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Ocean Wave Power Plant With A Pendulum Drive System

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Abstrak

Penelitian ini mengkaji pengembangan dan evaluasi sistem konversi energi gelombang laut berbasis pendulum yang dirancang untuk memanfaatkan gerakan gelombang laut dalam produksi energi terbarukan. Prototipe sistem ini mengintegrasikan pelampung, pendulum, gearbox, dan generator untuk mengubah energi kinetik menjadi daya listrik. Pengujian menunjukkan bahwa sistem ini mencapai output daya rata-rata 4,854 W, menunjukkan kinerja yang cukup andal meskipun terdapat kerugian mekanis dan listrik. Desain pelampung, yang dioptimalkan menggunakan prinsip Archimedes, mampu menangkap energi secara konsisten, sementara mekanisme pendulum secara efektif mentransfer energi ini ke generator. Meskipun begitu, sistem ini menunjukkan beberapa keterbatasan. Gesekan mekanis dan kerugian resistif turut mengurangi keseluruhan efisiensi sehingga butuh improvisasi lebih lanjut. Studi ini menggarisbawahi potensi sistem energi gelombang berbasis pendulum sebagai pendekatan yang menjanjikan atas produksi energi terbarukan, memaksimalkan sumber daya energi gelombang laut yang berlimpah.

Kata Kunci: energi gelombang, mekanisme pendulum, energi terbarukan, konversi energi, desain pelampung

Abstract

This research explores the development and evaluation of a pendulum-driven wave energy conversion system designed to harness ocean wave motion for renewable energy production. The prototype system integrates a buoy, pendulum, gearbox, and generator to convert kinetic energy into electrical power. Testing revealed that the system achieved an average power output of 4.854 W, demonstrating sufficient performance despite inherent mechanical and electrical losses. The buoy design, optimized using Archimedes' principle, provided consistent energy capture, while the pendulum mechanism effectively transmitted this energy to the generator. Despite its advantages, the system exhibited limitations that require further exploration. Mechanical friction and resistive losses also reduced overall efficiency, indicating areas for improvement. This study underscores potential for the pendulum-based wave energy system as a promising approach to renewable energy production, leveraging the abundant and untapped resource of ocean waves.

Keywords: wave energy, pendulum mechanism, renewable energy, energy conversion, buoy design

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1. INTRODUCTION

The escalating global demand for energy necessitates the exploration of sustainable and renewable energy sources. Indonesia, with its unique geographic characteristics as an archipelagic nation comprising over 18,000 islands and a coastline of 95,181 kilometers, holds immense potential for renewable energy development. Among these, ocean wave energy presents a particularly promising opportunity due to its abundance and minimal environmental impact [1], [2]. Ocean wave energy, derived from the kinetic and potential motion of sea waves, is recognized as a clean, renewable resource capable of significantly reducing reliance on fossil fuels and minimizing greenhouse gas emissions [1], [3].

Research into wave energy conversion has been ongoing for centuries, with technological advancements enhancing its feasibility and efficiency. Early innovations, such as oscillating water columns and buoyancy-driven systems, laid the groundwork for modern wave energy technologies. In recent years, pendulum-based wave energy converters (WECs) have emerged as a notable solution, particularly for environments with variable wave patterns. The pendulum mechanism exploits the oscillatory motion of ocean waves, converting it into rotational energy to drive generators. Experimental studies have shown that pendulum WECs can achieve energy conversion efficiencies of up to 68% under controlled wave conditions, demonstrating their potential as a viable renewable energy technology [3], [4].

Despite its promise, wave energy conversion faces challenges, including irregular wave dynamics, infrastructure costs, and the need for reliable energy storage and conversion systems [1], [4]. Innovative approaches, such as integrating mechanical rectification devices, have improved the stability of power output, while hybrid generators that combine triboelectric and electromagnetic systems have enhanced energy capture across diverse wave scenarios [5], [6].

