Energy Engineering

Tech Science Press

Doi:10.32604/ee.2025.058916

ARTICLE

Industrial Untapped Rotational Kinetic Energy Assessment for Sustainable Energy Recycling

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Received: 24 September 2024; Accepted: 15 November 2024; Published: 07 March 2025

ABSTRACT: Electrical energy can be harvested from the rotational kinetic energy of moving bodies, consisting of both mechanical and kinetic energy as a potential power source through electromagnetic induction, similar to wind energy applications. In industries, rotational bodies are commonly present in operations, yet this kinetic energy remains untapped. This research explores the energy generation characteristics of two rotational body types, disk-shaped and cylinder-shaped under specific experimental setups. The hardware setup included a direct current (DC) motor driver, power supply, DC generator, mechanical support, and load resistance, while the software setup involved automation testing tools and data logging. Electromagnetic induction was used to harvest energy, and experiments were conducted at room temperature (25°C) with controlled variables like speed and friction. Results showed the disk-shaped body exhibited higher energy efficiency than the cylinder-shaped body, largely due to lower mechanical losses. The disk required only two bearings, while the cylinder required four, resulting in lower bearing losses for the disk. Additionally, the disk experienced only air friction, whereas the cylinder encountered friction from a soft, uneven rubber material, increasing surface contact losses. Under a 40 W resistive load, the disk demonstrated a 17.1% energy loss due to mechanical friction, achieving up to 15.55 J of recycled energy. Conversely, the cylinder body experienced a 48.05% energy loss, delivering only 51.95% of energy to the load. These insights suggest significant potential for designing efficient energy recycling systems in industrial settings, particularly in manufacturing and processing industries where rotational machinery is prevalent. Despite its lower energy density, this system could be beneficially integrated with energy storage solutions, enhancing sustainability in industrial practices.

KEYWORDS: Rotational kinetic energy; electromagnetic induction; energy harvesting; disk-shaped body; cylinder-shaped body; energy efficiency; mechanical loss; industrial energy recycling; sustainable energy solutions

1 Introduction

Electric motors play an essential role in various industries and applications, contributing significantly to global energy consumption. Enhancing energy efficiency in electric motors is crucial to reducing environmental impact and operational costs. This research overview explores the integration of energy storage systems and recycling methodologies to optimize energy efficiency in electric motors. Key concepts, such as the free-running load containing rotational kinetic energy, are examined to provide insights into innovative strategies for improving energy efficiency.

The industrial sector is the largest consumer of energy in Malaysia [1]. Industrial motors account for a major segment of total industrial energy use, and various energy-saving strategies have been developed to reduce energy consumption. These strategies include high-efficiency motors and variable speed drives

(VSDs) to improve the load factor of the entire system [2]. However, none of these strategies utilize the existing kinetic energy from the machines to perform regenerative braking, leading to unutilized energy dissipation through friction and heat. Devices that have been applied regenerative concept would be flywheel energy storage and electric vehicles. Regenerative braking systems, developed for electric vehicles, harvest electrical energy during braking by converting vehicle motion energy into electrical energy. Flywheel energy storage requires higher conditions such as high speed, huge installation space, dust control, and safety clearance. Whereas, in electric vehicles, the braking effect is the main concern. Thus, none of the efficient ways is developed for industrial application purposes. According to [3], energy can be saved by using recovery technology in industrial processes. Given the ongoing trend toward increased reliance on electrical energy, this proposal explores the feasibility of recycling rotational kinetic energy into usable electrical energy for diverse applications.

The environment, economy, and energy supplies are all severely strained in Malaysia, where 95% of energy is generated from non-renewable sources. Coal, which needs to be imported from other nations, accounts for around 53% of the energy produced [1]. This heavy reliance on fossil fuels not only increases carbon emissions but also exposes the country to fluctuations in global energy markets. To address these issues, the Malaysian government made a commitment to cut emissions in the Paris Agreement of 2016 that would amount to 13.113 million tonnes of CO_2 by the year 2030 [1]. To further support the aforementioned objectives, the government has also committed to creating green technologies. Establishing a feed-in-tariff system is one of these steps to draw funding to green energy, renewable energy, and carbon credit-eligible projects.

Given these objectives, this research on kinetic energy recycling is particularly timely and crucial for Malaysia. By focusing on industrial energy recycling, it aligns with the government's commitment to reducing reliance on imported fossil fuels, lowering emissions, and promoting cleaner energy practices. Furthermore, as Malaysia transitions towards renewable energy, such innovations in energy efficiency also support global efforts to create a sustainable, low-carbon economy.

This research paper will investigate the available energy in rotational objects using physics-based analysis. Analytical models, including mathematical, physical, and simulation-based approaches, are employed as needed. The research focuses on the general kinetic energy calculations for rotational machines. The rest of the paper is organized as follows: Section 2 provides a critical review of the literature related to kinetic energy harvesting from rotational objects. Section 3 describes the investigation of two physics models, highlighting their differences in potential energy losses in machines and the amount of available kinetic energy from rotating loads. The results and discussion are presented in Section 4. Finally, Section 5 provides conclusions and recommendations for future work.

2 Literature Review

The advancement of technology in the 21st century has led to the development of high-efficiency devices for harvesting energy. Renewable energy sources generate power from natural resources, which do not contribute to pollution and are replenished within a human lifetime. The primary objective of this research is to utilize only the necessary amount of energy while recycling the surplus for future use, storing it in an energy storage system. In a study by [4], utility-scale energy storage systems were analysed, with a focus on flywheel energy storage systems, which emerged as efficient and durable options for power generation. Research [5–7] highlighted the value of second-life electric energy storage due to its longevity. The study discussed in [8] emphasized the importance of recycling leftover energy to reduce waste and enhance energy accessibility, with a particular focus on electric vehicle (EV) batteries and flywheel systems. Moreover, references [9] and [10] explored energy generation, utilization, and storage methodologies, highlighting the need for further research into recycling energy from various natural resources. The review in [10] underscored the necessity of distinguishing between energy suitable for recycling and that which only requires storage. As global interest in renewable energy grows, reference [11] examined the environmental impact of recycling systems, including those involving wind turbines, batteries, solar panels, and fuel cells. Wind turbines, as highlighted in [12] and [13], demonstrate a high recyclability rate, making them a leading green energy option. Strategies to improve efficiency and reliability, alongside energy recycling, are crucial for long-term sustainability [14]. A review paper stated that advancements in battery technologies contribute to the overall improvement of energy storage systems, marking a revolution in renewable energy storage, leading to increased energy efficiency, lower overall costs, and greater energy availability [15].

Electricity is a crucial resource in modern society, making the exploration of alternative methods for generating renewable electrical power imperative. One innovative approach is the development of a power-generating revolving door, similar to a turbine but harnessing the energy exerted by individuals. A small-scale prototype was constructed and tested, providing insights into factors influencing its performance and efficiency. The study suggests that utilizing the revolving door for energy storage, rather than directly powering loads, may be more practical based on the collected data [16]. In remote areas where electricity is scarce, supplying power to facilities like weather stations poses significant challenges. To address this issue, a rotational Halbach array-based wind energy harvester is proposed. This harvester generates substantial output power to drive individual functional units and IoT sensors, enabling self-powered weather stations. By employing a Halbach array magnet to guide magnetic flux, the harvester achieves enhanced performance, with a significant increase in magnetic flux density compared to conventional magnets. Additionally, the use of MXene/PVDF-TrFE as a triboelectric material enhances wind speed determination. This research paves the way for high-performance energy harvesters and self-powered IoT systems [17].

