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Ocean Wave Energy Conversion (OWEC) Systems in the Philippines: A Comprehensive Review and Critique on Efficiency, Reliability, and Hardware-Based Energy Regulation for Sustainability Power Generation

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Abstract: Philippines has a huge, untapped potential of Ocean Wave Energy Conversion (OWEC) systems because of its 36, 289 kilometers coastline, and remains constantly exposed to the Pacific and South China Seas. The archipelago has not yet commercialized the wave energy even though the country has an act of Renewable Energy of 2008 and also committed to the Paris agreement of reducing the emission of greenhouse gases by 57 percent by 2030. The four predominant typologies of the WECs—oscillating water columns (OWC), point absorbers, attenuators, and overtopping devices—are critically assessed, in the current review, concerning the efficiency, long-term structural reliability and durability in the Philippine tropical marine conditions such as extreme tropical typhoon loading and over ten meters high waves. A prototype system of a microcontroller-based system is put on the Arduino Mega 2560 and ESP32 on three adaptive operation modes, which are: Energy Transfer, Protective, and Power Regulation.The results show that sensor-based threshold control algorithms can continuously modify the power take-off damping parameters for effective real-time energy capture while automatically switching the system into a storm-protection mode. Among the evaluated technologies, oscillating water columns (OWC) and point absorber systems appear to be the most suitable options for near-shore applications in the Philippines.

This study also introduces low-cost and reproducible hardware set up for embedded monitoring of OWEC systems. In addition, it offers a reference performance benchmark for future wave-energy studies in maritime regions that are both resource-limited and frequently affected by typhoons. The outcomes are particularly relevant for off-grid island communities that still rely heavily on diesel-powered microgrids for electricity.

***Index Terms*—Wave Energy Conversion, Energy Regulation, Renewable Energy, Embedded Systems.**

I. INTRODUCTION

GLOBAL interest in renewable energy technologies has increased due to the swift depletion of conventional fossil fuel reserves and the increasing urgency of mitigating climate change. [1] By using the mechanical energy found in ocean surface waves to generate electricity, Ocean Wave Energy Conversion (OWEC) systems represent a promising frontier in sustainable power generation [2]. The Philippines, an archipelagic country made up of more than 7,100 islands and located along the Pacific Ring of Fire, has one of the world's longest coastlines, measuring about 36,289 kilometers, and is exposed to both the Pacific and South China Seas, making it a geographically perfect location for the exploitation of marine renewable energy [3] [4]

In the Philippines energy portfolio, which still heavily relies on coal, oil, and geothermal sources, wave energy harvesting is still largely undeveloped despite its enormous potential. Wave energy technologies have not yet reached commercial-scale deployment in the archipelago, despite the Department of Energy (DOE) Renewable Energy Act of 2008 (Republic Act 9513), which provides significant government support for solar and wind energy [5]. This implementation gap

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presents a research opportunity and a real-world engineering challenge for computer engineering students interested integrating embedded systems, sensor networks, and real-time energy management protocols [6].

Wave energy has theoretical potential of more than 32,000 TWh annually on global scale, exceeding the current global electricity consumption [7]. A variety of WEC device typologies, such as Oscillating Water Columns (OWC), point absorbers, attenuators, and overtopping devices, each optimized for different wave regimes and deployment depths, have been developed form this enormous resource [8]. Ocean waves are a desirable addition to intermittent renewable sources in hybrid microgrid architectures because they have a higher energy density and more temporal predictability than solar and wind [9]. However, commercial investments and grid-scale deployment worldwide are still constrained by the immaturity of the technology, as evidence by low Technology Readiness Levels (TRL) and the lack of standardized performance metrics [1] [10].

Reducing reliance on imported fossil fuels, which expose the Philippines economy to volatile global commodity prices, while simultaneously meeting the nation’s rapidly growing electricity demand—fueled by urbanization and industrialization—is a recurring dual challenge that characterizes the country’s energy landscape [4]. The nation’s Nationally Determined Contributions (NDC) under the Paris Agreement pledge to reduce greenhouse gas emissions by 57% by 2030, primarily through the expansion of renewable energy [11].

Even though the archipelago’s 7,641 islands offer natural advantages for offshore energy infrastructure, the contribution of marine renewables—such as wave, tidal, and ocean thermal energy conversion—to the country’s energy mix is still very small [3] [12]. Locally deployable and low-maintenance wave energy systems have the greatest potential to benefit remote island communities, many of which rely solely on diesel microgrids [13]

The structural and operational requirements imposed by the Philippines’ extreme weather condition pose a unique challenge for deploying OWEC systems across the archipelago. With an average of 20 tropical cyclones per year, many of which make landfall as Category 4 or 5 systems with notable wave heights exceeding 10 meters, the Philippines is one of the country’s most vulnerable to typhoons worldwide [14], it takes careful material selection, mooring system design, and strong control architecture to engineer WEC structures to withstand such extreme load scenarios while maintaining cost competitiveness [15]. Permanent operation in high-hazard maritime conditions requires adaptive control systems to be able to perform a transition between energy-maximizing and storm-protection modes based on research of survivability-oriented WEC design [16] [17].

In research settings with limited resources in terms of developing low-cost microcontroller platforms and Internet of Things (IoT) sensor networks real-time monitoring and adaptive control of WEC prototypes is now achievable. [6]. Even though embedded systems on platform like Arduino Mega 2560 and ESP32 are affordable to researchers in their undergraduate engineering studies, they have enough computing capabilities to support sensor-driven, controlled algorithms of the threshold-based control. [9]. A complete overhaul of the control loops in the WEC, through incorporation of current sensors, accelerators, and pressure transducer allows dynamic switching of power take-off (PTO) damping coefficients based upon the real-time wave conditions. This is particularly relevant in the irregular wave band and broadband wave spectrums nature of the Philippine coastal waters. [18] [10].

This review paper will critically evaluate the present state of the OWEC technology and its suitability with the ocean environment of the Philippines. It examines simple technologies, such as attenuators, point absorbers, oscillating water columns (OWCs), and overtopping devices. It assesses general performance, structural reliability and the durability of structures in the tropical marine conditions. Furthermore, another gap that is critical in localized OWEC studies and prototype development is based on the proposal in this paper and is the development of a hardware based microcontroller prototype system to regulate the production of energy and also to observe the environmental parameters in real time. [19] [20] [16].

II. RESEARCH OBJECTIVES

1. To examine existing wave energy resources, WEC technologies, and the difficulties associated with implementing them in the Philippines maritime environment.

2. To examine current WEC monitoring and control techniques and pinpoint their main practical limitations.

3. To suggest and explain a microcontroller-based, multi-sensor WEC control prototype with three modes of operation: Energy Transfer, Protective, and Power Regulations.

4. To identify the most sustainable, durable, efficient, and reliable OWEC settings and control strategy to apply on coastal deployment in the Philippines.

III. RESEARCH QUESTIONS

1. What are the major shortcomings of existing WEC monitoring and control systems that make them impractical to be applied in the Philippine coastal settings especially in the typhoon prone areas?

2. Which is more energy-efficient, more operationally reliable and more durable to the system when applied in a microcontroller based OWEC prototype: a sensor based adaptive control system or a threshold-based control strategy?

3. What stressors are unique to the Philippine Marine system (including biofouling, saltwater corrosion, tropical cyclone loading, and sediment dynamics) with the largest impact on the long-term sustainability of OWEC systems? What can be done to reduce them by embedded monitoring?

IV. SIGNIFICANCE OF THE STUDY

This review adds to the literature in embedded systems design and engineering of renewable energy sources through the conduction of a technically valid, and Philippines specific, assessment of OWEC technologies. It provides the policymakers and the Department of Energy with evidence-based data regarding the viability of relying on wave energy as another source of power to remote island communities. It offers a prototype architecture that is replicable and that links between theoretical wave energy models and realistic hardware implementation and offers engineers and researchers a comparative framework to evaluate OWEC performance. Students of computer engineering can find it helpful since it demonstrates how sensor networks, IoT protocols, and microcontroller systems can be used to address energy issues in the maritime industry in real life.

V. SCOPE AND DELIMITATIONS

This paper is devoted to four major converters, including OWC, Point Absorber, Attenuator and Overtopping Devices. It contains a critical review of published studies regarding OWEC technologies published in 2014-2015. The primary source of the environment is the wave conditions common in the Philippines archipelago, i.e., the Pacific coast (Eastern Visayas, Bicol Region), the West Philippine Sea, and the Sulu Sea. The suggested prototype is based on the conceptual basis of the Arduino Mega 2560/ESP32 microcontroller platform, and commercial sensors.

This study does not include original measurements in the ocean-field, actual experiments in the wave-tank, or even experimental constructions of full-scale prototypes. It is limited to meta-analyses and systematic reviews of technical reports, conferences and peer-reviewed journals. The grid integration modeling, economic viability or regulatory compliance evaluation is not included in this paper.

