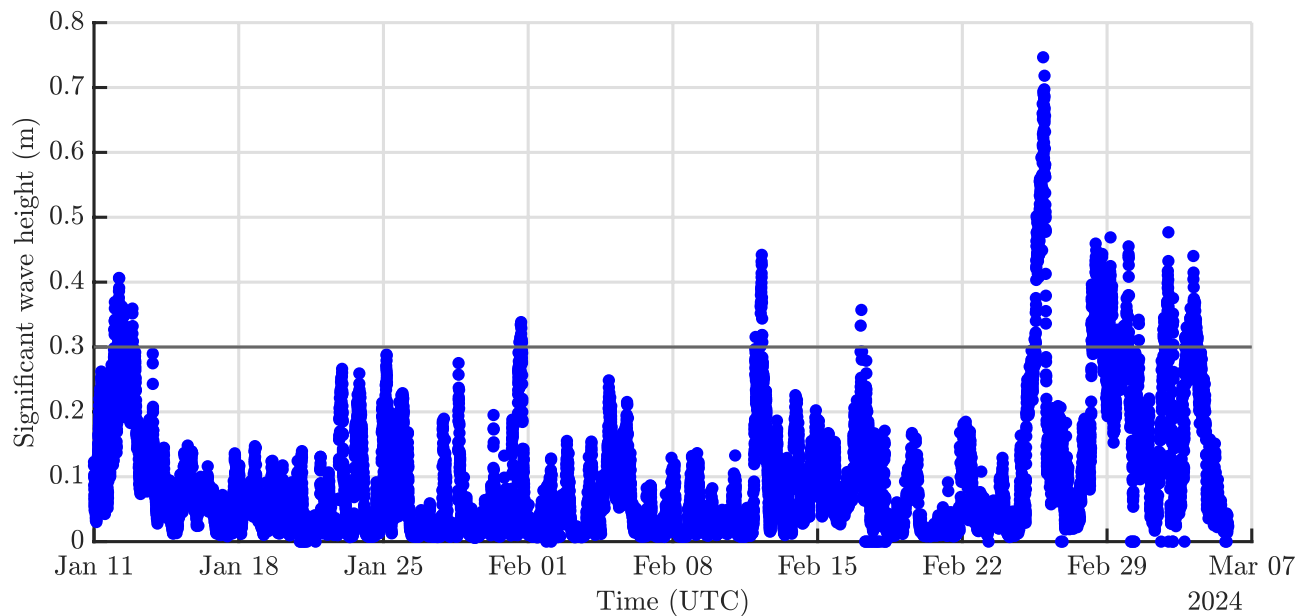


Fig. 9. Significant wave height measured by SWIFT buoys during moored deployment. The horizontal line at 0.3 m is representative of the approximate wave height required to generate power.

Date	Time on	Maximum 5 min. average power	Maximum H_s	Approx. wave direction (degrees clockwise from N)
Jan 10	4:30	0 W	0 m	N/A (deployment day)
Jan 12	1:45	16 W	0.39 m	325°
Jan 13	0:30	0 W	0.26 m	0°
Jan 22	0:30	1 W	0.25 m	190°
Jan 23	1:30	1 W	0.22 m	200°
Jan 24	0:30	<1 W	0.28 m	165°
Jan 25	0:30	<1 W	0.22 m	175°
Jan 31	2:00	8 W	0.34 m	120°
Feb 12	2:00	28 W	0.44 m	200°
Feb 25	10:00	55 W	0.55 m (with both PTOs working)	205°
Feb 28	6:00	24 W	0.5 m	160° → 200°
Feb 29	1:00	3 W	0.31 m (with PTO on)	200°
Mar 2	2:00	22 W	0.43 m	205°
Mar 3	6:00 (~1:30 of down time)	10 W	0.36 m (with PTO on)	210°

Table 2. Overview of data collected during 2024 TigerRAY moored deployment.

exceeded 0.7 m on February 25, but we did not collect power data for waves above 0.55 m on this day due to the failure of the power electronics during this day’s storm. Throughout the deployment, the communications system operated with approximately 100% up-time (we were always able to connect to TigerRAY remotely and turn on or off the PTO). We manually triggered the device on for each storm, and operated successfully for approximately 90% of the possible power-generating time periods. The only downtime that TigerRAY experienced was the end of the February 25 storm, after the failure of the power electronics and before the device was reprogrammed to use its resistors 100% of the time.

