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## WAVE-POWERED AUV RECHARGING: A FEASIBILITY STUDY

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### ABSTRACT

*The aim of this study is to determine whether multiple U.S. Navy autonomous underwater vehicles (AUVs) could be supported using a small, heaving wave energy converter (WEC). The U.S. Navy operates numerous AUVs that need to be charged periodically onshore or onboard a support ship. Ocean waves provide a vast source of energy that can be converted into electricity using a wave energy converter and stored using a conventional battery. The Navy would benefit from the development of a wave energy converter that could store electrical power and autonomously charge its AUVs offshore. A feasibility analysis is required to ensure that the WEC could support the energy needs of multiple AUVs, remain covert, and offer a strategic military advantage. This paper investigates the Navy's power demands for AUVs and decides whether or not these demands could be met utilizing various measures of WEC efficiency. Wave data from a potential geographic region is analyzed to determine optimal locations for the converter in order to meet the Navy's power demands and mission set.*

### INTRODUCTION

The U.S. Navy supports autonomous underwater vehicles (AUVs) that serve across multiple mission sets such as hydrographic surveying, mine countermeasures, and homeland security. AUVs utilized by the Navy currently need to be recharged manually either onshore or on a ship. This requires a significant amount of time and manpower; additionally, it limits mis-

sion endurance for the AUVs because they are unable to operate continuously without human intervention. For this reason, it is advantageous for the Navy to develop a charging system that is both self-sustainable and autonomous. It would need to use a renewable resource to generate electricity or else the system would need an external power supply, limiting its offshore capability. Solar power is a possible alternative, but it requires direct sunlight which is unattainable for the majority of a day. A charging system using wave energy for power generation could be the best alternative to meet the Navy's mission set.

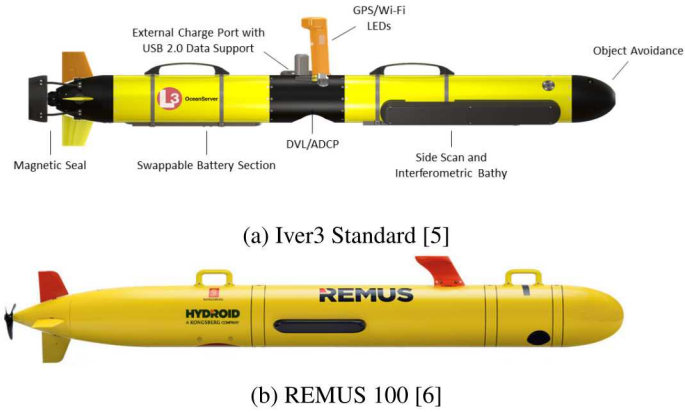
Studies have shown that wave energy converters (WECs) could be an efficient way to charge AUVs. A report done at Virginia Tech conceptualized pairing an AUV charging dock with a heaving buoy system by employing an artificial submerging seafloor [1]; this design also provides the ability to remain hidden from potential adversaries in open ocean. An AUV charging station could potentially charge multiple AUVs autonomously in a continuous cycle. Another group of researchers developed an augmented navigation system that successfully guided a small AUV into a cone-shaped dock [2].

One AUV currently utilized by the U.S. Navy is the Iver3, by L3 Ocean Server Inc (see Fig. 1a). Its mission areas include general survey and hydrography, environmental monitoring, and search/recovery. Numerous Iver AUVs have been used in conjunction with Naval Special Warfare during search and survey missions [3]. The AUV contains a variety of sensors, including a side scan sonar, inertial navigation system, and magnetometer. Data gathered by the Iver3 can be utilized to increase the situational awareness of a battlespace and detect mines.

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**FIGURE 1: TYPES OF AUVs USED DURING STUDY.**

Another AUV utilized by the U.S. Navy is the REMUS 100, by Kongsberg Maritime (see Fig. 1b). Similar to the Iver3, its primary mission sets include hydrographic surveying, undersea search, and scientific sampling. The REMUS 100 has also been utilized for missions involving shallow water mine countermeasures. According to Nicholson and Healy, the REMUS 100 was used to remotely clear mines during Operation Iraqi Freedom [4]. Overall, the REMUS 100 and Iver3 AUVs are comparable in regards to mission set capability.

