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Final Project Report

Wave Energy Converter for Drifter Applications (WECDA)

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Project Reference: EE-PA_ 202502_01

30 October 2025

Table of Contents

Introduction

The requirements of ocean monitoring have driven the continued development of sensor platforms such as Lagrangian drifters, where autonomy remains a key design consideration. Energy harvesting (EH) has proven to be a reliable approach for extending the operational lifetime of these autonomous systems [1]. While solar panels are the most common commercial EH solution for enhancing drifter autonomy (e.g., Sofar: Spotter; Fastwave: Voyager Solar), their applicability is limited. To ensure accurate surface current tracking, drifters must minimize wind influence by remaining mostly submerged, which significantly reduces the effectiveness of solar energy harvesting. Moreover, relying on a single EH source provides only a modest improvement in system autonomy.

In this project, we investigated the feasibility of harvesting the oscillatory motion of the drifter induced by ocean waves - a concept that has not been extensively explored to date. The work focused on understanding the dynamic interaction between the drifter and the surrounding water load, which is essential for designing an efficient wave energy converter (WEC). It was found that the captured energy can be maximized by properly designing the internal WEC with a natural frequency close to that of the drifter’s movement [2]. The aim was to achieve resonance between the WEC and the drifter’s motion in order to maximize the amplitude of the former’s moving parts and increase the harvested energy.

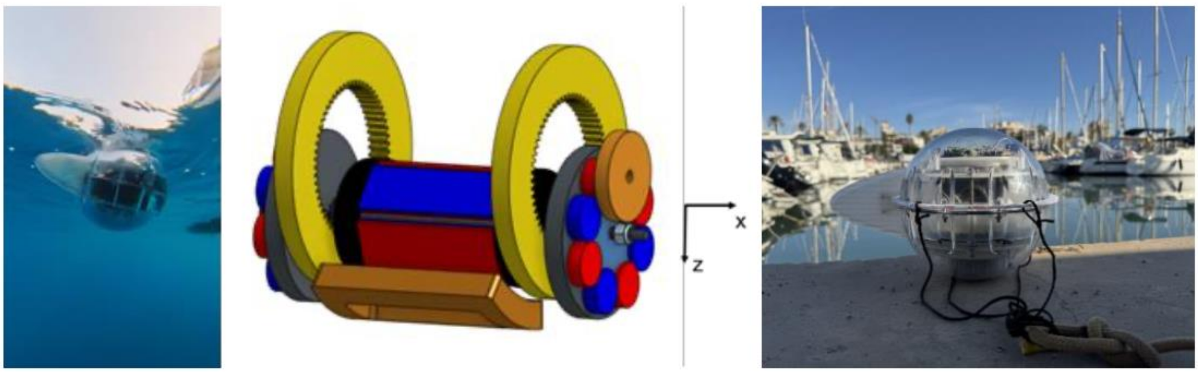

Figure 1: a) WEC in the water; b) Mechanical Design; c) WEC prepared for a long-term test

Objectives

The main objective of this project was to evaluate the feasibility of energy harvesting from ocean waves into electricity to power autonomous ocean drifters. Specifically, the project aimed to:

- **Validate** the performance of a wave energy converter prototype designed to capture the drifter's oscillatory motion.
- **Characterize** the dynamic interaction between the drifter and the surrounding water to optimize energy harvesting efficiency.
- **Assess** the performance of the autonomous measurement and power management systems under both laboratory and real-sea conditions.
- **Demonstrate** the long-term operational reliability of the WEC through an extended field deployment near the EMSO-OBSEA observatory.
- **Collect and analyze** environmental and performance data to support future improvements in energy harvesting for marine monitoring platforms.

Methodology

The project was carried out in three main stages. In the first stage, the energy harvester prototype was validated under controlled laboratory conditions using a robotic arm. This setup reproduced the drifter's oscillatory motion through programmable rotational and translational movements, allowing for the systematic evaluation of the WEC response at various excitation periods and amplitudes.

In the second stage, the system was tested in real sea conditions using the configuration shown in Figure 2 and Figure 3. The drifter incorporated an autonomous measurement system, a power management unit (PMU), an inertial measurement unit (IMU), and the WEC with its associated electronics. The PMU, based on the e-peas AEM30330 chip [3], performed maximum power extraction (ZMPPT) from the rolling-mass generator and managed the charging of the energy storage element (ESE). Electrical signals from the harvester were conditioned using a current sense amplifier (CSA) and digitized through an analog-to-digital converter (ADC) before being processed by an ESP32 microcontroller. The IMU provided tri-axial acceleration and angular rate measurements, while the wireless link enabled real-time data transmission to a computer onboard the support vessel. An external fin was installed to help maintain the drifter aligned with the wave direction, improving the efficiency of energy extraction. The system operated continuously during several-hour deployments under realistic sea states.

