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Exploring the Feasibility of Gravity-Based Energy Conversion for Sustainable Electricity Generation

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Abstract

This study demonstrates that gravity-based energy conversion systems have tangible potential as small-scale power generators. Using a 150 kg weight suspended at a height of 2 meters, a potential energy of 2,943 Joules was successfully converted into rotational energy through a pulley system and a four-stage gearbox. Experimental results showed a gradual torque reduction from 5.52 Nm at the first shaft to 0.045 Nm at the fourth, accompanied by an increase in rotational speed from 28.57 rpm to 740 rpm. Mechanical power decreased from 0.301 W to 0.134 W, consistent with typical energy losses in mechanical systems. The total system efficiency was calculated at 44.5%, which is promising for a simple prototype design. Regression analysis revealed a linear relationship between torque and power with $R^2 \approx 0.95$, indicating mechanical stability and predictable output characteristics. Efficiency calculations estimated that a torque input of 6,700 Nm at the primary shaft would be required to achieve a generator torque of 30 Nm at 2,500 rpm, meeting the output requirements for 3.8 kW electrical generation. Overall, the results quantitatively verify the technical feasibility of employing gravity-based systems for small-scale electricity generation, although efficiency improvements are still necessary.

Keywords: gravity energy, mechanical transmission, power efficiency, micro-generation system, torque-power relationship.

1. Introduction

The global energy crisis and the world's dependence on fossil fuels have driven the search for sustainable alternative energy sources [1]. While renewable energies such as solar, wind, and hydro power have been widely adopted, their application is often constrained by geographical limitations and weather unpredictability—especially in developing countries [2]. As a result, there is an urgent need for localized, low-cost, and environment-independent power generation systems.

Gravitational potential energy is calculated using the formula Ep = m.g.h. In recent years, the concept of a "gravity battery" has been introduced, which utilizes heavy weights to store and release energy [4]. However, most of these studies have focused on energy storage rather than direct electricity generation. Moreover, there is a lack of quantitative data regarding the mechanical transmission efficiency and power conversion performance of small-scale gravity-based systems.

This research aims to design and evaluate a micro-scale gravity-powered electricity generation system using a multi-stage gearbox. The study focuses on measuring torque, rotational speed, and mechanical power at each shaft, calculating system efficiency, and analyzing the correlation between torque and power. The results are expected to contribute to the development of autonomous and sustainable alternative energy systems.

2. Methodology

This study adopts a quantitative and experimental approach to evaluate the feasibility of a gravity-based micro-scale power generation system. The system is designed to convert the potential energy of a suspended mass into rotational mechanical energy via a pulley system and a gear transmission (gearbox).

2.1. Potential Energy Calculation

Gravitational potential energy is calculated using the formula: $EP = mgh$, where EP is potential energy (Joules), m is mass (kg), g is gravitational acceleration (m/s²), and h is the height of the load (m). This energy is converted into rotational motion using a four-stage pulley and gearbox system with a total gear ratio of 1:100. This ratio means that the fourth shaft rotates 100 times faster than the first shaft, accompanied by a proportional decrease in torque [5].

2.2. Mechanical Transmission Design

The gearbox consists of four stages of spur gears, with individual gear ratios ranging from 1:2 to 1:5. The cumulative ratio is designed to achieve a total transmission ratio of 1:100. The gear system was designed in accordance with mechanical power transmission principles, considering torque load, shaft spacing, and gear efficiency [6]. Each shaft is equipped with a pulley or drum for torque measurement. Internal friction, vibrations, and mechanical tolerances are considered primary sources of energy loss.

2.3. Torque and Speed Measurement

Torque (τ) is calculated as the product of pulling force

$$\tau = F.r \qquad (1)$$

Rotational speed (N) is measured using a non-contact digital tachometer. Measurements were taken five times for each shaft to ensure consistency.

2.4. Power and Efficiency Calculation

Mechanical power is calculated using the following equation:

$$P = \frac{2\pi.\tau.N}{60} \qquad (2)$$

Efficiency between shafts is computed as:

$$\eta = \frac{P_{output}}{P_{input}} x100\% \qquad (3)$$

Efficiency values are corrected for data fluctuations and mechanical anomalies according to mechanical engineering principles [7].