In this study, an operational scenario will be evaluated to determine whether wave energy is a feasible option for AUV recharging. Wave power density is calculated in the South China Sea and converted into WEC electrical power generation using linear wave theory and numerous efficiency values. Required WEC power generation is found for a charging station based on the number of docks and AUVs being supported.

## AUV SPECIFICATIONS

Physical specifications for both the Iver3 and REMUS 100 are shown in Table 1. Overall, the Iver3 and REMUS 100 are comparable with respect to size. For the Iver3, both length and mass are highly dependent on its mission packages which can include various computing systems and sensors. Both AUVs have a maximum depth of 100 m.

Battery specifications for the Iver3 and REMUS 100 are also shown in Table 1. The required power in dock is equal to each respective charging rate with an additional 90 W to keep the vehicle's non-propulsion systems running. To be conservative, endurance is estimated to be 8 hours for the Iver3 and 11 hours for the REMUS 100 during an operational scenario. The REMUS 100 is estimated to take 6 hours to recharge for the same reason and to simplify further calculations.

**TABLE 1: AUV PHYSICAL PARAMETERS.**

Parameter	Iver3 [5]	REMUS 100 [6]
Length (m)	1.52 - 2.16	1.70
Hull Diameter (cm)	14.7	19.0
Mass (kg)	27 - 38.5	36
Endurance (hrs)	8 - 14	$\leq 12$
Energy Storage (Wh)	800	1000
Charging Rate (W)	160	192
Time for Full Recharge (hrs)	5.00	5.21
Required Power in Dock (W)	250	282

## AUV OPERATIONAL SCENARIO

For an Iver3, the battery will take 5 hours to recharge at 160 W to reach full capacity. After recharge, the AUV has an endurance of 8 hours until it is required to recharge once again. It can be expected that two AUVs could be charged utilizing the dock in rotation. A typical operational scenario for the Iver3 is shown in Fig. 2.

In this scenario, the Iver3 begins a new recharge cycle every 13 hours. With two AUVs utilizing the dock in rotation, recharging periods never overlap. Power generated by the WEC directly charges the AUV while it is in dock. If the WEC power generation exceeds the required AUV power while in dock, any additional power will be used to charge the dock battery. After every ten hours of charging, there will be a three hour gap when the WEC could transfer energy to the dock battery without needing to power an AUV. The dock battery will be used as a supplementary source of power to charge the AUVs while in dock if the power requirement is not met by the WEC.

The REMUS 100 could be utilized in a similar rotation. A typical operational scenario for the REMUS 100 can be seen in Fig. 3.

Similar to the Iver3 scenario, the REMUS 100 will begin a new recharge cycle every 17 hours. After every 12 hours of charging, there will be a five hour gap allowing the WEC to recharge the dock battery without having an AUV in dock. All other conditions remain the same.

Table 2 summarizes the WEC power requirements and dock battery size for both the Iver3 and REMUS 100 scenarios. The average WEC power requirement can be calculated by dividing the energy required for two AUV recharges by the time between recharge cycles. The average dock battery power requirement can be calculated by subtracting the average WEC power requirement from the required AUV power in dock. Minimum dock battery size can be determined by multiplying the average dock

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Iver3 AUV #1	Start Recharge (250W)					Operational								Start Recharge (250W)				
Iver3 AUV #2	Start Recharge (250W)					Operational					Start Recharge (250W)							

FIGURE 2: OPERATIONAL SCHEDULE FOR IVER3.

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
REMUS100 AUV #1	Start Recharge (282W)					Operational												Start Recharge (282 W)					
REMUS100 AUV #2	Start Recharge (282 W)					Operational					Start Recharge (282 W)												

FIGURE 3: OPERATIONAL SCHEDULE FOR REMUS 100.

TABLE 2: REQUIRED WEC POWER AND BATTERY SIZE.

Parameter	Iver3 [5]	REMUS 100 [6]
Avg. WEC Power Req. (W)	193	200
Avg. Dock Battery Power Req. (W)	57	82
Min. Dock Battery Size (Wh)	570	984

battery power requirement by the time required for two full AUV recharges.

