ENGINEER - Vol. LIX, No. 01, pp. [123-132], 2026

DOI: https://doi.org/10.4038/engineer.v59i1.7738

Design, Development, and Field Testing of a Scalable Nearshore Wave Energy Converter Optimized for Sri Lanka's Shallow Sea Conditions

I.H.D. Seneviratne, J.A.A.E. Perera, D.A. Saminda, V.G.K.N. Senevirathna, K.T.K.M. De Silva, Hadi Amlashi and H.C.P. Karunasena

Abstract: Driven by the global demand for clean energy, wave energy has gained attention for its high density and predictability. However, the technology remains underutilised, particularly in tropical, shallow coastal regions. This study outlines the development of a shallow-water wave energy converter (WEC) that captures both potential and kinetic energy via a surface-mounted buoy coupled to a dual-rack-and-pinion power take-off (PTO) mechanism. The initial prototype was validated through computational fluid dynamics (CFD) simulations and subsequently field-tested off Galle (6.049714, 80.182934), Sri Lanka, in wave conditions approximating 0.5 m in height and a 6-8 s period. Based on observed performance, the second prototype was enhanced with improved buoyancy, structural modifications, and real-time monitoring. Field testing demonstrated a power output of approximately 20 W, peaking at over 60 W, thereby proving the technological feasibility of decentralised nearshore energy applications. The next step will be the research on scaling performance and long-term reliability in various sea-state conditions.

Keywords: Ocean Energy, Point Absorber, Small-Scale Wave Energy Converter, Wave Energy, Wave Energy Generation

1. Introduction

The energy of ocean waves is generally considered a promising renewable energy source, as it has high energy density, predictability, and a vast geographic extent. Although the theoretical global potential is estimated to exceed 2 terawatts, commercial deployment is still in its infancy, with few Wave Energy Converter (WEC) systems having progressed beyond pilot-scale trials. Most of these systems struggle to achieve long-term mechanical reliability and cost-effectiveness in harsh marine environments, particularly in developing nations [1–3].

WECs are generally classified into oscillating water columns (OWCs), overtopping devices, and oscillating body-type converters such as point absorbers (PAs), attenuators, and surge converters. Among these, point absorbers are particularly effective in offshore and moderate-depth waters due to their omnidirectional wave responsiveness and compact design [3–6]. However, the power take-off (PTO) systems in PAs are typically prone to failure and require frequent maintenance. International statistics show that there are 197 identified WECs, of which 96 are already operational, and 52 are point absorber systems, indicating their popularity and the need for further development [7]. Yet, the reliability data on wave energy deployments show that point absorber devices have almost twice the failure rate of oscillating water column devices, with an average of 4.2 failures per year for PAs

Eng. I.H.D. Seneviratne, *AMIE(SL), B.Sc. Eng. (Hons.) (Ruhuna), Lecturer (Probationary), Department of Marine Engineering and Naval Architecture, Faculty of Engineering, University of Ruhuna.*
Email: ihirunseneviratne@icloud.com
ORCID ID: https://orcid.org/0009-0000-4573-089X
Ms. J.A.A.E. Perera, *B.Sc. Eng. (Hons.) (Ruhuna), Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, University of Ruhuna.*
Email: edrperera@gmail.com
Mr. D.A. Saminda, *B.Sc. Eng. (Hons.) (Ruhuna), Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, University of Ruhuna.*
Email: dashensaminda@gmail.com
Mr. V.G.K.N. Senevirathna, *B.Sc. Eng. (Hons.) (Ruhuna), Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, University of Ruhuna.*
Email: senevi.kashyapa@gmail.com
Eng. (Dr.) K.T.K.M. De Silva, *AMIE(SL), PhD (Saitama, Japan), B.Sc. Eng. (Hons.) (Ruhuna), Senior Lecturer, Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, University of Ruhuna.*
Email: muthumali@mme.ruh.ac.lk
Prof. Hadi Amlashi, *PhD (NTNU), Associate Professor, Faculty of Technology, Natural Sciences and Maritime Sciences, University of South-Eastern Norway.*
Email: hadi.amlashi@usn.no
Eng. (Prof.) H.C.P. Karunasena, *AMIE(SL), AEng, PhD (QUT), MSc (Moratuwa), B.Sc. Eng. (Hons.) (Moratuwa), Professor, Dean, Faculty of Engineering, University of Ruhuna,*
Email: chaminda@mme.ruh.ac.lk

compared to 2.3 for OWCs. Furthermore, in point absorber systems, the power take-off accounts for approximately 53% of failure-related costs, followed by the electrical generator (15%), transmission and control systems (13%), structural components (12%), and station keeping (7%) [3,8]. These numbers highlight the need to simplify critical subsystems and improve mechanical reliability in PA design.

Sri Lanka's southern coastline offers consistent wave conditions year-round, with an average wave power of 12–15 kW/m [9]. It offers wave heights of 0.25–0.6 m and wave periods of 6-10 seconds, which are ideal for shallow-water WEC deployment [9]. Nevertheless, local solutions have largely been limited to simulations or small-scale laboratory prototypes, with very few having been deployed in the field. Key challenges include high capital costs, the lack of designs tailored to nearshore shallow conditions, and limited access to site-specific technology. Recent studies suggest that smaller, lower-rated WECs may deliver better economic performance by achieving higher capacity factors and longer operational periods [10]. These insights align with Sri Lanka's wave climate and underscore the value of simplified, modular systems for nearshore applications.

