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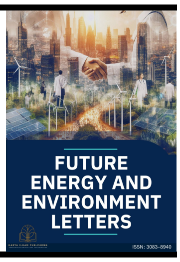

Sustainable Power in Maritime Emergencies: Developing A Wave Energy Converter for Life Rafts

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ABSTRACT

This paper presents the design and analysis of a wave energy converter (WEC) developed to power emergency life rafts sustainably. Traditional rafts depend on finite batteries, limiting the operational time of critical navigation and signalling equipment. The proposed system harnesses ocean wave energy to provide continuous, renewable power, directly addressing this limitation. The design prioritizes compactness, durability, and ease of deployment for small-scale applications. Through experimental testing, the equipment demonstrated the ability to generate sufficient electricity under moderate wave conditions to recharge onboard batteries. The results, showing an average energy conversion efficiency of 2.44%, confirm that this WEC technology can significantly enhance maritime survival rates by enabling the prolonged operation of essential devices. It offers a reliable, low-maintenance power source for equipment such as GPS, EPIRBs, and radios in open-water emergencies.

1. Introduction

Wave energy converters (WECs) represent a promising technology for harnessing oceanic power to generate clean, renewable electricity, thereby reducing dependence on fossil fuels and mitigating greenhouse gas emissions. The predictable nature of wave energy enhances grid stability and supports sustainable energy infrastructure. Furthermore, the development and deployment of WECs stimulate economic growth through job creation and the bolstering of local economies. Certain WEC designs offer the ancillary benefit of attenuating wave force, thereby reducing coastal erosion and providing combined environmental and economic advantages. A critical application for this technology exists in the domain of maritime safety. During maritime emergencies, survivors in life rafts are dependent on battery-powered devices for essential functions, including communication, navigation, and distress signaling. The finite energy capacity of these batteries poses a significant risk, as their rapid depletion directly compromises survival duration and the probability of successful rescue. Consequently, a critical gap exists in the availability of a sustainable and reliable power source for life support systems in prolonged emergency scenarios. The integration of a compact, durable,

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and efficient wave energy converter presents a viable solution to this problem. By leveraging the omnipresent motion of the ocean, such a device could provide a continuous power supply, ensuring the persistent operation of critical systems. This capability would significantly enhance the safety and survivability of individuals in open-water emergencies by extending the functional lifespan of life-saving equipment, as discussed by Ferreira *et al.,* [1] and Foteinis [2].

Conventional emergency life rafts are designed for temporary survivability, yet rescue operations in remote maritime environments can be significantly delayed, extending the required duration of survival beyond initial design parameters. This project addresses a critical vulnerability in such scenarios: the depletion of finite battery reserves. It proposes the integration of a renewable power source to ensure the persistent operation of essential systems, including communication, navigation, and signaling equipment. The proposed solution involves a wave energy converter (WEC) engineered to capture the kinetic and potential energy of ocean waves and transduce it into electrical energy for battery charging. While wave energy technology holds considerable promise as a renewable resource, its widespread adoption is hindered by challenges related to device longevity, reliability, and high maintenance costs, as noted by Ni [3], Shouqiang *et al.,* [4], and Yang *et al.*, [5]. Consequently, research and development efforts must prioritize the creation of smaller, more affordable, and highly resilient converters. This is particularly critical for deployment in low-energy sea states, such as those prevalent in the Mediterranean and Baltic Seas. The strategic implementation of WECs offers significant ancillary benefits. Nearshore deployments can be integrated into coastal defense infrastructure, providing both renewable energy and a mitigation strategy against shoreline erosion, as highlighted by Foteinis [2]. Furthermore, the technology can be coupled with secondary functions such as desalination and hydrogen production, enhancing its overall utility and economic viability, as explored by Shouqiang *et al.,* [4]. Globally, wave energy is gaining recognition as a valuable component of the renewable energy portfolio, with nations like China making substantial investments in its development. Although the initial capital costs remain high, strategic co-location of WECs with existing maritime activities---such as coastal defenses, tourism, desalination plants, and offshore aquaculture---can reduce levelized costs and improve sustainability. This integrated approach can also alleviate the intermittency of other renewable sources, bolster energy security, and provide auxiliary services such as supplying cooling water for thermal power plants. Recent research underscores that wave energy, though often overlooked, possesses significant potential. Advancements in geospatial mapping methodologies are crucial for optimizing site selection. Pairing specific WEC technologies with locations whose wave climate matches their operational characteristics can drastically improve energy capture efficiency, with studies indicating potential increases in capacity factor by up to 50%, as demonstrated by Del Río-Gamero *et al.,* [6], Nguyen *et al.,* [7], Wang *et al.,* [8], and Wu *et al.,* [9]. This underscores the importance of targeted development and optimized resource assessment.