Results

Data from the moored testing has been uploaded to the MHKDR, and a data guide has been created to aid in the public usage of this data set²⁸.

In quantifying performance of this WEC, we use the ‘input power’ when calculating TigerRAY’s ‘power output.’ This is calculated using the current and voltage measured at the generator output, so it does not include inefficiencies in the power electronics unit. In general, the power electronics (DC-DC converters) are approximately 90% efficient. Using this definition allows direct comparison of results from data collected

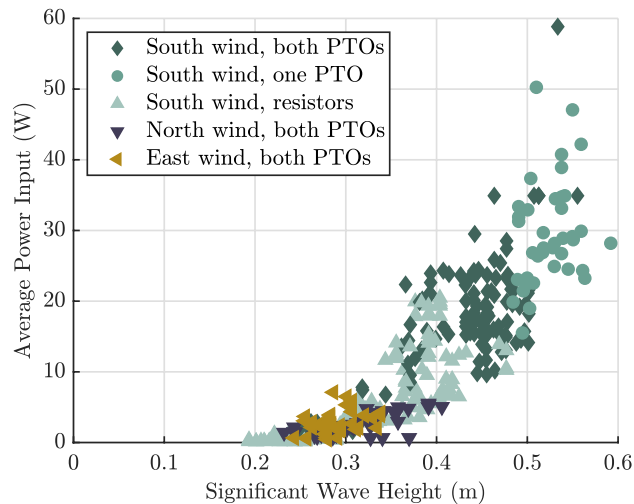


Fig. 10. Average power ‘input’ to the power electronics units as a function of significant wave height.

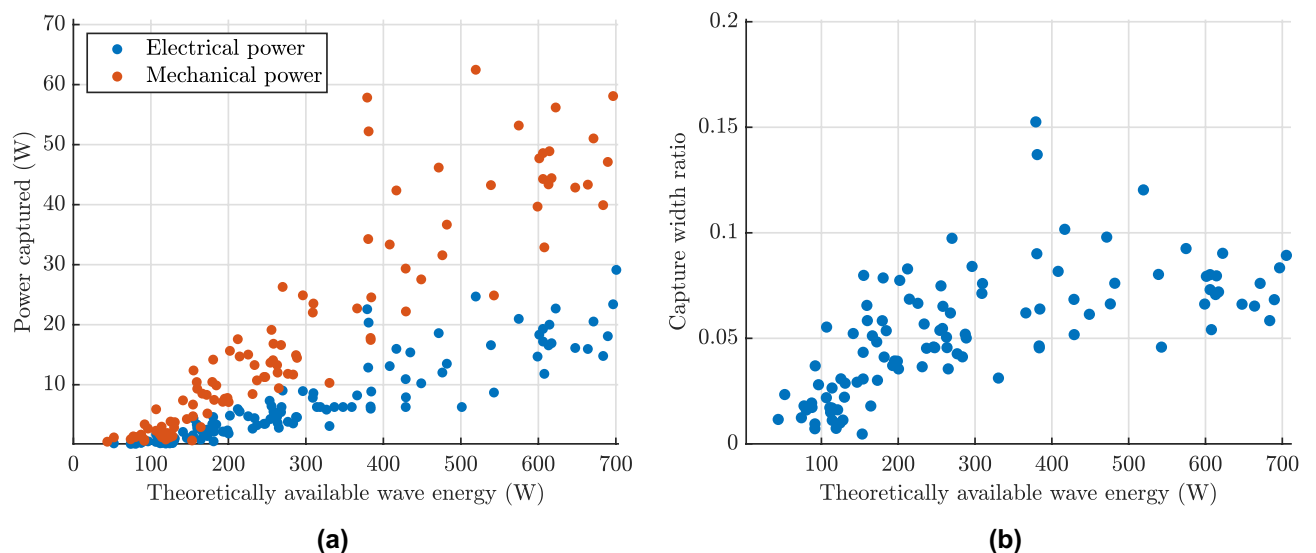


Fig. 11. Comparison of estimated electrical and mechanical power captured by TigerRAY during the moored deployment, and calculated capture width ratio from the moored deployment, both plotted against the theoretically available power. This power is calculated using equation 1, multiplied by the width of the device (3 m).

with operational power electronics and with resistors acting as the load (as necessitated after failure of power electronics in the final weeks of the deployment).

