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Design and Development of Sustainable Tidal Energy System for Coastal Regions

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Abstract

As fossil fuel dependency continues to rise, there is an urgent need for accessible and sustainable energy alternatives, especially in underdeveloped coastal regions. This research focuses on designing and testing a compact, low-cost tidal energy conversion system that harnesses the motion of waves using fiberglass flaps. These flaps transfer mechanical energy via a chain and sprocket mechanism to a flywheel for stability, and ultimately to a DC motor that generates electricity. The system is built entirely from simple, locally available materials and requires no complex electronics, making it easy to deploy and maintain. Testing revealed reliable performance across varying wave conditions, producing output voltages between 10 to 17 volts sufficient for small-scale uses such as battery charging. What makes this solution novel is its mechanical simplicity, affordability, and environmental friendliness, offering a scalable path toward clean energy in coastal and remote communities.

Keywords

Tidal Energy, Renewable Energy, Wave Energy Conversion, Sustainable Power, Coastal Electrification, Marine Energy, Mechanical-to-Electrical Conversion

1. Introduction

The worldwide energy transition focuses on renewable power sources because they reduce both environmental harm and energy supply risks. The predictable patterns of wave motion make tidal energy the most dependable renewable energy source. Those patterns are shown in **Figure 1**. Coastal regions in Pakistan and similar countries possess unexploited potential for marine energy development because they lack suitable infrastructure to deploy extensive renewable technology.

The proposed device primarily targets wave motion, representing shallow coastal waves where both tidal and surface oscillations influence energy capture. Although termed 'tidal,' the system converts *wave* motion energy from periodic tides rather than tidal current flow.

Whereas a small-scale wave tank was used to emulate shallow coastal wave conditions where wave height and period correspond to tidal oscillations. This scaling approach allows controlled testing of mechanical response and power conversion efficiency while maintaining hydrodynamic.

The establishment of large tidal power plants remains unfeasible in remote coastal areas because of their expensive installation requirements and environmental impact and complicated construction methods. The situation creates a rising demand for small-scale tidal power systems which must be cost-effective, efficient, and environmentally sustainable.

The research aims to develop a sustainable and scalable tidal energy solution which solves these three main problems:

1) Coastal communities without electrical connections or minimal resources can obtain power through this solution. The system reduces carbon emissions through its role as a fossil fuel generator replacement.

2) The system operates with minimal environmental impact since its mechanical design avoids any disturbance to marine ecosystems.

3) The proposed system utilizes basic mechanical elements along with corrosion-proof materials to provide an effective solution for harvesting clean energy from wave motion.

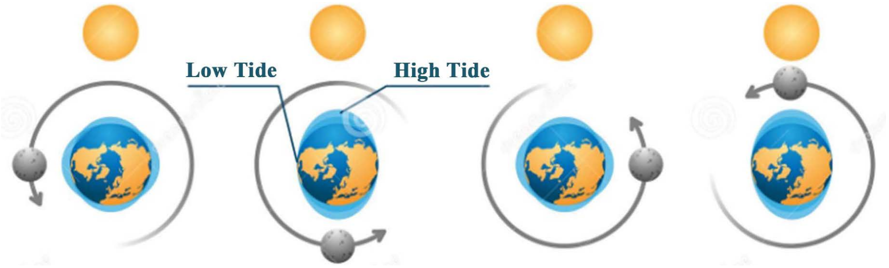

Figure 1. Tidal energy infographics.

1.1. Motivation of the Research

The research draws its motivation from the pressing energy requirements of coastal regions in Pakistan together with other developing countries. These communities experience consistent power interruptions while lacking proper electrical infrastructure which makes them perfect candidates for autonomous renewable energy systems.

Our interest in sustainability as mechanical engineering students led us to investigate how conventional mechanical design elements, including motion transmission, flywheel mechanics and wave interaction could integrate with renewable energy principles to develop functional sustainable power systems.

1.2. Regional Relevance

Despite Pakistan's vast coastal belt and favorable tidal conditions, the country's potential for harnessing tidal energy remains largely untapped and under-researched. As shown in **Figure 2**, the demand is very high and production is very low.

With over 1000 kilometers of coastline along the Arabian Sea, regions such as Karachi, Gwadar, and the Indus Delta have shown significant tidal range and current velocity characteristics suitable for energy extraction. According to recent studies, Pakistan possesses an estimated tidal energy potential exceeding 100 MW in key coastal zones, yet no large-scale project has been implemented to utilize this resource. This research aims to bridge the existing gap by exploring and proposing small-scale, cost-effective tidal energy conversion solutions tailored to the local marine environment. Highlighting these possibilities is crucial for future investment, policy formulation, and sustainable energy planning in Pakistan [1].

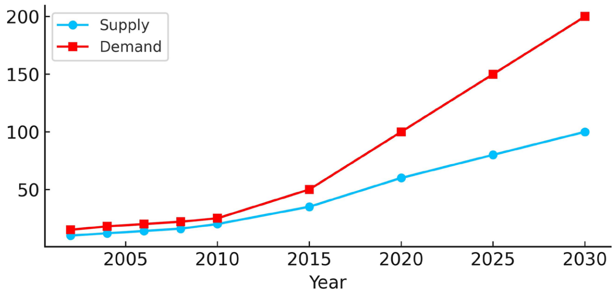

Figure 2. Power demand vs supply trends of Pakistan.

Our objective was to create a solution which proves technical viability under laboratory conditions yet shows practical potential for actual implementation and sustained environmental advantages.

2. Literature Review

2.1. Tidal Energy Potential of Karachi Coast

Insaf *et al.* (2016) conducted the first study utilizing real-time tidal data from Karachi, collected via automatic tide gauges provided by the Pakistan Navy. Over a three-month period, observed tidal ranges reached up to 3.5 meters, with power densities exceeding 4.4 W/m^2 during spring tides. The results highlight significant yet underutilized tidal energy potential in Pakistan's southeast coastal region, warranting further development of pilot projects and site-specific energy extraction systems.

Table 1. Tidal parameters for June, July and august for Karachi coast.