To address these challenges, this study presents SamudraGEN—a scalable, cost-effective wave energy converter designed explicitly for tropical nearshore conditions. The paper is organised so that Section 2 outlines the principles of wave energy conversion and theoretical modelling. Section 3 details the development methodology, including simulation, design, fabrication, and sea trials. Section 4 discusses the key design improvements implemented in the second-generation prototype and evaluates its field performance. Finally, Section 5 concludes with a summary of findings and highlights future research directions.

2. Wave Energy Conversion

Wave energy extraction in point absorber systems is primarily driven by the oscillatory motion of water particles, encompassing both heave and surge components. PAs react to the wave crests and troughs as they pass by, rising and falling with the surface, and thus transform the oscillatory motion of the water into mechanical energy through the motion of the buoy. The theoretical wave power per unit width of a wave front can be calculated as [11]:

$$P_{wave} = \frac{\rho g^2}{64\pi} T_e H_s^2 \qquad \ldots (1)$$

where ρ is the density of seawater (approximately 1025 kg/m^3), g is gravitational acceleration (9.81 m/s^2), T_e is the wave energy period, and H_s is the significant wave height. Under representative conditions for the southern coast of Sri Lanka (significant wave height 0.5-1 m and energy period 6-10 s), this corresponds to approximately 1–4 kW/m of wave front [9]. In shallow water, actual extractable energy depends on wave power, the WEC's responsiveness, and conversion efficiency.

In the SamudraGEN design, wave-induced motion, including both heave and surge components, is harnessed via a surface buoy coupled with the PTO system. As the buoy oscillates, its bidirectional linear motion is transferred via a dual rack-and-pinion system. Then it converts that movement into unidirectional rotational motion, which effectively powers a small DC generator. This is a mechanically robust yet straightforward PTO design that reduces maintenance needs and increases durability. The proposed point-absorber design is optimized for shallow, energetic coastal seas and aligns with the local wave-climate spectrum. Beyond proving that the technology works, the pilot system serves as a regional showcase, demonstrating that Sri Lanka can reliably convert nearshore waves into electricity. Due to these features, the SamudraGEN model aligns well with tropical nearshore settings, further supporting the case for larger deployments around the island.

3. Methodology

The development of the SamudraGEN 1.0 wave energy converter followed a structured process that included conceptual design, numerical simulation, and empirical performance testing. The main goal was to create a device suited to Sri Lanka's coastal waters, designed to produce a net electrical power output of 20 W, while accounting for both the practical energy requirements for initial testing and the project's budget constraints under typical regional wave conditions. In the initial phase of work, four design concepts were developed to convert the surface buoy's wave-induced motion into electrical energy. A morphological survey identified four mature configurations: a dual rack-and-pinion setup, a ball-screw drive, a single rack-and-pinion, and a cable-pulley system [4]. A weighted decision matrix was used to systematically compare the schemes based on mechanical simplicity, resistance to maritime corrosion, ease of manufacturing, estimated material cost, and overall energy conversion efficiency. The analysis favoured the device with a dual rack-and-pinion system as the most promising option.

Following the concept selection, detailed component design and simulations were undertaken. Gear sizing was performed to verify the gear's mechanical integrity under dynamic loading, in accordance with ISO 6336:2019. The dynamic response of the system to wave excitation was analysed and visualised using FreeCAD for 3D modelling, DualSPHysics computational fluid dynamics (CFD) software, and ParaView for visualising and validating the buoy's behaviour in 0.25 m wave height and 6-8 s wave period conditions. FEM analysis was also conducted on key structural components to ensure safety under operational loads. The buoy structure was fabricated using low-cost materials (approximately 0.58 m in diameter and 0.4 m in height), and the complete PTO system was integrated into a sealed floater assembly with anchoring features to ensure operational stability. Subsequent field trials demonstrated reliable energy conversion and power generation under real wave conditions. These iterative development stages ensured that the selected PTO mechanism met the required performance, durability, and manufacturability standards for deployment in Sri Lankan coastal waters.

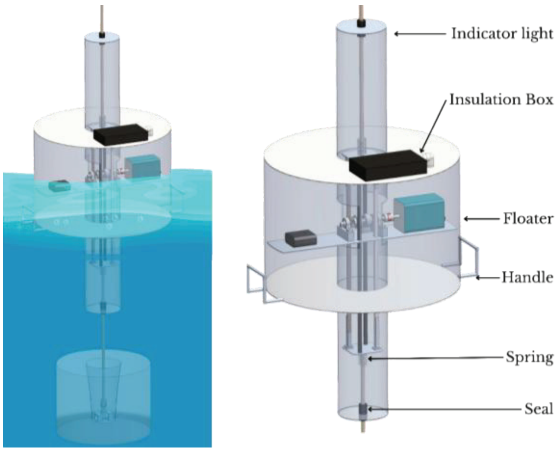


Figure 1 - Model of the Proposed WEC

3.1 Modelling of the PTO System

The SamudraGEN system uses a simplified mechanical power take-off mechanism to convert the buoy's vertical motion into unidirectional rotation. This power-take-off system, consisting of two vertical racks attached to the buoy, engages centrally located motion rectifiers supported by one-way bearings, providing continuous, unidirectional torque during both upward and downward buoy motion. The quasi-sinusoidal rotation of a primary output shaft is then conditioned through a gearbox before being supplied to the generator, while an Internet of Things (IoT) system logs real-time electrical output.

