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Electrifying subsea infrastructure through ocean-powered systems

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Introduction

The oil and gas industry is advancing toward electrified energy solutions for offshore upstream operations. The industry's energy transition is driven by the need for more affordable, reliable power to:

- Enable digital transformation and autonomy via real-time data communications and an Internet of Offshore Things
- Reduce operational cost and complexity
- Meet corporate and government decarbonization targets

This paper explores the potential for electrifying subsea oil and gas infrastructure using wave-powered ocean energy systems. It details how a type of system, an Autonomous Offshore Power System (AOPS), can provide a potential solution and outlines the work and findings to data of joint industry project that integrates and co-demonstrates an AOPS with an electrified subsea asset. In this Project (Project), an AOPS will provide power and data communications to an electrified subsea asset at the PacWave South test site off the U.S. Oregon coast. This paper provides a description and analysis of the system configuration, subsea asset integration process, and pre-deployment testing plans, along with projected benefits for the industry.

Market and Project Overview

In recent years, the oil and gas industry has accelerated a trend toward electrifying offshore operations. This transition is driven by innovations in robotic and electrical systems, as well as the need to reduce operational costs and complexity. In particular, offshore oil and gas operators are seeking affordable, reliable power and data communications in brownfield sites with power continuity issues and in sites where there is a desire to reduce power delivery costs and lead times, i.e., avoid power and data cabling for long subsea tiebacks. The offshore oil and gas industry is also exploring the potential for all-electric fields. Lastly, the industry has shown increased interest in energy solutions for carbon capture, utilization, and storage (CCUS) applications.

This Project is focused on the co-demonstration of an electrified operating asset supported by an AOPS in an 18-month field test that is co-sponsored by the U.S. Department of Energy (DOE). The integrated systems are slated for deployment at the PacWave South test site off the coast of Oregon, USA.

AOPS Overview

The purpose of an AOPS is to create an unattended, offshore power and data mini-grid for support of mobile and static marine assets located on the surface, in the water column, or on the seafloor. Using locally available renewable energy, the system is self-powered and provides a communications connection to the data cloud.

The AOPS for this project, referred to as the Project AOPS, consists of a wave power system (WPS) at the ocean's surface connected by a single combined mooring, power, and data communications line to a seafloor base unit (SBU). The WPS converts ocean wave energy into electricity. The power is conditioned and then stored. The SBU serves as the gravity anchor and provides energy storage, and energy and data communications management for remote command, control, and operation of subsea assets.

The Project AOPS is capable of supporting remote offshore activities and equipment, including subsea vehicles, sensor packages, and operating equipment. This AOPS configuration is transportable via standard ocean containers and deployable with smaller, lightly crewed vessels.

Industry benefits of deploying an AOPS would include decreased costs and carbon emissions, reduced operational complexity, and increased safety for offshore oil and gas operations.

AOPS Design History

In 2017, a project funded by the U.S. Defense Advanced Research Projects Agency (DARPA) identified a need for a WPS capable of providing reliable kilowatt-scale power and communications for offshore equipment. A novel WPS design was conceived, modeled, designed, built, and delivered in 14 months. It was a successful initial effort to apply knowledge gained from prior utility-scale power generation research and design (R&D) efforts to the design of kilowatt-scale ocean-powered systems.

The DARPA prototype served as the technical baseline for a second-generation WPS that was optimized for the lower-power needs of offshore customers and their suppliers. This next-generation WPS was acquired in 2022 by the U.S. Navy for testing by the University of Washington-Applied Physics Lab (UW-APL). That unit, which is full-scale for its intended purpose, has been bench-tested and deployed in-water three times. It was upgraded in late 2023 and completed a third round of in-water testing in January 2024.

In parallel to delivering the system to UW-APL, an extensive process was undertaken to identify key dual-use markets, use cases, and applications for a WPS. Through that process, the importance of coupling wave power systems with energy storage, along with data cloud communications, was identified.