Tidal Parameters (m)	June 2014	July 2014	August 2014
Highest Tide	3.416	3.366	3.542
Lowest Tide	0.586	−0.18	0.118
Largest Tidal range	2.391	3.083	3.074
Smallest Tidal Range	0.359	0.54	0.501
Mean Spring Range	1.937	2.328	2.481
Mean Tidal Range	1.278	1.821	1.875

Recent studies have highlighted the significant tidal energy potential along Pakistan's southeastern coastline, as shown in Table 1. Insaf *et al.* (2016) investigated tidal parameters along Karachi's coast, identifying strong tidal currents reaching up to 1.5 m/s in areas like Manora Island and Clifton. Their findings support the feasibility of small-scale tidal energy systems, such as the flap-type converter proposed in this thesis. Complementing this, Fakhar e Alam *et al.* (2024) used Delft3D modeling to analyze tidal flows in Waddi Khuddi and Daboo Creeks, estimating a combined generation potential of over 90 MW. Similarly, Riaz *et al.* (2021) identified Miani Hor near Gwadar as a promising site due to its confined geomorphology and high energy density, as shown in Figure 3. These studies emphasize the viability of tidal energy systems in Pakistan and the need for further site-specific pilot projects [2].

Figure 3. Map of study of the port.

These types of tides are divided on the basis of how many times they occur in a day. They are listed below:

- Semidiurnal
- Mixed (Predominantly Semidiurnal)
- Mixed (Predominantly Diurnal)
- Diurnal

The Formula for the Relative Importance of Wave is as below:

$$\partial = O_1 + K_1 / M_2 + S_2 \tag{1}$$

∂ is a dimensionless expression often used to quantify relative importance or influence of certain variables or factors in a system as shown in Table 2 and Table 3.

Table 2. Tides and their relative strengths.

Symbol	Relative Strength
M_2	100.00
S_2	37.80
K_1	5.00
O_1	24.30

Table 3. Wave type and strength ratio.

Ratio	Tidal Type
0.0 to 0.25	Semi Diurnal
0.25 to 1.5	Mixed (SD)
1.5 to 3.0	Mixed (BD)
>3.0	Diurnal

Generic case:

- O_1 and K_1: These are numerators, typically representing outputs**,** key observations, or important contributing factors in the analysis.
- M_2 and S_2: These are denominators, likely representing modifying or secondary suppressing facto**rs**, or system resistance/stability.
- ∂: This Greek letter (partial derivative symbol) is used here not in its calculus sense, but likely as a symbolic representation of relative importance or relative influence factor.

In our case:

- O_1: Output torque or energy gained from the flap.
- K_1: Kinetic contribution (wave velocity, flap movement).
- M_2: Mechanical resistance (e.g., system damping, friction, gear backlash, etc.).
- S_2: Structural drag and other energy losses.

$$\partial = \textbf{Opposing Factors/Useful Output}$$

This ratio can help you evaluate how efficient or effective your wave energy conversion system is under varying wave conditions or structural configurations.

The relative importance factor (∂) is used to evaluate system performance across different wave intensities. A higher ∂ value indicates a more favorable energy conversion condition, where the kinetic and output contributions outweigh the mechanical and structural resistances.

2.2. Significant Previous Researches

The conversion of wave and tidal energy into usable electrical power has attracted increasing attention in recent decades, driven by the global demand for sustainable and renewable energy solutions. Significant progress has been made in developing technologies that efficiently harvest energy from marine environments, particularly focusing on hydraulic power take-off (PTO) systems and advanced control models.

One of the foundational contributions to this field is a comprehensive analysis of hydraulic PTO systems for wave energy conversion. This review categorized PTO mechanisms into direct-drive and indirect-drive configurations and evaluated their performance under various marine conditions. The findings underscored the advantages of hydraulic PTOs, especially in terms of energy conversion efficiency and reliability. However, the study emphasized the need for further research on system durability and the optimization of energy capture techniques. A critical gap identified was the lack of economic evaluations, which are essential for assessing real-world feasibility [3].

Addressing the issue of wave energy intermittency, a novel approach was proposed involving the integration of hydraulic energy storage with pressure control mechanisms. Simulation-based studies demonstrated the potential of such systems to buffer wave fluctuations and deliver more stable power outputs, marking an important step toward making wave energy grid-compatible. Despite promising simulation outcomes, the necessity for large-scale field testing under diverse marine conditions remains a crucial next step [4].

Control system innovation has also been a key area of exploration. A Quasi-Proportional-Resonant (QPR) control strategy was developed specifically for hydraulic energy storage applications in wave power systems. This approach, grounded in analytical modeling and control theory, showed significant improvements in energy retrieval and system responsiveness. Yet, a lack of practical implementation examples suggests the need for further research into real-world deployment challenges [5].

Experimental validation of hydraulic wave energy systems has been another critical research direction. A notable study combined experimental testing with simulations across a range of wave conditions to evaluate system performance. The findings showed that applying optimization algorithms could significantly improve energy output and overall stability. Emphasis was placed on developing cost-effective materials and components to enhance the commercial feasibility of such systems [6].

The potential of tidal energy systems has also been widely explored. Technical reviews of existing tidal energy technologies highlight their predictability, reliability, and sustainability. However, persistent issues such as high capital costs and ecological impacts pose significant hurdles. Innovations in turbine design such as less intrusive and more efficient floating and bottom-mounted systems are being actively investigated to address these concerns [7].

Further insight into tidal technologies has been provided through analysis of emerging trends and future directions. Emphasis has been placed on the environmental trade-offs and regulatory barriers associated with large-scale deployment. While these studies provide valuable strategic overviews, there is still a need for deeper investigation into regional implementation strategies and site-specific constraints [8].

Large-scale reviews of wave and tidal energy research have mapped out key trends and collaborative efforts across academia, industry, and policy-making bodies. These studies highlight the importance of interdisciplinary collaboration and the need for practical case studies and economic assessments to bridge the gap between research and real-world deployment [9].

Finally, prototype testing continues to serve as a vital component in validating theoretical models. Full-scale testing projects have demonstrated the feasibility of wave energy conversion under real sea conditions, though ongoing challenges in long-term durability and efficiency remain. Additionally, open-access datasets from experimental arrays of wave energy converters are enabling researchers to refine system design and layout strategies. While these resources are invaluable for advancing the field, their practical application in commercial environments requires further development [10].