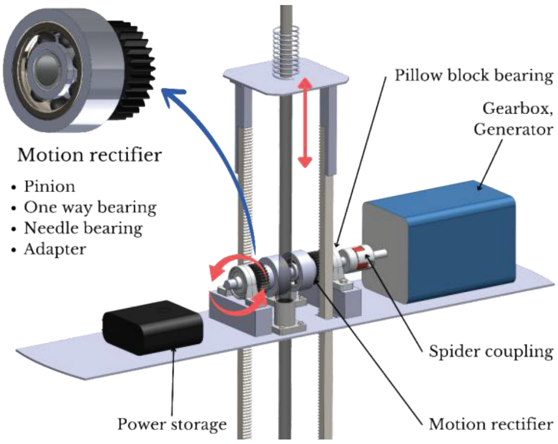


Figure 2 - PTO system

The buoy's vertical dynamics are modelled using linear wave theory. The fundamental motion is governed by:

$$m\ddot{x} = F_{PTO}(t,x,\dot{x},\ddot{x}) - F_{PTO} \quad \text{... (2)}$$

Here, m is the buoy mass, x is the vertical displacement, $F_{PTO}(t,x,\dot{x},\ddot{x})$ is the net hydrodynamic excitation force, and F_{PTO} Does the PTO system exert the resistive force. When the shaft angular velocity, $\dot{\theta}_s$, matches the rack velocity $\dot{x}/r$ the PTO is engaged, acting as a coupled mass-damper system:

$$(m + \frac{2J_p}{r^2} + m_e)\ddot{x} = F_{PTO} - c_e\dot{x} \quad \text{... (3)}$$

$$F_{PTO} = m_e\ddot{x} + c_e\dot{x} \quad \text{... (4)}$$

When the system disengages, i.e., $\dot{\theta}_s > \dot{x}/r$, the motion dynamics decouple into:

$$(m + \frac{2J_p}{r^2})\ddot{x} = F_{PTO} \quad \text{... (5)}$$

$$m_e\ddot{\theta}_s + c_e\dot{\theta}_s = 0 \quad \text{... (6)}$$

Here, Jp is the pinion's moment of inertia, r is the pinion radius, m_e is the equivalent inertia of the generator and gearbox, and c_e is the equivalent electrical damping. This mechanical PTO design supports bidirectional energy harvesting, minimizes complexity compared with hydraulic alternatives, and delivers stable performance under shallow to moderate wave conditions typical of southern Sri Lanka. This design reduces maintenance and improves nearshore robustness, with PTO sizing based on nearshore wave heights (0.25–0.6m) to enable scalability without major design changes.

3.2 Gear Sizing

The rack-and-pinion PTO mechanism of SamudraGEN was designed in KISSsoft, in accordance with ISO 6336:2019, to accommodate a 60 W load and facilitate future scalability. The design emphasised a compact and efficient layout with sufficient strength to withstand cyclic wave loading. A straight rack was paired with a pinion. Simulation results confirmed that tooth stresses and load transmission remained within safe limits, with suitable safety margins for both bending and pitting. Marine-grade grease was specified for lubrication to minimise friction and protect gear surfaces from corrosion. The finalised configuration ensured a smooth, reliable conversion from linear to rotational motion.

Table 1 - Gear Specifications

Parameter	Value
Gear Type	Spur gear with straight rack.
Number of Teeth	32 (Pinion)
Rack length	500 mm
Normal Module	1.0 mm
Pressure Angle	20°
Face Width	10 mm
Gear Quality (ISO 1328)	Grade 6
Material (Both Gears)	C45, Flank & Root Hardened
Reference Speed	60 rpm
Root Safety Factor (SF)	Pinion: 1.699, Rack: 1.709
Flank Safety Factor (SH)	Pinion: 1.261, Rack: 1.594

3.3 CFD Simulation

To assess the hydrodynamic performance and energy capture efficiency of SamudraGEN 1.0, a computational fluid dynamics simulation was conducted using DualSPHysics, an open-source smoothed particle hydrodynamics (SPH) tool. The model simulated a cylindrical buoy (0.58 m diameter, 0.4 m height, ~20 kg) in a virtual wave flume representing shallow-sea conditions off southern Sri Lanka. Regular sinusoidal waves (0.25 m height, 8 s period) were used to evaluate buoy response. The buoy was moored and tested with three PTO damping coefficients: 400, 800, and 1600 N·s/m, corresponding to different levels of mechanical resistance. Simulation outputs included buoy displacement, heave, pitch, velocity, acceleration, and reactive PTO force. Across all cases, the buoy displayed stable oscillations. As damping increased, heave amplitude and vertical velocity decreased, indicating improved energy absorption and reduced motion.

Pitch angle increased with higher damping, reducing stability and increasing structural stress. Acceleration spikes increased with higher damping coefficients, indicating greater impulse forces and potential mechanical stress under higher resistance levels. The dominant Z-direction fluid force increased and became more consistent with increased damping, while lateral forces remained minimal. The total fluid force increased with increasing damping but showed signs of saturation beyond moderate resistance levels. The net forces acting on the floater increased in magnitude as damping increased, indicating reduced stability. Nevertheless, the higher damping coefficient increased power capture by allowing more efficient wave energy absorption. These results show that increasing damping improves energy extraction efficiency, motion control, and structural performance. CFD simulations were used to evaluate motion response and stability under representative waves rather than to predict absolute power. Qualitative validation was achieved by comparing simulated stable oscillations with observed field behaviour, without capsize or PTO malfunction.