Overall, the power output of TigerRAY was relatively independent of wind direction, as shown in Figure 10. Because TigerRAY is deployed in a 3-point moor for these events, it cannot rotate when the waves come from different directions. As a result, for the north wind event, the waves were hitting TigerRAY on its aft-starboard corner, and for east wind, waves were traveling roughly parallel to the floats, hitting the port side first. For these cases, the balance of power generated by the two PTOs changed, but the overall power output of the device remained a consistent function of wave height. For wind out of the south, where waves directly impact the forward float first, the two PTOs generate roughly the same amount of power. Due to the shorter arm length and lower damping, the fore float rotates at a higher rpm than the aft float. From dynamometer tests, we determined approximate damping values for each PTO that include both electrical damping and frictional losses. For modeling purposes, values of 1801 Nms/rad was used for the aft PTO, and 1455 Nms/rad was used for the forward PTO.

Looking more closely at the power data, Figure 11a shows both the mechanical and electrical power captured by TigerRAY vs. the theoretically available wave power. Mechanical power is calculated as a product of shaft torque and speed. Since TigerRAY does not contain torque cells, we estimate torque from the measured shaft

speed using the torque-speed relationship discussed in the Dynamometer testing section. Electrical power is calculated using current and voltage sensors on cables exiting the generators. For the waves on Lake Washington, The theoretically available wave energy is calculated as

$$P = \frac{1}{64\pi} \rho g^2 H_s^2 T_e. \quad (1)$$

ρ is water density (freshwater, for Lake Washington deployments), g is gravity, H_s is the significant wave height, and T_e is the energy period. The significant wave height and energy period are reported by the SWIFT buoys during deployment²⁵. This equation applies to deep water waves. During this deployment, the maximum peak period is approximately 3 s, yielding a wavelength $L = gT_p^2/2\pi$ of 14.05 m. For the deployment depth of 52 m, these waves are well within the deep water assumption. This yields a power per unit of crest length, which is multiplied by 3 m, the length of the floats upon which this wave energy is incident. Figure 11a shows that power generation scales roughly linearly with available wave power, and that the electrical power is roughly 35–50% of the estimated mechanical power. From this data, we also calculate capture width ratio as $CWR = P_{mech}/(wP)$, where P_{mech} is the calculated mechanical power absorbed by TigerRAY, and w is the width of the device. Figure 11b shows that the CWR plateaus at values between 0.05 and 0.1. This number highlights the difficulty of generating electricity from small waves, and also highlights room for improvement in the technology.

Dynamometer testing is invaluable for determining the sources of inefficiency in the system. During dynamometer testing, a motor is coupled to a drive shaft on the nacelle, which is driven based on expected motion from simulation. Figure 12 shows the electrical power output from the generator compared to the approximate mechanical input to the drive shaft. The electrical output is calculated as the product of the current and voltage measured leaving the generator, and the mechanical input power is calculated as the product of the input shaft speed and torque. This plot shows a roughly linear relationship between input and output power, and indicates that the mechanical system operates with instantaneous efficiencies between 35–50% when driven with motion mimicking the low, fluctuating speeds seen in field testing. This efficiency mirrors what is shown in the field (Figure 11a.) The PTO has higher efficiency when operating at higher, constant speeds (~70% across the speeds we tested). This indicates that some of the system inefficiencies come from the constant acceleration and deceleration and low operating speeds in small wind waves.

Other inefficiencies come from shaft seals, friction and inertia in the gearbox, and the fact that most conditions are far from the generator's optimal operating point. To accommodate potential peak system loads, the generator is over-sized relative to the average conditions. For example, during February 25th data, the drive shaft hit maximum speeds of just under 15 rpm, which translates to 1500 rpm on the generator. Given the torque-speed curves developed on the dynamometer, this would put the maximum torque on the shaft at about 1000 Nm, with the maximum torque on the motor at about 10 Nm. The generator was designed for use up to 94 N-m of torque and speeds of about 9000 rpm. Manufacturer specified efficiencies plateau above 90% for speeds above 800 rpm. This means that typical operating conditions for TigerRAY frequently transit an area with high efficiency falloff. Resizing the generator to a lower operating range could improve the electrical efficiency of the system. Increasing the gear ratio is another potential solution, although it would also decrease torque, leaving the operating region on the edge of steep drop off in efficiency.