A novel Kinetic Energy Harvester (KEH) has been developed specifically to power oceanic and rogue drifters. This system utilizes a double pendulum mechanism to convert wave oscillations into rotational energy on a flywheel, which is then converted into DC power by an electrical generator. A power management unit (PMU) with maximum power point tracking optimizes energy production. Real sea tests demonstrated the drifter's performance, with the KEH generating a mean output power of 0.18 mW, reaching peaks of 2.5 mW. This research presents a promising solution for harnessing oceanic kinetic energy for practical applications [18].

The study also focuses on extracting kinetic energy from moving vehicles over speed breakers. The proposed system utilizes a rack-and-pinion mechanism to convert this kinetic energy into mechanical energy, subsequently driving a shaft that acts as the prime mover for a DC generator. While a prototype model demonstrates proof of concept, further modifications are necessary for large-scale electricity generation. This approach shows promise for reducing dependence on conventional energy sources and utilizing waste energy for sustainable electricity generation [19]. The study highlights the development of micro-hydro plants in rural areas, specifically focusing on the village of Sambangan in the District of Buleleng, Bali. With the potential to generate electricity from nearby streams or rivers and form irrigation systems, micro-hydro plants offer clean and sustainable energy solutions for remote communities [20,21]. The report outlines plans to enhance existing micro-hydro plants to provide more reliable electricity for villagers without access to the utility grid [22,23]. Technical specifications of the proposed 82 kW micro-hydro plant are detailed, along with estimated development costs. Additionally, an organization is identified to empower local manpower for effective and sustainable operation and maintenance of the power plant [24]. Table 1 is summarizing the research findings for energy harvesting system.

Table 1: Research findings for energy harvesting system

Aspect	Research summary	Research gaps	Future work	Ref.
Wind turbines and Concentrators	Methods have been proposed to augment energy harvesting using wind turbines and concentrators. These include using wind energy from solar chimneys, exhaust gases, and other industrial sources.	Limited exploration of how these systems interact with existing industrial processes and their overall impact on energy efficiency.	Integration with industrial processes and optimizing the interaction between energy harvesting systems and industrial operations.	[25,26]
VAWT systems in industrial settings	Research suggests the use of Vertical Axis Wind Turbines (VAWT) over cooling towers and in other industrial settings to harness kinetic energy from unnatural wind sources.	Limited large-scale implementation and testing in diverse industrial environments.	Expanding the use of VAWT systems in various industrial contexts, including full-scale testing and long-term performance analysis.	[27]
Hybrid solar-flue gas chimney	The concept of hybrid solar-flue gas chimneys combines solar and industrial flue gas to increase the efficiency of Solar Chimney Power Plants (SCPP).	Efficiency remains low compared to investment costs; environmental impacts are not fully understood.	Further development of hybrid systems and exploration of environmental benefits, particularly in reducing thermal pollution.	[28]
Exhaust air energy harvesting	Various studies have explored harvesting energy from exhaust air using turbines, with significant potential demonstrated in industrial exhaust systems.	The impact on overall system efficiency and the long-term durability of these systems is not well understood.	Investigation into the durability of energy harvesting systems and their integration with industrial exhaust systems for long-term use.	[29]
Small-scale wind turbines	Proposals for small-scale wind turbines, such as shaftless horizontal wind turbines, for use in industrial exhaust systems have been made, showing no negative impact on existing systems.	Limited research on the scalability and energy output of small-scale turbines in various industrial applications.	Further research on scaling these systems for larger applications and optimizing energy output in different industrial environments.	[30]

(Continued)

Table 1 (continued)

Aspect	Research summary	Research gaps	Future work	Ref.
Mathematical modelling for ERS	Mathematical models for Energy Recycling Systems (ERS) in industrial stacks suggest modifications to improve efficiency and maintain recommended exit velocities for pollutants.	The practical application of these models in real industrial settings is limited.	Implementation and testing of mathematical models in real-world industrial settings to validate theoretical findings.	[31]
Mine ventilation energy recovery	Research on recovering energy from underground mine exhausts indicates significant potential for energy savings and efficiency improvements in mine ventilation systems.	Variation in recovery potential based on site-specific factors needs further exploration.	Optimization of ventilator fan systems and design improvements to maximize energy recovery in different mining environments.	[32]
Industrial flue gas	Use of industrial flue gas to increase the efficiency of the SCPP, showing improvement in air velocity when using Savonius wind rotors.	More research needed to validate and improve efficiency in different industrial setups.	Extend the application of Savonius wind rotors in various industries and test long-term impacts on efficiency.	[33]
Steam from cooling towers	Use of guide vanes and side diffusers in a Horizontal Axis Wind Turbine (HAWT) setup for cooling towers, resulting in a 30.4% increase in energy generation.	Limited scalability and application across different types of cooling towers.	Further development of guide vane and diffuser designs to enhance efficiency in various cooling tower configurations.	[34]
Kinematic movement of trains	Implementation of VAWT in the vicinity of MRT train systems, with wind generated from the kinematic movement, showing potential for energy harvesting.	Limited testing under different environmental conditions and train speeds.	Expand testing to various train systems and investigate the scalability of VAWT installations in urban settings.	[35]
Air from industrial exhaust systems	Methods suggested for conserving velocity until reaching the wind turbine, with significant wind speed observed in industrial exhaust systems.	Need for real-world testing to understand the impact on energy efficiency and system durability.	Implement pilot projects in various industries to test the durability and efficiency of these systems.	[36]

(Continued)

Table 1 (continued)

Aspect	Research summary	Research gaps	Future work	Ref.
Industrial flue gas with VAWT	Proposed use of VAWT with augmenting velocity using diffusers, achieving higher energy extraction rates.	Need for practical implementation and analysis of energy gains in different industrial setups.	Test VAWT systems with various diffuser designs in real-world industrial environments to validate energy efficiency improvements.	[37]
Air conditioning exhaust	Proposed use of a small-scale SSHWT equipped with a novel BDC generator for air conditioning exhaust, showing potential for energy recovery without impacting the exhaust system.	Limited scalability and application to larger systems or other industrial exhaust sources.	Develop larger-scale prototypes and explore integration with other industrial exhaust systems to improve energy recovery efficiency.	[38]

3 Research Methodology

In this research, two different heavy mass bodies, a disk and a cylinder, were selected. The disk was defined as a simple model, while the cylinder was defined as a complex model. This distinction allows for a quantitative evaluation of the differences in their mechanical characteristics. Table 2 summarizes the advantages, limitations, and potential solutions for harnessing rotational kinetic energy from disc and cylinder bodies.