In the final stage, a long-term deployment was conducted near the EMSO-OBSEA observatory to study the WEC's performance under a wider range of natural forcing conditions. Environmental data from the local ADCP and weather station were used as contextual information to interpret the long-term behavior of the system.

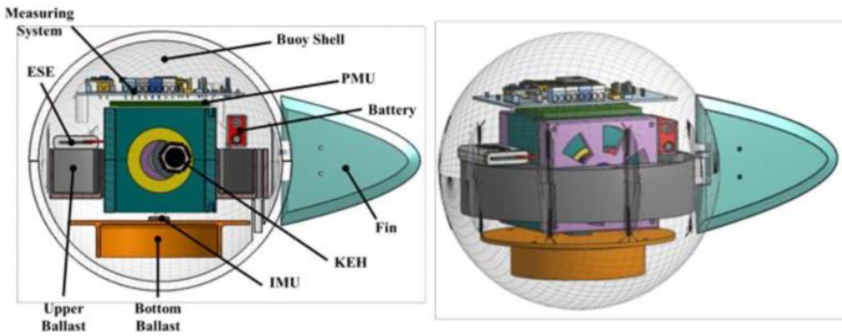

Figure 2: WEC setup of the second test including the Measurement system, the PMU and the external fin

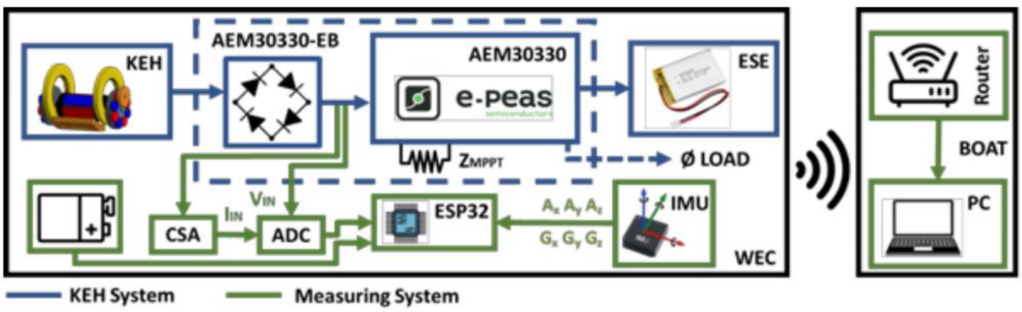

Figure 3: Overview of the WEC architecture. For further details on the measurement system, see [1].

Results

A comprehensive set of laboratory and short sea trials was performed to characterize the behaviour of the WEC under realistic excitation. All data is available at [4]. After the robotic-arm validation (Figure 4a), the fully integrated drifter (Figure 4b) was deployed over five days using different internal configurations of the generator, coil geometries, and load conditions. A total of nine measurement sets (M1–M9) were collected.

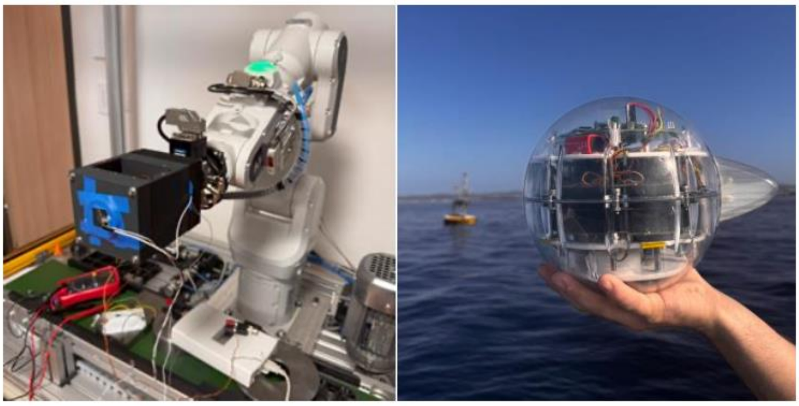

Figure 4: a) EH test on the Robot; b) WEC ready for deployment

During these deployments, the drifter experienced a wide range of wave-induced motions, with roll oscillations commonly within ±20°, as illustrated in Figure 5. The autonomous measurement system captured synchronous motion data from the IMU together with electrical output, enabling the estimation of instantaneous power.

Two load strategies were considered during the sea tests: fixed resistive loads, used to capture the raw electromechanical response of the system, and adaptive loads controlled by the AEM30330 chip through its ZMPPT functionality, which adjusts the electrical impedance to maximize energy transfer to the storage element.

