Listening to the Beat of New Ocean Technologies for Harvesting Marine Energy

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When we hear about offshore energy in the news media and other popular information sources, images of oil platforms and, more recently, wind farms flash across our screens. However, there is a new, rarely known sector of offshore energy under development that is focused on harnessing the renewable power contained in ocean waves and currents and converting it to electricity. These new technologies termed marine energy converters (MECs) are the topic of this article. They not only have the potential to make a significant contribution to our energy needs but may also generate new sources of anthropogenic sounds in the oceans that require measurement and characterization to ensure that there are no harmful effects to marine life.

Although many of these new technologies produce sound during their operations, making actual acoustic measurements of these devices in the high-energy ocean waves and tidal currents necessary for generating meaningful amounts of electrical power is anything but trivial. This type of energy conversion, known as marine energy, is an emerging renewable resource that is now in its testing and development phase. Because MECs contain multiple moving parts as well as electrical generation equipment, they can produce underwater noise audible to marine life, such as the whales, fishes, and sea turtles commonly observed around marine energy sites. Therefore, the sounds generated by these new technologies are of high interest to researchers, regulators, and industry developers. Whenever a new MEC is installed for testing, researchers deploy hydrophones to understand the characteristics of the sounds it generates. In turn, they inform regulators about what to expect from these new technologies while helping the technology developers understand what they might do to make them quieter during their next round of testing. However, placing a hydrophone in a tidal stream or near a surf zone is not only logistically challenging for the safe deployment, recovery, and survivability of the sensors but is often equally as tough for the scientists and engineers making those measurements in the pitching and rolling waves and strong currents.

Marine Energy: The Next Frontier of Renewable Energy

Globally, offshore renewable energy research is an emerging contributor to a more diversified and sustainable energy portfolio that can meet collective climate goals. Although land-based renewable energy solutions like solar and wind have gained momentum for decades and offshore wind has recently begun to be deployed at large scale, the lesser known sector of ocean energy technologies, collectively known as "marine energy," also has a significant potential to contribute. MECs come in many shapes and sizes and are used to harness the powerful movement of waves and currents to generate electricity. Private companies and research institutions have developed many innovative designs for capturing these renewable resources, which range from turbines spinning in tidal currents to bobbing, tethered buoys that capture and convert the mechanical energy from the rise and fall of surface waves. Yet, the diversity of MEC designs has raised permitting and regulatory stakeholder concerns about the potential environmental impacts of introducing these novel devices into marine ecosystems. Reducing the knowledge gap regarding sounds produced by MECs and the potential biological impacts remains a priority.

In this article, we introduce a range of MEC technologies, share the current state of knowledge around MEC sound emissions, and describe some of the tools that have been

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developed for the acoustic characterization of MECs with a look toward the future.

New Technologies, New Uncertainties

According to a recent study by the National Renewable Energy Laboratory, Golden, Colorado (see nrel.gov), "utilizing just one-tenth of the technically available marine energy resources in the 50 states would equate to 5.7% of our nation's current electricity generation, enough energy to power 22 million homes" (Kilcher et al., 2021). Although it may seem implausible for these technologies to contribute to electricity generation away from the coasts, underwater turbines similar to those used to harness the power of tidal currents can operate in rivers and constructed channels (e.g., irrigation systems).

Although relatively nascent when compared with established renewables like wind and solar, the adolescent marine energy industry is evolving and expanding rapidly. However, it remains some distance from coalescing on a single set of basic designs that are the most effective and economical. For example, although terrestrial and offshore wind projects ubiquitously employ three-bladed, horizontal-axis turbine designs, horizontal-axis tidal turbines employ a range of blade counts. Some turbines rotate on a different axis or depart entirely from wind, employing oscillating foils or "kites." For now, developers conceive, design, build, and test a wide range of progressive technologies for electricity production in a range of coastal and riverine environments from remote waterways to highly urbanized estuaries.

Although much of the emphasis in the industry has focused on relatively large, commercial-scale power generation, there is also a broad interest in the development of small-scale devices to power maritime operations, industries, and research applications that can take advantage of the greater availability of electrical power at sea (Geerlofs, 2021). Regardless of scale, the marine energy industry has significant potential to make meaningful contributions toward clean energy goals and coastal and maritime markets (Copping et al., 2020).