### WEC SURVEY AND SYSTEM EFFICIENCY

There are five basic wave energy conversion techniques: heaving and pitching bodies, cavity resonators, pressure devices, surging devices, and particle motion devices. Each technique can be used effectively to meet a specific set of system requirements. To maximize power generation, a wave energy converter must be designed to maximize motion in a certain wave region. For example, heaving body WECs are designed to have a natural heaving frequency that resonates with the frequency of the highest power wave [7]. For this study, the following equation was used to calculate wave power density [8]:

$$J = \frac{\rho g^2 H_s^2 T_e}{64000\pi}, \quad (1)$$

where  $J$  = wave power density (kW/m),  $\rho$  = water density ( $\text{kg/m}^3$ ),  $g = 9.81 \text{ (m/s}^2\text{)}$ ,  $H_s$  = significant wave height (m), and  $T_e$  = wave energy period (s).

It should be noted that although wave energy period and peak period ( $T_p$ ) are not exactly equal, the relationship between the two depends on the sea state spectrum. For example,  $T_p = 1.12T_e$  for a JONSWAP spectrum with peak enhancement factor  $\gamma = 3.3$  [8]. Because this study attempts to generalize across wide geographical areas with different sea states, it is assumed

that peak period and wave energy period are equal for all wave power calculations.

Unlike most wave energy converters, a design used to support a fleet of AUVs would benefit by remaining hidden from potential adversaries. In order to remain hidden, the WEC would need to be located a significant distance offshore. Additionally, it would need to be able to generate the required amount of electrical power without taking up a large amount of space. This would reduce the likelihood of it being detected visually or by radar.

Heaving bodies have proven to be the most efficient conversion technique in monochromatic waves. They are the cheapest to design and build, and they have the ability to generate the required amount of electrical power with a relatively small size [7]. In an operational scenario, the WEC would need to be in deep water and, most likely, open ocean. Most conversion techniques require massive construction, but heaving bodies can be installed using a single mooring attached to the sea floor. For these reasons, the heaving body was chosen as the preferred wave energy conversion technique during this study.

Heaving bodies can be combined with a variety of energy conversion subsystems to produce electricity. Linear permanent magnet generators are the most common electrical subsystem found on heaving bodies [9]. They have proven to be efficient in wave energy conversion because the translator is directly driven by the heaving motion of the WEC [10]. For these reasons, a linear permanent magnet generator was used as the energy conversion subsystem during this study.

For energy storage, a standard lead-acid battery was found to be the best option in this scenario. Lead-acid batteries have been used extensively in marine environments and are readily available. The battery would be recharged by the linear permanent magnet generator that produces electricity from the heaving body motion. It would also be connected to the AUV dock to supplement the power supply going into the AUVs when needed. Studies have shown that lead acid batteries have an energy density of 35-55 Wh/kg [11]. Using these estimates, the battery attached to the wave energy converter would be approximately 10-17 kg for the Iver3 and 17-29 kg for the REMUS 100.

Various measures of efficiency were used during this study

to predict WEC power generation. Hydrodynamic efficiency reflects the percentage of wave power flowing through the WEC that is absorbed by the WEC. According to a database of 49 different heaving WECs of various sizes, average hydrodynamic efficiency was 16% with a standard deviation of 10% [12]. The WECs were defined by their characteristic dimension, B, which is comparable to the WEC diameter for a circular waterplane area. Characteristic dimension for any shape WEC could be calculated using the following equation:

$$B = \sqrt{\frac{4A}{\pi}}, \quad (2)$$

where A is the maximum horizontal cross-sectional area of the device ( $m^2$ ).

According to the same source [12], hydrodynamic efficiency can be predicted based on a WEC's characteristic dimension using a line of best fit:

$$\eta = 1.3B + 5.6, \quad (3)$$

where  $\eta$  = hydrodynamic efficiency (%), B = characteristic dimension (m), and  $0 \leq \eta \leq 20$ .

While predicting WEC power generation, calculations were done using both a constant value for hydrodynamic efficiency and the line of best fit. To remain conservative in all calculations, a constant 6% was used as a value that lies one standard deviation below the mean hydrodynamic efficiency. Finding hydrodynamic efficiency with the line of best fit represented a more ideal scenario.

Generator efficiency ( $\alpha$ ) also had to be taken into account for all power calculations. Generator efficiency represents the percentage of kinetic energy in the heaving body that is being converted into electrical energy. According to a study on linear permanent magnet generators in WECs, generator efficiency typically lies between 80-95% [13]. Recent studies on design optimization for linear permanent magnet generators showed that generator efficiency in WECs is typically around 82% [14]. In order to remain conservative, a constant 80% for generator efficiency was used for the purpose of this study.