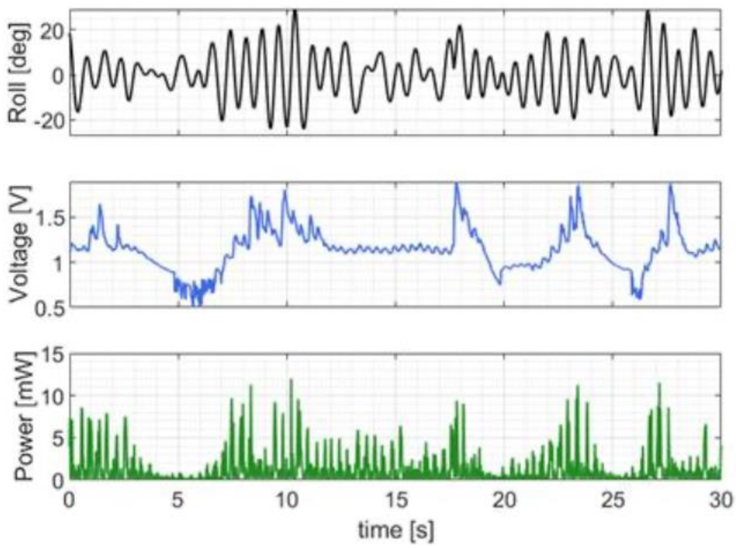

Figure 5: Time interval of 30-second duration from the measurement M9

Across all nine sea measurements, the average harvested power ranged from 0.16 to 0.80 mW, depending on the excitation conditions and coil configuration. Short-term peaks reached up to 13 mW, typically associated with high-amplitude roll events or favourable combinations of pitch and surge. Configurations using bottom-mounted coils and higher natural-frequency settings (around 1.32 Hz) produced the highest mean power levels. Measurements M8 and M9 exhibited the most stable performance, achieving average outputs close to 0.8 mW. These results validate the feasibility of harvesting sub-1 Hz drifter motion and demonstrate the effectiveness of combining a rolling-mass resonator with adaptive power management in real marine conditions.

For long-term deployment, the system was reconfigured to operate autonomously, without the high-rate measurement electronics used in the short-sea tests. The measurement system of Figure 3 was removed, as no nearby support vessel was available to receive real-time data. Instead, a Sigfox communication module (TD1205P - [4]) was connected at the load port and powered through the PMU using energy from both the KEH and the ESE. This module periodically measured the ESE voltage and the internal temperature, transmitting one data frame to the Sigfox network every hour. These two variables were therefore the only parameters monitored during the deployment.

Figure 6 shows the evolution of the battery (ESE) voltage and the internal temperature during the first week of operation. The voltage remained stable around 3.6 V, indicating reliable energy generation from the WEC and correct behaviour of the PMU. Occasional voltage peaks correspond to brief electronic resets, which reduce the load momentarily and cause the voltage to rise. The temperature trend reflects the microcontroller’s internal sensor, which follows the daily heating–cooling cycle of the drifter shell, confirming continuous system operation rather than changes in the external environment.

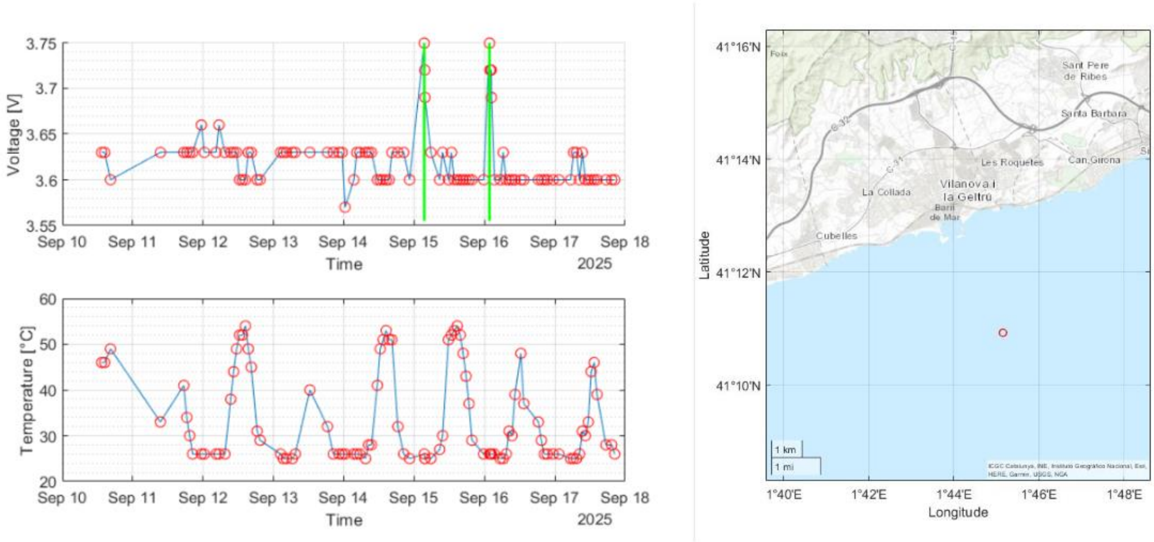

Figure 6: First week of long-term deployment results. a) Voltage and Temperature; b) Position of the drifter