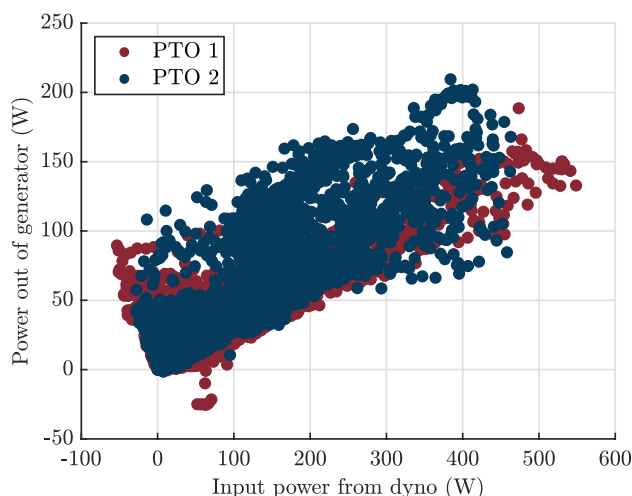


Fig. 12. Relationship between input power from the dynamometer to the drive shaft and output power from the generator, highlighting the losses in the drivetrain.

February 25th storm

The largest storm of the deployment occurred on February 25th, 2024, and generated waves that exceeded a 0.7 m significant wave height. Waves were large enough for operation for about 10 total hours. While a wealth of data was collected, two issues arose during the course of the day: 1) the forward float experienced many instances of 'overtopping', where it flipped up and over the nacelle, spending many hours operating on the aft side of the nacelle, and 2) through the day, the power electronics in both PTOs failed, with the forward float failing about 2 hours prior to the failure of the power electronics unit for the aft float. We address these issues, and what we learned from them, in this section.

Figure 13 shows both issues. First, in the upper panel, there is a sudden drop in output power from the fore float just after 1800 UTC. This was when the power electronics for the forward float failed. Around this time, we also see that there is a sudden discontinuity and change in the mean arm angle. This indicates an overtopping event and these events increased in frequency after the failure of the power electronics, which coincided with the peak of the storm between 2000 and 2200 UTC.

The aft float experienced a sudden increase in output power after the failure of the forward float and continued operating for approximately two more hours, failing just after 20:00 UTC. After failure, no power was generated for the remainder of the storm. In the case of both power electronics units, we determined (after recovery) that the issue was a simple soldered connection that broke off inside each unit. This was likely a result of the 'prototype' nature of the units, and the buildup of heat during this energetic event weakened the connection and led to the disconnect. Fortunately, the system was installed with resistors sized to match the damping of the power electronics, and after this storm, the resistors were reconfigured to provide load to the generator 100% of the time. As such, useful data was generated for the remainder of the storm, but power was not circulated to the batteries from this power, so we had to spend extra time at the WEC recharging the onboard batteries.

Another interesting result from this storm is that the overall power output of the WEC, and the relationship between the output power and the significant wave height (shown in Figure 10), is not affected by the location of the forward float and the failure of one of the power electronics units.

Discussion

The data collected throughout the development and testing of TigerRAY hold a wealth of information about the WEC's performance through a variety of conditions. In this section, we will present additional data that highlight some nuanced observations from field testing.

Figure 14 shows arm angle data from the February 25 storm in two different ways. First, Figure 14a shows that the forward float experienced a slightly larger range of motion compared to the aft float, with the difference increasing with significant wave height. This is likely related to its shorter arm length, which requires larger rotations to move the same vertical distance when compared to the longer arm attached to the aft float. Also, at about 0.5 m, we see a sudden change in behavior. Above this threshold, the forward float experienced 'overtopping', where it rotated up and over the nacelle multiple times, generating values near 180 degrees. This data generally follows a Rayleigh distribution, as observed in Figure 14b. Of note, during 'normal' operating conditions, the average angle for the forward float should be around 70 - 80 degrees. This highlights that, for the majority of the storm on February 25, the forward float was in the overtopped position. These float angles did not