As with any intermittent energy resource, the supply of power will not match the load profile. Adding energy storage allows time shifting of energy supply to meet demand and provide operational reliability. With the addition of energy storage to power generation and conditioning, a self-contained, in situ autonomous power and data mini-grid was created. This integrated technology is referred to as an AOPS.

A DOE and U.S. Navy-sponsored demonstration of an AOPS has been completed at the Navy's Wave Energy Test Site (WETS) in Hawai'i. This third-generation WPS was bench-tested at the National Renewable Energy Lab (NREL) Flatirons campus in Colorado prior to its open-ocean deployment. During the 10 months of testing at NREL prior to deployment, the drivetrain, power electronics (PE), supervisory control and data acquisition (SCADA), communications, ancillary, and other systems were fully tested for functionality using wave resource data from intended operational environments. During deployment, the AOPS successfully generated, stored, and distributed power and provided bidirectional data communications between the seafloor and the data cloud. Figure 1 highlights in-water testing of WPS and AOPS technologies to date, from DARPA to Hawaii.

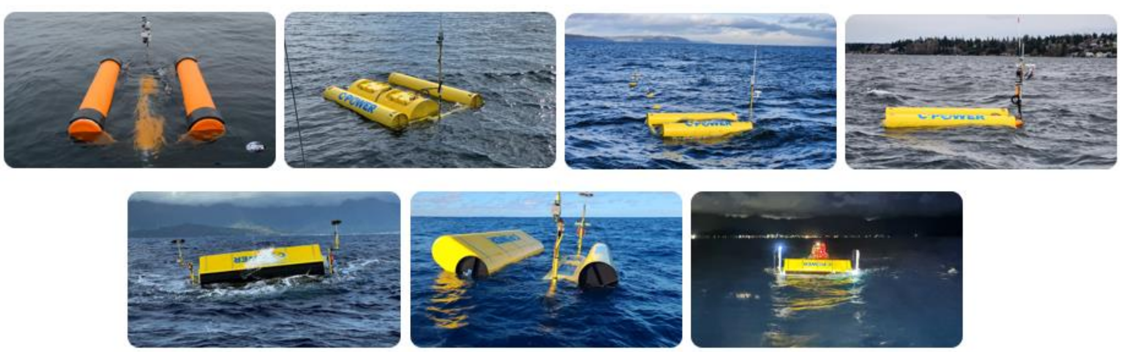

Fig. 1—Ocean-powered system demonstrations to date.

Project AOPS Design

The previous design cycles and deployments have yielded design enhancements for a fourth-generation commercial-scale WPS. This WPS will be used in the AOPS deployment at PacWave South in Oregon.

Design activities for the Project AOPS are underway and follow applicable standards from the International Electrotechnical Commission (IEC), Det Norske Veritas (DNV) and the International Organization of Standardization (ISO). The Project AOPS design is currently undergoing a technology qualification process with DNV. As part of the process, a Statement of Feasibility was issued in 2025. Additionally, applicable American Petroleum Institute (API) standards are being incorporated. This AOPS will demonstrate advancements over prior generations of systems, including a deep-water ready mooring design, more generating capacity, and improved installation, operations, and maintenance (IO&M).

The Project AOPS consists of a surface expression comprising three cylindrical bodies for power generation (the WPS), a mid-column heave plate providing a stable platform for the WPS to react against, and a SBU serving as gravity anchor and energy storage system (ESS). The WPS is intended to be moored, to generate and store electrical energy, and to provide the stored energy to various interfacing payloads. Figure 2 shows a model of the full Project AOPS stack.