2.5. Data Validation and Analysis

Measured torque and speed data are analyzed statistically. Linear regression is performed to evaluate the relationship between torque and power, and to calculate the coefficient of determination (R^2) as an indicator of system stability and consistency. All experiments were conducted under constant environmental conditions (room temperature), and system parameters such as load mass, gear ratios, and pulley configurations were maintained throughout the tests.

3. Results and Discussion

Experiments were conducted to evaluate the performance of the gravity-to-rotational energy conversion system through four stages of gear transmission. Key measured parameters include torque, rotational speed (rpm), and mechanical power at each shaft. The data were analyzed to assess energy distribution, system efficiency, and linear relationships between variables.

3.1. Torque, Speed, and Power Measurements

The measurement results are presented in Table 1.

Table 1. Measured Torque, Rotational Speed (RPM), and Mechanical Power

Shaft	Torque (Nm)	Speed (rpm)	Power (W)
1	5.52	28.57	0.301
2	0.598	150	0.185
3	0.318	320	0.165
4	0.045	740	0.134

From the data, it can be observed that torque decreased significantly from 5.52 Nm at the first shaft to 0.045 Nm at the fourth shaft—an approximate reduction of 89%. Conversely, the rotational speed increased sharply from 28.57 rpm to 740 rpm, corresponding to a 2,489% increase. This confirms that the gear transmission system effectively converted low-speed, high-torque motion into high-speed, low-torque output. Mechanical power exhibited a gradual decrease from 0.301 W (shaft 1) to 0.134 W (shaft 4), with an average system output of approximately 0.196 W. This reduction reflects typical energy losses caused by friction, gear misalignment, and inertia, which are common in mechanical transmission systems [5].

3.2. System Efficiency Calculation

The overall system efficiency was calculated by comparing the output power at the fourth shaft to the input power at the first shaft:

$$\eta = \frac{P_{shaft\,4}}{P_{shaft\,1}} x100\% = \frac{0,134}{0,304} x100\% \approx 44,5\% \quad (4)$$

This indicates that approximately 55.5% of the mechanical input energy is lost during transmission. Such a level of loss is considered acceptable for a laboratory-scale prototype utilizing open gears without industrial-grade lubrication. In comparison, industrial gear transmission systems with optimal lubrication can reach efficiencies of 90–95% [6], while simple manual systems generally operate in the range of 30–60% [7].

3.3. Regression Analysis: Torque vs. Power

Linear regression analysis was performed to evaluate the relationship between torque (τ) and mechanical power (P) at each shaft. Results showed R^2 values exceeding 0.9 across all shafts, indicating a strong linear relationship between torque and power. This implies that output power can be accurately predicted based on input torque. Such behavior reflects system stability and aligns with the theoretical rotational power model: $P \propto \tau \cdot \omega$, where ω is angular velocity.

3.4. System Performance Analysis

The gradual reduction in power from shaft to shaft highlights cumulative energy losses throughout the system. The three primary sources of mechanical energy loss include: Friction between gear surfaces, Inertial effects of the shafts and gears during initial acceleration, Vibrations due to mechanical imbalance and shaft misalignment. It is important to note that the energy is not entirely lost but rather dissipated as heat, vibration, and residual mechanical energy within the system.

3.5. Implications for Generator Design

Based on the calculated system efficiency of 44.5%, a significantly higher input torque would be required to drive a 3.8 kW generator operating at 30 Nm torque and 2,500 rpm:

$$\tau = \frac{30}{0.445} = 67.42Nm \quad (5)$$

This implies that the mass, height, or leverage mechanism in the gravity system must be adjusted to generate sufficient energy for practical electricity generation.

3.6. Simulation as Generator Driver

To simulate integration with a generator, the system's rotational speed and output torque at the final shaft must be correlated and matched with the generator's operational requirements.