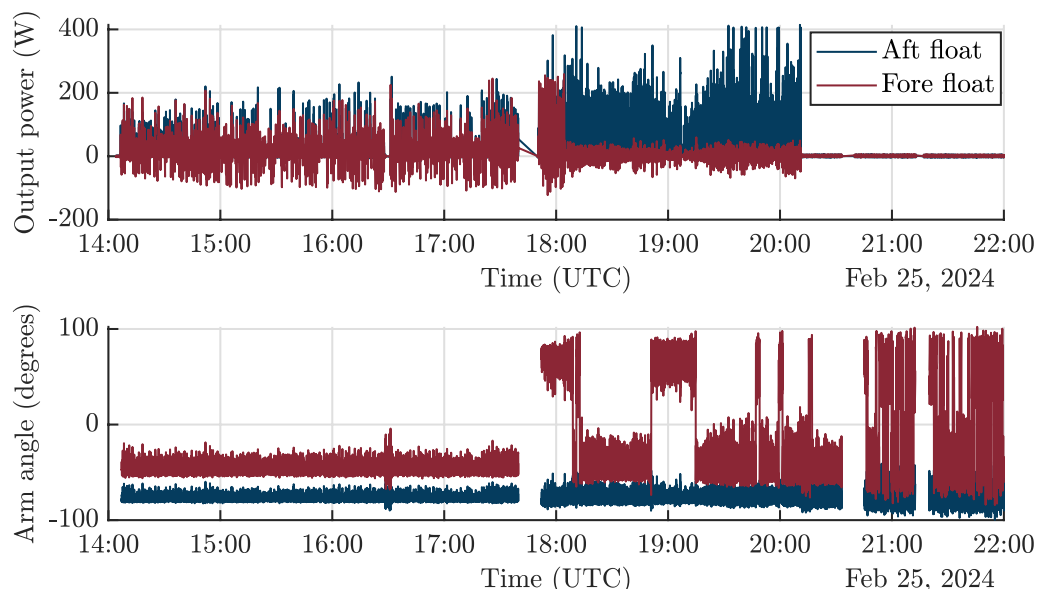


Figure 13. Forward and aft power and position over the course of the February 25th storm. This highlights the failure of the forward power electronics (just after 1800 UTC), the failure of the aft power electronics (just after 2000 UTC), and the overtopping response shown by the forward float throughout the storm. The WEC begins the day in the 'overtopped' position (forward float should be near 80 degrees when on the correct side).

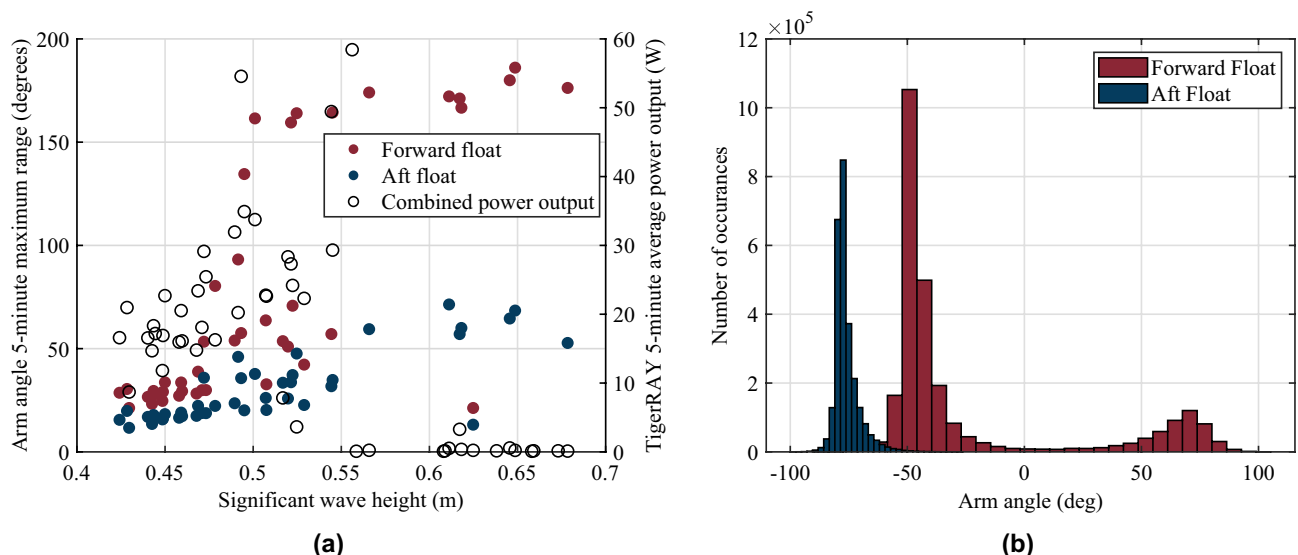


Fig. 14. (a) Maximum 5-minute range of arm angles as a function of significant wave height, plotted with the 5-minute average power output of TigerRAY and (b) histogram of arm angle values during testing on February 25.

show any relationship with wave steepness. In Figure 14a we can also see that the highest range, occurring during the highest sea states, is correlated with periods of zero power output. This is a result of the failure of the power electronics during this storm, allowing the generators to freewheel, and enabling larger arm motion.

