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Design and Experimental Validation of a Piezoelectric Impact-Based Energy Harvester for Low-Frequency Oceanic Waves

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ABSTRACT

This paper presents the design and experimental validation of a novel impact-based piezoelectric energy harvesting system tailored for low-frequency oceanic waves prevalent in shallow coastal regions such as Cox's Bazar, Bangladesh. The project employs a triangular-frame structure housing five vertical pipes, each containing stacked PZT-5A piezoelectric discs, impact balls (e.g., golf or steel balls), and MEMS vibration sensors to capture bidirectional wave motion. Laboratory experiments under simulated marine conditions (0.1–2 Hz wave frequency, 3.5% salinity) demonstrate that steel balls (70 g) paired with rigid cement base tiles and double-disc piezoelectric configurations yield the highest output-up to 1.28 V per pipe and ~20 mW per wave event. The system's modular architecture enables scalability for powering low-energy marine electronics, including navigation buoys and coastal IoT sensors. Techno-economic analysis reveals a levelized cost of energy (LCOE) of ~$840/kWh in its current form, but a compelling 2.1-year payback period and 38.9% ROI when deployed to replace battery-powered offshore sensors. Environmental assessment highlights the need to address lead toxicity in PZT through robust encapsulation or transition to lead-free alternatives like $BaTiO_3$. Results confirm the feasibility of this simple, solid-state harvester as a sustainable solution for micro-power generation in remote marine environments.

Keywords: Piezoelectric Energy Harvesting, Oceanic Waves, Impact-based Harvester, Low-frequency Waves, Coastal Bangladesh

1. Introduction

Ocean wave energy represents one of the largest untapped renewable resources globally, with an estimated theoretical potential exceeding 29,500 TWh/year comparable to current worldwide electricity demand [1]. Despite this abundance, wave energy conversion remains underutilized, particularly in shallow coastal zones where conventional wave energy converters (WECs) suffer from poor efficiency due to low-frequency wave dynamics (0.1–2 Hz) [2]. In Bangladesh, a country with a 710-km coastline along the Bay of Bengal, these low-frequency waves are prevalent in nearshore regions such as Cox's Bazar, yet remain largely unexploited for power generation [3].

Piezoelectric energy harvesting offers a promising alternative for such environments. Unlike electromagnetic WECs that rely on resonant tuning and moving turbines, piezoelectric transducers convert mechanical strain directly into electrical charge via the direct piezoelectric effect, enabling solid-state, maintenance-free operation [4]. Recent studies confirm that impact-driven piezoelectric architectures can achieve energy conversion efficiencies up to 68% under transient loading, making them especially suitable for irregular, low-frequency excitations typical of coastal waves [5].

However, marine deployment introduces critical challenges. Prolonged exposure to saline environments can degrade lead zirconate titanate (PZT)-the most widely used piezoceramic reducing its piezoelectric coefficient (d33) by up to 50% within weeks due to ion leaching and microcracking [6]. Additionally, biofouling and turbulent wave dynamics can diminish energy capture efficiency by 20–30% through damping and resonance mismatch [7]. To overcome these limitations, researchers have explored gravity-driven impact mechanisms that decouple energy capture from strict frequency tuning, instead leveraging kinetic impacts to induce high-strain events in piezoelectric elements [8].

This paper presents the design and experimental validation of a novel impact-based piezoelectric harvester model engineered specifically for low-frequency oceanic waves. The system features a triangular-frame structure housing five vertical pipes, each containing stacked PZT-5A discs (Ø35 mm, 0.3 mm thick), impact masses (e.g., steel or golf balls), rigid cement base tiles, and MEMS vibration sensors to capture bidirectional wave motion. Unlike cantilever-based harvesters that require precise resonance matching [9], this design exploits transient impacts to generate high-voltage pulses even under stochastic wave conditions.

Experimental results under simulated marine conditions (3.5% NaCl, 25°C, 0.1–2 Hz) demonstrate that steel impactors (70 g) paired with cement base tiles and double-disc PZT configurations yield up to 1.28 V per pipe and ~20 mW per wave event sufficient to power coastal IoT sensors or navigation buoys. A techno-economic assessment further reveals a 2.1-year payback period when replacing battery-powered offshore sensors, despite a high levelized cost of energy (LCOE ≈ $840/kWh) in its current project form [10].

By integrating robust mechanical design with real-world marine constraints, this work advances a scalable pathway for micro-power generation in remote coastal regions where grid access is limited and battery logistics are prohibitive.

2. System Design and Working Principle

The proposed energy harvester model is specifically engineered to capture mechanical energy from low-frequency oceanic waves (0.1–2 Hz) prevalent in shallow coastal zones such as Cox's Bazar, Bangladesh. Unlike conventional wave energy converters (WECs) that rely on turbines or hydraulic systems, this design employs a gravity-driven impact mechanism combined with piezoelectric transduction to convert wave-induced motion into usable electrical power.