From the recorded data, the average and maximum power densities were estimated at approximately 1 µW/cm3 and 16 µW/cm3, respectively. Considering the compact size of the device and its low resonant frequency (approximately 1–1.3 Hz), these values are competitive with those of existing small-scale electromagnetic harvesters and exceed the performance of several pendulum-based and hybrid mechanisms reported in the literature. Overall, the results confirm the WEC's capability to support autonomous drifter applications. With average power levels of approximately 0.8 mW, the system can intermittently operate low-power sensing hardware and sustain wireless data transmission over ultra-low-power networks, such as Sigfox, which require short energy bursts of only a few millijoules. Future tests combining the harvester with a communication module will be valuable to demonstrate this capability in an integrated configuration. In particular, using a smaller ESE would allow the voltage dynamics to better reflect the balance between KEH generation and Sigfox consumption, enabling a more detailed analysis of the system's energy behaviour.

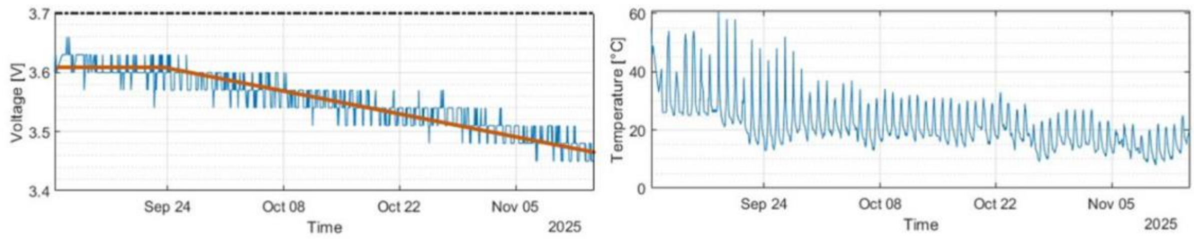

Figure 7: Long-term evolution of a) battery voltage and b) internal temperature during the full one-month period. The orange line represents the moving average of the voltage. The first phase shows a nearly constant trend consistent with continuous energy contribution from the WEC, while the later phase displays the expected gradual decrease when the system operates without additional energy input.

Finally, Figure 7 shows the evolution of voltage and internal temperature over the full one-month period. During the initial phase, when the drifter was deployed at sea, the average voltage remained nearly constant thanks to the energy supplied by the WEC (orange trend line). For safety reasons, the unit was later retrieved and continued to operate on land, transmitting data with the same consumption profile but without generating energy. That proves the WEC's capability to supply power to the system. In this second phase, the gradual decrease in voltage reflects the battery's discharge under identical load conditions. The temperature record also shows higher and sharper peaks on land due to direct solar exposure, while still confirming continuous system operation.

Conclusions and Future work

This project successfully demonstrated the feasibility of using a wave energy harvester to generate electrical power from the oscillatory motion of ocean drifters. The developed WEC showed stable operation and competitive power density compared to existing small-scale marine energy harvesters, confirming its potential for long-term ocean monitoring applications without relying exclusively on solar panels. Future work will focus on optimising the coil parameters, magnetic circuit geometry and power management strategy to further increase the conversion efficiency and adapt the system to different drifter designs. A journal article is currently being prepared to present all experimental configurations and results, along with a deeper analysis of the device's performance, in order to provide a comprehensive overview of the work carried out in this project. Overall, the achieved results show strong promise for autonomous marine buoys operating sustainably in low-frequency wave environments.

Acknowledgements

This work benefited from access to OBSEA, an EMSO ERIC Site, operated by Universitat Politècnica de Catalunya (UPC), and was financially supported by EMSO ERIC, Agreement No. EE-PA_202502_01. Authors acknowledge support provided by the project GAČR no. 25-14505L "Advanced techniques for effective kinetic nonlinear energy harvesting technologies". Additionally, this research was supported by the project "Mechanical Engineering of Biological and Bio-inspired Systems", funded as project No. CZ.02.01.01/00/22_008/0004634 by Programme Johannes Amos Commenius, call Excellent Research.

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