Pakistan's sustainable-energy landscape and argues that abundant but underused renewables especially solar, wind, and biomass plus smart-grid deployment can close the chronic demand supply gap and speed rural electrification. Using district-level data on installed/proposed projects and a SWOT of the energy system, it pinpoints policy, financing, and grid-integration constraints as the main bottlenecks [11].

One of the possible ways to obtain electrical energy is to use sea wave energy converters. First, it is necessary to carry out the analysis of energy potential in the zone of power station location, mathematical modeling using wind speed, direction, and bathymetric data to assess wave energy characteristics in the Black Sea, especially near Crimea. It finds that the region's mean annual wave power flux can reach approximately 4.8 kW/m, indicating promising potential for wave energy harvesting. The work underscores how rigorous modeling approaches are vital for accurately estimating energy yields and guiding converter design [12].

Malaysia has a great potential to harness energy in water due to its long coastline within the South China Sea and the Straits of Malacca. Malaysia's potential for harnessing marine current energy, focusing on resource availability, device technologies, and integration challenges. It highlights that while Malaysia's coastal waters especially the Strait of Malacca and East Malaysia offer feasible tidal stream resources, relatively low current velocities restrict large-scale applications. The diffuser-augmented and hybrid turbine designs, along with supportive policies and pilot projects, could make marine current devices a reliable supplementary renewable source in Malaysia's future energy mix [13].

To reach the objective of net-zero carbon by 2050, Japan is promoting the development of renewable energies. Among these, tidal current energy provides high predictability and stability. This study employs ocean numerical models to evaluate tidal Stream Energy resources across South-West Japan. It identifies potential sites, calculates current velocities, and estimates energy yields using specifications from nine different turbines. The results suggest a cumulative installable capacity of approximately 4422.5 MW and an annual energy yield of 8956.06 GWh, with over 78% of the resource concentrated in just six locations [14].

3. Global Perspective

Renewable energy technologies are being adopted worldwide in diverse forms, depending on geographical, environmental, and socioeconomic conditions. While some nations focus on solar and energy storage solutions, others invest in marine resources such as tidal and wave power to address their unique challenges. Examining international case studies provides valuable insights into the strategies, innovations, and constraints faced globally, helping to contextualize the relevance of tidal energy research and its potential contribution to sustainable energy systems.

3.1. Singapore-Urban Renewable Development

Singapore offers a unique example of how a highly urbanized and resource-constrained nation is adopting solar, energy storage, and regional power grid integration to secure a sustainable energy future. Its strategies highlight how innovation and policy can overcome geographical limitations.

Four-Switch Strategy

- Natural Gas (transition fuel)
- Solar (primary renewable option due to equatorial location)
- Regional Power Grids (ASEAN collaborations)
- Low-Carbon Alternatives (hydrogen, carbon capture, utilization, and storage—CCUS)

As the country is growing rapidly, they are also investing in future technologies as illustrated in Figure 4. Tidal energy systems can be a major breakthrough in their energy generation campaign [15].

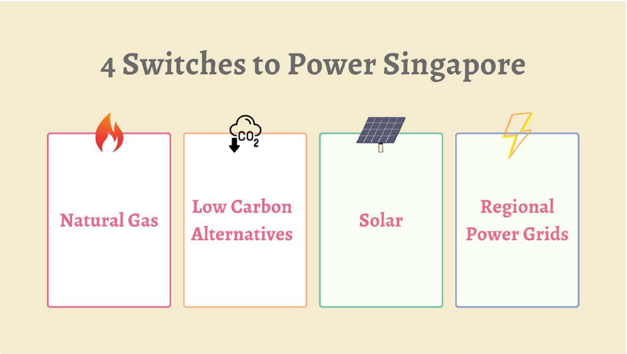

Figure 4. Four switches to power Singapore future.

3.2. Brazil Tidal Power Plant in Bacanga

Brazil's experience with the Bacanga Estuary demonstrates how tidal power can be harnessed in complex urban and environmental settings. This case illustrates the technical, social, and ecological challenges that accompany tidal projects in developing regions.

Ocean energy represents a new opportunity to increase the supply of electricity without leading to a rise in CO_2 emissions. Its total theoretical potential is estimated at approximately 2,000,000 TWh/year, while the annual global electricity consumption in 2010 was 19,730 TWh. This theoretical potential cannot be fully realized for logistical, environmental, and technological reasons. Technologies for harnessing this potential have only recently been designed and many of them are still in the developmental phase.

Proven International Projects:

- La Rance (France, 240 MW) and Sihwa (South Korea, 254 MW) are successful large-scale tidal power plants in operation.

Brazil's Untapped Tidal Potential:

- North coast (Maranhão, Pará, Amapá) estimated potential of 22 TWh/year.
- Despite this, only few studies and projects exist—showing how tidal energy is still emerging globally compared to solar/wind.

Bacanga Estuary (Case Study):

- Constraints: urban settlements, dam-roadway, limited space, and reservoir restrictions.
- Revised energy potential reduced from 154.2 GWh/year to 105.2 GWh/year due to water level limits.
- Proposed design: single-effect ebb generation with low-head Kaplan turbines → annual output 26.87 GWh/year, max power 12.46 MW.

Global Relevance:

- Shows how tidal energy can be viable even in constrained urban estuaries.
- Reinforces need for pilot projects in developing countries to build expertise and infrastructure.
- Lessons from Bacanga can be applied to other coastal regions with low-head tidal ranges [16].

3.3. China Tidal Energy System

The National Marine Energy Test Site of China is located in the Yellow Sea, north of Chudao Island and about 2 km away from Shandong Province. It is mainly aimed at the deployment and testing of small-scale prototypes of wave energy and tidal current energy converters.

1) Rising Interest in Ocean Energy:

- Ocean energy (wave + tidal current) is seen as a promising renewable source worldwide.
- Provides clean, predictable, and local electricity to coastal communities.
- China, Europe, and Canada are global leaders in wave & tidal resource map-

ping and pilot projects.