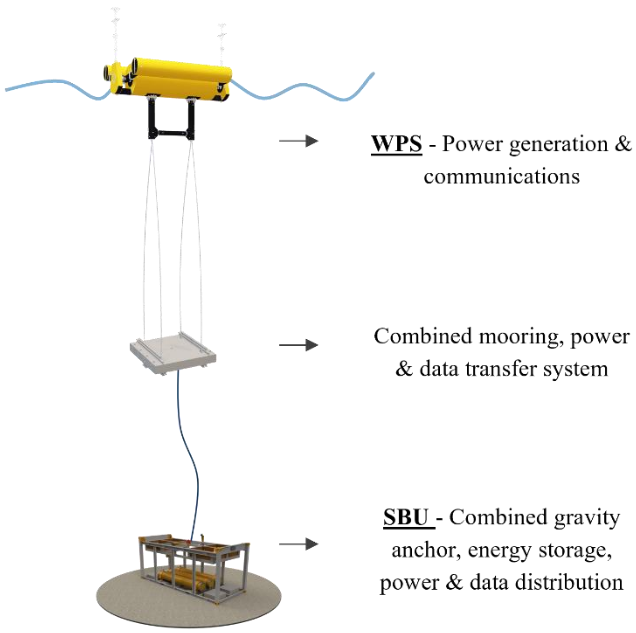

Fig. 2—Labeled Project AOPS rendering.

Power generation is accomplished through the relative movement of the nacelle to each of the floats (Figure 3). During operation, the nacelle is held relatively still in the water by the inertial mass of the heave plate, while the highly buoyant floats tend to follow the wave surface, resulting in the floats independently and partially oscillating about the nacelle as the waves propagate by. The relative motion between float and nacelle actuates its generator and produces electricity.

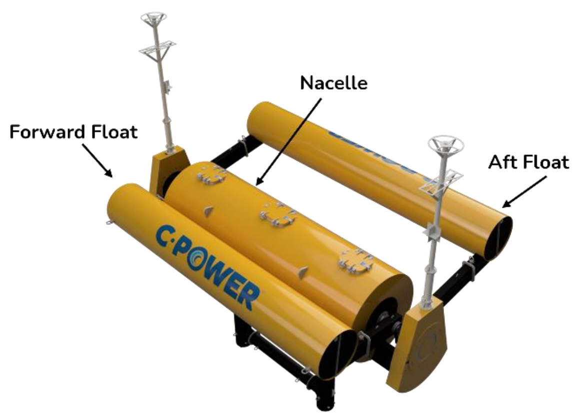

Fig. 3—Labeled Project WPS model.

The umbilical cable serves as the mooring line, as well as providing electrical and data transfer between the nacelle and the SBU. There are three distinct sections of umbilical. The upper section is non-load bearing and runs from the nacelle to the heave plate. The load bearing connection between the nacelle and heave plate comprises four lines, running from the nacelle mooring yoke to mooring lugs at the four corners of the heave plate. The middle section of umbilical is load bearing and provides necessary compliance. This umbilical is specifically designed for open ocean, single point mooring applications. The lower section is an armored umbilical cable and connects the middle section to the SBU. A large buoyancy module (1 mt) sits at the interface between middle and lower sections and ensures that the lower section remains taut. All umbilical sections have copper conductors and fiber optic lines. The mooring system is designed to maintain positive tension and eliminate any slack in the lines.

The seafloor base unit serves as a gravity anchor, primary ESS, and provides interfaces for the various assets served by the AOPS. The SBU is comprised of a seafloor rated, commercial energy storage product. Energy storage is typically provided by lithium-ion battery cells (Hammagren & Lesemann, 2024).

Table 1 has a high-level technical specification sheet for the Project AOPS.

	Project AOPS
Surface Dimensions	8.8m x 5.9m x 6.4m
Fully-integrated AOPS dry weight	46,500kg
Max lift	26,000kg
Deployment	Capable of tow or lift
Output Power*	Up to 10kW
Energy Storage	Minimum 55kWh with increases available in 35kWh and 55Wh intervals
Power output options	48VDC, 370VDC (Other Options Available)
Communications	Cellular, RF, or Satellite
Supported Assets	Sensors, Robotics, Operating equipment, Communications

Table 1—Project AOPS specifications.