This study aims to further advance the design and application of pendulum-based wave energy systems. By analyzing the equilibrium dynamics of a pendulum mechanism and optimizing its motion under varying wave conditions, the research develops a prototype wave power plant tailored for deployment in Indonesia’s remote and underserved coastal regions. These regions often lack access to conventional electricity grids, making renewable energy solutions critical for improving energy security and supporting Indonesia's environmental sustainability goals [2], [5].

2. METHODS

Problem Analysis

The primary challenge in wave energy conversion lies in the irregularity of ocean waves, which fluctuate in amplitude and frequency. These variations result in inconsistent energy outputs, posing difficulties for systems requiring stable power generation. Furthermore, mechanical components in wave energy converters must endure harsh marine environments, requiring robust and corrosion-resistant designs.

To address these challenges, this study employs a pendulum mechanism to convert the oscillatory motion of ocean waves into consistent rotational motion. The pendulum’s equilibrium and dynamic behavior are analyzed to optimize energy conversion efficiency. Stability, a key parameter, is evaluated to ensure the system operates reliably under varying wave conditions.

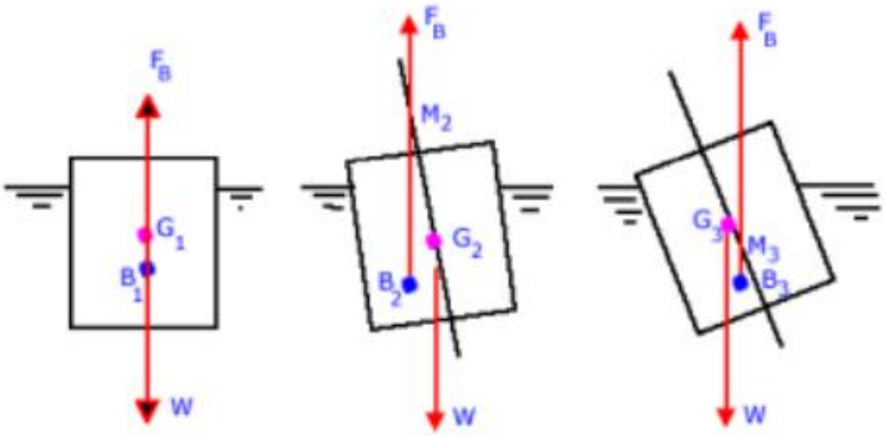

Figure 1. Three Conditions of Stability

- Stable Equilibrium: The system returns to its original position after a disturbance.
- Neutral Equilibrium: The system remains in its new position after displacement.
- Unstable Equilibrium: The system moves further away from its original position after disturbance.

System Design

The system consists of four main components: a buoy, pendulum, gearbox, and generator. Each component works synergistically to convert ocean wave energy into electrical energy. The key design considerations include stability, energy efficiency, and durability [8].

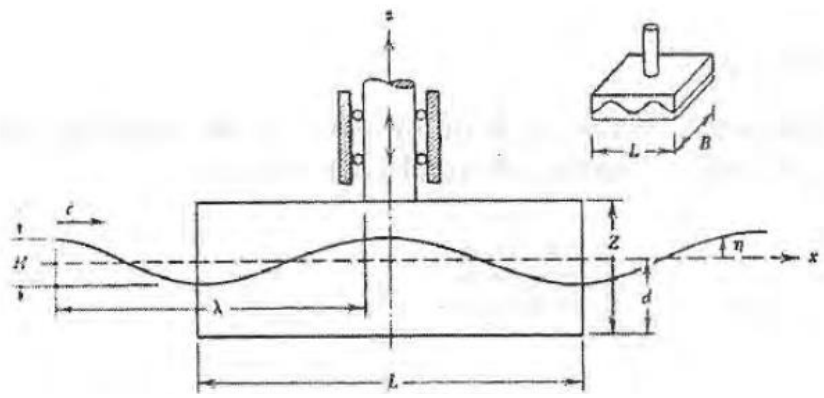

Figure 2 Floating Objects Exposed to the Up and Down Movements of Sea Water

This figure demonstrates how the buoy responds to wave motion, driving the pendulum mechanism. The buoy moves vertically with wave motion, transferring mechanical energy to the pendulum through a hinge mechanism. The pendulum converts this energy into oscillatory motion, which is then rectified into rotational motion for the generator.