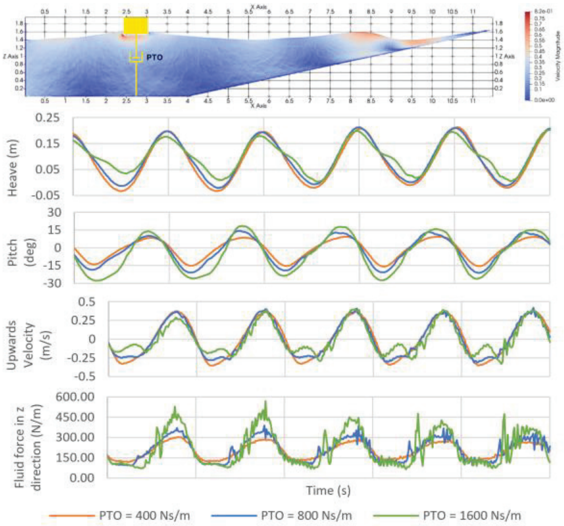


Figure 3 - Response Comparison Under Different PTO Damping Values Showing Heave, Pitch, Vertical Velocity, and Fluid Force Over Time

3.4 Electronics and Data Acquisition

SamudraGEN 1.0 included an integrated electronic and data-acquisition system specifically designed to monitor the real-time performance of its direct current generator. At the core of this system was an Arduino Uno microcontroller, enhanced with an ESP32 module for wireless communication. Voltage monitoring was achieved using a voltage divider circuit connected to the generator's DC output, with load resistors as the load. This setup allowed for continuous sampling of the output voltage, current, and power.

The sensor suite included an MD0492 voltage sensor for real-time direct current voltage measurement and an ACS712 current sensor for monitoring current, enabling power calculations. A 0.96" OLED display provided local system parameter readouts, while a DS1302 real-time clock module added time-stamping for logged data. An indicator LED signaled power generation events, and a relay module controlled connected loads. Although INA219 was considered for future versions, this setup offered adequate support for real-time analysis and visualization.

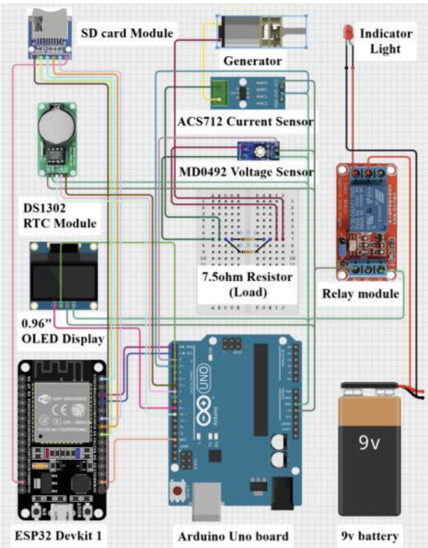


Figure 4 - SamudraGEN 1.0 Electronic system

3.5 Cloud Infrastructure and Monitoring Platform

Data captured by the Arduino was transmitted via serial and Wi-Fi, with the ESP32 enabling wireless communication for remote monitoring during sea trials. Node-RED, hosted locally and on an AWS EC2 instance, served as the processing and relay platform. It parsed sensor data and forwarded it to a Firebase real-time database, chosen for its lightweight architecture and compatibility with IoT systems. In SamudraGEN 1.0, no real-time dashboard was implemented. Instead, data collected during testing was transmitted and logged via Firebase for later analysis and review. The AWS-hosted environment enabled remote data storage, allowing the information to be accessed and reviewed after deployment. This combination of sensors, microcontrollers, and cloud-based infrastructure validated the feasibility of integrating IoT technology into wave energy systems. It enabled accurate, real-time assessment of electrical output and laid the foundation for expanded diagnostics in future versions.

3.6 Manufacturing and Assembly

SamudraGEN 1.0 was fabricated and assembled through a combination of machining, welding, and precision fitting, tailored to meet marine operational requirements. All major components were custom-manufactured to ensure durability and corrosion resistance in a wave energy environment. The steel base plate was machined with slots and mounting holes to accommodate the rack-and-guide system, which features linear bearings for smooth vertical motion. The motion rectifier unit was constructed using CSK12PP one-way bearings, HK1012 needle bearings, pinion gears, and precision-machined adapters. Two such assemblies were mounted on a central main shaft, enabling the conversion of bidirectional linear input into unidirectional rotary output. This system was installed on the base plate and supported by KP000 pillow block bearings. The rack assembly was inserted through the base plate cutouts and engaged with the pre-aligned rectifiers. The main shaft was then coupled to a DC generator using a flexible spider coupling to accommodate minor misalignments.

The base structure was welded to the floater, with additional supports added to reinforce stability and maintain watertight integrity. Oil seals were installed at the upper and lower sections of the floater to prevent water ingress. The electronics system, comprising sensors and a microcontroller, was housed in a waterproof enclosure positioned at the top of the floater for ease of access and monitoring. Manual pre-deployment tests were conducted by simulating wave-induced motion to assess the system's mechanical response and electrical output. The system reliably converted oscillatory motion into stable electrical power, confirming it is ready for sea deployment.

3.7 Field Trial Execution and Performance Analysis

SamudraGEN 1.0 underwent sea trials in the shallow coastal waters of Ginthota, Galle, Sri Lanka, near the geographic coordinates 6.049714° N, 80.182934° E. The initial deployment took place nearshore in low-wave conditions, where energy capture was limited.