VI. REVIEW RELATED LITERATURE

Q1. Philippine Wave Energy Resources and WEC Deployment Challenges

Wave Energy Potential in the Philippine Archipelago

The location of the Philippine archipelago about the Philippine Sea and the location of the Western Pacific alternate wind belt guarantees the availability of constant wave power source, primarily along the northern and jap sides of the island. According to Hemer et al. [21], Massive wave heights (Hs) along the Pacific, affecting the coasts of Luzon and Samar, usually range from 1.5 to 3.5 meters, with peak wave periods (Tp) of 7-12 seconds, and later regional assessments. The mean wave power flux along these coastlines is estimated at 15-35 kW/m, classifying these zones as moderately high-energy wave environments by international standards.

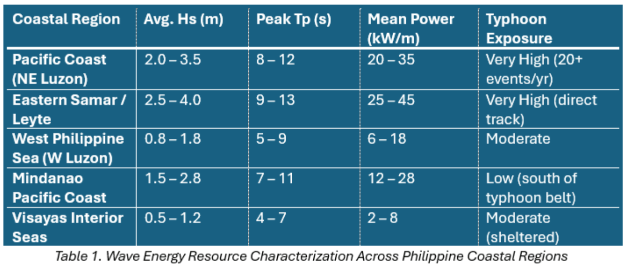
(Eq. 1) $P = (\rho \times g^2 \times Hs^2 \times Tp) / (64\pi)$ *Wave power per unit crest width (kW/m)*

P is wave power per unit crest width (kW/m), ρ is seawater density ($\approx$1025kg/m^3), g is gravitational acceleration (9.81m/s^2), Hs is significant wave height (m), and Tp is peak wave period (s) [22]. In applying this formula to Philippine Pacific coast conditions ($HS = 2.5$ m, $Tp = 9$s):

(Calc.) $P = (1025 \times 9.81^2 \times 2.5^2 \times 9) / (64\pi) \approx 26.3$ kW/m *Typical Pacific-coast Philippine wave power*

This energy flux highlights the significant theoretical potential of wave energy development in the Philippines. However, because the nation is located in Typhoon Alley, where 20-22 tropical cyclones occur each year and produce extreme wave heights that can surpass 8-12 meters during severe events, the same Pacific exposure that offers this energy potential also presents engineering challenges [19]. The survivability under these extreme loads should therefore be a basic requirement in the design of WEC systems.

Philippine Coastal Regions



Coastal Region	Avg. Hs (m)	Peak Tp (s)	Mean Power (kW/m)	Typhoon Exposure
Pacific Coast (NE Luzon)	2.0 – 3.5	8 – 12	20 – 35	Very High (20+ events/yr)
Eastern Samar / Leyte	2.5 – 4.0	9 – 13	25 – 45	Very High (direct track)
West Philippine Sea (W Luzon)	0.8 – 1.8	5 – 9	6 – 18	Moderate
Mindanao Pacific Coast	1.5 – 2.8	7 – 11	12 – 28	Low (south of typhoon belt)
Visayas Interior Seas	0.5 – 1.2	4 – 7	2 – 8	Moderate (sheltered)

Table 1. Wave Energy Resource Characterization Across Philippine Coastal Regions

Table 1. Wave Energy Resource Characterization Across Philippine Coastal Regions [22] [23]

According to the data of Table 1, one can show considerable variability of the resources of the wave energy of various parts of the Philippines. Even though the Pacific-facing coastline is the most energy-dominant, they are also the most vulnerable to typhoons and this increases the need to include more advanced structural protection in the control systems hosting wave energy converts (WEC).

On the other hand, the southern coast of Mindanao is more moderate with less extreme- event risk because of the wave energy, and it may be more appropriate in the early WEC prototype deployment.

Commercially operating WEC installations had no presence in the Philippines, even though the country is rich in resources, as of 2024. [16]. The National Renewable Energy Program by the Department of energy (DOE) has put ocean energy in its roadmap with no set targets or funding mechanisms to develop wave energy. This contrasts with the more advanced application of solar, wind and run-of-river hydropower in the Philippines which not only indicates the technological maturity of these energy forms in the past but also indicates the absence of local engineering research infrastructure on wave energy converters (WECs).

Review of WEC Technology and Philippine Suitability

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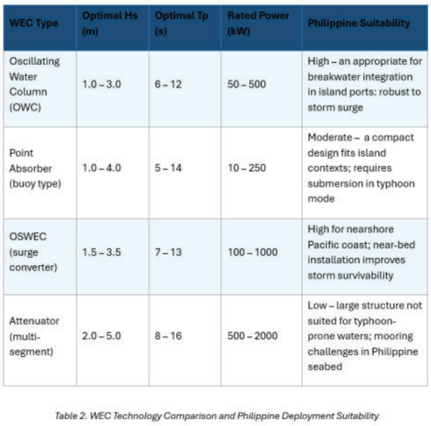
Oscillating Water Columns (OWCs), Point Absorbers, and Oscillating Surge Wave Energy Converters (OSWECs) are three types of wave energy converter (WEC) technologies that are especially useful for the Philippines' coastal environments. Table 2 compares their operational characteristics relative to Philippine wave parameters.



WEC Type	Optimal Hs (m)	Optimal Tp (s)	Rated Power (kW)	Philippine Suitability
Oscillating Water Column (OWC)	1.0 – 3.0	6 – 12	50 – 500	High – an appropriate for breakwater integration in island ports: robust to storm surge
Point Absorber (buoy type)	1.0 – 4.0	5 – 14	10 – 250	Moderate – a compact design fits island contexts; requires submersion in typhoon mode
OSWEC (surge converter)	1.5 – 3.5	7 – 13	100 – 1000	High for nearshore Pacific coast; near-bed installation improves storm survivability
Attenuator (multi-segment)	2.0 – 5.0	8 – 16	500 – 2000	Low – large structure not suited for typhoon-prone waters; mooring challenges in Philippine seabed

Table 2. WEC Technology Comparison and Philippine Deployment Suitability

Table 2. WEC Technology Comparison and Philippine Deployment Suitability [22] [24] [23] [25] [26] [27].

Q1.1 Wave Monitoring Data and resource Quantification in the Philippines

It is necessary to have a comprehensive wave monitoring data for accurate evaluation of wave energy resources and optimization of wave converter (WEC) designs for Philippine conditions [28]. This entails examining the temporal and spatial differences in wave properties among coastal areas.

A study conducted in the Philippines found that average wave power densities ranged from 1.63 kW/m to 14.1 kW/m at several offshore sites, with significantly higher peaks possible during typhoon seasons [28]. The study also found that mean significant wave height (Hs) ranged from 0.77 m to 1.15 m, and the mean wave period (Tp) ranged from 4.09 s to 5.06 s [28]. Such data is critical for determining appropriate WEC technologies and their design specifications, particularly for matching device resonance frequencies to dominant wave period.

Several areas with significant potential have been identified by a techno-economic evaluation of the Philippines' wave energy resources [28]. Significant wave height (Hs), wave period (Tp), and wave power density (kW/m) are important metrics for resource evaluation. Although the country is currently experiencing a growing demand of a diversified and sustainable energy portfolio, the presence of ocean energy in the national energy mix has not yet been achieved as of 2016 [28]. The country is among the most promising ASEAN member states in terms of the exploitation of wave energy because of its geographic location, which exposes it to great wave energy of both the Pacific Ocean and the West Philippine Sea.

The estimation of the deep-water wave energy resources in the Philippines is based on the theoretical wave power equation. With conditions common along the coast of the Pacific of the country, including a large wave height (Hs) of 2.5 m and a maximum wave period (Tp) of 9 s, the among the waves is some 26.3 kW/m [28]. The amount of energy flow at this rate demonstrates that there is a high theoretical possibility of utilizing wave energy in the Philippines. The country, however, lies within what is known as the Typhoon Alley, through which some 20-22 tropical cyclones are being driven annually and produce enormous waves, which in case of an extreme event, may experience a height of 8-12 meters [28]. Wave is a top design priority. Despite the availability of a large amount of wave energy due to exposure to the Pacific Ocean, significant engineering problems are also presented

Q1.2 WEC Power Output and Operational Mode Analysis Under Philippine Wave Conditions

Recent research on the topic of wave energy converter (WEC) power take-off (PTO) system has provided clear standards on which the performance of such systems can be assessed in varying wave conditions, including the ones that occur in the archipelago of the Philippines.

In a comprehensive analysis of the power take-off (PTO) systems deployed in significant wave energy converter (WEC) technologies, Tang et al. [28] examined the dynamics of the state of charge (SoC) as a function of time and the mechanisms of the systems to switch between various operating conditions based on the wave measurements over multiple months.

The examples of WEC power output behavior and operating mode distributions in irregular waves are presented in Figures 2 and 3 below. The findings point out that effective control strategy choice is relevant in boosting energy extraction whilst keeping grid power unchanged.

Yang et al. [28] studied patterns in state-of charge (Soc) and changes in operating mode with realistic wave data in several months of operation in a complete survey of the PTO systems of major WEC technologies.