The advancement of wave energy converter (WEC) technology is contingent upon the development of sophisticated modeling and optimization techniques to enhance efficiency, reduce costs, and improve reliability. Recent research demonstrates a multi-faceted approach to these challenges, spanning numerical modeling, novel platform design, and systematic optimization. A critical pathway to innovation is through high-fidelity, computationally efficient modeling. Research by Ayyad *et al.,* [10] focuses on the development of reduced-order models to optimize WEC geometry. Their methodology employs experimental data from quasi-static, free response, and torque-forced conditions to identify essential hydrodynamic parameters, including hydrostatic stiffness, radiation damping, added mass, and nonlinear damping coefficients. By applying a physics-informed neural network to this data, they derive a validated model and an analytical representation of the admittance function, providing a robust framework for design optimization, a direction also supported by the works of Dash *et al.,* [11], Jalón & Brennan [12], Lin *et al.,* [13], and Ye *et al.,* [14]. Beyond isolated device optimization, system integration presents a significant opportunity for performance gains. Huang *et al.,* [15] propose an integrated platform approach with a semi-submersible floating platform (SSP) that incorporates multiple self-reacting WECs (SRWECs). This SSP-SRWEC design serves a dual purpose: it enhances vibration control for the floating structure and concurrently improves energy harvesting. By isolating the WECs from direct wave action, the system is engineered to absorb and suppress vibrational energy from the platform itself, thereby extending effective vibration control across a broader frequency range and boosting energy capture performance even under identical device conditions. Finally, the selection of computational methods is paramount for navigating the complex design trade-offs inherent in WEC development. Acknowledging wave energy's potential to address the global energy crisis, Shadmani *et al.,* [16] conduct a comparative analysis of multi-objective optimization (MOO) algorithms for designing multi-axis WECs (MA-WECs). Utilizing the NEMOH boundary element method solver for hydrodynamic analysis, their research concludes that the choice of optimization algorithm significantly influences the final design outcome, with substantial implications for improving power efficiency and minimizing operational costs.

However, a significant research gap persists in the development of compact, cost-effective, and highly durable WECs specifically designed for low-power, emergency applications, such as powering life rafts. While substantial research, including that by Ayyad *et al.,* [10] and Shadmani *et al.,* [16], focuses on large-scale energy harvesting and complex optimization, the translation of these principles into small-scale, survival-grade technology that is reliable in harsh marine conditions remains underexplored.

Addressing this gap is of critical significance, as it directly impacts maritime safety. A successful implementation would provide a sustainable power source for life-saving equipment during prolonged emergencies, drastically improving survival odds by ensuring communication and signaling devices remain operational when traditional batteries are depleted.

Therefore, this study aims to design, fabricate, and test a prototype wave energy converter specifically for integration into an emergency life raft. The objective is to develop a compact, durable system capable of harnessing ocean wave energy to continuously recharge onboard batteries, thereby powering essential navigation and communication equipment and enhancing survivability in open-water emergencies.

2. Methodology

2.1 Design and Assembly

The fabrication and assembly of a wave generator as shown in Figure 1 for an emergency life raft involve designing a durable, lightweight, and corrosion-resistant device capable of withstanding harsh marine environments. Material selection as shown in Table 1 is a critical part of the process, with components like the dynamo, buoyant casing, chain, magnet, and energy storage unit being constructed from materials such as stainless steel, aluminum, and high-density plastics. The casing is either molded or welded into a streamlined shape to enhance its movement with the waves. Inside the casing, a magnet and coil are precisely positioned to maximize energy generation through electromagnetic induction. During assembly, all internal components are securely mounted and water-sealed to protect against corrosion and damage. Connections to the energy storage system, such as a battery or capacitor, are established to store the generated electricity, with waterproof ports added to enable energy transfer to life raft equipment. The completed wave generator is then subjected to rigorous testing to ensure its reliability and performance under extreme wave conditions.

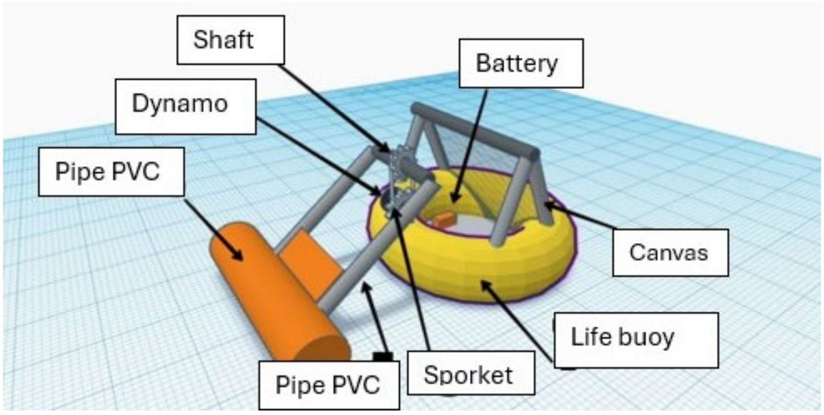

Fig. 1. Perspective views of WEC

Table 1
Equipment Part List

Item	Qty	Part Number	Material
1	1	Shaft	Steel
2	1	Battery	Lithium
3	1	Dynamo	Fluid Iron Core
4	1	Pipe PVC	Polyvinyl Chloride
5	7	Pipe PVC	Polyvinyl Chloride
6	2	Sprocket	Steel
7	1	Life Buoy	Rubber
8	1	Canvas	Fabric