To enhance testing accuracy, the device was relocated to a secondary site with more consistent wave activity. Deployment involved manually guiding the assembled unit into the ocean, where its weighted base provided passive anchoring without requiring mooring infrastructure. Once positioned, the floater responded effectively to wave motion, activating the power take-off mechanism and DC generator.

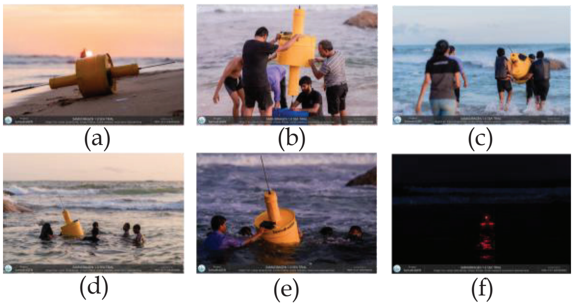


Figure 5 - Stepwise Deployment Sequence of the WEC During Sea Trials: (a) Floater, (b) Assembly with Base, (c) Device Transport, (d, e) Deployment at two Shallow Locations, and (f) Power Generation

The device maintained structural stability throughout the trial, with no observable water ingress or mechanical failures. The indicator LED accurately signalled power generation events exceeding 5 W. The system produced a consistent output of approximately 12 V DC, with peak power generation up to 20 W during energetic wave cycles and an average of 5-10 W. These results aligned with the system's design expectations for small-scale energy applications. Additionally, the sea trial verified the effectiveness and reliability of the PTO mechanism under real ocean conditions. However, site selection proved to be crucial, as wave conditions directly affected the amount of energy captured.

3.8 Observations and Design Recommendations

Insights from the field testing led to several recommendations for future iterations. The floater exhibited excessive upward buoyancy, affecting both energy capture and mechanical stability. This could be addressed by modifying its weight and geometry. Similarly, unrestricted joint rotation during high wave activity impaired stability; mechanical constraints would mitigate this issue. Deployment challenges were encountered due to the substantial base, which, although effective at stabilising the system, posed handling difficulties in shallow water. A redesign emphasizing a lighter yet structurally durable framework is recommended to improve manageability, especially in nearshore environments characterized by strong shoreward wave activity. Additionally, the floaters' existing geometry exhibited hydrodynamic inefficiencies; thus, a redesign to a more streamlined configuration is recommended to reduce drag and optimize interaction with wave forces.

The field trial also identified constraints in data-acquisition capabilities. Integrating more sophisticated IoT infrastructure, such as Amazon Web Services (AWS) and Node-RED, along with a real-time monitoring dashboard, would improve system management and data accessibility. Furthermore, broadening the sensor array to encompass motion, temperature, and humidity sensors would yield more comprehensive operational insights and support optimisation amidst variable maritime conditions. Overall, the sea trial confirmed the functional design of SamudraGEN 1.0 and its suitability for shallow-water wave-energy applications. These practical findings now inform the development of the next version of the prototype, aiming to enhance efficiency, simplify deployment, and improve environmental adaptability.

4. System Enhancements in SamudraGEN 2.0

Building on the feedback from SamudraGEN 1.0, the second-generation prototype has implemented a series of targeted enhancements across mechanical, electrical, and data-acquisition systems. These improvements are designed to optimise energy conversion efficiency, structural stability, monitoring capabilities, and long-term reliability within nearshore marine environments. These improvements were inspired by challenges during the SamudraGEN 1.0 sea trials, especially in stability, sensing resolution, and power conditioning.

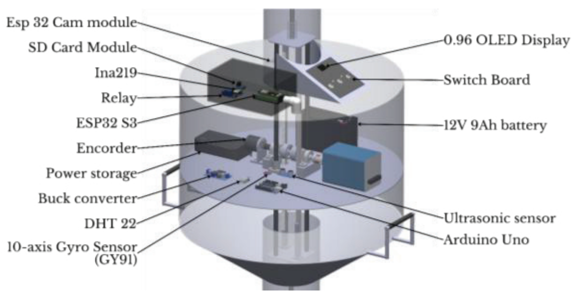


Figure 6 - Electronic System Configuration

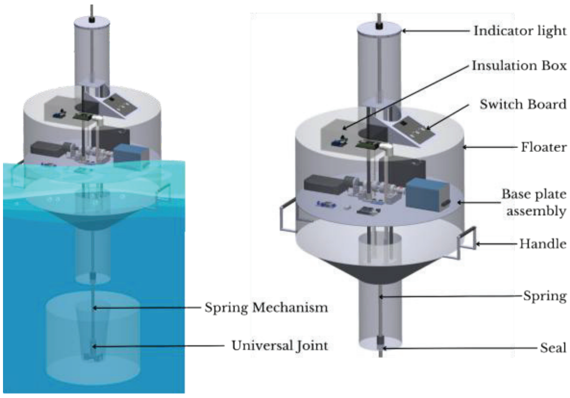


Figure 7 - Mechanical Structure Layout

4.1 Mechanical and Structural Improvements

SamudraGEN 2.0 featured a newly designed cone-shaped floater, selected for its hydrodynamic advantages and manufacturability. This simplified geometry enabled better wave interaction while maintaining ease of fabrication. The floater's assembly was enhanced with marine-grade sealants, resulting in a sealed, corrosion-resistant unit. To address handling difficulties observed in the previous version, the base structure was redesigned to reduce weight without compromising strength. This improvement simplified deployment while maintaining sufficient seabed stability. Adjustments to the floater's buoyancy and weight distribution corrected the excessive uplift seen in Version 1.0, leading to more controlled vertical motion. Additionally, mechanical stops were introduced to limit over-rotation, preventing the device from pitching excessively in high wave activity. These refinements significantly improved the system's balance, orientation control, and operational resilience.