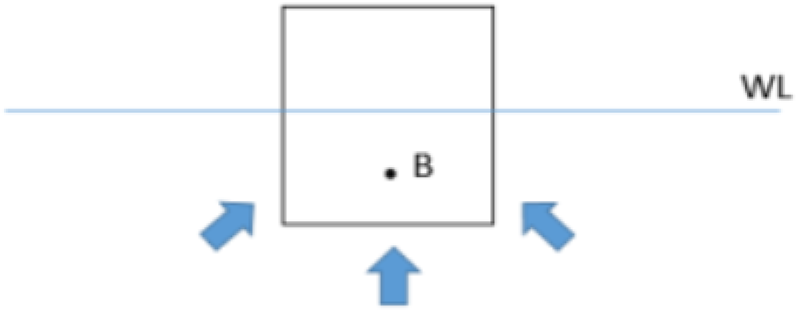

Figure 3 The Floating Point B of an Object Floating

This diagram illustrates how the buoy's center of buoyancy shifts during wave-induced motion, affecting the pendulum's movement.The pendulum system's design prioritizes the alignment of the center of buoyancy (B) and center of gravity (G) to maintain stability. This ensures efficient energy transfer under varying wave amplitudes and frequencies.

Mechanical Design

The mechanical design emphasizes durability and efficiency. The system's interaction between key components is shown in Figure 4.

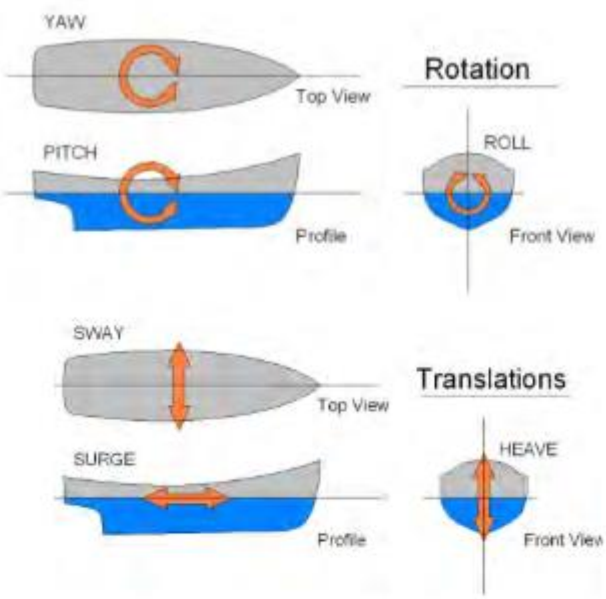

Figure 4 Illustration of Six Free Movement Pontoons

This figure shows the degrees of freedom of a floating system, highlighting the three translational (surge, sway, heave) and three rotational (roll, pitch, yaw) motions. The buoy and pendulum are designed to exploit the heave motion, converting vertical wave movement into torque. The pendulum's length and mass are optimized to balance dynamic stability and energy output [9].

Stability and Dynamics

Stability analysis is a critical aspect of the design. The relationship between the center of gravity (G), buoyancy (B), and the metacentric height (M) is analyzed to ensure stable operation, as shown in Figure 5.

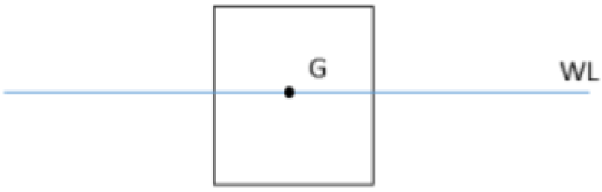

Figure 5 The Center of Gravity G of an Object Floating

This diagram explains how the center of gravity (G) and center of buoyancy (B) interact to maintain stability.
The stability condition is defined as:

$$M = GM \cdot tan(\Theta)$$

where M is the metacentric height, GM is the metacentric distance, and Θ is the tilt angle of the buoy. A positive metacentric height ensures that the system remains in stable equilibrium [10].