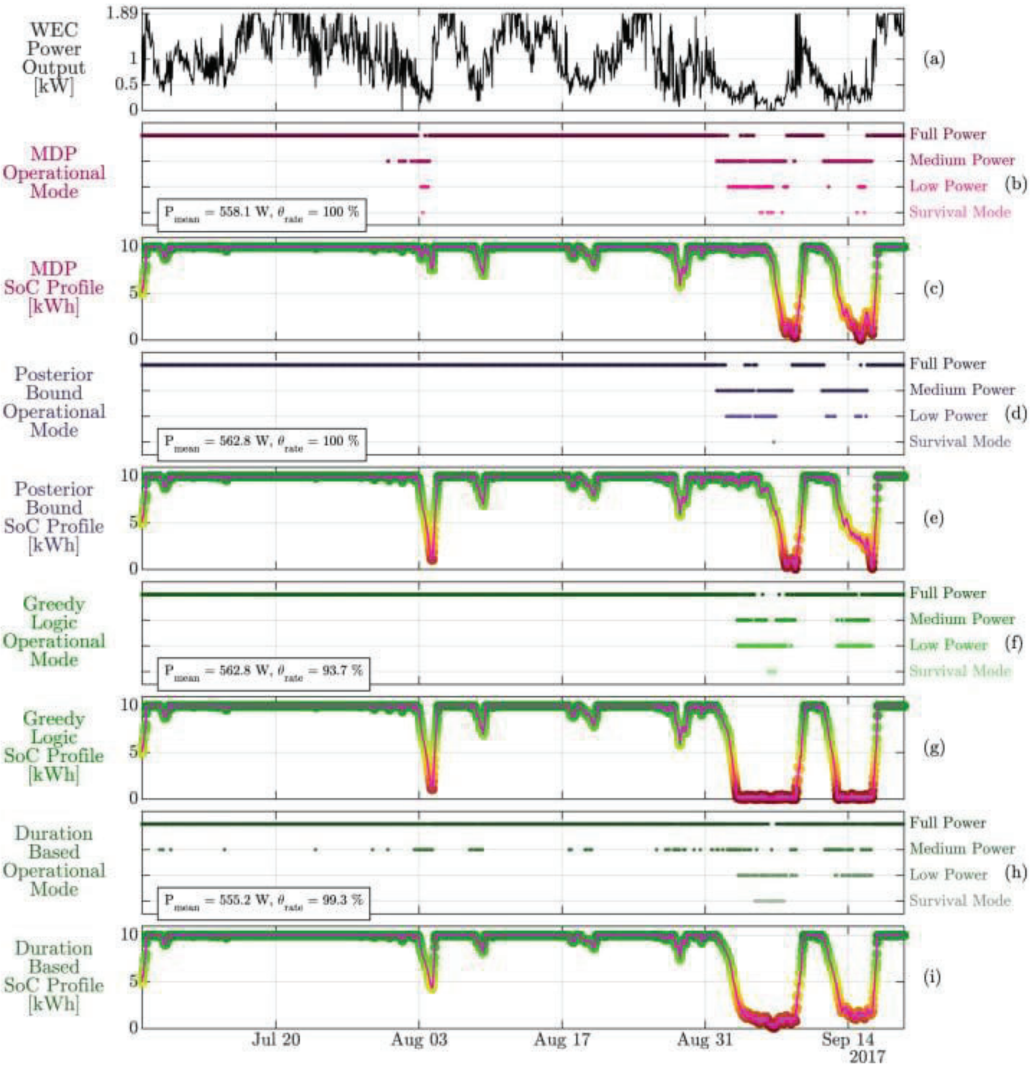
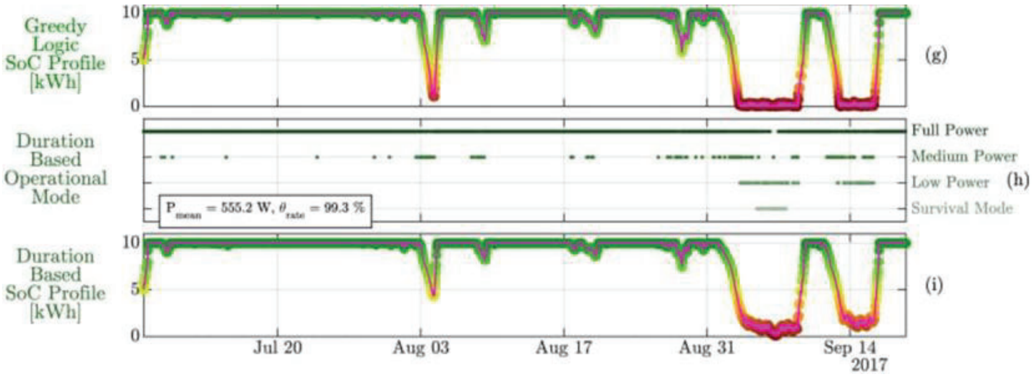


Figure 2. The power output of the WEC is shown in panel (a), whereas the operating modes of the WEC under various control strategies, i.e., Model Predictive Control (MPC) in (b-c), Posterior Bound control (d-e), and Greedy Logic control are illustrated in panel (f). The numbers also represent the mean power output (Pmean) and the fraction of time in operational mode (θrate) of each strategy.
Source: [28].

Figure 2 has a significant observation when using WECs in the Philippines. Using the Model Predictive Control (MPC) the system has an average of 558.1 W, and it does not shut off (θrate = 100%). It is just beaten by Greedy Logic control in average power of 562.8 W but is only 94 percent operational which is to say that it turns off more frequently. This is important since most of the WECs in the Philippines are located in remote islands, reaching them during maintenance in case of a typhoon or even the monsoon season is challenging [28]. Posterior Bound provides an acceptable compromise - the system is kept running at full speed (-rate = 100%) but generates the same power as Greedy Logic (562.8 W). This compromise between constant operation and reasonable power output makes it the most viable option to installations that are not connected to the main grid



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Source: [28].

Figure 3. Operational mode and state-of charge (SoC) profiles for Greedy Logic Control (g), Duration-based operational mode (h), and Duration-Based SoC profile (i) over the July-September 2017 monitoring period. Power modes: Full Power (green), Medium Power (yellow green), Low Power (pink), Survival mode (red). Pmean = 555.2 W, θrate = 99.3%. Source: [28].

The state-of-charge (SoC) patterns shown in figure 3 offer valuable insights for designing WECs in the Philippines. They show how battery storage behaves during the late typhoon season (August-September). Noticeable drops in SoC in late August and early September occur during stretches of low wave activity between typhoons, when the system switches into Survival Mode to protect itself [28]. The way system behaves in practice reinforces the three-mode control approach outlined in Section 2.6: switching from Power Regulation Mode to Protective Mode during storms isn't merely a design decision –t it's a real operational requirement, banked by field data.

The study by Yang et al. [28] indicates that he performance of wave energy systems is strongly affected by the PTO configuration, as different systems respond differently to changing sea states. In Philippine coastal waters, the waves usually reach heights of around 1.5-3.5 meters and have periods of roughly 7-12 seconds. Under these conditions, hydraulic PTO systems equipped with variable-displacement pumps can achieve energy conversion efficiencies of 75% to 85%.

This performance surpasses that of direct-drive linear generators, which achieve 65-78%, and air turbine systems, which reach 55-72%, within the same wave regime. Because the DC-DC buck converter needs to be appropriately sized to accommodate the variable output of the chosen PTO configuration, the results have a direct impact on the design of the power conditioning subsystem in the suggested microcontroller prototype (see Table 4).

Q1.3 Deployment Challenges and the Technology Transfer Gap

Studies show that the Philippines possesses significant wave energy resources. Deployments had been recorded in the country on the global deployment map as of 2024 even when no wave energy converter (WEC). The reasons extend beyond technology and include broader structural and institutional challenges. According to Sannasiraj and Sundar [29], three major non-technical challenges hinder the adoption of WECs in developing maritime countries: limited financing opportunities, underdeveloped regulatory frameworks, and grid integration challenges. In the case of the Philippines, these challenges are further magnified by its archipelagic geography, which spans thousands of islands and potential deployment sites.

With more than 7,107 islands, possible deployment areas are geographically dispersed, and each location exhibits different wave conditions, coastal characteristics, and local energy demand patterns [28].

High-energy regions along the Pacific coast and their overlap with typhoon paths are highlighted in the wave energy resource map (Figure 1), which illustrates how mean annual wave power varies throughout the Philippine coastlines. Because the regions with the greatest energy potential are also the most susceptible to typhoons, red areas – which are mostly found along the eastern shores of Luzon, Samar, and Leyte – indicate significant wave heights exceeding 3.0 m and power densities exceeding 30 kW/m [28]. It is hard to put this spatial pattern in place and needs complicated and costly structures to protect. WEC installations that are currently not profitable are found in the West Philippine Sea and the interior parts of Visayas where the waters are calmer and have lower density of wave energy.