(a) (b) (c)

Figure 8 - Upgrades in SamudraGEN 2.0: (a) New Electronics Unit, (b) Upgraded Base, (c) Complete System

4.2 Electronics, Sensing, and IoT Monitoring Enhancements

SamudraGEN 2.0 incorporated a vastly upgraded electronics architecture. A high-performance ESP32-S3 microcontroller replaced the Arduino-based controller, offering greater processing capability and integrated wireless connectivity. The electronics were housed in a larger, insulated enclosure for enhanced environmental protection and improved component organisation. An expanded sensor suite provided comprehensive monitoring of both device performance and environmental conditions. Key additions included an INA219 sensor for high-resolution voltage and current measurement, a 9-DOF IMU for motion and orientation tracking, a DHT22 sensor for ambient conditions, a rotary encoder for RPM monitoring, and an ultrasonic sensor for tracking rack displacement. The integration of an ESP32-CAM module enabled live visual monitoring of internal components, while data logging redundancy was achieved with an onboard SD card.

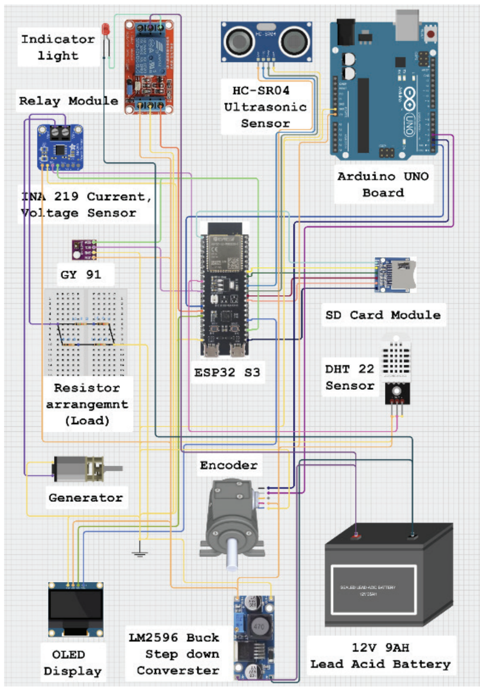


Figure 9 - SamudraGEN 2.0 Electronic System

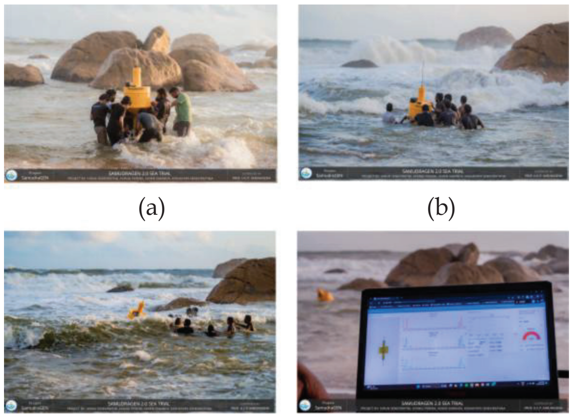
The IoT framework was significantly enhanced. Real-time sensor data was streamed to an AWS-hosted Node-RED dashboard, enabling remote monitoring via live gauges, alerts, and graphs. Threshold-based triggers allowed proactive system oversight. Historical data was stored in a cloud database using MongoDB Atlas, enabling trend analysis and predictive maintenance. These advancements ensured robust telemetry, real-time visualisation, and long-term system assessment capabilities. Altogether, SamudraGEN 2.0 demonstrated a holistic evolution of the original prototype, translating field trial insights into tangible improvements in design, functionality, and performance monitoring.

Figure 10 - Real-time Monitoring Dashboard

4.3 Sea Trial of SamudraGEN 2.0

SamudraGEN 2.0 was tested at the same site previously used by SamudraGEN 1.0. This test aimed to verify the new device's performance, stability, and operational reliability under real marine conditions. Lessons from the first prototype led to key improvements: a stronger buoy structure, a refined power take-off mechanism, and an expanded array of sensors and telemetry nodes for comprehensive, real-time data collection. Before deployment, the assembly was completed on land, with the buoy securely attached to its base. Moving the unit into the marine environment required precise coordination, and harsh marine conditions threatened to displace the apparatus; however, the device remained in place and continued to generate power, demonstrating the effectiveness of the mechanical improvements. The new buoy, in particular, minimized unintended movements, maintained a steady angle relative to incoming waves, and thus maximized energy capture while reducing mechanical wear.

Throughout the trial, several significant pitching and rolling motions were observed during high-wave events; however, the structural reinforcements implemented in the second version enabled the unit to withstand destabilising forces. A vital addition to SamudraGEN 2.0 was a cloud-based, real-time IoT dashboard that enables continuous, remote streaming of critical sensor data, such as voltage and current readings. This capability enabled monitoring of the system's operational condition and performance indicators from a remote site, facilitating immediate assessment of the WEC's response to variable marine environments. The successful deployment of SamudraGEN 2.0 thus validated the design modifications and functional upgrades implemented since the prior version, producing a system characterised by greater structural resilience, simplified installation, and enhanced episodic energy capture, and marking a significant step forward from the inaugural prototype.