Table 2: Advantages, limitations, and potential solutions for harnessing rotational kinetic energy from disc and cylinder bodies

Aspect	Advantages	Limitations	Potential solutions
Disc body [39]	- Higher efficiency: Disc-shaped bodies can achieve higher rotational speeds with less resistance due to their streamlined shape. - Lightweight: Discs generally have lower mass, which can result in higher angular acceleration for energy generation. - Compact design: Disc shapes allow for a more compact design, saving space in industrial applications.	- Structural integrity: High rotational speeds may cause structural stress, leading to potential deformation or failure. - Energy storage: Limited surface area for attaching energy harvesting mechanisms, which can reduce the efficiency of energy extraction. - Vibration issues: High-speed rotation can lead to vibrations, which may cause wear and tear on components.	- Material enhancement: Use high-strength materials like carbon composites to improve structural integrity under high rotational speeds. - Design optimization: Develop advanced designs for energy harvesting mechanisms that maximize contact with the disc surface for better energy extraction. - Vibration damping: Implement damping systems or balance the disc more effectively to minimize vibrations during operation.

(Continued)

Table 2 (continued)

Aspect	Advantages	Limitations	Potential solutions
Cylinder body [40]	- Larger surface area: Cylinders provide more surface area for attaching energy harvesting mechanisms, potentially increasing energy extraction. - Higher inertia: The mass distribution in cylinders can lead to higher inertia, allowing for more stable energy storage and release over time. - Versatility in design: Cylinders can be more easily integrated into various industrial systems due to their shape and size flexibility.	- Aerodynamic drag: Cylinders face higher aerodynamic drag compared to discs, which can reduce rotational efficiency. - Weight: Cylinders are generally heavier, which can increase the load on supporting structures and reduce acceleration. - Complex manufacturing: Manufacturing and balancing cylinder bodies for high-speed rotation can be more complex and costly.	- Streamlining: Use aerodynamic shaping or enclosures to reduce drag and improve rotational efficiency. - Weight reduction: Utilize lightweight materials or hollow designs to reduce overall weight without compromising structural integrity. - Advanced manufacturing techniques: Implement precision manufacturing and balancing techniques to ensure high performance and reliability.
General (Both disc and cylinder bodies)	- Energy recovery: Both shapes can be optimized to recover rotational kinetic energy efficiently, reducing waste in industrial processes. - Customizability: Both disc and cylinder bodies can be customized for specific industrial applications, offering flexibility in energy recovery systems.	- Maintenance requirements: Both designs require regular maintenance to ensure efficiency and prevent mechanical failure. - Wear and tear: Continuous operation at high speeds can cause wear and tear on both designs, leading to reduced efficiency over time.	- Predictive maintenance: Use AI and IoT for predictive maintenance to minimize downtime and extend the lifespan of the components. - Surface coating: Apply wear-resistant coatings to critical components to extend their operational life and maintain efficiency.

3.1 Physics-Based Rotating Kinetic Energy Calculations for Disc and Cylinder Bodies

In this section, two physics analyses will be discussed to identify the differences between the disk and cylinder bodies during rotational motion. These differences, including potential mechanical losses, will be evaluated to determine their impact on the recycling energy system. Additionally, the conversion of kinetic energy to electrical energy, as well as the relationship between the permanent magnet synchronous generator and the capacitor, will be explored.

3.1.1 Analysis of Force Gravity Acting on a Disk

As shown in Fig. 1, the disk is hanging on a shaft vertically, and the force of gravity acts uniformly across the entire disk body. The gravitational force affects the entire weight of the disk, pulling it downward either left or right side, which can be defined as:

$$F_{left} = F_{right} = m \times g\,[\mathrm{N}] \tag{1}$$

where m is the mass of the object in [kg], g is the free fall velocity at [9.81].

The total net force in equilibrium is zero.

$$F_{net} = F_{left} - F_{right}\, or - F_{left} + F_{right} = 0 \tag{2}$$

As the force is zero, the net torque is defined as the product of the force and radius of the circle, which is also zero:

$$\tau_{net} = F_{net} \times R = 0 \tag{3}$$

where R is the radius of the object [m].

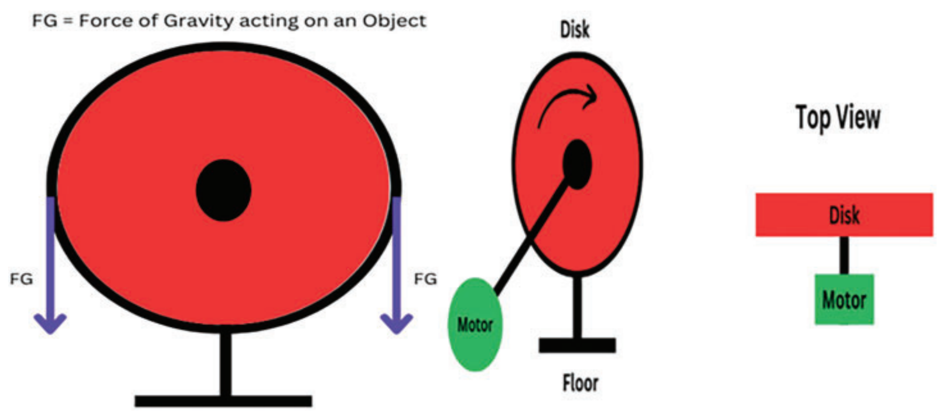

Figure 1: Disk body setup

In order to make the disk rotate in a circular motion, The net force must be greater than one of the sides, which is greater than mg. Let us assume rotate in a clockwise direction; the force on the right side must be greater than on the right. The difference between the force on the left and right cause the force on the disk to no longer be uniform.

$$F_{net} = F_{left} - F_{right} > 0 \, or < 0 \tag{4}$$

Substitute (4) into (3)

$$\tau_{net} = F_{net} \times Radius > 0 \, or < 0 = k \tag{5}$$

where k is defined as the difference in torque [Nm].

The k value is a constant value to overcome the force of gravity acting on the left side to keep the disk rotating in a clockwise direction.

Mechanical power is defined as:

$$P_{mech} = T_m \times W \tag{6}$$

where mechanical torque, T_m [Nm], is the angular velocity, $W \left[\frac{rads}{s}\right]$.

By substituting (5) into (6)

$$P_{mech} = k \times W \tag{7}$$

Eq. (7) shows the required mechanical power is needed when due to the force of gravity.

If now losses consider, by modifying (3)

$$\tau_{net} = k + l \tag{8}$$

where l is the lump sum mechanical losses [Nm].

Replacing (8) in (6)

$$P_{mech} = T_m \times W = (k + l) \times W \tag{9}$$

Eq. (9) represents the total mechanical power required when the force of gravity and friction loss are considered.

In this setup shown in Fig. 1, the motor drives the rotation of the disk, while the gravitational force consistently acts downward, influencing the disk's dynamics. The motor must produce the mechanical power defined as:

$$P_{motor} = P_{mech} = T_m \times W = (k + l) \times W \tag{10}$$

Maintaining equilibrium in practical systems is challenging due to external disturbances like vibrations, which can be mitigated using damping mechanisms, adaptive control, and feedback loops. Real-world complexities such as imperfect disks and non-vertical shafts introduce unbalanced forces, requiring tolerance limits, real-time monitoring, and compensatory components. Computational simulations and adaptive control systems further enhance robustness, aligning the idealized model with industrial applications.