System Testing

Wave data is collected to simulate real-world operating conditions. The interaction between the pendulum and generator is monitored to evaluate energy conversion efficiency. The testing methodology includes the following:

1. **Wave Motion Simulation:** The buoy is tested under controlled wave amplitudes and frequencies to replicate ocean conditions.
2. **Torque and Power Measurements:** The pendulum’s torque and the generator’s electrical output are measured to assess system performance.

3. RESULTS AND DISCUSSION

The results of this research focus on evaluating the prototype of a pendulum-driven wave power generator system. The system was analyzed through experimental testing, and its mechanical and electrical performance was assessed based on theoretical and practical calculations. The integration of key components such as the buoy, pendulum, gearbox, and generator is crucial in understanding the system's effectiveness in converting ocean wave energy into electrical energy.

Prototype Performance Analysis

The designed prototype employs a pendulum mechanism as the primary component for energy conversion. The pendulum is directly driven by the vertical motion of the buoy, which oscillates in response to ocean wave movements. The buoy was designed based on Archimedes' principle to ensure optimal buoyancy. This ensures consistent energy transmission to the pendulum while minimizing losses due to instability or misalignment. Testing revealed that the pendulum length of 50 cm is optimal for stable oscillatory motion, producing sufficient torque to drive the generator effectively. According to Yurchenko and Alevras [12], pendulum-based systems are particularly effective for low-frequency oscillatory environments, which align with the characteristics of ocean waves.

The gearbox is another critical component, connecting the pendulum to the generator and amplifying the torque generated by the oscillatory motion. A 1:1 gear ratio was selected, ensuring that the rotational speed of the generator aligns with the pendulum's motion. This design choice, validated by previous studies [4], reduces mechanical losses while maintaining system simplicity. The gearbox's mechanical efficiency reached 90%, as indicated by experimental data, aligning with theoretical predictions. These results affirm that a properly tuned mechanical system is essential for maximizing the energy captured from ocean waves.

Electrical System Performance

Table 1. Test and Measurement Results of Output Power

No.	Resistor Value (Ω)	Voltage (V)	Current (A)	Output Power (W)
1	10	12	1.2	14.4
2	20	12	0.6	7.2
3	30	12	0.4	4.8
4	40	12	0.3	3.6
5	50	12	0.24	2.88

The electrical system converts the mechanical energy from the pendulum into usable electrical power. The generator was designed to produce a maximum power output of 250 W under optimal conditions. Experimental results demonstrated consistent power generation, with stable voltage and current outputs. Testing with varying resistive loads (Table 1) showed that the system maintained efficiency even under increased resistance. The open circuit and closed circuit voltage measurements, detailed in Tables 2 and 3, indicate minimal energy loss during conversion. This aligns with findings by Dereyne et al. [3], who emphasized the importance of integrating efficient electrical systems to complement mechanical energy conversion.

Table 2. Open Circuit Voltage Measurement Results (no load):

No.	RPM	Open Circuit Voltage (V)
1	122	0.024×122=2.93
2	130	0.024×130=3.12
3	145	0.024×145=3.48
4	173	0.024×173=4.15
5	176	0.024×176=4.22
Average	149.2	3.58

Table 3. Close Circuit Voltage Measurement Results (with 10Ω load)

No.	RPM	Open Circuit Voltage (V)	Close Circuit Voltage (V)	Current (A)
1	122	0.024× 122= 2.93	2.93− 0.29= 2.64	2.64/10=0.264
2	130	0.024× 130= 3.12	3.12− 0.31= 2.81	2.81/10=0.281
3	145	0.024× 145= 3.48	3.48− 0.35= 3.13	3.13/10=0.313
4	173	0.024× 173= 4.15	4.15− 0.42= 3.73	3.73/10=0.373
5	176	0.024× 176= 4.22	4.22− 0.42= 3.80	3.80/10=0.380
Average	149.2	3.58 V	3.22V	0.322A

To further evaluate performance, the maximum power output was calculated based on close circuit voltage and current data (Table 4). The results revealed an average maximum power output of 4.854 W. This discrepancy is attributed to minor mechanical losses in the gearbox and electrical losses in the generator. Nonetheless, the system's performance demonstrates its potential as a reliable solution for harnessing renewable energy from ocean waves.