Meanwhile, consideration and mitigation of the potential environmental risks associated with the transition to renewable energy resources is also critical for the success of the marine energy industry. Given the youthful state of the marine energy sector, reducing carbon emissions and driving down energy costs are key factors for technology development, but ensuring a "do no harm" approach is also an important priority.

Marine Energy Converters 101

Wave, tidal, and current energy converters may operate differently from one another, but all translate the kinetic and/or potential energy associated with water motion to the mechanical motion of MEC components and ultimately to electrical power. As these devices operate, several systems components including generators, gearboxes, structure components, and supporting infrastructure like chains and anchors may produce sound (Polagye, 2017).

The marine energy industry has many players at different stages of technological development. As acousticians, our role in this emerging industry is to perform high-quality measurements of sound radiated from devices and to minimize the incorrect attribution of confounding sounds in the environment to the devices. Our collective experience is that this is often more difficult than one might anticipate and that doing so requires establishing reasonable a priori expectations for what sounds the MECs might produce. This also requires some background in the design and operation of the devices. We now provide some background to familiarize the reader with the operating principles and basic device designs that provide context for the types of sounds that MECs produce.

Wave Energy

Wave energy converters (WECs) transform the potential and kinetic energy of waves into electrical power through a variety of approaches. Some device developers focus on deeper water (>50 m) for their WECs to take advantage of the more intense wave energy resources in open water environments. Other designs target relatively shallow areas to capture the energy from shoaling waves that are slowed, shortened, and steepened as they approach the coastline and interact with the seafloor (**Figure 1**). In both cases, although we often conceive of waves as a periodic rise and fall of the water surface, this is only, on average, half of the energy contained in wave motion. The other half is kinetic energy in rotating "wave orbitals" that are strongest near the sea surface and decrease exponentially with depth. Although waves can be generated by wind shear across any body of water, consistently

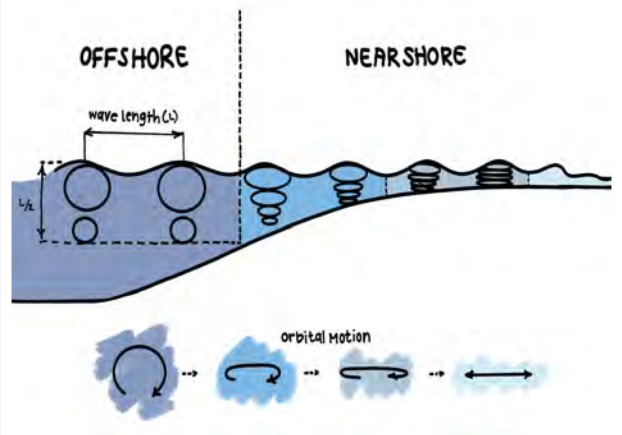


Figure 1. *Ocean waves propagating toward shore interact with the seafloor and change shape, becoming steeper and shorter. The orbital motion of the wave energy is altered from circular in deep water to largely horizontal as the depth becomes shallower.*

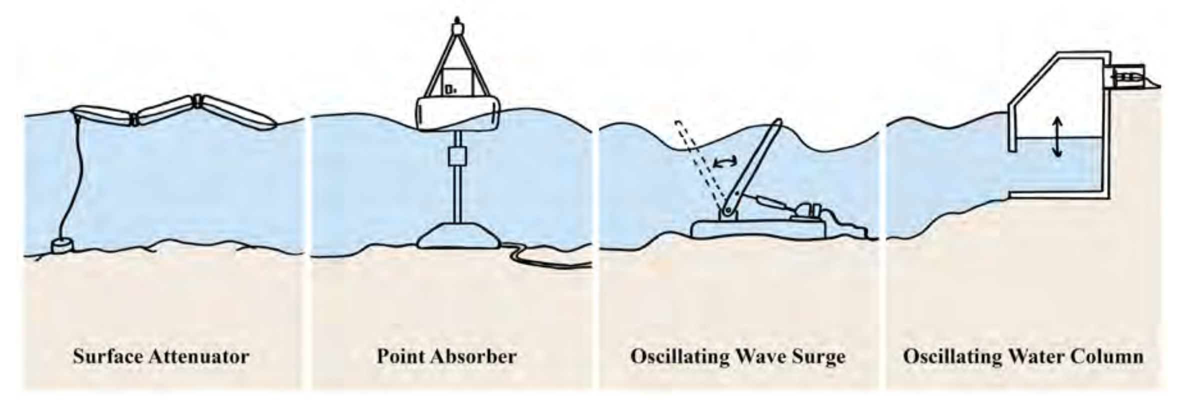
energetic waves occur primarily on coasts adjacent to the oceans. However, the same water motion that is desirable for energy conversion poses a unique challenge for acousticians.