3.1.2 Analysis of Force Gravity on a Cylinder Body

In the analysis of the cylinder body setup, depicted in Fig. 2, the cylinder is mounted on wheels, with a motor providing the necessary rotational force. The force of gravity (FG) acts uniformly on the entire cylinder body, affecting its weight. The various forces acting on the cylinder include the gravitational force (FG) acting downward, the normal contact force (FN) exerted by the wheels upward, and the frictional force (F) opposing the motion. Force equilibrium (FE) is maintained by balancing these forces. Fig. 2 does not currently account for the impact of wear and tear on the wheels, which can significantly alter the frictional force over time. This change in friction could lead to increased energy consumption, negatively affecting the system's long-term energy efficiency.

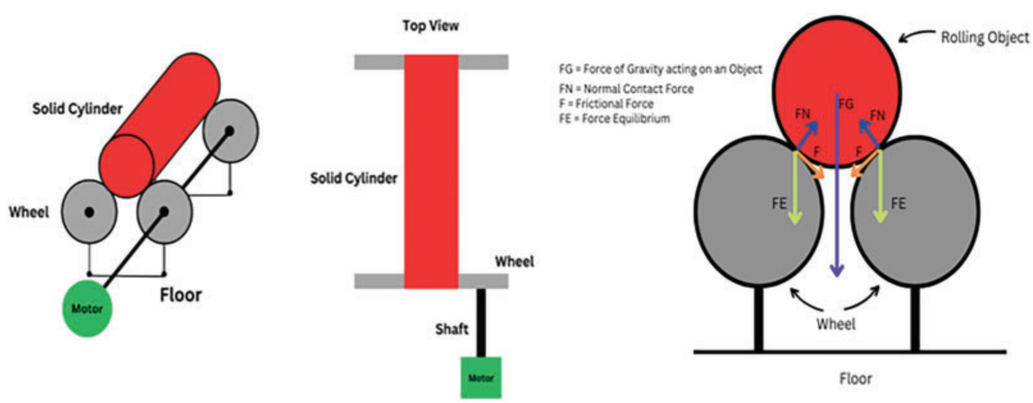

Figure 2: Cylinder body setup

In this setup, the motor drives the cylinder's rotation while the gravitational force consistently acts downward. The normal contact force (FN) provided by the wheels counteracts this gravitational force, ensuring that the cylinder remains in equilibrium. The frictional force (F) plays a crucial role in enabling the rolling motion of the cylinder by opposing the direction of movement and providing the necessary traction. The total force acting on the wheel is defined as:

$$F_{total} = m \times g$$

The force acting on four wheels is defined as:

$$FE = \frac{F_{total}}{4} = \frac{F_{total}}{n} \tag{11}$$

where FE is a force acting on each wheel, and n is the number of wheels.

The normal contact force is defined as:

$$FN = mg\cos\theta \tag{12}$$

The frictional force is defined as:

$$F = mg\sin\theta \tag{13}$$

Recall (3), the torque exerts on both sides as:

$$T_{net} = F_{net} \times R = m_o g\sin\theta \times R = 0 \tag{14}$$

So, for equilibrium,

$$T_{net} = 0 \tag{15}$$

As in the previous case, the equation of motor power is the same as (10). which is:

$$P_{motor} = P_{mech} = T_m \times W = (k + l) \times W$$

The main difference between the two cases lies in the method of torque transfer to the body. The disk uses a direct-drive method, whereas the cylinder employs an indirect-drive method. In the indirect-drive method, torque is transferred through the contact between the surface of the wheel and the cylinder body. Therefore, the surface condition of both the wheel and cylinder is a crucial factor affecting the system's overall efficiency. This phenomenon, known as rolling friction, can cause the rolling objects to eventually come to a stop. There are typically two types of rolling friction: deformation and adhesion between the contact surfaces, as illustrated in Fig. 3. Therefore, modifying Eq. (10),

$$P_{motor} = P_{mech} = T_m \times W = (k + l + j) \times W \tag{16}$$

where j is the loss due to the deformation and adhesion between the contact surface. The Eq. (16) indicates that the mechanical power P_{mech} influenced by the total torque T_m generated by the motor, which consists of contributions from various frictional forces, including rolling friction.

3.1.3 Power Balance Model

Assuming resistive load connected to the generator shown in Fig. 4, then the electrical power, Pg becomes:

$$P_g = \frac{V^2}{R} = I^2 R \tag{17}$$

Supposing the electrical motor is switched off, but the rotational body keeps rotating due to the inertia effect of body mass, The mechanical power is defined as:

$$P_{mech} = P_g \tag{18}$$

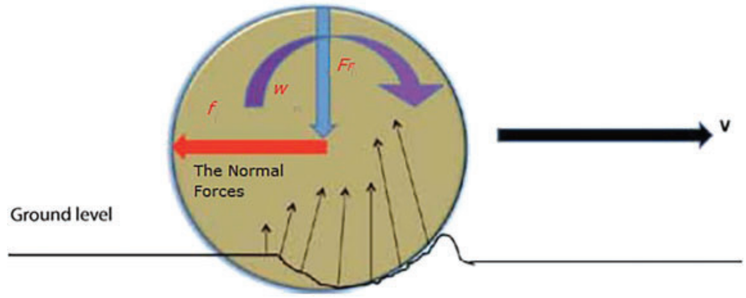

Figure 3: Rolling friction, Reprinted from reference [41]

The mechanical time constant, T_0 is defined time for the motor speed to fall to one-half its previous value in a second.

$$T_0 = \frac{Jn^2}{131.5\, P_i} \tag{19}$$

where J is the moment of inertia [kg.m^2], n is the initial speed of the motor when braking starts [rpm], p_{i} is the initial power delivered by the motor to the braking resistor [W], and 131.5 is a constant value.

Substituting (18) into (19),

$$T_0 = \frac{Jn^2}{131.5\, P_{mech}} = \frac{Jn^2}{131.5\, P_g} \tag{20}$$

Eq. (19) shows the relationship between harvested electrical power and mechanical time constant. This equation is based on upon the assumption that the braking effect is caused by generator and extra braking torque due to windage and friction. In general, the actual mechanical time constant will be less than the calculated mechanical time constant.

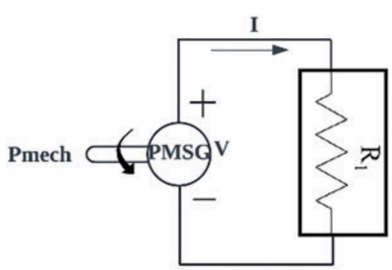

Figure 4: Generator and resistive load circuit diagram

3.1.4 Power Curve Characteristics of a Permanent Magnet Synchronous Generator (PMSG)

Fig. 5 illustrates a typical power curve, depicting the relationship between the turbine's mechanical power and wind speed. This curve identifies three critical wind speeds: cut-in wind speed, rated wind speed, and cut-out wind speed. In Fig. 3, mechanical power generated by the turbine is represented alongside wind speed. The cut-in wind speed denotes the minimum speed required for turbine operation and the initiation of power generation. The rated wind speed signifies the velocity at which the system reaches its nominal power output, equivalent to the generator's rated output power. Finally, the cut-out wind speed represents the maximum wind speed at which the turbine can safely operate before shutdown.