Lastly, power transfer efficiency ( $\epsilon$ ) needed to be considered for all power calculations. Power transfer efficiency represents the percentage of electrical energy that could be transferred through inductive coils into the AUV. According to recent testing at the U.S. Naval Academy, power transfer efficiency was consistently above 70% over a range of power levels and orientations [15]; therefore, 70% was used in this study. Combining all of these efficiency terms, WEC electrical power generation (P) was calculated using the following equation:

$$P = JB\eta\alpha\epsilon, \quad (4)$$

Budal's limit restricts the amount of electrical power generation based on the water volume swept by the WEC, preventing the assumption that a device can move completely in and out of the water while still being excited by a wave. It can be calculated with the following equation, assuming the displaced volume to be a sphere submerged halfway in the water:

$$P_{limit} = \frac{\rho g \pi^2 (0.5B)^3 H_s}{6T_p}, \quad (5)$$

where  $P_{limit}$  = WEC electrical power generation limit (W) [16].

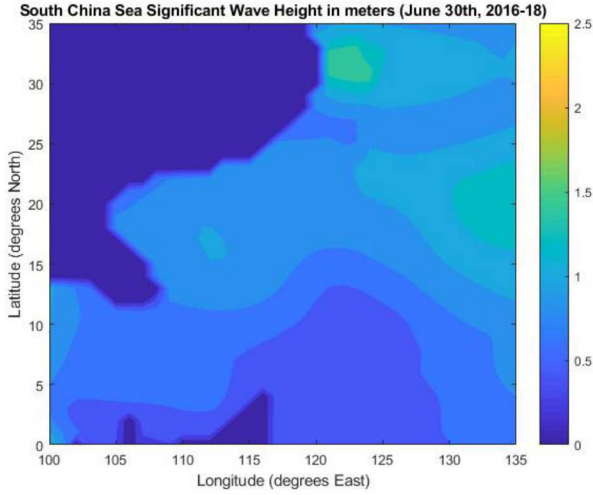
## POTENTIAL GEOGRAPHIC LOCATION

WECs are typically limited in depth because they have to be able to transfer electricity ashore. However, a combined wave energy converter and AUV docking system would only need to store the acquired energy in order to transfer it directly to the AUV or dock battery. For this reason, offshore distance would not be a limiting factor in potential mooring locations.

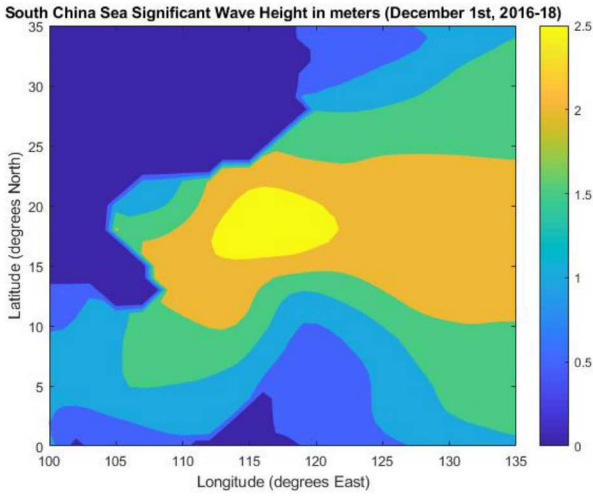
Ideally, a converter would be moored in deep water because it is where the waves have the highest amount of energy and the converter could remain hidden from potential adversaries. Studies have shown that for heaving wave energy converters, maximum power can only be obtained when the deep water criteria is met [17]. To balance both the risk and the reward of mooring a wave energy converter in open ocean, a maximum depth of 1000 meters should be set in the search for potential docking locations. This has been used as the maximum depth for numerous wave energy converters that are sold commercially [18].

The South China Sea is a strategic maritime domain that is of interest to several countries. Many regions off the coast of southern China are also shallower than the maximum depth of 1000 m set above. For these reasons, the South China Sea was chosen as a representative region for potential deployment of wave-powered AUV recharging systems. Fig. 4 shows maps of the significant wave heights for the region during June and December, 2016-2018.