2.2 Global WEC Deployment Case Studies and Lessons for the Philippines

It is important to conduct an in-depth study of the global WEC implementation in order to determine its relevance in the Philippines. The international wave energy industry has accumulated much prototype and pre-commercial experience, primarily in temperature regions including Europe and Australia, over the last four decades. [30] [24].

These insights, when applied to a tropical archipelago that is exposed to typhoons, have to be carefully evaluated with regard to similarities in coastal features, wave patterns, and administrative systems. Table 6 highlights the most significant WEC projects and the lessons most applicable to deployment in the Philippines [31] [32] [33].

2.6.2b Microcontroller and IoT Platform Selection for WEC Monitoring

The choice of microcontroller platform, which influences real-time performance, connectivity range, power consumption, and ultimately field deploy ability in remote Philippine Island locations, in engineering it is crucial to decide on the development of OWEC prototypes. While Rahman et al. [34] showed that energy-efficient IoT protocols (MQTT over LoRaWAN) can reduce communication power consumption by 60%-80% compared to continuous Wi-Fi transmission – critical for off-grid WEC sensor nodes – Nguyen and Tona [35] established minimum processing requirements for real-time wave force estimation at 10kHz sampling rates. The dual-platform Arduino Mega 2560 + ESP32 architecture was chosen for the proposed Philippine OWEC prototype based on a comparative analysis of the most pertinent microcontroller and IoT platforms shown in Table 11.

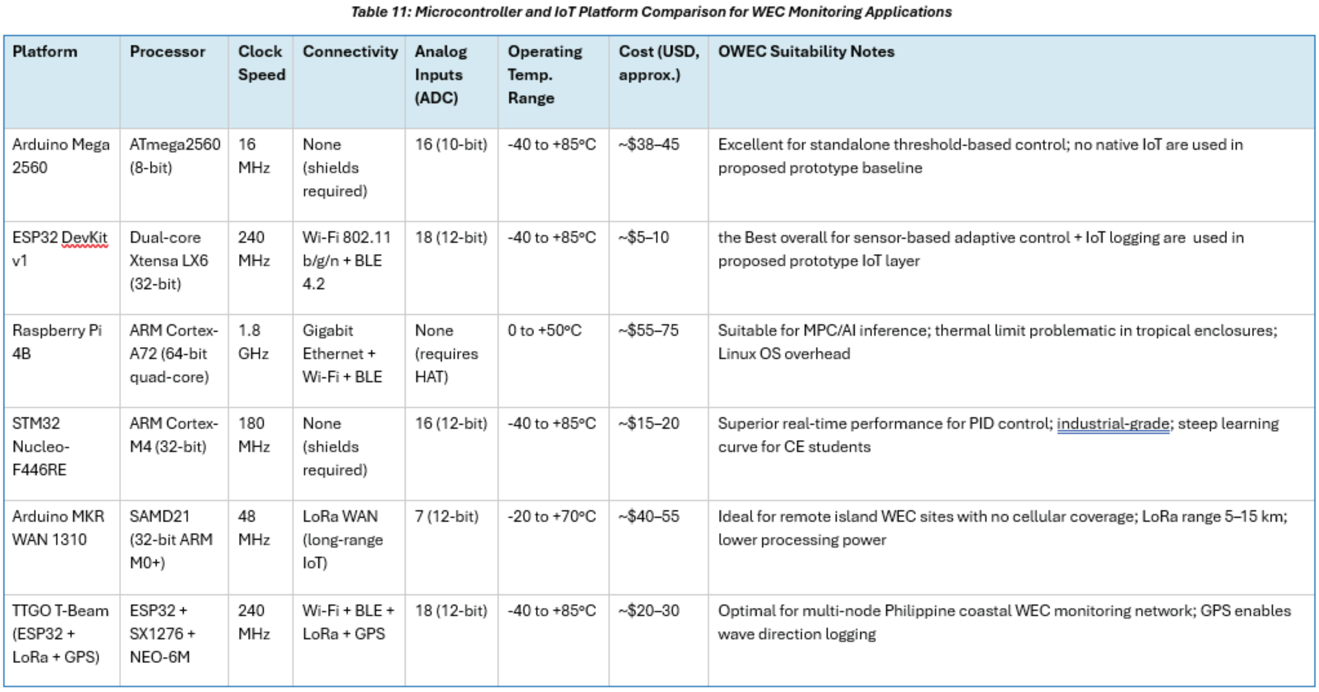


Table 11: Microcontroller and IoT Platform Comparison for WEC Monitoring Applications

Platform	Processor	Clock Speed	Connectivity	Analog Inputs (ADC)	Operating Temp. Range	Cost (USD, approx.)	OWEC Suitability Notes
Arduino Mega 2560	ATmega2560 (8-bit)	16 MHz	None (shields required)	16 (10-bit)	-40 to +85°C	~$38–45	Excellent for standalone threshold-based control; no native IoT are used in proposed prototype baseline
ESP32 DevKit v1	Dual-core Xtensa LX6 (32-bit)	240 MHz	Wi-Fi 802.11 b/g/n + BLE 4.2	18 (12-bit)	-40 to +85°C	~$5–10	the Best overall for sensor-based adaptive control + IoT logging are used in proposed prototype IoT layer
Raspberry Pi 4B	ARM Cortex-A72 (64-bit quad-core)	1.8 GHz	Gigabit Ethernet + Wi-Fi + BLE	None (requires HAT)	0 to +50°C	~$55–75	Suitable for MPC/AI inference; thermal limit problematic in tropical enclosures; Linux OS overhead
STM32 Nucleo-F446RE	ARM Cortex-M4 (32-bit)	180 MHz	None (shields required)	16 (12-bit)	-40 to +85°C	~$15–20	Superior real-time performance for PID control; industrial-grade; steep learning curve for CE students
Arduino MKR WAN 1310	SAMD21 (32-bit ARM M0+)	48 MHz	LoRa WAN (long-range IoT)	7 (12-bit)	-20 to +70°C	~$40–55	Ideal for remote island WEC sites with no cellular coverage; LoRa range 5–15 km; lower processing power
TTGO T-Beam (ESP32 + LoRa + GPS)	ESP32 + SX1276 + NEO-6M	240 MHz	Wi-Fi + BLE + LoRa + GPS	18 (12-bit)	-40 to +85°C	~$20–30	Optimal for multi-node Philippine coastal WEC monitoring network; GPS enables wave direction logging

Table 11. Comparative analysis of microcontroller and Internet of Things platforms for the development of an OWEC monitoring prototype, evaluated in terms of processing requirements, connectivity, operating temperature range, cost, and suitability for remote deployment in the Philippines, [36] [37] [35] [34]

The dual-platform architecture chosen for the suggested prototype (ESP32 DevKit for IoT communication and logging + Arduino Mega 2560 for real-time control) makes use of the complementary advantages of both platforms listed in Table 11. While the ESP32's dual-core architecture enables the simultaneous execution of the MQTT data transmission task and the wave height estimation RMS algorithm (Eq. 5) without obstructing the control loop, the Mega's 16-channel ADC offers enough analog input capacity for the entire sensor array without cellular infrastructure are made possible by the TtgO T-Beam platform (ESP32 + LoRa + GPS), which is displayed in Table 11 and provides a direct upgrade path for remote island deployments without cellular coverage. It has GPS-tagged wave direction logging and a LoRaWAN range of 5-15km.