2) Chudao Island Case Study:

- Location: North of Chudao Island, Bohai Strait, China.
- Region selected due to strong tidal currents and wave activity.
- Represents a model for offshore island energy self-sufficiency, reducing dependence on Chinese mainland grid imports.

3) Wave Energy Potential:

- Wave energy density ~3 - 9 kW/m in the region.
- Average wave power flux estimated at ~4.6 kW/m, indicating medium-level wave energy resource.
- Seasonal variation: higher in winter (due to strong winds), lower in **summer**.

4) Tidal Current Energy Potential:

- Maximum tidal current velocity: 1.5 - 2.0 m/s.
- Average extractable tidal current energy: ~0.1 - 0.5 kW/m^2 (depending on season).
- More stable and predictable compared to wave energy.

5) Combined Wave + Tidal Utilization:

- Best approach is hybrid systems, where wave and tidal energy balance each other seasonally.
- For Chudao, tidal is more reliable, wave is seasonal and supplementary.

6) Technology Insights (Global Implications):

- Devices considered: Horizontal-axis tidal turbines and oscillating water column (OWC) wave devices.
- Highlights global challenge: technology must withstand harsh marine conditions (corrosion, storms, biofouling).
- Data-driven site-specific assessment is crucial before deployment [17].

4. Methodology

4.1. Concept Design

In our effort to harness wave energy along coastal areas, we aimed to develop a solution that is simple, affordable, and environmentally responsible. The result is a purely mechanical system designed to convert the natural motion of ocean waves into usable electrical energy without the need for complex electronics or heavy infrastructure. At the start of the system are Water Storage Tank, fiberglass flaps that move up and down with the rhythm of the waves. This motion is transferred through a chain and sprocket mechanism to a flywheel, which helps to stabilize the energy. The Rotational motion is then used to drive a DC motor, which acts as a generator and produces electrical output. The DC motor is shown in **Figure 5**.

Before choosing this approach, we explored various other wave energy harvesting methods such as point absorbers, oscillating water columns, and overtopping devices. After careful comparison, we chose the flap-based system because of its efficiency in waters, its ease of fabrication and maintenance, and the mechanical simplicity it offers. It allowed us to build a working, reliable system using locally available materials, making it practical not just for research but for real-world impact in coastal communities.

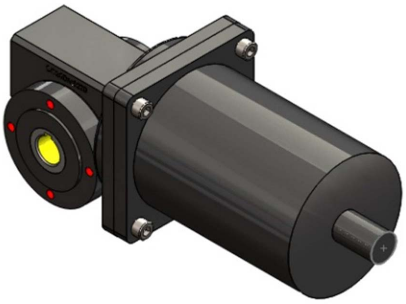

Figure 5. DC motor.

The wave tank (6 ft × 1.5 ft × 1.5 ft), as shown in Figure 6, contains freshwater at 25˚C with a density of 997 kg/m^3. Waves were generated manually with the amplitude of about (0.05 - 0.18 m) and frequency (0.3 - 0.9 Hz), corresponding to shallow coastal waves.

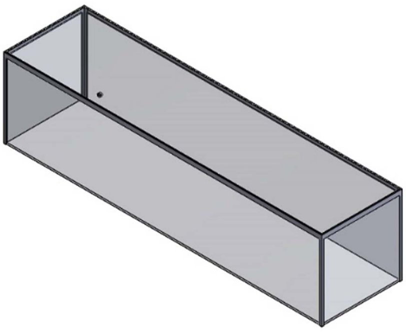

Figure 6. Ripple tank.

Each wave condition (low, medium, high) was repeated in **five replicates**, and the average of the recorded outputs was reported. Between tests, water level and temperature were monitored to ensure consistency. The mechanical setup was recalibrated before each trial to eliminate bias.

4.2. Designing the Flap and Selection for Material

The flap is the heart of our system it's where the wave's motion is first captured and transformed into mechanical energy. During the design phase, we explored two different flap shapes: trapezoidal and oval as shown in Figure 7. After careful testing and analysis, we chose the oval flap, and for good reason. Its smooth, rounded edges allowed for better interaction with water, resulting in more stable and consistent oscillations. It also handled the repeated impact of waves more effectively, with stress distributed evenly across its surface, reducing the chances of material fatigue over time.

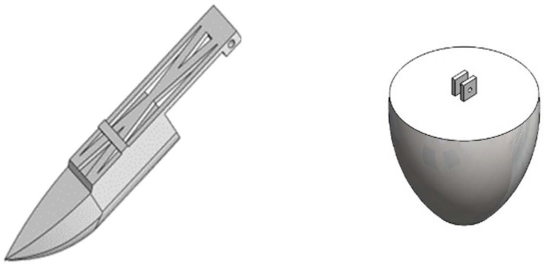

Figure 7. Trapezoidal vs oval flap.

When it came to materials, fiberglass was our best choice. Its lightweight structure, combined with a high strength-to-weight ratio and natural resistance to corrosion, made it ideal for the harsh and unpredictable conditions of marine environments. By using fiberglass, we ensured that our system remains durable, low-maintenance cost, and reliable even when exposed to rough coastal weather. Figure 8 shows our final 3D model.

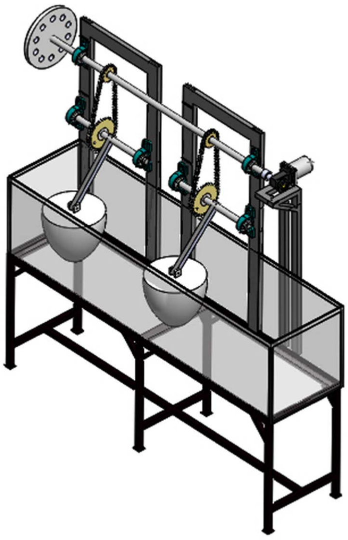

Figure 8. Final 3D prototype model.

5. Calculations

In our project, a fiberglass flap moves due to wave motion, and this oscillation is transferred mechanically via a chain-sprocket system to a flywheel, which acts as an energy buffer. This stored rotational energy drives a DC motor, functioning as a generator.

The underlying physical principles involve:

- Work Done.
- Mechanical Energy Transmission.
- Electricity Generation.