Looking at PTO data from across all three years of field testing highlights other important takeaways. As described in the dynamometer testing section, improvement of the PTO and power electronics was a key focus of much of the development of TigerRAY between 2022 and 2024. The power electronics units were custom made by Vicor Power for CPower and delivered to UW APL for installation in TigerRAY. While dynamometer testing is key to optimizing control signals and damping being implemented, dynamometer testing cannot perfectly represent how a device will react in the water.

In the 2022 drifting tests, the power electronics units drew an inrush current from the generator during start up. Figure 15a shows the impact of this in the field in 2022. The inrush current leads to a sudden increase in generator resistance, and as a result, for conditions with marginal float motion, this increased resistance slows the drive shaft down to a speed below cut-in, thus turning off the power electronics. This feedback is not something that we could easily replicate in lab testing, since the dynamometer uses velocity control, and can instantaneously increase its applied torque to motor past these instances of startup. This response was exacerbated by improper ballasting, which yielded lower than expected float motion. The case highlighted in Figure 15a is the only wave in which the system produced power during 2022 drifting sea trials.

Improvements in 2023 focused on properly ballasting the WEC, integration of a smaller power electronics unit to help generate power at high efficiency up to about 35 V, and rewiring the main power electronics unit to draw from the output supercapacitor during startup. This eliminated the issue of increased resistance in the generator during startup events, yielding a smooth shaft speed profile, as shown in Figure 15b. What this did not fix, however, is the overall power budget of the system. The larger power electronics unit drew about 30 W when turned on, which means that the system was consuming more energy than it was producing for much of the deployment.

Work in 2024 focused on improving the efficiency of the power electronics unit. As shown in Figure 15c, this improvement was largely successful, with units producing power across a wide range of conditions at $> 90\%$ efficiency. The 'catch' is that these units need to be shut down when input voltages exceed 145 V. When the power electronics units shut down, the generators enter a freewheel state, which is not ideal when the floats are rotating at high speeds. To address this issue, we installed resistors and relays to allow the generator load to be transferred to the resistors in times when the power electronics shut down. The resistors are sized so that their damping profile approximately matches that of each power electronics side, allowing a smooth transfer of load during over-voltage events. These resistors proved extremely useful for data generation, since the power electronics units malfunctioned during the February 25th storm. We were able to permanently flip the relays to allow the resistors to load the generators for all operational voltages, thus still producing electricity from the generator and valuable data.

The success of this project would not have been possible without the dynamometer testing we conducted prior to each year of field testing. Dynamometer testing, where the PTO of the system is directly connected to a motor and driven at different speeds and accelerations, provided an opportunity to debug the PTO prior to field testing, increasing the success of each year's field testing. In multiple instances, we not only used dynamometer testing to adjust the software and tune the controls to yield the desired damping values, but we also ordered and installed new hardware in the system to smooth the electrical signal entering the power electronics and