There are several categories of WECs (shown in **Figure 2**) that capitalize on wave motion. These include but are not limited to:

- *Surface Attenuators*. These are snakelike devices with multiple segments connected to one another and positioned parallel to incoming waves. As the attenuator segments move with the waves, generators capture the flexing motion between segments and convert this into a rotation that drives generators (for a video, see bit.ly/wave-attenuator).
- *Point Absorbers*. These consist of buoys that oscillate, usually in the vertical direction, from passing waves and generate power from the force differential between a buoy and a reaction surface like the seafloor (for a video, see bit.ly/point-absorber).
- *Oscillating Wave Surge*. This typically has one end fixed to the seabed or a substructure, whereas the other end can move freely like a paddle or arm perpendicular to the base. The movement of the arm around the pivot point drives a generator (for a video, see bit.ly/oscillating-wave-surge).
- *Oscillating Water Column*. This device consists of a hollow structure open to the sea below the water line and enclosing a column of air on top of a column of water. It takes advantage of the rise and fall of waves to pressurize the column of air and force it through an in-air turbine on the surface. The turbine is usually bidirectional; as waves undulate, the air is pushed or pulled through the turbine. Because the power generation components of this type of WEC are above the water surface, this type of design has more concern for noise emissions in air, whereas the other devices generate more sounds underwater. (for a video, see bit.ly/oscillating-wave-column).

Sounds from WECs most likely originate from the mechanical or hydraulic components of a device that are often housed within a hollow-shelled structure on the water surface that oscillates with the waves. Coupling of these components with the structure can result

Figure 2. *Four common types of wave energy converters (WECs) that include (**left to right**) a surface attenuator, point absorber, oscillating wave surge, and oscillating water column.*



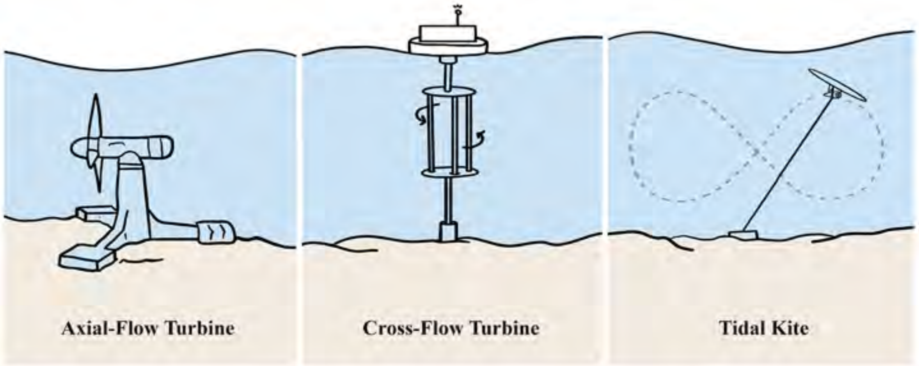


Figure 3. *Three common types of current energy converters (CECs) that include (**left to right**) an axial flow turbine, cross-flow turbine, and tidal kite (**dashed line** shows the path of the device).*

in vibrations and ultimately acoustic emissions into the water column. Hydraulic and electrical generation systems involve rotating components such as gearboxes, pumps, and generators, all capable of producing sounds. Additionally, the electronics used to smooth and regulate electrical power for end use may emit discrete tones and the mooring system used to keep the WEC in place can also produce significant sounds.