This project utilizes a combination of hydrodynamic principles, mechanical engineering, and electromechanical conversion to harness wave energy. A detailed explanation of these principles is provided below.

1) Work Done:

The mechanical power (P_m) from waves is given by:

- Wave height: 20 to 30 cm (average = 0.25 m).
- Flap width = 0.3 m.
- Flap depth = 0.3 m.
- Wave pushes flap by 0.25 m vertically.
- Flap mass ≈ 1 kg Calculations:

Gravitational force (F)

$$F = m * g$$

$= m \times g = 1 \times 9.81 = 9.81$ N

Work done by wave on 1 flap (W)

$$W = F * d$$

$= F \times d = 9.81 \times 0.25 = 2.45$ J

Total for 2 flaps (Wtotal) = 2 × 2.45 = **4.91 J**

2) Mechanical Power Transmission Calculations:

Sprocket teeth:

Large = 41

Small = 16

Gear ratio = 2:5 (speed doubles, torque halves)

If flap oscillates at 1 Hz (1 full cycle/sec)

Flap shaft: 0.5 rotation/sec

Motor-side shaft: 1 rotation/sec due to gear ratio

3) Electricity Generation:

Power = 90 W

Voltage = 24 - 28 V

Assuming ~60% mechanical to electrical efficiency:

$$P_{\text{Electrical}} = P_{\text{Mechanical}} * \eta$$

Rpm: 65, Torque: 1.5 Nm, Time: 30 mints

$$P_{\text{Electrical}} = 2\pi NT/60$$

$P_{\text{mech}} = 10.3$ W

$P_{\text{electrical}} = 0.6 \times 10.3 = 6.18$ W

$$\begin{aligned} \omega &= 2\pi N/60 \\ &= 2 \times 3.142 \times 65/60 \\ &= 6.0806 \text{ rads/s} \end{aligned}$$

$$\begin{aligned} P_{\text{Mechanical}} &= \tau * \omega \\ &= 1.5 \times 6.08 \\ &= 10.21 \text{ W} \end{aligned}$$

Total Efficiency

Gear Box $\eta = 0.90$

Chain Sprocket etc $\eta = 0.93$

So, the Transmitted

$\eta = 0.90 \times 0.93 = 0.837$

$P_{\text{Generated, shaft}} = 10.21 \times 0.837 = 8.546$ W

As we have used 5 v LED light at the end of the generator as a load so according to that

Current I

$$\begin{aligned} I &= P/V \\ &= 6.18/5.0 \\ &= 1.236 \text{ A} \end{aligned}$$

Resistance

$$\begin{aligned} R &= V/I \\ &= 5.0/1.236 \\ &= 4.046\ \Omega \end{aligned}$$

Energy Generated per Hour:

$E = 6.18 \times 3600 = 22{,}248 \text{ J} = 22.2 \text{ kJ} \approx 0.00618 \text{ kWh}$

Flywheel Calculations

Radius = 0.15 m

Mass = 5.5 kg

$$\begin{aligned} \text{Inertia} &= 1/2\, mr^2 \\ &= 0.5 \times 5.55 \times 0.15^2 \\ &= 0.0619 \text{ kg/cdotpm}^2 \end{aligned}$$

Rotational Energy

$$\begin{aligned} E &= 1/2\, I\omega^2 \\ &= 0.5 \times 0.0619 \times 6.08^2 \\ &= 1.435 \text{ J} \end{aligned}$$

Generator

$$\begin{aligned} \eta_{\text{Gen}} &= P_{\text{Electric}} / P_{\text{Gen}} \\ &= 6.18/8.55 \\ &= 72.36\% \end{aligned}$$

$$\begin{aligned} \eta_{\text{all}} &= \eta_{\text{Trans}} \times \eta_{\text{Gen}} \\ &= 0.837 \times 0.723 \\ &= 0.6053 \\ &= 60.53\% \end{aligned}$$

6. Results

6.1. Prototype Testing

To assess how well our tidal energy system performs, we conducted tests using a custom-built wave tank measuring 6 feet in length and 1.5 feet in both width and height. This setup allowed us to create a controlled environment that mimics real coastal wave conditions on a smaller scale.

We tested the system under three different wave intensities low, moderate, and high all generated manually to simulate the natural variation found in ocean tides. For each condition, we closely monitored how the system responded, focusing on three key aspects: voltage output, mechanical stability, and consistency in energy conversion. **Figure 9** shows our final prototype.

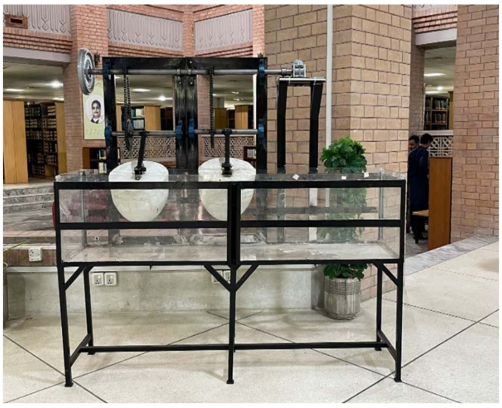

Figure 9. Final prototype.

These tests helped us understand how reliably the system performs under changing wave patterns and how effectively it can maintain stable energy output despite the dynamic nature of its environment. The insights gained from this testing phase were crucial in validating the system's practicality for real-world coastal use.

6.2. Electrical Output

In addition to the physical testing conducted with the tidal energy system, a Simulink model was developed to simulate and predict the system's electrical output under different wave conditions. The model was designed to replicate the behavior of the system by integrating key parameters such as wave height, flap motion, torque, and the conversion of mechanical motion to electrical power. By using the Simulink model, we were able to forecast the system's performance and validate the real-world data collected during the experimental tests.

For the simulation, three different wave heights were used as inputs to assess how varying wave conditions would impact the system's power output. The chosen wave heights were:

1) **0.01 meters**—Representing low wave conditions

The graph given below tells us that on the low wave conditions when the wave height is approximately 10 cm we got the power output of 8 - 10 volts pers rise of the flap. **Figure 10** shows the results.