2.2 Testing Setup

Prior to the charging process, the power storage system should be maintained to ensure it is in good working condition. When waves interact with the buoyancy mechanism, they generate motion that initiates the charging of the power storage system as shown in Figure 2 and Figure 3. After the charging process is complete, the system's functionality can be tested by visually inspection of the electrical circuit. To perform this test, the dynamo gear is manually rotated, and the connected light is observed. If the light turns on brighter, it confirms that the circuit is functioning correctly as shown in Figure 4 and Figure 5.

Fig. 2. Initial value of 6.88 Wh (before charging)

Fig. 3. Final value of 7.04 Wh (after charging)

Fig. 4. System functionality test (before charging)

Fig. 5. System functionality test (after charging)

2.3 Quantitative Evaluation

The qualitative evaluation of the converter is based on watt-hour energy unit (Wh) which It measures the total amount of energy consumed or produced over a period and is calculated by multiplying the power (in watts) by the time (in hours) or by multiplying the voltage (V) and ampere hour rating (Ah). Watt-hours are often used to describe the capacity of batteries and portable power stations, helping users comprehend how long a device can run on a single charge.

3. Results

3.1 Wave Energy Conversion Efficiency

The prototype wave energy converter (WEC) demonstrated a mean energy conversion efficiency of 2.44% across a range of simulated wave conditions. As detailed in Table 2 and Figure 4., peak efficiency reached 3.66%, a value achieved during periods of higher wave amplitude. The resultant energy output of the system varied from 0.1 to 0.26 watt-hours (Wh), exhibiting a direct correlation with wave frequency and amplitude.

Table 2
Energy Output

Test No.	Duration (min)	Initial Energy Amount (Wh)	Final Energy Amount (Wh)	Gain Percentage (Wh)	Gain Percentage (%)
1	1	6.45	6.55	0.10	1.55%
2	1	6.55	6.70	0.15	2.29%
3	1	6.72	6.88	0.16	2.38%
4	1	6.88	7.04	0.16	2.33%
5	1	7.10	7.36	0.26	3.66%
			Average	0.17	2.44%