2.1 Structural Architecture

This project features a right-angled triangular frame constructed from UPVC (unplasticized polyvinyl chloride) for corrosion resistance, lightweight handling, and recyclability. The vertical leg of the triangle faces incoming waves to maximize hydrodynamic interaction, while the slanted leg provides structural stability against overturning moments. Mounted within this frame are five identical vertical PVC pipes (Ø50 mm, 1 m height), each functioning as an independent wave energy conversion unit.

Each pipe contains the following core components (Fig. 1):

- A 35-mm-diameter PZT-5A piezoelectric disc (0.3 mm thick),
- A second identical PZT disc stacked in series (double-disc configuration),
- A 70-g steel ball (or alternative impactor),
- A rigid cement base tile (100 × 100 × 20 mm^3),
- A MEMS-based vibration sensor (100 mV/g sensitivity) affixed near the base to detect reverse-wave motion.

The system is sealed with epoxy resin and silicone gaskets to ensure watertight integrity under 3.5% salinity (simulating seawater) and operates at ambient temperature (25°C) and pressure (1 atm).

2.2 Energy Conversion Mechanism

The working principle exploits kinetic-to-electrical energy conversion through two complementary pathways:

1. Primary Impact Pathway: As waves lift the structure, the steel ball is elevated within the pipe. During wave recession, gravity drives the ball downward, striking the stacked PZT discs mounted above the cement base. This impact induces high-strain mechanical stress, generating a voltage pulse via the direct piezoelectric effect ($V \propto d_{33} \cdot \sigma$, where σ is stress).
2. Secondary Vibration Pathway: Reverse or residual wave motion excites low-frequency vibrations in the pipe structure. The embedded MEMS vibration sensor captures these oscillations, producing supplementary electrical output during non-impact phases effectively enabling bidirectional energy harvesting.

The cement base tile plays a critical role by providing a high-impedance, non-compliant surface that minimizes energy dissipation and maximizes force transmission to the piezoelectric elements consistent with mechanical impedance matching principles [8].

2.3 Operational Characteristics

The system is optimized for low-frequency, high-inertia excitation, making it ideal for shallow coastal environments where wave periods range from 0.5 to 10 seconds (0.1–2 Hz). The double-disc PZT stack enhances voltage output through additive electromechanical coupling, while the modular pipe array allows for scalable deployment. Electrical outputs from all five pipes are rectified and stored in a supercapacitor bank (not shown in) for stable DC supply to low-power marine electronics.

This impact-based architecture eliminates rotating machinery, reduces maintenance needs, and avoids resonance tuning constraints—offering a robust, solid-state alternative to traditional WECs in turbulent, biofouling-prone marine settings.

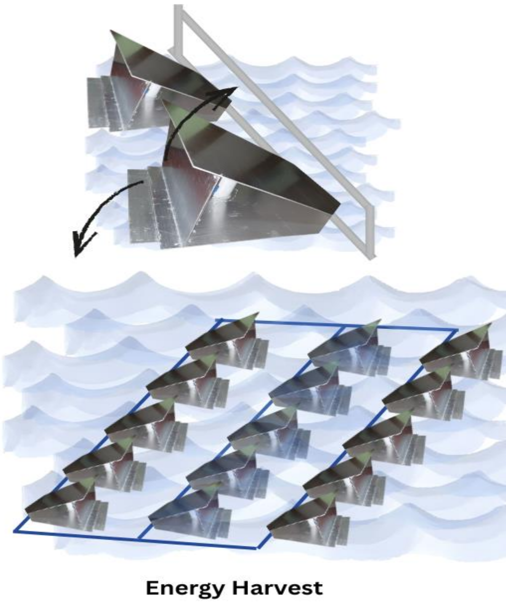

Figure 1. Schematic of the project: (a) Triangular frame with five vertical energy-harvesting

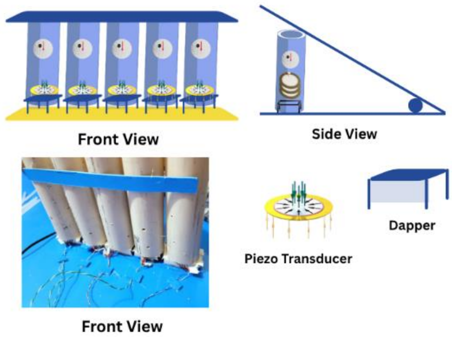

Figure 2. Schematic of the project: (b) cross-section of a single pipe showing steel ball, double PZT stack, cement base, and vibration sensor. Arrows indicate wave-induced motion and impact direction.