(a) (b)

(c) (d)

Figure 11 - SamudraGEN 2.0 sea trial — (a) assembling base and floater, (b) moving to deployment site, (c) deploying WEC, (d) real-time dashboard monitoring

4.4 Power Generation Results

Sea trials evaluated the electrical performance of the SamudraGEN 2.0 directly in oceanic conditions. During the voyage, onboard sensors continuously recorded voltage and current, enabling detailed temporal analysis of the device's output. Voltage fluctuated between 0 V and around 15 V, reflecting the dynamic forces from the sea surface. Immediate voltage spikes were observed in sync with advancing wave crests, while the gaps between these peaks showed a less prominent, yet still detectable, quasi-steady voltage just below the surge maximums. These fluctuations confirm the converter's ability to respond to wave energy, but they also highlight notable voltage irregularities. This suggests that although the device can operate, integrating effective power conditioning circuits will be crucial to convert the harvested energy into a steady, commercially usable supply.

The current observations showed a similar pattern of variability to those previously reported, characterized by intermittent peaks of up to 4 A during episodes of increased wave forcing. These peaks coincided with measurable increases in surface wave amplitude, while the electrical output decreased during calmer environmental conditions. Nonetheless, the apparatus maintained continuous current production during the more energetic conditions, with brief lapses during quieter periods. This behaviour demonstrates both the mechanical and electrical durability of the setup, confirming that it can reliably convert wave motion into electricity under various maritime conditions. Supporting this, records of the PTO shaft speed showed pronounced oscillations, including recurring peaks approaching 120 RPM during the early testing phases; these oscillations directly correlated with wave forcing. Reduced sea-state energy caused a predictable drop in shaft speed, reflected in voltage and current profiles. Data show the energy system is adaptable and reliable across different wave conditions.

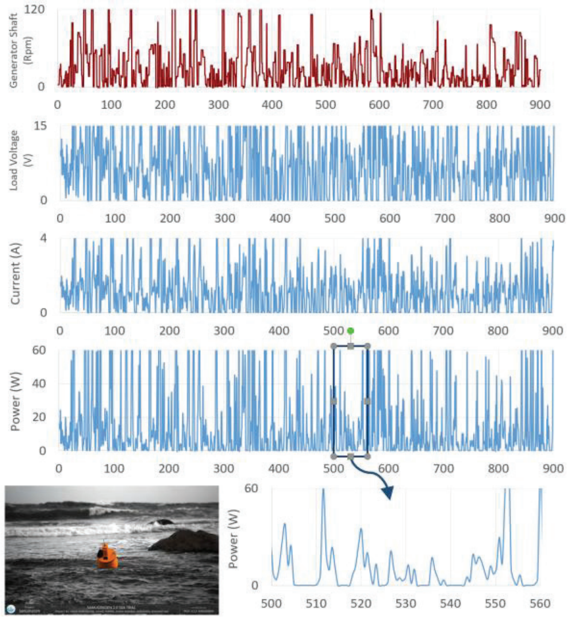


Figure 12 - Experimental Results Showing Generator RPM, Voltage, Current, and Power Output During Sea Trial

Instantaneous power, calculated from real-time voltage and current data, peaked at approximately 60 W under the most favorable wave conditions. These instances of increased power output demonstrated the WEC's ability to effectively harness wave energy. Even outside peak periods, the device consistently produced usable power within design specs. The power profile matched sea-state changes while maintaining a reliable baseline, averaging about 20 W during testing. The successful autonomous, sustained generation validated the SamudraGEN 2.0 upgrades. Additionally, a cloud dashboard confirmed that sensor data, such as voltage and power, remained stable and within expected parameters. These results confirm the converter's readiness for scaled testing and potential use in distributed nearshore energy systems [12]. Based on an average electrical output of approximately 20 W and a representative incident wave power of 0.7–1.4 kW/m, the estimated capture width is approximately 0.01–0.03 m, increasing to approximately 0.08 m at peak power. The measured power was constrained by the generator rating selected to meet project budget limits, and higher output is expected with an appropriately rated generator.

4.5 Environmental Condition Effects

SamudraGEN 2.0 maintained stable thermodynamic and hygrometric parameters throughout the comparison marine trial conducted under variable late-afternoon-to-early-evening conditions. The internal thermal monitoring revealed a controlled drop from 28.5 °C to 27.5 °C, consistent with the normal nocturnal cooling pattern and indicating the system's thermal mass and the enclosure's ability to reduce incident thermal fluctuations. At the same time, the internal relative humidity gradually decreased from 58% to 57% due to earlier thermal exposure, which temporarily increased the air's moisture capacity; subsequent ventilation and thermal stability allowed for a slow recovery. The lack of humidity transients, oscillations, or deliquescence effects inside the enclosure confirms the integrity of the vapor seal and the absence of liquid ingress. These findings confirm the effectiveness of the thermal insulation and hydrophobic barrier, showing the enclosure's readiness for reliable offshore energy operations.

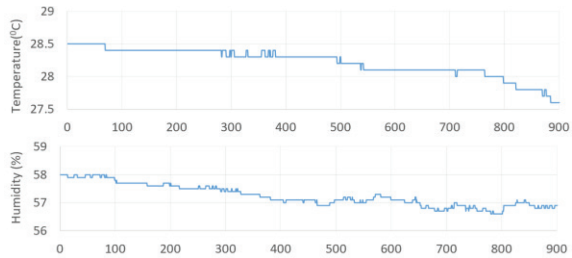


Figure 13 - Internal Temperature and Humidity inside WEC

4.6 Visual Inspection of Internal Mechanism

An internal video captured by the onboard ESP32-CAM module provided a clear view of the mechanical assembly inside the SamudraGEN 2.0 floater. The real-time video showed the rack-and-pinion interface, couplings, and bearing supports in operation, allowing remote assessment of mechanical integrity during sea trials. The observed cleanliness, absence of fluid ingress, and the coaxial alignment of the parts confirmed the success of the sealing measures. Overall, these features validated the operational effectiveness of embedded visual surveillance as an additional layer of real-time diagnostic intelligence. Figure 14 shows an ESP32-CAM view confirming stable rack-and-pinion engagement, proper alignment, and no water ingress during sea trials.