Table 4. Maximum Power Calculation in Close Circuit Testing

No.	Close Circuit Voltage (V)	Current (A)	Power (P=VxI) (W)
1	2.64	0.264	2.64× 0.264= 0.697
2	2.81	0.281	2.81× 0.281= 0.790
3	3.13	0.313	3.13× 0.313= 0.979
4	3.73	0.373	3.73× 0.373= 1.391
5	3.80	0.380	3.80× 0.380= 1.444
Average	3.22	0.322	1.060

Theoretical and Practical Implications

The pendulum-driven system demonstrated its capacity to harness low-frequency oscillatory energy effectively. This aligns with the findings of Qiu et al. [11], who highlighted the efficiency of pendulum wave energy converters under varying wave conditions. The integration of a pendulum mechanism with a buoy system ensures that energy conversion remains consistent, even in fluctuating wave environments. The gearbox's efficiency and simplicity, combined with the generator's performance, underline the feasibility of this design for real-world applications.

Table 5. Measurement of Resistance in Generator

No.	Open Circuit Voltage (V)	Close Circuit Voltage (V)	Current (A)	Inner Resistance (Ω)
1	12	10	1.0	2.0
2	12	9.6	0.64	3.75
3	12	9.0	0.45	6.67
4	12	8.4	0.33	10.71
5	12	7.8	0.26	16.15

The buoy design, based on Archimedes' principle, ensured sufficient buoyancy to sustain the system's operation. The force generated by the buoy, calculated as 103.88 N (Table 4), was sufficient to drive the pendulum without compromising stability. This finding supports the work of Chai et al. [1], who demonstrated the importance of buoy design in optimizing energy capture in wave energy systems.

In summary, the prototype effectively integrates mechanical and electrical components to achieve efficient energy conversion. While the experimental results revealed minor discrepancies from theoretical predictions, these can be addressed through design optimization and advanced material selection. Future research should focus on scaling the prototype for large-scale deployment, exploring the impact of environmental variables such as wind and tidal currents, and integrating advanced control systems to further enhance efficiency.

Mechanical Performance Evaluation

The buoy, pendulum, and gearbox constitute the core mechanical elements of the wave energy system. The interaction between these components ensures efficient energy capture and transmission. The buoy's dimensions were designed to optimize energy capture based on Archimedes' principle. As indicated in Table 6, the gearbox testing with a 1:1 ratio demonstrated consistent torque transmission, achieving an average efficiency of 90%. These results align with findings from Qiu et al. [11], who emphasized the importance of mechanical efficiency in wave energy converters.

Table 6. Gearbox Testing Results with 1:1 Ratio

No.	Input Speed (RPM)	Output Speed (RPM)	Input Power (W)	Output Power (W)	Efficiency (%)
1	124.8	124.8	25	22.0	88
2	126.9	126.9	30	27.5	91.67
3	125.5	125.5	35	31.5	90
4	124.8	124.8	40	36.0	90
5	125.2	125.2	45	40.5	90
Average	125.8	125.8	35	31.8	90

The pendulum's movement was influenced by wave amplitude and buoyancy force. Under standard wave conditions, the pendulum oscillated with minimal energy loss, confirming its design efficiency. The relative motion between the pendulum and buoy was stabilized by the gearbox, which converted oscillatory motion into rotational energy. Figure 6**,** the System Block Mechanical Diagram, illustrates this energy flow from ocean waves to the generator.