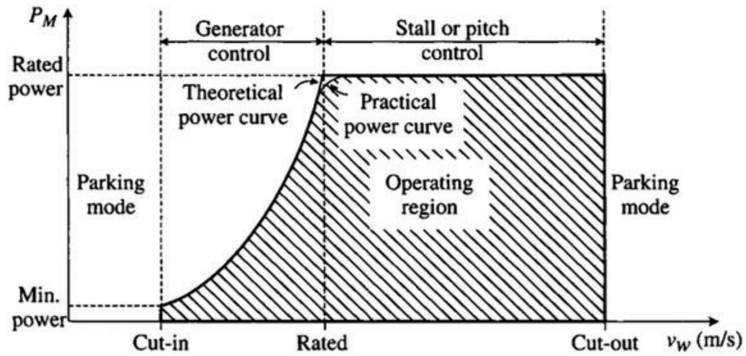

Figure 5: Typical power curve characteristics of wind turbine using PMSG [42]

In this research, the rotational body acts like a wind turbine, driving the generator shaft to produce electrical power. The angular velocity of the rotational body can be compared to wind speed. The power curve is characterized by two key angular velocities: cut-in and rated speeds.

The theoretical power curve equation for the generator control region is defined as follows:

$$P_{max} \propto w_m^3 \tag{21}$$

where P_{max} is maximum mechanical power, w_m is the angular velocity.

Since the mechanical power captured by the turbine is related to the turbine torque, τ_{max}, by:

$$P_{max} = \tau_{max} \times w_m \tag{22}$$

Substitute (20) into (21), the turbine mechanical torque becomes:

$$\tau_{max} = \frac{w_m^3}{w_m} = w_m^2 \tag{23}$$

From (20) to (22), it is observed that the output power is strongly increasing exponentially with the input speed.

3.1.5 Analogy between Rotational Kinetic Energy and Electrical Potential Energy

The analogy between a capacitor storing electric charge and an object storing rotational kinetic energy offers a way to elucidate the fundamental principles underlying both phenomena within the frameworks of classical mechanics and electromagnetism.

Fig. 6 shows a flywheel linked to a Permanent Magnet Synchronous Generator (PMSG), representing the capacitor, which is mechanically connected to a motor, symbolizing the power source that charges the capacitor. Initially, when at rest, the flywheel mirrors the uncharged state of a capacitor. Upon activation of the motor, energy is imparted to the flywheel, inducing rotational motion, akin to the accumulation of charge in a capacitor when a voltage is applied across its terminals. The energy stored within the rotating flywheel parallels the electric charge held within the capacitor. Just as the energy storage in the flywheel depends on its angular velocity and moment of inertia, the energy stored in the capacitor depends on the magnitude of the charge it holds and the voltage difference across it.

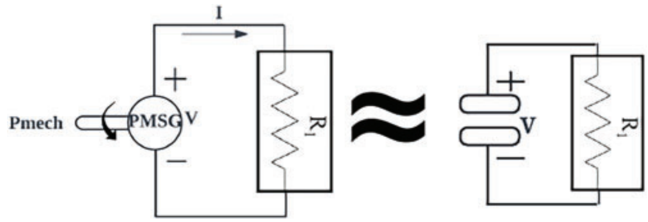

Figure 6: Analogy approach

Continued energy input from the motor propels the flywheel to higher rotational speeds until it reaches its maximum kinetic energy state. Similarly, sustained charging of the capacitor results in the accumulation of charge until the capacitor reaches its maximum capacity. Upon cessation of the motor's operation, the rotational motion of the flywheel gradually diminishes due to dissipative forces such as friction and air resistance, releasing the stored rotational kinetic energy. In a parallel manner, disconnecting the power source from the capacitor initiates a discharge process, leading to the dissipation of the stored electric energy.

In this case, the capacitor stored energy known as electrostatic potential energy, which is defined as:

$$E_c = \frac{1}{2} \times C \times V^2 \quad (24)$$

3.2 Experimental Setups to Harvest Electrical Energy

In most energy harvesting techniques, the harvester is unable to directly supply continuous power to the load due to the low instantaneous power output compared to the power required by electrical appliances. This limitation arises because the harvester collects energy from external sources. Consequently, a power management circuit is necessary to store and discharge energy at appropriate intervals, ensuring the load operates reliably.

Fig. 7 presents the proposed block diagram for the energy harvesting system. Electrical energy from the utility is supplied to the load (motor) and the heavy mass body. The rotational kinetic energy generated by the heavy mass body (either a disk or cylinder) is then utilized. This rotational kinetic energy is converted into mechanical power, which is subsequently converted back into electrical energy by a generator. The electrical energy generated is directed to the secondary system for storage. The stored energy in the battery can be used to power the load when needed. Fig. 8 shows the final outlook of the prototype.

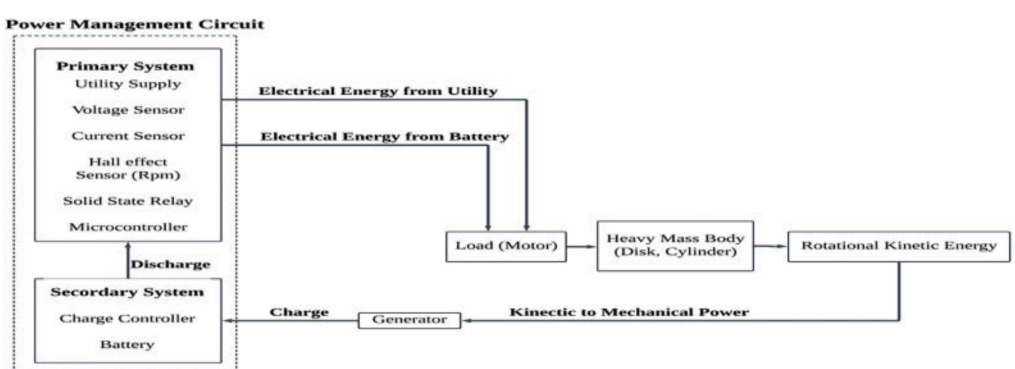

Figure 7: Block diagram for energy harvesting system

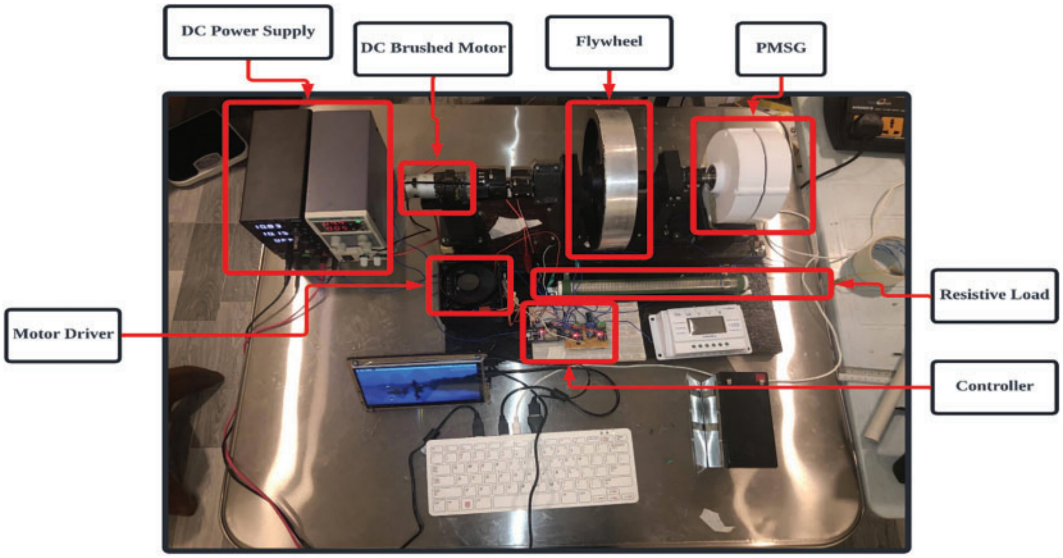

Figure 8: Final outlook for prototype

4 Results and Discussion

This section presents the results obtained from each step used to evaluate the amount of available rotational kinetic energy that can be harvested from the rotational mass bodies (disk and cylinder).