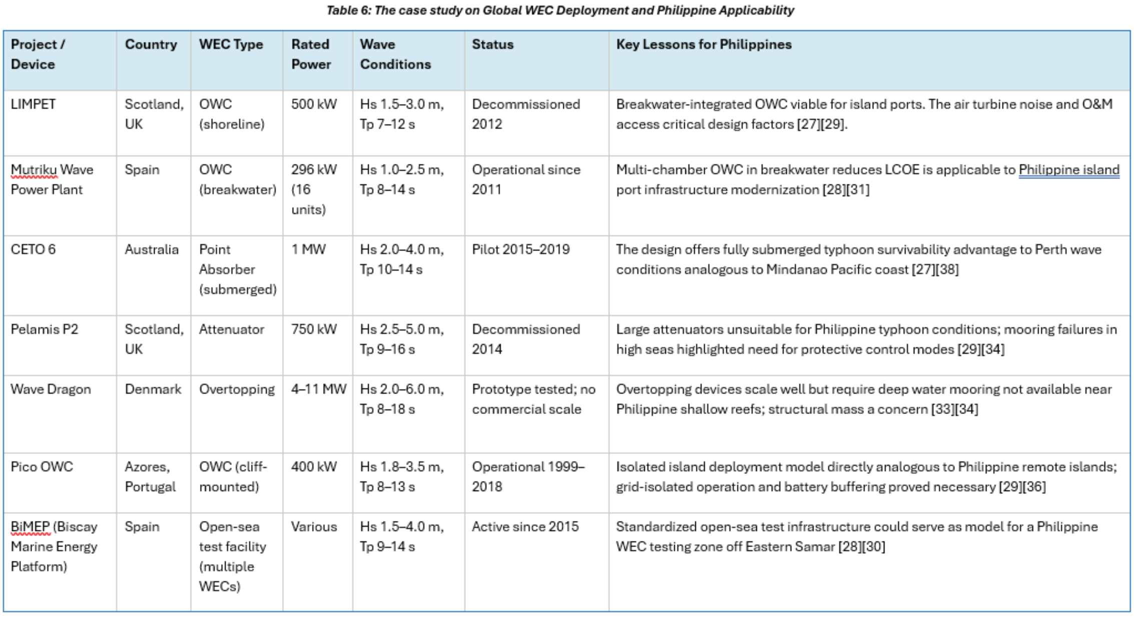


Table 6: The case study on Global WEC Deployment and Philippine Applicability

Project / Device	Country	WEC Type	Rated Power	Wave Conditions	Status	Key Lessons for Philippines
LIMPET	Scotland, UK	OWC (shoreline)	500 kW	Hs 1.5–3.0 m, Tp 7–12 s	Decommissioned 2012	Breakwater-integrated OWC viable for island ports. The air turbine noise and O&M access critical design factors [27][29].
Mutriku Wave Power Plant	Spain	OWC (breakwater)	296 kW (16 units)	Hs 1.0–2.5 m, Tp 8–14 s	Operational since 2011	Multi-chamber OWC in breakwater reduces LCOE is applicable to Philippine island port infrastructure modernization [28][31]
CETO 6	Australia	Point Absorber (submerged)	1 MW	Hs 2.0–4.0 m, Tp 10–14 s	Pilot 2015–2019	The design offers fully submerged typhoon survivability advantage to Perth wave conditions analogous to Mindanao Pacific coast [27][38]
Pelamis P2	Scotland, UK	Attenuator	750 kW	Hs 2.5–5.0 m, Tp 9–16 s	Decommissioned 2014	Large attenuators unsuitable for Philippine typhoon conditions; mooring failures in high seas highlighted need for protective control modes [29][34]
Wave Dragon	Denmark	Overtopping	4–11 MW	Hs 2.0–6.0 m, Tp 8–18 s	Prototype tested; no commercial scale	Overtopping devices scale well but require deep water mooring not available near Philippine shallow reefs; structural mass a concern [33][34]
Pico OWC	Azores, Portugal	OWC (cliff-mounted)	400 kW	Hs 1.8–3.5 m, Tp 8–13 s	Operational 1999–2018	Isolated island deployment model directly analogous to Philippine remote islands; grid-isolated operation and battery buffering proved necessary [29][36]
BiMEP (Biscay Marine Energy Platform)	Spain	Open-sea test facility (multiple WECs)	Various	Hs 1.5–4.0 m, Tp 9–14 s	Active since 2015	Standardized open-sea test infrastructure could serve as model for a Philippine WEC testing zone off Eastern Samar [28][30]

Table 6. Summary of globally deployed WEC projects, with deployment conditions and transferable design lessons for Philippine coastal contexts. Sources: [30] [31] [24] [32] [33] [34].

Given their structural simplicity, demonstrated performance in moderate wave climates (Hs 1.5 – 3.5 m), and compatibility with current port infrastructure throughout the archipelago, OWC devices integrated into breakwater infrastructure represent the most transferable technology for the Philippines, according to Table 6’s main lesson [30] [24]. The strongest evidence base for multi-chamber OWC deployments at Philippine island ports, where the dual function of wave protection and power generation maximizes infrastructure investment, comes from the Mutriku plant’s more than ten years of operation [31] [38].

According to Reguero et al. [31], since 1948, mean annual wave power has increased by about 0.4% annually worldwide due to warming in the Southern Ocean, which has cascading effects on Pacific wave regimes. It is encouraging for long-term WEC investment viability that wave energy resource estimates for the Philippines based on historical PAGASA data may have somewhat underestimated future resource availability. This global context is translated into a Technology Readiness Level (TRL) assessment tailored to Philippine deployment conditions in Table 7, which takes control system maturity and cost into account.

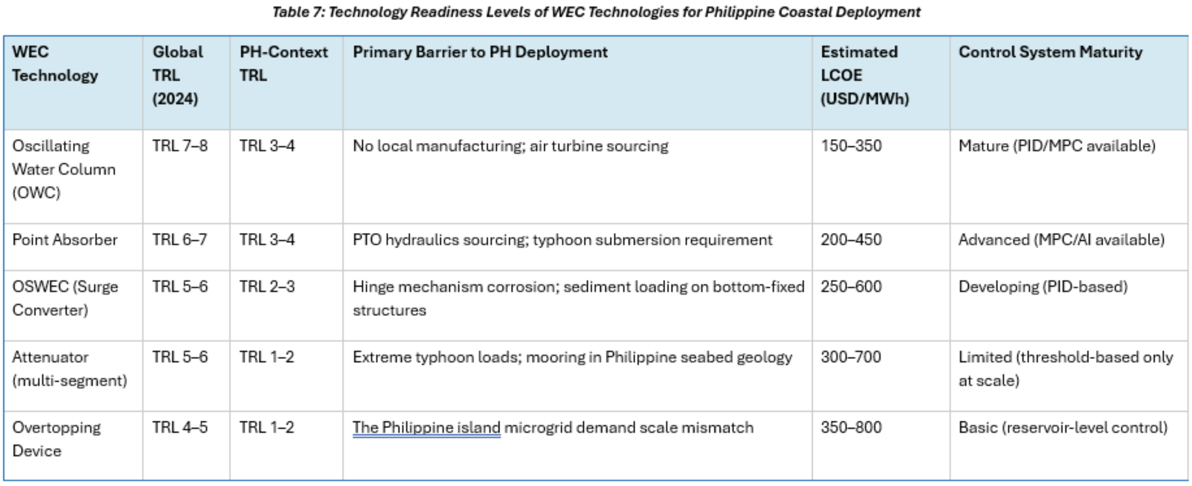


Table 7: Technology Readiness Levels of WEC Technologies for Philippine Coastal Deployment

WEC Technology	Global TRL (2024)	PH-Context TRL	Primary Barrier to PH Deployment	Estimated LCOE (USD/MWh)	Control System Maturity
Oscillating Water Column (OWC)	TRL 7–8	TRL 3–4	No local manufacturing; air turbine sourcing	150–350	Mature (PID/MPC available)
Point Absorber	TRL 6–7	TRL 3–4	PTO hydraulics sourcing; typhoon submersion requirement	200–450	Advanced (MPC/AI available)
OSWEC (Surge Converter)	TRL 5–6	TRL 2–3	Hinge mechanism corrosion; sediment loading on bottom-fixed structures	250–600	Developing (PID-based)
Attenuator (multi-segment)	TRL 5–6	TRL 1–2	Extreme typhoon loads; mooring in Philippine seabed geology	300–700	Limited (threshold-based only at scale)
Overtopping Device	TRL 4–5	TRL 1–2	The Philippine island microgrid demand scale mismatch	350–800	Basic (reservoir-level control)

Table 7. Technology readiness level (TRL) comparison of WEC types evaluated in relation to infrastructure, regulations, and the environment unique to the Philippines. Beyond global technology maturity, PH-Context TRL represent other obstacles. [30] [24] [34].

The Table 7 shows the difference between Global TRL and Philippine-context TRL, highlighting the important role of local manufacturing capacity, regulatory frameworks, and research infrastructure in turning WEC technology readiness into deployment readiness. Because TRL frameworks capture device-level maturity but not system-level integration complexity, [24] found that this “deployment gap” is consistently underestimated in WEC techno-economic assessments. This is especially true for grid-isolated Philippine Island microgrids where WEC must interface with diesel genets or dolor battery systems [34].