Current Energy

Ocean tides are one of the most consistent and predictable natural phenomena resulting from the gravitational pull of the sun and moon on the Earth's oceans. Coastal features such as inlets and passages between islands often constrict water flow and increase current speeds. Current energy converters (CECs) include relatively familiar turbine designs derived from wind as well as a few more novel approaches described in this section.

In addition to tidal currents, there is significant renewable energy potential associated with riverine and major open ocean currents like the Gulf Stream in the Atlantic Ocean or the Kuroshio Current in the Pacific. Although the specifics of the environment in which a current energy converter is deployed dictate some aspects of design, the operating principles are generally the same.

CECs come in a variety of shapes and scales (shown in **Figure 3**) and can be installed as a single device or in arrays. Although water currents are much slower than wind, the thousandfold difference between the density of water and air enables a current turbine with an equivalent power rating to a wind turbine to have a much smaller spatial footprint. Here, we describe a few of the most common types of tidal energy devices.

- *Axial Flow Turbines.* These are functionally similar to commercial wind turbines. They are typically two- or three-bladed, horizontally oriented turbines that face the direction of flow and spin as water moves past (for a video, see bit.ly/axial-flow-turbine).
- *Cross-Flow Turbines*. These might be thought of as similar in design to a kitchen mixer in which multiple blades rotate around a center axis oriented perpendicular to the incoming flow. The advantages of this technology allow the blades to spin and produce power in either direction efficiently, reducing the need for active control mechanisms. These systems can be deployed at the surface from a fixed structure, platform, or barge as well as mounted to the seafloor (for a video, see bit.ly/cross-flow-turbine).
- *Tidal Kite.* This is composed of a hydrodynamic wing equipped with a turbine that is tethered by a cable to the seafloor. Much like how a toy kite moves through the air on a windy day, the wing of the tidal kite leverages the flow of water to lift the wing, causing the device to "fly," looping through the water column as the wing encounters currents (for a video, see bit.ly/tidal-kite).

CECs are subject to relatively high mechanical loads and turbulence that results in blade and system vibrations and measurable acoustic emissions. River and ocean currents can be stable over multiday periods, but tidal currents rise and fall on a roughly six-hour cycle. Because of this, the radiated noise from CECs in river and ocean settings can be relatively consistent over a longer time period, whereas noise from CECs in tidal channels can change over a period of minutes. Like WECs, other components in the CEC power conversion chain, including bearings, generators, and power electronics, may generate underwater sounds.

Sounds Effects from Marine Energy Converters

The range of device types in combination with a limited number of MEC deployments, has resulted in significant uncertainties around how the introduction of these devices may impact marine ecosystems and wildlife. Audition is the primary sensory modality for many marine species. Marine mammals, invertebrates, and fishes use acoustic signals in the ocean for a host of life functions such as communication, navigation, reproduction, and foraging (Erbe et al., 2019; Popper and Hawkins, 2021). Understanding the effects of anthropogenic contributions to ocean soundscapes is key for assessing ecosystem health (Merchant et al., 2022). A common concern raised in relation to marine energy technologies is the sound radiated by devices during operation, construction, and maintenance and what the broader impacts of this sound will be on the local environment. Fortunately, common sources of underwater sounds, from animal vocalizations to physical processes and anthropogenic noise, have been researched extensively (e.g., Hildebrand, 2009). These studies provide a valuable context that researchers can use in considering the potential impacts from the introduction of new anthropogenic noise sources when they are coupled with knowledge related to auditory capabilities and animal behavior.

Addressing Gaps in Technology and Data

To date, the lack of published measurements of the sound produced by MECs have sometimes delayed the permitting process and increased costs for open water testing and demonstration, slowing the development of MEC technology. Because of this, the International Energy Agency's Ocean Energy Systems (IEA-OES) environmental group (see tinyurl.com/3aufct2z) has produced a series of comprehensive reports on the "state of science" about environmental effects from MECs, including underwater noise (Copping et al., 2016; Copping and Hemery, 2020). In addition, national governments have made investments to ensure that technology for measuring known stressors, including but not limited to sound, are available for monitoring around MECs as the pace of deployments increases (Chang et al., 2021).