4.1 Physics Analysis of Disk Body

The disk body is made of cast iron and has a mass of 5 kg with a uniform diameter of 24 cm. To enable its rotation in free space, a 3D-printed shaft fabricated from PLA material with 100% infill is used. Table 3 summarizes the calculated results using Eqs. (10), (20) and (24). The power loss due to mechanical parts was measured at 20 W using Eq. (5) with the known weight. The results show that the disk body stores 23.33 J of energy when rotating at 375 rpm. In an electrical coordinate system, it behaves like a capacitor with a capacitance of 0.081 F when the capacitor voltage is 24 V. The time constant for three different scenarios free running, a 50 W load, and a 20 W charge controller decreases as the harvested power increases. These results suggest that higher power generated on the Permanent Magnet Synchronous Generator (PMSG) leads to a greater braking torque effect on the disk body during energy generation. Table 4 gives the comparison of energy loss and harvested energy from various conditions.

Table 3: Physics analysis available kinetic energy in disk

Physical aspect	Equation	Calculation	Value
Estimated available rotational kinetic energy, J (Ws)	$E_W = \frac{1}{2} \times I \times w^2$	$\frac{1}{2} \times \left(\frac{1}{2} \times (5) \times (0.11^2)\right) \times (39.27)^2$	23.33
Estimated capacitance, F	$C = \frac{E_c \times 2}{V^2}$	$\frac{23.33 \times 2}{(24)^2}$	0.081
Time constant, free running without harvesting condition, s	$T_0 = \frac{Jn^2}{131.5\ P_i}$	$\frac{\left(0.03 \times (375)^2\right)}{131.5 \times (20)}$	1.62

(Continued)

Table 3 (continued)

Physical aspect	Equation	Calculation	Value
Time constant, 40 W, Resistive load, s	$T_0 = \frac{Jn^2}{131.5\, P_i}$	$\frac{\left(0.03 \times (375)^2\right)}{131.5 \times (20 + 40)}$	0.54
Time constant, 20 W, Charge controller, s	$T_0 = \frac{Jn^2}{131.5\, P_i}$	$\frac{\left(0.03 \times (375)^2\right)}{131.5 \times (20 + 20)}$	0.78

Table 4: Comparison of energy loss in friction and harvested energy from disk body

No.	Condition	Input mechanical power, P_m [W]	Mechanical loss, P_l [W]	Energy loss in Friction (%)	Harvested energy (%)
1	Free running	20	20	100	0
2	40 W, Resistive load	60	20	33.33	66.66
3	20 W, Charge controller	40	20	50	50

From Table 5, it is observed that under free-running conditions, the available rotational kinetic energy is fully dissipated (100%) into mechanical parts, such as bearing friction and the Permanent Magnet Synchronous Generator (PMSG) starting torque. In contrast, under a 40 W resistive load and a 20 W charge controller, it is estimated that a portion of the rotational kinetic energy can be recycled for useful work.

Table 5: Recycling energy efficiency through physics analysis from disk body

Rotational kinetic energy, J = 23.33 J	Free running	40 W Resistive load	20 W Charge controller
Recycling energy, J	0	15.55	11.67

Fig. 9 displays the speed-time curves of the disk body under three different conditions. It is observed that under free-running conditions, the disk maintains its speed the longest due to the minimal braking torque effect. In contrast, a 40 W resistive load significantly reduces the disk speed, with a decrease occurring in less than 5 s. For a 20 W charge controller, the speed drops to zero within 5 to 10 s. These results indicate that recycling energy can be improved by increasing the generated power to the load. As the load power increases, the power loss due to mechanical parts decreases, leading to a shorter mechanical time constant.

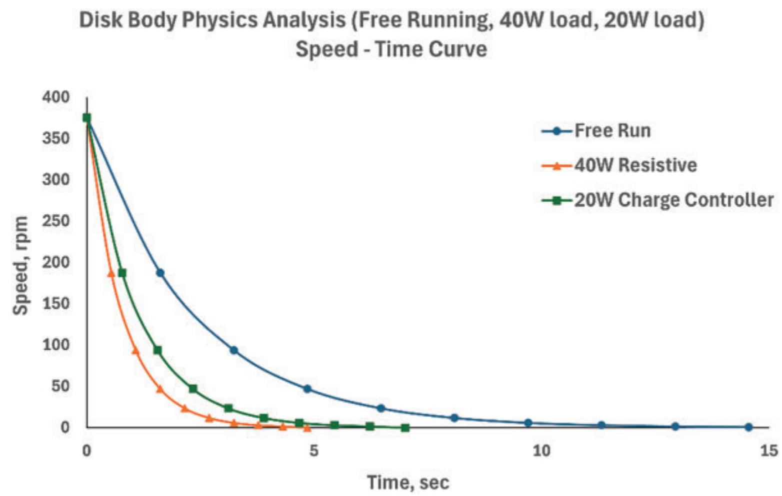

Figure 9: Comparison of speed-time curve from disk body under three different conditions

4.2 Physics Analysis of Cylinder Body

The cylinder body, with a mass of 15 kg and made of concrete, is enclosed in a PVC tube with a diameter of 15.24 cm and a length of 36 cm. Four wheels are used to distribute the force evenly across each spinner to prevent damage to the mechanical parts, with the wheels spaced 20 cm apart. Table 6 summarizes the calculated results using the same methods as the previous analysis. The mechanical loss was measured at 37 W, and the results indicate that the cylinder body stores 33.63 J of energy when rotating at 375 rpm. In an electrical coordinate system, it behaves like a capacitor with a capacitance of 0.117 F when the capacitor voltage is 24 V, according to the PMSG rated voltage. Similar to the previous case, the mechanical time constant for three scenarios—free running, a 40 W load, and a 20 W charge controller—decreases as the harvested power increases.