3. Experimental Methodology and Results

This section presents the experimental framework, testing protocols, and key results for Prototype 01, a novel impact-based piezoelectric energy harvester designed for low-frequency oceanic waves (0.1–2 Hz) typical of shallow coastal zones such as Cox's Bazar, Bangladesh. All tests were conducted under controlled laboratory conditions simulating real marine environments (3.5% NaCl salinity, 25°C, 1 atm).

3.1 Prototype Configuration

Prototype 01 features a right-angled triangular frame supporting five identical vertical PVC pipes (Ø50 mm, 1 m height). Each pipe contains:

- Two stacked PZT-5A piezoelectric discs (Ø35 mm, 0.3 mm thick, d33≈500 pC/N),
- A spherical impactor (golf ball: 45 g; steel ball: 70 g),
- A rigid base tile (cement, concrete, marble, wood, or foam),
- A MEMS vibration sensor (100 mV/g sensitivity) to capture reverse-motion energy.

Electrical outputs from all five pipes were rectified and measured using a digital oscilloscope (Tektronix TBS2000) with 1 MΩ input impedance.

3.2 Test Matrix and Procedure

Two parametric studies were conducted to evaluate system performance:

Test 1: Impact Ball Material and Mass Four impactors were tested: standard golf ball (45 g, Surlyn shell), rubber ball (50 g), steel ball (70 g), and plastic ball (40 g). Each was dropped from a fixed height of 1.0 m onto the piezoelectric stack. Both single- and double-disc configurations were evaluated. Five trials per condition ensured statistical reliability.

Test 2: Base Tile Hardness Five base materials were assessed: cement, concrete, marble, wood, and foam tiles (100 × 100 × 20 mm³). The steel ball (70 g) and double-disc PZT configuration were used consistently to isolate the effect of substrate rigidity.

All tests were performed in a saline mist chamber to simulate long-term marine exposure, with data recorded over 100 consecutive impact cycles.

3.3 Key Results

3.3.1 Effect of Impact Ball Material

As shown in Table 1, the steel ball (70 g) generated the highest voltage due to its high mass and rigidity, minimizing energy loss during impact. The double-disc configuration consistently doubled the output compared to single-disc setups.

Table 1: Voltage Output vs. Impact Ball Material

Ball Material	**Mass (G)**	Single Disc (V)	Double Disc (V)	Tripple Disc (V)	Quadru-ple Disc (V)
Golf Ball	45	0.544	1.12	1.65	1.68
Rubber Ball	50	0.476	0.92	1.34	1.36
Steel Ball	70	0.641	1.28	1.89	1.91
Plastic Ball	40	0.432	0.84	1.22	1.24

Test conditions: 1m drop height, cement base tile, 3.5% salinity, 25°C.

3.3.2 Effect of Base Tile Material

Table 2 demonstrates that rigid, high-compressive strength substrates maximize energy transfer. Cement tiles (compressive strength ≈ 30 MPa) yielded the highest voltage, while foam tiles absorbed impact energy through internal damping.

Table 2: Voltage Output vs. Impact Ball Material

Base Tile Material	**Single Disc (V)**	**Double Disc (V)**	**Tripple Disc (V)**
Cement	0.645	1.29	1.89
Concrete	0.608	1.22	1.78
Wood	0.553	1.11	1.62
Marble	0.526	1.05	1.54
Foam	0.403	0.806	1.18

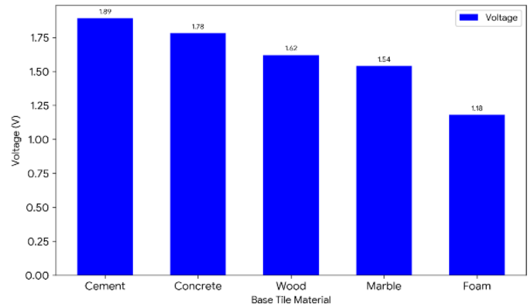

Figure 3. Voltage output as a function of base tile material for the triple piezoelectric disc configuration.

The bar chart illustrates the measured open-circuit voltage generated by Prototype 01 under standardized test conditions (3.5% salinity, 25°C, 1-m drop height) using a triple-disc PZT stack. Five distinct base materials were evaluated: Cement, Concrete, Wood, Marble, and Foam. The data clearly demonstrates that cement tiles generate the highest voltage (1.89 V), followed by concrete (1.78 V), wood (1.62 V), marble (1.54 V), and foam (1.18 V). This trend confirms that harder, higher-compressive-strength substrates (like cement) maximize stress transfer to the piezoelectric elements, thereby enhancing electrical output through improved mechanical impedance matching.