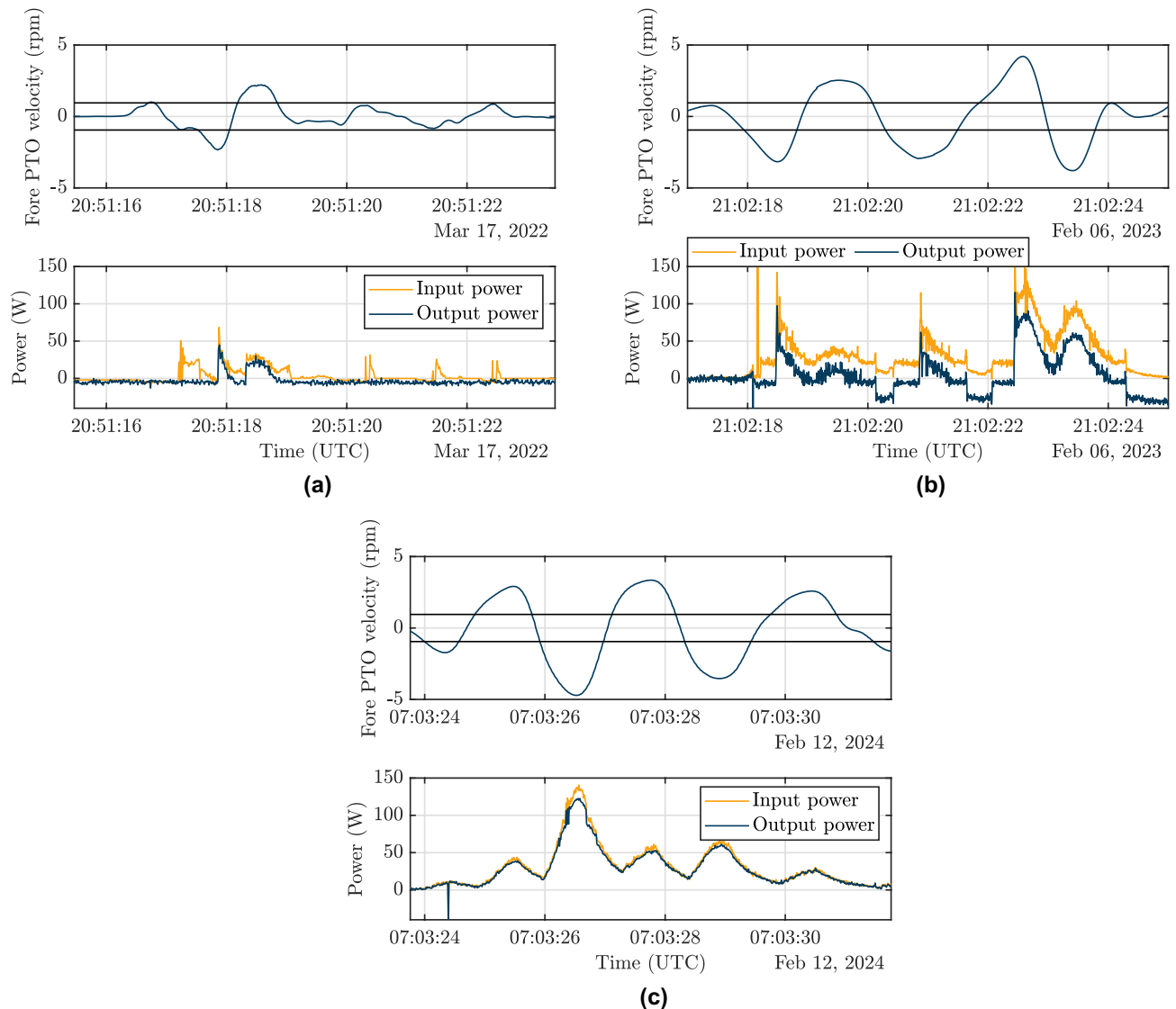


Fig. 15. Comparison of PTO performance during field testing in similar conditions from (a) 2022, (b) 2023, and (c) 2024. This highlights the improvements made to the PTO throughout testing.

isolate the generator from inrush current. Allowing at least 2 months of dynamometer testing prior to a field deployment enabled these changes to be made in a measured and well-thought-out manner. We found that running test with constant speed, sinusoidal oscillations, and irregular oscillations, in both freewheel and with the PTO on, allowed us to thoroughly characterize PTO response. Further details on dynamometer testing for TigerRAY can be found in a Rusch et al. conference proceeding²².

Conclusions

There were four major conclusions that we drew from this project related to WEC development - 1) dynamometer testing is a critical step in WEC development, 2) power electronics are critical not only to the electrical output of the system, but the dynamics of the full WEC, and 3) ballasting and waterline testing is a crucial and often overlooked part of testing, and 4) docking an ROV with a wave energy converter for recharge is feasible.

Dynamometer testing enabled far more progress in the development of TigerRAY than would be possible through field testing alone. Through dynamometer testing, we were able to test hardware and software performance and test changes in a controlled environment. We were also able to characterize the torque-speed relationship for both PTOs, and measure the friction and inertia contributing to PTO dynamics.

Coupling dynamometer testing with field testing was critical to understanding the performance of the system when power electronics impact device dynamics. We saw that high inrush current from the generator this significantly reduced float motion, and as a result, also reduced the power output. Power electronics improvements were the primary changes to the system after the first year of testing, and these changes led to net positive power production.