2) **0.02 meters**—Representing moderate wave conditions

The graph given below tells us that on the moderate wave conditions when the wave height is approximately 10 cm we got the power output of 10 - 18 volts pers rise of the flap on the prediction model. The results are shown in **Figure 11**.

3) **0.03 meters**—Representing high wave conditions

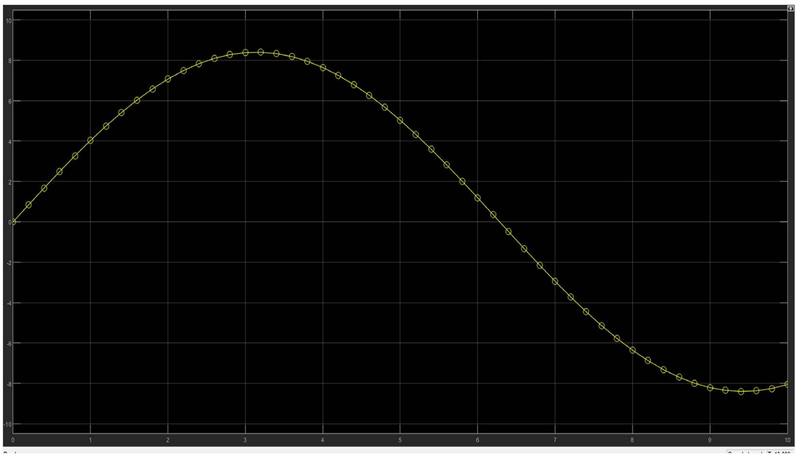

Figure 10. Low wave conditions.

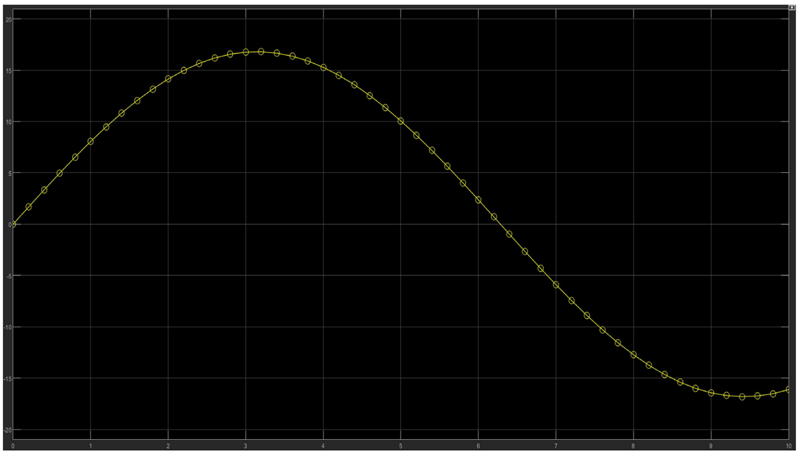

Figure 11. Modrate wave conditions.

The graph given below tells us that on the high wave conditions when the wave height is approximately 10 cm we got the power output of 14 - 23 volts pers rise of the flap on the prediction model. Figure 12 shows the final results.

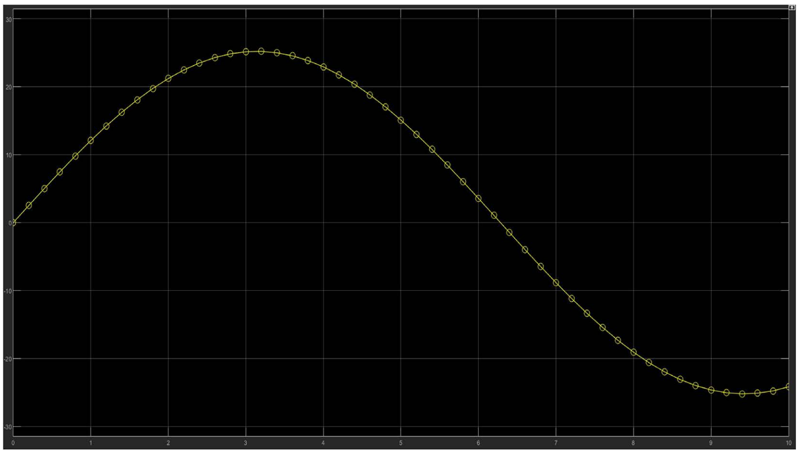

Figure 12. High wave conditions.

Voltage generation was measured using a Digital Multimeter (DMM) connected to the terminals of the DC motor acting as the generator. The system included an LED and a basic voltage regulation circuit to provide visual feedback on output consistency. Table 4 shows the final results.

Table 4. Results.

Wave Intensity	Estimated Frequency	Voltage Output	LED Indicator
Low	0.3 Hz	4.5 - 6.5 V	Dim
Moderate	0.6 Hz	10 - 13 V	Clearly Visible
High	0.9 Hz	13 - 17 V	Bright

- Under high wave intensity, voltage output peaked near 16.5 V as shown in Figure 13.
- The system consistently generated electricity across all wave intensities.
- The LED brightness provided a reliable visual indicator of system responsiveness.
- The Voltage Output Comparison is shown in Figure 14.

Figure 13. Electrical output rating.

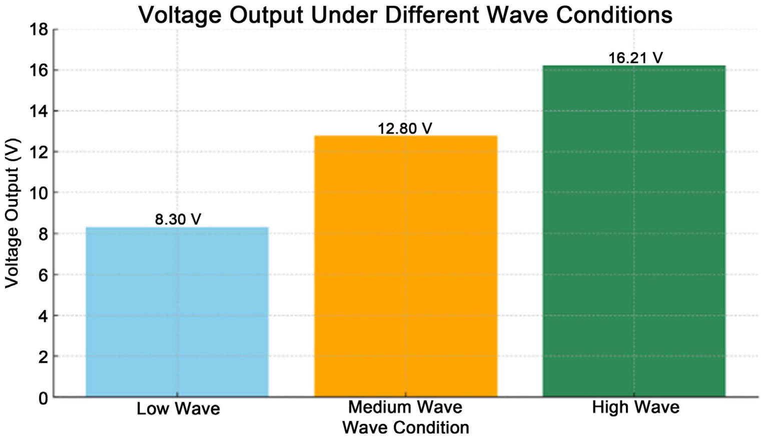

Figure 14. Voltage output graph.