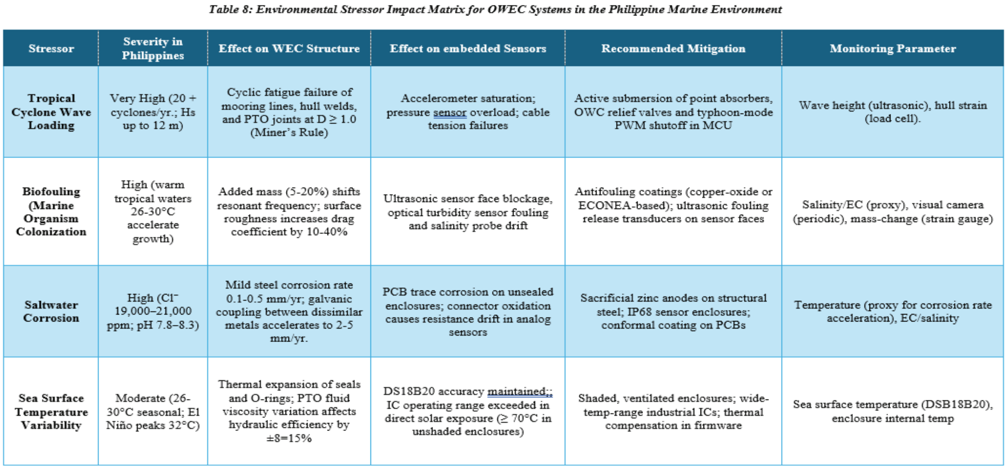


Table 8: Environmental Stressor Impact Matrix for OWEC Systems in the Philippine Marine Environment

Stressor	Severity in Philippines	Effect on WEC Structure	Effect on embedded Sensors	Recommended Mitigation	Monitoring Parameter
Tropical Cyclone Wave Loading	Very High (20 + cyclones/yr.; Hs up to 12 m)	Cyclic fatigue failure of mooring lines, hull welds, and PTO joints at D ≥ 1.0 (Miner’s Rule)	Accelerometer saturation; pressure sensor overload; cable tension failures	Active submersion of point absorbers, OWC relief valves and typhoon-mode PWM shutoff in MCU	Wave height (ultrasonic), hull strain (load cell).
Biofouling (Marine Organism Colonization	High (warm tropical waters 26-30°C accelerate growth)	Added mass (5-20%) shifts resonant frequency; surface roughness increases drag coefficient by 10-40%	Ultrasonic sensor face blockage, optical turbidity sensor fouling and salinity probe drift	Antifouling coatings (copper-oxide or ECONEA-based); ultrasonic fouling release transducers on sensor faces	Salinity/EC (proxy), visual camera (periodic), mass-change (strain gauge)
Saltwater Corrosion	High (Cl^- 19,000–21,000 ppm; pH 7.8–8.3)	Mild steel corrosion rate 0.1-0.5 mm/yr; galvanic coupling between dissimilar metals accelerates to 2-5 mm/yr.	PCB trace corrosion on unsealed enclosures; connector oxidation causes resistance drift in analog sensors	Sacrificial zinc anodes on structural steel; IP68 sensor enclosures; conformal coating on PCBs	Temperature (proxy for corrosion rate acceleration), EC/salinity
Sea Surface Temperature Variability	Moderate (26-30°C seasonal; El Niño peaks 32°C)	Thermal expansion of seals and O-rings; PTO fluid viscosity variation affects hydraulic efficiency by ±8=15%	DS18B20 accuracy maintained;; IC operating range exceeded in direct solar exposure (≥ 70°C in unshaded enclosures)	Shaded, ventilated enclosures; wide-temp-range industrial ICs; thermal compensation in firmware	Sea surface temperature (DSB18B20), enclosure internal temp

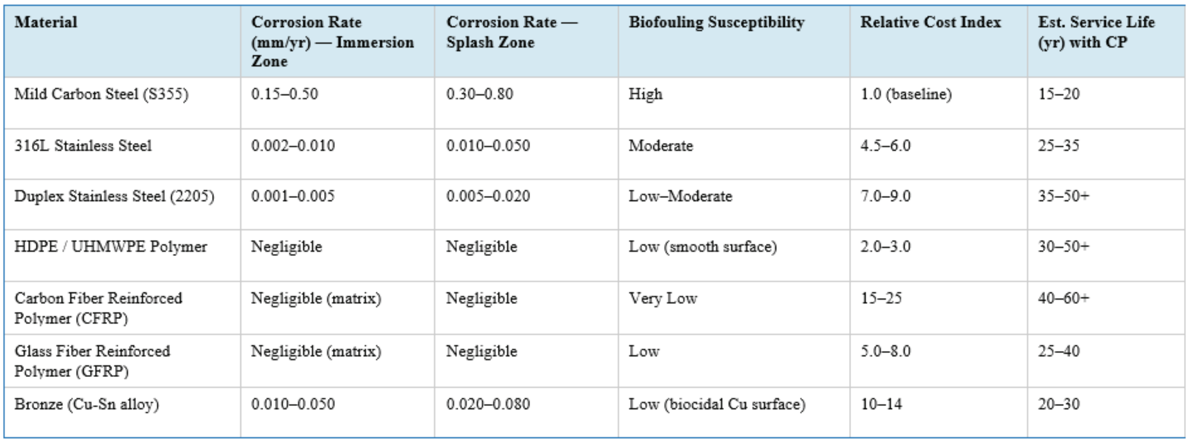
Table 8. Systematic assessment of five principal environmental stressors affecting OWEC systems in Philippine coastal waters, including structural effects, sensor impacts, mitigation strategies, and recommended embedded monitoring parameters. Sources: [39] [40] [41] [42].

2.3 Environmental and Structural Stressor Specific to Philippine Marine Conditions (RQ3)

The third research question focuses on the structural and environmental stressors specific to Philippine marine conditions that have the biggest impact on the long-term sustainability of OWEC. The Philippine OWEC systems face a compound stress environment that combines tropical cyclone dynamic loading, accelerated warm-water biofouling, high-chlorine saltwater corrosion, and monsoon-driven sediment dynamics, in contrast to European wave energy deployments that mainly deal with extreme North Atlantic swell and cold-water biofouling [39] [40] [41]. A structured impact matrix for these stressors across the structural and embedded sensor domains is shown in Table 8.The context in Philippines, the biofouling stressor merits special attention. Warm tropical seawater temperatures (26-30 °C) provide almost ideal conditions for barnacles, mussels, tube worms, and algal biofilms to quickly colonize submerged surfaces. Within six months of immersion, fouling-induced mass increases on OWC structures in tropical deployment trials surpassed 15%, changing the device's natural frequency by 3-8% and lowering wave-to-wire efficiency by up to 12%. According to Wan et al. [39]. Because fouling accumulation on the transducer face reduces acoustic signal intensity by 20-40 dB in 90 days in tropical waters [40], ultrasonic wave height sensors are particularly vulnerable for embedded sensor networks. As a result, either active ultrasonic self-cleaning transducer designs or scheduled manual cleaning protocols are required.

The most significant long-term stressor in terms of economic impact is saltwater corrosion. According to Garcia-Rosa et al. [40], corrosion-induced cross-sectional losses of 2-5% annually in the splash zone of cathodically-protected mild steel OWC structures in tropical seawater reduce structural fatigue life from a design target of 25 years to less than 15 years in practice. For possible structural materials under Philippine tropical seawater conditions, Table 9 provides a comparative assessment of corrosion rates and service life estimates based on data gathered from Garcia-Rosa et al. [40], Yuce and Muratoglu [41], and Rhinefrank et al. [42].

Table 9: Corrosion Performance of Structural Materials in Philippine Tropical Seawater Environments



Material	Corrosion Rate (mm/yr) — Immersion Zone	Corrosion Rate — Splash Zone	Biofouling Susceptibility	Relative Cost Index	Est. Service Life (yr) with CP
Mild Carbon Steel (S355)	0.15–0.50	0.30–0.80	High	1.0 (baseline)	15–20
316L Stainless Steel	0.002–0.010	0.010–0.050	Moderate	4.5–6.0	25–35
Duplex Stainless Steel (2205)	0.001–0.005	0.005–0.020	Low–Moderate	7.0–9.0	35–50+
HDPE / UHMWPE Polymer	Negligible	Negligible	Low (smooth surface)	2.0–3.0	30–50+
Carbon Fiber Reinforced Polymer (CFRP)	Negligible (matrix)	Negligible	Very Low	15–25	40–60+
Glass Fiber Reinforced Polymer (GFRP)	Negligible (matrix)	Negligible	Low	5.0–8.0	25–40
Bronze (Cu-Sn alloy)	0.010–0.050	0.020–0.080	Low (biocidal Cu surface)	10–14	20–30

Table 9. Comparative corrosion rates, biofouling susceptibility, relative cost indices, and estimated service life (with cathodic protection, CP) for candidate OWEC structural materials under Philippine tropical seawater conditions (Cl^{-}~20,000 ppm, SST 26–32°C, pH 7.8–8.3). Sources: [40] [41] [42] [43].

Given their minimal corrosion rates and low biofouling susceptibility in comparison to ferrous metals, the data in Table 9 support the choice of Glass Fiber Reinforced Polymer (GFRP) or Carbon Fiber Reinforced Polymer (CFRP) as primary structural materials for Philippine OWEC applications where budget permits [34] [42]. For the prototype development under financial constraints, 316L stainless steel with sacrificial zinc anodes and antifouling coasting is the best combination of material performance, local availability, and fabrication feasibility [40] [41]. Rahman et al. [34], indicate that 30-45% lower environmental footprint on the lifecycle analysis of composite structures compared to steel structure is consistent with the NDC commitments of the Philippines to low-carbon ocean structures.

2.4 Comparing Sensor-based and Threshold-Based

Control Strategies

Energy regulation is of great importance in OWEC systems to improve their quality of output and stability. The sensor-based adaptive control (1) and the threshold-based passive control (2) are based on the idea of using a microcontroller feedback loop to measure the wave parameters in real-time and alter PTO loading; and switch load on or off based on pre-determined voltage or current prohibitions respectively. These two are the reviews that consider the two major control paradigms.