Significant wave heights can be measured based on satellite altimetry data. Each map was developed as the average of the significant wave heights during one day (June 30th and December 1st) over three years (2016-2018). As shown on the plots, wave heights during December are notably higher than those during June.



(a) June



(b) December

**FIGURE 4: SOUTH CHINA SEA SIGNIFICANT WAVE HEIGHTS.**

The most probable peak period for each significant wave height was found based on a joint probability wave scatter diagram from the South China Sea [19]. Depth is assumed to be 1000m and water density equal to 1025 kg/m<sup>3</sup> for all calculations. Table 3 outlines the wave power density based on prevalent significant wave heights and peak periods in the region using Eq (1).

### FEASIBILITY RESULTS AND DISCUSSION

Using tools in MATLAB, a function was generated in order to calculate WEC electrical power generation through vari-

**TABLE 3: WAVE POWER DENSITIES IN SOUTH CHINA SEA.**

$H_s$ (m)	$T_p$ (s)	Wave Power Density (kW/m)
1.0	4	1.96
1.5	4	4.42
2.0	5	9.81
2.5	5	15.33

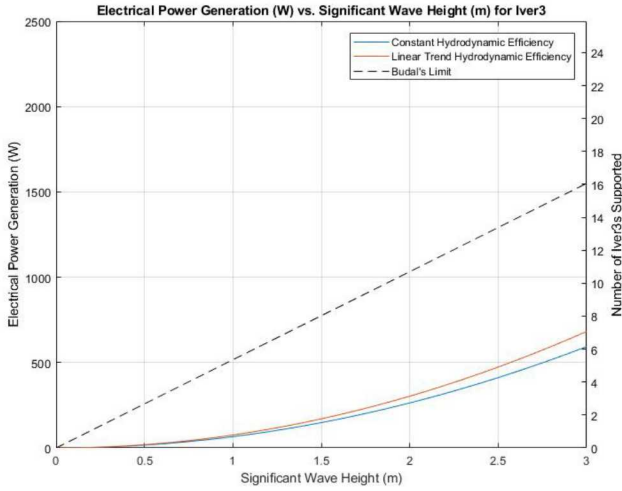
ous linear wave theory equations and measures of efficiency. Its inputs were significant wave height ( $H_s$ , m), peak period ( $T_p$ , s), WEC waterplane area ( $A$ , m<sup>2</sup>), water depth ( $d$ , m), and water density ( $\rho$ , kg/m<sup>3</sup>). The function was able to generate the wave power density using significant wave height, peak period, water depth, and water density [see Eq (1)]. Next, waterplane area was converted to characteristic dimension ( $B$ , m) using Eq (2). WEC electrical power generation was then calculated based on the wave power density, characteristic dimension, and the three efficiency values (hydrodynamic, generator, power transfer) described earlier in Eq (4). Budal's limit was calculated based on characteristic dimension, significant wave height, and peak period [see Eq (5)].

Constant hydrodynamic efficiency assumes that  $\eta = 6\%$ , while linear trend hydrodynamic efficiency indicates that the line of best fit [Eq (3)] calculates  $\eta$  based on the characteristic dimension ( $B$ ). The power generation plots in Fig. 5 show significant wave height (m) varying on the x-axis with the constants shown in Table 4.