Table 6: Physics analysis available kinetic energy in cylinder

Physical aspect	Equation	Equation	Value
Estimated rotational kinetic energy	$E_w = \frac{1}{2} \times I \times w^2$	$\frac{1}{2} \times \left(\frac{1}{2} \times (15) \times \left(0.076^2\right)\right) \times (39.05)^2$	33.25
Estimated capacitance	$C = \frac{E_c \times 2}{V^2}$	$\frac{33.25 \times 2}{(24)^2}$	0.115
Time constant, free running without harvesting condition	$T_0 = \frac{Jn^2}{131.5\,P_i}$	$\frac{\left(0.044 \times (375)^2\right)}{131.5 \times (37)}$	1.26
Time constant, 40 W resistive load	$T_0 = \frac{Jn^2}{131.5\,P_i}$	$\frac{\left(0.044 \times (375)^2\right)}{131.5 \times (37 + 40)}$	0.54
Time constant, 20 W, Charge controller	$T_0 = \frac{Jn^2}{131.5\,P_i}$	$\frac{\left(0.044 \times (375)^2\right)}{131.5 \times (37 + 20)}$	0.80

Table 7 gives the comparison of energy loss in mechanical parts and harvested energy from various conditions.

Table 7: Comparison of energy loss in friction and harvested energy

Number	Condition	Input mechanical power, P_m [W]	Mechanical loss, P_l [W]	Energy loss in friction (%)	Harvested energy (%)
1	Free running	37	37	100	0
2	40 W, Resistive load	77	37	48.05	51.95
3	20 W, Charge controller	57	37	64.91	35.09

From Tables 7 and 8, it is observed that the outcomes are consistent with the previous case: no energy was harvested during free running. Under a 40 W resistive load, there was a 48.05% energy loss due to mechanical friction, with only 51.95% of the energy (17.47 J) delivered to the load. Under a 20 W charge controller, there was a 64.91% energy loss due to mechanical parts, and only 35.09% (11.80 J) of the energy was consumed by the charge controller. These results indicate that higher efficiency can be achieved if the power generation exceeds the power loss in the cylinder body.

Table 8: Energy efficiency through experiment from cylinder body

Rotational kinetic energy, J = 33.63 J	Free running	40 W Resistive load	20 W Charge controller
Recycling energy, J	0	17.47	11.80

Fig. 10 summarised all the speed-time curve under various conditions. It shows the rate of change in speed reducing exponentially when the power generation increases.

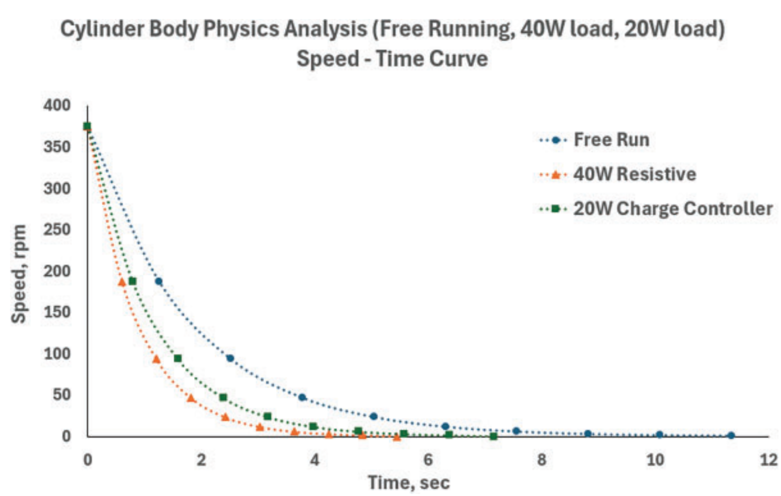

Figure 10: Comparison of speed-time curve from cylinder body under three different conditions

4.3 Comparison between Physics Analysis of Disk and Cylinder Body

From Table 9, it was observed that the available kinetic energy stored in the disk body is 36.17% less than that of the cylinder body due to differences in dimensions and weight. However, the overall time constant for the disk body is significantly higher than that for the cylinder body, indicating that the disk body experiences less friction loss and therefore requires a longer time to come to a stop. Under the 20 W charge controller condition, the differences between the disk and cylinder were minimal, with only a 12.17% variance, as shown in Fig. 11, where their curve lines overlap.

Table 9: Comparison between physics analysis of disk and cylinder body

Physical aspect	Disk	Cylinder	Percent difference (%)
Estimated rotational kinetic energy, J	23.33	33.63	−36.17
Estimated capacitance, J	0.081	0.1157	−35.28
Time constant, free running without harvesting condition, sec	1.62	1.26	25.00
Time constant, 50 W Resistive load, sec	0.54	0.61	−12.17
Time constant, 20 W Charge controller, sec	0.78	0.80	−2.53
Recycling energy, J—Free running	0	0	−36.17
Recycling energy, J—40 W Resistive load	19.60	17.27	−35.28
Recycling energy, J—20 W Charge controller	13.73	11.67	25.00

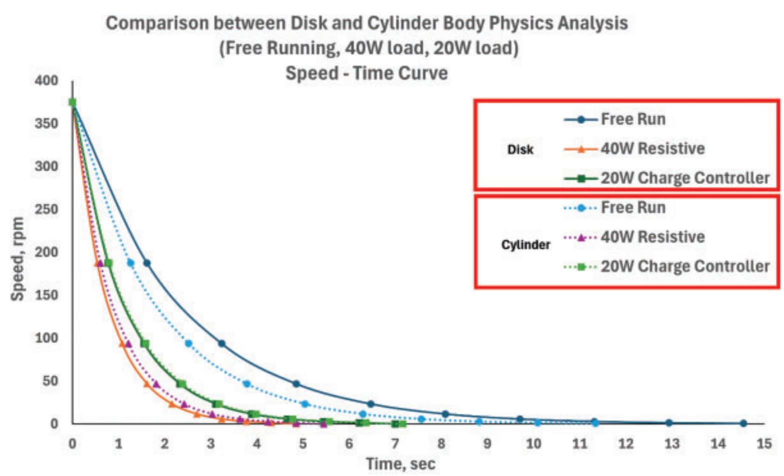

Figure 11: Comparison of speed-time curve from disk and cylinder body

Fig. 11 summarised all the speed-time curves and shows the variation between disk and cylinder body.

5 Energy Harvesting for Environmental Sustainability

Through the conversion of lost or otherwise unutilized energy into useable electricity, energy harvesting technologies provide a crucial chance to improve environmental sustainability. To lessen the load on traditional power plants, this method collects kinetic energy that would have gone to waste, such as the rotating kinetic energy of industrial gears, and puts it to another use. Energy harvesting devices allow enterprises to drastically reduce their impact on the environment and make a positive difference in running more sustainable operations [43]. These devices have a dual purpose: lowering emissions of greenhouse gases and saving money on energy bills [44,45]. Potential energy recovery, prices, and sustainability advantages of energy harvesting systems are highlighted in the following Table 10, which highlights diverse industrial uses of these technology. Where assesses the efficiency of different energy harvesting systems in relation to diverse industrial equipment. An industrial turbine equipped with a flywheel system can generate 150,000 kWh/year. The installation cost for this system is $100,000. The yearly savings from using this system amount to $15,000, and it also reduces CO_2 emissions by 45 tons/year. The cost efficiency of this system is 15%. An electric motor equipped with a regenerative braking system has the capability to collect 80,000 kilowatt-hours per year. The initial cost of this motor is $60,000, but it results in yearly savings of $10,000. Additionally, it reduces carbon dioxide emissions by 30 tons per year and achieves a cost efficiency of 16.7%. Additional equipment such as spinning shafts, conveyor systems, and fan systems also provide favourable energy conservation and emission reduction outcomes, but with differing expenses and efficiencies [46,47].