Implementation of Oscilloscope

An oscilloscope is an essential electronic measuring instrument used to visualize and analyze varying electrical signals with respect to time. It displays the waveform of a signal, allowing observation of parameters such as amplitude, frequency, and noise, which are critical for performance evaluation of energy conversion systems.

In this project, the oscilloscope was employed to monitor and analyze the output voltage waveform generated by the tidal energy conversion mechanism. By using the oscilloscope, variations in signal stability and fluctuations in electrical output were observed, which helped in validating the system's efficiency and the effectiveness of the flywheel in damping irregularities. This ensured accurate assessment of the electrical characteristics of the proposed design, thereby strengthening the reliability of the experimental results.

The visual representation of the oscilloscope graph is shown in **Figure 15**. As we can observe that the voltage is not constant and there are some slight fluctuations at every wave which in turn lead to a variable graph.

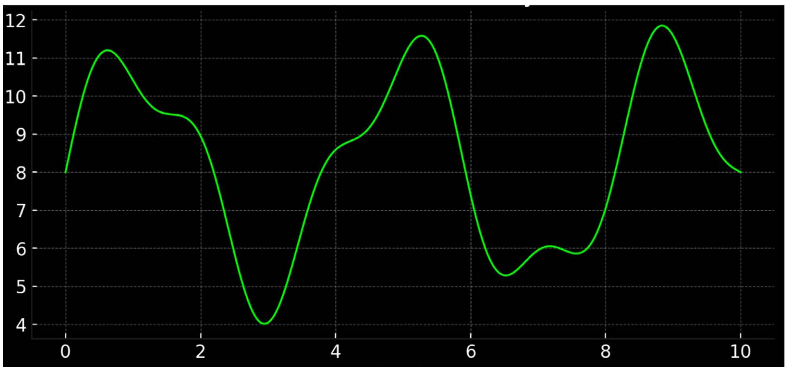

Figure 15. Voltage vs time plot.

The graph here is showing the comparison of energy production between low wave conditions and high wave conditions with the passage of time. From the graph we can see that when the waves are strong more voltage can be obtained hence more energy can be produced.

6.3. Mechanical Performance and Energy Transmission

- The fiberglass flaps oscillated smoothly and showed no signs of fatigue or material degradation during testing.
- The chain-sprocket and ratchet mechanisms effectively transmitted motion without noticeable slippage or energy loss.
- The flywheel played a vital role in smoothing the intermittent wave-induced motion, ensuring stable DC motor rotation and reducing fluctuations in voltage output.

These observations confirmed that the mechanical design was both efficient and resilient under simulated wave conditions.

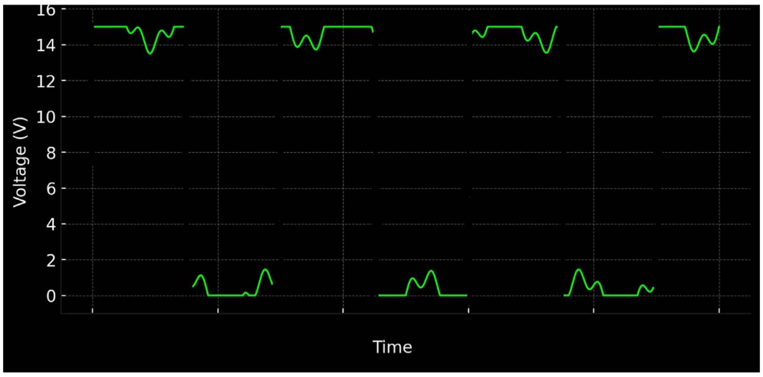

Figure 16. Low vs high wave conditons.

6.4. Operational Stability and Repeatability

Multiple test cycles were conducted to assess the system's repeatability and stability. As you can see from **Figure 16**, how system responds to low and high wave conditions. The system was able to reproduce consistent results across all trials, with minor variations due to manual wave generation. Despite this, the output remained within expected ranges, highlighting the system's reliability.

No significant alignment or mechanical issues were observed during or after testing, confirming the structural integrity and proper calibration of all components.

6.5. Visual Output Verification

The presence of a 12V LED provided a simple, real-time indicator of system performance. The LED illuminated successfully under moderate and high wave intensities, correlating well with the electrical measurements. This not only validated the energy conversion process but also demonstrated the system's practical application for powering low-voltage devices in real-world settings.

7. Discussions

The results from our prototype testing revealed several encouraging insights, reinforcing the idea that even a simple, mechanically driven system can effectively harness tidal energy. One of the most important takeaways is that wave energy can be captured and converted into usable electrical power without relying on complex electronics or high-end materials. This validates our original goal: to design a solution that's both accessible and efficient, particularly for remote or underdeveloped coastal areas.

The consistent voltage output ranging from 5 to 17 volts approximately volts demonstrates that the system can provide steady, low-level power suitable for essential applications like lighting, battery charging, or powering basic appliances. It's not about competing with large-scale renewable plants but about offering a localized energy solution where it's needed most.

Equally important was the role of the flywheel in smoothing out the system's response to fluctuating wave motion. Without it, the energy transfer would have been uneven and unstable. Choosing an oval flap over a trapezoidal one proved to be another key decision. The smoother geometry allowed for better movement through water and more uniform load distribution, which not only improved performance but also reduced mechanical stress and wear on the components. This could have a big impact on long-term durability, especially in marine environments where maintenance access is limited.

Finally, the choice of fiberglass was a good decision. It handled repeated wave impact with ease, resisted corrosion, and kept the system light making it more responsive to smaller wave movements. This reinforces the idea that affordable materials, when selected thoughtfully, can match or even exceed the performance of more expensive alternatives in certain applications.

Overall, the project highlights how thoughtful design, smart material choices, and mechanical simplicity can come together to create a system that is not only functional but also practical for real-world deployment. While there's room for optimization such as improving efficiency in very low wave conditions or integrating energy storage the foundation we've built is promising and points toward a viable path for sustainable coastal energy solutions.