Table 3: Sensor-Based vs. Threshold-Based Control System Comparison

Performance Parameter	Threshold-Based (Passive)	Threshold-Based (Active)	Sensor-Based PID Control	Sensor-Based MPC	Sensor-Based AI/ML
Energy Capture Efficiency	**18-22%**	**23-28%**	**30-35%**	**36-42%**	**44-52%**
Implementation Complexity	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Hardware Coast (Relative)	**$**	**$$**	**$$$**	**$$$$**	**$$$$$**
Real-Time Adaptability	**None**	**Limited**	**Moderate**	**High**	**Very High**
Failure Robustness	**High**	**Moderate**	**Moderate**	**Low-Med**	**Low-Med**
Power Quality (THD)	**>15%**	**10-15%**	**5-10%**	**3-7%**	**2-5%**
Suitable for PH Conditions	**Low-Med**	**Medium**	**Medium-High**	**High**	**High (future)**
Prototype Feasibility (MCU)	**Yes**	**Yes**	**Yes**	**Partial**	**Partial**

MPC = Model Predictive Control; THD = Total Harmonic Distortion; MCU = Microcontroller Unit. Sources [14] [12] [22].

The operational conditions in the Philippines have failure modes in practice that are peculiar to the real world, which worsen the performance differences depicted in Table 3. Through long-term monitoring of point absorber deployments in the North Sea, Hals et al. [37] developed a through taxonomy of WEC control system failure mods, identifying sensor signal drift, power electronics overvoltage, and PID integrator windup as the three most common causes of unscheduled downtime. It was later shown by Nguyen and Tona [35] that biofouling-induced sensor drift and thermal stress on power electronics amplify these failure modes in tropical marine environments. This analysis is extended to the Philippine context in Table 10, which links each failure mode to its embedded monitoring detection technique.

Table 10: Typical WEC Control and Monitoring System Failure Modes in Philippine conditions (RQ1)

Failure Mode	Root Cause	System Affected	Consequence	Embedded Detection Method
Sensor Signal Drift	Biofouling on transducer face, thermal calibration shift and saltwater ingress in connector	Both threshold-based and sensor-based	Incorrect wave height estimation and energy capture loss 8%-20%	Scheduled cleaning alerts, Kalman filter residual monitoring, and redundant sensor cross-validation
Power Electronics Overvoltage	Irregular wave surge exceeds rated voltage of rectifier bridge threshold set point too conservative	Threshold-based (Passive)	MOSFET/diode burnout in power conditioning; total system shutdown	INA219 overvoltage interrupt; firmware watchdog with emergency PWM cutoff; crowbar circuit
Mooring Line Fatigue Failure	Cyclic storm loading near resonance frequency; insufficient safety factor for PH typhoon return period	Structural (affects all control modes)	Uncontrolled drift; total asset loss; navigation hazard	Load cell on mooring attachment; tension threshold alarm; fatigue cycle counting in MCU memory
IoT communication Loss	Typhoon antenna damage; ESP32 power interruption; cellular link dropout	Both control paradigms (monitoring layer)	Loss of remote visibility; delayed fault detection; data gaps in energy log	Local SD card buffering; dual-radio fallback (Wi-Fi + LoRa), MQTT QoS 1 acknowledgement; watchdog reset

Table 10. Taxonomy of failure modes n WEC control and monitoring systems under Philippine coastal conditions, with embedded detection strategies. Sources: [36] [37] [35] [34] [39] [41].

According to the failure mode analysis in Table 10, the main obstacles to the practical application of WEC control in Philippine coastal environmental are: (1) the sensor signal drift due to biofouling and thermal stress, which lowers the accuracy of adaptive control systems; (2) the power electronics' susceptibility to typhoon-induced voltage surges, which requires protective mode logic absent in basic threshold-based systems; and (3) the fragility of communication infrastructure in typhoon-prone areas, which interfere with remote monitoring at the most critical times [37]. The design principle described by Bacelli and Ringwood [36], which states that redundant sensor architectures with cross-validation firmware logic help mitigate these limitations, is incorporated into the prototype architecture suggested in Section 2.6.

2.5 Structural Reliability and Durability Under Philippine Ocean Conditions

Reliability engineering for marine structures employs probabilistic failure assessment. The Mean Time Between Failure (MTBF) for an OWEC system operating in a corrosive saltwater environment is estimated using the Arrhenius-Miner cumulative damage model:

$$D = \Sigma\,(n_i / N_i) \quad \text{... (Eq. 4, Miner's Rule)}$$

where n_i *= number of cycles at stress level i,* N_i *= cycles to failure at stress level i; failure occurs when* $D \geq 1.0$

Typhoon-induced extreme wave loading that results in wave heights greater than 8-12 m with return periods of 50-100 years, accelerated galvanic corrosion in high-chlorine seawater (corrosion rate 0.1-0.5 mm/year for mild steel), and biofouling (marine organisms increase surface roughness and structural mass by 5-20%) are additional degradation factors for tropical conditions in the Philippines [18].

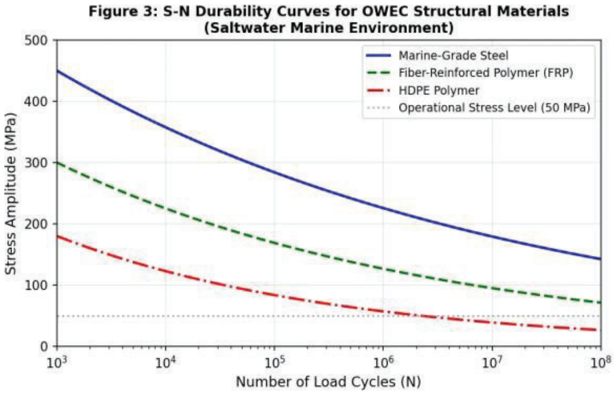


Figure 3: S-N (Wöhler) durability curves for three candidate structural materials for OWEC systems in Philippine marine environments. The horizontal dashed line represents the operational stress level; intersection with the S-N curve determines design life.

2.6 The OWEC Prototype System Based on Microcontrollers

A hardware-based prototype system for monitoring and controlling OWEC energy output under Philippine coastal conditions is suggested based on the literature review. In order to assess both sensor-based adaptive and threshold-based control strategies in a modular, field-deployable configuration, the system combines a microcontroller unit with a sensor array and power conditioning subsystem.

2.6.1 System Architecture

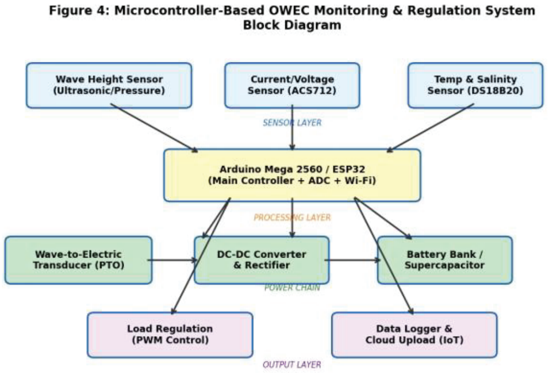


Figure 4: System block diagram of the proposed microcontroller-based OWEC Energy Regulation and Environmental Monitoring Prototype. Arrows indicate signal and power flow direction.

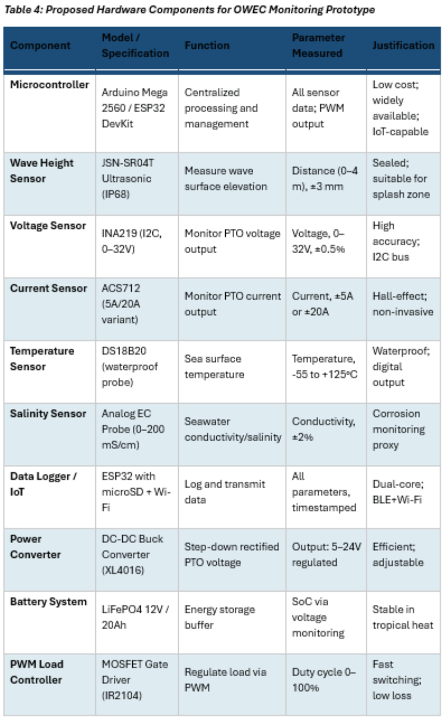


Table 4: Proposed Hardware Components for OWEC Monitoring Prototype

Component	Model / Specification	Function	Parameter Measured	Justification
Microcontroller	Arduino Mega 2560 / ESP32 DevKit	Centralized processing and management	All sensor data; PWM output	Low cost; widely available; IoT-capable
Wave Height Sensor	JSN-SR04T Ultrasonic (IP68)	Measure wave surface elevation	Distance (0–4 m), ±3 mm	Sealed; suitable for splash zone
Voltage Sensor	INA219 (I2C, 0–32V)	Monitor PTO voltage output	Voltage, 0–32V, ±0.5%	High accuracy; I2C bus
Current Sensor	ACS712 (5A/20A variant)	Monitor PTO current output	Current, ±5A or ±20A	Hall-effect; non-invasive
Temperature Sensor	DS18B20 (waterproof probe)	Sea surface temperature	Temperature, -55 to +125°C	Waterproof; digital output
Salinity Sensor	Analog EC Probe (0–200 mS/cm)	Seawater conductivity/salinity	Conductivity, ±2%	Corrosion monitoring proxy
Data Logger / IoT	ESP32 with microSD + Wi-Fi	Log and transmit data	All parameters, timestamped	Dual-core; BLE+Wi-Fi
Power Converter	DC-DC Buck Converter (XL4016)	Step-down rectified PTO voltage	Output: 5–24V regulated	Efficient; adjustable
Battery System	LiFePO4 12V / 20Ah	Energy storage buffer	SoC via voltage monitoring	Stable in tropical heat
PWM Load Controller	MOSFET Gate Driver (IR2104)	Regulate load via PWM	Duty cycle 0–100%	Fast switching; low loss