To those familiar with oceanographic and acoustic sampling, the inherent challenges of deploying costly equipment and collecting measurements in environments with strong currents (e.g., >3 m/s) or energetic wave climates may be familiar. The conditions where MECs are sited for deployment are often dynamic and unforgiving. The challenges of working in these environments have necessitated the development of dependable and effective equipment and sampling for obtaining reliable measurements across a diversity of sites and device types.

Understanding the Effects on Animals

Often the most suitable and valuable places to install MECs are also some of the noisiest. These devices enter a soundscape teeming with activity: shipping vessels, breaking waves, chattering animals, storms, and the sounds from sediment and cobblestones shifting on the seabed. Distinguishing operational MEC signals from other nearby sources in elevated ambient conditions is no easy task. Thus, along with characterizing sound emissions from MEC systems, efforts to research the frequencies and levels of the sound emitted from MECs and determining if device-generated signals overlap with frequencies used by sensitive marine species are under investigation. The duration or exposure of MEC-associated sound levels and how they impact the behavior of marine cohabitants are all being evaluated in the effort to better understand and quantify the possible environmental impacts of these devices and address data gaps (Copping and Hemery, 2020).

Unlike offshore wind farms in "shallow" water (up to 30 m depth), MECs are rarely installed with pile driving, and therefore device installation activities are usually short lived and produce lower intensity sound. The primary acoustic concern for regulators therefore involves sound generated during the long-term operations. So far, there is no evidence showing sounds produced by individual MECs could cause auditory injury to marine animals, although there have been very few studies on a limited number of species (Tougaard, 2015). Rather, the results from acoustic studies of MECs summarized in Copping et al. (2016) and updated in Copping and

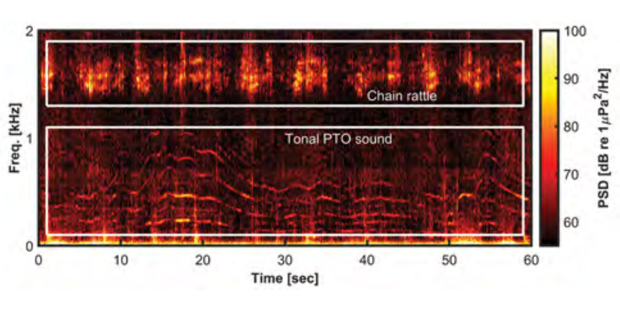


Figure 4. *Power spectral densities (PSDs; dB re 1* μPa^2Hz^{-1}*) from recordings of a WEC off the coast of Oahu, Hawai'i, showing tonal sounds and harmonics from the power take off (PTO) generator (**bottom**) as well as chain rattle (**top**) from the mooring (from Polagye and Murphy, 2019). At the time of the measurements, the significant wave height and energy period were approximately 4 m and 12.6 s, respectively. The hydrophone was deployed on the seafloor approximately 100 m from the WEC.*

Hemery (2020) indicate that sounds radiated by operational devices could potentially influence behavior or physiological stress responses in various animals.

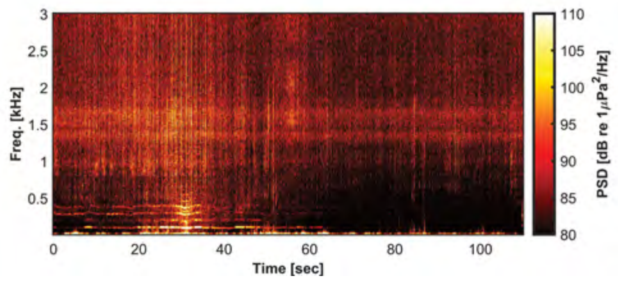
However, the available published measurements are relatively limited in scope (Walsh et al., 2017) and do not cover the great diversity of designs and scales of existing as well as anticipated MECs. The uncertainties around possible acoustic impacts can only be addressed through further study. Moreover, although most of the attention around underwater noise from MECs has focused on marine mammals, Popper et al., (2023) introduce the potential and importance of acoustic particle motion disturbance from MECs as a key measure for the effects on fish and invertebrates. This work further identified gaps in understanding around the effects of MEC sounds from the animals' perspective (Popper et al., 2020), inspired new questions for research, and highlighted areas of concern for the regulatory community.