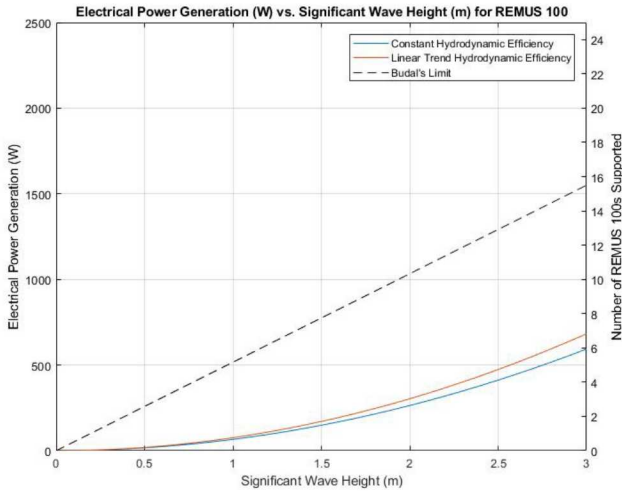
**TABLE 4: CONSTANTS USED WITH VARYING SIGNIFICANT WAVE HEIGHT.**

$T_p$ (s)	$B$ (m)	$d$ (m)	$\rho$ (kg/m <sup>3</sup> )
4	1	1000	1025

The left y-axis represents the amount of electrical power generated by the WEC that can be used to recharge AUVs. The right y-axis represents the number of AUVs that can be supported based on WEC electrical power generation. Since the operational scenarios (Figs. 2 and 3) conceptualize one dock for every two AUVs, the tick marks on the right y-axis represent discrete bins rather than a continuous scale. For example, if a point on the power generation curve lies between 2 and 4 on the right y-axis, the corresponding significant wave height can only support 2 AUVs. The number of AUVs supported would be twice the



(a) Iver3



(b) REMUS 100

**FIGURE 5:** WEC POWER GENERATION: VARYING SIGNIFICANT WAVE HEIGHT.

number of AUV docks connected to the WEC.

Using the same methodology, the power generation plots in Fig. 6 show peak period (s) varying on the x-axis with the constants shown in Table 5.

The power generation plots in Fig. 7 show characteristic dimension (m) varying on the x-axis with the constants shown in Table 6.

Analysis shows that powering two AUVs is feasible using a WEC with a characteristic dimension between 1.0-1.5 m in certain regions. Using the linear trend hydrodynamic efficiency, the only condition where the power generation requirement could

**TABLE 5:** CONSTANTS USED WITH VARYING PEAK PERIOD.

$H_s$ (m)	B (m)	d (m)	$\rho$ (kg/m <sup>3</sup> )
1.5	1	1000	1025

**TABLE 6:** CONSTANTS USED WITH VARYING CHARACTERISTIC DIMENSION.

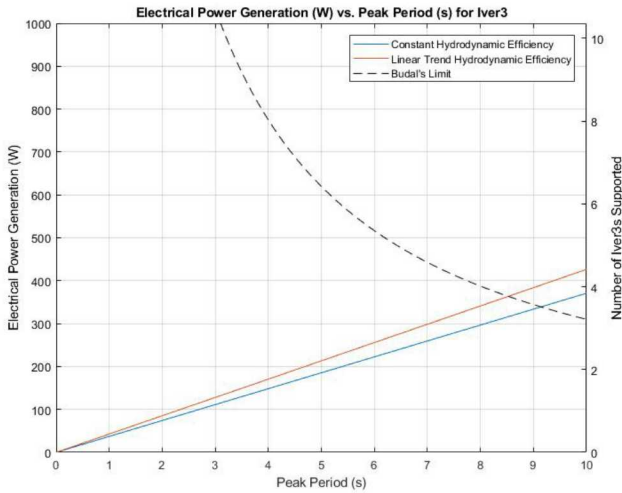
	Black	Red	Blue	Green
$H_s$ (m)	1.0	1.5	2.0	2.5
$T_p$ (s)	4	4	5	5
d (m)	1000	1000	1000	1000
$\rho$ (kg/m <sup>3</sup> )	1025	1025	1025	1025

not be met is if the wave power density is lower than 4.42 kW/m (i.e.,  $H_s = 1.5$  m,  $T_p = 4$  s). As shown in Fig. 4, this wave power density is met or exceeded by a large area of the South China Sea during December, and is met by small areas during June. For a wave power density greater than or equal to 9.81 kW/m (i.e.  $H_s = 2.0$  m,  $T_p = 5$  s), it is possible to power 4 AUVs in rotation with a characteristic dimension between 1.0-1.5 m. This wave power density can be found in large areas of the South China Sea during December.