Through the iterative AOPS design, development, and prototyping process, as well as feedback from the offshore energy industry, has informed innovation and technical specification that ensure the system:

- enables autonomous or remote operation, longer residency, and digitalization of offshore equipment.
- is vendor and technology agnostic, enabling the full suite of desired capabilities for offshore equipment from any technology supplier.
- can be easily transported and deployed at low cost and with low complexity, anywhere in the world.
- meets offshore energy needs in any ocean environment, whether the wave energy resource is high or low, requiring scaled WPS designs and energy storage systems to ensure adequate energy generation and availability (Hammagren & Lesemann, 2024).

The Project AOPS can support a wide range of surface and sub-surface assets, including operating equipment, metocean data gathering sensors, and uncrewed vehicles. During the deployment at PacWave, the AOPS will provide power and data communications to three assets that can demonstrate critical marine applications, including met-ocean data collection and reporting and environmental monitoring.

Electrified Subsea Asset

The electrified subsea asset consists of an electric actuator, valve, subsea hydraulic power unit (SHPU), and wireless subsea comms. These components will provide close proxies for real loads that an AOPS would power in a live offshore oil and gas field. The wireless subsea comms modem is at the forefront of innovation in subsea technology. Because an AOPS includes a surface expression, it offers a redundant communications hub from seafloor to surface. This communication network ensures critical system redundancy and enables command and control of assets from shore. The asset is shown in Figure 4.

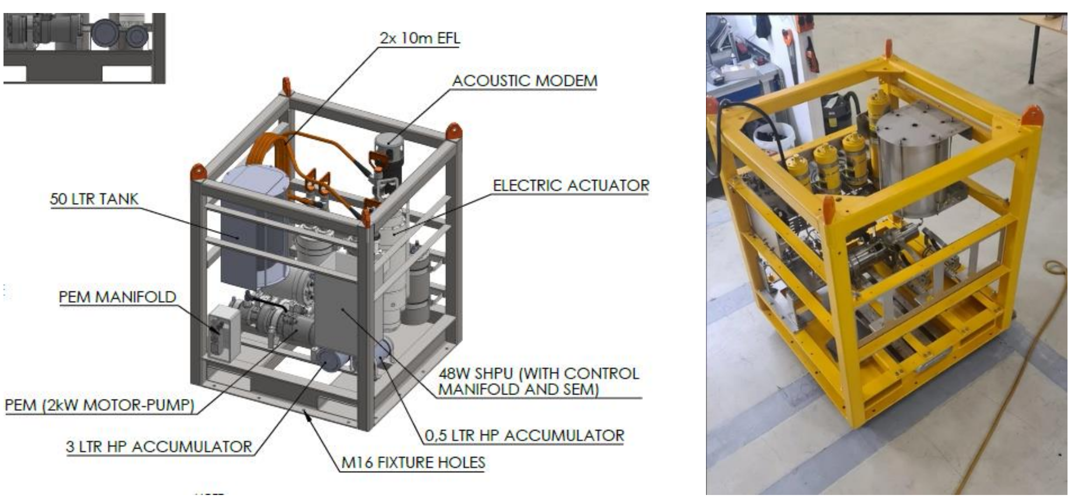

Fig. 4—Left, the design concept for the electrified subsea asset that will be co-demonstrated with the AOPS at PacWave South. Right, the partially completed asset as of January 2025.

Asset Co-demonstration

The design and fabrication of the wave power system and asset are underway, followed by integration, dry testing, and calm water testing prior to deployment at PacWave.

PacWave Test Site

PacWave is an open ocean wave energy testing facility consisting of two sites, each located just a few miles from the deep-water port of Newport, Oregon, in the Pacific Ocean (Figure 5).