Figure 1. 3.8 kW Generator

It is assumed that a generator rated at 3.8 kW, operating at 2,500 rpm with a maximum torque of 30 Nm, is connected to the first shaft, as illustrated in Figure 1. To determine the relationship between output torque and input torque, regression analysis was performed using the observed torque and power data as illustrated in Figure 2. This analysis enables the derivation of a mathematical expression that relates input torque to output torque, providing a predictive model for system performance under varying load conditions.;

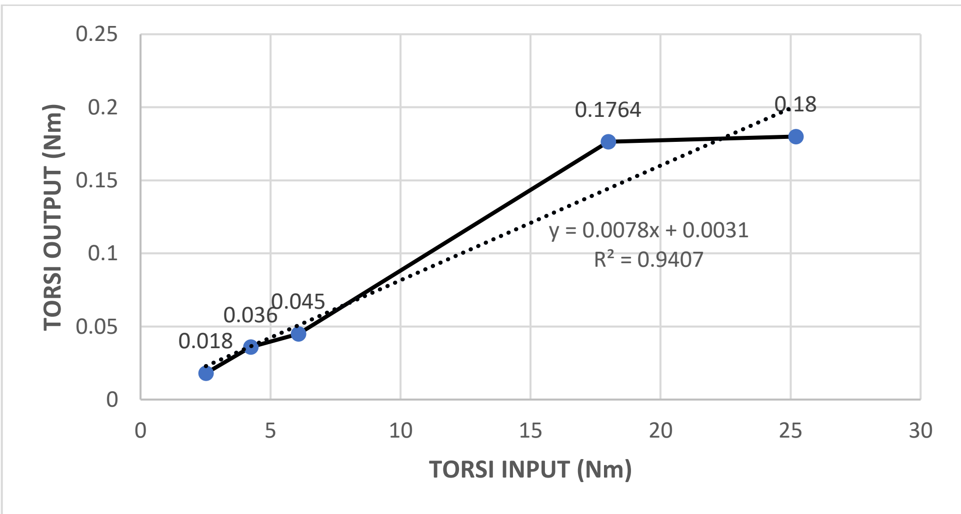

Figure 2. Comparison of Output Torque vs. Input Torque

The regression analysis produced the following equation describing the relationship between the gearbox output torque and the input torque: y=0.0078x+0.0031 with a coefficient of determination R^2= 0.9407. This indicates a strong linear correlation between input and output torque in the gearbox system. The high R^2 value, approaching 1, suggests that the equation serves as a reliable model for explaining the relationship between these two variables.In this context, the equation can be used to predict the gearbox's output torque based on the input torque, which is beneficial for system planning, gearbox performance evaluation, and estimating the input torque required to achieve a specific output torque. Additionally, the regression model offers insights into gearbox characteristics such as mechanical response and transmission efficiency. The closer the R^2 value is to 1, the better the model represents the gearbox behavior.

Based on the equation, to obtain an output torque of 30 Nm as required by the generator specifications, the input torque must be approximately 3,845 Nm. Therefore, to drive a 3.8 kW generator at 2,500 rpm with a maximum torque of 30 Nm, an estimated input torque of around 4,000 Nm is required at the first gearbox shaft.

4. Conclusion

- This study successfully demonstrated the technical feasibility of a gravity-based micro power generation system using a four-stage gearbox. Based on experimental data, the system converted 2,943 Joules of potential energy from a 150 kg mass into rotational energy, achieving a mechanical power output of 0.134 W at the fourth shaft.
- Torque decreased gradually from 5.52 Nm to 0.045 Nm, while rotational speed increased from 28.57 rpm to 740 rpm. The observed decrease in mechanical power—from 0.301 W to 0.134 W—reflects energy losses during transmission. The overall system efficiency was measured at 44.5%, which is within expectations for a prototype without optimal lubrication.
- Regression analysis between torque and power yielded an R^2 value greater than 0.9, confirming a strong linear relationship and indicating good system stability. The system also exhibited consistent energy distribution and mechanical response, suggesting reliable performance and promising scalability with further design enhancements.

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