7.1. Performance Evaluation

The results obtained from controlled testing confirmed the viability of the proposed tidal energy system for small-scale electricity generation. The voltage outputs recorded under varying wave intensities demonstrated that the system could respond effectively to different energy inputs, validating the mechanical-to-electrical energy conversion process. Even during low wave activity, the system produced sufficient voltage to power low-energy applications, while higher wave conditions showed strong potential for charging 12 V and 24 V battery systems.

The smooth oscillation of the fiberglass flaps, combined with the stability provided by the flywheel, ensured that output voltage fluctuations were minimal. This highlights the system's capability to deliver consistent energy, which is particularly important for standalone power systems in off-grid coastal areas.

7.2. Mechanical Design Efficiency

The use of simple mechanical components such as the chain-sprocket system, ratchet mechanism, and flywheel proved to be both reliable and effective. These components allowed the system to function without dependence on complex electronics, making it highly suitable for rural or underdeveloped settings where technical support and resources are limited.

The ratchet mechanism ensured unidirectional energy transfer, eliminating backflow losses, while the flywheel helped to smooth out irregular wave impulses. These design elements contribute significantly to the efficiency and robustness of the energy conversion process.

7.3. Environmental and Practical Benefits

One of the most significant advantages of the proposed system is its low environmental impact. Unlike large-scale tidal barrages or turbines, this flap-based system does not interfere with marine life, seabed sedimentation, or coastal water flow. The materials used particularly fiberglass are corrosion-resistant and environmentally stable, ensuring long-term deployment with minimal ecological disruption. It also aligns with four Sustainable Development Goals (**SDG)** which are also shown in Figure 17.

Figure 17. Sustainable Dvelopment Goals (SDGs).

SGD 7: Affordable and Clean Energy
SGD 11: Sustainable Cities and Communities
SGD 13: Climate Action
SGD 14: Life Below Water

Moreover, the system's modular structure allows for scalability and easy maintenance. The Communities with access to basic mechanical tools could build, repair, or scale the system as needed, making it a self-sufficient and sustainable solution for energy generation.

7.4. Comparison with Existing Systems

Compared to conventional wave energy converters (WECs), such as point absorbers and overtopping devices, the proposed design offers:

- **Lower capital and maintenance costs**
- **Simplified construction**
- **Minimal environmental footprint**

While high-tech WECs may offer greater efficiency, they often require advanced manufacturing, control systems, and maintenance facilities. This research prioritizes practicality, accessibility, and local deployment, which makes it better suited for rural or resource-constrained coastal environments.

7.5. Limitations and Considerations

Despite the promising results, the study has several limitations:

- Testing was conducted in a controlled indoor environment, which may not fully replicate real ocean conditions such as salinity, current variations, or biofouling.
- Manual wave generation introduced slight inconsistencies in test conditions, although these were accounted for during repeated trials.
- The system's current design is optimized for small-scale power generation, primarily for low-voltage applications. Scaling up the system for higher energy demands will require further engineering considerations, especially for durability and electrical load management.

7.6. Implications for Future Applications

The findings of this research suggest that decentralized, flap-based tidal energy systems could play a significant role in addressing energy poverty in coastal regions. With further optimization and testing in real ocean conditions, this design could be adapted for:

- Remote coastal villages
- Island communities
- Emergency relief zones
- Marine research stations

In summary, the project provides a solid foundation for scalable, sustainable, and community driven renewable energy solutions.

7.7. Scalability and Deployment Considerations

The scalability of the proposed energy harvesting system is a critical factor for its practical deployment. To assess this, an estimation of the annual energy yield was conducted for a representative coastal site.

7.8. Annual Energy Yield Estimation

For a representative, moderately energetic coastal site with an average wave power density of 8 kW/m, a single full-scale unit of the proposed harvester, with a designated capture width of 2 meters, would have an estimated mechanical power input of 16 kW. Accounting for the measured 60.5% system efficiency, the average electrical power output (P_{avg}) is estimated to be approximately 9.7 kW. The annual energy yield (E) is calculated using equation

$$E = P_{\text{Average}} \times T$$

where T is the number of hours in a year (8760 hours). This results in an estimated annual energy yield of approximately 85,000 kWh per unit.

7.9. Durability and Countermeasures

The successful scaling of the system necessitates robust countermeasures against the challenging marine environment.

Anchoring: For scalable deployment in shallow water sites (<50 m depth), a gravity-based anchor foundation is proposed for its simplicity. For deeper waters, a piled foundation or a taut-moored floating platform would be required to maintain station-keeping under extreme loads.

Corrosion: All critical submerged components will be fabricated from duplex stainless steel. This will be complemented by a combined protection strategy using sacrificial aluminum alloy anodes and protective coatings on surfaces in the splash zone.

Biofouling: To counter biofouling, which increases drag and mass, an anti-fouling strategy employing silicone-based foul-release coatings is recommended. These coatings prevent the strong adhesion of marine organisms, facilitating easy cleaning and maintaining system efficiency.

8. Conclusions

This research successfully demonstrates the design, development, and testing of a small-scale, flap-based tidal energy conversion system tailored for coastal regions with limited access to electricity. By utilizing a mechanically driven setup including fiberglass flaps, a chain-sprocket transmission system, a ratchet mechanism, and a flywheel, the system effectively converts wave-induced motion into usable electrical energy.

Controlled laboratory testing confirmed the system's ability to generate voltage consistently across varying wave intensities. The presence of a flywheel proved crucial in stabilizing output, while the ratchet mechanism ensured efficient, unidirectional energy transfer. The overall mechanical design was simple, durable, and practical for low-resource environments.

One of the most compelling advantages of this system is its environmental friendliness. Unlike large-scale tidal projects, this design avoids ecological disruption and utilizes corrosion-resistant, non-toxic materials. Its low cost, ease of fabrication, and modularity make it a highly viable solution for remote coastal communities, particularly in developing countries.

Although testing was conducted under controlled conditions, the findings provide strong evidence that the system has real-world application potential. With further refinement, real-ocean trials, and integration with battery storage and smart controls, the proposed system could contribute meaningfully to global efforts in sustainable, decentralized, and renewable energy generation.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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