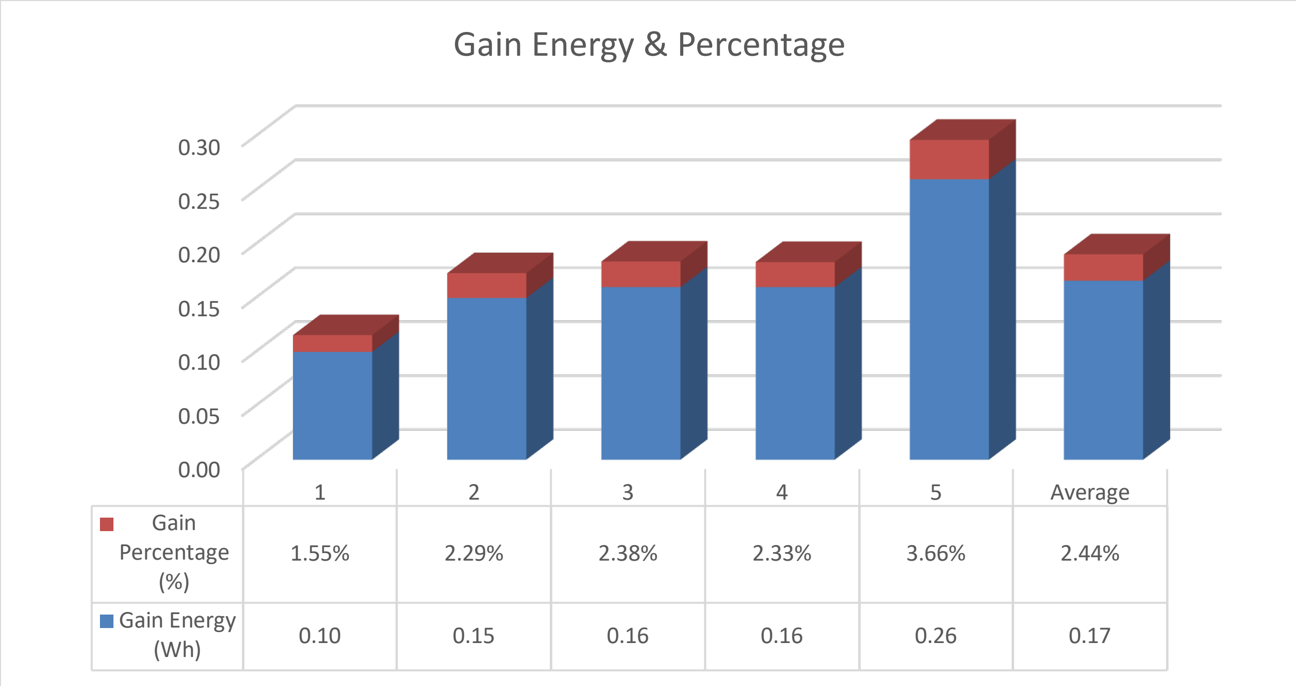

Fig. 6. Gain energy and percentage

3.2 Power Storage Performance

The integrated power storage system successfully accumulated electrical energy harvested by the wave energy converter (WEC). Experimental results demonstrated a maximum energy storage capacity gain of 0.26 Wh within. This level of energy accumulation is sufficient to reliably power critical survival equipment, including emergency lighting, maritime communication systems, and small-scale thermal devices, for operationally relevant durations.

3.3 Durability and Reliability

The buoyancy mechanism and dynamo assembly exhibited robust structural integrity and operational durability throughout testing under simulated harsh marine conditions. The components demonstrated significant resistance to sustained mechanical stress induced by repeated wave impacts. No measurable performance decline or significant material degradation was observed over the duration of the testing period.

3.4 Functionality Testing

Manual operational testing of the dynamo gear assembly was conducted to verify the integrity of the electrical circuit. The test confirmed successful functionality; manual rotation of the dynamo rotor consistently induced illumination in the connected load (a light-emitting diode). This result empirically validates the effective transduction of mechanical energy into electrical current and confirms the operational integrity of the core power generation system.

The system demonstrated strong performance in moderate wave conditions but exhibited reduced efficiency in calmer seas due to the limited motion of the buoyancy mechanism. To address this, future designs could include features such as adjustable buoyancy or oscillation enhancers to amplify motion in low-energy wave environments. The storage capacity was adequate for powering basic survival equipment but may fall short for more energy-intensive devices, such as GPS trackers or larger communication systems. Enhancing usability could involve increasing battery capacity or exploring alternative storage solutions, such as supercapacitors. The converter's lightweight and compact design makes it well-suited for integration with life rafts. However, improving the design to allow easier assembly and deployment by untrained users would enhance its utility in emergency situations. The wave energy converter faces several challenges and limitations. First, saltwater exposure may cause long-term corrosion despite its initial durability, making the use of more corrosion- resistant materials essential. Second, the variability in wave energy results in inconsistent power generation; this could be mitigated by incorporating a small backup power source, such as a solar panel. Lastly, while the system is well-suited for individual life rafts, scaling it up for larger emergency setups may require redesigning components to achieve higher energy output. Future improvements to the wave energy converter could focus on enhancing the buoyancy mechanism to optimize energy capture. Additionally, implementing a hybrid system that combines wave, and solar energy would enable continuous power generation. Finally, testing the system in real-life maritime environments would provide more accurate data, helping to refine and improve the design. In conclusion, the developed wave energy converter shows significant promise for emergency applications on life rafts, offering a sustainable and compact energy solution. With further improvements in efficiency and durability, it can become an indispensable tool for maritime survival scenarios.

4. Conclusions

This study developed a prototype wave energy converter (WEC) for integration into maritime life rafts to address the critical limitation of finite battery power in survival equipment. In contrast to previous solutions that rely solely on limited-capacity batteries or intermittent solar charging, this technology harnesses the pervasive kinetic energy of ocean waves. Experimental results demonstrated that the system achieved an average energy conversion efficiency of 2.44% under moderate wave conditions, proving its capability to provide a renewable source of electricity for essential functions like communication, navigation, and distress signalling.

The benefits of this WEC are twofold, enhancing both maritime safety and environmental sustainability. It extends the operational window of life-saving equipment, thereby increasing survival odds, while simultaneously reducing the environmental footprint of maritime operations by supplanting non-renewable battery packs.

While the prototype shows significant promise, its practical realization necessitates further development. Key challenges include optimizing energy conversion efficiency, ensuring long-term durability against corrosion, and adapting to a wider spectrum of wave climates. This study successfully established a proof-of-concept; future work will focus on design refinements and, crucially, real-sea trials to advance the technology readiness level and validate performance in genuine emergency conditions. This work marks a step forward in converging survival needs with sustainable energy solutions for maritime safety.

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