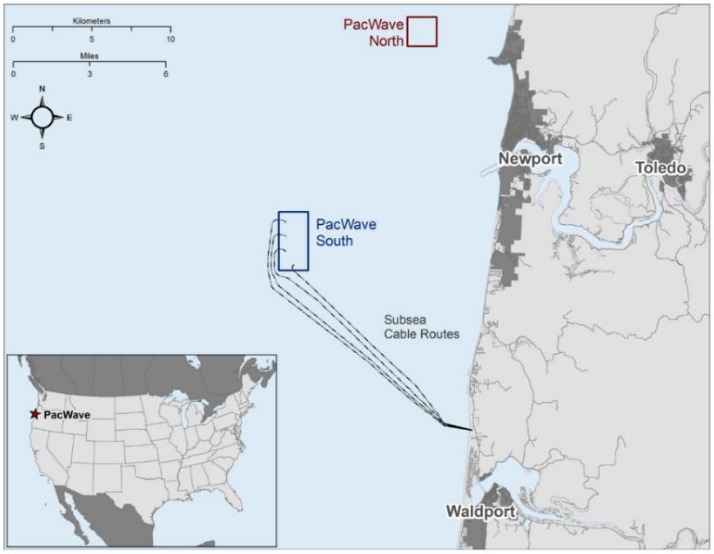

Fig. 5— PacWave consists of the PacWave North test site and the new PacWave South test site.

The joint project demonstration will be held at the PacWave South test site. PacWave South is a state-of-the-art, pre-permitted, accredited, wave energy test facility developed in partnership with the DOE, Oregon, and Oregon State University. The two-square-nautical-mile ocean test site will consist of four berths and include a 12-mile cable route to shore. Each test berth is approximately 6,080 feet by 3,040 feet and is located in up to 215 to 255 feet of water. As PacWave South is pre-permitted for most wave energy device types, site users will not have to undertake a costly and time-consuming permitting process prior to testing, which will enable more rapid technological development.

At PacWave South, the seafloor in the area is generally soft sand. The most commonly occurring seas feature a significant wave height of 1.75 m and an energy period of 8.5 s (~528 hours per year), while the highest annualized wave energy sea state is at a significant wave height of 2.75 m and at an energy period of 10.5 s (~231 hours per year) (PacWave, 2025).

Subsea Asset Integration

The subsea electrified asset will be deployed with the Project AOPS at PacWave South for the entire duration of field testing. The asset will be bolted to the SBU (Figure 6). The SBU provides the interface to deliver power to the asset and to upload and download data. The “bolted-in” design will allow for extensive pre-deployment testing and an all-in-one deployment and recovery.

Fig. 6—Left, the concept drawing of the cage within the SBU the electrified asset will be bolted into. Right, concept drawing including rendering of the asset.

This project will leverage the latest advancements in subsea digitalization, electrification, and fiber optic systems to deliver reliable communications seafloor to surface and surface to shore.

Performance Metrics

International Energy Agency (IEA) Ocean Energy Systems (OES) Technology Collaboration Programme released the 2nd edition of their Framework for Ocean Energy Technology in 2023 (Hodges et al, 2023). This document is primarily targeted at providing a common set of international guidance for evaluating utility-scale electricity generation from ocean waves and tidal streams. Though the Project AOPS is not a utility-scale system, the Evaluation Areas outlined in Figure 7 provide definitions and criteria relevant for evaluating the performance of the system during the PacWave deployment.

Evaluation Area	Definition
Power Capture	Power Capture is the process of extracting energy from the natural resource by the interaction with a device and making it available as an input to a power take-off (PTO).
Power Conversion	Power Conversion represents the second step in the power conversion chain, whereby the mechanical power captured by the device is converted to electricity.
Controllability	Controllability is defined as the ability for control systems to be implemented to a subsystem or device and incorporates evaluation of the benefits control can deliver and the reliance of a subsystem or device on it.
Reliability	Reliability is defined as the "probability that an item can perform a necessary function under given conditions for a given time interval".
Survivability	Survivability is a measure of the ability of a subsystem or device to experience an event ('Survival Event') outside the expected design conditions, and not sustain damage or loss of functionality beyond an acceptable level, allowing a return to an acceptable level of operation after the event have passed.
Maintainability	Maintainability is defined as the "ability to be retained in, or restored to a state to perform as required, under given conditions of use and maintenance".
Installability	Installability is defined as is the ease with which a component, subsystem or device can be prepared, deployed at the operational open-water site and commissioned, resulting in a condition of operational readiness. Installability also includes the ease with which the component, subsystem or device can be recovered.
Manufacturability	Manufacturability is defined as the ability for the technology to be manufactured quickly, cheaply and with minimum waste, and therefore its compatibility with the supply chain's capability, readiness and maturity.
Affordability	Evaluation of Affordability relates to the cost of electricity generated from the wave or tidal stream resource.
Environmental Acceptability	Environmental acceptability can be defined as the ability to make effective use of natural resources, reduce the risks and harms to the operating environment, comply with the relevant regulations, and generate induced benefits whenever possible.