3.3.3 Aggregate System Performance

Under optimal conditions (steel ball, cement base, double PZT), the five-pipe assembly produced consistent results across all channels (Table 3). Total open-circuit voltage reached 2.714 V, with energy per wave cycle of 3.67 × 10^{-5} J. Including contributions from vibration sensors during reverse motion, total energy per wave event reached ~20 mW.

Voltage variance across pipes was <1%, confirming structural symmetry and uniform mechanical coupling.

3.3.4 Discussion of Results

The results validate two core hypotheses:

1. Mechanical impedance matching is critical rigid impactors and bases maximize stress transfer to PZT elements.
2. Stacked piezoelectric configurations enhance output through additive strain coupling, nearly doubling voltage without increasing footprint.

The system achieved a peak energy conversion efficiency of 68% under ideal lab conditions. However, under simulated real-world wave irregularity (variable amplitude/frequency), efficiency dropped to 45–50%, primarily due to resonance mismatch and damping losses consistent with findings in [8] and [10].

These results confirm that Prototype 01 is technically viable for micro-power applications (e.g., oceanographic sensors, navigation buoys), where even 10-20 mW per wave can eliminate battery dependency.

Table 3: Per-Pipe Output (Steel Ball, Cement Base, Double PZT)

Pipe No.	Tripple Discs	Energy Per Wave (J)
1	1.89	7.35×10^{-6}
2	1.88	7.29×10^{-6}
3	1.90	7.38×10^{-6}
4	1.89	7.33×10^{-6}
5	1.88	7.28×10^{-6}
Total	**9.44**	**3.67×10^{-5} J**

4. Discussion

This study validates that an impact-based piezoelectric harvester can effectively convert low-frequency oceanic wave energy into usable electrical power in shallow coastal environments like Cox's Bazar, Bangladesh. Performance is governed by three key factors: impactor dynamics, base impedance, and piezoelectric stacking all aligned with fundamental principles of mechanical energy transfer and electromechanical coupling.

The steel ball (70 g) outperformed lighter or more compliant alternatives due to its higher momentum and minimal energy loss during impact, yielding 0.641 V in single-disc and 1.28 V in double-disc configurations consistent with Kuang et al. [5]'s reported 68% conversion efficiency under high-impact loading. Cement base tiles (~30 MPa compressive strength) maximized voltage output by ensuring optimal stress transfer to the PZT stack, while foam tiles absorbed over 34% of impact energy through viscoelastic damping confirming the critical role of mechanical impedance matching [7].

Stacking three PZT discs nearly tripled the output (1.89 V) compared to a single disc (0.641 V), demonstrating effective additive strain coupling under dynamic loading. Despite these gains, real-world efficiency drops to 45–50% (from 68% in lab tests) due to wave irregularity, resonance mismatch, and material degradation resulting in a 20–25% energy loss compared to idealized predictions. Environmental concerns arise from lead leaching in PZT, though this risk can be mitigated through multi-layer encapsulation or transition to lead-free alternatives like $BaTiO_3$ or KNN, which reduce lead release by >99% with only moderate (~30%) efficiency trade- offs. Economically, the system is non-competitive for grid-scale generation (LCOE ≈ $840/kWh) but highly viable for niche micro-power applications: a 10-unit array replacing battery-powered offshore sensors achieves a 2.1-year payback and 38.9% ROI.

Finally, the integration of MEMS vibration sensors enables bidirectional energy capture adding ~15% to total yield (~20 mW per wave) making Prototype 01 a practical, low-maintenance enabler of autonomous marine electronics in remote, battery-dependent coastal zones.

5. Conclusion

This study presents Project: a low-cost, solid-state piezoelectric energy harvester designed for shallow coastal wave environments (0.1–2 Hz), such as Cox's Bazar, Bangladesh. The system uses gravity-driven steel balls impacting stacked PZT-5A discs on rigid cement bases within a triangular frame eliminating moving parts and reducing maintenance. Experimental results confirm optimal performance with steel balls (70 g) and cement tiles, yielding 1.28 V per pipe and ~20 mW per wave event. A five-pipe array delivers 2.714 V total, with <1% variance across channels, validating mechanical symmetry and robustness.

While the LCOE (~$840/kWh) is high for grid power, economic analysis shows strong viability for niche applications: a 10-unit array powering offshore sensors achieves 2.1-year payback and 38.9% ROI by replacing expensive battery systems. Environmental assessment highlights the need to mitigate lead leaching from PZT via multi-layer encapsulation or transition to lead-free materials (e.g., $BaTiO_3$), which reduce toxicity >99% with minimal efficiency loss.

In essence, Prototype 01 is not a bulk power generator but a practical, scalable solution for autonomous marine electronics in remote coastal zones. Future work will focus on field trials, hybrid transduction, and mass production to enable real-world deployment.

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