What We Know About Energy Marine Converter Sounds

WEC sound characterization studies are limited due to a small number of global device deployments where acoustic measurements during operations were prioritized and reported. Thus far, because of technological limitations, many WEC studies have characterized the devices as part of the collective soundscape rather than isolating the sound emissions from the device compared with the ambient environment. Additionally, most of these deployments and recordings are from point absorber devices (**Figure 2**), leaving other archetypes uncertain. Moored hydrophone and drifting hydrophone systems have been used to measure sound at fixed and dynamic ranges from WECs with acoustic data collected from both the seafloor and near the surface. WEC-generated sounds have mostly been observed as low-frequency (<1,000-Hz) pulses and tones that vary in amplitude with passing waves and changing wave conditions (**Figure 4**) and are attributed to the power generation components of the device (Bassett et al., 2011; Lepper and Robinson, 2016). Direct comparisons of WEC-generated sounds have been difficult thus far due to the lack of measurement standardization, but, generally, sound pressure levels integrated over several tens of kilohertz measured at distances ≥100 m from a WEC have been below auditory threshold levels for marine mammal species such as harbor seals (*Phoca vitulina*) and harbor porpoise (*Phocoena phocoena*) (Tougaard, 2015). Other sounds like mooring chains and hull slap have also been observed during WEC acoustic studies, but these signals are not unique to MECs and are found across maritime industries and recreational activities.

Research characterizing sounds from CECs such as tidal turbines have largely been focused in waters near the United Kingdom, with a few exceptions of turbine

Figure 5. *PSDs (dB re 1* μPa^2Hz^{-1}*) recorded by a drifting hydrophone near an operational cross-flow turbine in Alaska. Note the tones and harmonics correlated with turbine rotation rate and power output (from Polagye and Murphy, 2015). The closest point of approach to the turbine (a direct pass over the top) occurs at around 30 s into the drift.*



deployments in areas of the northeast United States and Canada. One of the technical challenges at these sites has to do with signal contamination from flow noise or pseudosound caused by the flow of water past a hydrophone (e.g., Bassett at al., 2014) that is similar to the sound you hear while trying to talk on a phone on a blustery day. As a result, drifting hydrophones have emerged as the preferred technology for measuring CEC sounds in high-energy currents because of their effectiveness at reducing flow noise.

Like WECs, CECs produce mostly low-frequency (<1,000-Hz) sounds that vary in amplitude with the rotor speed and turbine rotation rate (Risch et al., 2020). In some cases, turbine sounds are tonal, with signals attributed to components of the power electronics (**Figure 5**), whereas other signals have been found to vary with turbine rotation rate. Like WECs, single turbine sound measurements to date have not raised significant concerns for exceeding regulatory thresholds (Lossent et al., 2018), and in some cases are indistinguishable within background levels (Haxel et al., 2022), good news for the industry and for marine life.

Acoustic Technology Research and Development

In addition to the environmental regulatory hurdles facing new marine energy technologies, national governments have recognized the technical challenges inherent to acoustic measurements in the high-energy environments that are most promising for the harnessing of ocean energy. Investments in research and development resulted in significant technology advances and a suite of state-of-the-art acoustic tools equipped to tackle MEC sound characterization challenges (**Figure 6**) (Wilson et al., 2014; Chang et al., 2021). These instruments include the University of Washington's (Seattle) Drifting Acoustic Instrumentation SYstem (DAISY), a system that can be optimized for MEC acoustic measurements in both current and wave environments. The design employs an effective flow shield in currents that reduces the complicating signals from flow noise, incorporates meteorological sensors on the topside buoy and, with several deployed in an array configuration, can provide MEC sound source localization capability. In waves, the flow shield is exchanged for a longer tether and damping plate that isolates the hydrophone from surface buoy motion.