We also show that ballasting is a critical component of field testing. While hydrostatics are fairly straightforward, differences between CAD models and a manufactured device can yield meaningful changes in the required ballast. For a device that is sensitive to waterline like TigerRAY, proper ballasting is crucial.

Finally, this project acted as a field demonstration for a coupled WEC-UUV system. We demonstrated an architecture that utilizes the heave plate to support a winch and dock for ROV operation. We demonstrated remote docking the ROV in the heave plate, with a successful docking in all six demonstrations. With power from the waves, a WEC-UUV system could support resident underwater robots. There were many mechanical and electrical design challenges that were overcome to make this demonstration a success.

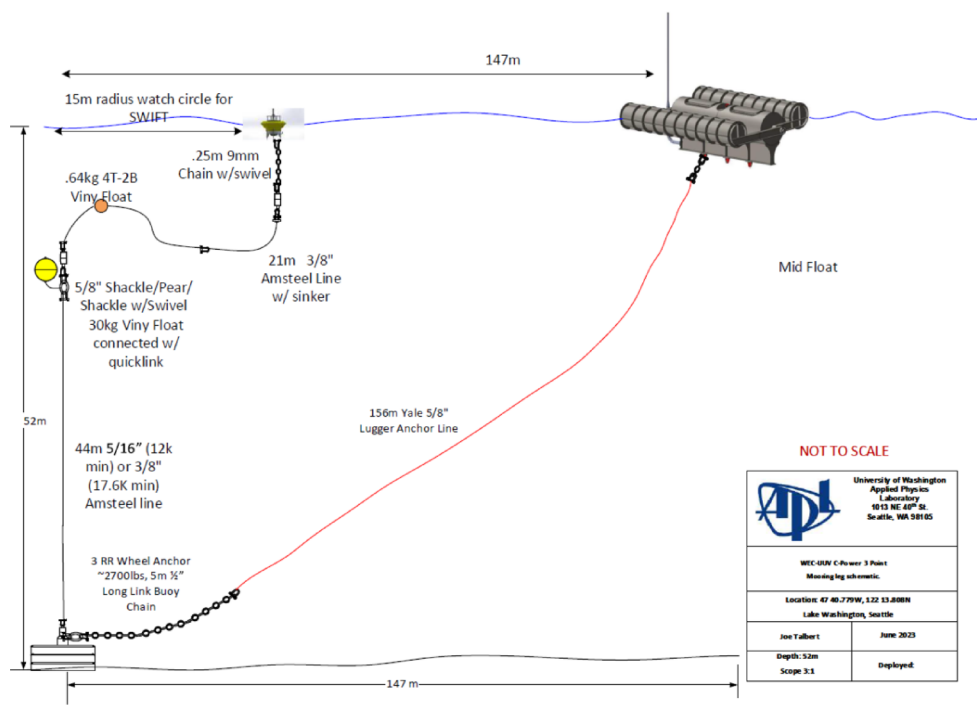
Overall, this project highlights successes and challenges present in wave energy. This project has specifically illuminated the need for increased work on power electronics tailor-made for wave energy applications. As we have shown, a hydrodynamically well designed WEC may not perform as expected without properly designed power electronics. For a small wave energy converter generating 10's to 100's of Watts, power electronics performance through low voltage regions can be particularly impactful. Performance in the low-voltage region may be overlooked for grid-scale devices operating at higher voltages. Further WEC development, particularly at small scales, should consider power electronics early in the design process.

Data availability

The data presented in this study can be found in the Department of Energy's Marine and Hydrokinetic Data Repository (MHKDR), at <https://mhkdr.openei.org/submissions/614> and <https://mhkdr.openei.org/submissions/625>

Appendix

Fig. 16. Drawing of mooring and anchor for one leg of the three-legged mooring. NOTE: A 2 railroad wheel stack was used for the anchors, rather than the 3 railroad wheel stack shown in the drawing.



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Author contributions

J.T. and E.H. conceived the project, all authors contributed to system design, Z.Z. developed numerical models of the system, C.R. and J.T. conducted field testing and led data acquisition and analysis, all authors contributed to data interpretation. C.R. drafted the manuscript and prepared the figures. All authors reviewed the manuscript.

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Declarations

Competing interests

E.H., J.P., and Z.Z. are employees of C-Power, a for-profit company that develops wave energy converters, and the TigerRAY floating body is a C-Power product.

Additional information

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