Fig. 7—Evaluation Areas for ocean energy technologies developed by the IEA.

The Oregon demonstration will primarily be evaluating power capture and conversion, reliability, maintainability, and installability. The WPS for this Project is a higher power unit than previous designs with the next generation of electric plant and power electronics increasing efficiency. This increased efficiency will be measured through electrical power output to the seafloor energy storage and subsequent assets compared to mechanical power coming off the generators.

Reliability will be measured across the 18-month deployment as this will be the longest open-water demonstration of the AOPS. Reliability will be assessed through sustained periods of continuous operation, monitoring of system failures, and validation against the established Failure Modes and Effects Analysis (FMEA).

For planned or unplanned maintenance, the surface WPS unit can be swapped in-situ for a shoreside spare unit. First, the incoming WPS is placed into the water and held on station by a small support vessel. Next, the heave plate is brought to the surface by either divers de-ballasting with air to raise it in the water column, or by lifting it to the surface with a ship-mounted crane while the WPS nacelle is tended clear by a small support vessel. Once recovered to the surface, the four bridles and slack umbilical between the heave plate and WPS nacelle are disconnected, and the outgoing unit is tended away. The bridles and slack umbilical are then reconnected to the incoming unit, communication and power flow checks completed, and then the heave plate is flooded back to its normal position below the WPS. For the Oregon demonstration, there will be an analog float rather than a shoreside spare. If time and resources permit toward the end of the demonstration and no unplanned maintenance has occurred, the project team will test and validate the swappable maintenance model, building on previous maintenance experience in Hawaii.

Advances in the Project AOPS installability are discussed more in depth below. The primary evaluation criteria for the Oregon deployment will be acceptable wave height for installation, mean time to install, and cost to install.

Installation, Maintenance, and Decommissioning

The Project AOPS is intended to be deployed in less than 1 hour once on station. The system is capable of being towed to location or deployed by a variety of work class vessels. For the deployment at PacWave, a new technical capability will be demonstrated. This capability has been informed by installation, operation, maintenance, and decommissioning improvements made following the AOPS deployment in Hawaii. In Hawaii, the AOPS was towed to WETS using the configuration pictured in Figure 8. The Oregon deployment will employ an advanced process, utilizing a newly designed deployment and recovery vessel (DRV) capable of safely lifting a variety of assets in heavier sea states, thus greatly expanding deployment windows and enabling an all-in-one deployment with the subsea asset (Figure 9).

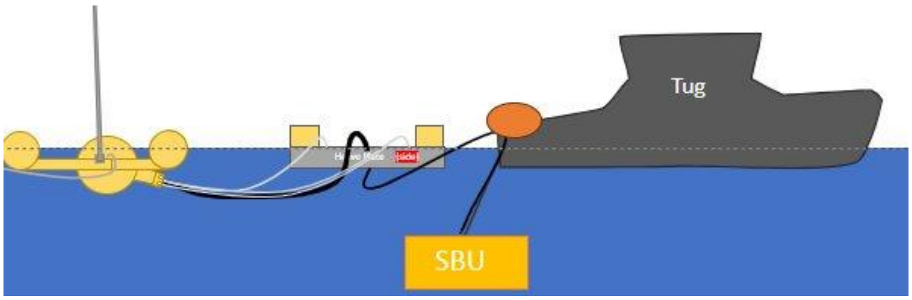

Fig. 8—The towing configuration used to deploy the AOPS in Hawaii.