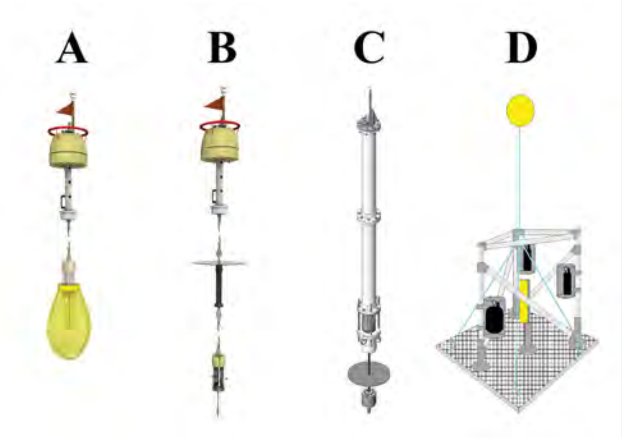


Figure 6. *Schematic diagrams of the University of Washington's Drifting Acoustic Instrumentation SYstem (DAISY) drifting hydrophone design for currents (**A**) and waves (**B**), Oregon State University's spar buoy drifting hydrophone for waves (**C**), and Integral Consulting Inc.'s Noisespotter vector sensor array (**D**). Note that these drawings are not to scale.*

Similarly, the Noisespotter developed by Integral Consulting (**Figure 6D**) comprises a three-dimensional array of vector sensors targeting low-frequency (<3-kHz) acoustic particle motion, sound pressure level measurements, and source localization of MEC sound with a high degree of spatial resolution, advancing the ability to determine both the location and identity of a sound source (Raghukumar et al., 2020). Similarly, Oregon State University, Corvallis; the NOAA Pacific Marine Environmental Laboratory, Seattle, Washington; and the Pacific Northwest National Laboratory, Richland, Washington, have collaborated on the development of a tall, thin, and upright floating ocean spar buoy drifting hydrophone system for open water WEC measurements (**Figure 6**) as well as a fixed seafloor hydrophone system with an underwater acoustic link to a surface buoy for real-time reporting of WEC associated spectral levels (called the Coastal Real-time Acoustic Buoy [CRAB]).

Standards and Acoustic Characterization of Marine Energy Converters

Given the inherent challenges of acoustic data collection at marine energy sites and the general importance of the subject from the environmental consenting perspective, there is an ongoing effort to develop a standard for acoustic characterization of MECs. This process is underway with work by the International Electrotechnical Commission

Technical Committee 114 who released Technical Specification 62600-40: *Acoustic Characterization of Marine Energy Converters* in 2019. This document provides an important set of technical guidelines for acoustic sensor specifications, data collection methodologies, coincident environmental measurements, MEC power performance information, and data analysis and presentation of results. MEC-related sound levels are correlated with the power production state of the device and the time series of environmental conditions, things like tidal current velocity, wave heights and periods, and wind speeds. This type of standardized approach to measurement fosters confidence for those responsible for permitting and licensing marine energy projects, at least from an underwater noise impact perspective.

Looking Ahead

Rapid, iterative testing cycles in real ocean and tidal conditions are critical for the technology advancement of the budding marine energy industry. Fortunately, in the United States and Europe (see emec.org.uk), several MEC test facilities such as the US Navy Wave Energy Test Site (WETS) (see bit.ly/Hawaii-WETS) have been operating for several years, and a new open ocean test center known as PacWave (see pacwaveenergy.org) is currently under construction off the Oregon coast in the United States. As MECs enter the waters of these test facilities, opportunities for acoustic characterization should be prioritized, filling data gaps and supporting the growth and success of a sustainable marine energy industry. In the future, as the marine energy industry moves toward the deployment of arrays at commercial scales and explores potential colocation with offshore wind, stakeholders of all kinds will benefit from the knowledge gained by characterizing individual MECs and understanding the drivers for sound production.

Collectively, offshore renewables are needed to help meet the goals for reduced carbon emissions, develop energy security and coastal resilience, promote energy equity, and power ocean observations and marine-based industries. Marine energy is part of the portfolio of ocean-based solutions, and despite the often nausea-inducing fieldwork deploying equipment in pitching and rolling waves from a small boat or cleaning six months of barnacle growth from a hydrophone, the acoustic data that we collect during MEC deployments are priceless. It is all an important part of the process and evolution toward a better understanding of acoustic emissions and potential effects of marine renewable energy.

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