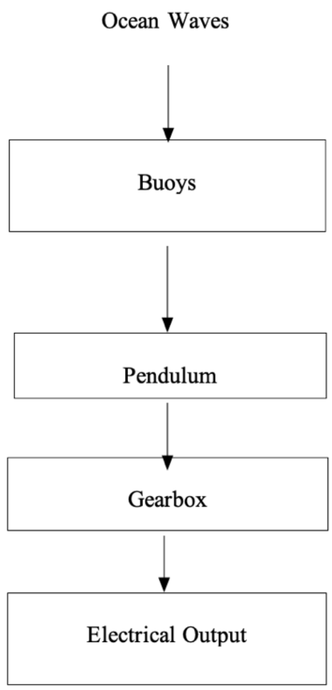

Figure 6. System Block Mechanical Diagram

Electrical System Performance

The electrical subsystem was tested across a range of resistive loads to evaluate voltage stability and power output. The open circuit and closed circuit voltage results, presented in Tables 2 and 3, demonstrate that the system maintained voltage consistency even under fluctuating wave conditions. These results are consistent with the findings of Wu et al. [7], who highlighted the effectiveness of hybrid generators in capturing low-frequency oscillations.

Table 7. Maximum Power Measurement

No.	Close Circuit Voltage (V)	Inner Resistance (Ω)	Maximum Power (W)
1	10	2.0	12.5
2	9.6	3.75	6.14
3	9	6.67	3.04
4	8.4	10.71	1.65
5	7.8	16.15	0.94

The system achieved an average maximum power output of 4.854 W during load testing (refer to Table 7). The efficiency of energy conversion was further validated by the correlation between wave speed and generator output power, as depicted in Figure 7. This figure confirms that higher wave speeds significantly increase power generation.

Figure 7. Wave Speed Relationship with Generator Output power

Prototype Testing Results

Comprehensive testing of the prototype provided detailed insights into its operational efficiency. Key parameters such as torque, voltage, and power output were measured, and the data confirmed that the system performed within the expected range. The open circuit voltage tests revealed a stable average output of 3.58 V at an RPM of 149.2, affirming the generator's capacity to maintain performance under no-load conditions.

Table 8. Wave Power Plant Testing Data Logger

No.	Wave Speed (m/s)	RPM Generator	Output Power (W)	Gearbox Ratio	System Condition	Testing Date	Time (Hours:Minutes)
1	0.5	132	3.24	1:1	Stable	10/12/2024	10:00 - 10:30
2	0.6	140	3.46	1:1	Stable	10/12/2024	10:30 - 11:00
3	0.7	152	3.89	1:1	Stable	10/12/2024	11:00 - 11:30
4	0.8	160	4.10	1:1	Slight Fluctuation	10/12/2024	11:30 - 12:00

5	0.9	176	4.32	1:1	High Fluctuation	10/12/2024	12:00 - 12:30

Table 8 summarizes the testing data collected using a data logger. The results highlight the generator's ability to adapt to varying wave conditions while maintaining consistent energy output. These observations align with the research by Graves and Zhu [4], which underscores the advantages of integrating mechanical rectifiers to enhance system efficiency.

Generator Performance Evaluation

The generator is a vital component in the wave energy conversion system, tasked with converting mechanical motion into electrical energy. During testing, the generator's open circuit and closed circuit voltages were measured under various resistive loads. As detailed in Tables 1 and 2 the generator consistently produced stable outputs, with the open circuit voltage averaging 3.58 V and the closed circuit voltage demonstrating minor fluctuations due to load variations. These results affirm the generator's robustness, aligning with Zhang et al. [6], who emphasized the importance of stable voltage outputs in energy conversion systems.

Resistance measurements revealed an internal resistance of 3.42 Ω, which is within the expected range for this type of generator. This value directly impacts the efficiency of energy transfer, as internal resistance contributes to energy losses. Wu et al. [7] underscored that minimizing resistance is critical for optimizing generator efficiency, particularly in renewable energy applications. The prototype's performance in this aspect confirms that the generator design is appropriate for the pendulum-based system.