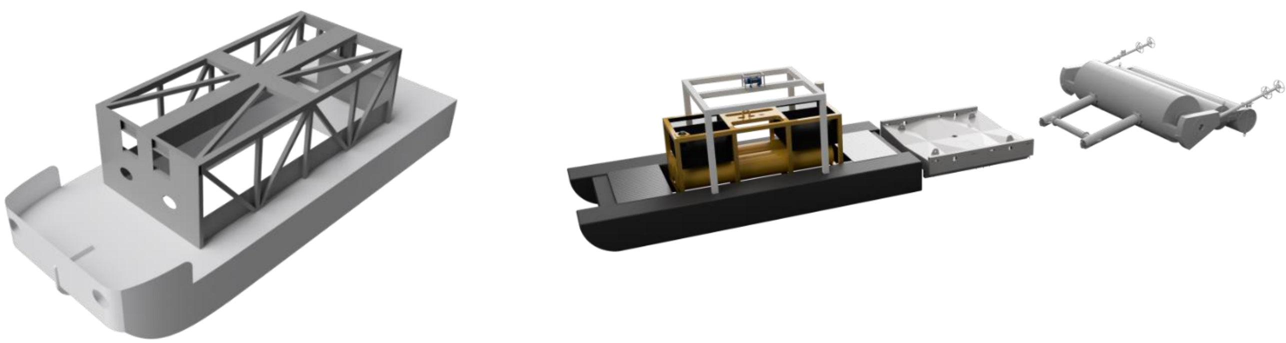

Fig. 9—The novel DRV design, which will be used to deploy the integrated AOPS and subsea assets at the PacWave South test site.

The DRV will be capable of deploying assets up to 20 feet long, eight feet wide and 8.5 feet tall. Deployable assets can weigh up to 40,000 pounds. The DRV can be easily towed behind common ocean-going tow vessels. This innovation provides operational versatility and allows deployment via smaller, cheaper tugboats, avoiding air lifts at sea in locations where vessels with lifting capacity may not be temporarily or typically available.

Once deployed and brought online, the Project AOPS is intended to operate as a completely autonomous system that will generate energy during periods of sufficient wave energy, using this energy to charge the SBU. Onboard sensors and computers monitor the health of all equipment and provide automatic notification in the event of setpoints being exceeded. No maintenance or repair is expected to be required during the Oregon demonstration and testing.

Conclusions

Offshore oil and gas operators are actively seeking affordable, reliable energy solutions to electrify subsea infrastructure — even entire fields. Wave-powered ocean energy systems are rapidly advancing as a commercial solution to help the oil and gas industry achieve its electrification goals. The industry's interest is highlighted by innovative partnerships and integrations, such as the work both completed and to be completed in this joint industry project.

Successfully demonstrating an AOPS's ability to provide power and data for offshore oil and gas use cases will accelerate the oil and gas industry's move toward cleaner, more efficient offshore energy solutions. The project will enable an AOPS to demonstrate power, energy storage, and real-time communications capabilities that deliver benefits to offshore oil and gas operations, including:

- Reduced capital and operational costs
- Reduced operational complexity
- Reduced carbon emissions
- Improved operational safety via a reduction in crewed "dirty and dangerous" work
- Increased operational efficiency, including increased autonomy and residency of assets
- Easier maintenance of mobile and static operating assets
- Accelerated digital transformation and autonomy via real-time data communications and enablement of an Internet of Offshore Things

In addition to the above benefits, a concurrent effort is underway to extend the AOPS technology to deep water applications. Part of that process will be accomplished with the deep-water capable mooring in place for the PacWave demonstration. Continued work will be identified, factoring in the assessment and analysis of the reliability, performance, and cost of the deployed mooring.

Acknowledgements

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