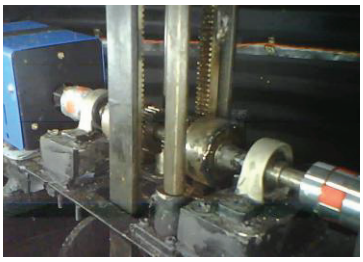


Figure 14 - Internal view via ESP32-CAM

5. Conclusion

The SamudraGEN project has successfully demonstrated the feasibility of developing a wave energy converter specifically optimised for shallow coastal environments. Through two iterative prototypes, the system evolved from a proof-of-concept model (SamudraGEN 1.0) to a more refined, intelligent platform (SamudraGEN 2.0) capable of sustained power generation and real-time monitoring under real ocean conditions. This study focused on a small-scale prototype, developed to validate the mechanical design and evaluate system performance in the shallow waters typical of Sri Lanka's southern coast.

Importantly, the device's small-scale performance lays the groundwork for future scalability. According to established hydrodynamic scaling laws, when a geometric factor λ scales the system, key performance parameters scale accordingly: the wave-induced force on the floater scales as λ^3, torque as λ^4, and the velocity of motion as $\sqrt{\lambda}$. These scaling relationships confirm that, beyond proof-of-concept validation, the SamudraGEN design has strong theoretical foundations for transitioning to larger-scale deployments. The implications are significant—scaled-up versions of the system could serve not only isolated coastal communities but also contribute to the development of distributed renewable energy networks. Overall, the SamudraGEN system offers a promising pathway for harnessing nearshore wave energy in developing maritime regions. Its compact design, modularity, and adaptability to low- to moderate-energy sea states provide a unique advantage over conventional offshore technologies. Future work will focus on longer sea trials, quantitative CFD–field validation using onboard sensors, and upgrades to generators and power conditioning to enable higher electrical output. By bridging engineering innovation with scalable energy access, this project demonstrates how localized renewable energy solutions can be realized through iterative, context-aware design.

References

1. Coe, R.G., Yu, Y.H., Van, Rij, J., A survey of WEC reliability, survival and design practices, Energies (Basel). 11 (2018). https://doi.org/10.3390/en11010004.
2. Qiao, D., Haider, R., Yan, J., Ning, D., Li, B., Review of wave energy converter and design of mooring system, Sustainability (Switzerland) 12 (2020). https://doi.org/10.3390/su12198251.
3. Seneviratne, H., Karunasena, C., Amlashi, H., A multi-dimensional review on performance enhancement opportunities of next generation wave energy converters, Proceedings of the European Wave and Tidal Energy Conference 16 (2025). https://doi.org/10.36688/ewtec-2025-850.
4. Li, H., Shi, X., Kong, W., Kong, L., Hu, Y., Wu, X., Pan, H., Zhang, Z., Pan, Y., Yan, J., Advanced wave energy conversion technologies for sustainable and smart sea: A comprehensive review, Renew. Energy 238 (2025). https://doi.org/10.1016/j.renene.2024.121980.
5. Drew, B., Plummer, A.R., Sahinkaya, M.N., A review of wave energy converter technology, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 223 (2009) 887–902. https://doi.org/10.1243/09576509JPE782.
6. Lian, J., Wang, X., Wang, X., Wu, D., Research on Wave Energy Converters, Energies (Basel). 17 (2024). https://doi.org/10.3390/en17071577.
7. Projects Database, (n.d.). https://openei.org/wiki/PRIMRE/Databases/Projects_Database (accessed March 27, 2025).
8. Kamidelivand, M., Deeney, P., Murphy, J., Rodrigues, J.M., Garcia-Rosa, P.B., Atcheson Cruz, M., Alessandri, G., Gallorini, F., Failure Consequence Cost Analysis of Wave Energy Converters—Component Failures, Site Impacts, and Maintenance Interval Scenarios, J. Mar. Sci. Eng. 12 (2024). https://doi.org/10.3390/jmse12081251.
9. Karunarathna, H., Maduwantha, P., Ratnasooriya, H., De Silva, K., Kamranzad, B., Wave Power Potential of Sri Lanka, Engineer: Journal of the Institution of Engineers, Sri Lanka 54 (2021) 1. https://doi.org/10.4038/engineer.v54i2.7404.
10. Coe, R.G., Ahn, S., Neary, V.S., Kobos, P.H., Bacelli, G., Maybe less is more: Considering capacity factor, saturation, variability, and filtering effects of wave energy devices, Appl. Energy 291 (2021). https://doi.org/10.1016/j.apenergy.2021.116763.
11. Rusu, E., Onea, F., A review of the technologies for wave energy extraction, Clean Energy 2 (2018) 10–19. https://doi.org/10.1093/ce/zky003.
12. Martić, I., Degiuli, N., Grlj, C.G., Scaling of wave energy converters for optimum performance in the Adriatic Sea, Energy 294 (2024) 130922. https://doi.org/10.1016/j.energy.2024.130922.