Table 10: The efficiency of different energy harvesting systems in relation to diverse industrial equipment

Machinery/ Equipment	Estimated rotational kinetic energy (kWh/year)	Energy harvesting technology	Installation cost ($)	Annual energy savings ($)	Environmental impact reduction (CO_2 emissions, tons/year)	Cost efficiency (%)
Industrial turbine	150,000	Flywheel energy storage	100,000	15,000	45	15%
Electric motor	80,000	Regenerative braking system	60,000	10,000	30	16.7%
Rotating shaft	50,000	Energy recovery generator	40,000	8000	20	20%
Conveyor system	30,000	Dynamic energy recovery system	30,000	5000	15	16.7%
Fan system	20,000	Integrated flywheel system	25,000	3000	10	12%

In order to optimise efficiency and reduce environmental effect, future proposals for energy harvesting in environmental sustainability centre on merging cutting-edge technology with renewable energy sources [48]. The performance and endurance of energy harvesting devices may be improved by placing an emphasis on the development of novel materials and well-designed structures. Furthermore, developing multidisciplinary research and cooperation will be essential to developing scalable solutions that support the objectives of global sustainability. Table 11 is summarizing future recommendations for energy harvesting to enhance environmental sustainability.

Table 11: Future recommendations for energy harvesting to enhance environmental sustainability

Aspect	Future recommendations	Potential benefits	Challenges
Technology integration	- Develop hybrid systems: Integrate multiple energy harvesting technologies (e.g., solar, wind, kinetic) to optimize energy capture.	- Increased energy efficiency: Maximizes energy harvesting potential by leveraging various sources.	- Complexity in integration: Challenges in combining different technologies and optimizing their performance.
Material innovation	- Utilize advanced materials: Employ new materials such as nanomaterials or composites for better energy capture and durability.	- Enhanced performance: Improved efficiency and longevity of energy harvesting devices.	- Material cost and Availability: High costs and limited availability of advanced materials.
System scalability	- Design scalable solutions: Develop energy harvesting systems that can be scaled from small to large applications.	- Versatility: Adaptable for various scales, from individual devices to large industrial systems.	- Scalability challenges: Ensuring efficiency and performance across different sizes and applications.

(Continued)

Table 11 (continued)

Aspect	Future recommendations	Potential benefits	Challenges
Efficiency optimization	- Optimize energy conversion: Improve conversion efficiency through advanced technologies and designs.	- Maximized energy output: Higher efficiency translates to more usable energy from harvested sources.	- Technical complexity: Developing and implementing high-efficiency conversion technologies can be complex.
Environmental impact	- Conduct life cycle assessments: Evaluate the environmental impact of energy harvesting systems throughout their lifecycle.	- Sustainable design: Ensures that systems are environmentally friendly from production to disposal.	- Comprehensive analysis: Requires thorough assessments and data collection.
Economic viability	- Promote cost-effective solutions: Focus on reducing costs through innovation and economies of scale.	- Increased adoption: Lower costs can lead to wider adoption and implementation.	- Balancing costs and performance: Ensuring cost reductions do not compromise system performance.
Policy and Regulation	- Advocate for supportive policies: Encourage policies and incentives that support the development and adoption of energy harvesting technologies.	- Enhanced industry support: Government backing can accelerate innovation and deployment.	- Policy variability: Differences in policy support across regions and countries.
Public awareness and Education	- Increase awareness: Educate the public and industry about the benefits and applications of energy harvesting technologies.	- Informed decision-making: Greater understanding can lead to more widespread adoption.	- Educational outreach: Requires effective communication and educational programs.
Research and Development	- Invest in R&D: Prioritize research and development to explore new energy harvesting methods and improve existing technologies.	- Innovation and progress: Drives advancements in technology and increases efficiency.	- Funding and resource allocation: Securing adequate funding for research initiatives.
Maintenance and Longevity	- Enhance durability: Develop systems that are more resilient and require less maintenance.	- Reduced operational costs: Fewer maintenance requirements can lower overall costs.	- Design challenges: Creating durable systems that still perform efficiently.

6 Conclusion

The theoretical and experimental results for both the disk and cylinder bodies under free-running conditions indicated zero recyclable energy, confirming the accuracy of the theoretical models in no-load scenarios. However, discrepancies were observed under loaded conditions, suggesting that the theoretical models do not fully account for practical inefficiencies such as heat dissipation and resistance variations.

For the disk body, the theoretical recycling energy under a 40 W resistive load condition was 15.55 J, while under a 20 W charge controller condition, it was 13.73 J. Similarly, for the cylinder body, the theoretical recycling energy was 17.27 J under a 40 W resistive load and 11.67 J under a 20 W charge controller. These findings highlight that practical inefficiencies such as control system inefficiencies, electronic losses, and mechanical friction are not completely captured by the theoretical models. This study underscores the need to consider these practical inefficiencies when designing energy recycling systems for industrial applications. Additionally, the comparison between the disk and cylinder bodies reveals that the disk body generally exhibits higher efficiency in energy recovery under similar conditions, making it a more favorable candidate for energy recycling in rotational systems.

The insights from this research could significantly impact the design of more efficient energy recycling systems, leading to enhanced sustainability in industrial practices. Future research should focus on several key areas to further improve the understanding and efficiency of energy recycling systems in industrial applications. Long-term experimental studies are needed to investigate mechanical power transmission via magnetic coupling, which could provide more insights into potential energy savings and efficiency improvements. Establishing precise and safe procedures to address faults such as overspeed, short circuits, and overvoltage protection will be crucial for ensuring the reliability and safety of these systems.

Acknowledgment: Authors would like to thank Multimedia University, Malaysia, for their financial, lab and their logistic support throughout the journey.

Funding Statement: The APC was funded by Research Management Center, Multimedia University, Malaysia.

Author Contributions: Conceptualization, See Wei Jing, Md Tanjil Sarker and Gobbi Ramasamy; Methodology, See Wei Jing, Md Tanjil Sarker and Gobbi Ramasamy; Validation, See Wei Jing and Md Tanjil Sarker; Formal analysis, See Wei Jing and Md Tanjil Sarker; Investigation, See Wei Jing, Md Tanjil Sarker, Gobbi Ramasamy, Siva Priya Thiagarajah and Fazlul Aman; Data curation, See Wei Jing, Md Tanjil Sarker and Gobbi Ramasamy; Writing—original draft, See Wei Jing and Md Tanjil Sarker; Writing—review & editing, See Wei Jing, Md Tanjil Sarker, Gobbi Ramasamy, Siva Priya Thiagarajah and Fazlul Aman; Visualization, See Wei Jing, Md Tanjil Sarker and Gobbi Ramasamy; Supervision, Md Tanjil Sarker, Gobbi Ramasamy and Siva Priya Thiagarajah; Funding acquisition, Gobbi Ramasamy. All authors reviewed the results and approved the final version of the manuscript.

Availability of Data and Materials: The data that support the findings of this study are available from the corresponding author, (G. R.), upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

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