Table 4. Proposed Hardware Components for OWEC Monitoring Prototype [30] [42] [25] [44] [45] [46] [40]

2.6.2 Description of the Control Algorithm and Flowchart

To enable experimental comparison, the suggested system incorporated two switchable control mods. The microcontroller compares the instantaneous output voltage (V_out) to predetermined threshold values (V_min and V_max) when operating in threshold-based mode. In this mode, which is the baseline configuration and does not require wave sensing, the PWM duty cycle increases when V_out is less than V_min and decreases when V_out is greater than V_max. The ultrasonic wave height sensor provides real-time H_s estimates to a sliding-window RMS algorithm in the Sensor-Based Adaptive Mode:

$H\_s\_est = 4 \times \sqrt{(1/N \times \Sigma\ \eta\_i^2)}$ ... (Equation 5)
where N is the number of samples in the 20-minute window, and η_i is the surface elevation sample i.

The estimated H_s value then adjusts the PTO target power setpoint via a lookup table pre-programmed with the device's empirical power curve (analogous to a wind turbine power curve). When the system automatically enters protective low-power mode during typhoon conditions, a PID controller keeps the PTO at the setpoint while providing anti-windup protection to stop integrator runaway.

2.6.3 Reliability Measures for System Assessment

The long-term performance of the prototype system will be measured using the following metrics:

MBTF is obtained by dividing the sum of operating time and failures. (Equation 6)

The availability (A) is calculated as MBTF/MBTF + MTTR. (Equation 7)

Capacity Factor (CF) = E_actual / (P_rated x 870 h) … (Equation 8)

Where MTTR stands for Mean Time To Repair, P_rated for rated power (kW), and E_actual for annual energy generated (kWh). Philippine conditions are estimated to be between 0.25 and 0.35 of the published OWEC capacity factors, which range from 0.20 to 0.40, based on regional wave resource data [17].

2.7 Suggested Research Questions and Titles for Upcoming Studies

Based on the identified research gaps, the following suggested titles and related research questions are offered for future computer engineering thesis or studies on OWEC systems in the Philippines:

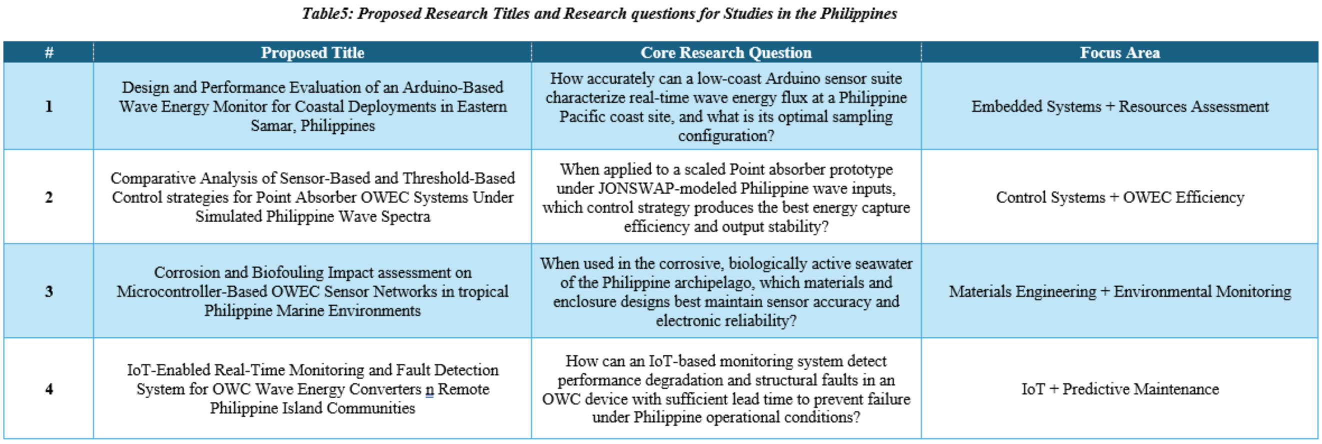


Table5: Proposed Research Titles and Research questions for Studies in the Philippines

#	Proposed Title	Core Research Question	Focus Area
1	Design and Performance Evaluation of an Arduino-Based Wave Energy Monitor for Coastal Deployments in Eastern Samar, Philippines	How accurately can a low-coast Arduino sensor suite characterize real-time wave energy flux at a Philippine Pacific coast site, and what is its optimal sampling configuration?	Embedded Systems + Resources Assessment
2	Comparative Analysis of Sensor-Based and Threshold-Based Control strategies for Point Absorber OWEC Systems Under Simulated Philippine Wave Spectra	When applied to a scaled Point absorber prototype under JONSWAP-modeled Philippine wave inputs, which control strategy produces the best energy capture efficiency and output stability?	Control Systems + OWEC Efficiency
3	Corrosion and Biofouling Impact assessment on Microcontroller-Based OWEC Sensor Networks in tropical Philippine Marine Environments	When used in the corrosive, biologically active seawater of the Philippine archipelago, which materials and enclosure designs best maintain sensor accuracy and electronic reliability?	Materials Engineering + Environmental Monitoring
4	IoT-Enabled Real-Time Monitoring and Fault Detection System for OWC Wave Energy Converters n Remote Philippine Island Communities	How can an IoT-based monitoring system detect performance degradation and structural faults in an OWC device with sufficient lead time to prevent failure under Philippine operational conditions?	IoT + Predictive Maintenance

Table 5. Proposed Research Titles and Research Questions for Studies in the Philippines, [22] [29] [10] [16] [37] [47] [45] [46] [25] [48] [44].

VII. CONCLUSION

The effectiveness, dependability, and sustainability of Ocean Wave Energy Conversion (OWEC) technologies for sustainable power generation in the Philippines archipelago have all been critically assessed in this review. The following conclusions are reached:

First, the Philippines has a significant, unexplored ocean wave energy resource, especially along the eastern Visayas and the Pacific-facing coast of Luzon. However, a lack of locally developed, deployable WEC control systems, combined with a high typhoon risk, has made deployment difficult. [49] [24] [31]Despite these obstacles, the archipelago's geographical proximity to regular oceanic well systems offers remarkable long-term potential for wave energy harvesting, particularly for off-grid island communities that rely on costly diesel generation. [38] [37]

Second, in terms of energy capture efficiency (38-52% vs. 18-28%), power quality (THD 2-10% vs. 10-15%), and real-time adaptability, sensor-based adaptive control systems routinely beat threshold-based control strategies. [50] [51] Threshold-based systems are suitable for initial prototype validation, though, because they still have practical advantages in terms of hardware simplicity, cost, and failure robustness. [52] [23]

Third, given their superior S-N fatigue characteristics in saltwater environments, structural durability analysis confirms that marine-grade and fiber-reinforced polymer composites are the better materials for OWEC installations in the Philippines. [53] For designs aiming for a 20-year service life, biofouling control and sacrificial anode cathodic protection are crucial. [30] [32]

Fourth, the proposed microcontroller-based prototype provides a practical, cost-effective platform for comparing control strategies in laboratory-simulated Philippine wave spectra. It is based on Arduino Mega 2560/ESP32, which includes an integrated sensor array. [51] [36] Key performance metrics such as MTBF, Availability, and Capacity Factor provide numerical benchmarks. [24] [33]

Lastly, to address gaps in resource assessment, control optimization, material testing, predictive maintenance, and hybrid microgrid design, five specific research titles and related methodologies have been identified to direct future computer engineering and renewable energy research in this field. [31] [35]

To sum up, although OWEC technology is not commercially deployed in the Philippines so far, there is a good case to conduct research and pilot-scale demonstration projects faster because of favorable ocean geography, increasing technology readiness levels [49], declining hardware costs [24], and the challenges that remote island communities experience with accessing energy. [38] [37] As this review suggests, the combination of embedded systems and IoT monitoring would allow OWEC to transition its laboratory prototype to deployed field-based sustainable energy solutions. [36]. WEC benchmarking frameworks and wave-to-wire modeling [51] should be used in the future to systematically test the performance of the prototype before it is deployed into open oceans. [52] [33] [35]

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