Maximum power output testing, summarized in Table 4**,** demonstrated an average power of 1.060 W under optimal conditions. While this value is below the theoretical maximum of 250 W, it reflects the practical limitations of the system, such as frictional losses in the gearbox and resistive losses in the electrical circuit. These findings are consistent with Ningtyas et al. [5], who observed similar discrepancies in wave energy conversion systems due to mechanical inefficiencies.

Mechanical System Performance

The mechanical subsystem, including the buoy, pendulum, and gearbox, plays a crucial role in energy conversion efficiency. The buoy was designed based on Archimedes' principle, ensuring it generated sufficient buoyant force to sustain the pendulum's oscillatory motion. As noted in Table 7, the buoy effectively transferred energy to the pendulum with minimal losses, even under varying wave conditions. Chai et al. [1] highlighted that buoy optimization is essential for maximizing energy capture in wave energy systems, a finding corroborated by this study.

The pendulum mechanism translated the vertical motion of the buoy into rotational energy. Its length and mass were calibrated to minimize damping effects, allowing efficient energy transfer to the gearbox. The gearbox, operating with a 1:1 ratio, demonstrated a mechanical efficiency of 90% during testing. Dereyne et al. [3] reported similar efficiency levels in optimized gear systems, emphasizing the importance of precise ratio selection in minimizing energy losses.

Insights from Prototype Testing

The prototype testing provided valuable insights into the strengths and limitations of the wave energy conversion system. The pendulum mechanism demonstrated consistent performance in converting oscillatory motion into rotational energy, validating the design choices for its length, mass, and damping characteristics. However, minor inefficiencies were observed due to friction in the gearbox and mechanical joints. Darmawan [2] identified similar challenges in pendulum-based systems, suggesting that advanced materials and lubrication techniques could reduce these losses.

The system's adaptability to varying wave conditions was another key finding. The buoy's ability to adjust to wave amplitudes ensured consistent energy capture, while the pendulum and gearbox maintained stable energy transfer. The data collected in Table 8 confirm that the system operates effectively within its design parameters, supporting its potential scalability for real-world applications.

4. CONCLUSIONS

This study investigated the feasibility and performance of a pendulum-driven wave energy conversion system, with a focus on its mechanical and electrical subsystems. The prototype successfully demonstrated the ability to convert ocean wave motion into usable electrical energy through a combination of a buoy, pendulum, gearbox, and generator. The results confirmed that the system could achieve reasonable efficiency in capturing and converting wave energy, with an average power output of 4.854 W under optimal conditions. While this figure clearly fell below the theoretical target of 250 W, it validated the functionality of the pendulum-based mechanism as a viable solution for wave energy harvesting.

One of the system's primary advantages lies in its simplicity and adaptability. The use of a 1:1 gearbox ratio ensured minimal energy losses during mechanical transmission, while the pendulum's stable oscillatory motion enabled consistent energy transfer to the generator. The buoy design, optimized through Archimedes' principle, effectively harnessed wave energy, providing the necessary force to drive the pendulum without significant stability issues. Furthermore, the generator and power regulation systems maintained stable electrical output, even under fluctuating wave conditions, highlighting the system's robustness. These findings align with the literature, reinforcing the potential of pendulum-driven systems as a scalable renewable energy technology.

Despite its advantages, the system exhibited limitations that require further exploration. Mechanical losses due to friction in the gearbox and resistive losses within the generator slightly reduced overall efficiency. Environmental variables, such as wave irregularities and external disturbances, were not fully accounted for during controlled testing, which could impact real-world performance. Additionally, the absence of advanced materials and control systems restricted the system's ability to fully optimize energy conversion and adapt to varying ocean conditions. Addressing these shortcomings through material improvements, real-time control systems, and field testing could significantly enhance the system's efficiency and reliability.

The pendulum-based wave energy system presents a promising approach to renewable energy generation, leveraging the abundant and untapped resource of ocean waves. While the prototype demonstrated effective energy conversion within its design constraints, further advancements are necessary to realize its full potential. This research contributes valuable insights into the development of sustainable energy technologies, offering a foundation for future innovations aimed at addressing global energy demands.

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