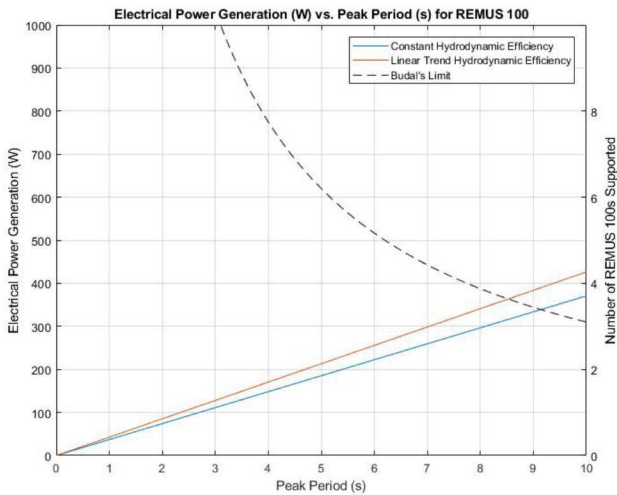
Powering more than two AUVs using a WEC with a characteristic dimension less than 1.5 m would not be feasible year-round. As shown in Fig. 4, the wave power density during June would not be able to support the necessary power generation if the WEC had a characteristic dimension less than 1.5 m except in rare cases. While using a WEC with a characteristic dimension greater than 1.5 m might be unwieldy and more challenging for operations, it may be possible to use a series of smaller devices in cases such as this.

## CONCLUSION

AUVs currently need to be recharged manually which limits their mission endurance and requires a significant amount of time. The Navy would benefit from developing a system that could charge AUVs autonomously offshore. Wave energy converters have the ability to produce electricity from the mechanical energy in ocean waves and could potentially supply renewable energy to an AUV recharging station. A small, heaving WEC would be best suited to remain hidden and meet the requirements for power generation. Using equations from linear wave theory and various measures of efficiency, electrical power



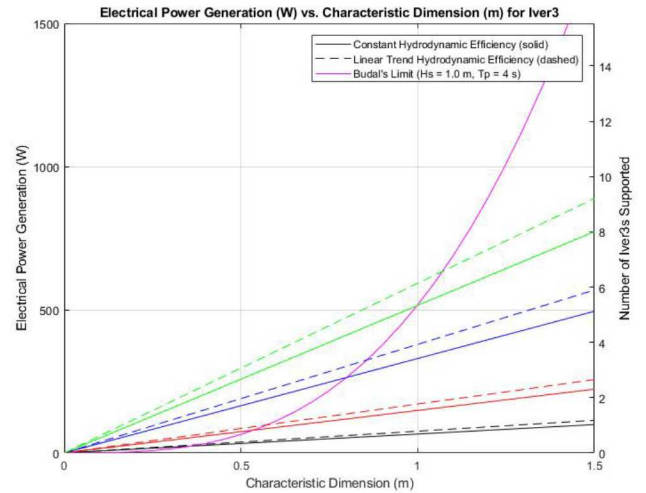
(a) Iver3



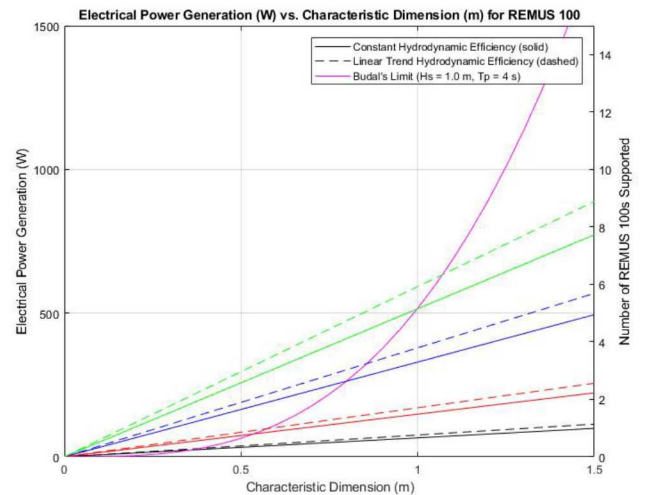
(b) REMUS 100

**FIGURE 6: WEC POWER GENERATION: VARYING PEAK PERIOD.**

generation could be calculated according to the wave characteristics of a region and WEC waterplane area. Analysis of power generation plots showed that, in a representative geographic region (South China Sea), it is feasible to support a system of two AUVs with a heaving WEC between 1.0-1.5 m in diameter in certain regions. Supporting more than two AUVs is possible, but would be significantly more difficult due to cost and size restrictions. The methodology described in this paper could be used to evaluate the feasibility of wave-powered AUV support in any geographic area of interest, given sufficient wave data.



(a) Iver3



(b) REMUS 100

**FIGURE 7: WEC POWER GENERATION: VARYING CHARACTERISTIC DIMENSION.**

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that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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